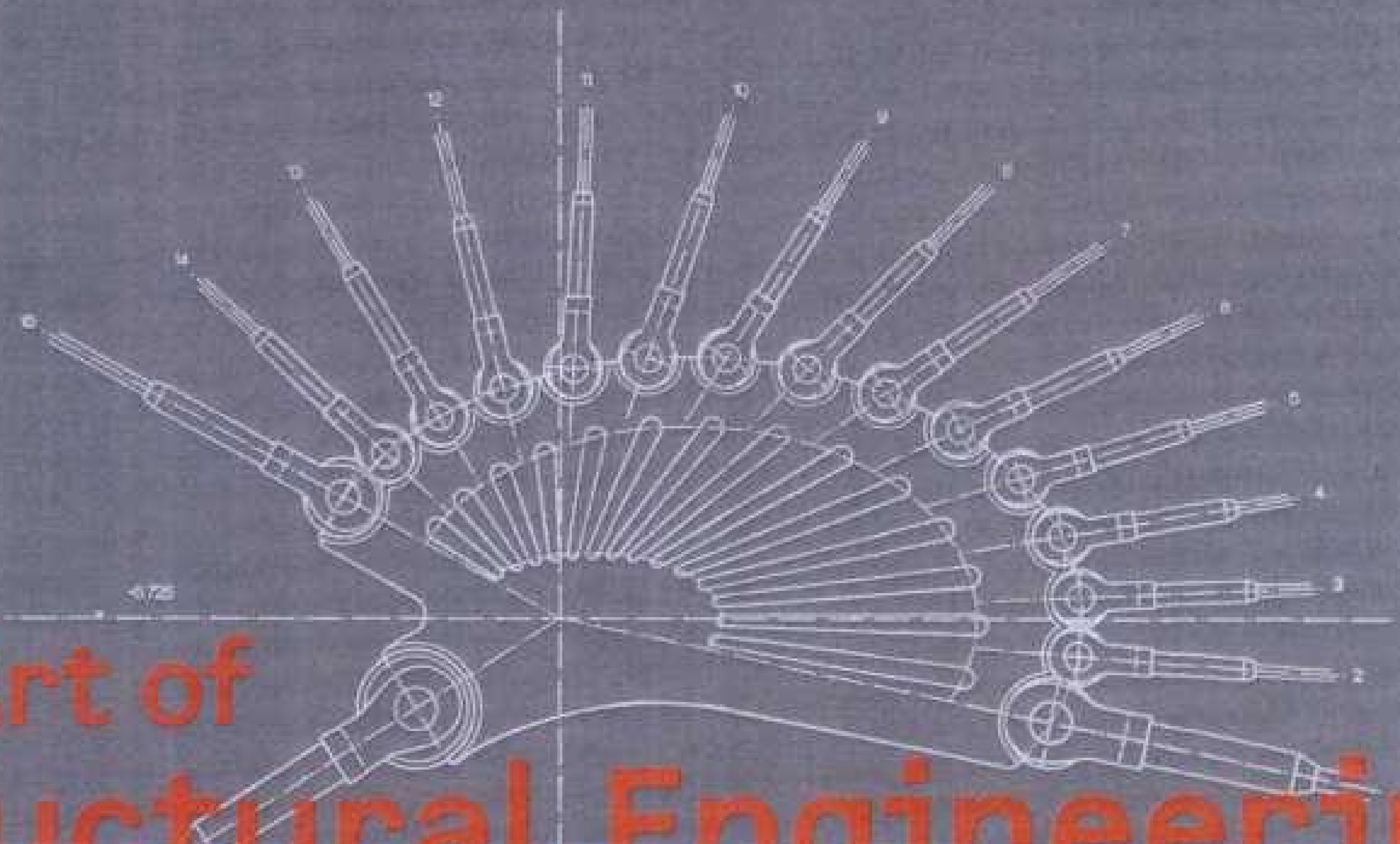
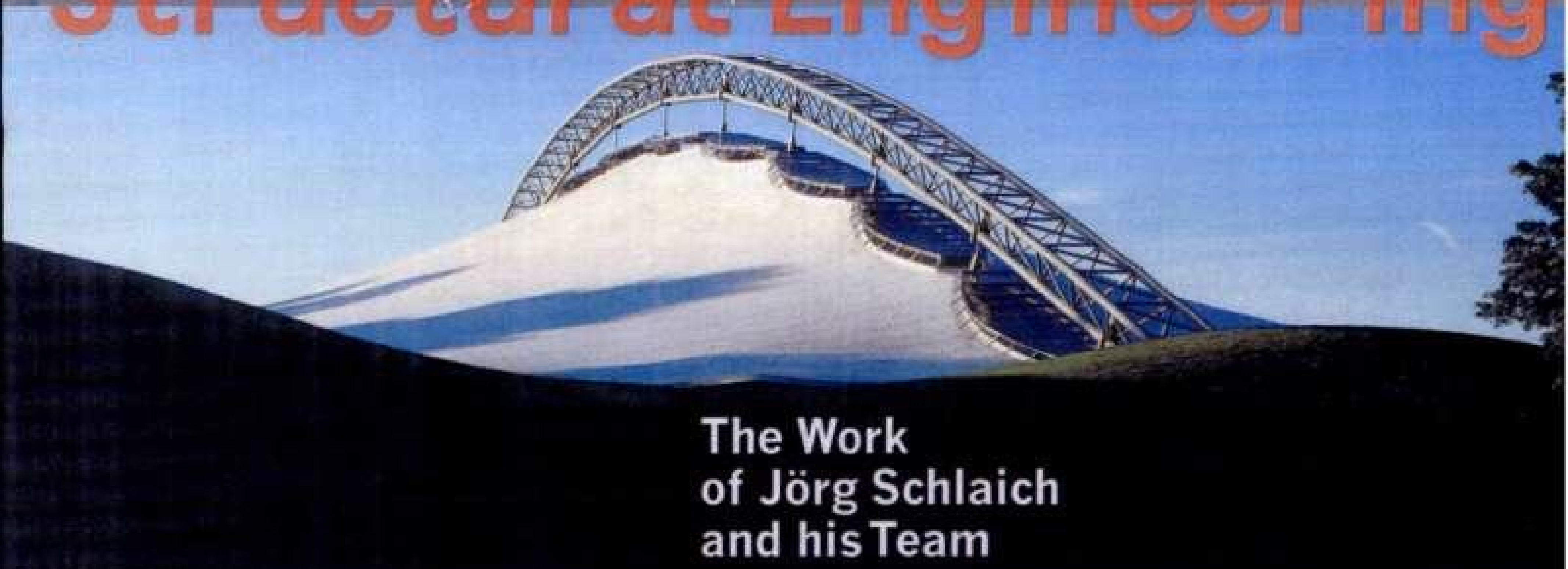
Alan Holgate



The Art of Structural Engineering



The Work of Jörg Schlaich and his Team

Edition Axel Menges

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The idea of writing a book such as this first occurred to me during a period of sabbatical leave in late 1984 which included visits to a large number of internationally recognized structural engineers and architects. Jörg Schlaich's friendliness, his infectious enthusiasm, and his frank discussion of the challenges and difficulties of structural design convinced me that he would make an ideal subject for a study that would convey the fascination of structural engineering to engineers and architects as well as to non-specialists, students, and young engineers alike. His ideas are innovative, he utilizes advanced technology, and he takes a keen interest in the aesthetic quality of his structures. These factors and his commitment to lightness and transparency give his work a special character. Amongst his other achievements, he has made an art-form of the design of footbridges: a field in which the individual engineer can achieve a high degree of individual control over form and detail. He has also published much easily accessible material (in English as well as German) and this greatly facilitates the study of his ideas.

The production of the book was to have a rather lengthy and complex history. Having conceived the idea in 1984, I was obliged to shelve it for the time being as I was committed to start solid work on my previous volume, *Aesthetics of built form*. However in late 1987 I took the opportunity of a further period of sabbatical leave to conduct more discussions with Professor Schlaich and in 1990 I approached potential publishers and applied for funding for further investigations from the Australian Research Grants Commission. On hearing that this application had been successful I finally informed Professor Schlaich of my plans early in 1991, only to learn that Axel Menges had in the meantime approached him with a similar proposal. On Menges's behalf, Rosemarie Wagner had already assembled a great deal of information concerning the history and technical details of the Schlaich Bergermann projects (information that forms the backbone of Chapters 3 to 11) and had placed it in the context of intensive studies of the history and nature of the various structural types concerned (towers, shells, etc). Dr Wagner kindly agreed that I should collaborate in a joint venture but as work progressed, because I was keen to include more personal material concerning Schlaich's background and his philosophy of design, a gradual hand-over occurred. I added Chapters 1, 2, and 12 and recast Chapters 3 to 11, largely omitting the more general material and reducing the technical content, thus permitting more emphasis on Schlaich's personal contribution.

The aim of the book in its final form is to convey an impression of the art of structural engineering through an account of the ideas and projects of one of its leading exponents. The word "art" is used advisedly. Although decision-making in technology is dominated by the laws of nature, and by economic and practical realities, the individual designer enjoys much greater freedom of choice than is generally recognized. As a result, decisions are influenced by the personality of the individual engineer and by his or her attitude to a wide range of technical and non-technical issues.

Such an approach presents some problems for the author and even more for his subject. Structures are designed and erected by closely integrated teams of engineers drawing on the expertise of many specialists. Naturally, some of these stand out as leaders in the conception, initiation, and execution of a project, but it is difficult to isolate the precise contribution of any one member of the team. I have therefore tried to strike a balance between my desire to highlight the work and ideas of an individual and my obligation to acknowledge the importance of Schlaich's collaboration with his partners Rudolf Bergermann, Hans Schober and Andreas Keil, with close colleagues in the university, mainly Knut Gabriel, Kurt Schäfer, and Karl-Heinz Reineck, and with project engineers in the design office. Many of these have remained as a team since they engineered the roofs for the Munich Olympic Stadiums between 1968 and 1971.

In trying to discover ways in which Schlaich's personality, intellectual background, and response to his current work environment have influenced the nature of his solutions to design problems, I make no claim to be psychologist, biographer, or historian. Although some evaluation of Schlaich's structures has been included (mainly in terms of aesthetics) this has not been one of my primary aims, partly because of the complexity of the art of structural engineering as indicated by the range of opinion amongst eminent engineers. An impressive aspect of the Schlaich Bergermann oeuvre is its prolific nature – there are a multitude of projects covering a wide range of fields. It is impossible to give adequate coverage to all of these. Many of them – such as the Munich Olympic Roofs, the Hooghly Bridge in Calcutta, or the solar updraft power station at Manzanares – merit at least one book in themselves. The same could be said of the continuing research carried out under Schlaich's leadership, and with his direct involvement, in the Institute for Conceptual and Structural Design at the University of Stuttgart. The German custom of appointing successful practitioners to teach and research in universities ensures a very fruitful interaction between all aspects of their work. As a result, this study can provide only a glimpse of the technical complexity of form, of innovative practical detail, of structural analysis and design, of learned research, and of the diligence and sheer volume of effort that has gone into the design of the structures listed.

Melbourne, Summer 1995
Alan Holgate

I am greatly indebted to the following organizations and individuals:

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Rosemarie Wagner, who fully documented the technical details and development of the individual projects and prepared a draft on which the technical content of Chapters 3 to 11 is based.

Ilse Guy, Professor Schlaich's secretary at the university who translated Dr Wagner's highly technical draft into English.

Margot Zalbeygi, Professor Schlaich's secretary in the consulting practise, who searched the office archives for material suitable for inclusion in the book.

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Axel Menges, who provided advice and encouragement to all concerned throughout the gestation of the book.

Jörg Schlaich, who during many interviews answered my questions and explained complex technical matters with great patience. He also checked the basic historical facts and the accuracy of my technical explanations.

A. H.

1 An Introduction

Before considering Jorg Schlaich's career in detail, it is appropriate to introduce him by looking at some of the ideals which inspire his work and at certain aspects of his personal background which may have contributed to their formation. It is these ideals which place him amongst the leaders of his profession and give his work a very special character.

Amongst Schlaich's foremost concerns are the quality of the natural and built environment and the interests of the less powerful members of society at home and overseas. The latter are expressed in his drive to find cheap and renewable sources of energy, and his special interest in the Third World. As a structural engineer, he strives constantly to improve the general quality of design in both the technical and aesthetic sense, and to enhance the philosophical and social values which guide engineers and architects. He argues in particular for a more adventurous, less conservative approach to projects. He does not shrink from conflict in propagating and defending his ideals and the decisions and arguments which flow from them.

In a paper published in the proceedings of the International Association for Bridge and Structural Engineering (IABSE) in 1990 Schlaich wrote: "The only answer to the greatest threat in the history of mankind – the population explosion with undignified poverty in large areas of the world and, as a result of that, climatic and environmental catastrophes all over the world – is a clean, safe source of energy available in sufficient quantity for all of mankind. It would be both technically feasible and affordable, and a fraction of the earth's desert areas would be enough to obtain from solar radiation the amount of energy needed to avert these catastrophes ... [but] ... It has to be said that unparalleled material and political effort will be needed to gradually bring about a solar economy. To face up to this challenge and to demand this effort of society can be said to be a matter of paramount political urgency."[1]

Writing in 1983 about his experimental solar power station at Manzanares (Chapter 11) he stated "At present it is simply too early to make a well-founded statement about the economic prospects of using renewable sources in general or of solar chimneys in particular. Neither the naivete of the environmentalists nor the occasional arrogance of the 'Megawatt Clan' is sufficiently capable of handling the greatest challenge in the history of mankind ... We owe it to the Third World with its crying need for energy even today, to develop energy sources that they can afford."[2]

In an editorial for the journal *Die Bautechnik* he asks how the western world can remain preoccupied by its quest for ever more efficient production, depriving the Third World of its only capital – its labour – and contributing further to the vicious spiral of increasing population, increasing energy use, and increasing destruction of natural resources.[3] He sees this as the greatest threat to the future of all nations and calls on engineers to "come out of their shells" and apply their skills in tackling the overwhelming problems which the politicians, held in thrall by small but powerful lobbies within the industrialized nations, cannot or will not recognize.[4] We shall see in later chapters how the themes mentioned above have inspired much of Schlaich's work on membrane and cable structures and resulted in a number of promising prototypes for the production of electrical energy: the Manzanares power station and the refined versions of spherical-mirror solar collectors (Chapter 11). To further propagate these ideas he produced an attractive book, with his daughter Sibylle as graphic designer, entitled *Erneuerbare Energien nutzen* – "Use Renewable Energy Sources!"

Schlaich sees it as the public duty of designers to create an aesthetic environment and ensure a minimum level of "honesty" and rationality in structural form. In a further paper in the IABSE journal he states that "the engineer's mission in the name of society and culture [is] to build well and to build beautifully"[5] and elsewhere, noting that we are all obliged to live with buildings, and thinking particularly of bridges, he writes: "Ugly structures can destroy the environment and make people sick. They also contribute to hatred of technology ... We [engineers] cannot push this problem off onto the architects, or leave them alone with it, especially as many structures ... are designed only by engineers."[6]

These beliefs have led him to join committees which advise cities such as Stuttgart and Ingolstadt on aesthetic matters relating to the built environment. He does not shrink from conflict if he feels principles are at stake, and is willing to put his thoughts in writing, but so far is not greatly satisfied with his achievements in this regard.[7]

The forcefulness of Schlaich's feelings on these matters has much to do with a heightened aesthetic sensibility. "Footbridges have a very strong effect on the built environment of cities. Unfortunately, it is all too often negative. This is attested by countless bad examples: [their members] clumsily, insensitively designed 'sticks' with ugly flights of stairs, grandiose ramps, dripping and muddy prefabricated joints, heavy landings and in case of doubt, furnished with balconies and candelabras and decorated with greenery. In fact, these small bridges demand, from those who design in earnest, much diligence and trouble. This is particularly so when ramps for the handicapped, necessarily long, must be inserted in confined conditions, and the whole lighted, drained, and proofed against corrosion from the salt used to remove ice. To be sure, there are no general rules for the solution of these complex design problems. When one realizes, however, that footbridges are much closer to us than other types of bridge; that we can touch them, and that they trouble us when they are big and heavy, then it becomes clear that they must possess human scale overall and in detail, and therefore must be delicate, slender, and filigree. Therefore, it is necessary to avoid direct bending and to dissolve [solid] beams into trussed girders, arches, or systems of cables. No particular type of structure should be given precedence, because diversity and change are indispensable means to beautiful form. Uniformity is boring."[8]

Noting that for much of their length many bridges and viaducts pass low above the ground he insists that they be made less alienating. "We come into physical contact with them, and are concerned if they are clumsy and heavy. The lower they are over a valley, an allotment, footpaths or roofs, so the lighter, more filigree, and transparent must we build them, and we must give them human dimensions."[9]

Elsewhere, he condemns the uniformity and often "inhuman scale" of major bridge construction: "parallel-sided hollow box girders ... all identical, as if they came from the same mould" in total disregard of the shape and size of the valleys which they cross. He contrasts much modern bridge construction with the "beautiful and proud" bridges built at the start of the 150-year history of the German railways.[10]

Schlaich insists that structures should be adapted both technically and aesthetically to their environmental setting. In one instance he opposed a proposal to run a road bridge at a highly skewed angle across a river just outside the old town of Ingolstadt on the grounds that this technical tour-de-force diminished the significance of the river. He felt that the approach roads should be curved to allow a shorter-span bridge to make a more direct crossing, thus making obvious recognition of the existence of the river. As a result of his opposition the bridge was not built. In contrast, Schlaich's own structures, wherever possible, are self-effacing both in the visual sense, and in being relatively easy to remove or recycle. He commented in a recent lecture: "if you see a bridge that you cannot see, it must be one of ours!" On another occasion he said that if there were no longer a need for one of his bridges, he would be happy that it could be easily and cheaply dismantled leaving the site free to return to nature or become available for a young designer to start anew.

It is possible to link Schlaich's enthusiasms and many of his personal qualities with his Swabian background. Stuttgart, the capital of the modern state of Baden-Württemberg, lies in the old duchy of Swabia (Schwaben). Regional loyalties are still strong in Germany, and many people see themselves as, for example, Saxons or Bavarians first, and Germans second. Inevitably, each group has its caricature image. These cannot be taken too seriously, but they are worth mentioning, especially as they have some currency amongst Germans themselves. Schlaich points out that Swabians are known as the "German Scots" and adds that they have a serious, and somewhat gloomy temperament exemplified by the works of Schiller and Hegel. The commentator Hans Bayer, in his humorous *Deutschland deine Schwaben*, characterizes his fellows as deliberate, slow, obstinate and reserved, but also prudent, frugal, tenacious, hard-working, and energetic.[11]

Schlaich's upbringing was strongly influenced by religious ideals. His father was a minister and principal of a large church-owned hospital for the mentally disturbed and one of his brothers was his successor. As a boy, Jörg spent long periods in the country to escape the continuous air-raids of World War 2, lodged in the household of a Pietist farmer. Pietism developed in the late 17th century as a first cousin of English Puritanism and its outlook accords in many ways with the Swabian, particularly in its resentment of authority figures who claim a respect they have not earned, and in a sense of mission to right wrongs.[12] Schlaich recalls that his father who received much support in his work from the Pietist community often took up public causes and that, once he had made up his mind that something needed to be done, there was no stopping him until the matter had been resolved. (These crusades tended to "turn the household upside down".)

It could be said that there is an element of puritanism in most engineers: a desire to serve others; a tendency to find quiet joy in achievement through hard work; and a suspicion of ostentation and superficiality. Schlaich's family background undoubtedly accentuates this. Like many noted designers he has a strong sense of what is appropriate in structure – a conviction that the laws of nature point the designer in certain directions and that it is wrong to diverge from these wilfully. "The engineer has, in the ever-present pressure for economy, a strict but good master. This leads to efficient structures in which all that is unnecessary has been discarded."[13] The weight of a structure and the loads applied to it should be carried to the ground by the most direct paths consistent with the structure's function as an encloser of space or a provider of pathway. Circuitous and distorted load paths are justified only by the most pressing functional needs.

Such principles are closely related to the concept of "honesty" in structural design. Schlaich feels that structural forms which act mainly in direct tension or compression, with a minimum of bending, are particularly honest. These include shells, tents and cable nets. In extolling the virtues of the shell he wrote: "The shell is the most honest of [concrete] structures ... [it] lends itself less than any other structure to attempts to hide inadequate design under camouflage or cladding."[14]

There is an element of puritanism in Schlaich's insistence that the joy and satisfaction of successful structural design must be won through a lifetime's dedication involving many struggles and much hard work.[15] He notes that "creativity in structural design can only be based on competence. Without competence you can only repeat, or at best improve on, what has been done before; you cannot conceive of fresh ideas, invent, be innovative!" However, he hopes this will not discourage young people from entering the profession, and suggests there are other approaches besides his own: "A Saxon might see things differently!" In describing the opening of the Max-Eyth-See footbridge in Stuttgart (Chapter 9) he writes of the joy of building, Freude am Gebauten. "All involved [in the creation] of this bridge, whether they were responsible for it through the City of Stuttgart, or planned and built it, are happy that their bridge is successful and beautiful, and that it has met with much approval from the population. It was opened officially with a four-day celebration with a church service, speeches, music, performances, lectures on bridge building, and a great deal of fun. Few use it without thought, most look carefully at it and take an interest in its construction. Let us hope that this will benefit the standing of the profession of the structural engineer and its appeal to creative young people."[16]

For him, the most rewarding moment in the life of a project is when, after months or years of creative effort, of examining and sifting ideas, of analyzing, of making difficult choices between alternatives, of producing drawings and specifications, construction finally starts. He speaks enthusiastically of watching the deck of the Hooghly River bridge gradually reaching out across the river (Chapter 8) and of seeing the cable-net roof of his skating rink in Munich rising into position (Chapter 5). Finally, after months or even years of construction, through the efforts of many collaborators, a new structure: something solid, useful, and reasonably lasting, has been brought into being.

Alongside the more sober characteristics of the Schlaich household there existed a lively interest in the arts. For a long time the family regularly played music together on Sundays, the father being a competent pianist, and all five children instrumentalists. Jörg played the violin. He was able to maintain his skills throughout his student days and still makes time occasionally to play quartets with a group of old friends from that period. His mother had a special interest in art and collected Bauhaus furniture and household ware. His sister Brigitte developed similar interests and has since then had a continuing influence on his aesthetic thinking. She studied architecture at the University of Stuttgart and then at the Illinois Institute of Technology, where the architecture school was headed by Mies van der Rohe, one of the "founding fathers" of the Modern Movement in architecture. While in America she met and married Walther Peterhans, the photographer of the Bauhaus School and became Brigitte Schlaich-Peterhans. She worked in Chicago until recently for the famous American firm of Skidmore Owings and Merrill, building a solid reputation as a practising architect.

It is quite easy to see in Schlaich's work, particularly in his acceptance that aesthetic considerations are an integral part of engineering design, a tradition which goes back to the Deutscher Werkbund movement and the Bauhaus.[17] He readily agrees with this analysis, and suggests that his aesthetic sense includes a practical component which stems from his mother, and an abstract component (related to musicality) which he owes to his father.

In conclusion it should be noted that Schlaich's sense of mission, his adventurousness, his appreciation of the joy of building, and his aesthetic sensitivity must be balanced against an engineer's heavy responsibility for safety and economy.[18] Some engineers find this burden so great that they abandon hope of achieving major innovations, of designing unconventional structures, or even of allowing aesthetic considerations to influence their designs. It is Schlaich's particular response to this challenge that has placed him high amongst the leaders in his field and earned world-wide respect from fellow engineers.

Notes to Chapter 1

[1] J. Schlaich: "How much desert does a car need? The case for more intensive research into the utilization of solar energy", *IABSE Periodica*, 2/1990, *Proceedings*, P-144/90, p. 58. See also *Structural Engineering International*, 1/1993 and 3/1993.

[2] J. Schlaich: "Solar chimneys: the principle – the pilot plant – prospects for the future", *IABSE Periodica*, 3/1983, *IABSE Structures*, C-26/83, p. 58. See also J. Schlaich, W. Haaf and H. Lautenschlager: "Das Aufwindkraftwerk Manzanares – Zusammenfassung der bisherigen Ergebnisse, Stand Febr. 1984," *BMFT-Report*.

[3] J. Schlaich: editorial, *Die Bautechnik*, 69, Heft 5/1992.

[4] Schlaich's interest in the underdeveloped and desert regions of the world has been inspired and reinforced by a number of adventurous expeditions. As a student in 1955 he travelled extensively in the Middle East. Later, he made a 2000 km round trip through the Sahara desert with his wife and two young children in a four-wheel drive vehicle, and in 1976 completed an overland journey by car "with the same crew" from Stuttgart to Calcutta to inspect the site of the Hooghly River Bridge. More recently he has travelled with his wife in the Ladakh, the Yemen, India, Nepal, China (the Silk Road), Pakistan (Karakorum Highway), and Africa always touring the less populated areas.

[5] J. Schlaich: "The Computer between Science and Practice in Structural Engineering", *Structural Engineering International*, 1/1991 (Feb. 1991), p. 35.

[6] J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61/1986, p. 49.

[7] He qualifies this with "... ich mich durch die Schrift von G. E. Lessing 'Der Rezensent braucht nicht besser machen zu konnen, was er tadelt' beschutzt fuhle". J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61/1986, p. 49.

[8] J. Schlaich: "Fußgangerhangebrucken oder: es lebe die Vielfalt!", *Schweizer Ingenieur und Architekt*, 12/87, 283–286.

[9] J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61, 1986, p. 51.

[10] J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61, 1986, p. 49.

[11] H. Bayer (Thaddäus Troll): *Deutschland deine Schwaben*, Deutsche Buch-Gemeinschaft, Berlin, 1967. (See also his: *Preisend mit viel schönen Reden*, Hoffmann und Campe, Hamburg, 1972.)

[12] The Pietist movement arose in reaction to the complacency of the Lutheran church of the late 17th Century. The church was felt to have lost its reforming zeal and to have accommodated too well to the interests of the local princes, who were aping the hedonism and political absolutism of Versailles. Although the Wurttemberg variety of Pietism was less actively political than Puritanism, it differed from the Prussian version by its strong antagonism to this phenomenon. (See e. g. M. Fulbrook: *Piety and Politics: Religion and the rise of absolutism in England, Württemberg and Prussia*, Cambridge University Press, Cambridge, 1983.) The main drive for reform came from low-ranking clerics and lay people. As conditions stabilized in the following century, the movement took less interest in political matters and became more concerned with biblical study and education. To quote Petig's summary: "Pietism differed fundamentally from orthodoxy in its social concern for the lower classes, which expressed itself, for example, in the establishment of charitable organizations, a strong commitment to popular education, and the use of the vernacular ... in church and school." (W. E. Petig: *Literary antipietism in Germany during the first half of the 18th Century*, Peter Lang, New York, 1984, p. 24.)

[13] Speech on acceptance of the Fritz Schumacher Prize, Hanover, 4 December 1992.

[14] J. Schlaich: "Les structures légères", *Annales de l'Institut Technique du Bâtiment et des Travaux Publiques*, No. 479, Dec. 1989, p. 4–42. Schlaich later noted in conversation that it was perhaps "overdoing it a bit" to place the shell ahead of arches, membranes, and cable nets in this regard.

[15] Schlaich sees the aim of engineering education as "to liberate the student from the chains of incompetence". When the author complained that intense concentration on theory would distort the student's perception of engineering, he said: "I would tell him you have to accept that you are distorted now, but in ten years you will be able to see the whole picture – and that can happen only through competence!"

[16] J. Schlaich and E. Schurr: "Fußgangerhangebrucke uber den Neckar bei Stuttgart", *Beton- und Stahlbetonbau*, 85/1990, Heft 8, p. 198.

[17] See, e. g. F. Whitford: *Bauhaus*, Thames and Hudson, London, 1984; and L. Burckhardt (ed.): *The Werkbund: history and ideology 1907–1933*, American edition: Barron's, New York, 1980.

[18] In a paper with Professor Fritz Leonhardt concerning the design of giant television towers he writes: "It is a constant challenge for the structural engineer to strike the right balance between a readiness to take risks to achieve economic design on the one hand, and [assurance of] the necessary safety on the other". J. Schlaich and F. Leonhardt: "Zur konstruktiven Entwicklung der Fernmeldeturme in der Bundesrepublik Deutschland", *Jahrbuch des elektrischen Fernmeldewesens*, 1974.

2 Formation and Career

Jörg Schlaich was born in 1934 in Stetten/Remstal, a village seventeen kilometres to the east of Stuttgart, where he commenced his primary schooling. This continued when the family moved to Heilbronn, but life was extremely hard owing to the war. Added to the constant danger and shortages of food and fuel was the distress caused by uncertainty about the whereabouts of his father. Because of random bombing raids on Heilbronn, the small group was obliged to live for a year entirely in the cellar. On 4th December 1944, the town was attacked by a formation of 500 bombers while the Schlaichs and their hosts sheltered in the cellar. Within half an hour the town had been reduced to rubble above their heads, leaving some ten thousand civilian casualties.

2.1
The Töss-Steg, Winterthur (1934) by Robert Maillart (from Max Bill's book)

2.2
The Raleigh Arena at Raleigh, NC, 1953, by M. Nowicki (idea), W. H. Deitrick (architect), F. Severud (engineer) (from Frei Otto's book)

Times were still hard after the war, but the family was reunited and returned to Stetten where Jörg progressed to the Oberschule. At that time German high schools finished the day at 2.00 pm and pupils were expected to continue their studies at home for the rest of the day. The young Schlaich preferred to play football or build cubby houses in the local forest. To counteract this tendency, his father sent him to work several afternoons a week in a joiner's shop. He gradually came to enjoy the work and is now grateful for his father's initiative. Having passed his school leaving examination, the Abitur, he worked from March to October 1953 full time at the joinery to pass the final trade examination (the Gesellenprüfung) and become fully accredited as a joiner. The experience gave him a lasting respect for the skills and opinions of tradespeople and enabled him to feel at ease later in his career in talking with construction workers. The exacting nature of the joiner's task proved a useful training for his professional work while the practical skills acquired enabled him to build scale models to assist in the planning and design of engineering projects.[2]

Schlaich's tertiary education began in October 1953 at what was then the Technische Hochschule in Stuttgart. The first step on the academic ladder was the two-year Vordiplom. Like many young people with an interest in construction, he found it difficult to choose between engineering and architecture. The former offered rigour and practicality; the latter an outlet for artistic aspirations. He resolved the problem by enrolling formally as an engineering student, but attending concurrent lecture courses in architecture. A slight problem was that the engineering school was then in the centre of Stuttgart, while the architecture school was situated on the steep hill next to the famous Weissenhofsiedlung. For two years he cycled back and forth between the two, trying to reconcile conflicting timetables. It proved possible to cover all of the subjects required for the Vordiplom in architecture except those that had direct equivalents in the engineering course. Schlaich thus gained a training in visual perception, sketching, and basic architectural design. (Student projects included an office building and an exhibition centre.) His teachers in the architecture school at the time included Hans Kammerer, with whom he was later to work as an engineer. He remembers that his visits to the architecture school helped him tolerate "the rather annoying maths and statics lectures" of his engineering course.

During this time his sister fostered his interest with gifts of inspiring books concerning structural engineers who were recognized as "honorary architects" because of their innovative approach and their mastery of aesthetic form. These included Max Bill's book on Robert Maillart (2.1), and Jurgen Joedicke's book on Pier Luigi Nervi. Another major influence was Frei Otto's book on lightweight suspended roofs: *Das Hängende Dach* (2.2). Schlaich discovered a copy in a bookshop in Ankara where he had gone to obtain site experience during one of his summer vacations. He bought the book with his few remaining Turkish lira and carried it with him on a journey by bus, camel, donkey, and boat through Syria, Lebanon, and Egypt. At the end of this voyage he knew it by heart.

In October 1955, having obtained his Vordiplom, Schlaich moved to Berlin to complete the rest of his studies (the Diplom itself) at the Technische Universität. He was attracted to the Berlin school by the reputation of its professors for expertise in the complex mathematical analysis of thin concrete shell structures.[3] A further incentive was the availability of a one-year "exchange scholarship" providing tuition fees and a stipend, to encourage students from the rest of what was then West Germany to maintain contact with the island state surrounded by the communist East. In addition, the Berlin institution was unusual in requiring its engineering students to study subjects in the humanities. Schlaich opted for History, Philosophy, and English Literature and was thus able to maintain his wider interests.[4]

Berlin provided a vibrant intellectual and cultural environment at the end of the 1950s. Brecht was in his heyday, and access to the theatre for opera and drama was cheap and readily obtainable. Karajan, Felsenstein, and many others were part of the cultural scene. Schlaich remembers night-long queuing for tickets and many lengthy discussions with fellow students on politics, philosophy, literature and music which continued until the early hours. Klaus-Jürgen Schneider now a professor at Minden became one of his best friends, as did Fritz Bacher who came a year later from Stuttgart and is now in his design office. Together, they formed the core of the student Christian choir. Bacher and Schlaich, playing respectively cello and violin, were members of the very competent orchestra of the Free University at Berlin-Dahlem which was conducted by Forster.

The school at Berlin-Charlottenberg had a highly theoretical bias. This contrasted with the Stuttgart approach, inspired by the great Morsch, which was practical and pragmatic. Schlaich's decision to go to Berlin rather than remain at Stuttgart to complete his diploma is thus indicative of his approach to engineering. It was at this time, also, that he began to meet some of the leading figures in the world of engineering who were to influence his outlook either as mentors or as inspirational figures.

His professor of concrete structures at Berlin was Werner Koepcke, whose predecessor had been Franz Dischinger, the pioneer theorist and designer in the field of thin shell structures. The approach was strictly mathematical: "Koepcke really made you study eighth-order differential equations." These being pre-computer days, even third- and fourth-order "d.e.'s" struck terror in the hearts of student engineers. Practising engineers generally managed to avoid them altogether. However, Schlaich saw the course as a challenge. The magic of the word "shell" was enhanced and has remained with him ever since.

To support himself and gain practical experience, Schlaich obtained a position as Hilfsassistent to Koepcke for 25 hours per week at the rate of 2 DM per hour. One of his tasks was to perform routine calculations for a doctoral thesis, cranking the mechanical calculators then in use. Also assisting Koepcke, by calculating influence lines for cylindrical shells for his thesis, was Klaus-Wolfgang Bieger the Oberingenieur or second in charge of the Institut. Bieger later became Professor at Hannover and he and Schlaich have kept in contact since that time.

Koepcke was Prüfingenieur for many important structures in all fields, checking the methods and calculations of design engineers and certifying that their structures were safe. He made a point of inviting his assistants to accompany him on site visits to observe the construction of these projects. Amongst the many important projects that went through Koepcke's office at that time were the famous Dywidag sewage tanks and the Berlin Congress Hall (Chapter 4). Twenty-five years later the roof of the Congress Hall was to collapse, and Schlaich was to be appointed chief investigator, embroiling him in a great deal of conflict.[5]

A teacher of great importance to Schlaich was Alfred Teichmann, who taught Theory of Structures (Statik) from a fundamental standpoint, using the deductive approach to proceed from the general to the specific. Schlaich is convinced that the reverse, inductive approach which is perhaps more common results in a fragmentation of knowledge into small packages, each one appropriate to a limited range of practical situations. The fundamental approach, reinforced by the ideas of Karl Popper, became part of his general philosophy of engineering. Amongst other teachers, Schlaich remembers in particular Konrad Sattler, famous for steelconcrete composite structures, and "an Austrian Mozartfan".

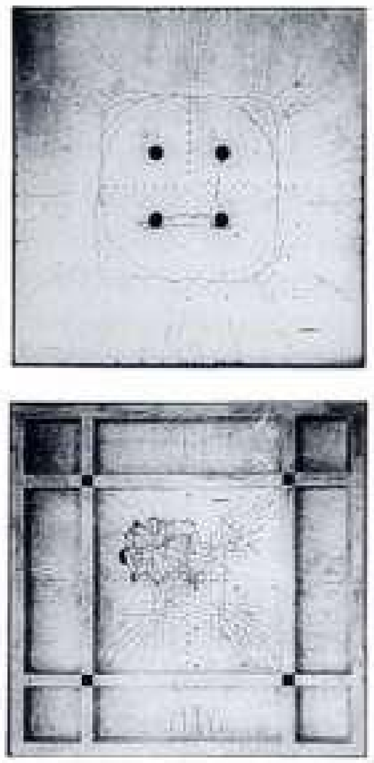
While in Berlin, Schlaich was able to visit Frei Otto for the first time, and thus commence what was to become an important, but tempestuous relationship. In Stetten during the summer vacation of 1955 his sister introduced him to the renowned Chicago architect Myron Goldsmith who in turn took him to meet Fritz Leonhardt, an outstanding figure in German structural engineering who had recently been appointed professor of concrete structures (Massivbau) at the University of Stuttgart, and then to visit the construction site of Leonhardt's pioneering communications tower on the hills above Stuttgart (2.3 and Chapter 3).


2.3
The prestressing cables of Leonhardt's Stuttgart tower foundation (1955)

After completing his studies in Berlin in February 1959, Schlaich returned to Stuttgart and applied to commence an "external doctorate" under Leonhardt. He started work on a thesis concerning arching action in reinforced concrete slabs and although he now has reservations about the empiricism of the approach, he looks back on this laboratory work as solid training. After a short time, however, he received word that a concurrent application to study in the United States had been successful and he had been awarded a Fulbright scholarship. His elder sister and elder brother had earlier received Fulbright scholarships in architecture and theology respectively, and their reports encouraged Jörg to take the opportunity to travel.

Schlaich therefore left to study for a Master's degree at the Case Institute of Technology in Cleveland. After his arrival, he invited his future wife Eve, whom he had known since 1955 to join him, and in April 1960 their first son Michael (Mike) was born there. The course at Cleveland included lectures from Lucien Schmidt who taught certain approaches to structural analysis which Schlaich had not met in Berlin.[6] This allowed him to reinforce his understanding and skills in mathematics and structures. In turn, he gave lectures to undergraduates, using the German *Betonkalender* as a text book of design in reinforced concrete. Despite teaching and research commitments, he found time to make an eight-week trip by car to the West Coast and Mexico. He relates, almost incidentally, that he also completed an "experimental, though silly" MSc thesis on reinforced concrete footings. He submitted this shortly before leaving the country in October 1960, having been asked by Leonhardt to return to Germany to take advantage of a scholarship which was available for the period November 1960 to April 1961. Although he felt there were shortcomings in the education system in the USA, Schlaich's overall impression was that "the country and the people were superb".[7]

The scholarship in Germany allowed him to continue work on his original doctoral thesis. While carrying out his tests on large reinforced concrete slabs at the university's laboratory at the Otto-Graf-Institut, he first met René Walther who was



2.4
Tests on the arching action of slabs. Stuttgart Otto-Graf-Institut 1961 (Immediate supervisor: Dr René Walther. Overall supervisor: Professor Fritz Leonhardt): Cracking patterns in slabs after test loading to failure

2.5
Slab tests: Discussing the results René Walter, Jörg Schlaich and Arnulf Förstner (from left) 1961

2.6
René Walther and Jörg Schlaich (1994)

to become a firm and very close friend.[8] (2.4–2.6) The two were to collaborate later in a number of interesting projects such as the winning design for the replacement of the Williamsburg Bridge in New York (Chapter 8). They now share a chalet in Switzerland and meet as often as possible "trying to solve the burning problems of this planet whilst skiing or mountaineering". A new family including two boys and later two girls proved something of a distraction from the thesis, and Schlaich spent much time making furniture for his new home. He also obtained work with a Stuttgart-based contracting firm named Lubau after its founder Ludwig Bauer. With them he worked mainly in the field of precast concrete construction for multi-storey apartment blocks. His two years with this firm taught him a great deal, especially about prefabrication of concrete members and industrialized formwork: knowledge which he was able to exploit in future projects. It was with Lubau that he did his first structural designs: a conventional apartment block which is still one of the largest and highest in Stuttgart (the Fasanenhof), and a second building with the renowned Hans Scharoun as architect. Schlaich and Dr Reinhard Bauer still maintain close contact.

Until the autumn of 1963, Schlaich continued to work on his doctoral thesis in the evenings. When it was completed, Bauer asked him to assume a responsible position in the firm, but he decided instead to apply for a position with his professor's consulting group, Leonhardt und Andra (2.7). With this move, his professional career began in earnest. Further details will emerge during the description of the individual projects, but a brief chronological overview is presented in the following pages.

Schlaich started work with Leonhardt und Andra under the supervision of Kuno Boll, one of the partners, assisting him initially with the design of the Finnlandhaus office building at Hamburg: "an interesting suspended structure" (Chapter 10). Then, with Leonhardt himself, he worked on the Hamburg television tower: the first large project in which he had the opportunity to develop, under Leonhardt's "extremely competent" supervision and guidance, his own ideas. For this project he was able to develop structural details from his fundamental understanding of the flow of forces in shells, having regard to the need for highly efficient construction methods (Chapter 3). In 1966 Leonhardt generously sent Schlaich to a Symposium in Leningrad organized by the International Association for Shell and Spatial Structures. Since that time he has been an enthusiastic member of the IASS which he considers to be "a most fascinating, though small, international association". He was able to meet a large number of leading figures in the world of innovative structural engineering, and many have remained personal friends and mentors. They included Yoshikatsu Tsuboi, Mamoru Kawaguchi (2.8), Heinz Isler (2.9), Anton Tedesko (12.2) Alex Scordelis, and Herrmann Rühle. In 1967 Leonhardt suggested that Schlaich take over a weekly lecture course on concrete slabs and shells at the University of Stuttgart.

As a practitioner in the Leonhardt und Andra partnership Schlaich continued to work on concrete communications towers including the second Stuttgart tower ("similar to Hamburg but with novel prestressing of the foundation"), Kiel ("similar but with interesting prefabrication"), and Cologne and Mannheim ("with steel heads and suspended floors") (Chapter 3). His experience in this field included a range of smaller standard communications towers and some water towers. It inspired his first two research projects at the university concerning the stiffness of concrete tubes after cracking (the doctoral thesis of Hans Schober who later became a partner in his office) and wind effects on tall towers. It also led to his first "popular" paper to be published in a learned journal concerning wind effects on towers. This period was particularly influential because it convinced Schlaich of the need to overcome the traditional division between concrete, steel, and timber design and the split between the separate professional worlds of design and construction. It prepared the ground for future work on his "solar chimney" project (Chapter 11), stimulated innovative designs and patents (such as a special joint for prefabricated masts) and brought him into contact with the architect Erwin Heinle with whom he was to work on many future projects. He was also able to observe, "in the next room", the work of Harald Egger (now professor at Graz) on the structural detailing of Frei Otto's design for the cable-net roof of the German Pavilion at the 1967 Expo in Montreal.

It was during this period that Schlaich was confronted with an extremely tricky problem in the design of a double hyperbolic paraboloid shell roof (Chapter 4). He surmounted the technical difficulties expertly, but now feels that he should have refused to do so because the original concept was flawed from an engineer's point of view. On the other hand, the challenge further developed his habits of hard work and mental discipline, and in 1968 these stood him in good stead for his part in preparing the Leonhardt und Andra entry for the Munich Olympic Stadium competition.

The architects for this project were Heinle Wischer und Partner, and Kuno Boll was partner responsible for the structural engineering. The team won third prize in the competition and much praise for their engineering of the stadium roof. The first prize was awarded to a team led by the architect Günter Behnisch with Heinz Isler as engineer. However, the competition jury had serious doubts about the technical viability of Behnisch's roof, and eventually appointed the Leonhardt und Andra team and Frei Otto to help Behnisch to develop a modified version. Schlaich was made project leader by Leonhardt and Boll and worked close to Behnisch's office in Munich where he was able to assemble his own team of carefully selected young engineers, many of whom are still close colleagues in the Schlaich Bergermann office or in his Institut at the university. For about two years, the Olympic Roof project took over his entire professional life, and much of his personal life as well. He writes, "I hope that my family did not suffer too much". It was at this time that they built their own house in Stetten. The Munich period deserves an entire book, but is covered briefly in a chapter 5. Schlaich was promoted in 1970 to become a full partner of Leonhardt und Andra.

On returning to Stuttgart in 1971, the Munich team remained together and formed a separate entity within the Leonhardt und Andrä partnership. Altogether there were five partners in the practice, with four working predominantly on bridges. Schlaich's group concentrated almost exclusively on other structures including buildings. This of course involved cooperation with several architects. One of the highlights of this period was the development of the cable-net cooling tower at Schmehausen (Chapter 5). Various circumstances did, however, lead Schlaich to become involved now and then with bridges. His interest in far-away places led him to India, with projects for cable-stayed bridges over the Ganges at Allahabad and Patna and, later, the design of the Hooghly River Bridge in Calcutta (Chapter 8). At home, through a family connection with the landscape architect Hans Luz, he became involved in the design of a series of footbridges to link the public gardens of Stuttgart, the first of which were constructed in 1976. This brought him into touch with what he calls "human size" bridges (Chapter 9).

In October 1974 Schlaich succeeded Leonhardt as professor of concrete structures at the University of Stuttgart. Having strong reservations about the standard "black-box" rules for reinforced and prestressed concrete, and being unwilling to teach them to his students, he immediately instituted work to develop an improved theory for understanding the internal workings of these materials. This is now known as the Strut-and-Tie Method or "STM". His colleagues in this project included Professor Kurt Schäfer, Karl-Heinz Reineck, Dietger Weischede, and Mattias Jennewein amongst many others. The work, which is still in progress, has been published in many forums ranging from the German *Betonkalender* to the American *Journal of the Prestressed Concrete Institute* and is now widely accepted (2.12). It has been incorporated into codes of practice for the design of reinforced and prestressed concrete around the world, including the new Euro-Code and the codes of the American Concrete Institute and Standards Australia. Schlaich's appointment to the Institut enabled him to direct its efforts further towards the development of new forms of construction. With interest in shell roofs waning amongst architects and engineers because of practical difficulties and economic pressures, he was keen to develop more efficient means of building them and to perfect methods for the design and construction of membrane and cable-net surfaces. Structures which grew out of these investigations were the glass fibre reinforced concrete shell roof for the 1977 Federal Garden Exhibition, and a shell roof cast on pneumatic formwork (Chapter 4).

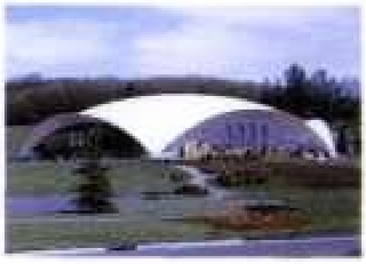
The Leonhardt und Andrä practice in which Schlaich had worked until now was composed of a loose grouping of relatively independent partners and he greatly appreciated and benefited from the freedom this afforded. However, as the number of engineers employed grew from 40 to about 120, he and a number of colleagues attempted to introduce a more formal organization for the sake of efficiency. Leonhardt and Andrä saw this as interference in their affairs and proposed that Schlaich leave. At the beginning of 1980, he separated from the practice with 18 colleagues, adopting the name Schlaich und Partner. While this was in many ways a natural progression, it caused some temporary tension between Leonhardt and Schlaich. The name of the new practice later became Schlaich Bergermann und Partner, in recognition of the crucial role played by Rudolf Bergermann and the later partners.[9]

Although he would not have left Leonhardt und Andrä of his own accord, Schlaich now felt more free, with Bergermann, to pursue his interest in bridges. With Leonhardt's agreement, they had brought the design and supervision of the Hooghly Bridge with them into the new practice. They now initiated the design of a bridge at Akkar in Sikkim, and won a competition to design a curved pedestrian bridge at Kelheim and a large cable-stayed bridge in Germany at Obere Argen, competing for the last against the Leonhardt und Andrä office. This line of development led on to a major bridge at Evripos in Greece, and to a number of schemes and entries for very large crossings (Chapter 8). At the same time the new partners continued the design of small cable-supported footbridges (Chapter 9). Their developing mastery of this field was extended to cover cable-stayed roofs, culminating in the design of the Europahalle in Karlsruhe (Chapter 10).

The experience of the Olympic roof design resulted in a number of other fruitful lines of development. One of these led, by way of the Schmehausen cooling tower, to the "solar chimney" at Manzanares in Spain in 1982, and on to a project for a cable-net observation tower for one of the hills above Stuttgart in 1990. Another led, through a project for a stadium roof in Hannover, to the design of the roof for a second indoor skating rink, the Eissporthalle, within the Olympic complex at Munich in 1985.

2.7
Fritz Leonhardt's bridge over the Rhine at Rhodenkirchen (1941)

2.8
The Tokyo Olympics arenas (1968) K. Tange (arch.), and Y. Tsuboi, M. Kawaguchi (eng.)



2.9
One of Heinz Isler's fabulous concrete shells

Schlaich continued to grapple with the problem that, while doubly-curved surfaces (membrane structures, cable nets and shells) offer the best economy in materials, they are generally expensive to construct. Attempts to develop new forms of membrane construction had led him to study the use of metal rather than fabric for the membrane, and this permitted a major step forward in the design of solar collector dishes (Chapter 11). Schlaich took the opportunity of the 1992 Rio Summit on the environment to urge the further development of the solar chimney, but finds that even with the smaller "solar concentrator" it is very difficult to convince people of the need for research and development in this field. He notes that for the past few years the solar research group in the office has been lead by Wolfgang Schiel, a physicist: "a very enthusiastic, efficient and communicative colleague who deserves credit for considerable progress in the field".

2.10
The Normandy Bridge, 1994, 856 m span, designed by Michel Virlogeux

Experience with more conventional membrane structures was gained in consulting the contractor of Skidmore, Owings & Merrill's Jeddah Airport roof and by doing the detailed structural design of the Riyadh Stadium roof (Chapter 7). A commission to finalize the design of the convertible roof for the Montreal Olympic Stadium provided Schlaich and Bergermann with their greatest technical challenge in recent years, but brought none of the usual satisfaction. Because the tower and part of the membrane had been completed some years earlier, the partnership was committed to a structural system devised by others. Experiences with the design of membrane structures in which the partners had full control of the process have been much better. These include roofs at Nîmes, Zaragoza, Hamburg, and recently the Daimlerstadion roof at Stuttgart.

Extremely light and transparent "grid roofs" formed from a mesh of linear members braced with diagonal cables and covered in glass, were designed for a swimming centre at Neckarsulm and for a Museum at Hamburg (Chapter 6). Many more were to follow including those at Dresden and Singapore, where much earlier the partnership was involved in the roof for the huge hangar at Changi Airport. These grid roofs were a direct development from the partnership's interest in doubly-curved surfaces.

2.11
Rudolf Bergermann and Jörg Schlaich

Throughout this period, Schlaich continued to work with architects, with varying degrees of success and personal reward. He is content to have worked with many good German architects such as Erwin Heinle, Robert Wischer, Günter Behnisch, Fritz Auer, Kurt Ackermann, Uwe Kiessler and Thomas Herzog, where he and his team are "satisfied to have done a decent structural design" (Chapters 10 and 12). In recent years, a design for the Kempinski hotel in Munich brought him into contact with the German-American architect Helmut Jahn, whilst his work with Meinhard von Gerkan and with Volkwin Marg on glass roofs, large exhibition halls, and railroad stations has greatly intensified (Chapter 5, 6 and 10).

Schlaich continues to battle for the cause of innovative and aesthetic bridge design and for the greater involvement of the structural engineer in decision-making regarding the form of structures. He thought he had scored a major victory in initiating design competitions for bridges but notes that on many occasions "bureaucracy has taken over the jury-membership and praises only standard design!" Even these juries tend to be overloaded with architects and to pay more attention to aesthetic formalism than to the equally important technical merit of proposals. A particular interest at the time of writing is Schlaich's crusade to persuade the German railway authorities to modify the design of their low-level viaducts for the new high-speed trains. These are conventionally prestressed concrete box girders, sitting on solid piers. Schlaich wants to dissolve the structure into slender steel elements which will have a much less adverse visual impact on the countryside (Chapter 8).

An important task in recent years, has been the provision of expert advice for major projects on an international scale. Examples include the Pont de Normandie in France (2.10), and the proposal for a bridge across the Strait of Messina, joining Sicily to the Italian mainland. The partnership's expertise has been recognized recently with the award of the design contract for the Ting Kau cable stayed bridge in Hong Kong.

While the practice has gone from strength to strength, the partners prefer to keep it relatively small. It grew to about 50 people and Schlaich states that even this is too big for his liking. He would prefer to be able to give each project a greater degree of personal attention, but "a consultant must have five or six larger projects going at once" to provide continuity of work.

This account of the work of the design office cannot conclude without a special mention of Rudolf Bergermann, who has been Schlaich's senior colleague since the formation of the practice. Bergermann was born in 1941 in Düsseldorf and studied civil engineering at the University of Stuttgart. He joined Leonhardt und Andra in 1967 after a short period working for a contractor. In 1968 he joined Schlaich's team on the Munich Olympic Roof and they have remained together ever since. They became particularly close during their battle over many years to see the design and construction of the Hooghly Bridge through to a successful conclusion. They continue to work very closely together and "there is no project in the practice in which Bergermann is not also involved: a very good engineer" (2.11). Proportional contributions have been made by many other talented engineers who have been members of the practice. Their names will appear in later chapters in connection with particular projects.

Schlaich comments: "In addition to these project engineers our office heavily depends on four designers: Jochen Bettermann, Peter Schulze, Volkwin Schlosser and Brian Hunt, who have been with us for 25 years. With these evolved a lifetime friendship (if one can say that such a packed professional life permits the time to allow it). Young talent follows. And then where would we get without our secretaries?" These include Schlaich's Margot Zalbeygi, Bergermann's Cornelie Schmid, Gerlinde Callies and at the university Ilse Guy.

In parallel with his work in the practice, Schlaich has continued to be an enthusiastic leader of teaching and research at his Institut at the University of Stuttgart. It is usual in German technical faculties for professors to be drawn from the ranks of experienced engineers who continue the active practice of their profession. This close liaison between industry and academia is one of the great strengths of German engineering. Although fundamental research is by no means neglected, practical problems may be brought directly into the university for investigation, and the results fed back immediately for application in practice. A less desirable aspect is the narrow specialisation which exists within the academic world and to some extent in practice. In the anglo-saxon system, the typical Faculty of Engineering is divided only into Departments of Chemical, Civil, Electrical, and Mechanical Engineering, with perhaps two or three professors (chairs) in each. In Germany, there may be individual Instituts for each material of construction (steel, concrete, timber, etc.) and perhaps for different forms of construction (for example, bridges or industrial buildings). Each has considerable administrative independence and each professor is expected to keep to his own preserve.

Schlaich designs equally well in any material and has always seen the over-specialization of academia as a hindrance to the development of fundamental approaches to design philosophy. In an attempt to overcome this, he persuaded the University some years ago to allow him to rename his Institut für Massivbau (concrete construction) the Institut für Tragwerksentwurf und Konstruktion (Institute of Conceptual and Structural Design).[10] The move encountered considerable resistance from some of his fellow professors who felt that he was encroaching on their territory. However, he has always taken a holistic view of design, considering issues such as construction and aesthetics as well as pure structural efficiency.[11] Some years ago, with Knut Gabriel, he formed a research group under the banner Forschungsgruppe "Ingenieurbauten – Wege zu einer ganzheitlichen Betrachtung" (FOGIB) to investigate the development of an holistic view of structural design and promote its adoption. This will try to tackle the complex problem of how the designer can compare intangibles: weighting, for example, social consequences against construction costs and consumption of material resources.[12]

As regards the more formal side of university education, Schlaich states that he has "always liked teaching" at both undergraduate level, which involves mainly lectures, and post-graduate level, which involves more personal contact. However, like all academics he has problems striking a balance between teaching, research, and administrative matters and has the additional heavy burden of the practice. Besides publishing about 300 papers, he has given more than 400 public lectures. He feels that he has too little time for each assistant or collaborator and so wastes "a lot of effort, and even some good will". On the other hand, "there are so many things to keep up with which get lost if not constantly observed". One such issue is the framing and development of the codes of practice which provide guidance to design engineers and a measure of uniformity throughout the industry. He puts his intense involvement in this field down to his fundamental approach to theory and his desire to see a totally consistent approach to codes of practice. Like many practitioners, he considers most codes "poorly structured and conceived back-wards" because most "code makers and bureaucrats" have never been designers themselves and therefore cannot have an holistic conception of quality in structures. Though for some time heavily involved in the framing of the European code through the CEB (Comité Européen du Béton) he feels that he wore himself out "with too little real success". It was for this reason that he created FOGIB.

Schlaich sees the conception of the strut-and-tie model for reinforced concrete as an example of the correct sort of approach and a step in the right direction (2.12). He notes that fundamental work in this field in the Institut has been the special responsibility of Professor Schäfer, at the Institut since 1977, "very clear in his fundamental thinking and very cooperative". He is also keen to recognize the general contribution of other colleagues in the Institut, particularly Knut Gabriel, another colleague since 1968 from the Munich Olympic roof design and in consequence his partner in research on cable- and light weight structures on whom he has "always depended heavily for advice and opinion on all sorts of issues" and of Karl-Heinz Reineck, who was already at the Institut when Schlaich came in 1974 and "who really knows everything about structural concrete design and is very reliable".

Schlaich sometimes feels that it might be better to tackle fewer topics and to research them more deeply but, like many engineers with a passionate interest in their field, finds he cannot refuse to become involved in new and exciting topics. The "cost" is that from time to time the Institut must abandon work on a particular line of investigation earlier than he would like. (Examples are research into fibre-reinforced concrete and his studies of wind effects on towers.) "But," he asks, "how can one specialize further within an already specialized field like structural engineering?"

2.12
The strut-and-tie concept for modelling the forces acting within reinforced concrete structures, featured on the cover of the journal of the US-based Prestressed Concrete Institute in 1987

2.13
John E. Breen and Jörg Schlaich chairing a IABSE-symposium on "Structural concrete", 1991

2.14
Myron Goldsmith and Jörg Schlaich under the Olympic roof in Munich, 1972

2.15
René Walther's stress ribbon overpass near Zürichsee, 1965

2.16
Christian Menn's Ganter Bridge on the Simplon Pass, 1980

On the other hand he continues to invest much time in serving national and international associations as chairman or member of working committees. In addition to his contribution to IASS he is mainly involved with IABSE (the International Association for Bridge and Structural Engineering) where he tries to be instrumental in helping to organize conferences and writing for its journal. This has again resulted in a large number of personal contacts and friendships, mainly with Jörg Schneider, "the soul of IABSE", and with Jack Breen of Austin, Texas a most active and successful researcher in "structural concrete" design and "very instrumental" in supporting Schlaich's efforts to improve rational approaches to structural engineering (2.13).

It can be seen that in discussing his career Schlaich makes constant reference to teachers, mentors, colleagues, friends, and family members who have inspired him either through personal contact or through their publications.[13] The list is lengthy and it is perhaps invidious to make a selection. However, the aim here is to emphasize the importance of such inspirational figures in the careers of successful engineers and the following selection is intended to be typical rather than comprehensive. An important place must be held of course by Myron Goldsmith (2.14) who since their first meeting in 1956 gave Schlaich "permanent professional companionship, criticism, encouragement, and advice". Schlaich notes: "he always took an intense interest in your work and asked penetrating questions: 'why are you doing this, why are you doing that?' - and when you thought about it, you realized that more consideration was needed." Also important was Anton Tedesko, the German-Austrian engineer who introduced concrete shells to the USA. Tedesko was to become "a real fatherly friend" and Schlaich recently completed a biographical tribute to him.[14] He describes Professor Yoshikatsu Tsuboi, structural consultant for Kenzo Tange's Olympic Stadiums in Tokyo (2.8), as "the Japanese engineer-god" and was proud to speak at the first Tsuboi memorial seminar in Tokyo in 1991. Mamuro Kawaguchi, Tsuboi's junior, is described as "one of the most imaginative engineers and a continuous friend". Schlaich also makes special mention of two of his architect friends and colleagues: Günter Behnisch, who turned 70 in 1992, and Erwin Heinle, now aged 75, with whom at the time of writing he is preparing a book on domes. He values his close personal and professional contacts with René Walther and with Christian Menn and has a great respect for their work (2.15 and 2.16). He is in "continuous contact" with Heinz Isler, the Swiss shell builder of genius (2.9) and Bruno Thürliman whom he describes as "Mr Plasticity-theory". He admires Stefan Polonyi for contributing much to the discourse on structural engineering. He liked to discuss with Peter Rice and more often with Edmund Happold, the two most creative British engineers, who unfortunately died most recently. He has long been in contact with David Billington and enjoys to discuss with him his concept of "structural art". Of Ulrich Finsterwalder he is proud to relate: "I invited him to lecture in Stuttgart for the first time at the age of 90 in 1989!" He considers Frei Otto to be a giant amongst the pioneers of modern construction and has been greatly influenced by his work and ideas. However, the two fell out when they attempted to work together on the design of the cable-net roof for the Munich Olympic Stadiums. The causes were common enough: two very different temperaments, two strong personalities, two conflicting viewpoints on technical and aesthetic matters.[15]

As we have seen, there have also been tense passages in Schlaich's relationship with Fritz Leonhardt, the "grand old man" of post-war structural engineering in Germany. Once more, there was the problem of two people, both self-confident, determined, and strong, trying to work together. Those who were close to the practice agree that there was simply not enough room in it for two such people. Schlaich readily acknowledges Leonhardt's great influence - not only in passing on knowledge directly, but because he "struck sparks off him". He describes Leonhardt as his teacher: "I owe so much to the fact that I was in his office since 1963 - from 1970 to 1979 as a partner. There were interesting projects, little organization or interference ... and Leonhardt never hesitated to give me the most difficult assignments without any doubts that I could fail. This gave me confidence."

2.17

The office at the time of writing (1994):

Sitting in front, from left to right:
Ulrich Otto, Knut Göppert, Michael Werwigk

Standing from left to right:
Frank Simon, Manfred Arend, Andreas Keil, Petri Kela, Jochen Bettermann, Feridun Tomalak, Tefera Solomon, El-Araby El-Schenawy, Rudolf Bergermann, Axel Schweitzer, Birgit Graupner-Saba, Jürgen Kern, Thomas Keck, Gerlinde Callies, Kirsten Martin, Thomas Bulenda, Dorothea Krebs, Margot Zalbeygi, Hans Schober, Cornelie Schmid, Thorsten Helbig, Thomas Moschner, Birgit Piehl, Xavier de Nettancourt, Sven Plieninger, Hansmartin Fritz, Peter Schulze, Mohamed Nouri, Brian Hunt, Fritz Bacher, Volkwin Schlosser

Absent on the day the photograph was taken:
Frauke Bettermann, Leonardo Bevilacqua, Nevenka Breitling, Ulrich Dillmann, Thomas Fackler, Jan Knippers, Wolfgang Schiel, Jörg and Michael Schlaich, Ingeborg Vöhringer

2.18

Schlaich's Institut at the University of Stuttgart:

First row from left to right: **Hiroshi Kikuchi, Japan (e), Hermann Hottmann (c), Manfred Arend (c), Salim Al Bosta (c), Ilse Guy (b)**

Second row from left to right:
Mingzeng Bai, China (e), Jochen Gugeler (c), Thomas Kuchler (c), Volker Schreiber (c), Michael Pötzl (c), Jürgen Ruth (c),

Third row, staggered from left to right: **Jörg Schlaich (a), Andreas Stumpfl (c), Karl-Heinz Reineck (a), Rosemarie Wagner (c), Elke Mennle (b), Peter Saradshow (c), Elfriede Schnee (b), Kurt Schäfer (a), Matthias Schüller (c), Salah Din-El-Metwally, Egypt (e), Klaus Zimmermann (d), Christoph Lehmann (d)**

Note:
(a) permanent academic staff, absent on the day the photograph was taken (in June 1992): **Knut Gabriel**
(b) permanent non-academic staff
(c) scientific assistants with five-year contracts for teaching and research. Since this core of the team is permanently rotating, it makes no sense to name those absent on the day of photograph. Such photograph will look different whenever taken during the period covered by this book
(d) "Hiwis", selected senior students[3]
(e) guest scientists

Notes to Chapter 2

[1] Many engineering educators (particularly those involved in European cooperation) have begun to use the term "formation" in English to include both the education and the training required to prepare people for the professions. This corresponds with the French formation (professionelle) and the German (Berufs-) Ausbildung

[2] It is interesting how many of the founding architects of the Modern Movement had some similar contact with a trade in their educational background. As we have seen, the tradition of a close connection between art, craft (or trade), and professional endeavour has been strong in Germany since the time of the Werkbund.

[3] This formerly common practice amongst German students requires some explanation. In the German academic world (in engineering at least) the basic administrative unit is the Lehrstuhl or, as it is now more often called, the Institut, an organization somewhat smaller and more specialized than the British "department" and responsible for one basic subject such as concrete, steel, soil mechanics, construction management, etc. Until recently it was unusual for academics to work their way up the career ladder entirely within the university system. Engineers were expected to serve an apprenticeship in research, but then to build up practical experience (and preferably a successful business) in the "real" world, before being invited to occupy a chair while simultaneously continuing to run their business. This system ensures a close and fruitful connection between academic research and practice which is one of the main strengths of German engineering. The head of such an Institut has great status and considerable authority. The system is referred to by admirers and detractors alike as the "god-professor" system. There are two important effects. Reputations are built around individual professors rather than around departments. Students who have a special interest in a particular area or form of construction will travel far to attach themselves to individual professors whose specialism accords with their interests. A professor will frequently be called upon to act as a Prufingenieur, checking the design concepts and computations of a consulting office. He will involve members of the staff and senior students in checking the computations. (Selected senior students who earn money in this fashion are known as Hilfswissenschaftler or "Hiwis".)

[4] When formal engineering education at tertiary level was introduced in Germany it was not incorporated into the universities, as in the Anglo-Saxon world, but was taught in separate institutions. These were originally known as Technische Hochschule (now Technische Universitat.) When Schlaich was a student there, Berlin had the only Technische Universitat in Germany and it was given this superior title because of its compulsory humanity courses. Schlaich notes: "with ongoing democratization (= levelization) all were called University".

[5] For the Berlin Congress Hall, see e. g. *Bauwelt*, 1/1958, p. 7–16; *Beton- und Stahlbetonbau*, 12/1980, p. 281–294 and 1/1986, p. 22–25; and *Der Bauingenieur*, 12/1986, p. 569–576. For brief English-language accounts see *New Civil Engineer* (NCE), 16 Oct./1980; 29 May 1980, and 5 June 1980. For the Dywidag tanks see e. g. C. Siegel: *Structure and Form in Modern Architecture*, UK edn., Crosby and Lockwood, London 1962, p. 246 and Dyckerhoff und Widman: *Festschrift Ulrich Finsterwalder: 50 Jahre fur Dywidag*, Braun, Karlsruhe, 1973, p. 90.

[6] Timoshenko's and Bleich's energy methods.

[7] Like most engineers, Schlaich has complemented his formal studies with continual self-education. Over the years he has visited many countries to inspect structures in situ, particularly those of famous engineers like Maillart, renowned for his bridges, and Nervi, renowned for his individualistic stadiums and shell roofs in ferro-concrete. In Paris, he greatly admired the iron-and-glass dome of the Paris Bourse of 1811. As we shall see, its influence is evident in the part of his later work which develops this theme. On his visit to the USA he was inspired by that country's highrise buildings, geodesic domes, and cable bridges.

[8] Professor Walther now has a consulting practice in Basle (Basel) and the chair of the Institut du Béton Armé et Precontrainte (IBAP) at the Ecole Polytechnique Fédérale de Lausanne. He is renowned for his work on prestressed concrete and cable-stayed bridges and his interest in the aesthetics of structures and has served as President of the Fédération Internationale de la Précontrainte, FIP.

[9] In German the plural of the word Partner is Partner. Thus Schlaich Bergermann und Partner is translated as Schlaich Bergermann and Partners.

[10] There is a major problem in matching words relating to engineering design across the German and English languages. (The same problem occurs between French and English.) In English the word design is used by engineers to refer to every part of the process from the initial and sometimes creative conception of the form of a structure right through to the mundane (and now largely computerized) task of calculating the required cross-section sizes of conventional structural members such as beams and columns. Some English-speaking engineers use the term "dimensioning", perhaps borrowed from French "dimensionnement", to try to distinguish the latter process. The word design is loosely applied by some English-speakers even to the numerical analysis of structures. The German word "Entwurf" (like French "conception") is confined more to the creative part of the process. The word "construction" is just as awkward. In English, engineers use it mainly to refer to the process of putting a structure together. Architects use it also to refer to what might be called the fabric of a building (the physical reality) and perhaps to the manner in which the parts fit together. In German, the word "Konstruktion" extends to include the more routine aspects of the design of structures: dimensioning and detailing. It is therefore difficult to find an accurate translation of the name of Schlaich's Institut which is not as long as this footnote.

[11] J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61, 1986.

[12] Schlaich finds that traffic engineers are more used than structural engineers to this sort of approach. Aeronautical engineers can also contribute much because they are used to dealing with complex systems and adopting a "systems approach". The FOGIB group is studying the general problem of choosing criteria for structural design – least weight, least cost, lowest maintenance, etc.

[13] Many such names have been mentioned in private correspondence with the author and more are to be found in papers in the technical journals. See e. g. "On the conceptual design of engineering structures" (Zum Entwerfen von Ingenieurbauten), *Jahrbuch 1991 der VDI-Gesellschaft Bautechnik*.

[14] J. Schlaich: "Anton Tedesko: Schalenbauer und Kommunikator", *Beton- und Stahlbetonbau*, 88/1993, Heft 5, p. 137-146.

[15] In discussion on this issue, Schlaich protested: "I don't think you should place me on the same level as Otto – he is several times higher up the scale." He regards Otto's work on the development of cable-net structures as work of genius.

List of selected publications by Jörg Schlaich
to Chapter 2: see the end of Chapter 12.

3 Towers

The projects discussed in the following chapters are grouped according to structural type and function (communications towers, shell roofs, etc.) to facilitate explanation of their general principles. As a result, the account from now on is strictly chronological only within these groupings. Schlaich's early experience with Leonhardt und Andra was on the design of the Finnlandhaus with Kuno Boll as a partner (Chapter 10) and the Hamburg hypar shell roof, beginning in 1965 (Chapter 4). Following this period Schlaich became a close collaborator of Leonhardt himself and thus heavily involved in the design of the communications towers which are now a feature of the German landscape.

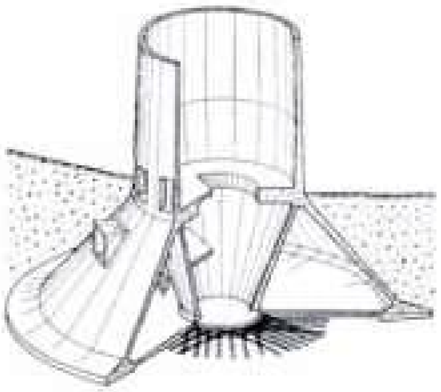
3.1
An example of the once-standard steel lattice transmission towers

In the 1950s the Bundespost needed many of these towers for its new communications system. Because microwave links depend on line-of-sight transmission there was a strong economic incentive to build the towers high, so that fewer would be needed. The conventional transmission tower at that time was a steel lattice construction (3.1). Reinforced concrete had, however, been used for smaller towers in the form of simple cylindrical pipes from 45 to 70 metres in height. Some very tall towers were required to serve a dual purpose in providing television coverage for the major cities. Because these would need to be located on nearby hills, the idea arose of equipping them with viewing platforms and rotating restaurants. In addition, the Post Office required antenna platforms and rooms to house electronic equipment and personnel.

3.2
The Stuttgart television tower of Fritz Leonhardt and Erwin Heinle (completed 1955)

The structural engineers were thus confronted with a major technical challenge: to support a facility the size of a small office building at a level some 150 metres above ground where, at that time, the behaviour of the wind was still poorly understood. Sufficient rigidity was required to ensure that sway and vibration did not interfere with the quality of transmission or the comfort of the occupants. There was also an aesthetic challenge because the major towers would be prominent, and often situated in environmentally-sensitive locations. As usual, all this was required at minimum feasible cost.

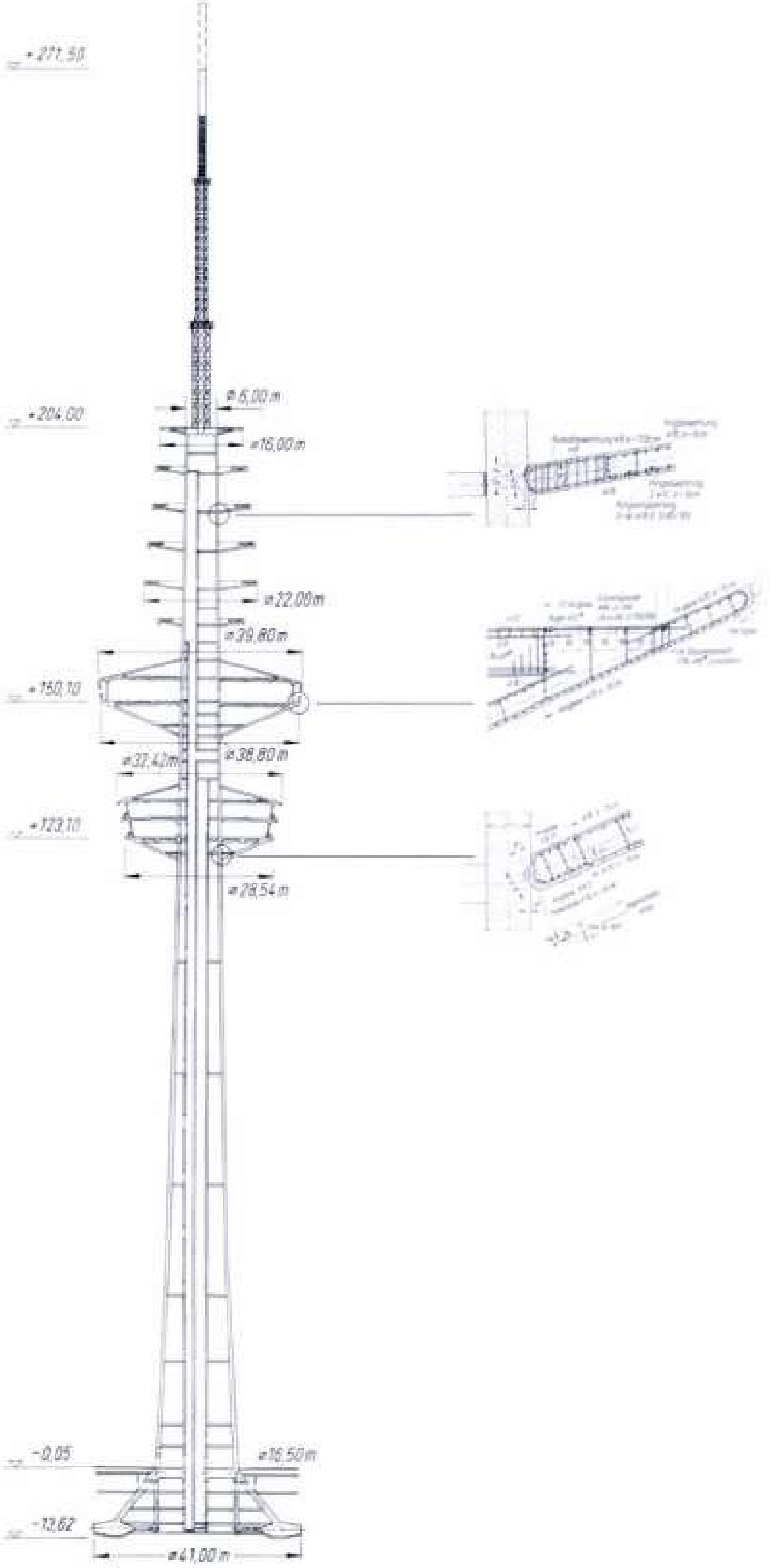
When a 210-metre lattice tower was planned for the hills above Stuttgart, Leonhardt considered that it lacked aesthetic merit. He therefore proposed a reinforced concrete alternative: a slender tube which would depend for its lateral rigidity entirely on its own stiffness, rather like a reed projecting from the ground. With architectural advice for the interior design from Erwin Heinle, he envisaged the facilities as enclosed in a four-storey pod 160 metres above ground. The shaft would continue through the pod, and to its top would be attached a steel transmission mast 51 metres high (3.2). The tower would exploit the sculptural potentialities of concrete: its mouldability and its continuity, expressed in the smooth tapering form of the shaft. The circular cross-section would minimize wind forces, and provide uniform resistance in all directions.



3.3
Its shell foundation

Nevertheless, the wind forces, especially those acting on the pod high above the ground, would give rise to high overturning moments at the base, and require extensive foundations. The closest precedents for this pioneering type of structure were reinforced concrete chimneys, and these had normally employed a simple circular foundation slab. However, Leonhardt realized that a foundation in the form of an annulus would distribute pressures more certainly and reduce the risk of differential settlement of one side of the footing with respect to the other. To distribute the load from the shaft to the ring, he employed a truncated cone of concrete, and inside this, a second cone which served to stiffen the first (3.3).

The Stuttgart tower was designed in 1952 and was in service by 1955.[1] It set in train the development of many similar towers in Germany and throughout the world. Some time after Schlaich entered the Leonhardt und Andra office, another large tower was proposed for **Hamburg**. The city authorities planned a revolving restaurant, while the Post Office required a service floor area of about 1000 square metres, surmounted by six large antenna platforms with a diameter of about 20 metres. Above these was to be an antenna 70 metres high for mobile telephones, and above that again, a television mast. In 1963 a competition was organized amongst five selected Hamburg architects and a proposal by Trautwein and Leonhardt was awarded first prize. The entire service area was located on one large floor, 40 metres in diameter, and the public facilities were placed in a separate pod underneath. The six antenna platforms were spread at various heights above the two pods and the whole assembly reached a height of 272 metres (3.4 + 3.5).



3.4
The Hamburg telecommunications tower: vertical section and details

3.5
The Hamburg telecommunications tower, completed 1967

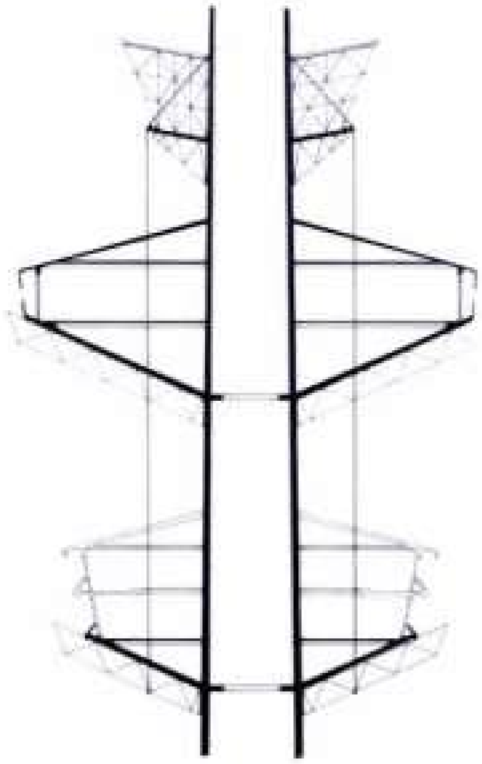
Schlaich was set to work on detailed design under the guidance of Leonhardt. Together they worked out a major development of the Stuttgart scheme. It had been established that, while the double cone of the Stuttgart foundation was economical in terms of material usage, it required a large amount of expensive formwork. The internal cone was therefore replaced by a simpler vertical cylinder which was a continuation of the main shaft. To ensure that this cylinder took no part in carrying the weight transmitted from the shaft, its base was knife-edged, and the surrounding annular floor slab to which it was attached was made thin and flexible (3.4).[2]

Concrete shafts are most economically built with climbing formwork which moves gradually upwards as the concrete is poured and hardens within it (3.6). However, at Stuttgart awkward problems had been experienced in accommodating the reinforcing bars which would eventually project from the shaft to form the connection with the platforms. Conventional practice is either to bend these flat against the vertical surface to allow the climbing formwork to pass, and then to bend them out again to receive the horizontal elements, or to interrupt the climbing process and dismantle the formwork to reassemble it above the level of the platform. For the Hamburg tower, Leonhardt and Schlaich devised a scheme whereby the base of each platform pod was formed as a shallow inverted cone supporting a circular floor slab. They recognized that circumferential prestressing of the outer rim would be sufficient to develop conical shell behaviour and to cause the entire cone to contract and grip the shaft. There was therefore no need for reinforcement to pass from shaft to platform, and the lower end of the cone could sit simply in a shallow triangular recess in the surface of the shaft, 3.5 cm deep and 16 cm high (3.4, lower detail). The shaft could thus be built without any interruption to the climbing process. This scheme had the additional advantage that the junction would barely interrupt the smooth transmission of vertical force within the shaft due to the weight above. Acting integrally, the cone and its associated floor slab form an efficient structure which in the lower pod supports the intermediate floor at its perimeter. The "roof" of each pod is formed from a similar structure inverted. The outer rim of the lower pod and the inner rim of the roof shell were prestressed using continuous circumferential prestressing cables formed by specially devised connectors (3.4, middle detail and 3.7). Schlaich emphasizes that this improvement could never have resulted from thinking about the problem in isolation but was based on a theoretical and analytical understanding of shell behaviour. He remembers long discussions on this subject with the famous author on shells, Professor Rabich at Dresden.

3.6
Climbing formwork for a tower shaft

3.7
Cables and anchorages for circumferential prestressing of a platform (view from above)

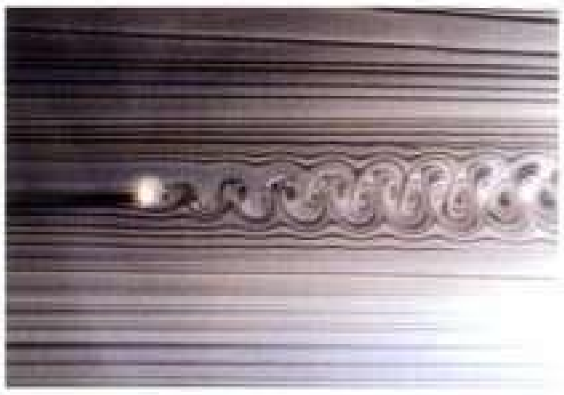
Extremely flat conical shells were also used for the antenna platforms to permit similar connections with the shaft (3.4, upper detail). The more efficient structural action of all elements resulted in a substantial reduction in weight compared with conventional circular plates and this in turn permitted an ingenious system of temporary support during the construction. This made it possible for work to be carried out at four levels simultaneously many metres above the ground (3.8–3.12).



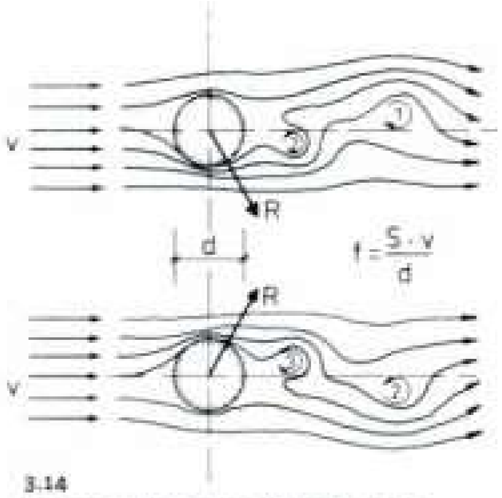
3.8
Construction sequence of the platforms of the Hamburg tower:

- a) the lowest antenna platform was constructed by conventional means
- b) lifting cables were draped over its edge
- c) pre-assembled formwork was hoisted into position for concreting the cone of the upper pod (3.9–3.11)
- d) formwork was then lowered for concreting of the cone of the lower pod
- e) from that stage, work was continuous in four levels (3.12):
  - concreting of top part of shaft
  - concreting of antenna platforms one above the other
  - concreting of both pods

3.9–3.12
Construction sequence, 1965/66

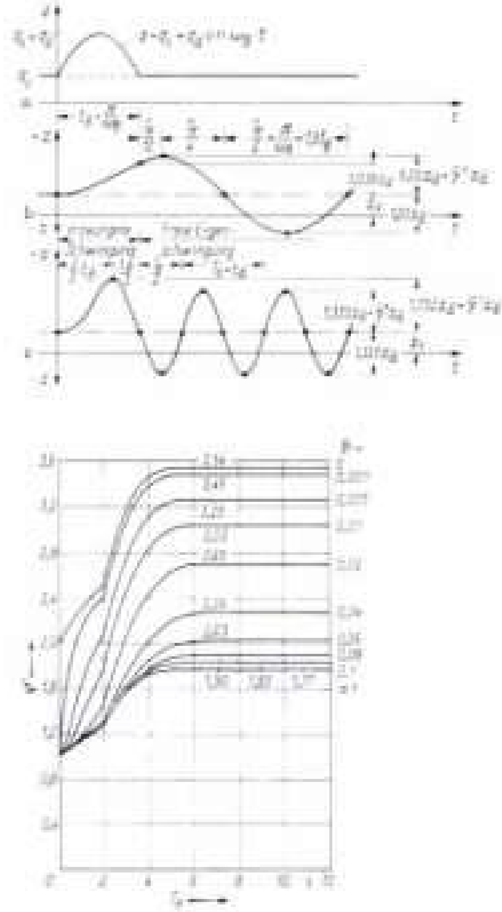


3.13
A typical pattern made by vortices shed from a cylindrical body



3.14
Forces resulting from alternate eddies
f = frequency of eddy shedding
S = Strouhal number
= 0.2 for cylindrical bodies

At this point Schlaich also initiated his own **research** into the response of the new towers to **wind effects**, inspired by a number of spectacular failures. Gusting causes oscillation in the direction of the wind, while the alternate shedding of von Kármán eddies from either side causes across-wind motion (3.13 + 3.14). The result is a complex random motion of the tower. If the natural frequency of vibration of the structure is roughly the same as that of the eddies, large transverse vibrations may occur of sufficient violence to cause destruction. The critical factors governing the natural frequency of the tower are its form and its stiffness. The damping properties of the particular material and type of construction employed govern the accumulation of vibrations and thus the maximum amplitudes.[3] The designer has two options. One is to ensure that the natural frequency of the tower is so low that excitation occurs only at wind speeds for which the energy input is small. The other is to ensure that it is so high that the corresponding theoretical wind speed is extremely unlikely to occur. Both require an estimate of the frequency and energy input of the wind and an understanding of the possibly close interaction between wind and structure.

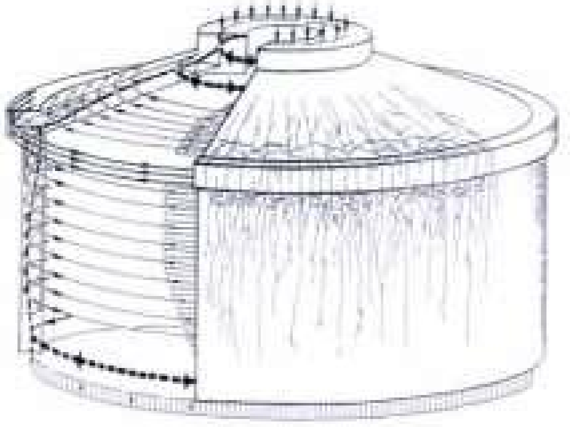


3.15
Dynamic factor as a function of the period of a structure and its logarithmic damping to account for the gustiness of the natural wind (deterministic approach)

While studying the research literature on the behaviour of slender towers in the natural gusty wind, Schlaich was struck by an anomaly in conventional thinking and was able to make an important contribution in resolving it (3.15). In 1965 he presented his ideas as part of a series of weekly "self education" meetings which he and his colleagues had instituted at Leonhardt und Andrä to enable engineers to share their current interests. Leonhardt suggested that he publish them in the form of a paper and this was widely acclaimed for the way in which it de-mystified a very complex problem. Although Schlaich now dismisses it as "old stuff" in view of A. Davenport's stochastic approach, it is still used by practising engineers and teachers.[4]

To gain further understanding of the characteristics of the wind and its interaction with slender structures, Leonhardt and Schlaich in 1976 set in train a series of measurements on the 139-metre tower at Aufhausen (designed by Leonhardt und Andrä) which continued for many years. Later, with Hans Schober and Hermann Meier at the university, he instituted a research project on the behaviour of reinforced **concrete tubes** of the type used in the towers (3.16). When these bend under the action of high wind, tension occurs in the concrete on the windward side.

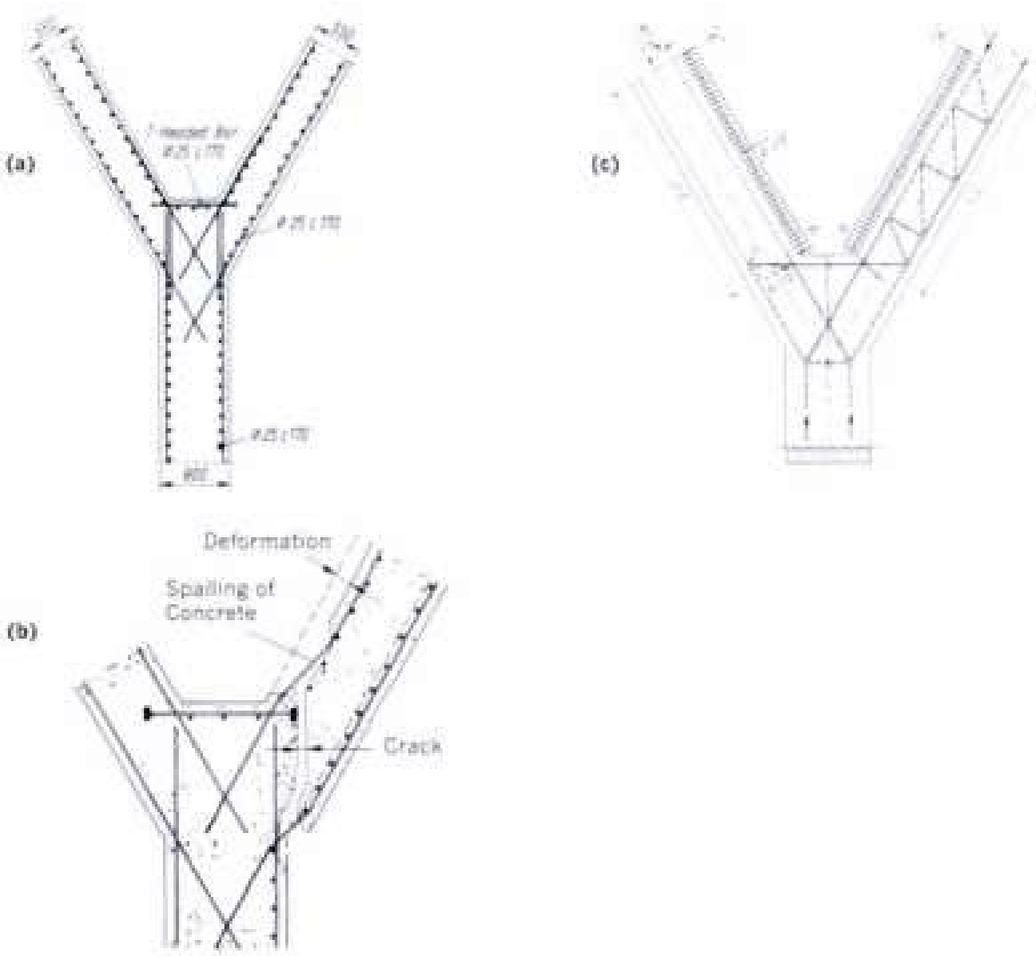
3.16
Tests on concrete tubes under axial force and bending at the Otto-Graf-Institut, University of Stuttgart



3.17
Cracking patterns and force distribution in the joint regions of composite rotational shells

Cracks develop, and the force in this region is transferred to the reinforcing bars. Codes of practice at the time required that the tension strength of the concrete on the cracked side be ignored completely when calculating the stiffness of the cross-section. This resulted in such large calculated deformations that designers were discouraged from using concrete for such towers. The tests at the Institut showed that, thanks to the "tension stiffening" effect of the concrete, the reduction in stiffness was much less than previously thought. This led to the development of a new method of calculation which gave realistic estimates of deflection.

This combination of experience in the behaviour of rotational shells and reinforced concrete tubes subjected to combined bending and tension was to be very useful later on when the University Institute was approached by industry to research the structural behaviour of **off-shore containment vessels**. The Institute was asked to determine how forces were redistributed from the "edge-disturbance" zones near the junction of walls and roof after cracking, and how shear could be resisted without the use of stirrup reinforcement.[5] After analytical studies, large scale tests were carried out with Karl-Heinz Reineck as group leader. These supplied further insight into the "plastic" behaviour of such shells (3.17), experience which was again useful in 1992 in the investigation of the Sleipner **platform failure** in the North Sea. In this latter case a large amount of computer analysis was carried out, though a simple strut-and-tie model would have sufficed to explain the pattern of force transmission within the structure and to find that the platform failed because the T-headed bars were too short (3.18).



3.18
The Sleipner A platform:
(a) its initial (insufficient) reinforcement
(b) the crack causing failure
(c) the "strut-and-tie" model explaining this failure

3.19
Comparison of the first Stuttgart tower (right), the second tower as built (middle), and an alternative proposal with permanent columns providing direct support from the ground (left)

3.20
The second Stuttgart tower (completed 1970)

As demand for communications and television services increased, a need arose for a second tower to service **Stuttgart**. The new tower was to be situated on a hill known as the Frauenkopf, not far from the first. The service floor was to be 40 metres in diameter, as at Hamburg, and there were to be two further platforms, each of 25 metres diameter for antennas. This time, however, there were to be no restaurants or viewing platforms and the tower was not to be open to the public. Leonhardt and Heinle's now classic first tower had become a source of pride for the people of Stuttgart, and it was considered essential that the new tower should not detract from its visual qualities or its importance. It was therefore decided that the prominent service floor of the new tower should be situated just above the tree line, only 35 metres above ground. In form it was to be similar to the upper pod of the Hamburg tower, with a conical shell cantilevering from the mast.

It was obvious that the construction method developed for Hamburg would be inappropriate in this case. It was more logical and cheaper to build the necessary falsework like scaffolding from ground level. To Schlaich it seemed unreasonable to build a complex and expensive temporary structure and then remove it, to leave the platform cantilevering from the mast, with the loads transmitted to the base of the tower by an unnecessarily circuitous route. It would be much more sensible to make the supporting structure permanent, carrying the loads logically and efficiently direct to the ground. However, his alternative proposal was favoured neither by Leonhardt nor by the authorities (3.19+3.20).

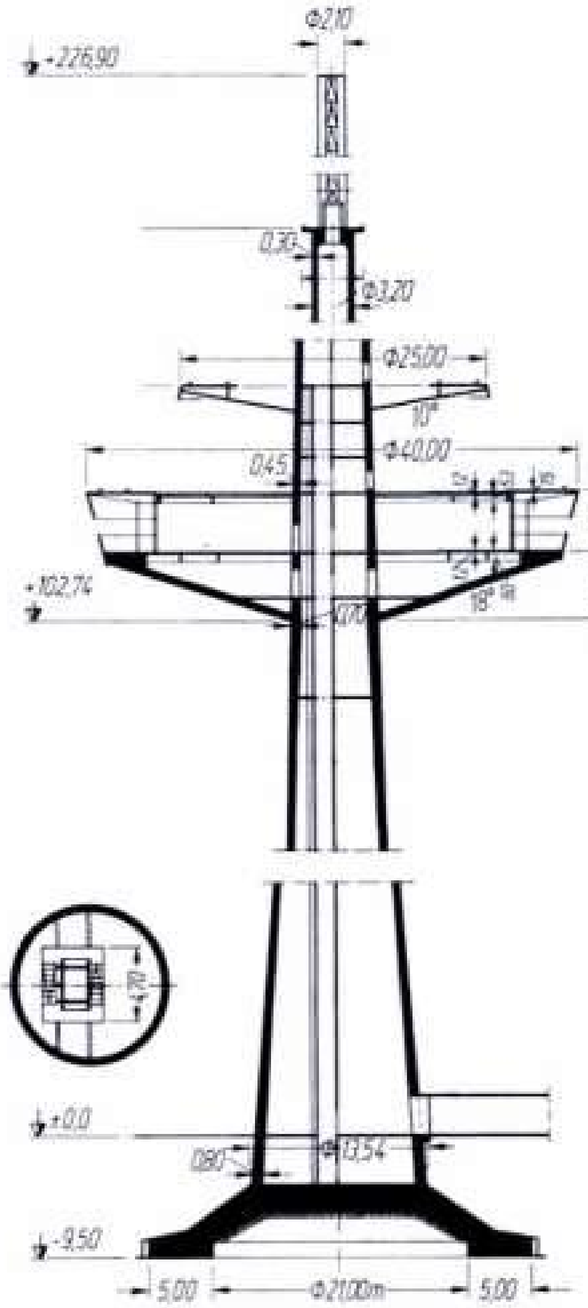
Questions of structural logic aside, the Frauenkopf tower as completed in 1970 is very handsome. Its angular profile is as much a part of late 1960s styling as Leonhardt and Heinle's tower is a product of 1950s streamlining. The low positioning of the platform and the marked taper of the shaft contribute to a satisfying impression of stability. The two towers form an impressive view from the window of Schlaich's Stuttgart house (3.21–3.23).

Schlaich's next tower with Leonhardt und Andrä was for the city of **Kiel**, with a platform at a height of 100 metres (3.24+3.25). It was becoming increasingly evident to him that possible methods of construction should be considered from the very start of the design process and that, where possible, features should be incorporated in the design to ease and simplify the construction. Drawing on his experience with Lubau he offered tenderers for the Kiel tower two alternative designs. One called for free cantilevering construction with cast-in-situ concrete used for the construction of the cone. The other proposed that the cone be formed from precast concrete segments which would be lifted by crane. Temporary ties from the mast would remain in place until the whole cone was complete, at which stage circumferential

3.21–3.23
The two Stuttgart towers overlooking the city

prestressing could be installed. The contractor adopted the second proposal and construction was completed successfully (3.26 to 3.29).

For the base of the Kiel tower, further economy was achieved by flattening the foundation cone to the extent that it could be cast on a carefully prepared mound of earth. To prevent the surface of the cone from bearing on the earth, the concrete was cast on a foam rubber matt placed on the mound. The strength and stiffness of the foam was carefully designed so that it would carry the weight of the wet concrete but would not transmit significant pressure and thus subject the cone to bending moments in service. The relative flatness of the cone meant that it was required to carry higher compressive forces, but the cost of the extra material required to resist these was compensated by savings in construction costs.

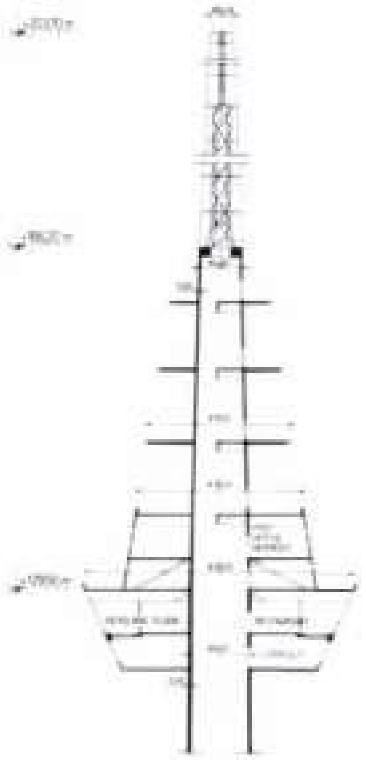


3.24
Kiel: Vertical cross sections of top, platform, and base. Horizontal cross section of shaft

3.25
The telecommunication tower at Kiel (completed 1976)

3.26
Details of the service platform's precast concrete segments

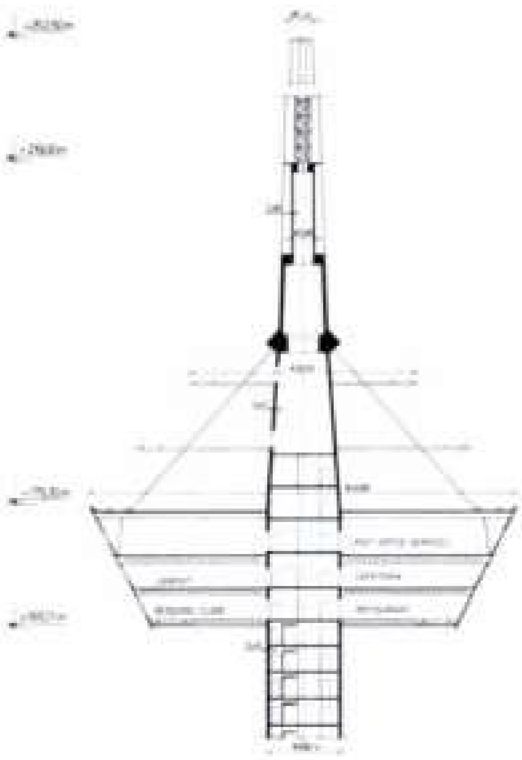
3.27 – 3.29
Construction of the service platform



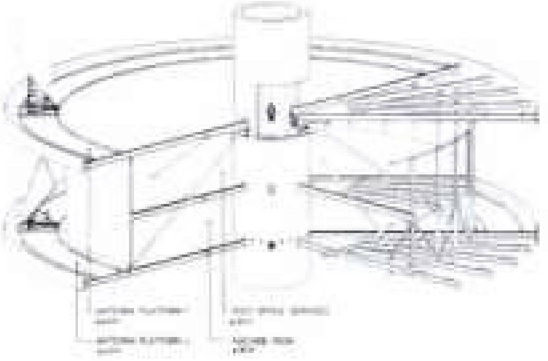
3.30+3.31
The Mannheim tower
(completed 1975)

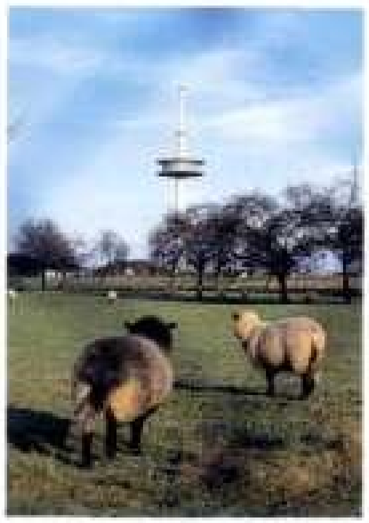
Further changes in tower design occurred because of the desire of Erwin Heinle, architect for many of the projects, to provide each city with its own distinctive tower. The search for new forms eventually led to the abandonment of the system of supporting platforms on inverted cones. Inspired by temporary ties used in the construction at Kiel, for the later **Mannheim** tower a scheme for permanent steel ties was devised, which would be concealed within the equipment floors (3.30 and 3.31). At **Cologne**, however, these tension members were clearly expressed above the single pod, providing intermediate support to two antenna platforms (3.32+3.33). The lower floors of the pod are supported by vertical tension members attached to the ends of the inclined hangers.

To complete the communications system, a large number of low- to medium-level towers was required. Demand was so great that the Post Office developed several series of **standard designs** for them. Leonhardt und Andra took part in these studies in conjunction with Heinle Wischer and Partners. (3.34–3.36).



3.32+3.33
The Köln (Cologne) tower
(completed 1980)

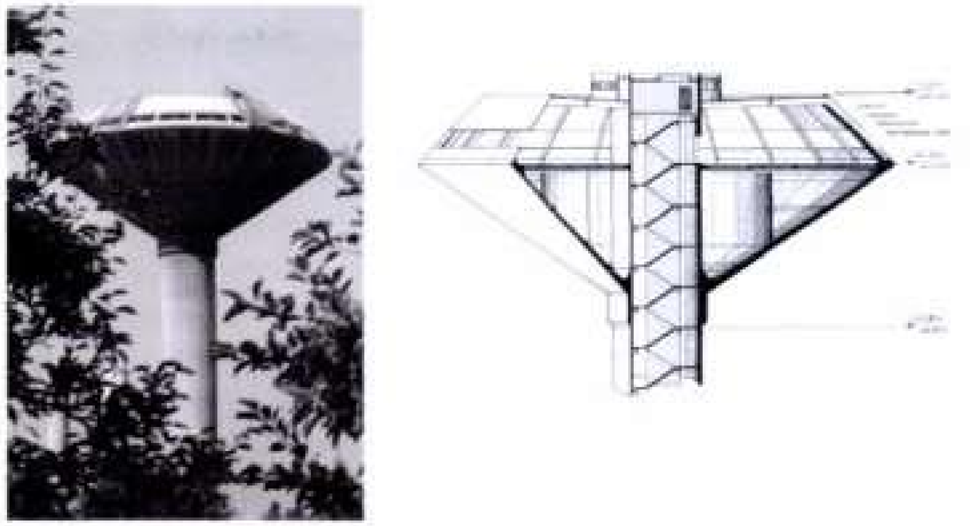




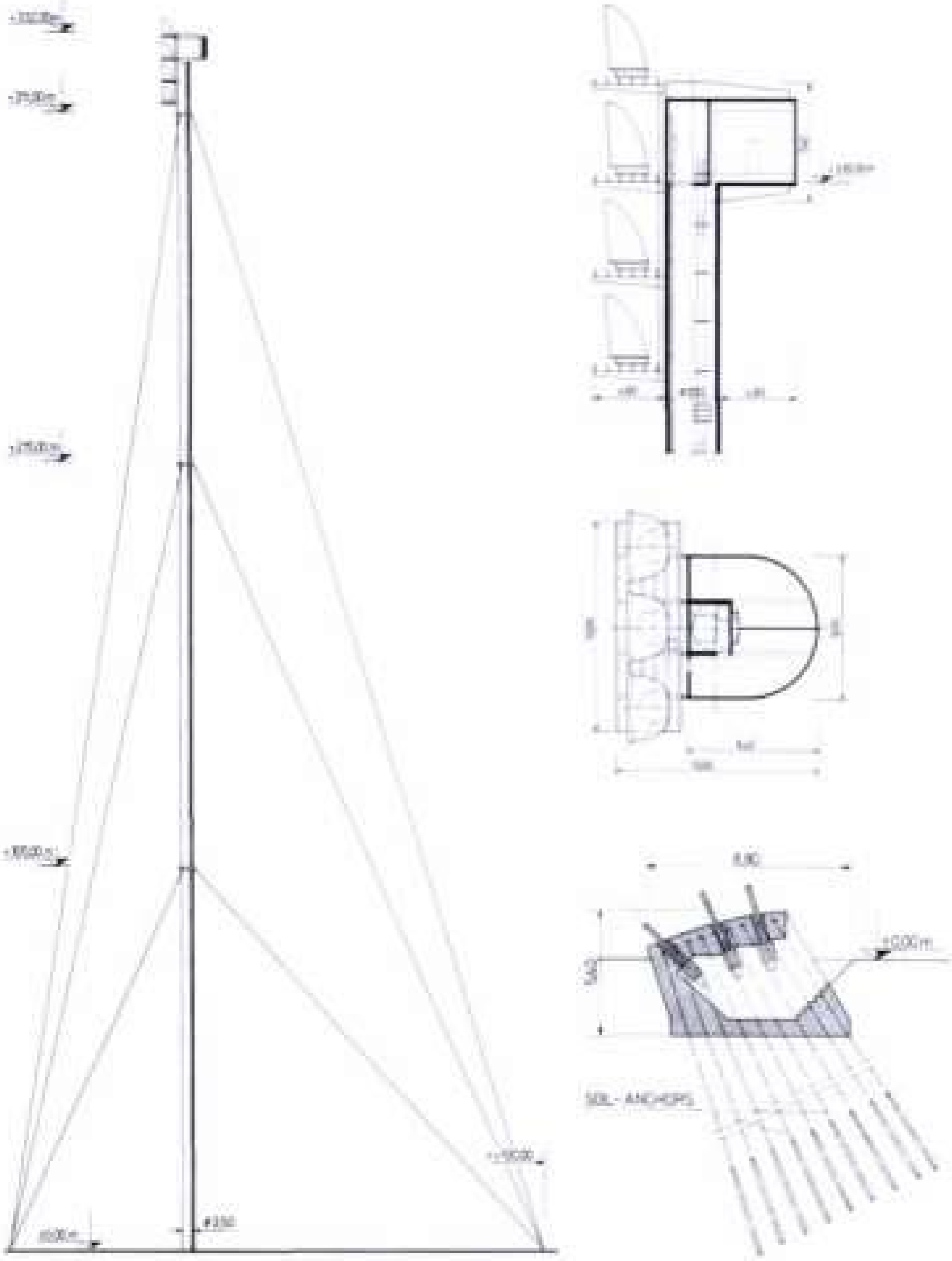
3.34–3.36
Two of the standard
communications towers

The experience gained with the construction of the concrete platforms for these towers was also useful in the design of **water towers** (3.37 + 3.38).

Inspired by their work with cables for the roofs of the Munich Olympic Stadium, Schlaich, together with his "olympic" colleagues Rudolf Bergermann, Knut Gabriel and Ulrich Otto (the latter was Schlaichs project engineer for several towers) realized that if tensioned guy cables were used to stabilize communications towers, the downward force could serve with great advantage to prestress a concrete shaft (3.39). This would permit a more efficient use of this material for high towers by ensuring that tensile cracking could not develop on the upwind face. The **guyed concrete mast** would be stiffer, and less reinforcement would be required. Further, the cables could be sloped at a much steeper angle than is conventional for a guyed metal lattice tower. Combined with an increased prestressing force, this would reduce the sag of the cables and increase the stiffness of the entire system. Calculations showed that this would permit construction of a 300-metre-high tower with a concrete shaft only 5 metres in diameter. (In contrast, the Hamburg shaft has a diameter of 16.5 metres at its base.) The area of land required to accommodate the cables would be far less than that required for a conventional guyed mast. Unfortunately, the Telecommunications authorities insisted, even after the collapse of a guyed steel tower, that all such towers should still be built in steel. As Schlaich notes: "conservative thinking!" He hopes that the ongoing research work of Fathy Saad – which he initiated some 15 years later – at his University institute will demonstrate the merits of concrete shafts for guyed towers.



3.37 + 3.38
The water tower at Leverkusen



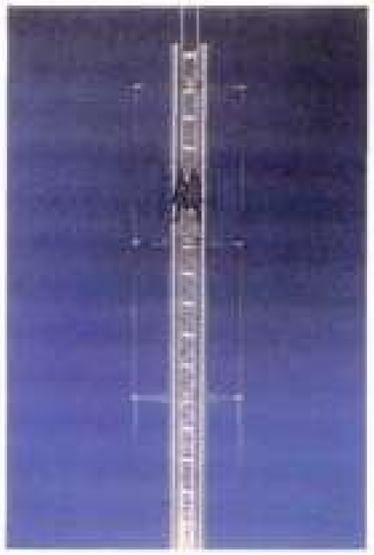
3.39
Proposal for a tall guyed concrete telecommunications mast

These ideas were developed further when the Post Office held an invited-entry competition in 1987. Here, together with Hans Kammerer as architect, Schlaich proposed that the guys be vertical and attached to outriggers projecting from the top of the mast. Again, the proposal was unsuccessful.

Much later, in 1994, a similar idea was applied in the design of a tower for the new **Leipzig Fair**, with the architect Volkwin Marg. The light square outrigger structure supports four thick non-load bearing chimney tubes and a central stairway for access to the famous fair symbol. This complicated job was successful handled by Andreas Keil and Xavier de Nettancourt (3.40–3.42).

As in any design office, many similar projects were envisaged and carried to a certain stage but were never built for a variety of reasons – many of them being competition entries. These included imaginative schemes for major towers at New Delhi and **Abu Dhabi** (3.43+3.44). The experience with large concrete towers also bore fruit in projects for 1000-metre-high vertical draft solar power stations (Chapter 11).

As we have seen, Schlaich's two periods of tower design had a formative influence on his professional career: confirming that clean structures with simple details may be realized by striving for a smooth flow of forces; bringing him into closer contact with his "teacher" Fritz Leonhardt; introducing him to Erwin Heinle; convincing him of the importance of construction processes in the initial conception of a structure; prompting his first "popular" paper and his first two research projects at the university; and bearing fruit in many designs and patents. An aspect on which he places great value was the opportunity to increase his experience with shell structures.



3.40+3.41
The model of the Leipzig Fair tower. Parallel guy wires acting through outriggers prestress and stiffen a core consisting of four tubes which are surrounded by four non-load bearing chimney tubes and with a central access shaft. The tower will support the symbol of the Leipzig Fair

3.43+3.44
The model and the vertical cross-section for a projected tower for Abu Dhabi, (1978)

3.42
The Leipzig Fair tower
nearing completion
at the time of writing
(with a concrete high-way
bridge designed by
the same team)

Notes to Chapter 3

[1] F. Leonhardt: "Der Stuttgarter Fernsehturm". *Beton- und Stahlbetonbau*, 1956, Heft 4 and 5.

[2] This is an interesting case for teachers of engineering and anyone studying analytical thinking in structural engineering. Engineers whose thinking is two-dimensional (as a result of almost exclusive concentration on this aspect in their early training) might see the arrangement at Stuttgart as typical of truss action and therefore stiffer than the arrangement at Hamburg. In fact the latter arrangement is stiffer because it incorporates a rotational (3-dimensional) shell.

[3] Damping is a measure of ability to dissipate energy. This may occur within the internal structure of the material itself, or in joints between components. For example, reinforced concrete after cracking is better than prestressed concrete, while bolted steel structures have much better damping properties than welded ones due to slip and friction between surfaces in contact.

[4] J. Schlaich: "Beitrag zur Frage der Wirkung von Windstoßen auf Bauwerke". *Der Bauingenieur*, 3/1966, S. 102–106. Schlaich was initially reluctant to publish this paper, but is now grateful to Leonhardt because "you need someone to give you a push like that at the right moment".

[5] To ensure that the mathematics is tractable, "classical" theory of the stresses within shells is based on certain assumptions about conditions of support and restraint at their boundaries. Conditions in practice rarely accord with these assumptions. The magnitude of stresses in the body of the shell is not greatly affected, but values near the edges differ significantly from those predicted by general theory and must be computed by additional analysis. This is known as "edge disturbance".

Selected publications by Jörg Schlaich and coauthors (if given) up to 1995 to Chapter 3:
Towers, Tall Buildings, Research on Wind Effects on Structures and on Concrete Tubes

month/year

03/66: "Beitrag zur Frage der Wirkung von Windstößen auf Bauwerke", *Der Bauingenieur*. Translation: "The effect of wind gusts on structures."

09/66: "Flache Kegelschalen fur Antennenplattformen", with F. Leonhardt, Proceedings IASS-Congress, Leningrad, and *Beton- und Stahlbetonbau*, 6/67.

01/67: "Der kontinuierlich gelagerte Kreisring unter antimetrischer Belastung", *Beton- und Stahlbetonbau*.

09/68: "Der Hamburger Fernmeldeturm", with F. Leonhardt, *Beton- und Stahlbetonbau*.

04/71: "Der neue Richtfunkturm auf dem Frauenkopf in Stuttgart", *Beton- und Stahlbetonbau*.

01/74: "Zur konstruktiven Entwicklung der Fernmeldetürme in der Bundesrepublik Deutschland", with F. Leonhardt, *Jahrbuch des elektrischen Fernmeldewesens 1974*.

06/74: "Measurements of wind loads and wind effects on a slender TV-tower in Southern Germany", with K. Kleinhanss and W. Neuerburg, Proceedings of the Symposium on Full Scale Measurements on Wind effects, London/Ontario.

05/77: "Der Fernmeldeturm Kiel", with U. Otto, *Beton- und Stahlbetonbau*.

05/77: "Der Fernmeldeturm Mannheim", with W. Kunzl, *Beton- und Stahlbetonbau*.

08/78: "Torres e struturas especiais", *Engenharia* (Brasil), no. 406, 413 and 414.

03/81: "Winddruck- und Verformungsmessungen am Funkturm Aufhausen", with K. Schafer and W. Neuerburg, *Konstruktiver Ingenieurbau, Universitat Bochum, Berichte*, 35/36.

05/84: "Tall Structures in Steel and Concrete", with R. Bergermann, *General Report, IABSE-Seminar on Tall Structures*, Srinagar, India.

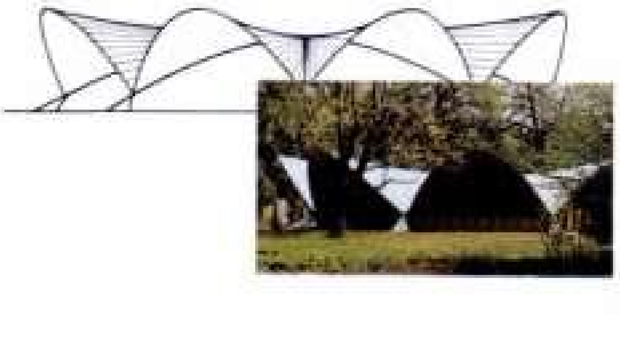
010/84: "Ultimate Strength of Reinforced Concrete Chimneys", with H. Schober, Funfter Internationaler Schornstein-Kongreß, Essen.

09/85: "Versuche zur Mitwirkung des Betons in der Zugzone von Stahlbetonröhren", with H. Schober, *DAfStb-Heft*, 363.

01/93: "Die Ursache fur den Totalverlust der Betonplattform Sleipner A", with K.-H. Reineck, *Beton- und Stahlbetonbau*. Norwegian translation in: *Cement*, 45 E.

01/94 "Nonlinear Analysis of Cable Guyed R.C. Masts for Wind Loads", with F. Saad, Fifth International Colloquium on Concrete in Developing Countries, Cairo, Egypt.

4 Concrete Shell Structures



4.1
Model photographs as presented by the architects

4.2+4.3
The Hamburg-Sechslingspforte swimming centre hypar shell roof (completed 1967)

The communications towers, with their combined conical and cylindrical shells subjected to asymmetrical loading, presented a major challenge in mathematical analysis in their day. However, their regular form and support conditions meant that they were reasonably amenable to established procedures. In the early 1960s, Schlaich's mathematical ability and his intuition concerning the behaviour of structures were tested in a very different way. The architects Niessen and Stormer had won a prize for an imaginative **hypar shell roof** for a swimming centre at **Hamburg**-Sechslingspforte (4.1). The problem now was to turn it into reality – and for this they approached Leonhardt.

Hypar shell roofs were rather popular at this time with both engineers and architects. Interest had been stimulated particularly by the work of Felix Candela which was readily accessible in Colin Faber's book on the great designer and constructor.[1] The dramatic saddle shape of the **hy**perbolic **para**boloid had featured in many roofs, generally bounded by four straight edges so as to appear kite-shaped in plan. The simplest way to understand its geometry is to imagine the edges formed from four sticks linked loosely at their ends. Two sets of rubber bands stretched between them, parallel to the sides, represent the surface. If one of the four corners of the "kite" is raised, the "surface" becomes saddle-shaped, even though the rubber bands remain straight (4.4). These straight lines are termed the "generators" of the surface. However, if we trace a line over the surface between the two lower corners, we find that it has the shape of a parabolic arch (4.5). A similar line traced between the higher corners appears as a suspended parabola, somewhat like the shape of a hanging chain. In the same way, other lines traced parallel to these appear either as "arches" whose feet rest on the edge beams, or as "cables" which appear to hang between them. In this form, the hyperbolic paraboloid may therefore be imagined to contain within it the two most efficient means of carrying distributed loads such as the weight of the roof itself or layers of snow.

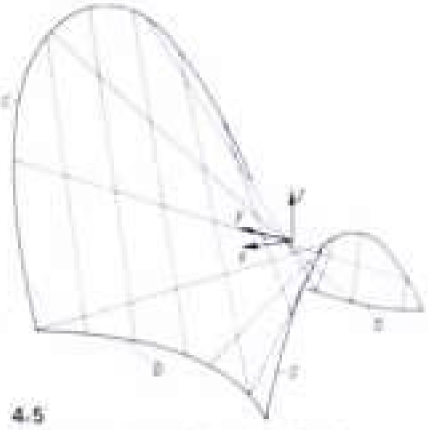
Perhaps more importantly, the two systems are curved in opposite directions so that each is effective in resisting any change in the shape of the other. This enhances resistance to buckling and to distortion under eccentric loads such as local accumulations of snow.

This hypar roof is usually conceived as a thin, flexible, saddle-shaped skin of reinforced concrete suspended within a framework formed by stiff edge beams. The job of the edge beams is to balance the inward pull of the "cables" against the outward thrust of the "arches", leaving mainly compressive forces to be transmitted along the beam axis to the foundations (4.6). A common and simplified assumption at the time, legitimised by Candela, was that the edge supports do not disturb the structural action of the shell membrane as described above. To justify this assumption, Candela used to support his edge beams continuously by closely spaced columns (or mullions) (4.7). This made it possible to keep the edge beams fairly small and flexible, and thus compatible with the shells. The arrangement also efficiently resisted overturning of the whole shell along an axis through its two lower supports in cases of unsymmetrical geometry and/or one-sided loading such as wind pressure or unsymmetrical accumulation of snow.

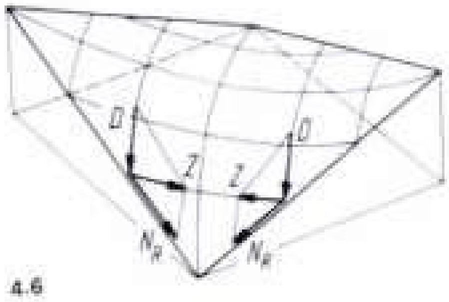
The architects at Hamburg were presumably unaware of these considerations when they conceived their roof, especially as far as the support of the edge beams was concerned. Their model consisted of two large hypars side by side, each 56 metres by 76 metres in plan (4.1, see also 4.8). They decided that the shells could share a common support in the middle, making only three for the whole roof. The two hypars were rotated in plan to be joined along one side, so that one "edge-beam" served both shells. The architects further decided to locate the curtain wall well in from the edge of the roof, to provide a large overhang. This left the future outer edge beams, and of course also the common inner edge beam, without direct support. From an engineer's point of view the resulting structure was totally illogical – and it was on an unusually large scale!

It was German engineers who had pioneered the development of shell theory and construction, and the "bible" of designers and theorists around the world was Flugge's *Statik und Dynamik der Schalen*. In this, Flugge had included a specific warning that the edge beams of hypar shells must be supported from below, on the grounds that the weight of an unsupported beam would shear off the edge of the shell.[2] On the other hand, the overall stability of the roof made of the two shells was guaranteed by the fact that it rested on three supports which did not lie on one line. Each individual shell would have a tendency to topple about the axis joining its two feet, but this rotation would cause the two shells to press against each other along their common edge and so hold each other up. However, the vertical angle between the two outer and the inner edge beams is so flat, and the interaction between shells and edge beams so complicated, that it would have been reasonable for an engineer to provide a fourth support: a column underneath the common edge beam. Unfortunately, this fourth column would have destroyed the elegance of the building and was therefore not acceptable to the architects.

4.4
Hypar surface with four straight edges (borders formed by a skewed quadrilateral)

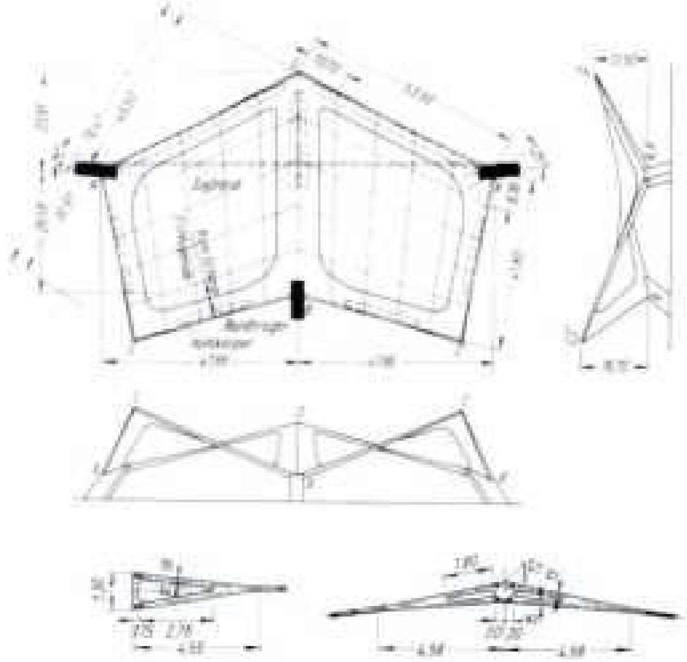


4.5
Hypar surface with borders in the form of (a) a parabola
(b) (c) hyperbolas

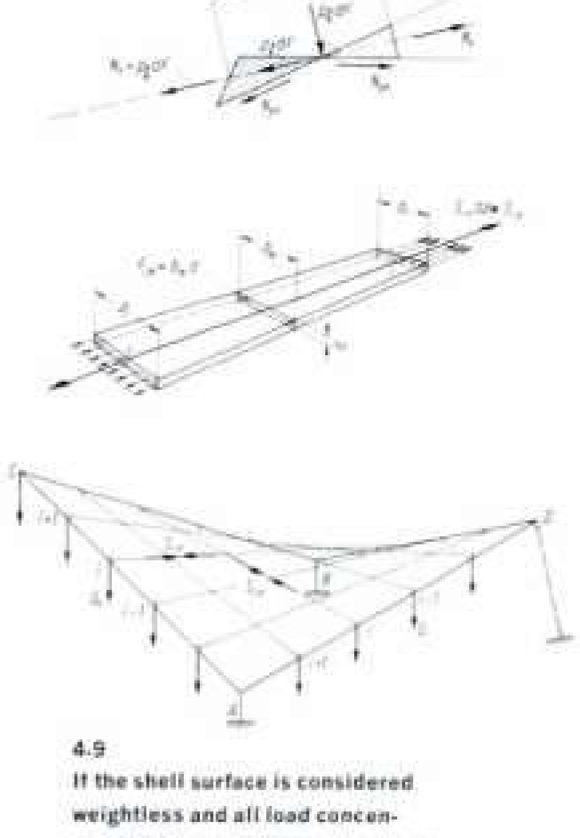


4.6
Simplified representation of the load bearing behaviour of a hypar shell
D = Druck = compression
Z = Zug = tension
N_R = Normalkraft Randträger = axial (compression) force in edge beam

4.7
A beautiful hypar shell designed by Felix Candela with edge beams propped by mullions



4.8
The roof in plan and sections. The enlarged edge beam sections show their hollowing as finally built



4.9
If the shell surface is considered weightless and all load concentrated at the edge beams, the hypar shell may be represented as a cable system spanning between its edge beams

Schlaich's involvement began when he met Leonhardt on the stairs of the office one day in 1964, and was asked if he would like to do an "interesting shell". He replied "of course". He was not aware at the time that Leonhardt had been approached by the client only after two leading authorities on shells had declared the roof unbuildable without the fourth support. Looking back, he recognizes that a more appropriate course of action would indeed have been to try to persuade the architects to modify their concept, but remembers that at the time he had only recently graduated from university and was too excited by the technical challenge to even imagine this.

Work started with a discussion between Schlaich and Leonhardt over the best approach to the design. The latter, as a pragmatist with a keen intuition for the load-bearing behaviour of structures, preferred to investigate the problem by experimenting with a large scale structural model. Before the development of the computer this was often the only way of estimating the stresses in very complex structures. However, it was an expensive and time-consuming process, and there was much art involved in ensuring that the model behaved in a reasonably similar fashion to the real structure, in scaling the readings, and in interpreting the results. Schlaich on the other hand argued that before there could be a model, there had to be at least a design, based on the best possible prior calculation, because the designer's preconceptions are inevitably built into any physical model. (The cardinal rule "garbage in – garbage out" applies as much to physical models as it does to computer analysis.) In an internal memorandum he wrote "testing [which is not based on] a consistent design is like a relapse to the middle ages". In this case, the main purpose of the analysis was to prove that the structure was actually stable. Special objectives were to find out how, despite Flügge's warning, the shell could carry the heavy weight of the non-supported edge beams and how the edge beams and shells would interact. The final aims were to understand the flow of forces and to be able to shape the edge beams in the most suitable manner.

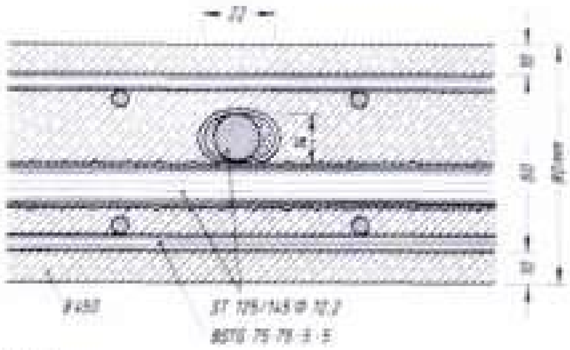
4.10
Plexiglass model under test loading

In looking at the differential equation of a hypar shell which is loaded at its edges only, Schlaich found that it behaves for this special case (with only the edge beams loaded) like a cable net with the cables following the lines of the generators and connecting the edge beams. The behaviour of a net is more easily comprehended (4.9) than that of a shell. It is relatively easy to see how the heavy weight of the unsupported edge beams results in a tendency for the higher corners to fall away from each other, thus increasing the tension in the "cable" direction. With much diligent work Schlaich was able to derive his own mathematical formulation of this behaviour and produce a theory applicable to shells with unsupported edge beams. It was, perforce, a method adapted for hand calculation using the higher mathematics to which he had been introduced in Berlin. He had derived the theory entirely from fundamental principles and made a major contribution in showing that one of the tenets of the shell designers' "bible" was unnecessarily restrictive. Through his university colleague Professor Schäfer, who shares his interest in shells and had been a student of Flügge's at Stanford University, Schlaich was later able to meet Flügge and was proud to welcome him to his home.

Schlaich was grateful to Leonhardt for being given precious time to carry out this analysis and despite his confidence in his theoretical analysis he was in fact glad that Leonhardt insisted that a large-scale model be built in plexiglass to verify the results. This was constructed by J. Peter of Leonhardt's Institut (a classmate of Schlaich's and still a friend) and R. Kayser of the Institut für Modellstatik at the University of Stuttgart. Overall guidance was provided by Schlaich's future colleague Professor Müller (4.10). The model itself and its complex loading and measuring devices were a superb scientific and technical achievement. There was great excitement when the model results proved quite different from those predicted by the analysis.

Suspicion fell almost naturally on the calculations, but it was eventually discovered that there had been a slight outward movement of the feet of the model which had had a disproportionate effect on the test results. (In the actual structure the column bases were to be tied together by prestressing strands buried below floor level as shown in 4.8 and 4.16). Schlaich was gratified by this demonstration of Popper's principle that experiments can not verify but can only falsify a hypothesis, and that their results must be treated with caution. He notes also that physical models of structures are of restricted value as design tools because they do not permit an assessment of the sensitivity of the structure to the variation of individual parameters.[3] On the other hand, taking the long view, he sees an important role in this regard for computers. He considers that they may eventually replace model tests and be versatile enough to permit sensitivity studies.[4] The huge plexiglass model is still on exhibit at the university of Stuttgart.

The shells at Sechslingspforte offered further challenges and opportunities for ingenuity. Leonhardt and Schlaich cleverly varied the weight of the edge beams by introducing hollow and solid portions to balance the loads better, thus minimizing the bending moments and hence the size of the beams (4.8). Schlaich sees this as the main feature of the design: a solution which was conceived only as a result of insights into structural behaviour gained through the theoretical analysis of the system. Aware of unavoidable deficiencies in the theory concerning stress disturbances in the region where the shell surface was connected to the edge beams, Leonhardt and Schlaich made special provision to minimize these stresses, especially by making the transition from the edge beams to the shells structurally continuous. To minimize the thickness, and therefore the weight of the shell, they used oval tubes for the prestressing cables, making it possible to accommodate two layers of prestress and mesh reinforcement on either side within a shell thickness of only 80 mm (4.11). They conceived a novel method of construction, building the framework of the edge beams first and then pretensioning the cables (running in the direction of the generators) so that the framework was in a finely-balanced state of free-cantilevering equilibrium before the shell surfaces were cast within it (4.12 to 4.16).



4.11
Cross section through the 8 cm thick shell with prestressed reinforcement (inner) and passive reinforcement (outer)

4.12–4.15
Construction of the Hamburg hypar shells

A jungle of falsework

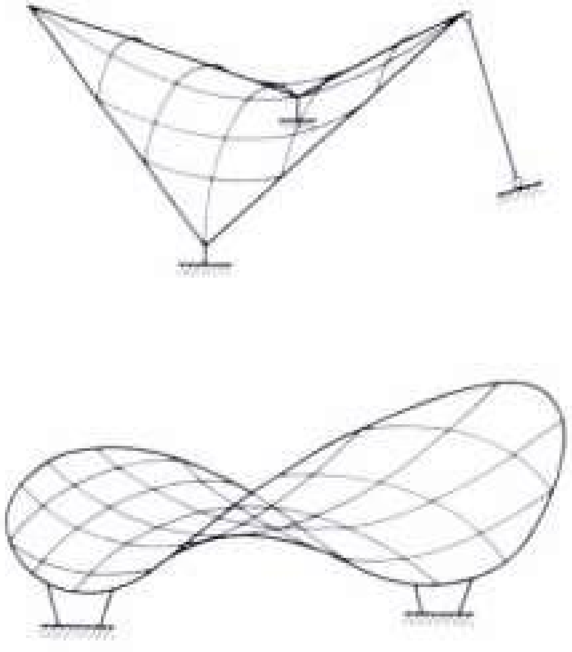
A form for a hollow portion of an edge beam

Laying the reinforcement

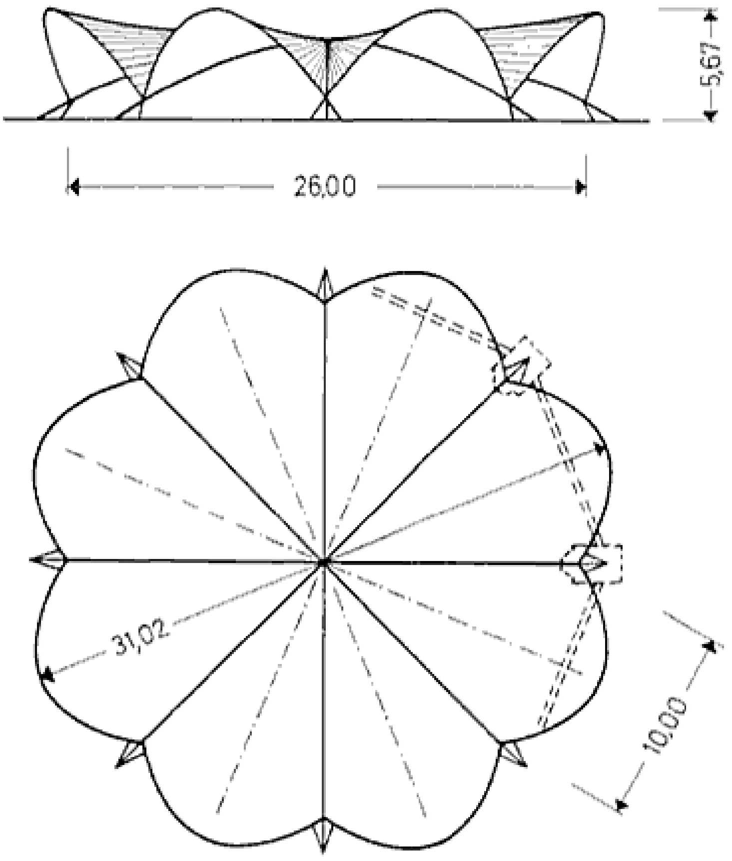
Reinforcement of the valley

4.16
The completed shell

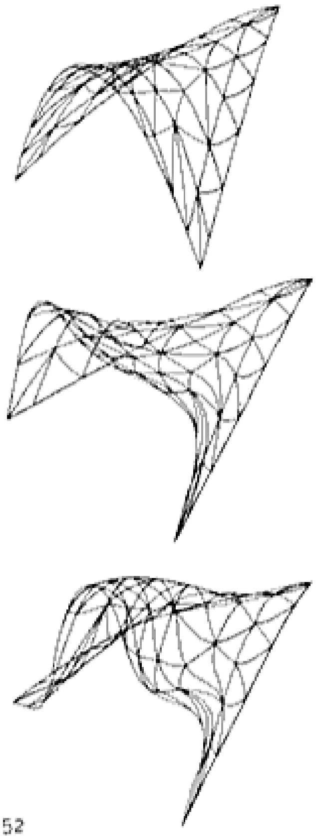
Schlaich looks back on this project with mixed feelings (4.2+4.3). He considers that the basic concept of the roof was "a child of its time" and, in terms of current thinking, flawed from an engineer's point of view. He now regrets his youthful eagerness to test his prowess in turning it into reality. The result was typical of many similar cases. The architects' original concept (here a thin, light membrane appearing to "float" over the pools) was completely lost in the technical measures (the large edge beams and the heavy piers) which were an inevitable consequence of their early decisions regarding the nature of the structure. Schlaich would not now accept such a commission, where "the structure is the building", unless the architect were willing to start at the beginning again and go through the development of the concept with the engineer at his side as an equal partner, as sensitive as possible to the aesthetic aspirations of the architect, but insisting on a degree of structural logic "as large as possible". On the other hand he gained much from the experience, particularly in learning the lesson that "a technical challenge may make engineers blind to a holistic view".[5] This particular challenge proved his capacity for concentrated mental effort, backed up by advanced analytical ability and the experience that if one tries hard, it is always possible in structural engineering to work from a complex reality to a simplified but valid theoretical model, and from there to a physical model.[6] (He considers this ability very important to achieve an innovative and, even more importantly, a safe design, now that many engineers must depend on computer analysis as a "black-box" tool.) He gained in confidence to the extent that he was ready for the challenge of engineering the cable-net roofs for the Olympic Stadiums at Munich several years later. In fact, as mentioned above, he demonstrated that there is a close theoretical link between the shell and the cable-net roof (4.9 and 4.17). In 1969 Schlaich wrote a paper outlining his contribution to the theory of hypar shells and dedicated it to Leonhardt in honour of his sixtieth birthday. Leonhardt himself submitted it for publication, and it appeared in 1970.[7]



4.17
Illustrations used by Schlaich to show how the forms of cable nets are more 'readable' visually than those of featureless shell surfaces. (Taken from a 1969 paper on the Hamburg roof dedicated to Fritz Leonhardt.)



4.18
Basic form and dimensions of the Stuttgart GRC shell roof (thickness 12 mm) following Candela's Xochimilco restaurant roof



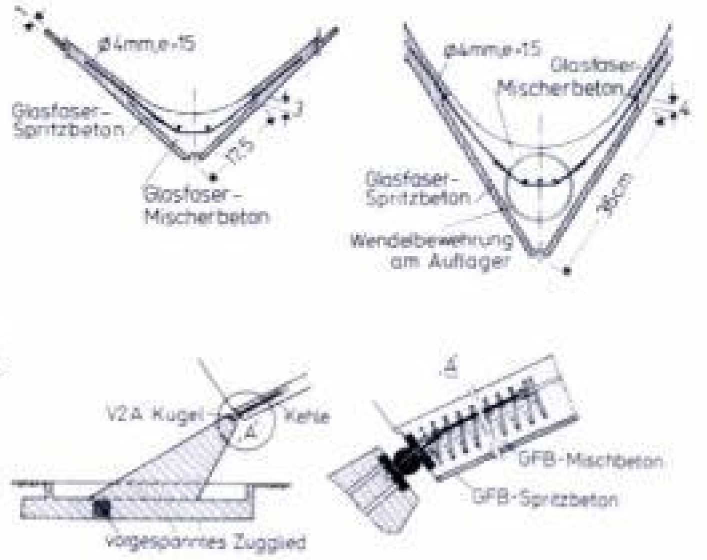
4.19
Computer output showing (at an exaggerated scale) the symmetrical and antisymmetrical buckling modes of a shell segment

Following a period of enthusiasm for concrete shell roofs in the 1960s, their popularity waned considerably. There were a number of reasons for this, but a major factor was the cost of the complex and extensive formwork required to support the wet concrete (4.12).[8] Schlaich therefore instituted a number of research initiatives aimed at improved construction methods. The recent development by Pilkington Brothers of alkali-resistant glass fibres as strong as steel had led to their use as reinforcement in fine concrete to form a new composite material (glass-reinforced concrete, or GRC). This was much more homogeneous than conventional reinforced concrete and its high tensile strength made it possible to dispense with conventional reinforcing bars. Whereas for practical reasons, a concrete shell with two layers of reinforcement and the necessary cover cannot be less than six to eight centimetres thick, the thickness of a GRC shell may be exactly that required to resist the stresses. The Heidelberger Zement company had been carrying out research on GRC under the direction of Professor Meyer, not far from Stuttgart. When it was decided to hold the Federal Garden Exhibition, the Bundesgartenschau 1977, in **Stuttgart**, Schlaich realized that the need for temporary buildings offered a great opportunity to test the new material. It was decided to build a pavilion utilizing a **shell roof of GRC** as a research project of Schlaich's university institute, with Wolfgang Menz as his research assistant.

The strength and lightness of GRC meant that an extremely thin layer would be capable of resisting the forces caused by self weight, snow, and wind loads. Its lightness would make it possible to cast the roof in segments which could then be lifted into position by crane. The repetition and precasting would permit great economies in the cost of formwork. However, there would be a greatly increased danger of buckling, because of the thinness of the surface, so the shell must be given a form which was inherently resistant to buckling. In thinking of a shell shape which could demonstrate the advantages of GRC, a natural choice was that used by Candela for his restaurant at Xochimilco. This has eight curved segments - hyperbolic paraboloid saddles with edges curved in plan - whose double curvature provides the necessary resistance to buckling (4.18+4.19).

With respect to buckling the required thickness of GRC proved to be only 12 mm for a span of 26 metres between supports. For an overall covered area of 31 metres diameter, the segments would weigh only 2500 kg each, ideal for prefabrication. As usual, the major innovative leap was not the end of the story. Many subsidiary problems had to be solved, including the manufacturing technique for a precise 12 mm GRC-layer (4.20 and 4.21), the design of localized steel reinforcement for the connection of the shells and near the eight ball-bearing supports (4.22+4.23), and the development of special techniques involving "strong-backs" and suction strips for handling the delicate segments before they could be joined along their common edges and acquire their full stiffness as integral parts of the whole shell (4.24-4.26). The Rostan company in Friedrichshafen played an important role in these developments.

4.20+4.21
Glass fibre reinforced concrete: spraying on the form and rolling



4.22
Details showing the connection of the shell segments and the ball support at the foundations

4.23
One of the eight steel balls which support the shell

4.24–4.26
The GRC shell under construction

A completed segment still resting on its form

Lifting the hardened segment with the aid of suction strips

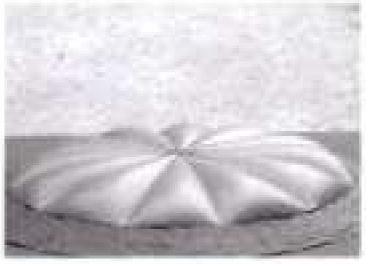
Six segments in their final position temporarily supported only at their common edges

The shell was a bold experiment in many ways. It was made possible only because the building regulations of Stuttgart were temporarily waived by a progressive bureaucracy on the understanding that the shell would stand for not more than one summer season. Major aims of the test were to find out how the GRC would react when exposed to natural climatic conditions (especially in relation to brittleness and creep) and to gain experience in the design, fabrication, and construction of very thin shells in a new material. Schlaich also saw the experiment as a tribute to Candela and an extension of his design: an exercise in pushing it to the limit to reveal its full potential. The Xochimilco shell required 40 millimetres of concrete, even following Mexican practice where it is considered acceptable to use only one central layer of reinforcement. At Stuttgart this was reduced to 12 millimetres of GRC. To emphasize the lightness of the roof and to facilitate erection it was supported on eight steel balls serving as bearings (4.23+4.27). These permitted local rotation in any direction and thus reduced the stresses caused by expansion and contraction of the roof following temperature changes.

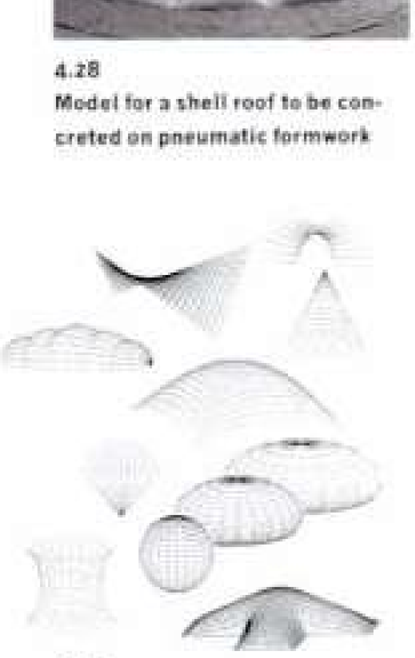
The construction of the pavilion gave rise to some controversy. Schlaich had felt that in using the new material to clearly and publicly demonstrate the full potential of Candela's Xochimilco roof, he was paying due recognition to the talent of the great designer. On the other hand Frei Otto saw the adaptation of the concept as an insult. By a fortunate coincidence Candela was at that time in Paris presenting a series of lectures and Schlaich was able to invite him to Stuttgart, promising to show him "a shell that will interest you". He entertained him at his home and then took him to see the new structure. He remembers that Candela, who was then 67, was delighted with it and, climbing to the top of the shell, jumped up and down to test its deflection. (This proved to be several centimetres.) With tears in his eyes he declared that he was gladdened to know that his ideas were being passed on and developed in such a way.

The shell proved so successful that the authorities allowed it to stand for five years rather than the originally planned six months. Valuable observations were made during this period and a great deal of further research and analytical work on the use of GRC was carried out at the Institut by Wolfgang Menz under Schlaich's guidance. However, in 1982 the shell was badly damaged by hooligans. By this time it had also suffered appreciable creep deformation and the GRC was becoming brittle.[9] It was therefore decided not to spend money on repairing it, but to carry out a few final load tests and demolish it.

4.27
The completed shell with a temporary façade for the Stuttgart Federal Garden Fair 1977



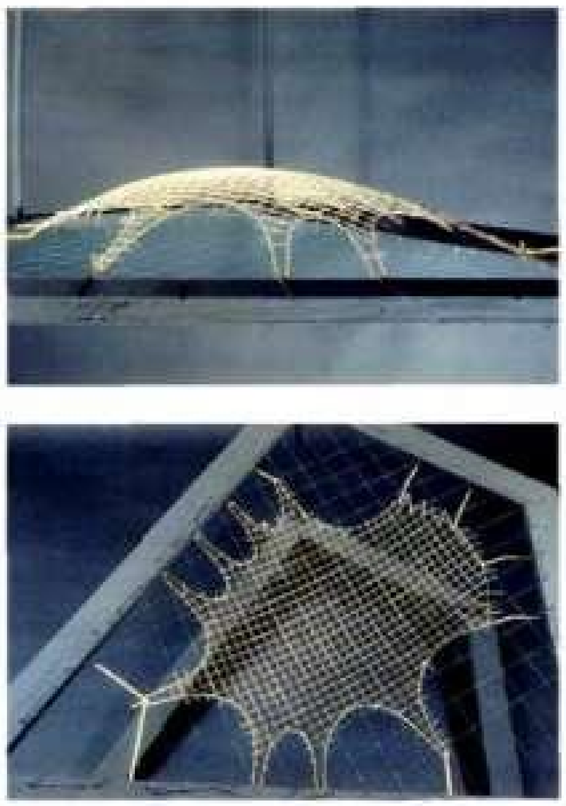
4.28
Model for a shell roof to be concreted on pneumatic formwork



4.29
Ideal shell shapes derived from inflated membranes restrained by cables (from the doctoral dissertation of Werner Sobek)

4.30
Inflated shell formwork using the van Eeden system

Another way to reduce the cost of shell construction is to replace the expensive falsework with a **pneumatic formwork** which is blown up like a balloon either before or even after the wet concrete is laid.[10] The simple balloon shape, in the form of a spherical dome, has certain disadvantages. At the low pressures appropriate to the construction site, the centre portion of the balloon tends to sag under the weight of wet concrete and become undesirably flat. This increases the danger of buckling in this region when the shell must support its own weight and any superimposed loads due to wind, snow, or maintenance work. Schlaich therefore instituted research on pneumatic forms whose dome shape was modified by cables passed over the surface and tensioned to create a form rather like that of the GRC shell. The cables permit an increased internal pressure and this reduces sagging during construction (4.28). The more complex shape increases the strength of the finished shell and, most importantly, its resistance to buckling. In addition, a shell of this shape would have better internal acoustics than a smooth dome, and would be easier to fit out internally.



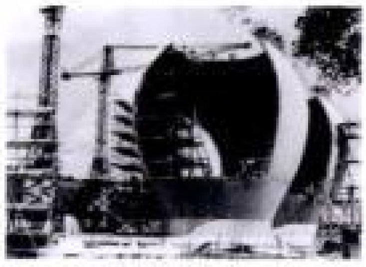
4.31+4.32
A free shell shape developed by inverting a model tension net

Schlaich's first design experience with this concept occurred in a project to cover an ice-skating rink at Stuttgart's Max-Eyth-See recreation ground with a 100-metre-diameter shell roof. To gain practical experience, the technique was first applied to the construction of a similar roof for a small water reservoir near Heilbronn in 1983, the design being carried out by Werner Sobek and Fritz Bacher. The Max-Eyth-See roof was never built, but the experience gained in its design and with the Heilbronn prototype was extremely valuable. Sobek went on to write a dissertation on the subject at the Institut which was submitted in 1986 (4.29). He then entered the Schlaich Bergermann office and worked there for some years before taking up an appointment as Professor at the University of Hannover and thereafter succeeding Frei Otto at Stuttgart. Much later, in 1991, the partnership took the opportunity to contribute to the realization of large silos in Germany on the basis of a patented system in which the concrete is sprayed onto the interior of a pneumatic form (4.30).

Another form-finding technique was applied for a **free shaped shell roof**, built with the architect R. Ostertag in 1990 in **Stuttgart**, to obtain a free architecturally appealing shape that was at the same time structurally sound (4.31+4.32). These techniques have been developed and publicized in recent times by Heinz Isler and Frei Otto.[11] Unfortunately this shell as realized in Stuttgart is squeezed between office buildings and its free-shape character completely obscured.

In the early seventies Schlaich worked with the architect Kurt Ackermann on the design of **sewage digester tanks** for the **Klärwerk Gut Marienhof** in Dietersheim, near Munich.[12] These are needed to store large volumes of liquid while biological processes act to break down the waste matter. A fine structural solution had earlier been pioneered by Ulrich Finsterwalder for the firm of Dyckerhoff and Widmann (4.33). With Dietger Weischede as project engineer, Ackermann and Schlaich applied both advanced shell theory and prestressed concrete technology to develop a cone shape which could be constructed more efficiently, was as ideally suited to resist the outward pressure of the liquid, and permitted smooth internal flow and efficient cleaning. They felt that it would be an advantage to sink the lower portion of the tanks below ground level, to reduce their apparent size and to leave only the clear and evidently stable geometric form of a truncated cone protruding (4.34 - 4.36). As usual this aesthetic decision was reinforced by a technical advantage. The pressure of earth against the lower part could be used to counteract the outward pressure of the contents, thus relieving the shell of part of this task.

The result at Gut Marienhof, completed in 1987, is an inspired and competent engineering solution, but for the purposes of insulation and for architectural reasons, the cones are covered in a cladding made of troughed aluminium sheets and the casual observer is unaware of the concrete shells within.

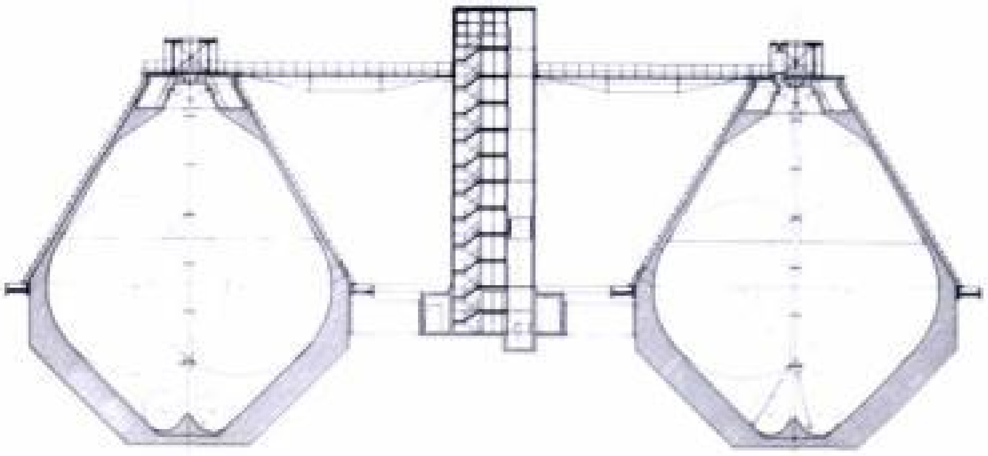


4.33
Dywidag egg-shaped sewage digester tanks (for comparison)

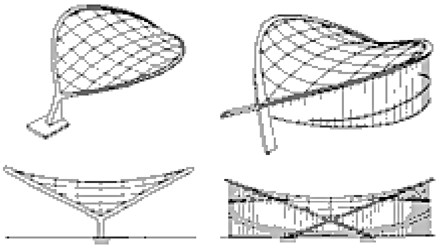
4.34 - 4.36
Gut Marienhof sewage treatment plant

Three of the tanks with central access tower and linking walkways

The project under construction



Cross-section through two tanks and the access tower

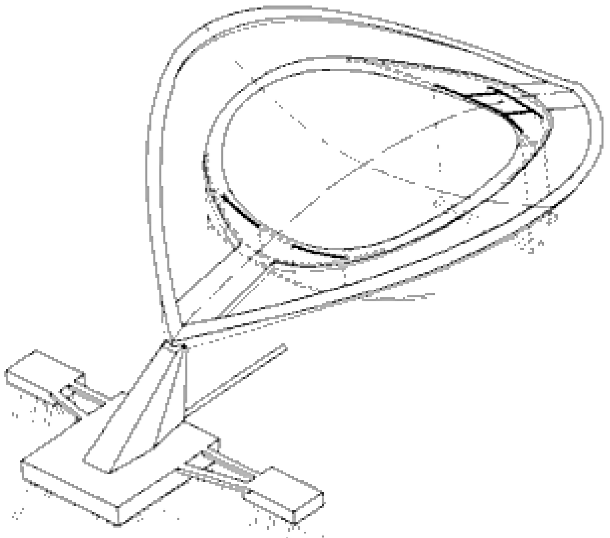


4.37
A comparison of structural forms: the original architectural concept of the Berlin Congress Hall (left) and the Raleigh Arena (right) (see 2.2)

In 1980 Schlaich was called to give an expert opinion on a case where the disjunction between architectural concept and engineering had led to disaster: the **collapse of the roof of the Congress Hall in Berlin**.[13] This building was designed by a US team led by the architect Hugh Stubbins, with Severud, Elstadt and Krueger as engineers. Its construction in 1957 was a gift from the American to the German people. In its structural scheme it bore some similarity to Ralph Nowicki's famous stadium at Raleigh in North Carolina, designed by the same engineers. Schlaich considers the Raleigh Stadium to be one of the most significant buildings to be completed since the war and worthy of veneration by everybody interested in lightweight structures. There, two slender arches are leaned over at a steep angle to support a cable-net roof suspended between them. The tendency for the arches to fall outwards is balanced by the inward pull of the net but, to ensure stability, each arch is directly propped by a row of columns, similar to those mentioned in the discussion of the Hamburg hypar roof. A similar system was adopted for the Congress Hall, but with a prestressed concrete hypar shell in place of the cable net. Its two arches were not placed on the ground, but sprang from the tops of a pair of piers (4.37). A wall surrounded the auditorium, elliptical in plan. Photographs of the architectural model show the roof projecting far over the boundaries of the substructure to give the impression of "floating" above the concourse. The arches are apparently freely cantilevered, with no suggestion of support from below.

However, after this concept had crystallized, an investigation suggested that the system was not really stable and that corrective changes would be necessary if it were to be built satisfactorily. This conclusion should have sparked a complete reconsideration of the structural and architectural concept. However, as often happens, the principals chose not to abandon their original formal concept and decided to divide the hypar roof into an entirely independent inner roof, suspended within a concrete ring beam which would be supported on the auditorium wall, and two outer roof zones spanning the remaining distance to the arches (4.38+4.41). The arches were now mainly decorative in function yet it was necessary to find some means of supporting their weight. The most logical solution of propping them from below was out of the question for architectural reasons, so it was decided to tie them back to the ring beam by means of prestressing cables embedded in the outer concrete slab (4.39). It was recognized that the latter would be subject to constant flexing (as well as extremely high tension) as the arches rose and fell due to the effects of snow and wind load and temperature changes. There would also be cumulative movement due to creep and shrinkage of the concrete arches.

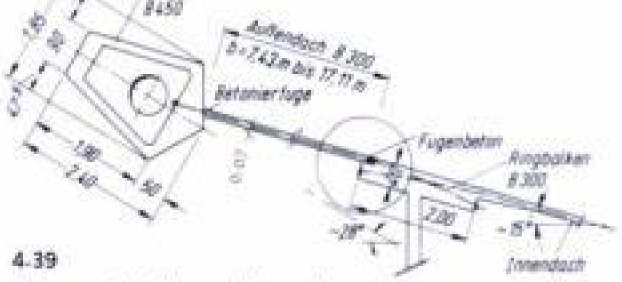
Given the state of knowledge and experience at the time it was probably assumed that the 70 mm thick concrete slabs of the outer roof would be sufficiently flexible to follow this movement without distress and that, even if significant cracking of the concrete did occur, the sheaths and the alkaline nature of the grouting surrounding the prestressing cables would protect them from corrosion. In the event, due to the tension, all movement and resultant cracking was concentrated in a narrow band adjacent to the perimeter of the roof (4.40). Rain, and spray from the



4.38
The structural scheme of the Congress Hall as built in 1957

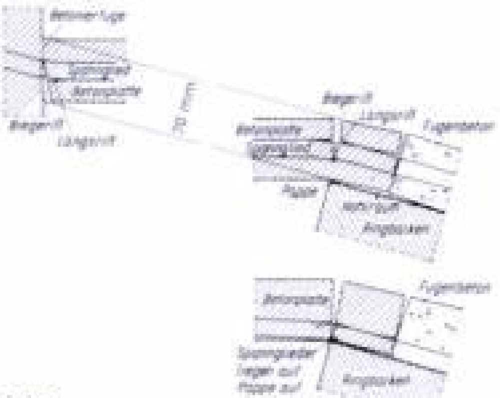
ornamental fountains in front of the building, reached the highly stressed steel and led to corrosion and brittleness. The problem was exacerbated by deficiencies in workmanship due to the very short construction period of only 10 months. These included inaccurately placed reinforcement and prestressing cables (4.40, lower right), porous concrete at joints, and a leaking roof membrane. In 1980, after 25 years service, the southern arch without warning tore away from the outer slab and collapsed to the ground (4.42). Fortunately, the hall was not in use at the time. One person was killed, but the disaster could have been very much worse. Schlaich's report contains the following conclusion: "The collapse of the southern outer roof and arch was caused by deficiencies in the engineering design and construction of this portion of the roof. The result was failure of the tension members supporting the rim arches, due to corrosion cracking. This exposed the technical dishonesty of the design, in that the inclined arches did not carry the roof [as they appeared to do] but were merely attached to it, to satisfy the architect's formal concept, which had been criticised from the beginning by engineering experts. The inner roof, the real auditorium roof, remained standing!"

Despite this, the Senate of Berlin decided that the hall should be repaired in such a way that its outward appearance as well as its functioning would not be altered. The tender documents suggested that demolition start with the inner roof. However, Schlaich prepared for a contractor a proposal to span the entire building with a cable net stretched between two inclined arches. This would have sailed over the inner roof and protected it from the weather. Thus the inner roof, still basically sound and now required only to carry its own weight, could have been retained and the arches made much more slender than the original ones. Some strengthening of the main supports would have been necessary, involving modifications to their shape, but in Schlaich's view the new shape would have been more logical. Although this scheme was backed by the contractors Philipp Holzmann AG it was not accepted by the authorities, and in 1984 the roof was built as a prestressed concrete shell by another company.[14]



4.39

Cross section through the arch, prestressed outer slab and inner ring beam



4.40

Details of the joints connecting the outer slab to the arch (left) and to the inner ring beam (right) after cracking

4.41

Berlin Congress Hall: exterior view before collapse

4.42

Bird's eye view showing the collapsed arch

Notes to Chapter 4

[1] C. Faber: *Candela, the shell builder*, Reinhold, New York, 1963.

[2] „So einfach dieses Kraftespiel (des Hypars) aussieht, so unvollkommen ist es in Wirklichkeit. Schon die Gewichte der Randglieder lassen sich nicht aufnehmen, denn eine lotrechte Last kann der Schalenrand uberhaupt nicht vertragen. ... Die Tatsache, daß die Schale keine außere Schubbelastung beliebiger Größe zu tragen vermag, bedeutet kinematisch, daß die Schale mit den Randgliedern nicht starr ist, sondern einer dehnungslosen Deformation fahig ist. Das bedeutet, daß Schalenformen dieser Art [mit nicht unterstutzten Randgliedern] mit außerster Vorsicht zu gebrauchen sind." W. Flugge: *Statik und Dynamik der Schalen*, 2nd ed., Springer, Berlin/Gottingen/Heidelberg, 1957.

[3] This is partly because the parameters are inherently linked in the physical model, and partly because the cost and time required to build and test such models are so great that in most cases only a single model is used.

[4] J. Schlaich: "The computer between science and practice", *Structural Engineering International*, 1/1991 (Feb. 1991).

[5] But, he remarks ruefully, "it happened again twenty years later, with the Montreal roof!"

[6] However, he notes that important structural details incorporated in the design (such as the nature of the continuous edge beams, which minimized local stresses in the joint between edge beam and membrane) meant that certain deficiencies of the analysis were acceptable. He notes that "later on, this was exactly the joint where the shell roof of the Berlin Congress Hall failed", but that inspections carried out on the Hamburg roof immediately following the Berlin collapse proved its soundness.

[7] J. Schlaich: "Zum Tragverhalten von Hyparschalen mit nicht unterstutzten Randtragern, (Herrn Professor Dr.-Ing. Fritz Leonhardt zum 60. Geburtstag im Juli 1969 gewidmet.)", *Beton- und Stahlbetonbau*, 1970, Heft 3.

[8] Partly, this was a question of simple changes of fashion in engineering as well as architectural circles. The fact that the architect must be willing to accept considerable guidance from the engineer if a technically sound form is to be achieved may also have contributed. On the practical side, in addition to the cost of falsework, special care is needed to ensure water-tightness. It is difficult to marry a conventional planar wall system aesthetically with a curved shell, and there are practical problems because the shell is subject to relatively large deformations due to temperature changes.

[9] Since that time further development has greatly improved the properties of glass fibres.

[10] Major advances in this technique were due to Dr. Dante Bini. See e. g. *New Civil Engineer*, 20 Feb. 1976, p. 26–8; and *Constructional Review*, May 1976, p. 60–66.

[11] If the structure of a wide-spanning roof is to be light in weight, bending stresses must be kept to a minimum. This applies whether the structure is a shell composed of masonry or concrete whose thickness must be minimized, or a grid (Chapter 6) whose individual members are to be kept as slender as possible. The shape of the surface must be chosen so that individual members are placed in a state of almost pure compression under the effect of self-weight and reasonably uniform superimposed loads. An established method of achieving this is to build a model tension structure usually in the form of a cable net or woven fabric having the same (model) boundaries as the projected roof. Because the model is completely flexible it hangs naturally in a state of pure tension. If the form so obtained is unsatisfactory for functional reasons, it may be altered by changing the cutting pattern of the net or fabric. When the designer is satisfied with the form, the model is inverted either in reality or mathematically. Its dimensions are factored up to provide those of a full-scale structure which under self-weight and symmetrical loading will act entirely in compression. The wide applicability of the technique highlights the close relationship between the mechanics of grid domes, cable-nets, shells, and membranes. A similar technique was used around 1900 by Antonio Gaudi to find a suitable shape for neo-gothic churches (J. Tomlow: *IL 34, Das Modell/The Model/El Modelo*, Institute for Lightweight Structures, Stuttgart, 1989). Otto's best known example is the enclosure for the Bundesgartenschau at Mannheim, designed with Ted Happold (Happold and Liddell, *Structural Engineer*, March 1975, p.99). Heinz Isler has put the technique to brilliant use in designing his concrete shell roofs (H. Isler: "Concrete shells derived from experimental shapes", *Structural Engineer International*, 3/1994, March 1994, p. 142-147).

[12] See also H. Schulitz: *Constructa-Preis 1990: Industriearchitektur in Europa*, Vincentz Verlag, Hannover, 1990.

[13] Such investigations are called in German Gutachten. The noun comes from the verb *gutachten*: "to act as an expert witness" and is usually translated as "an expertise". In this case it was a sort of professional "second opinion". At Berlin the expertise was to be based on a preliminary investigation by Professors H. H. Engell, of MPI Dusseldorf and K. Kordina, of TU Braunschweig, who had pointed to the fact that the wires of the tension cables connecting the edge arch and the ring beam on top of the auditorium wall were highly corroded and that their rupture caused the arch to collapse. In his Gutachten, Schlaich explained the deficiencies in design which caused cracking and corrosion.

[14] See *Beton- und Stahlbetonbau*, 12/1980, p. 281–294 and 1/1986, p. 22-25.

Selected publications by Jörg Schlaich and co-authors (if given) up to 1995 to Chapter 4: **Concrete Shells, Research on Glass-Fibre-Reinforced Concrete**

month/year

03/70: "Zum Tragverhalten von Hyparschalen mit nicht unterstutzten Randtragern", *Beton- und Stahlbetonbau.*

09/70: "Das Hyparschalen-Dach des Hallenbades Hamburg Sechslingspforte", with F. Leonhardt. *Beton- und Stahlbetonbau.*

09/70: "Hypar Shells for Roofing Indoor Swimming Pool in Hamburg", IASS-Kongreß, Wien.

04/77: "Die Glasfaserbetonschale fur die Bundesgartenschau 1977 in Stuttgart". Betontag 1977. Deutscher Betonverein e. V.

09/77: "A first long-span, lightweight glass-fibre-reinforced concrete shell", with W. Menz. Proceedings. IASS Congress. Alma-Ata.

01/79: "Faserbetone", with W. Menz. *Baukalender 1979.*

12/80: "Teileinsturz der Kongreßhalle Berlin - Schadensursachen – Zusammenfassendes Gutachten", with K. Kordina and H.-J. Engell, *Beton- und Stahlbetonbau.*

01/81: "Glasfaserbeton – Eigenschaften und Moglichkeiten", with W. Menz. *Aus der Forschung fur die Praxis. FBW-Blatter,* 1.

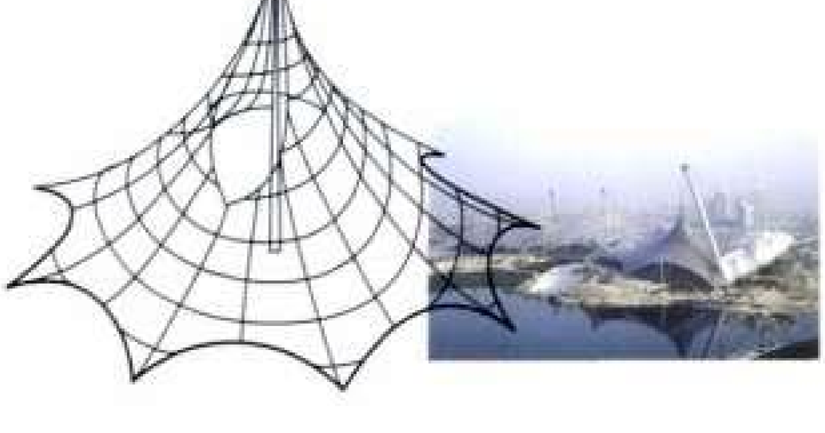
09/82: "Haben Betonschalen eine Zukunft". *Beton.*

10/84: "Rißwiderstand und Rißfortschritt bei Glasfaserbeton", with W. Menz. *Fortschritte im Konstruktiven Ingenieurbau. Festschrift: Gallus Rehm zum 60. Geburtstag.*

01/86: "Suitable Shell Shapes", with W. Sobek. *Concrete International*, vol. 8, no. 1.

06/86: "Do Concrete Shells have a Future?", *IASS-Bulletin.*

12/94: "Anton Tedesko and the early history of concrete shells", with P. Saradshow, *IASS-Bulletin.*



5 Cable-Net Structures

5.1
Munich Olympic Stadiums: Model of the scheme which won First Prize for Günter Behnisch und Partner

5.2
Model of the scheme which won Third Prize for Heinle Wischer und Partner

5.3
From 5.2: The stadium

When the decision was made in 1967 to hold the **1972 Olympic Games in Munich**, the German government called a **competition** for the design of the necessary stadiums. The committee in charge set novel themes, intended to reflect the nature of democratic post-war Germany. The project was to have minimum impact on the natural and visual environment, blending as far as possible with the landscape. The ambience was to be youthful, light-hearted, and unforced.[1] Structures could be impermanent or even dispensed with altogether. Buildings for Olympiads and Expos are generally seen as opportunities for nations to display their technical and architectural prowess and, with such an exciting and challenging task ahead, competing architects formed teams with renowned consulting engineers.

Heinle Wischer und Partner joined with Leonhardt und Andrä. In the engineering practice, Kuno Boll took on the role of active partner, while Schlaich became project engineer. The Stuttgart architect Günter Behnisch and his partners formed a team with the Swiss engineer Heinz Isler, renowned for his free-form concrete shells. Behnisch also sought the advice of the architectural historian Joedicke, whose books on shell roofs had contributed greatly to their popularity in the 1960s. Behnisch finally opted to use a **cable net for the roof structure**, possibly inspired by Frei Otto's roof for the Montreal Expo of 1967, and the competition theme of transience. Cable-net construction lay outside the range of Isler's direct experience, and Schlaich has commented that this was, in a way, a good thing. Any conventional engineer, including Schlaich himself, would have told Behnisch that the free-form cable net envisaged in his competition model could not possibly work. If this had happened, the present roof would not now exist (albeit in necessarily modified form). The Behnisch entry was awarded **first prize**, with the Heinle proposal coming **third** (5.1 – 5.3). The jury considered Behnisch's scheme to be an outstanding realization of the competition themes. However, their enthusiasm was qualified by their concern that the proposed roof represented a step into the unknown. It was to be on a much larger scale than Otto's Montreal roof, its nearest equivalent (5.4). The Munich net was to be draped sharply over a number of masts within its boundaries and this would lead to very high forces in the cables in the immediate vicinity of the mast heads. To that date, no satisfactory means had been found of coping with this problem. On the other hand, in some parts of the roof the surface was to be extremely flat. In these locations the low curvature would permit large deformations under static load and possibly large vibrations in strong winds. Even though "transience" was a theme of the competition, additional questions were raised concerning the durability of cable-net roofs.

The competition jury naturally felt that the construction of such a large and crucially important structure to a tight time-schedule was not the occasion to attempt major breakthroughs in technique. They suggested that Behnisch's brilliant response to the environmental and architectural themes would not be greatly diminished by omitting its roofs completely, or by covering the stadiums with the roofs designed by the Leonhardt und Andrä team for the Heinle scheme. These roofs, which consisted of saddle-shaped cable nets suspended from large perimeter arches and cables, were also novel in conception and size but definitely practicable.

The award and the accompanying reservations caused intense excitement and public discussion. In Schlaich's words "the newspapers and television stations consulted every expert and, even more, every non expert who assumed he had an opinion. Everybody was asked and few knew what they were talking about".

The majority opinion amongst experienced engineers throughout the world was that the proposed roof was indeed impracticable. At the end of 1967, Leonhardt joined with Professors Rusch and Burkhardt in a detailed evaluation of the problem.[2] They stated:

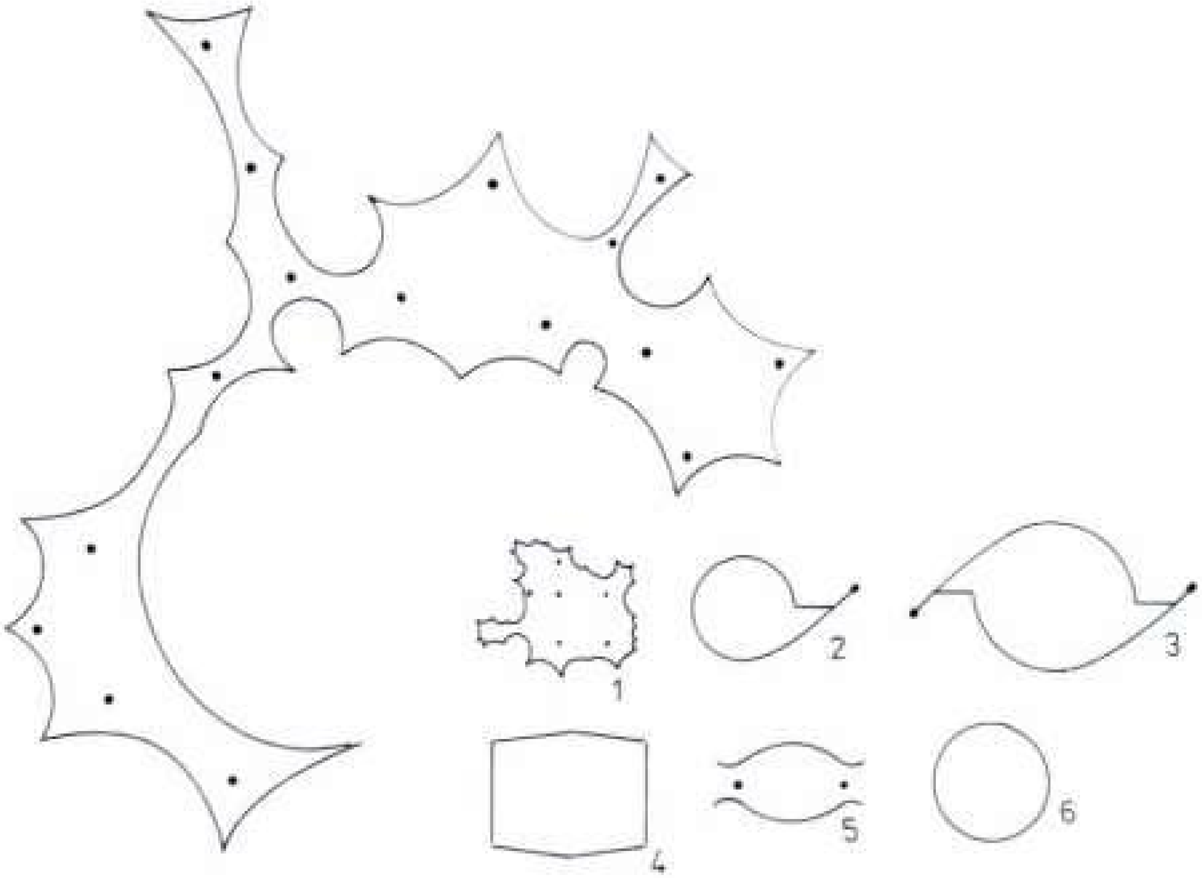
"It is pointless, for technical and economic reasons, to build a roof of this form and size, especially since the jury found that the omission of the roof would not diminish the artistic value of the conception. Therefore the client would be ill-advised to base planning only on the solution proposed by the winner of the first prize without examining genuine alternatives to the tent design."[3]

Eventually, to break the impasse, the Bavarian Prime Minister F. J. Strauss decided that the two teams led by Heinle and Behnisch should combine and that, if they found the so called "point supported roof" of the prize-winning scheme impracticable, they should build Behnisch's scheme with the Leonhardt und Andra roofs.

Not surprisingly, Behnisch and Heinle were unable to find a mutually agreeable architectural compromise. Schlaich remembers a crucial meeting at Heinle's office towards the end of 1967 with the two teams of architects, advisors, and engineers sitting facing each other, either side of a long narrow table. There was a total failure to communicate. Behnisch maintained, justifiably, that it would be ridiculous to build his scheme with someone else's roof – it would be "no scheme at all". Eventually Heinle, recognizing the merit of Behnisch's concept, decided to withdraw "in the interests of the nation and its Olympic effort". To achieve an integral work of architecture, the project must be left in the hands of one designer. He also recommended that the Leonhardt und Andra team should move across to join with Behnisch in an attempt to make the original scheme work. Schlaich's loyalty to Heinle led him at first to refuse, but he was finally persuaded by Heinle himself to join the Behnisch team.

Behnisch called in Professors Kupfer and Gattnar from the Technical University of Munich and the team, now based in Munich, began to search earnestly for suitable solutions. On the architectural design side, Schlaich worked mainly with two young architects from Behnisch's firm, Fritz Auer and Karl-Heinz Weber. On the more technical side he worked with Erhard Trankner and Wilfried Buxel (5.5). They postulated a variety of cable net forms which included versions supported radially or on arches, and stiffened by panels of timber or corrugated sheet metal. Small models made from matchsticks and pantihose were used to investigate possible forms. (The latter is an excellent material for simulating the properties and characteristics of a net surface). Work on the "point-supported" solution, in which the net sat directly on the mast tops, resulted in a form which differed from Behnisch's original scheme only by "a couple of additional matchsticks" and was considered by the engineers to be still unbuildable. More purposeful work continued on "edge-supported" alternatives inspired by the Leonhardt und Andra scheme, but greatly extended in area to correspond as closely as possible to Behnisch's scheme (5.6). At that time, the engineers were naturally still happier with the latter.

On 1 March 1968, the committee charged with overseeing the design (the Olympia-Baugesellschaft or OBG), finally decided to adopt Behnisch's first prize scheme for the southern areas of the Olympic Park, leaving open the decision on the type of roof to go with it. Heinle's office was invited to take over the design of the northern area including the Olympic Village, with K. Boll as structural consultant.



5.4
Comparison of the size of the Munich Olympic roof with that of: 1 Montreal Expo, 2 and 3 Tokyo, 4 Stockholm, 5 New Haven, 6 Raleigh

5.5
The Behnisch team in 1969. From left: Karl-Heinz Weber, Erhard Tränker, Günter Behnisch, Fritz Auer and Wilfried Büxel

5.6
One of the "edge-supported" schemes

5.7
Fritz Leonhardt conferring with (from left to right) Heinz Isler, Fritz Auer, Frei Otto, Jörg Schlaich, Rudolf Bergermann and Knut Gabriel

5.8
The initial pantihose model for the stadium roof

At this time Frei Otto, whose office was then in Berlin, accepted Behnisch's invitation to become involved in the project. On the engineering side, Leonhardt, who was taking his turn as Rektor of the University of Stuttgart and had been preoccupied with the student unrest of 1968, replaced Boll as active partner. The two offices in Munich and Berlin now produced a large number of proposals for the point-supported alternative. Schlaich remembers this period as another highlight in his professional life. He worked eighteen hours a day from Monday to Friday and returned to Stuttgart for the weekend to relax by working on the construction of his new house! In the design office he was left very much to his own devices. Leonhardt's duties allowed him to visit Munich only every month or so, but Schlaich recalls that his presence on these occasions and his immense experience were "extremely helpful and reassuring" (5.7).

It was Otto who provided the inspiration to set the project moving in the direction of the point-supported system favoured by Behnisch for the half roof over the stadium. He had recently tackled the high concentration of forces around mast heads in his design for a stadium roof in Gelsenkirchen, and had evolved a solution which would need only slight modification for Munich. He also brought a certain order to the overall scheme by proposing that the roof consist of a number of distinct, though adjoining, saddle shaped nets (5.8). These would be suspended from sloping cables attached to tall inclined masts situated behind the grandstand. A massive edge cable curving around the boundary of the playing field, just above the front of the grandstand, would be fastened to ground anchors and tightened to place all the nets in a state of tension. With further rough textile models, the team convinced itself that on this basis "point-supported" roofs could be adopted also for the sports and swimming arena and for the areas in between. They therefore submitted this initial design of a point supported roof as their favourite solution. However, at the request of the client, they again included the alternative edge supported scheme, which had been worked out in much more detail in the meantime.

Schlaich remembers that Behnisch and his partners did not really like this point supported solution architecturally (although they much preferred it to the edge-supported scheme) because it lacked the freedom of form that had been the main feature of his original proposal. However, as he knew that a decision for one of the two solutions must soon be taken, his words in paraphrase were "look, I know you are trying to do the best you can just get it as close as possible to my design and I'll be happy with that". At this stage the OBG, very concerned about technical matters, hurriedly appointed an international group of expert engineers to advise on the choice between the two schemes. The experts questioned the design team about form, structural action (especially aerodynamic stability and deformation under snow load), cladding, fabrication and construction, and the time required for completion. The answers for the edge-supported alternative were clear and convincing, while those for the point-supported scheme could only be approximate. However, knowing that the competition jury would shortly be reconvened and would in all likelihood confirm its decision in favour of the point-supported roof, the engineering experts agreed in May 1968 that the design team should press on with the "point-supported" option covering all sporting arenas under one large roof. Even so, they left open the possibility that the scheme might still be abandoned in favour of the more conventional solution.

The expert group was especially concerned by the danger of aerodynamic flutter, and demanded that the design team prove analytically that the roof would not be susceptible to this problem or, failing that, suggested that it be stiffened by some form of sheeting to achieve a type of "shell" action. The complexity of the problem made it impossible even to approach the analysis theoretically.

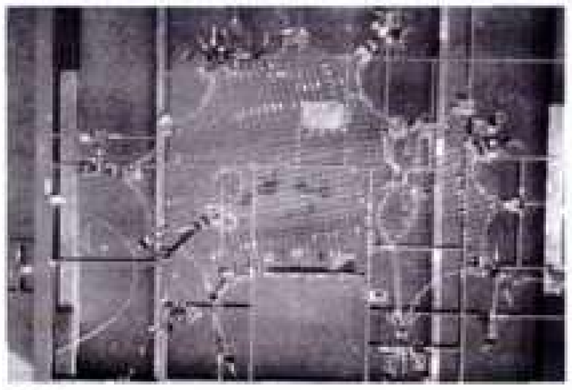
However, Schlaich's intuition, based on experience in the analysis of more simple cases, suggested that in a form as convoluted as the Munich roof the natural vibrations of one section would be counteracted by out-of-phase vibrations transmitted from adjacent areas. Tests conducted later on a small-scale and much simpler experimental roof provided the reassurance he had been seeking. Provision was made in the final design for installation of extra bracing cables after construction, but these have proved to be unnecessary. On 21 June 1968, the OBG declared that the point-supported roof, as so far developed, should be built with "shell-type" timber stiffening.[4] They decided that work on the edge-supported roofs should be terminated, offering the consolation that it had contributed greatly in making possible a clear decision between the two alternative types. For Schlaich, however, the real benefit of this work had been the welding together of a team of young engineers and architects who respected each other's abilities and had developed a camaraderie which would stand them in good stead in the coming struggle. Behnisch declared his absolute trust in this team and said he could want for no better.

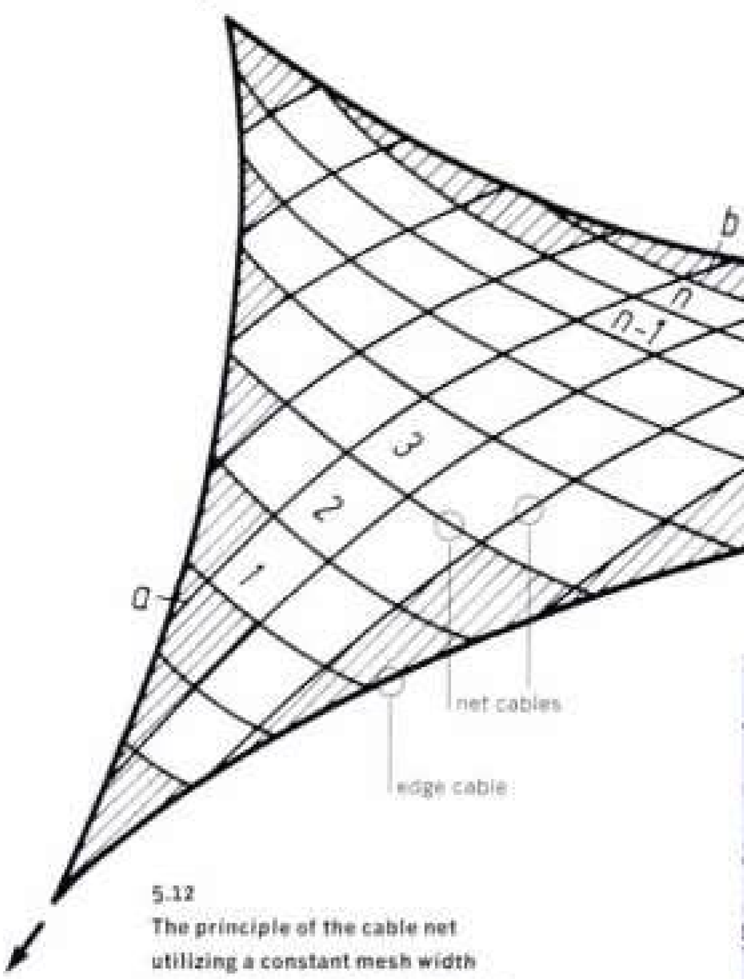
With the decks at last clear for action, the team was keen to get on with the main task. Public interference in the project ceased for the time being, contracts were awarded, and money became available to start building up the design teams and commence testing materials, components, and models. The design group adopted the lengthy title of Architekten und Ingenieure Behnisch & Partner mit Jürgen Joedicke, Frei Otto, Leonhardt und Andrä. Isler moved to take over the design of the stadium substructures while Professors Kupfer and Schuller were asked to become Proof Engineers for the roof.[5] This was a task they performed, in Schlaich's words, in an "exceptionally constructive and courageous manner". He and Herbert Kupfer later became colleagues and good friends. The engineering design team formed on 1 July 1968 under the guidance of Leonhardt had Schlaich as leader with Rudolf Bergermann responsible for the stadium roof, Knut Gabriel for the sport hall roof, Ulrich Otto for the swimming hall roof, and Karl Kleinhanß for the connecting roofs. Schlaich, at 33, was the oldest member of the team.

Within a few months, the form of the roof had been refined and finalized using tulle models (5.9). The engineering analysis and design of Cable-net roofs at that time was based wholly on tests and measurements made on physical models using techniques pioneered by Frei Otto and his team at the Institute of Lightweight Structures (IL) in the University of Stuttgart. Wire models were used to determine the forces and deflections in the cables, the cutting lengths, the patterns for the cladding, and the geometry of the connections. The IL therefore began constructing models for the Munich roofs (5.10+5.11). Later, Professor Linkwitz of the Institut für angewandte Geodäsie (applied geodesy) at the University of Stuttgart was called in to determine the exact dimensions of the model using photogrammetry and analytical models simultaneously, and to work out the geometry of the many cutting patterns required. Before long, the engineering design team in Munich became concerned that this process was not providing information quickly enough to meet the deadline, or with sufficient accuracy. Small inaccuracies in cable length may greatly affect the distribution of forces within the net. The typical stretch in a cable 25 metres long under the prestress necessary to define the desired form is only 15 mm. Thus a mistake of only 5 mm in the calculation (and therefore in the length supplied by the manufacturer) will result in a 30 per cent error in the prestressing force which develops when the net is pulled taut. This will cause a corresponding change in the structural form.


5.9
The final tulle model of the entire roof


5.10
The wire model of the stadium roof (side view)

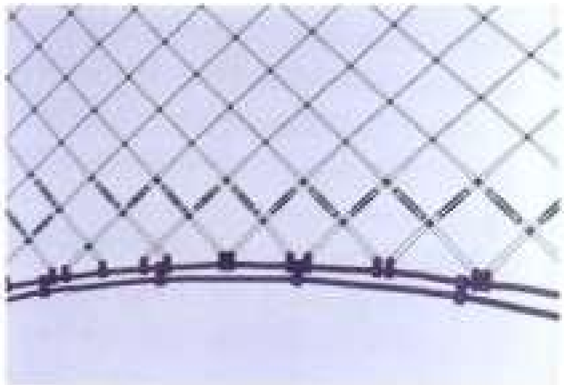

5.11
The wire model of the roof over the swimming arena (seen from above)



5.12
The principle of the cable net utilizing a constant mesh width (except at the edges) and adapting to double curvature by change of mesh angles. The total length L of one net cable is given by

$$L = a + n \cdot \underbrace{\text{meshwidth}}_{\text{here 75 cm}} + b$$

5.13
The Munich cable net with its 75 cm mesh width



5.14
An edge of the net, showing the double locked-coil edge cables and the turnbuckles provided to adjust tension in the net cables (see 5.45)

5.15
The main multiple cable forming the edge of the stadium roof and the adjacent cable nets (see 5.41)

5.16
The standard cable-net clamp, before and after press fitting (see 5.42)

These considerations prompted a 22-year old French engineer in the team, Marc Biguenet, to start work in the summer of 1968 on developing an entirely computational method for calculating cable lengths and joint locations. The team sought assistance from D. Scharpf and Th. Angelopoulos of the Institute for the Statics and Dynamics of Aero and Space Structures at the University of Stuttgart, led by Professor Argyris. Schlaich recalls that he went to Argyris to ask him if he would be able to solve 4000 simultaneous equations. (This was at a time when the average engineer, working by hand, would baulk at nine.) Although these were very early days in the development and exploitation of the digital computer, Argyris bravely said "yes". His response to the challenge played a large part in establishing computer applications in structural engineering. The computer method was developed in time to apply it to the roof of the sports hall. This was the first time that a cable-net roof had been analyzed by calculation rather than physical modelling, and it is possible that Schlaich's strong preference for fundamental theory over experimentation increased his motivation to obtain an analytical solution. The accuracy achieved was of course much greater.

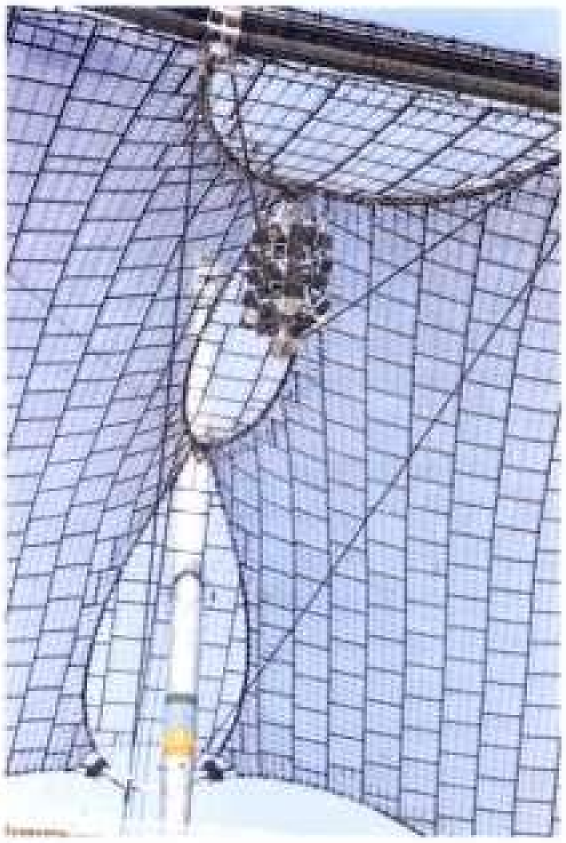
Unfortunately, this development was distressing for those at the IL who had spent a large part of their lives developing the model technique at a period when the development of the electronic computer could not have been foreseen.[6] Its effects may have contributed to the gradual deterioration which was then occurring in the relationship between Schlaich and Otto. Many differences over technical matters added to the problem. Otto wanted to use, as far as possible, the ideas he had developed for his Montreal building, especially in regard to cable and connection details. However, a visit to Canada showed that the detailing had already led to partial deterioration and Schlaich wished to introduce modifications to avoid this. He also wanted, as an engineer, to make maximum use of symmetry and repetition in the shape and details of the roof. He argued that, at the minimum, there should be some sort of orderly progression in the size of masts, net panels, and other features. Otto's inclination as an architect was to strive as far as possible for the freedom of form which Behnisch had originally envisaged. As Schlaich remembers, "everything had to be random". This greatly complicated the engineering.

Lengthy discussions arose over the size of the mesh to be used in the net, and the design of the clamps used to connect crossing cables. Otto wished to use a net 50 cm square. Schlaich, with Leonhardt's support, argued that a 75 cm net would greatly reduce the number of cables and joints while still making it possible for workers to walk on the net in safety (5.12–5.15). In previous nets he had noticed serious geometrical distortions to cables caused by the fact that the clamps held the angle between the crossing cables rigid. The engineers therefore conceived a clamp consisting of a single bolt which would allow the cables to rotate relative to one another. To maintain symmetry in the connection it was necessary to use two smaller cables, one either side of the bolt, rather than a larger single cable (5.16).

Schlaich writes that the period from summer 1968 to summer 1969 was hard, but wonderful and fruitful (*hart, aber schön und fruchtbar*). He relates that the team "built a wall around itself" for protection from the inconsistency of the OBG and attempts to impose critical path planning methods on its work. (It adopted the humorous slogan "as fast as possible, but no faster".) As has been the case in several prestige projects where great haste was necessary, the foundations were designed and construction started before the nature of the roof had been determined (5.17).[7] This, and the requirement for a clear view for the television cameras, placed inconvenient limits on the positioning of the masts, causing great problems for the roof designers.

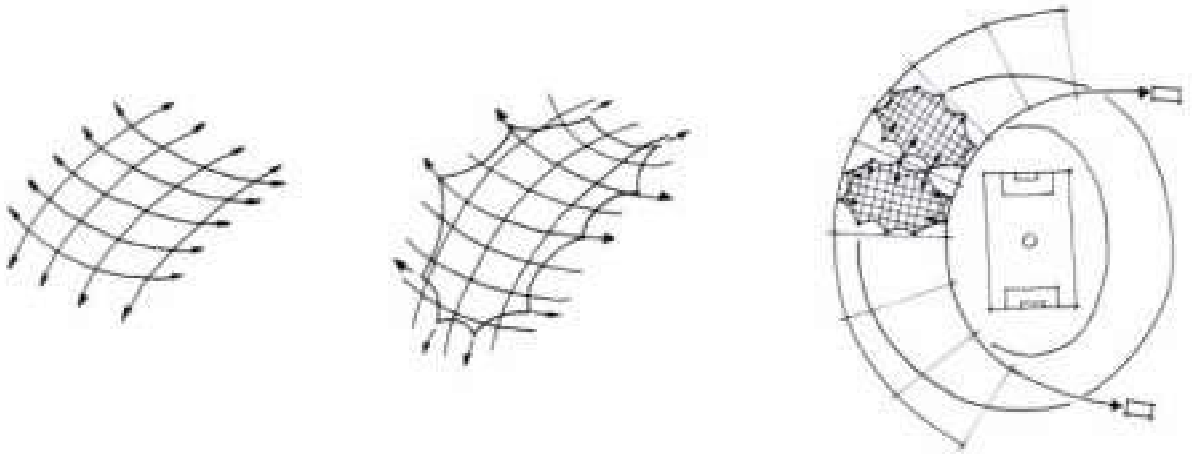
The cladding for the roof was the subject of much debate. At one stage it was even suggested that it be clad in lightweight sprayed concrete ("gunite") to guard against the problem of flutter. However, the experts' recommendation concerning "shell-type timber cladding" was quietly forgotten. Eventually the question was resolved when those responsible for televising the Games insisted that the roof be transparent. It was therefore decided to clad it with acrylic glass (Plexiglas) (5.18 + 5.19).

5.17
The huge anchor block for the main cable of the stadium roof, designed to resist a horizontal force of about 4500 tons



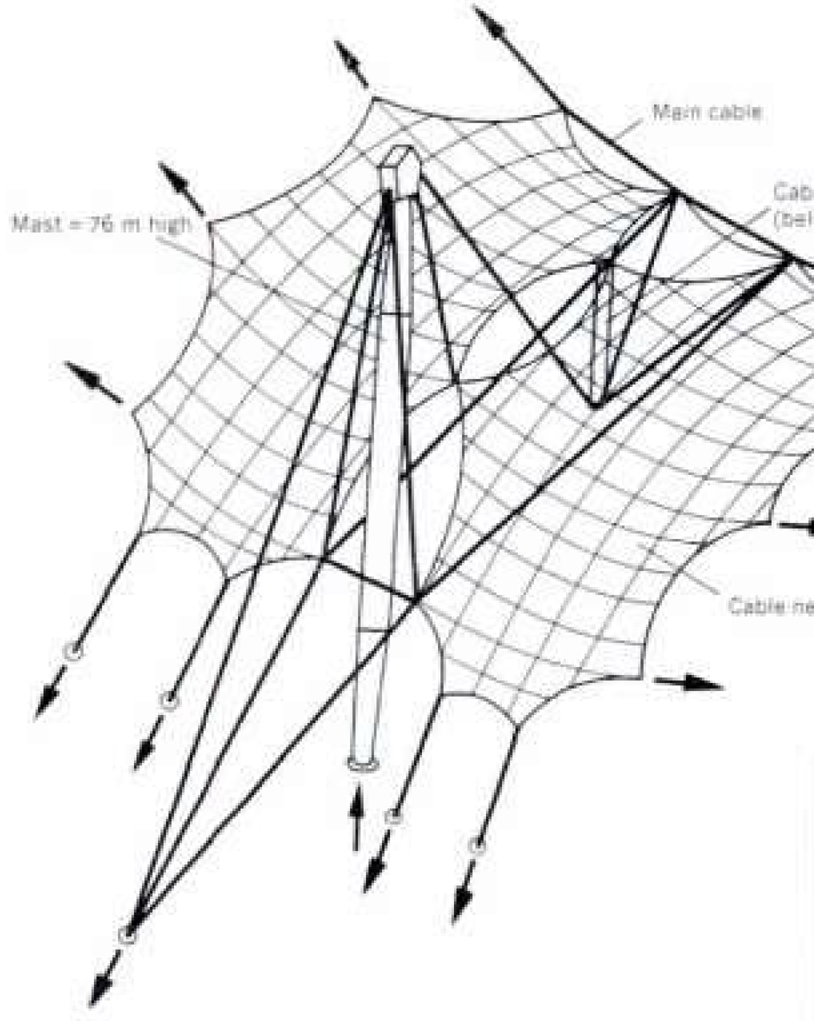
5.18
A section of the plexiglass cladding viewed from below

5.19
Detail showing attachment of the plexiglass cladding panels to the net cables

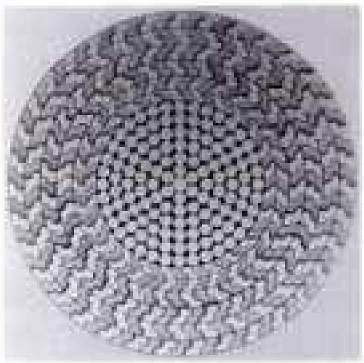


5.20–5.25
The development of the structural concept of the roof over the stadium utilizing a square mesh cable net surrounded by edge cables and supported by a primary structure of masts and ties.

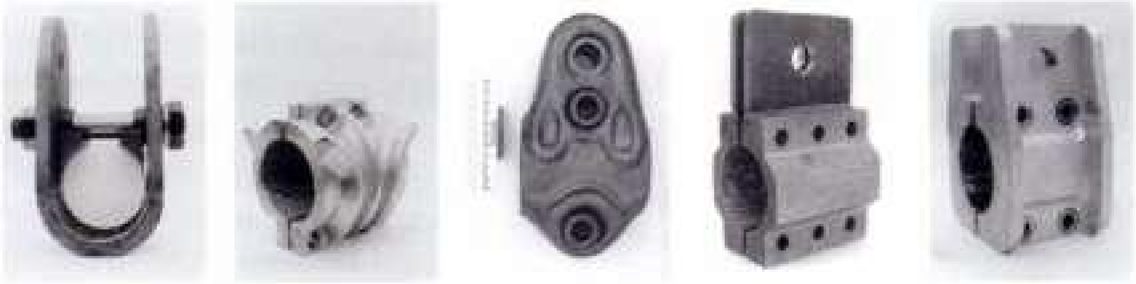
Below:
Perspective view of two of a total of 9 nets, covering the stadium (see 5.9)



The design of the stadium roof gave rise to many innovations in addition to those mentioned above. These are all documented in the technical literature (see list of publications at end of chapter) and it is sufficient here to provide a few illustrative examples. The design of the cable-net clamp was optimized and tested (5.16 + 5.42). Its two parts were automatically press-fitted in the factory, leading to greater precision on site. A standard edge cable of 80 mm diameter was chosen for the entire roof (5.26) and this was used either singly or in groups of up to eight, depending on the force to be carried (5.14, 5.37 + 5.44) in order to need only one type of edge cable clamp (5.32 + 5.43). The designers found themselves restricted by a code of practice which stated that cables could not be bent into an arc of radius less than 40 times their diameter. The team took a gamble that it could prove that high-quality cables could in fact be bent on a radius of only ten times their diameter. Tests showed this intuition to be justified, and the codes of practice were later changed to take account of revised thinking.

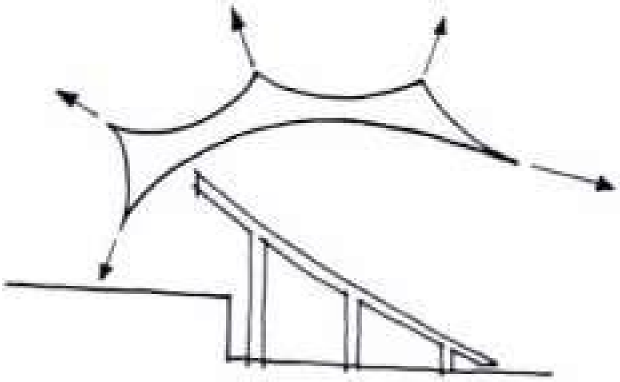


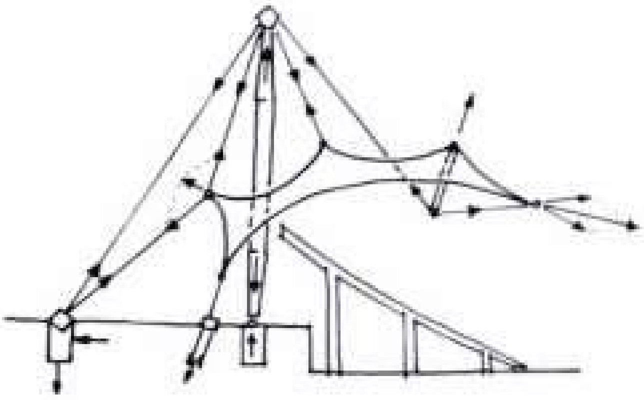
5.26
Section through a locked-coil rope



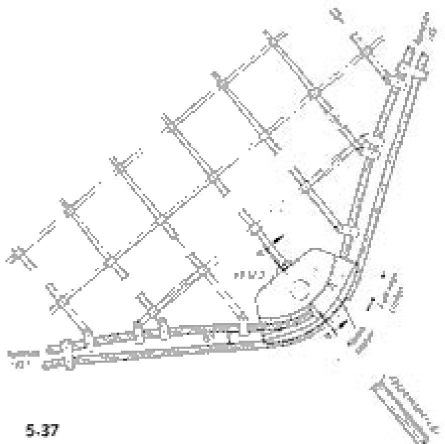
5.27–5.31
Experimental versions of the edge cable clamp

5.32
The adopted form of the edge cable clamp (testing see 5.49)

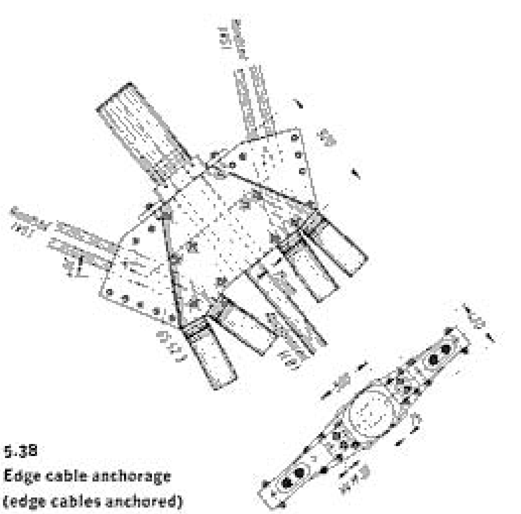




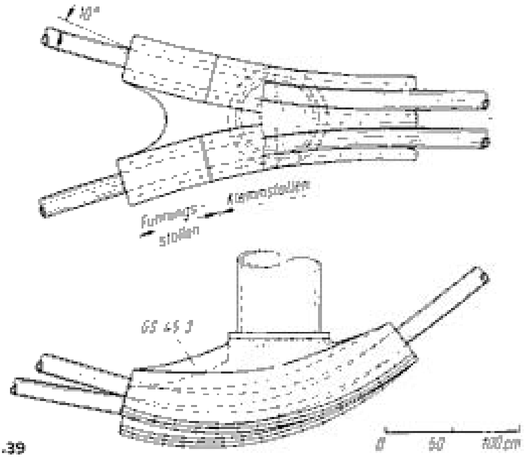
5.33–5.36
Details of the cable-net structure as built



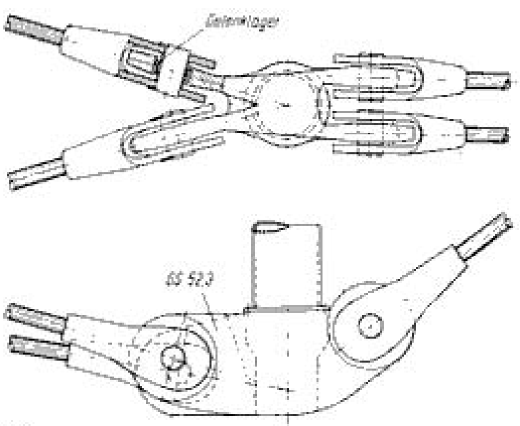
5.37
Edge cable anchorage
(edge cables continuous)



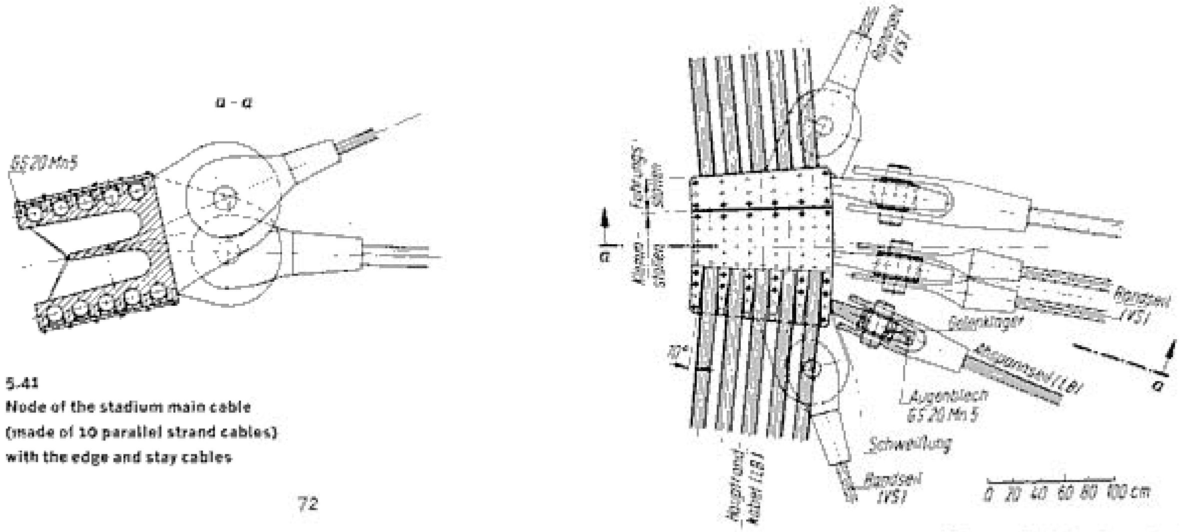
5.38
Edge cable anchorage
(edge cables anchored)



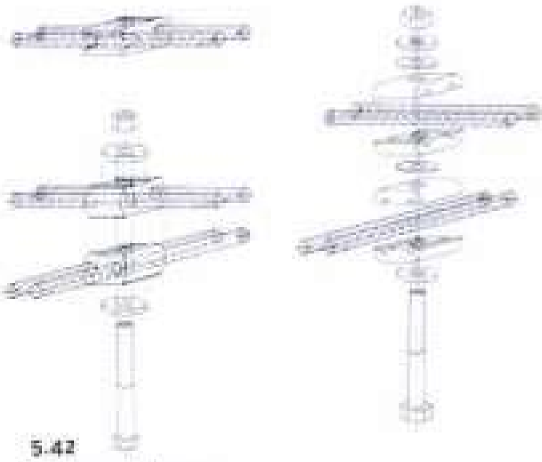
5.39
Base of a cable supported mast
(cables continuous)



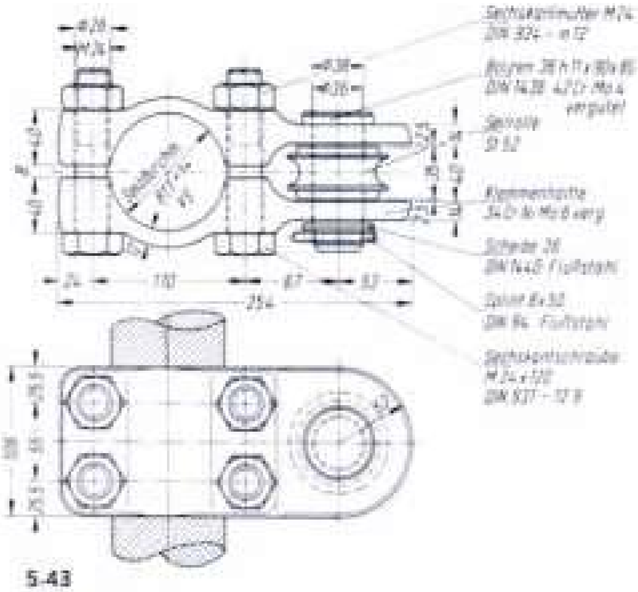
5.40
Base of a cable supported mast
(cables anchored)



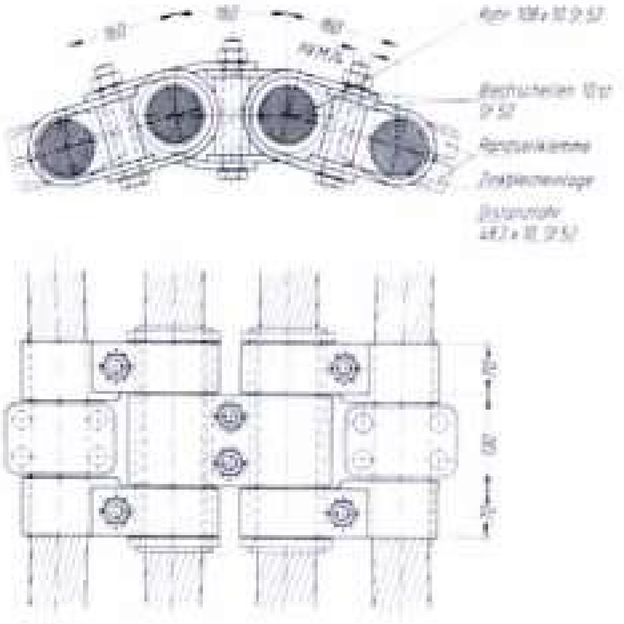
5.41
Node of the stadium main cable
(made of 10 parallel strand cables)
with the edge and stay cables



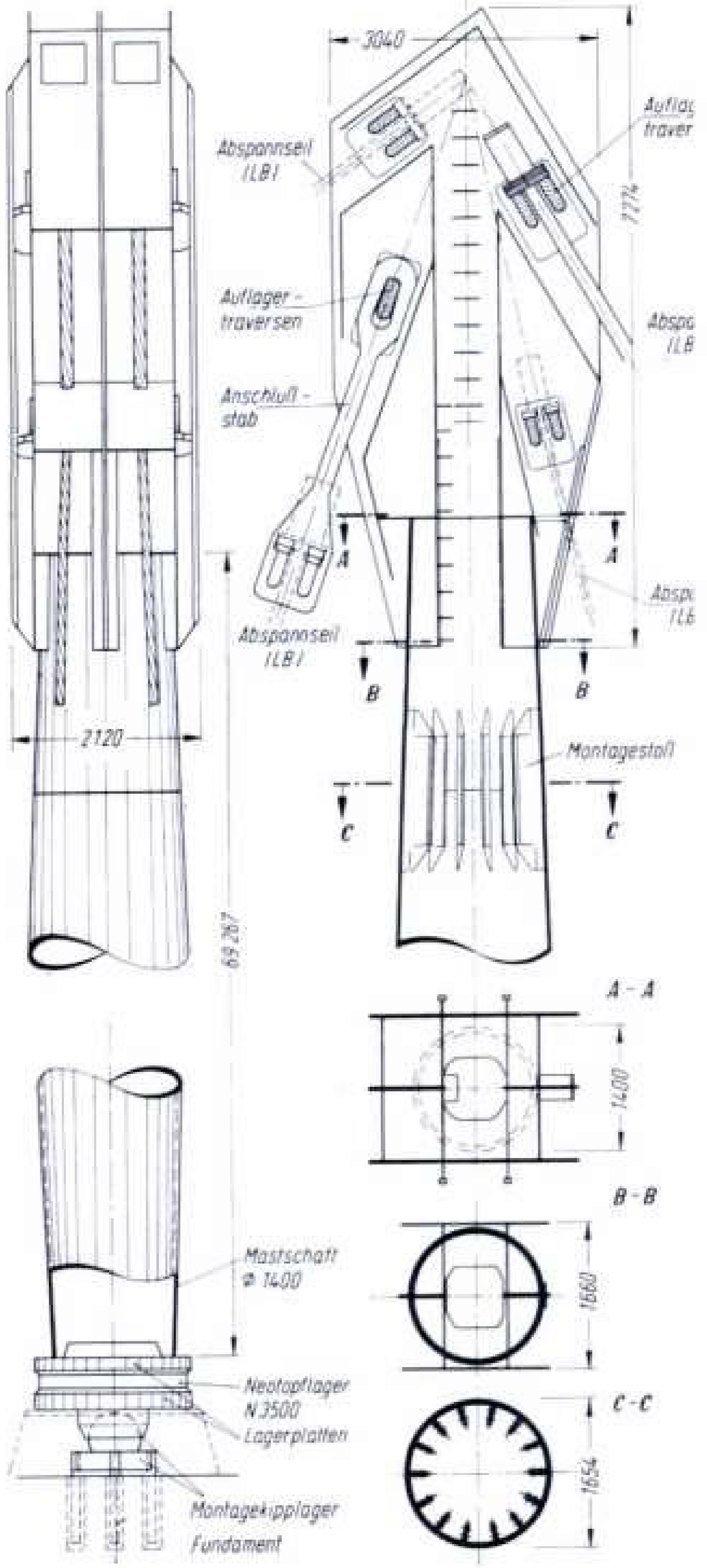
5.42
Cable-net clamps, pressfitted and bolted



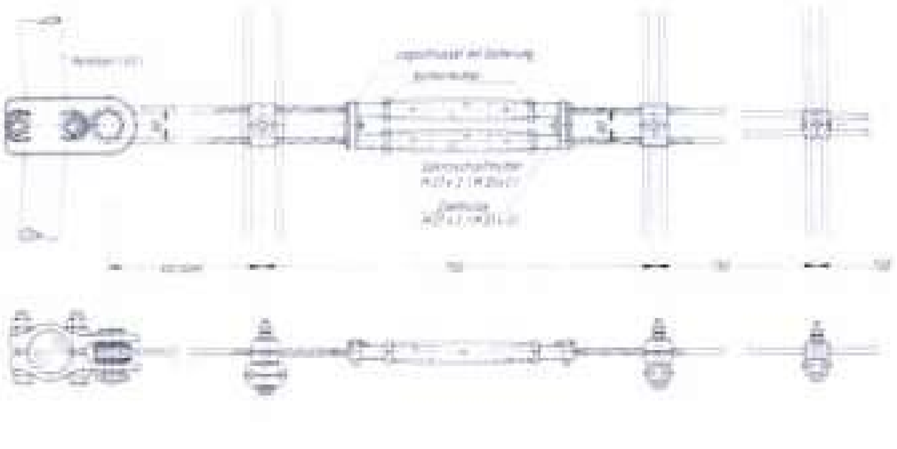
5.43
Edge cable clamp



5.44
Ridge cable clamps



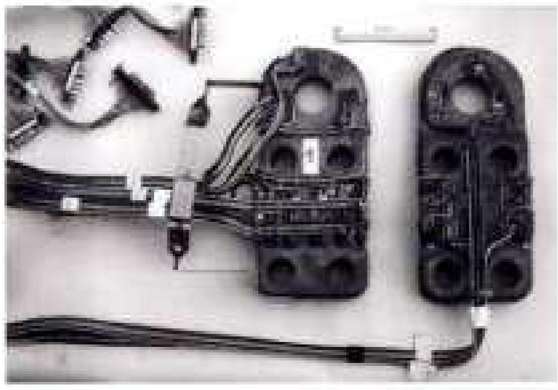
5.46
The top and base of a typical mast



5.45
Edge cable/net cable connection with turnbuckle

5.47
The cable-saddle fatigue testing machine at the Zurich ETH

5.48
A socket instrumented for testing



5.49
The edge cable clamp prototype instrumented for testing (see 5.43)

The design team also instituted experiments to check the fatigue resistance of the cables at bends, anchorages and clamps. This work was carried out at the ETH Zurich with Dr. Rösli (5.47) and at the University of Stuttgart by Professors G. Rehm and H. Muller (5.48 and 5.49). Later Gallus Rehm and Schlaich became very close when belonging to the same faculty.

From today's point of view it is significant that this project played a large part in resurrecting the art of steel casting, with invaluable cooperation from the firm of Pohlig-Haeckel-Bleichert (PHB). Casting of iron components had been discontinued at the turn of the century because of the unreliability of the product and the cost of preparing the moulds, so its reintroduction for important steel elements using modern techniques for fabrication and testing was a pioneering step (5.50–5.54).

The motivation for this development came from problems encountered in the design of the massive steel units required to connect the main cables at junction points (or nodes). The initial proposal to form these from welded steel plates presented several difficulties. Welding leads to uneven heating and cooling of localized areas and it is very difficult in complex components to control the resulting distortion. Because the geometry of the nodes was so complex, its description in conventional drawings would take considerable time and present severe difficulties of decipherment in the fabrication shop. These problems were multiplied by the fact that all the nodes were different. The designers realized that if the units could be made of cast steel, greater accuracy would be achieved, and it would be necessary only to describe the geometry of the surfaces required to accommodate the cables. The body of the unit between these surfaces could be roughly indicated by the engineers and sculptured freehand by the technician who would make the full-size model to be used in preparing the moulds. Conventionally, the model is made of wood which means that the mould to be cast around it must be designed so that it can be taken apart to extract the model and then reassembled leaving a void for casting. In many cases, the nodes at Munich contained reentrant angles which would have prevented this process. PHB therefore introduced the use of styrofoam plastic which could be left inside the mould and melted as soon as the molten steel was poured in. PHB later profited from their role in the development of steel casting by obtaining the contract to supply major components for the famous Centre Georges Pompidou in Paris.

The saddles on the tops of the main masts were of more regular form than the nodes and so for economy were made of welded steel plate 100 mm thick (5.46). Photoelastic stress analysis of these details was carried out by Professor R. K. Müller of Stuttgart.

The resolution of the roof design was by no means the only challenge met by the design team. Gigantic foundations and tension anchorages were necessary (5.17) and city government officials had to be convinced of the safety of new ground anchors as well as new cable types. Finally, it was necessary to find suitable suppliers (who came from France and Austria as well as Germany) and with their cooperation convert the information into working drawings and develop suitable manufacturing and construction techniques. Constant communication and supervision were necessary.

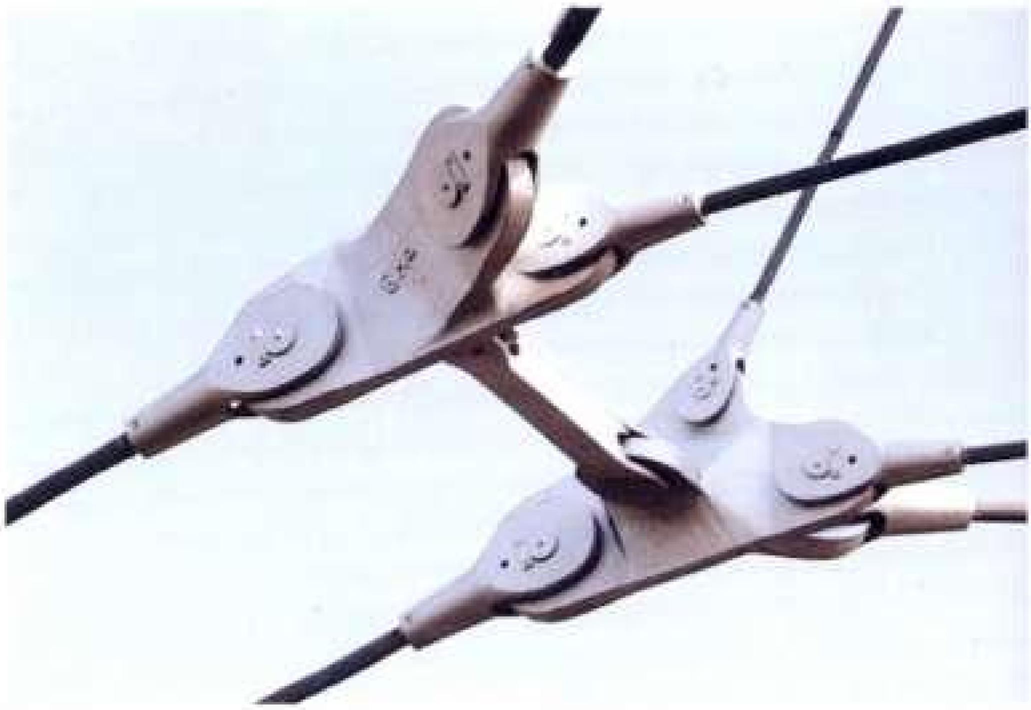
A major set-back threatened when tenders for the construction of the roof were received in July 1969. Only two firms made offers. The price was twice as high as the design team's latest estimate and five times as high as the initial estimates, and the offers were hedged about with many disclaimers. The problem was resolved by the new chief of the OBG, Carl Mertz, who proposed that the two firms merge their teams for the project, and guaranteed them generous financial returns. The design team were pleased to find that Harald Egger, a former colleague from Leonhardt und Andra who had worked on the Montreal roof, was to lead the contractor's planning of construction.

In retrospect, the design of the Olympic roofs can be seen as a unique, highly varied, difficult and interesting task, performed in the spotlight of public criticism and scepticism, especially concerning the durability and the cost of the project. It was impossible to prepare a cost estimate in the conventional way because design decisions taken along the way could be firmed up only as research and investigation provided the necessary information. Thus the client was obliged to foot the bill as expenditure developed. The short life expectancy was an issue of much public criticism, but after more than 20 years the main structure of the roof is still in excellent condition and maintenance costs have been minimal. Recently some corrosion was detected where the cables are embedded in the cast steel saddles. Due to poor silicone grouting, water had penetrated in places, requiring cleaning and replacement grouting. This can easily be fixed. The acrylic glass cover is also due for replacement.

Schlaich feels that some of the major structural elements: the masts, stays and anchorages; and many of the details: the nodes and saddles, are excessively heavy from both an architectural and an engineering point of view. This was partly due to the flatness of the roofs, as conceived by the architects, which caused the forces throughout the structure to be higher than optimum. However, it can also be ascribed to a degree of conservatism on the part of the engineers, adopted because of the magnitude of the task, the limited time available for design and research, and some remaining uncertainty about the exact behaviour of the cables (especially with regard to creep under long-term load).[8] Nevertheless, Behnisch was content that the roof had turned out largely as envisaged: "light, transparent, surprising ..." and declared himself well pleased with the contribution of the engineers (5.55-5.61).[9]

On several occasions disaster has resulted when engineers have been pressured to meet fixed deadlines for technically complex, innovative projects, with local or national prestige or the interests of clients or politicians at stake. In this case the venture was carried off successfully, due largely to the drive and competence displayed by the engineers responsible. The Olympic roof set the stage for two lines of development in the work of the Schlaich Bergermann partnership which will be described in this chapter. One leads through a project for a stadium roof in Hannover on to the Eissporthalle at Munich, in all its details and to the Hotel Kempinski façade. The other leads through the cooling tower at Schmehausen to the solar chimney at Manzanares and on to the lookout tower on the Killesberg at Stuttgart.

5.50-5.54
The renaissance of cast steel: manufacture of a typical large node for the stadium roof


Two nodes in their final position

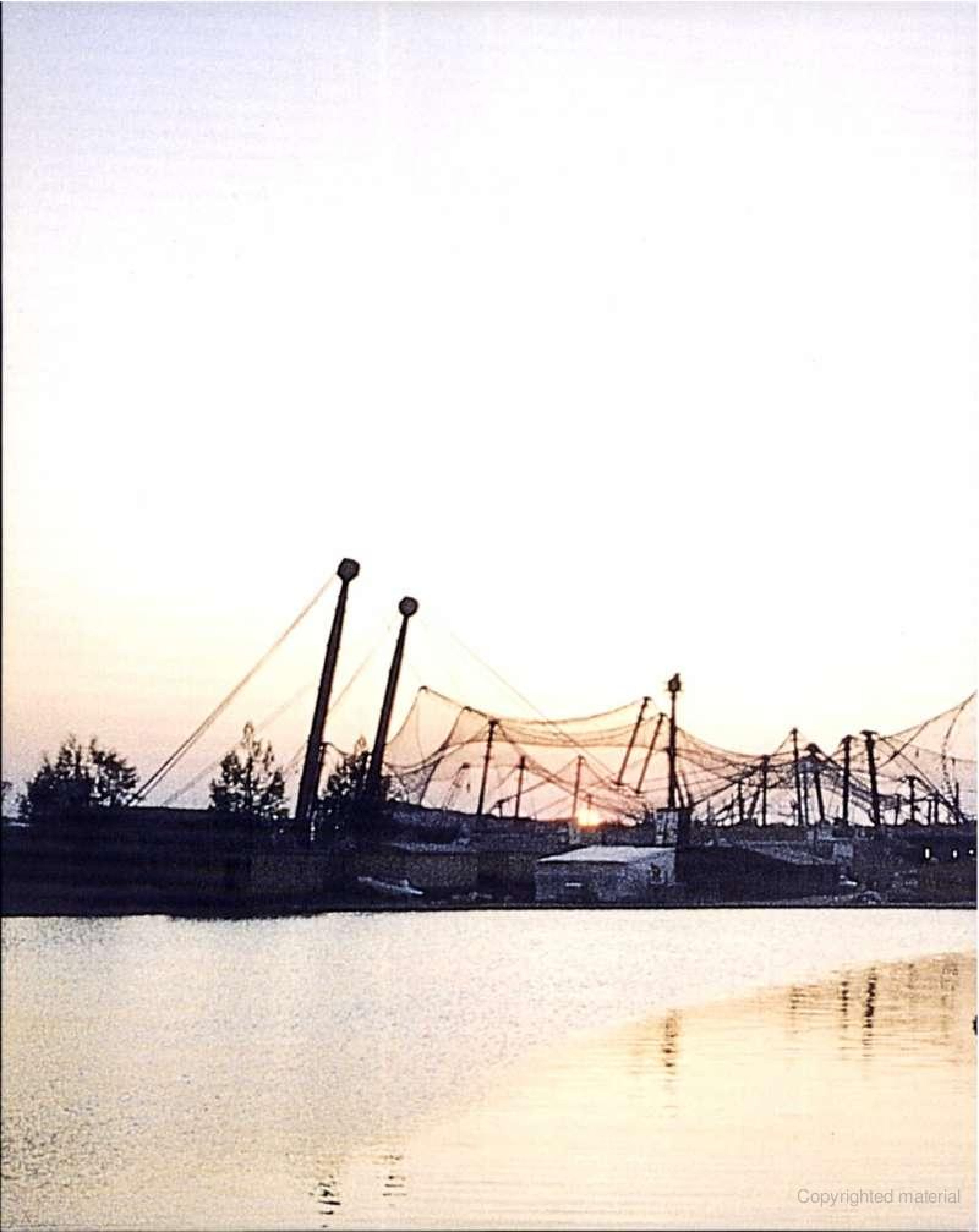

Oven and moulds

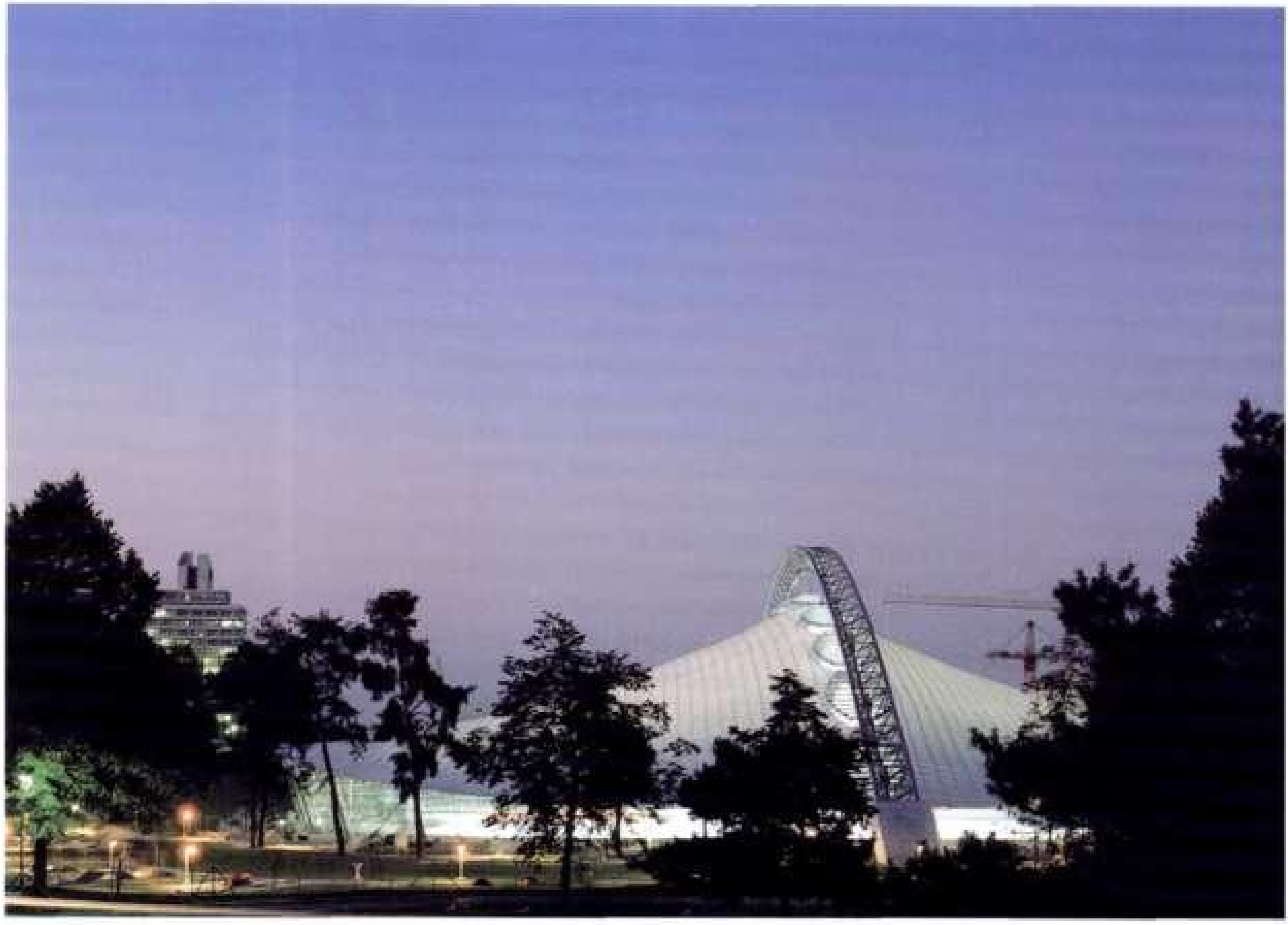

Styrofoam model


Casting in process


Surface finishing

5.55–5.61
Impressions of the completed roof

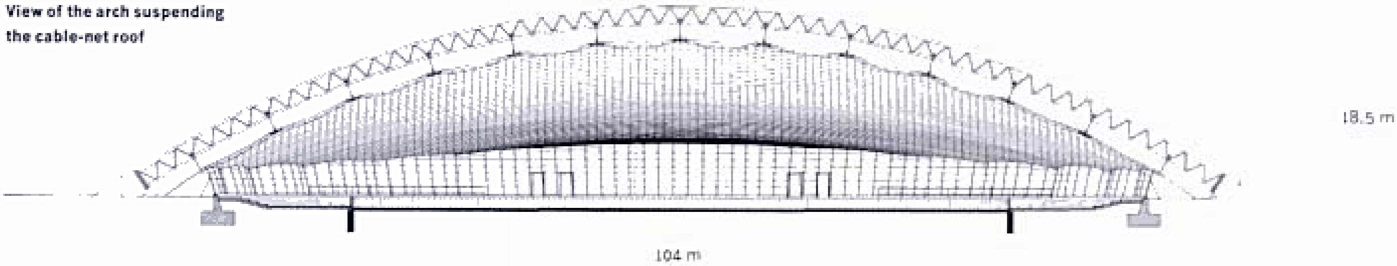




5.62+5.63
Ice-skating rink, Munich 1985

Fig. 5.64
The design model for the cable net roof of the soccer stadium, Hannover (1973)

The Olympic complex at **Munich** now additionally includes three ice-skating rinks side-by-side. Two of the buildings were designed by Ackermann und Partner with Schlaich Bergermann und Partner as engineers. Their first project, in the early 1980s, was the **enclosure of an existing open-air rink** to permit year-round use, which will be described here. Ackermann was keen to ensure that the form of the new enclosure would be in harmony with its architectural context. This presented some difficulty because there was already a clash between the free-flowing outlines of the cable-net roofs over the main stadiums, and the rigid rectangular structure covering the existing indoor rink. Ackermann initially decided that the closer form must dominate, and chose a flat-topped, box-like shape for the new envelope. Schlaich collaborated with Ackermann on the elaboration of a number of proposals incorporating steel frameworks but suggested, as a further alternative, a cable-net roof supported on a large arch running the length of the rink: a classic tent concept (5.62 + 5.63, 5.65). This would reflect the form of the Olympic roofs without clash-



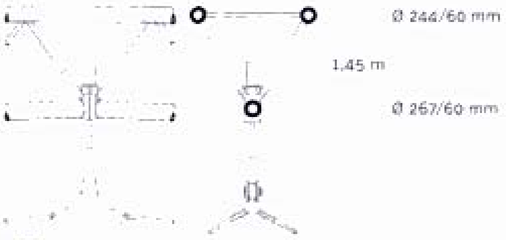
5.65
View of the arch suspending the cable-net roof

ing too strongly with the existing rink. In their work on this scheme Schlaich and Bergermann drew on their experience in preparing a design study in 1973 for an arch-supported roof for the Hannover soccer stadium (5.64).[10]

Convinced by ten years' relatively trouble-free experience with the roofs of the arenas, the client (the successor to the OBG) readily accepted Ackermann and Schlaich's proposal to use a cable net. They did however specify that the total height of the roof should not be much greater than 18 metres so that it would not overshadow the adjacent building.

The roof is roughly elliptical in plan with major axes of 88 metres and 67 metres, and covers an area of 4,200 square metres. The layout and details of the cable net were based on those of the main stadium roofs. Its outer rim is defined by cables 60 mm in diameter carried on top of the perimeter wall and tied back to anchor blocks at ground level. The net itself is formed by smaller cables each consisting of two strands, and connected at the node points by pressed aluminium clamps through which passes a single bolt. One family runs parallel to the arch and the other perpendicular to it. The longitudinal cables were tensioned to pull the net downwards into its predetermined shape, at the same time placing the lateral cables in a state of tension. Due to the limitation on the height of the arena, the lateral cables have a very low curvature and this results in high forces under the heavy Munich snow loads. As a consequence, the arch, edge columns, foundations, cast steel elements, and guys are all larger and heavier than they would otherwise have been. This was not the first time that the design team had found itself severely limited by arbitrary restrictions on the height of a structure, and it was not to be the last.

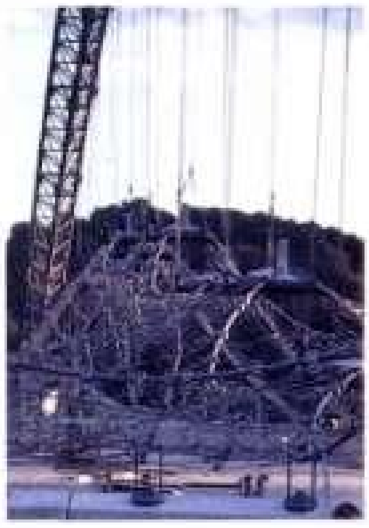
The steel arch took the form of a light three-dimensional framework with a triangular cross section, made of tubular steel members (5.66). The depth of the arch crosssection is only 1.45 metres for a span of over 104 metres and a rise of 17.6. This degree of slenderness is possible only because the cable net provides vertical and horizontal restraint which stiffens the arch in all directions against buckling. Thus the arch carries the net and its superimposed wind and snow loads, while the net stiffens the arch. This mutual support is the "secret" of the design, and makes for a highly elegant structural system whose slenderness and lightness is evident to the most casual observer.



5.66
Details of the arch and hangers

5.67
The cable net ready for lifting

5.68
The arch erected: the cable net assembled on the ground

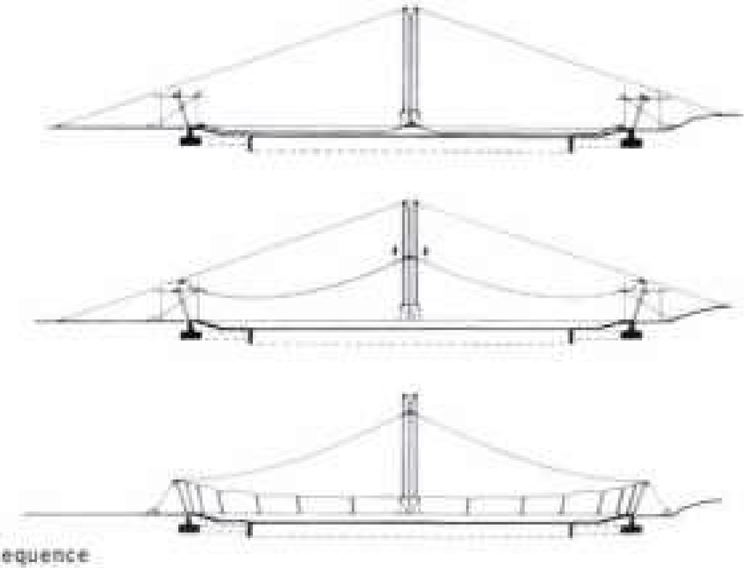


5.69
Lifting the cable net

5.70
The cable net in position and tensioned

5.71
The head of an edge column

5.72
Details of the ridge cable arrangement

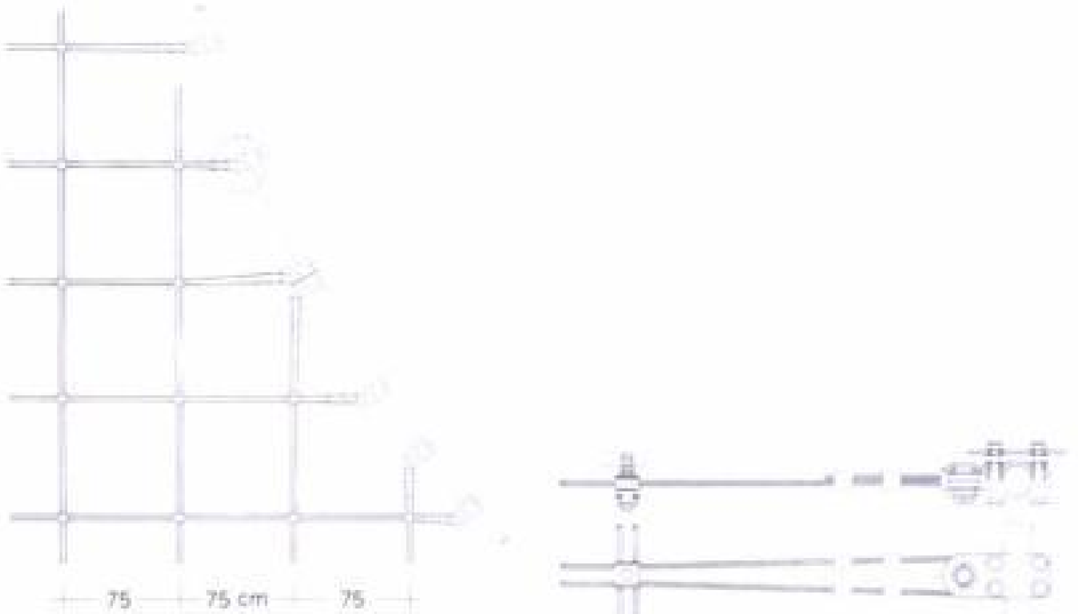


5.73
The erection sequence

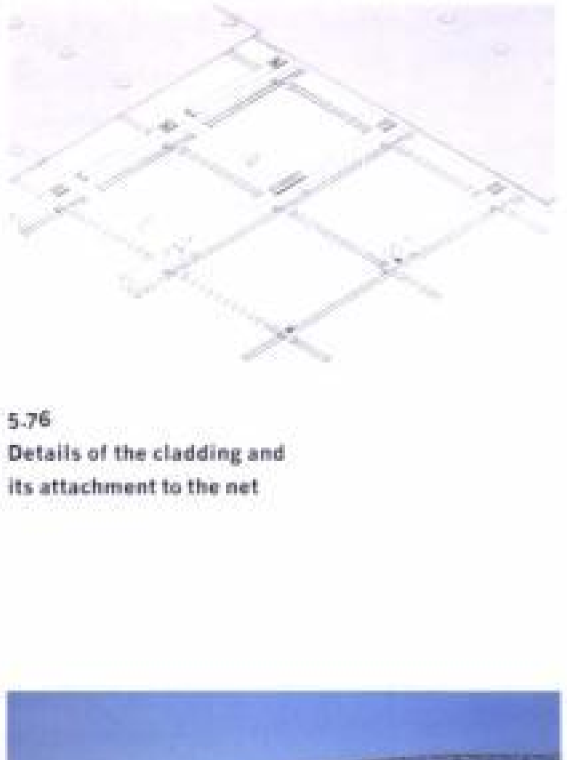
It would have been possible, and in some respects advantageous, to drape the net over the arch, enclosing the latter within the building envelope. As in so many of the partnership's structures, the decision to expose the arch by suspending the net beneath it was taken for a blend of practical and aesthetic reasons. The chosen solution made it possible to construct the arch first, braced against buckling by temporary guys. The net could then be assembled flat on the ground beneath it and hoisted into position, to be supported from the arch by short hanger cables (5.67–5.73).

Between the hanger cables, at intervals of 7.5 metres, the ridge cables separate, making it possible to utilize the same connection details as are used at the perimeter (5.71 and 5.72). The ridge cables embrace and support transparent polycarbonate skylights (5.74). At the perimeter, the edge cables pass over cast steel saddles on top of slanted steel props resting on steel balls. During construction, these permitted the system to accommodate the large rotations which occurred during assembly and tensioning of the net and in service they allow for the continual slight movement of the roof boundary due to wind and snow loads (5.79).

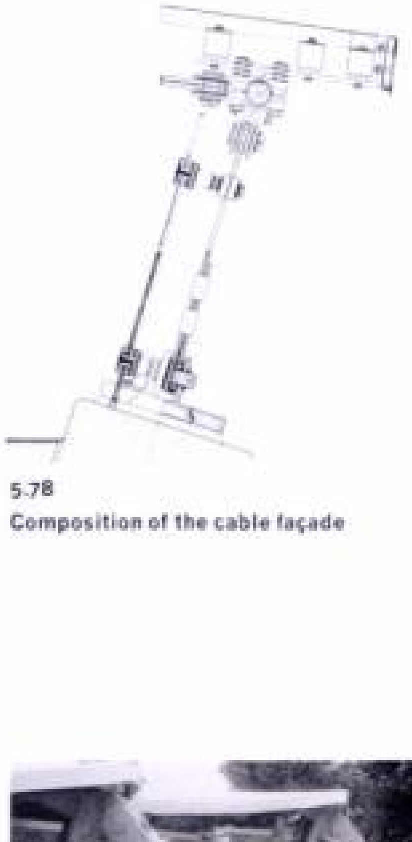
At first it was proposed that the cladding consist of wooden sheeting resting directly on the cable net and covered with sheet metal or shingles. However, this would have been too stiff in its own plane to accommodate the calculated deformations of the cable net. Realizing that heat insulation was not really essential, the design team dematerialized the sheeting into a wooden grid



5.75
The attachment of net cables to an edge cable



5.76
Details of the cladding and its attachment to the net



5.78
Composition of the cable façade

5.74
The skylights in position

5.77
Installation of cladding

5.79
An exterior view showing the cable-net façade

which could be screwed to the connectors at the nodes of the cable net and support a PVC-coated transparent polyester membrane nailed to the grid (5.76 + 5.77). They realized that near the ridge the steep slope would tend to shed snow. As a result, less strength, and hence less timber, would be needed in this region than near the eaves where the roof is flat and must support a heavy accumulation. It would thus be reasonable to vary the spacing of the grid from 18.5 cm at the eaves to 75 cm at the ridge. The reduced amount of combustible material in the vicinity of the arch would mean that no special fireproofing would be needed for the steel. Thus yet another opportunity was seized to draw an aesthetic advantage from purely technical considerations (5.80). The change in spacing of cables and timber leads to a gradual variation in the translucence of the roof, enhancing its upward sweep and producing an impression of lightness and airiness near the ridge. To some extent, this overcomes the problem imposed by the restriction on the real height of the building. Schlaich was pleased to find that the technical requirements could be satisfied by "old fashioned" and environmentally-friendly wood.[11]

A major problem in buildings with cable-net roofs is the large relative movement between the edge of the highly flexible cable net and the top of a stiff, conventional perimeter wall. The usual solution at the time was to leave a large gap between the two and fill it with bellows-like seals. These were, however, visually heavy and made an unfortunate contrast with the lightness of the roofs. Even in the Olympic structure a fairly bulky truss is provided to support the glass panels. To avoid these problems the designers conceived the walls of the skating rink as a sort of continuation of the cable net. Glass panes housed in aluminium profiles are attached by flexible connectors to vertical cables (5.78 + 5.79), which span between the edge cable and the ring foundation. The façade thus offers no resistance to horizontal movements of the roof boundaries and is not stressed by them. The vertical cables are given sufficient prestress to ensure that they do not become slack due to downward movement of the edge cable. This concept was the genesis of the partnership's design for the façades of the Kempinski hotel foyer (see below).

Previously, it had been normal practice to install turnbuckles in cable-net roofs to permit accurate tensioning of the net after construction (5.45). This made it possible to obtain the desired shape of the roof and to ensure that each cable carried its intended share of the load. However, the turnbuckles had proved to be of little value in the roofs of the sporting arenas due to the complexity of the relationship between force and shape within cable nets. They were therefore dispensed with at the Eissporthalle and the cables were manufactured exactly to the required size (5.75). The building was completed in 1985.

Schlaich describes this roof as incorporating "all the experience we collected when doing research in the field at the university – precise cutting patterns, cast steel, etc", and notes that "Jürgen Seidel did a brilliant job as project engineer". He remembers the raising of the preassembled net to take its predetermined shape beneath the arch, as another of the great moments in his professional life: *Ein schöner Augenblick*. Although further progress has been made since that time in the technical understanding of cable nets, including the work of the Sonderforschungsbereich 64, he contends that these structures have not yet fulfilled their early promise. The ice-skating rink remains the only major structure of the type to be built in Germany since the roofs of the main Olympic stadiums. He feels that Frei Otto's roof over the sports arena in Jeddah, Saudi Arabia which was completed in 1980 harks back to the design philosophies of the 1967 Montreal pavilion and fails to exploit the experience and knowledge gained so arduously at Munich. "It is just as if the Munich roofs had never been built."

5.80
Munich ice-skating rink, (Ackermann und Partner), interior view

5.81 (overleaf)
Exterior view

5.82
Munich Kempinski Hotel: looking through both glass walls of the courtyard

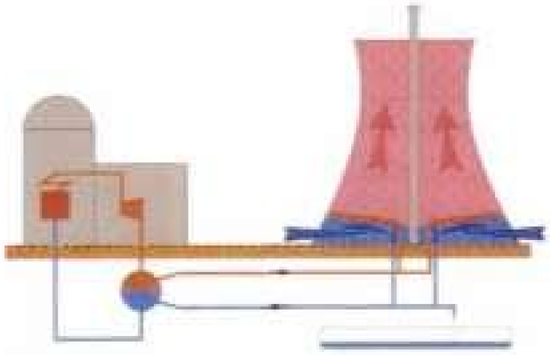
The atrium of the **Kempinski Hotel at Munich** airport is a large rectangular volume sandwiched between two long accommodation blocks. The space is covered by a cable-supported cylindrical **steel-and-glass roof** spanning between the blocks and is enclosed by a **glazed façade** at each end, 40 metres wide and 25 metres high (5.82 + 5.83). Each façade includes entrance doors. The German-American architect Helmut Jahn of Murphy/Jahn, Chicago, consulted Schlaich and Bergermann on the final design for the roof which they accepted and and carried out more or less as prescribed. In one of the meetings Schlaich was shown the original proposal for the façades, with the glass walls supported by steel space trusses. In a conventional scheme of this nature the trusses must carry their own weight as well as that of the glass, but their most important function is to resist the bending effect of horizontal wind pressure and suction. The result is a visually complex tangle of heavy members which counteracts the effect sought by the architect. In a major departure from convention, Schlaich suggested an unobtrusive minimalist structure consisting only of a simple, completely flat cable net. This concept was even more bold than some recent extremely attractive developments such as Peter Rice's glass façades at La Villette in Paris. He was agreeably surprised when Jahn accepted the proposal straightaway saying, "Great – if it works: Yes!"

The innovative **Cable-net cooling tower at Schmehausen** evolved in response to two factors. The first was the increasing public demand for electricity, which was leading to a constant increase in the size of power stations. The second was a desire to change to a new and less environmentally damaging form of cooling.

Electric power stations produce vast amounts of waste heat. In some cases this is carried away by cooling water which is obtained from, and returned to, nearby lakes or rivers, seriously interfering with their ecological balance. A somewhat less objectionable method is to discharge the heat to the atmosphere by means of a cooling tower – a form of huge chimney. Steam from the cooling system is blown in at the base and the resulting updraft draws in air through slots at the bottom of the tower. As the steam evaporates, it transmits its heat to the air and much of it falls back like rain. However, a great deal of water escapes from the top of the tower (see 5.88 background) and this must be continuously replaced with water from rivers or lakes. The process is detrimental to the climate and competes with domestic water supplies. (The water consumption of one typical cooling tower is equal to that of a city of 200,000 inhabitants.) The requirement for adequate water supply also places restrictions on the location of power stations. For these reasons there was a move towards the use of the so-called dry cooling system in which both water and heat are largely retained in a closed cycle (5.89). The only problem is that this system requires much larger cooling towers: about twice the size of "wet" ones, and up to 300 metres in height.

In the decades leading up to the 1970s, cooling towers had taken the form of reinforced concrete hyperbolic paraboloids. With the radii becoming very large in comparison to the thickness, the stiffening effect of the dual curvature of the shell was becoming much less effective. When its curvature was meas-

5.88
The cable-net dry cooling tower at Schmehausen. (In the background, a conventional concrete-shell wet cooling tower), photo taken in June 1991



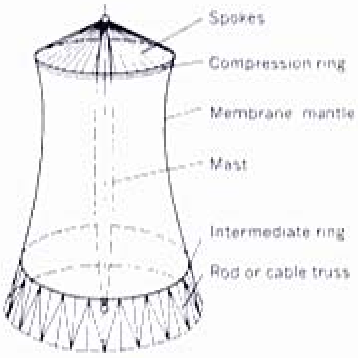
5.89
The principle of the closed circuit dry cooling system

ured in terms of its thickness, the wall could be described as almost flat. The ability of the shell to resist localized wind pressures was thus placed in question. Cooling towers at Ferrybridge in England had recently collapsed due to the effect of wind gusts (exacerbated by funnelling between adjacent towers) which caused resonant deformation of the horizontal cross-section. In addition, relatively minor inaccuracies in the shaping of the shells during construction were becoming more significant and were leading to an increased danger of buckling. The shells were also very sensitive to differential settlement of their supports. It seemed that a limit on the size of concrete cooling towers was fast being reached.

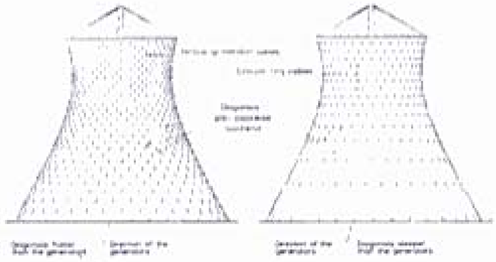
Balcke-Dürr of Ratingen, a firm which specialized in the design of cooling towers, had been wrestling with this problem for some time. In 1972, a representative approached Schlaich at the Leonhardt und Andrä offices with a suggestion that the solution might be to form cooling towers from cable nets covered with an appropriate cladding material.[12]

It happened that, since his experience at Munich, Schlaich had been pondering the problem of the high deformability of rectangular meshes which have cables running in only two directions. This can be overcome by adding a third set of cables to produce a triangular mesh, but there is a price to pay: the resulting system is applicable only to a limited number of regular, mathematically defined surfaces. He had therefore given careful consideration to appropriate applications of these forms and to their structural behaviour, drawing once more on his mathematical training and his experience with shells and cable nets. In this he profited from the presence of Josef Eibl who was spending a year in the design office to freshen up his practical background and is now a direct colleague as Professor at the University of Karlsruhe. Schlaich was thus particularly receptive to the suggestion from Balcke-Dürr. However, there was as usual much hard work to be done to bring the basic good idea to fruition.

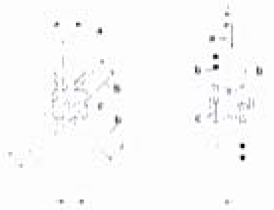
The Vereinigte Elektrizitätswerke (VEW) of Dortmund accepted Balcke-Dürr's proposal to use a cable-net tower for their 300 MW thorium high-temperature reactor in Schmehausen Hamm-Uentrop. The conformation and height of the tower were determined by the thermodynamic requirements and the arrangement of the heat exchangers and air intakes. These defined a mantle 146 metres high with a diameter of 141 metres at the base and 92 at the top. Schlaich's colleagues in the design were Günter Mayr (who had been with him since the Olympic roof project and had worked on the structural detailing there), Jurgen Noesgen and Josef Eibl.



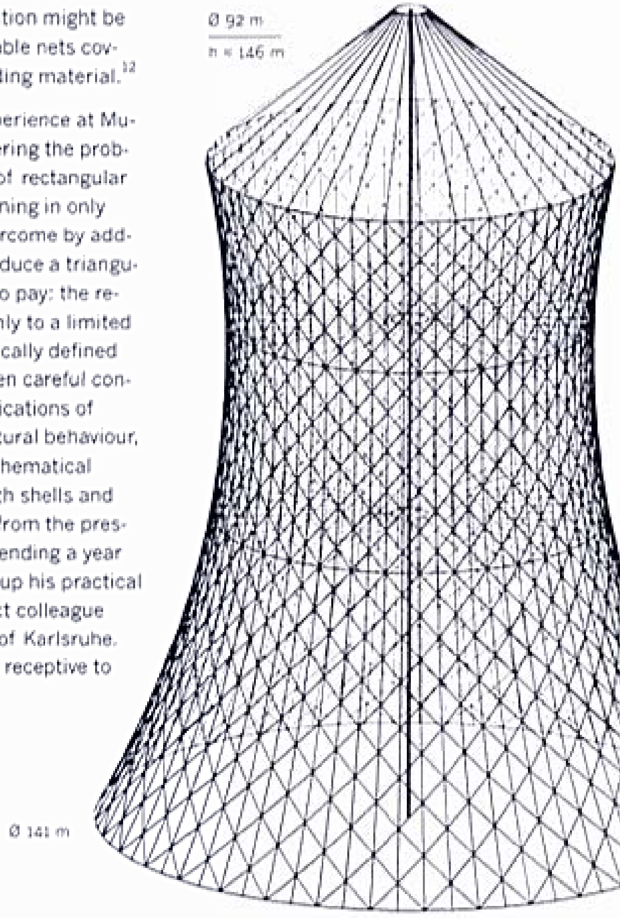
5.90
A membrane cooling tower



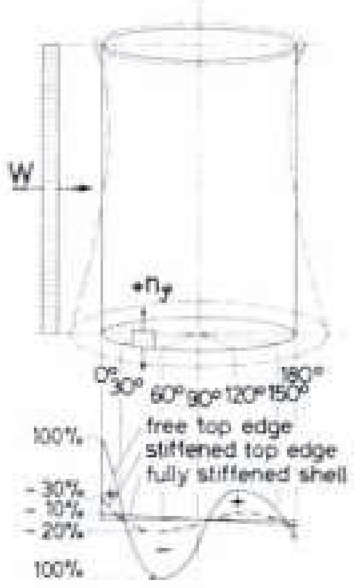
5.91
cable-net cooling towers: Alternative ways of arranging three families of cables



5.92
The three cable-layers (a-meridian, b-diagonal), c-press-fitted clamps connected with one bolt (see 5.16)



5.93
The geometry of the cable net as built with stiffening rings (not all cables shown)

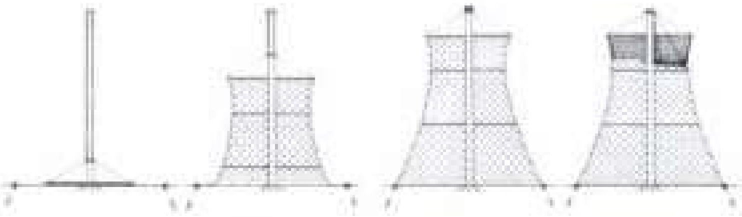


5.94
If a tubular shell is stiffenend at its top edge by a diaphragm (or spoked wheel) the vertical stresses at its base due to wind load are substantially reduced

The basic concept was to support the upper rim of the hyperbolic paraboloid from a central mast. In the early planning stages the team seriously considered forming the surface from a true shell made of aluminium or stainless steel sheeting. This would have been prestressed to control deformation due to self-weight and wind load (5.90). However, investigation showed that the difficulties and expense of fabrication and the cost of temporary stays to resist the wind pressures to be expected during erection would outweigh the advantages. It was therefore decided to use a cable net to carry the loads, and clad it with sheets of metal or plastic which need span only the width of the mesh. The thickness of the corrugated aluminium sheeting eventually used for this purpose was one millimetre.

The next question was the arrangement of the cables. The hyperbolic paraboloid form of a cooling tower may be defined by a horizontal circle at top and bottom with two families of straight cables stretched between them lying on the "generators" of the surface. However, to add a third layer of cables and to prestress all three layers simultaneously it is essential to give the two layers of cables an inclination greater or less than that of the generators, so that they follow a curved path in space. If the main cables run at a less steep (flatter) angle than the generators, they follow a trajectory which loops outwards around the surface of the tower. When pretension is applied, these cables tend to straighten and pull inwards. If a third family of cables is provided, lying on the meridians so that their curvature is in the opposite direction to that of the main cables, the inward pull of the latter may be resisted by the meridional cables which are also placed in a state of tension (5.91, left). The alternative approach is to incline the main cables at an angle to the horizontal greater than that of the generators so that they loop inwards. When pretension is applied, such cables tend to straighten and pull outwards. This tendency may be countered by a series of horizontal circular cables, like belts around the waist of the tower, which are similarly placed in a state of tension as the main cables move outwards (5.91, right).

The design team chose to use the first system for Schmehausen. This has the overriding advantage that all the meridional cables are of equal length and the arrangement of all the nodes is identical, greatly simplifying manufacture. In the other alternative the horizontal circular cables are of different lengths and the spacing of node points differs at each level. For the design of the structure which would support the cable net, Schlaich drew on his experience of tower design. The vertical component of

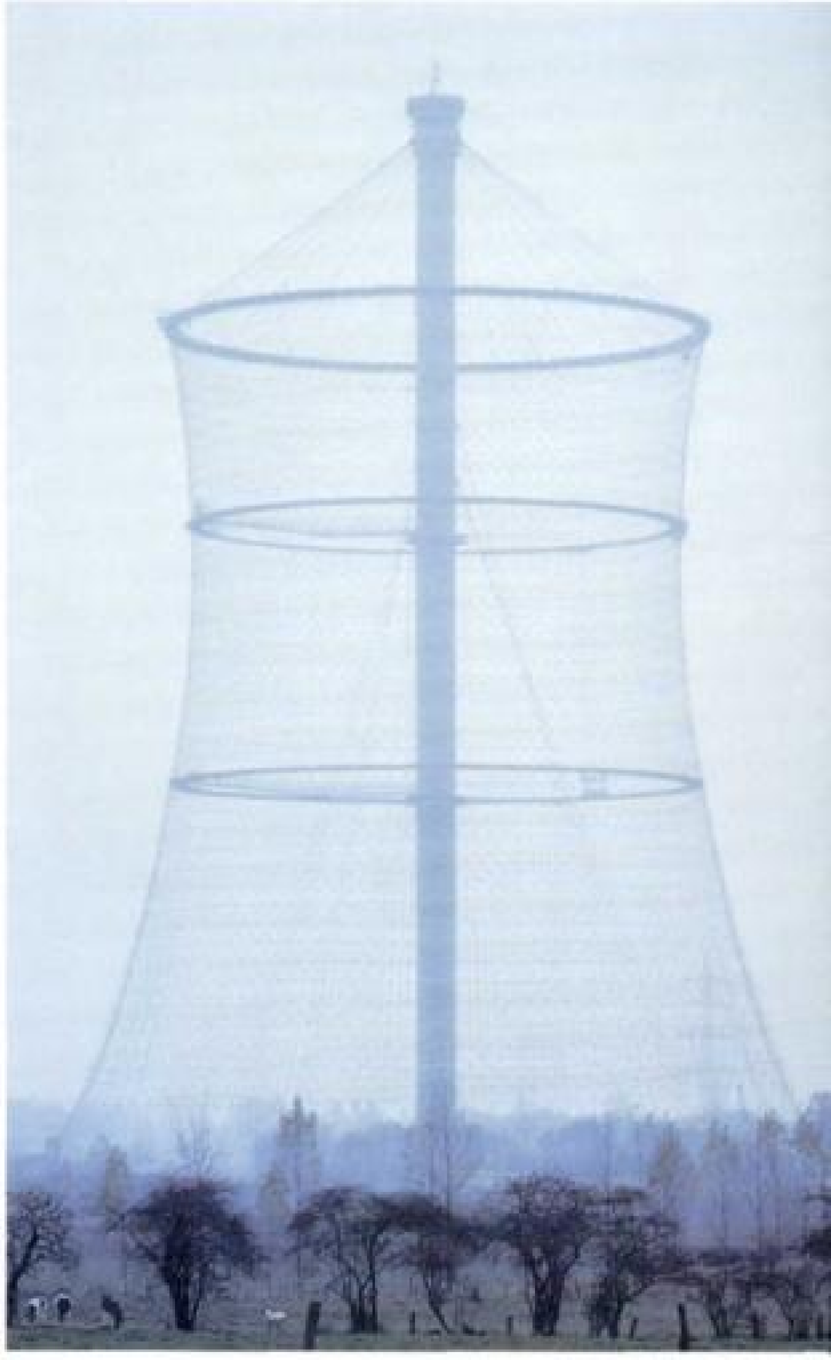


5.95
The erection procedure

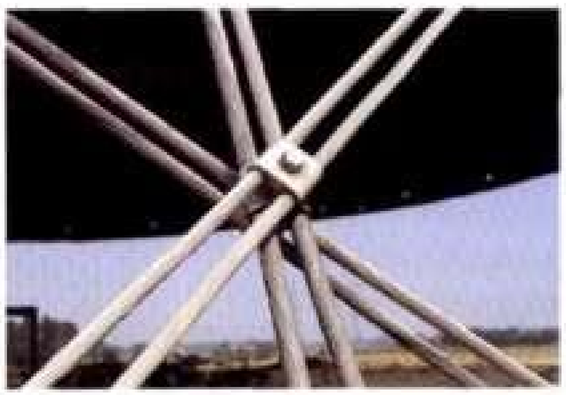
5.96–5.100
Lifting the net

the prestressing forces necessary to tension the mesh, plus the weight of the structure, could be carried in direct compression by a single slender, hollow reinforced concrete mast, a mere 6.6 metres in diameter, situated on the centreline of the tower. From the top of this, the upper ring could be suspended by radiating cables (5.93). These would be attached to a collar around the top of the mast and this could be used for lifting the cable net. The extra compression due to the pretensioning of the cable net would enhance the strength and stiffness of the concrete mast in the manner explained in Chapter 3 in relation to communications towers. The wind force would be carried directly to the ground by the cable system.

The top ring would be naturally stiff in the horizontal plane because of its inclined radial supporting cables and would thus maintain its circular shape without difficulty. In addition, this stiffenend ring has the effect of a diaphragm with respect to the forces in the cable net. They are reduced considerably. This effect was a "free bonus" (5.94). However, computations indicated that if the hypar were stiffened only at its top and bottom, large deformations would occur due to wind pressure and suction. The deflections could have been reduced by increasing the prestressing forces within the net, but this would have demanded larger cables and a stronger mast, and it was found equally economical to provide the stiffening by means of two further "bicycle wheels" at heights of 68 metres and 112 metres. These consisted of compression rings in the net surface, with tensioned horizontal radial cables forming the "spokes". The inside ends of the cables were connected to a second collar which was somewhat larger in diameter than the mast and did not touch it (5.93). At this point the partnership's practice of working out constructional procedures in the early stages of design and deriving from them all further structural details came to the fore (5.95). The designers realized that it would be a routine matter to erect the mast first, using standard slip-form techniques as employed in the construction of the communications towers. The top ring could then be placed on the ground around the base of the mast, with the upper and lower collars, supporting cables, and spokes attached to it (5.96). The cables which would form the net surface could then be attached to the ring and the whole conical upper assembly hoisted gradually up the mast, with the surface cables being paid out as the ring rose. All node connections could be made at

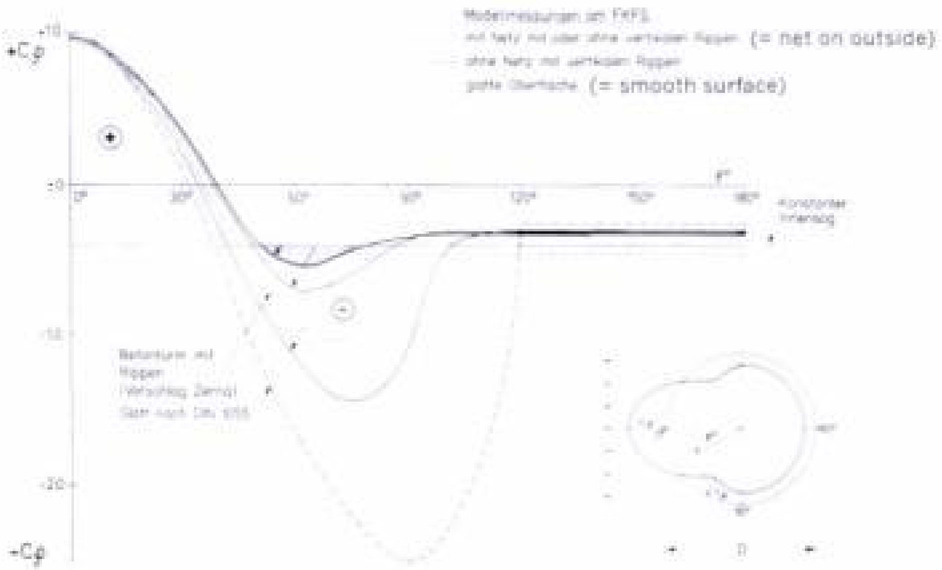


5.101–5.104
Knitting, lifting and
anchoring the net



ground level at predetermined intervals along the length of the cables. The net would thus adopt its hyperbolic paraboloid form as it rose. Prefitted clamps were again used, with one bolt for all three cables intersecting at the node (5.97–5.104).

Schlaich was keen to see the cables located on the outside of the aluminium sheeting for aesthetic reasons: to give some measure of scale to the structure, and to make its vast unified form more comprehensible to the observer. However, the VEW engineers preferred the cables to be on the inside for protection against the weather. They argued that cables formed from galvanized wires would corrode rapidly if placed on the outside. The only way to avoid this would be to provide them with an aluminium coating at additional expense. Fortunately, additional wind tunnel tests showed that having the cables on the outside actually reduced wind suction on the surface of the tower by breaking up the airflow (5.105 and 5.106). This reduced the total forces that the cables would need to resist, and meant that they could be smaller and less costly to balance the additional cost for the aluminium coating. A further advantage was that removing the cables from the inside surface increased the effectiveness of the thermal updraught. Thus the team managed to find a solution which was at the same time economically justifiable and aesthetically pleasing. Later, when Schlaich was asked by a leading architectural journal whether aesthetic considerations had played a major part in the design of the tower, he was able to answer with a definite "no".[13] Although he had his aesthetic preferences, the final form and details of the cooling tower were developed from purely technical considerations to overcome the limitations of conventional reinforced concrete towers. It could even be argued that the cable net with circumferential bands would have conformed more to classical aesthetic principles because its lines offer greater "balance" and "repose" in architectural terms (5.107–5.109).



5.105
Test results: the shaded area represents minimum suction with the cable net outside the cladding

5.106
A model of the Schmehausen cooling tower undergoing testing in the wind tunnel

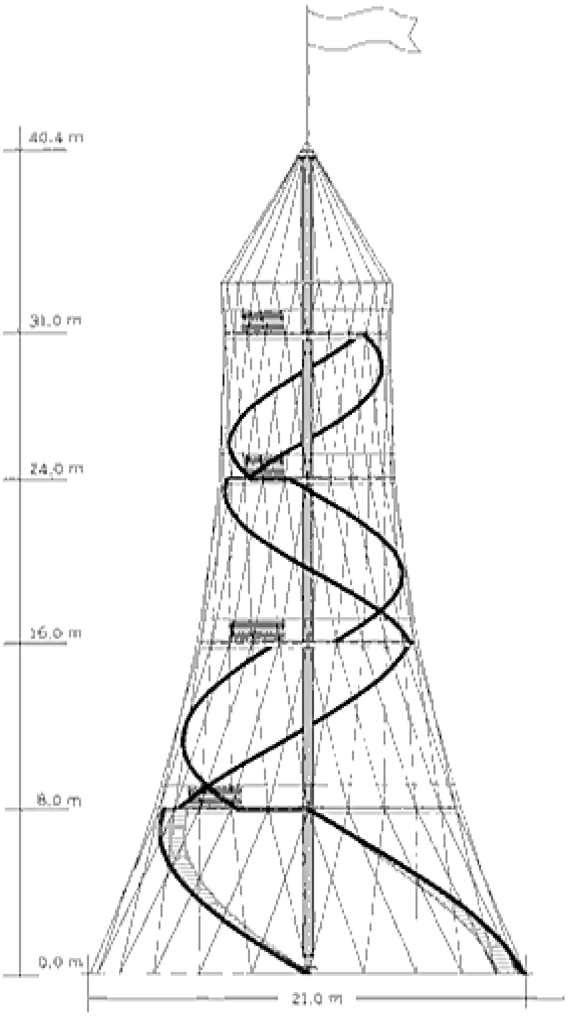
5.107
The completed cable net

5.108
Installation of cladding

The tower was completed in 1974. In 1991, for a combination of political and safety reasons, the nuclear power plant was closed down and scheduled for demolition. Unfortunately, VEW decided to start with the cooling tower, and quickly obtained permission from the local authorities to demolish it. Engineers and architectural historians came from many sides to fight to save this unique structure for posterity, arguing that it was a landmark in the history of structural engineering.[14] Despite intense opposition on the part of the informed public, the company retained permission to demolish on the grounds that the 17-year old tower could not be classified as a "historic monument". On 9th of July 1991 it was brought down by explosives. Schlaich was particularly distressed that no attempt was made to reverse the construction process and lower the net to the ground in an orderly fashion so that the materials could be recycled. This is an eventuality that he considers in the design of all his *lightweight* structures. The aluminium-coated cables were still in perfect condition after 17 years' exposure outside the sheathing (5.101).

Despite this set-back, design studies suggest that 300-metre-high cooling towers would be quite practicable in this form of construction and the experience laid the groundwork for Schlaich and Bergermann's later development of thermal updraught solar power stations (Chapter 11).

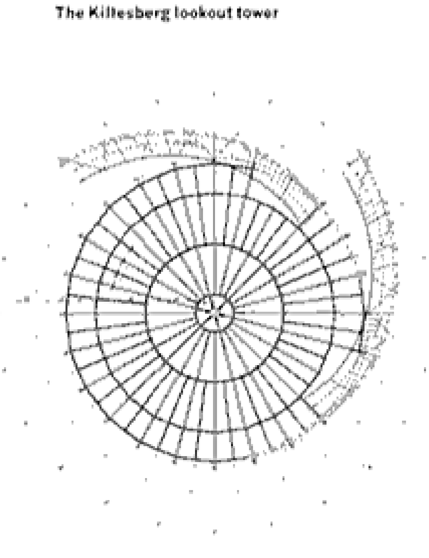
5.109
The cable net with the "bicycle wheels"



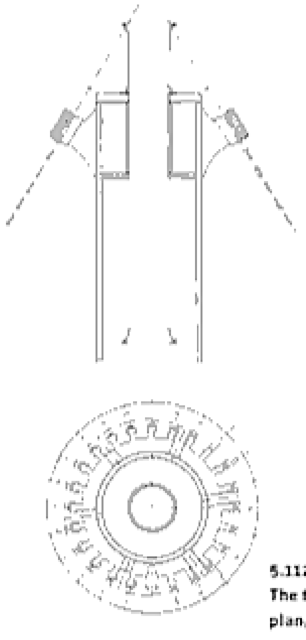
5.110
The Killesberg lookout tower

Following the decision to hold the 1993 **International Garden Exhibition in Stuttgart**, a competition was held for the planning and design of relevant facilities including bridges. The landscape architect Hans Luz joined with Schlaich and Bergermann to prepare a winning scheme which included a **lookout tower** to be built on the **summit of the Killesberg**, a favourite recreational area which overlooks the city, with walks, woodlands, and beer gardens. The idea was that, as far as it would be seen at all, the tower should appear as a visual continuation of the hill. Thus it was conceived as a miniature, modified version of Schmehausen, without the cladding. Two light spiral staircases, one to lead visitors up and the other to bring them down, would wind round the inner surface of the *hypar*-shaped cable net (5.110–5.113). Schlaich did have qualms about building any structure on the Killesberg, but found it hard to resist the challenge of conceiving a construction which would be unobtrusive and yet provide people with a unique experience of panorama and spatial movement. In the initial stages of design he commented: "If people said we should not build it here, I could agree with them. But oh! – just think of people in colourful clothes spiralling in opposite directions on those stairs!" To these concerns he added his usual passion for structural logic and aesthetic quality. Economic constraints were severe, with a strict limit of DM 2 million on the cost of the project.

The structure at the Killesberg would differ in significant ways from that at Schmehausen. The spoked stiffening rings would be replaced by lightweight floors which could serve as viewing platforms. At Schmehausen it had been necessary to isolate the mast from the "spoked wheels" to avoid loading it with wind forces transmitted from the cladding. However, the absence of cladding at the Killesberg meant that the wind forces on the structure would be relatively small. On the other hand, the vertical load on the floors would be substantial. It was therefore approriate to attach the inner end of the floor beams directly to the mast. The net, through the floors, would hold the mast in position at several levels and reduce its tendency to buckle under vertical compression. As a result, the mast could be made extremely slender. Because the scale was so much smaller than at Schmehausen, the designers chose to use a steel mast which could be easily transported to the site and erected by crane in a single operation. Although their first wish was to provide a grid-like industrial steel flooring for the observation decks, to enhance the impression of lightness, they decided eventually that this might make visitors feel insecure and that rain water might drop on the clothes of those beneath. Their next choice would have been timber decking with rubber studs, of the type used on yachts to prevent slip, but for reasons of economy they reluctantly settled for thin steel ripple plating.



5.111
Plan of the first platform with stairs



5.112
The top of the mast plan, section

The technical and aesthetic detailing of the tower provides an impression of the careful thought which Schlaich and his team put into the design of their structures.[15] Around most of the perimeter of the platforms, the cables were attached at regular intervals to the ends of the joists. This held the cables in position, and gave the hypar its desired form. However, at two points in each platform, it was necessary to leave holes in the floor adjacent to the perimeter to allow the spiral staircases to pass through (5.111). Where this happened, the joists would need to be cut short and a number of cables would thus have no point of attachment at that level. They would simply stretch in a straight line from their points of attachment on the level below to those on the level above. Their intersections would therefore not conform to the rhythmic spacing of others, destroying the visual unity and regularity of the cable net. An obvious solution was to run a short length of beam around the outside of the gap to complete the perimeter and permit the cables to be attached at points conforming to the mathematical definition of the hypar surface. This solution would have had appeal for the technical as well as the aesthetic purist because it would be mathematically as well as visually "neat". However, Schlaich argued that it was unjustifiable from a load bearing point of view, because at these points there is no platform and therefore no load justifying a node, and also from a purely constructional point of view because the non-conforming alignment of these cables would not affect the load-carrying capacity of the structure as a whole in any way. Also, an added perimeter beam would block the visitors' view of the scenery just as their heads reached platform level, greatly diminishing the experience of visual freedom for which he was aiming. In the end, a solution was adopted in which additional clamps will be used to prevent the crossing cables from fretting and to establish mathematical regularity without the need for a perimeter beam.

Yet another problem was presented by the runner beams for the staircases whose outer sides are fixed to the cable net while their inner sides support the stair treads. A rectangular hollow section would have good strength and permit convenient attachment of the stair treads. However, because the runner follows a spiral path, a rectangular member would be seen to twist in space. Schlaich thus felt that a cylindrical tube would be better from a visual point of view even though it would present greater practical problems with connection of the treads. At a more detailed level, he was greatly concerned about the inconsistencies which arose in the positioning and form of the numerous clamps because of the need to support the staircase as well as connect the cables at their crossing points. In reviewing all these problems, he seemed disappointed that his formalist sense was competing with his sense of functionalism, and that a functionalist approach had not so far resulted in beauty. All have now been resolved and the result shows the extreme care which went into its conception.

After the design of the tower had been taken to an advanced stage, a state election occurred in which economic and social matters played a major role and the established parties lost. As a result, the city council decided in 1991 that the money which had been allocated for construction of the tower should be spent instead on social services. Schlaich was philosophical about this set-back. He commented that the work invested in projects is never wasted, but generates new skills and ideas which always come to fruition, even though it might take "twenty years" for this to happen. Since then the project has attracted a great deal of public attention, and the Verschonerungsverein, a society formed by private initiative and devoted to improving the visual environment of Stuttgart, has come to the rescue and donated a considerable sum of money, so that there is still a good chance that the tower will be completed, some day.

5.113
Model of the proposed Stuttgart Killesberg lookout tower

Notes to Chapter 5

[1] The themes in German were "Olympiade im Grunen", "Olympiade der kurzen Wege", "Sport und Kunst" and "ungezwungen, heiter, jugendlich, verganglich".

[2] Professors Rusch and Burkhardt came from, respectively, the Institut fur Massivbau, and the Institut fur Baubetriebslehre, at the University of Munich. Because of the basically independent status of partners within German consulting practices, Leonhardt had so far stood aside from Boll and Schlaich's work on the Heinle proposal. He was thus able to offer an independent assessment.

[3] "... daß es aus technischen und wirtschaftlichen Grunden nicht sinnvoll ist, ein Dach dieser Form und in diesem Ausmaß zu bauen, zumal vom Preisgericht festgestellt wurde, daß der kunstlerische Wert der Konzeption bei Wegfall dieses Daches nicht beeintrachtigt wurde. Es kann daher dem Bauherr nicht empfohlen werden, nur die vom 1. Preistrager vorgeschlagene Lösung ohne Prufung echter Alternativen zu dem Zeltentwurf der Planung zugrundezulegen."

[4] In Schlaich's view this decision had much to do also with a desire in certain quarters to put "Bavarian timber" on display.

[5] As we saw in Chapter 2, the Prufingenieur is a highly respected engineer who maintains an independent role in verifying the basic approach and methods of the design engineers and, if he considers it necessary, suggesting changes.

[6] See for example W. Addis: *Structural engineering; the nature of theory and design*, Ellis Horwood, Chichester, 1990.

[7] See e.g. O. N. Arup: "Problems and Progress in the Construction of the Sydney Opera House", *Civil Engineering and Public Works Review*, vol. 60, 1965, p. 204.

[8] Collaboration between some of the prize-winning offices and university institutes working on the Olympic roof led, initiated by Leonhardt, to the financing of the Sonderforschungsbereich 64: a special research group based at the University of Stuttgart and devoted to research into "wide spanning surface structures". This included Otto, Linkwitz, Argyris, Rehm, Joedicke, and Schlaich.

[9] See *Behnisch & Partner: Bauten und Entwürfe*, Hatje, Stuttgart, 1975, p. 24. "Die Uberdachung der Sportstatten ist in vielem so geworden, wie wir sie uns vorgestellt hatten: leicht, transparent, uberraschend ..." Also H. Klotz: *Architektur in der Bundesrepublik*, Ullstein, Frankfurt/M 1977, p. 52. "Wir haben seitdem eine besondere Hochachtung vor den Leistungen der Ingenieure, ihrem Engagement und der Treue zur gemeinsamen Arbeit. Schlaich, seine Kollegen von Leonhardt u. Andra, die Wissenschaftler Linkwitz, Argyris, die hervorragenden Konstruktions- und Montageingenieure der verschiedenen Firmen – mein Gott, was hatten wir ohne sie gemacht. Das Dach war perfekt geplant und ebenso perfekt montiert. Das war beste Ingenieurarbeit." "Since then we have had a particularly high opinion of the efficiency of engineers, their commitment, and their devotion to the common task. Schlaich, his colleagues from Leonhardt und Andra, the researchers Linkwitz and Argyris, the excellent construction engineers from the various firms – good heavens, what would we have done without them? The roof was perfectly designed and equally perfectly erected. That was great engineering!"

[10] The pedigree of this scheme may in turn be traced back to a similar scheme which Frei Otto had proposed in 1971 for a sports centre in Kuwait, and before that to Eero Saarinen's Ingalls Hockey Rink (1958) at New Haven, CT, a building which Schlaich greatly admires.

[11] J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61, 1986, p. 58. See also J. Schlaich: "Practices which integrate architecture and engineering", *Bridging the Gap*, van Nostrand Reinhold, New York, 1991, p. 109–122.

[12] Some years after the design of the cooling tower, on the occasion of an exhibition in Stuttgart of the work of V. G. Suchov, Schlaich discovered that at the beginning of this century the Russian engineer had built electricity transmission towers by superimposing a number of narrow hyperbolic paraboloids made from thin steel members of angle crosssection. He is now an ardent admirer of the Russian designer.

[13] J. Schlaich: "Haben beim Entwurf des Seilnetzkuhlturms Schmehausen gestalterische Uberlegungen eine Rolle gespielt?", *Der Architekt*, Heft 7+8, 1977.

[14] See E. Grunsky: "Der Seilnetzkuhlturm in Hamm-Uentrop: zu jung, um Denkmal zu sein", *Deutsche Kunst und Denkmalpflege*, 51/1993. See also M. Sack: "Kunst und Kohle oder uber den Umgang mit Baudenkmalern", *Die Zeit*, 28 June 1991.

[15] This account can be given in greater detail because the author happened to be in Stuttgart at the time that Schlaich and his team were developing the detailed design of the lookout tower.

Selected Publications by Jorg Schlaich and co-authors (if given) up to 1995 to Chapter 5:
Cable-Net Structures. Research on Cables and their Anchorages

month/year

01/72: *Einige Besonderheiten vorgespannter Seilnetzkonstruktionen, Experimentelle Spannungsanalyse*, Werner-Verlag.

03/72: "Naturzugkuhlturme mit Seilnetzmantel", VGB-Bautagung Dortmund.

03/72: "Structural Design of the Roofs over the Sports Arenas for the 1972 Olympic Games: some problems of prestressed cable-net structures", with F. Leonhardt. *The Structural Engineer*.

05/72: "Das Olympiadach in Munchen", with collaborators, IABSE Congress, Amsterdam.

07/72: "Cable Suspended Roof for Munich Olympics", with F. Leonhardt, *Civil Engineering – ASCE*.

09/10/12/1972 + 02/03/04/06/1973: "Vorgespannte Seilnetzkonstruktionen – das Olympiadach in Munchen", with F. Leonhardt and collaborators, *Der Stahlbau*.

02/74: "Naturzugkuhlturm mit vorgespanntem Membranmantel", with G. Mayr. *Der Bauingenieur*.

04/74: "Membran-skin and Cable-Net Cooling Towers", International Conference on Tension Roof Structures. London.

08/75: "On the Development of Cable-structures in Western Germany", IASS Congress, Bratislava, and *IASS Bulletin*.

11/76: "Der Seilnetzkuhlturm Schmehausen", with G. Mayr. P. Weber and E. Jasch, *Der Bauingenieur*.

08/77: "Haben beim Entwurf des Seilnetzkuhlturmes Schmehausen gestalterische Uberlegungen eine Rolle gespielt?" *Der Architekt*.

09/77: "The Lightweight Cable-Net Cooling Tower at Schmehausen", with G. Mayr, *Proceedings IASS Congress, Alma-Ata*.

09/80: "Seiltragwerke: Entwurf, Konstruktion und Bauausfuhrung", with U. Dillmann and K. Gabriel. *Berichtsheft der Studientagung SIA an der ETH Lausanne*.

09/81: "Planung und Realisation von Seiltragwerken und zugbeanspruchten Systemen", *Berichtsheft: Seile und Bündel im Bauwesen*, Haus der Technik, Essen, und *SFB-Mitteilungen*.

11/83: "Ice Skating Hall at Munich", with J. Seidel, *IABSE Structures*, C-27/83.

05/84: "New Fatigue Resistant Cables for Indian Cable-Stayed Bridges", with R. Bergermann and U. Dillmann, ING/IABSE Seminar on Tall Structures, Srinagar, India.

05/85: "On Cable Structures – Research - Design – Construction", with K. Gabriel and R. Bergermann, *Proceedings of the 1985 Int. Engineering Symposium on Structural Steel, Chicago*.

08/85: "Die Eislaufhalle im Olympiapark Munchen", with J. Seidel, *Der Bauingenieur*.

03/87: "Freigespannte Zugglieder mit großer Tragkraft – Drahtseile und -bundel", with K. Gabriel, *Festschrift Joachim Scheer zum 60. Geburtstag*, Braunschweig.

06/88: "Cable and Membrane Structures for Buildings", *1st Oleg Kerensky Memorial Conference, London, Volume 1*.

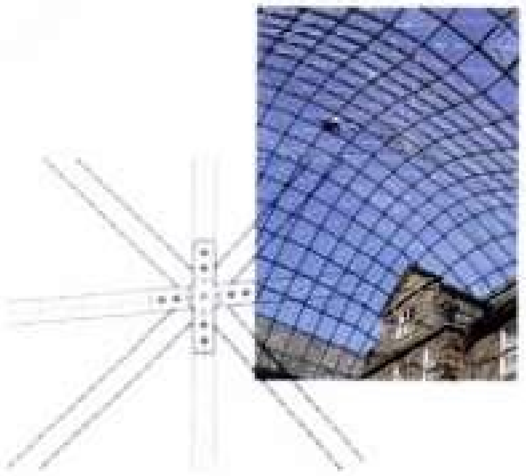
12/89: "Les Structures Légères", *Annales*, 1989, no. 479.

06/90: *Uber das Vorspannen in Leicht und Weit – Zur Konstruktion weitgespannter Flachentragwerke*. DFG-Sonderforschungsbereiche, VCH-Verlagsgesellschaft.

09/92: "Das Olympiadach in Munchen, Wie war das damals? Was hat es gebracht?", *Behnisch & Partner*, exhibition catalogue, Galerie der Stadt Stuttgart.

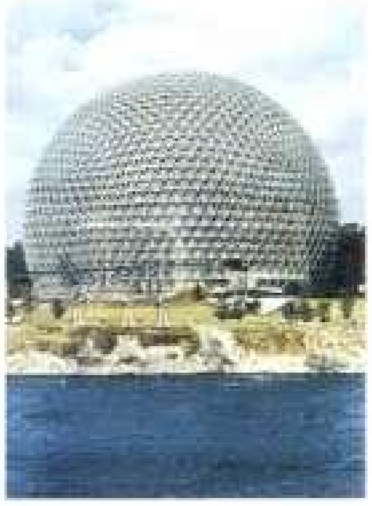
06/95: "Hybrid Tension Structures", with R. Wagner, key note lecture, IASS Symposium, Milan.

08/95: "Robustness of Stranded Cables in Suspended Bridges", with K. Gabriel. *Proceedings IABSE Symposium Extending the Lifespan of Structures, San Francisco*.



6 Glass Grid Roofs

6.1
Framework for the Planetarium on the roof of the Zeiss company building, with a span of 16 m the first icosahedron-grid or geodesic dome, 1925



6.2
Buckminster Fuller's US Pavilion for the Montreal Expo, 1967

6.3
The geometry of the geodesic dome based on the icosahedron principle

In 1952, while he was still at school, Schlaich made a bicycle trip to Milan and saw the impressive cylindrical glass roof of the Galleria Vittorio Emmanuelle II, built in 1867 (12.10). As a student in 1955 he visited Paris and saw the ethereal glass dome of what is now the Paris stock exchange, built even earlier in 1811 (12.9). Their filigree cast-iron-and-glass construction appealed immediately to his taste for lightness in structures. However, the spectacular domes and gallerias of the early 19th Century possessed no diagonal members to provide bracing and prevent their approximately rectangular facets from racking. The stability of the Paris dome must depend to some extent on the fact that the glass panes have considerable rigidity in their own plane. Thus, there was a risk that if large areas of glass were damaged, the bare metal framework would become unstable, especially under eccentric loading. In the case of the Milan roof the problem of stiffening was obviously solved by giving considerable bending stiffness to the members, reducing the visual lightness. To overcome this problem, engineers later in the century introduced diagonals into their domes and barrel vaults, but these again increased their visual weight and their complexity, robbing them of the lightness and classic simplicity which was their main appeal.[1] Major progress took place when Buckminster Fuller, profiting from the earlier work of Bauersfeld and Dischinger[2] (6.1) developed the concept of spherical "geodesic" domes, eventually employed in major structures such as the US Pavilion at the Montreal Expo in 1967 (6.2 + 6.3). However, all these grid structures had regular mathematical shapes, most being segments of spheres. Such forms appeal greatly to aesthetic classicists and rationalists, but others find their limited geometry uninspiring. As noted in Chapter 4, Frei Otto was amongst those who sought greater freedom of form, utilizing physical models to overcome analytical complexity.

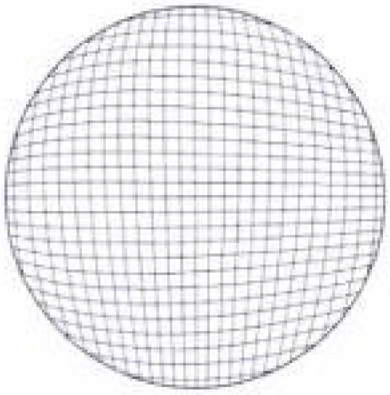
Schlaich had been greatly inspired by the work of Fuller and Otto, but felt that designers of the twentieth century had not yet emulated the lightness and fine tracery (Leichtigkeit und Filigranitat) of the early iron and glass roofs. He felt it must be possible to achieve a similar delicacy by taking develop-

6.4
Plato's five regular polyhedrons

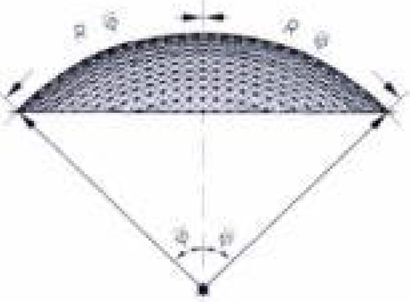
ment a stage further. His other concern was to reduce the cost of analyzing and building grid roofs so that clients and designers would come to see them as a normal form of construction, rather than one reserved for prestigious or specialized applications. The cost of fabrication and construction could be reduced by ensuring that most members were of equal length and that details were standardized. Rigidity could be achieved using fine cables on the diagonals which would be less visually intrusive than solid bars. The lightness of the structure thus springs from this interplay of tension and compression, with bending almost eliminated. Schlaich's extensive understanding of shell theory and cable-net structures meant that he was well placed to exploit these ideas. In this he was joined by Hans Schober, who studied for his doctorate at Schlaich's Institut and entered the design office in 1982. He is now a partner in the practice and together they continue to push forward this development, with the strong support of young engineers especially Thomas Bulenda, Jan Knippers, Thomas Moschner and Sven Plieninger.

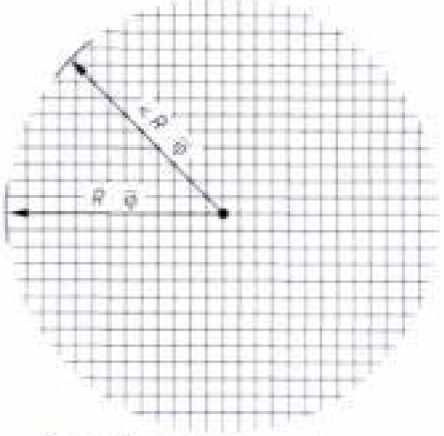
6.5 + 6.6
Frei Otto's timber grid roof at Mannheim (with C. Mutschler and E. Happold), 1974

6.7–6.11
The principle of the grid shell

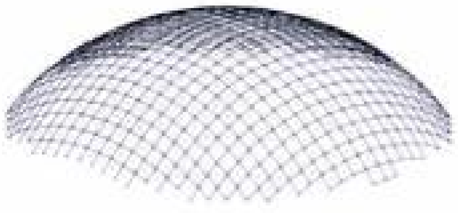


Plan view (above diagonals omitted) and elevation (below) of a spherical grid surface

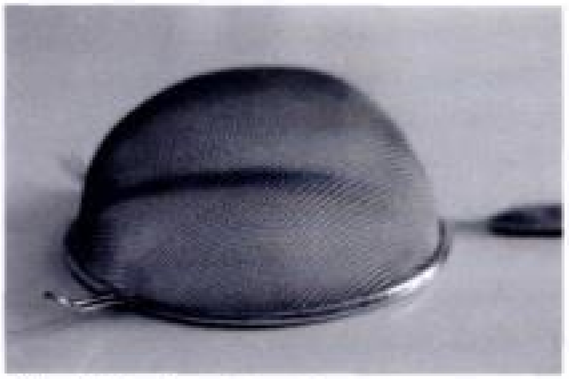




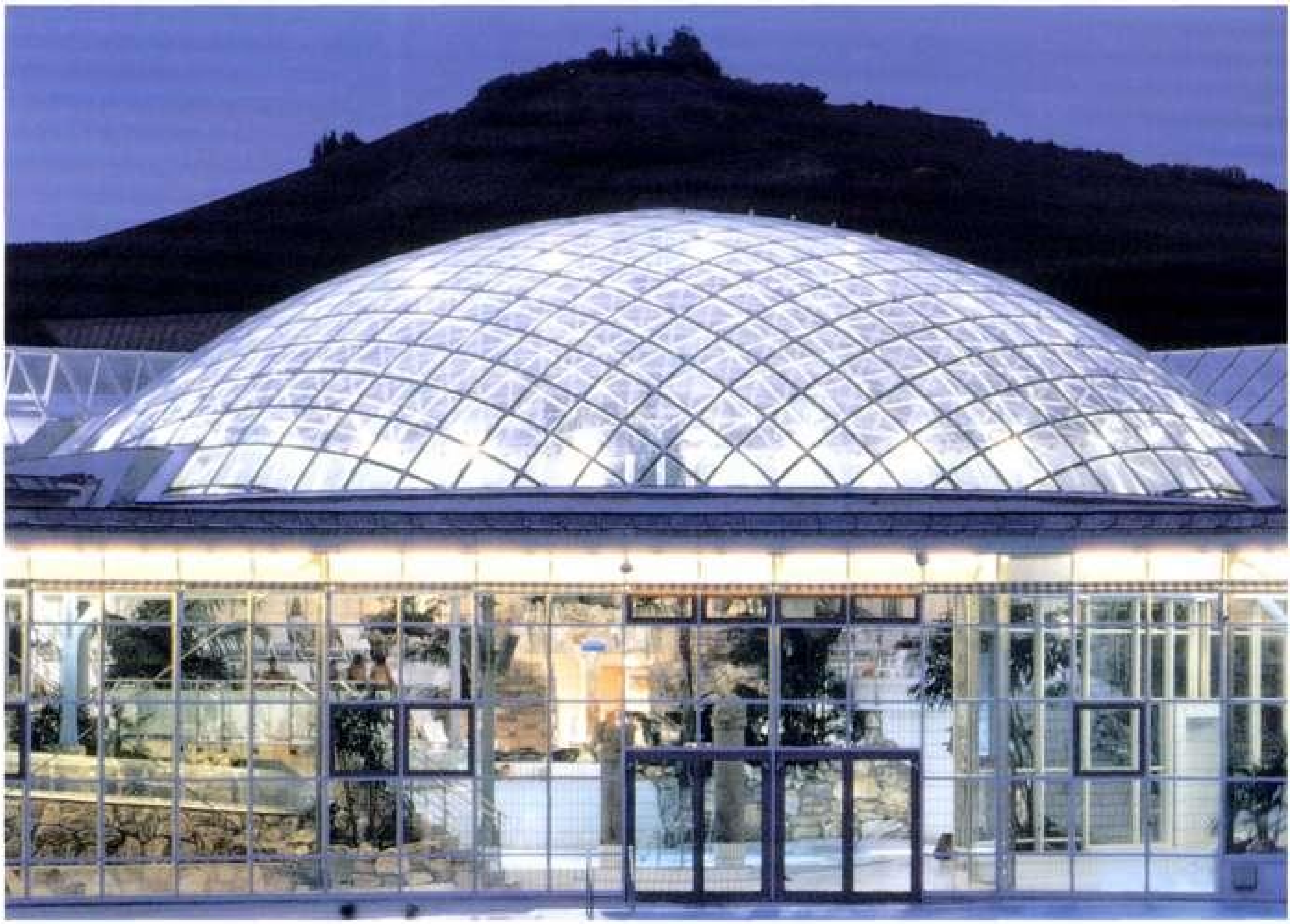
The cutting pattern for a grid when placed flat on the ground with gridlines at 90° to each other



A computer model of the Neckarsulm grid (see 6.12)



A wire kitchen sieve, a hemisphere formed from a flat sheet of square mesh provides a useful demonstration of the principle

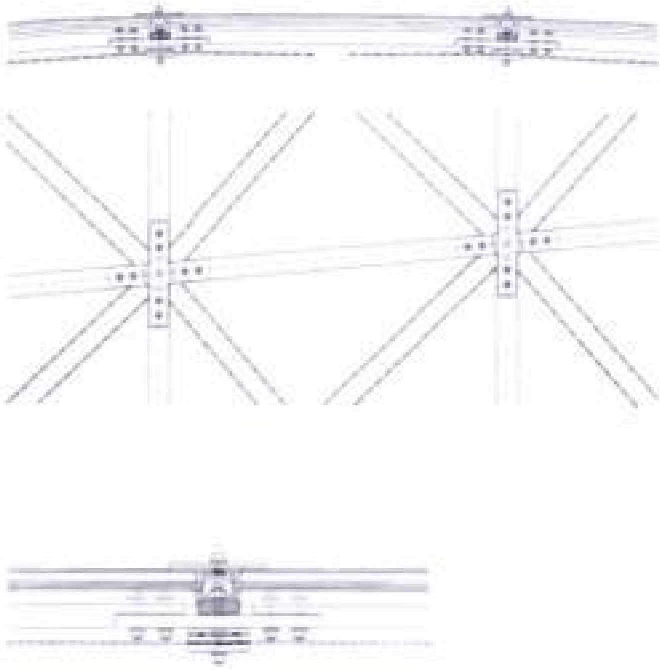


6.12
The glass-grid dome of the Neckarsulm indoor swimming pool at night

The first opportunity came in a commission for a grid dome to cover the Aquatoll **swimming pool at Neckarsulm** (6.12).[3] The architect K.-U. Bechler had conceived the idea of an ethereal spherical dome supported from a terraced substructure and, after some persuasion, the city council had agreed to adopt the attractive and novel design despite its slightly higher cost. Schlaich decided that the dome could be built efficiently by exploiting and expanding an idea which Frei Otto had used for the Bundesgartenschau building in Mannheim (6.5+6.6), with Ted Happold as engineer. This concept makes it possible to form any free shape from members which are all equal in length, except at the periphery. Similar in layout to a cable net with a square mesh (Chapter 5), such grids make doubly-curved surfaces "developable", adapting to the required surface by change of angles between the two sets of gridlines. When explaining the concept to his students, Schlaich uses the homely analogy of an old-fashioned wire kitchen sieve: a completely spherical surface formed from an initially flat sheet of woven wire fabric (6.7-6.11). Hans Schober developed a computer program to calculate the number of equal mesh spaces, plus the two additional end-lengths for each continuous gridline, required to produce exactly the prescribed surface.

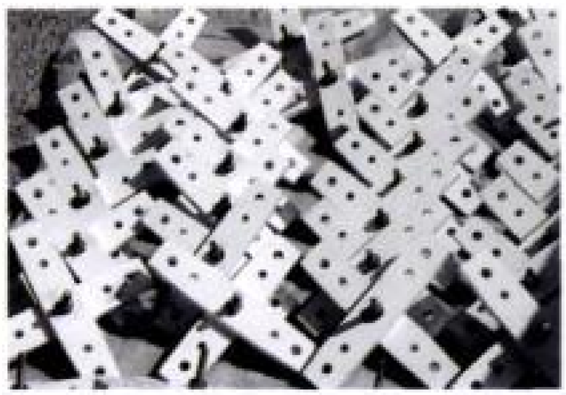
This grid with quadrangle mesh is however not really able to carry loads, especially if they are unevenly distributed over the surface of the dome, such as wind and snow. So Schlaich's decisive idea was to stiffen the grid by diagonal prestressed cables producing a triangular mesh geometry. Thus the load bearing behavior becomes that of an ideal membrane shell.

The flexibility of cables means that they can be transported to site on spools and, as we saw in Chapter 5, a net roof may be completely assembled on the ground and then lifted into position. With grid roofs, a different system of erection is necessary because the relatively rigid members cannot be transported in long lengths. Therefore for the Aquatoll roof individual slats were designed, all of one metre length (equal to the mesh width) and thus of a size which could be handled manually. Their ends were provided with rotatable joints. Assembly of such roofs starts with the single ring of special-length members at the periphery. From then on, as the standard members are added, the dome gradually assumes its exact, pre-determined shape (6.13 – 6.16). To obtain the pure spherical shape it was necessary for slight additional deformation to take place in the members themselves. The steel slats at the Aquatoll Centre therefore needed to be slender enough to bend and twist slightly, but still sufficiently rigid to carry the imposed compressive loads without buckling. These conflicting requirements were satisfied by using slats with a rectangular cross-section of 60 mm by 40 mm.



6.13
Neckarsulm: details of the joints

6.14
The slats



6.15
The rotatable joints

6.16
Assembly of the grid elements

6.17
Close-up of the joint assembly with diagonal cables installed

6.18
A segment of the grid showing the double pattern formed by the slats and cables

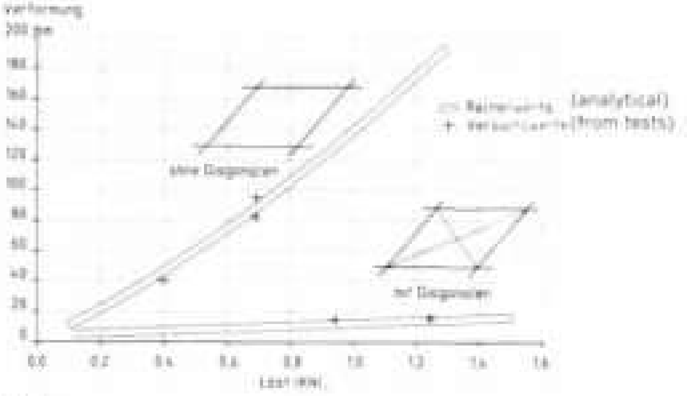
6.19
A segment of the completed roof with the spherically-curved glass panes

Once the dome was in position, diagonal cables could be passed around the surface and prestressed to prevent any further change in the angles at the intersection points and establish an extremely rigid structural system. The length of these diagonals would vary throughout the structure, but this presented no problem because the cables were continuous and could be clamped to the nodes at any desired point (6.17 + 6.18).
It was, however, necessary to "pay" for the many advantages of this system in that the shape of the mesh elements would not be square when the grid was in its final position. There would thus be a number of different shapes of rhombus over the surface of the dome and the spherically-curved double-layer laminated insulation glass panes which formed the cladding would have to be cut to suit them (6.19). The computer program developed to control the cutting machines permitted the accurate shaping of the panes to fit the varied openings in the mesh.

The dome, completed in 1989, was erected within a period of only two months. Before it was covered with glazing, the design team seized the opportunity to research the behaviour of the structure by performing a full-scale load test. Barrels filled with water were hung from one quarter of the nodes both before and after the installation of the bracing cables, to simulate the effect of unsymmetrical snow load. The effectiveness of the cables in stabilizing the structure was proved, and deflections with the cables in place were shown to be extremely low (6.20 + 6.21).

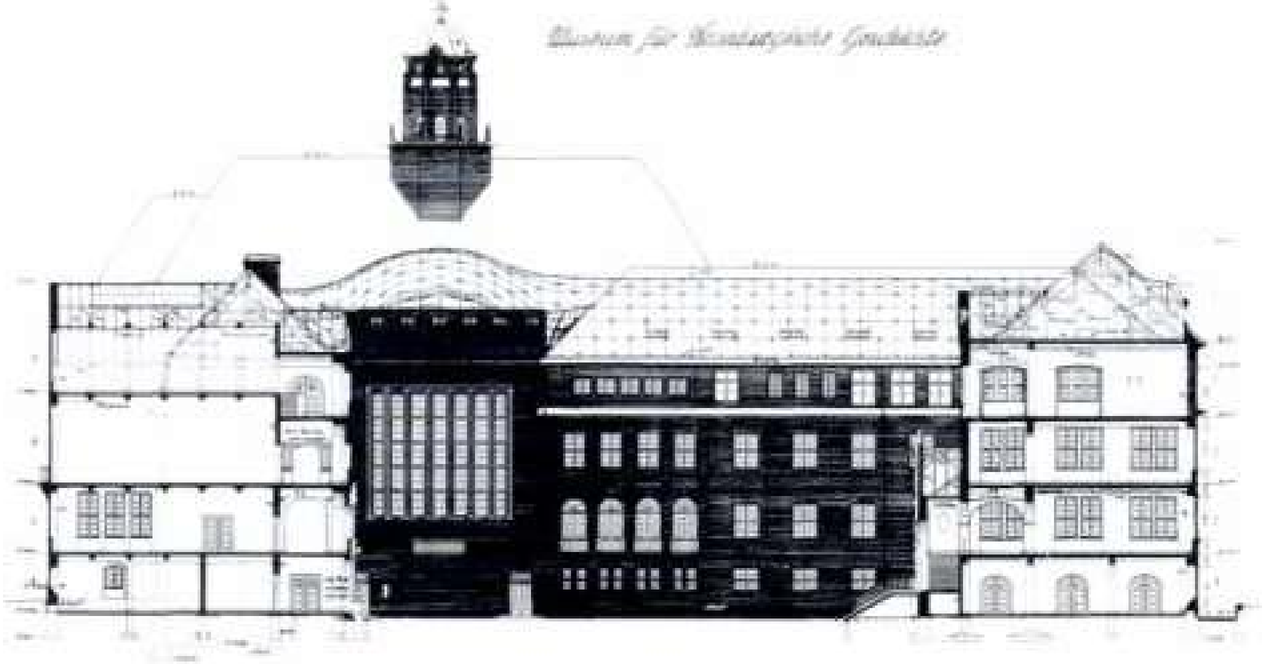
Although Schlaich is pleased with the engineering of this dome, the project as a whole seems to have slipped somewhat between the hands of architect and engineer (6.12). It is always difficult to marry a dramatic roof shape with a basically conventional building form and in this case the dome does not appear from the outside to "float" above the lower structure as freely as was hoped. Theories of aesthetic composition suggest that if two elements are visually disparate, it may be preferable to emphasize their difference, rather than strive for unity or harmony. The first approach was adopted at the Aqua-toll Centre by making a clean break between dome and substructure. However, Schlaich feels that it was not successful, describing the two parts as "Fremdes neben Fremden" which has the approximate sense of "strange bedfellows". It may be that the terraced form of the substructure, which the lower edge of the dome follows, appears to anchor the roof visually to its base. Nevertheless the interior view is splendid (6.22).

6.20
Water barrels representing partial snow load



6.21
Load (kN)-deformation (mm) graphs of grid with and without diagonal cables

6.22
**Neckarsulm indoor swimm
pool (K.-U. Bechler, archit
interior view**



6.23
A section through the museum of the History of Hamburg and its new grid roof

6.24
Volkwin Marg's sketch for the courtyard and roof

Despite the slight disappointment occasioned by the Aquatoll dome, the technical challenge gave birth to valuable concepts which Schlaich was able to exploit fully in another grid roof. This, although designed later, was erected at the same time as the Neckarsulm dome in the summer of 1989. It was needed to provide cover over the internal **courtyard of the Museum of the History of Hamburg**, built in the heart of the old city between 1914 and 1923. The courtyard has an L-shape in plan with one arm 14 metres in width and the other 18 metres wide (6.23 to 6.25). While it would have presented awkward problems to the designers of a conventional roof, Schlaich saw it as a most welcome opportunity to demonstrate the ability of the system used at Neckarsulm to adapt to a free and complex form.

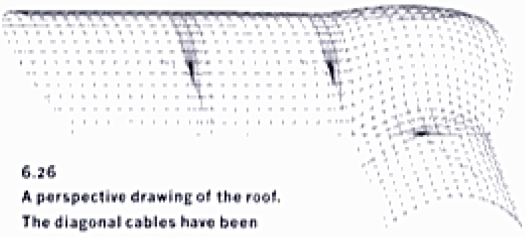
There had been provision for roofing the courtyard in the plans of the original building, but construction had been deferred. It was only in the late 1980s that a decision was made to go ahead because of an urgent need to provide extra enclosed space for display and to protect statues already in the courtyard from modern levels of atmospheric pollution. There were two major constraints. The money for the roof was provided by a private donation which, though generous, presented a tight budget for the task in hand. Furthermore, the historic value of the old building required that any new construction have a minimum of impact on the existing fabric. The roof must thus be light in weight as well as appearance.

Fortunately on this occasion a high degree of integration was achieved between architecture and engineering thanks to an ideal collaboration with the architect Volkwin Marg. The conventional solution at the time would have been to roof each arm of the L with a barrel vault similar to those used in many shopping centres. These consist of a series of semi-circular (usually metal) arches joined by straight longitudinal members. However, this solution would have been ungainly and expensive, and the architectural treatment of the junction of the two barrels would have presented major problems. Marg was seeking something totally different: a roof which would be light, transparent, and flowing; overlapping the edges of the old tiled roof, and seeming to hover protectively over the cherished building. He described this vision eloquently to Schlaich, in a few words and sketches (6.24). However he made no attempt to impose any particular geometrical form or structural system.

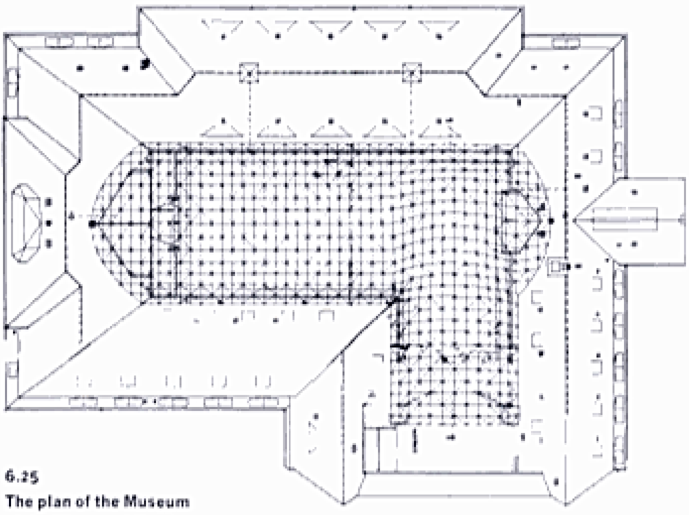
This left the engineer free to go back to fundamental principles in search of a shape and structure that would be lightweight and economical, while meeting all of the architect's requirements and avoiding the problem of the junction in the angle of the L. On the basis of his experience at Neckarsulm, Schlaich realized that a grid shell would offer an ideal solution. The arms themselves could be covered by the familiar barrel vaults. However, grid construction, stiffened by pretensioned cables, would ensure that they were light in weight and in appearance. Then to solve the problem of the joint, the two strictly cylindrical surfaces could rise where they met above the corner of the L and flow freely into one another forming, in a natural way as a soap bubble might, the shape of an irregular dome and emphasizing the architectural importance of this point in the museum (6.26).

Never losing sight of practical considerations, Schlaich and his project engineer Karl Friedrich arranged the final form in this region to minimise the irregularity of the mesh elements by keeping the angle between crossing slats as close to a right angle as possible. To ensure that the cylindrical portions retained their form, the engineers devised vertical fans of cables radiating from a central plate. In function and appearance these are reminiscent of the "spoked wheels" of the Schmehausen cooling tower, bracing the vaults against unsymmetrical loads caused by the drifting of snow and its accumulation in the valleys between the old roof and the new vaults (6.26 + 6.32). As usual, these technical devices have aesthetic appeal and were welcomed by Marg as a means of defining space and emphasizing the three-dimensional form of the roof. The engineers also realized that, because the heating and air-conditioning requirements for the courtyard were less strict than those for internal spaces, it would be possible to use simple sheets of flat, laminated glass 10 mm thick which would be able to bend to follow the curvature of the steel slats when clamped directly to them. However electric heating is provided along the slats to avoid condensation.

The next problem was to carry the weight of the new roof to the ground without modifying the old structure any more than was absolutely necessary. For this purpose, the engineers provided a rigid supporting beam to collect the forces from the lower edge of the grid. It was then necessary to break through the old roof only at a small number of discrete points to install props. These rest on the original reinforced concrete ceiling slab (6.33). This made it possible to fit the new structure neatly within the inner edge of the old roofscape, without interfering with its dormer windows and other excrescences. The water from the new roof drains onto the old and is carried away by its existing gutters. Because of the lightness of the new roof, the brick walls of the original building are able to carry the additional weight without any strengthening or modification whatsoever (6.27 – 6.31).



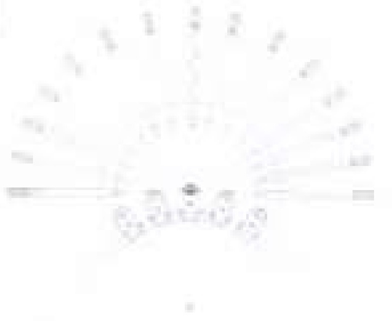
6.26
A perspective drawing of the roof. The diagonal cables have been omitted for clarity and the three "spoked wheels" are apparent



6.25
The plan of the Museum of the History of Hamburg

6.38

6.27–6.31
The roof under construction

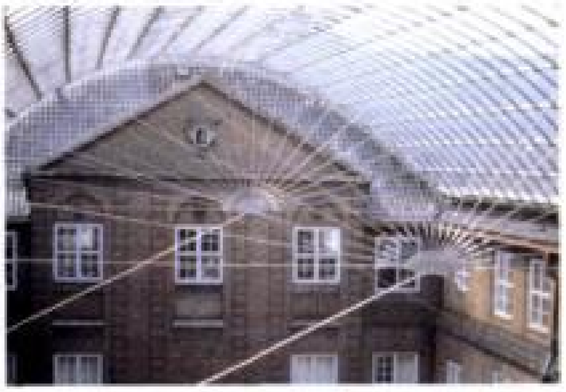


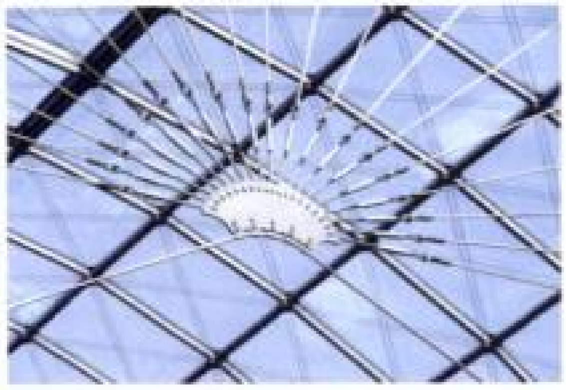
6.32
Detail of a "spoked wheel"

6.33
A support point on the old building

The architectural effect of the roof is evident in photographs of the interior (6.34 - 6.38). The problem of diagonal bracing members competing for visual interest with those of an orthogonal grid has been solved by the lightness of the prestressed cables which here form a delicate accompaniment to the stronger lines of the steel slats. As usual, much thought has been given to the details from both an architectural and a technical standpoint. These are an essential element in the success of the roof. The project is an excellent outcome of the quest for lightness, delicacy, minimalism, and unobtrusiveness in structure characteristic of the Schlaich Bergermann partnership. It is a major breakthrough in architectural terms, bursting free of the formal bounds of the conventional *galleria* barrel vault as revived by post-modern architects in countless suburban shopping centres.

It is worth noting that this complex roof could not have been designed and built without the aid of the modern computer. Its form is so complex that it would have been impossible to determine its geometry and analyze its internal forces using the old hand methods of calculation, or even to describe it adequately in specifications for the builder. It is one project with which Schlaich is very satisfied. Cooperation between architect and engineer was good and the keys to success were the resolution of the geometrical problems of the junction and the consideration of construction techniques during the structural design process.

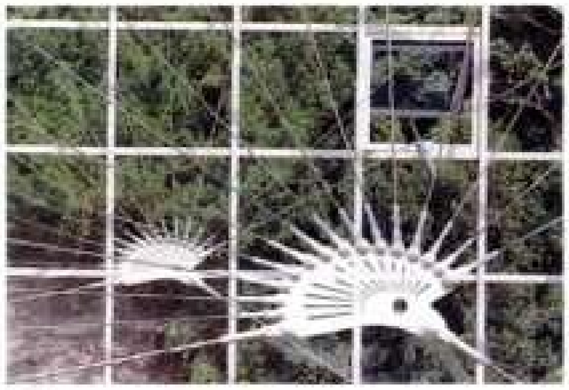




6.34 - 6.38
The roof over the courtyard of the Museum of the History of Hamburg (V. Marg, architect), interieur view and details

6.39
Mineral Spa at Stuttgart-Bad Cannstatt. Interior view, 1993

6.41
Connections of the pretensioned cable "spokes" to the "rim"

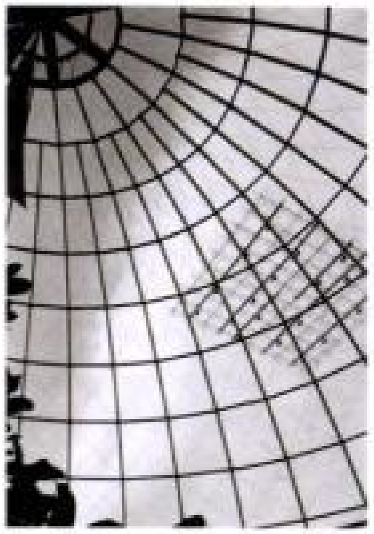


6.40
The hub connections (see the drawing on the cover of this book)

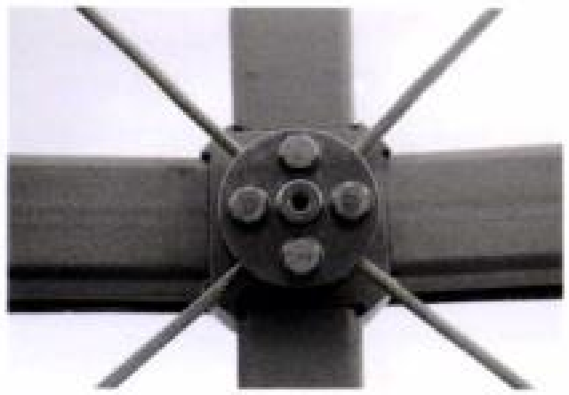
The developments achieved at Hamburg, and the recognition thus gained, have resulted in commissions for several more roofs with similar function and architectural effect. In these applications however, the design team has felt restricted by certain limitations of the quadrangular grid solution used in the two projects described above. To achieve a truly free-form doubly curved surface it is necessary to use curved glass, because the four corners of each opening rarely lie in the same plane. Single-layer panes can normally be bent sufficiently (as for the Hamburg roof) but when climatic control requires the use of double-layer, laminated insulation glass, bending is very difficult. Spherical curvature of the panes as at Neckarsulm is expensive and of course not applicable to a completely free shape. The partnership therefore, in antithesis, investigated the architectural appeal of various simple and straight forward forms of glass-grid construction, exemplified by the following projects.

The roof of the **mineral spa at Stuttgart-Bad Cannstatt** conceived by the architect W. Beck-Erlang covers a simple rectangular area of 20 m by 16 m and the opportunity was taken to use flat panes of glass to form an attractive, facetted cylindrical shape. The profile is again stiffened by fans of cables (6.39–6.41).

In the case of a strictly spherical dome for a **clinic at Neustadt/Rhön**, designed with and for the Mero company, the "principle of the kitchen sieve" (6.11) was abandoned in favour of Schwedler's principle[1], with radial and circumferential slats following the lines of latitude and longitude and the whole stiffened by diagonal cables. The regularity of this system means that the four corners of each segment lie in the same plane, again permitting the use of flat panes (6.42). All nodes are identical in geometry and all the stiffening cables intersect at 90 degrees. Therefore, only one cable could be arranged along each diagonal, requiring the adoption of a node clamp with four bolts instead of the preferred single bolt possible when double strands are used (6.43 as against 6.17 + 6.35).



6.42
The dome at Neustadt/Rhön – similar in layout to Schwedler's domes

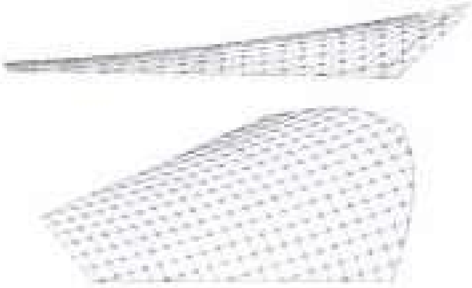


6.43
Joint of slats and cables

Another way to avoid the problem of having to bend glass is to use a triangular grid, because the three corners of each element must lie in one plane. Schlaich sees this as a "trivial" solution. A triangular grid does not require stiffening cables, but the nodes are more complicated as each must connect six slats. At each level the angles of intersection are different, requiring a large number of different node geometries. An example of such a solution is the roof over the courtyard for the Bernheim Palais at Munich. Another is the roof over the **Flemish Council Building in Brussels** (6.44 + 6.45). All glass roofs described here, except at Neustadt, were built by H. Fischer of Talheim, a small but creative and active manufacturer of special steel structures.

6.44 + 6.45
The glass roof of the Flemish Council in Brussels

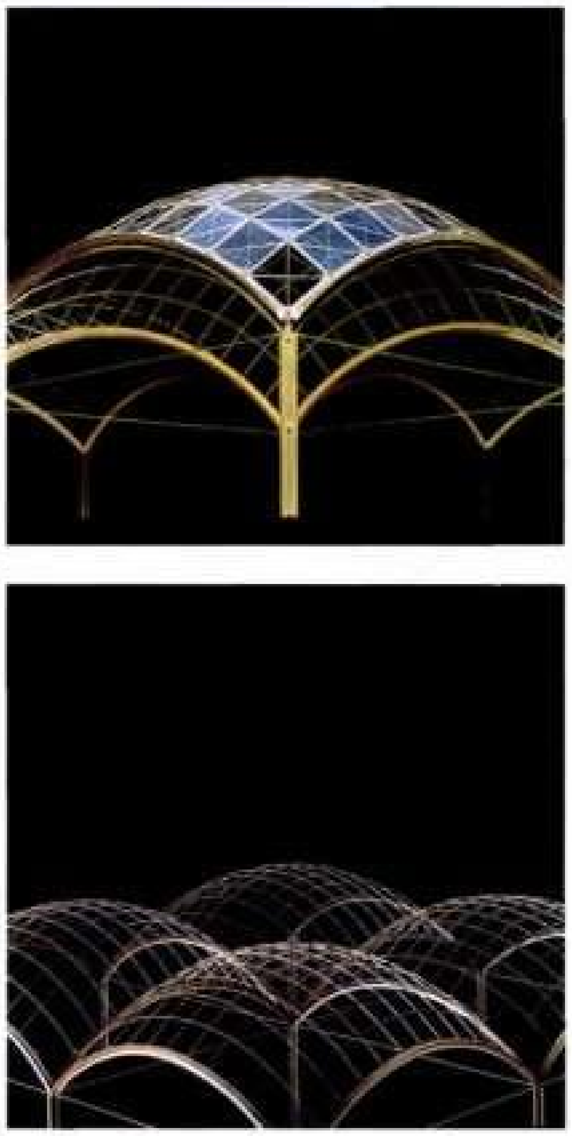
6.46
Two examples of double-curved surfaces of translational origin permitting cladding with plane (glass) panels



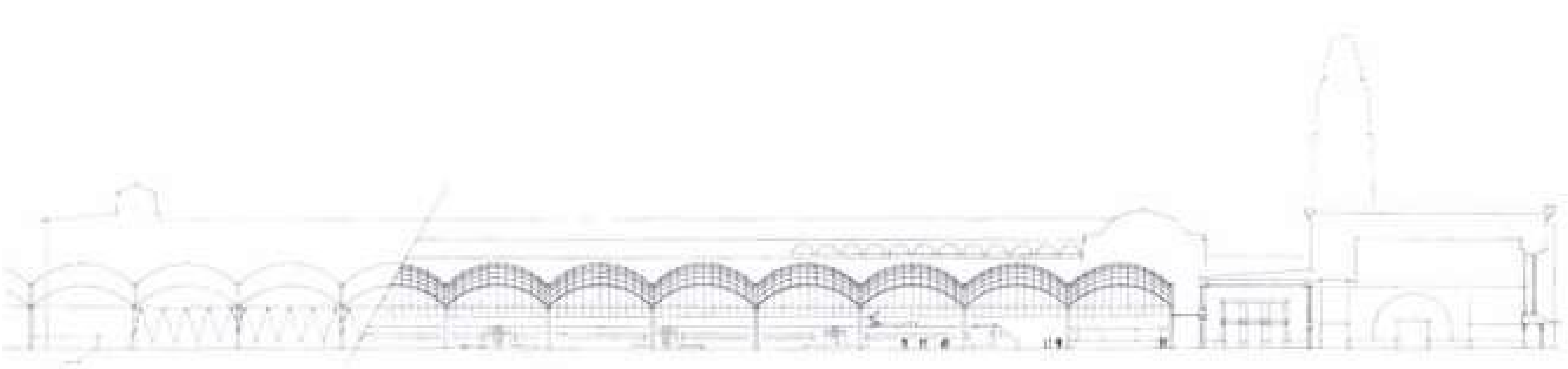
6.47
Roof at Leipzig with anticlastic surface translational

A much more clever solution, in Schlaich's opinion, is to adopt a doubly-curved surface of translational origin. If a generatrix translates along any generator to define a grid, the four corners of the resulting elements will always lie in the same plane. Hans Schober has shown, by mathematical means, that this seemingly restricted technique gives rise to a great variety of negative anticlastic and positive synclastic doubly-curved surfaces. (He has published a demonstration of this in a paper in honour of Schlaich's sixtieth birthday) (6.46) The first roof to be defined and recently built in this way covers another historic courtyard at the Industrie-Palast at **Leipzig** (6.47).

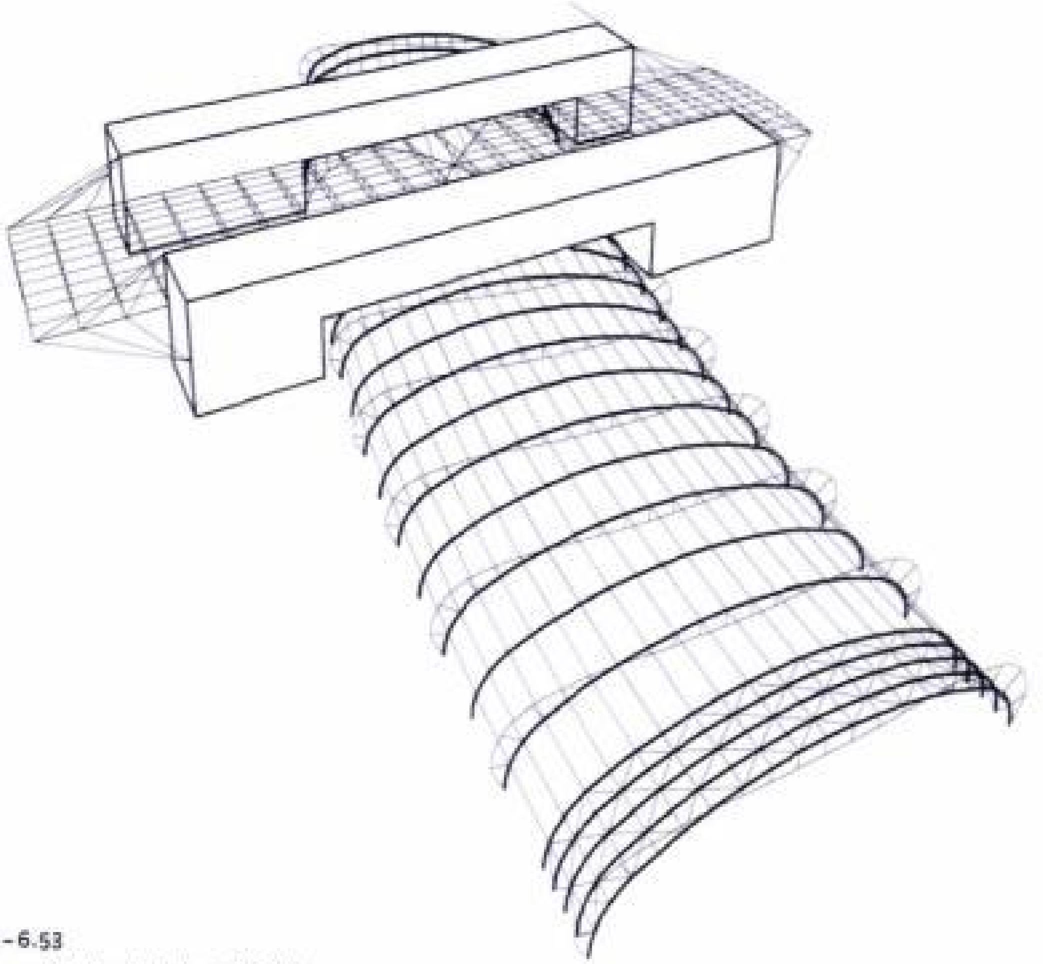
Schlaich and Volkwin Marg applied the same principle in an (unsuccessful) competition design for a roof over the platforms for the **Helsinki station** (6.48 – 6.50).

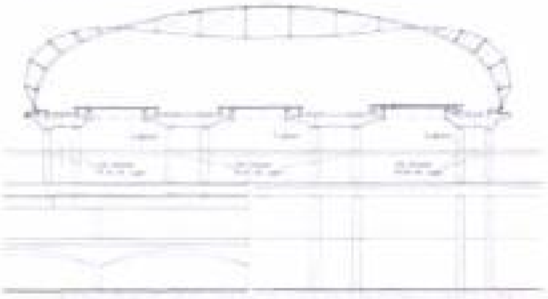


6.48 – 6.50
Helsinki station competition entry. The roof modules 16/16 m have synclastic translational surfaces



At the time of writing, further roofs in Berlin-Spandau, Dresden, Singapore and elsewhere are being designed or constructed. These include a dramatic roof 400 metres long and 66 metres in span to cover the seven platforms of the new **Lehrter Bahnhof at Berlin**. Its glass-grid shell is stiffened by arches, spaced at intervals of 12 metres. They are stabilized by cables following the shape of their moment diagram. These cables make it possible to give the arches a profile which, compared with a parabola, is flatter at the crown and steeper at the abutments, to correspond with the requirements for train clearance (6.51 - 6.53). This future main railroad station of Berlin was designed by the architect Meinhard von Gerkan and includes the railroad bridges as shown in (8.106).





6.51 - 6.53
The new Lehrter Bahnhof at Berlin (M. von Gerkan, architect). Drawings and model showing the long glass roof over the platforms. It crosses another roof in between two large office blocks which span the railroad.

Notes to Chapter 6

[1] From 1863 onwards, the German engineer Schwedler introduced diagonals into his dome structures. Suchov built grid roofs in the form of cylindrical barrel shells in 1896, and later introduced double curvature to overcome instability.

[2] It is not well known that the "geodesic" dome based on the icosahedron, almost universally associated with the name of Buckminster Fuller, was used as early as the 1920s by Bauersfeld and Dischinger as framework for the construction of the Zeiss planetarium in Jena. The self-supporting framework was covered in fine concrete sprayed onto a 3 m by 3 m reusable internal timber form supported temporarily from the frame.

[3] See "Filigrankuppel des Freizeitbades Neckarsulm", *Archiv des Badewesens*, 7/1990, p. 265–268.

Selected Publications by Jorg Schlaich and co-authors (if given) up to 1995 to Chapter 6:
Glass Covered Grid Roofs:

month/year

01/92: "Verglaste Netzkuppeln", mit H. Schober, *Die Bautechnik*.

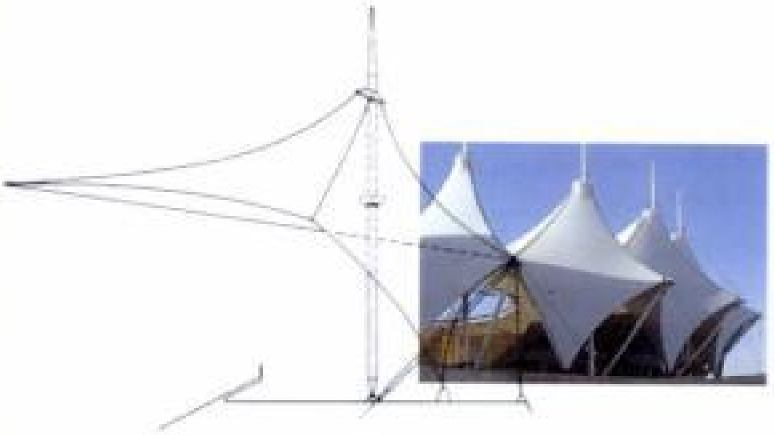
10/92: "Transparente Netztragwerke" *Stahl und Form*.

01/93: "Das Visionare der Raumstrukturen", *Mero-Vision*, Nr. 28, 1992/1993.

05/94: "Glass-covered Lightweight Spatial Structures", with H. Schober, IASS-ASCE International Symposium 1994, Atlanta, Georgia.

08/95 "Ingeniose Losung (Bahnhof in Helsinki)", with V. Marg, *Bauwelt*, H. 31.

7 Textile Membrane Roofs

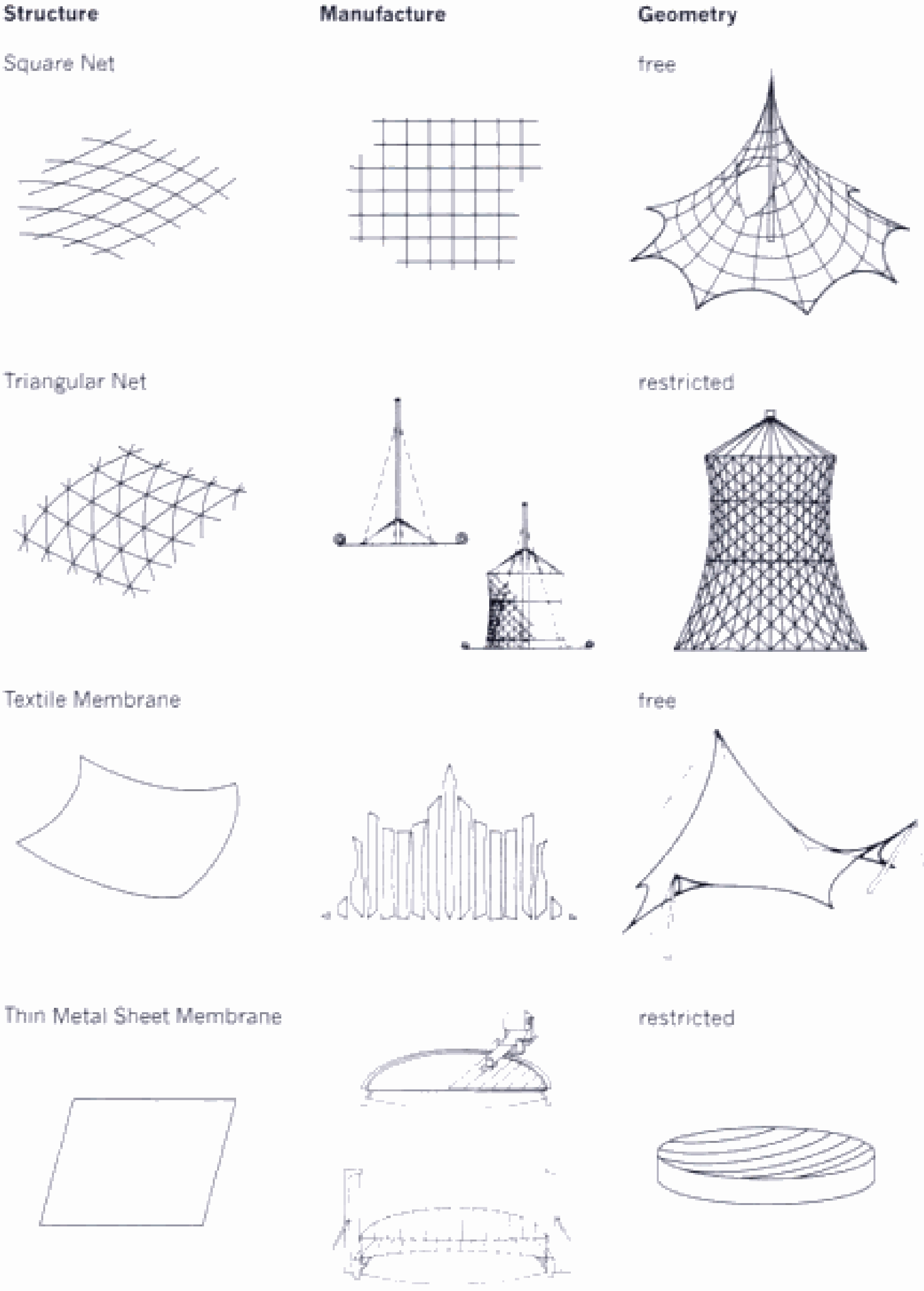


Pioneers of modern large-scale membrane structures envisaged that, as in a vacationer's tent, the interior would be light and airy while the supporting structure, the props and guy-ropes and their accessories, would be unobtrusive. However, the increase in scale presents major problems in engineering. The strong woven fabrics employed are anisotropic, having different mechanical properties in different directions. This makes analysis of stress and deformation extremely complex. To prevent flutter in strong winds and avoid wrinkling under load, especially in re-entrant corners, the membrane must be prestressed. The resulting forces are large and it is difficult to transfer them to masts and ground anchors. The conventional solution is to gather them from the edges of the membrane with loops of cable suspended from mast tops and with heavy curved perimeter cables. The result is frequently stout masts, thick cables, and bulky connections which are especially conspicuous in the smaller structures. Thus, the ease and elegance of design expressed in the architect's tulle model is often totally lost in execution. Creating a three-dimensional form from a two-dimensional material, akin to tailoring a suit from a sheet of cloth, presents further problems in precise computation and fabrication. The membrane must be cut exactly to pattern, working in the case of engineering structures on a scale of tens of metres. Design of the seams to ensure strength and compatibility presents additional challenges.

There is an important and interesting interrelationship amongst the different types of lightweight structure: between manufacture and erection processes on the one hand, and geometry and load-bearing behaviour on the other. Schlaich likes to explain this in his lectures using Figure (7.1). The better the load paths offered by a type, the more restricted is the range of geometrical forms available, and vice versa.

Schlaich's interest in membrane structures was aroused by his visit as a student to Frei Otto's studio in Berlin, and later at the International Expo in Lausanne.[1] However he felt that most examples built so far, particularly those in which Otto himself was not involved, possessed neither the mathematical clarity of shells, nor the structural clarity of cable nets in which the lines of force are immediately visible. To overcome the immediate problem of the transfer of tangential forces from fabric membranes into edge cables, Schlaich initiated research at the Institut aimed at developing a new form of reinforced membrane with an integral belt seam.[2] In addition, sensing that the major problem lay in the nature of the available fabrics (anisotropic, difficult to join, and rapidly ageing), he also set in train a study at the Institut into the practicability of using metal sheet in place of fabric. This bore fruit in the parabolic membranes of the solar concentrators (Chapter 11).

In the meantime the partnership tried to avoid major involvement with the practical design of fabric structures, but a series of commissions drew them gradually into the field. Schlaich notes: "For many years we were involved in the design of small membrane structures without being able to overcome their nasty details." Their first encounter occurred when he and his colleagues were working on the Munich Olympic project (Chapter 5). The grandstand of the Olympic Swimming Hall was to be extended for the duration of the games and a temporary roof was required (5.58 + 5.60). Because of the short time available for design and construction, and the fact that the structure would be used for only two weeks, the design team employed a conventional approach. Further encounters came in the late 1970s, when Leonhardt und Andrä was called in to assess wind damage to a membrane roof over the open-air theatre in Wunsiedel and to proof-check the designs for structures in Gaffenberg (near Heilbronn) and Elspe. These commissions merely served to reinforce Schlaich's low opinion of fabric membranes. The cause of the damage at Wunsiedel was mainly the incompatibility between the extremely flexible material of the membrane and the edge cables. It seemed clear that membrane structures could develop further only if a quite different structural configuration were used and if analysis were placed on a thoroughly scientific footing.



7.1
Manufacturing doubly-curved light weight surfaces acting in tension

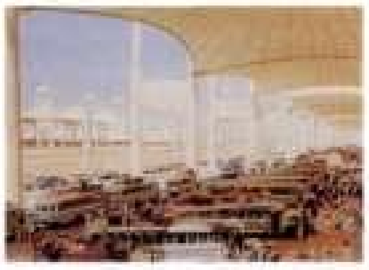
Lightweight doubly-curved surface structures categorized by Schlaich according to geometrical characteristics and method of manufacture.

First row: A **cable net** with an initially **square mesh**, is "developable". Manufactured flat on the ground (5.67) it is able to adapt itself during lifting to any doubly-curved shape by changes in the angles of intersection of the cables. Only the meshes at the edges need to be trimmed to suit a specific shape (5.12). This versatility is gained, however, at the cost of poor load-bearing behaviour and low rigidity, because loads at any node can be transmitted basically only in two directions.

Second row: A **cable net** with a **triangular mesh** is non-developable and thus must be manufactured in situ, in its destined form (5.95). Only a limited number of geometries provide a desirable regularity of node spacing. These disadvantages are compensated by the ideal load-carrying and stiffness characteristics associated with membrane shell behaviour.

Third row: **Textile membranes**, like articles of clothing, are manufactured in the workshop by cutting initially flat pieces of fabric to a predetermined pattern and joining them along seams. They may then be folded, packed, and brought to the site, where they are attached to a primary structure which usually consists of foundations, edge beams, masts, and cables with cast steel joints. Stretched (or inflated) between these elements they may, like square nets, adopt any predetermined form, including doubly-curved shapes. Disadvantages are that their load-bearing behaviour depends on the make-up and orientation of the weave and the type of coating, and that the plastic materials employed have a limited life.

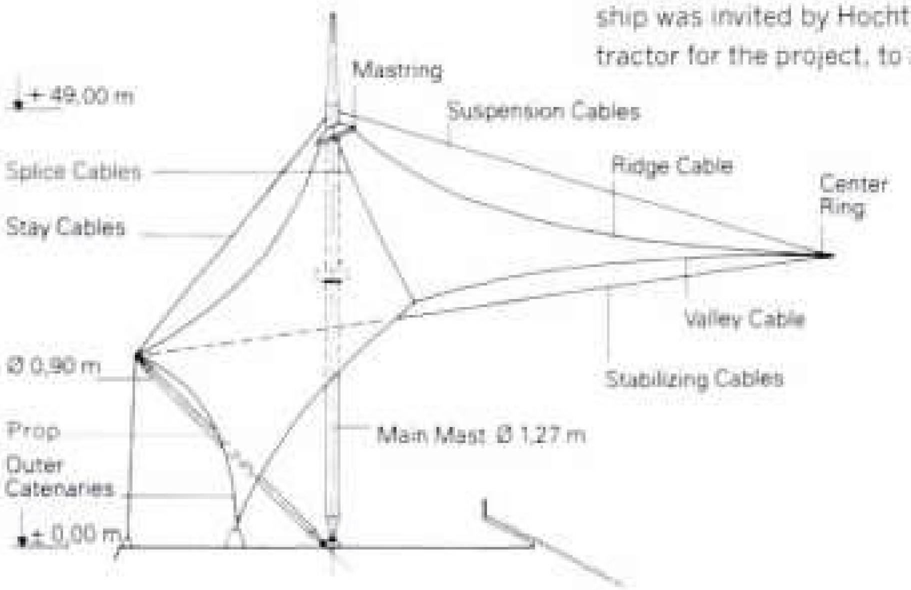
Fourth row: **Metal membranes** of stainless steel have greater durability and perfectly controlled material characteristics. However, they cannot be folded. Doubly-curved surfaces may be obtained from flat sheets through plastic deformation of the metal using pneumatic or mechanical loading (11.2–11.4). The range of geometries achievable is limited (cf. triangular nets) but ideal membrane shell behaviour is ensured.



7.2 + 7.3
Jeddah Airport Haj Terminal Building – the tent roofs

Schlaich and Bergermann's growing involvement then led to invitations to complete the realization of three large membrane roofs which had already been partly designed by others. These were for the Haj Terminal at Jeddah Airport, the Sports Stadium at Riyadh, and the main Olympic Stadium at Montreal. There is nothing worse in terms of design and administrative problems than stepping in to finish a job started by somebody else, and the two partners were reluctant in all cases to become involved. However, the challenges presented meant that they were obliged to come to grips with this difficult material and eventually to master it in a number of later projects over which the office had more complete control.

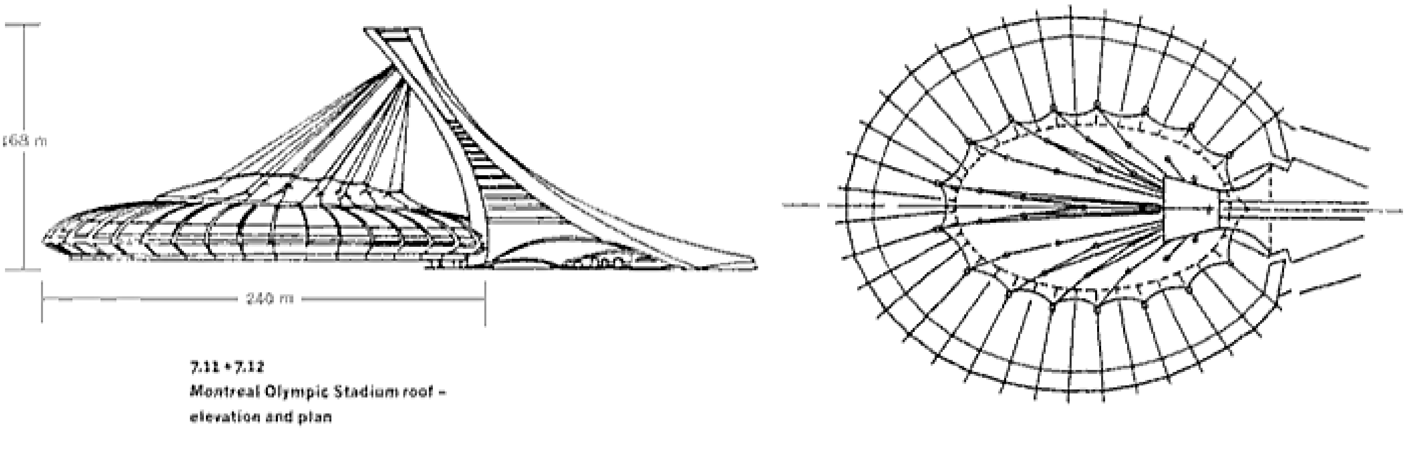
The design of the **Jeddah Airport roofs** (7.2 and 7.3) had been taken to a detailed stage by Fazlur Khan of Skidmore, Owings & Merrill, a good friend of Schlaich's and several times a visitor to his home in Stetten, and by Horst Berger, working for Owens Corning, the roof contractor. The Schlaich Bergermann partnership was invited by Hochtief, the general contractor for the project, to advise them during the construction stage and completion in 1982. Bergermann played a leading role, and Schlaich notes that they "learned a lot" about the problems of membrane structures and their solution. The partnership took a larger role in the design of the **stadium roof at Riyadh**. This is an extensive structure covering 50,000 square metres and consisting of 24 identical units grouped in a circle (7.4–7.10). The initial concept was due to the English architect Ian Fraser who worked out its final form with the American engineers Geiger and Berger, renowned as specialists in membrane structures. Schlaich and Bergermann were once more called in at the request of the contractor, this time Philipp Holzman AG, to bring the design to completion. Given the chance, they would have liked to modify the units because stability could have been ensured with a single tension cable at the rear of each unit instead of the prop included in the original design, and the whole structure would have appeared much lighter. Because work was so far advanced it was impracticable to introduce these changes, but Schlaich notes that the interior as originally designed is "very pleasant" (7.9). The partnership gained valuable experience on the project, especially in the manufacture and erection of such structures. The building was completed in 1984.



7.4
Riyadh Stadium – elevation of one unit

7.5 + 7.6
Riyadh Stadium – Lifting of the membrane

7.7–7.10
The tent roof of the Riyadh Stadium (Horst Berger, conceptual design)



7.11 + 7.12
Montreal Olympic Stadium roof – elevation and plan

Some time later, Schlaich and Bergermann were asked to advise on the final design of the **retractable membrane roof for the Olympic Stadium in Montreal**. The stadium, built for the 1976 Games, is elliptical in plan and the grandstands are covered by a cantilevered concrete roof which runs around the full periphery (7.11 + 7.12). It was planned to cover the central arena by a large membrane, attached at its edges to the inner rim of the grandstand roof and hung from a dramatically shaped inclined tower. Provision was to be made to draw the membrane up towards the top of the tower to open the arena to the sky in good weather. The project was conceived by the French architect Roger Taillibert who had designed a number of swimming pools in Europe with somewhat similar retractable roofs. However, the Montreal roof was to be on a far larger scale than anything attempted before. The elliptical inner convertible membrane covers an area of 20 000 square metres.

The announcement that Taillibert's project had been awarded first prize in the competition, and its subsequent construction, gave rise to considerable controversy which culminated in a debate organized by IASS and published in the magazine of the American Society of Civil Engineers.[3] Its opponents argued that the permanent roof could have been designed to exploit its potential to act as an annular shell, rather than being composed of massive individual cantilevers. They predicted that the complexity of the design would lead to major delays. Work did indeed progress slowly. The workers' unions were concerned about safety issues and exploited the fact that the building was required by a specific deadline. Industrial unrest thus increased the delays and the project soon became embroiled in political controversy.[4] Eventually, it proved impossible to complete the inclined concrete tower and the retractable roof in time for the Games. Fortunately the stadium was quite usable without these facilities because the grandstand roof provided adequate cover at that time of the year. Construction work was halted when only the lower part of the tower had been completed and half of the membrane had been supplied.

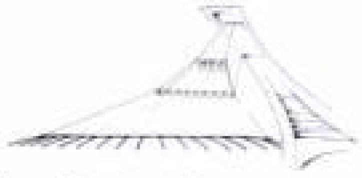
After an interval of fifteen years, the City of Montreal decided to raise funds from its tobacco tax to complete the project. The local design and construction firm of Lavalin was appointed to complete the construction, and their Normand Morin asked Schlaich to act as consultant. It says much for his willingness to confront awkward problems that he accepted, albeit reluctantly. In the case of Jeddah and Riyadh, Schlaich and Bergermann had been comfortable with the basic approach of those who had conceived the project. In this case they had major misgivings about the architectural and technical conception of the original scheme, so in 1987 signed a contract in which the partnership would act only as advisor. This led to one of the less satisfactory experiences of Schlaich's career. Their main contact was with the consulting engineer for the design, Luc Lainey, an extremely gifted and committed young French-Canadian. Although the Stuttgart and Montreal teams enjoyed good personal relationships, the apportionment of authority and responsibility between the three parties (Schlaich Bergermann, Lavalin design, and Lavalin manufacture) was not satisfactorily resolved. In principle Schlaich Bergermann were responsible for the cable design, and Lavalin for the seams of the membrane and the moving mechanism and control.

From the start the Stuttgart team (Schlaich, Bergermann, Werner Sobek and Klaus Horstkotter) were not happy about the choice of material for the membrane, a PVC-Aramid fabric which has high strength, but is rigid and brittle and sensitive to ultra-violet radiation. Its rigidity makes the manufacture of seams difficult and costly, and demands a very exact cutting pattern. However, it would have been unacceptably costly to reject the material which had already been supplied and stored in the 1970s. A much greater problem was the design of a cable system which would allow for the extension and retraction of the membrane roof while still being strong enough to support the very heavy snow falls common in Montreal. The original scheme had been to support the membrane on 26 cables (7.11 + 7.12). These were to fan out from the top of the tower and be anchored at their far ends to the inner edge of the grandstand roof. Winches placed in the head of the hollow tower would haul in the supporting cables to retract the roof. As the edge of the tent receded, secondary cables would be paid out gradually to control its shape. The main cables would wrap around the drums of the winches, and the membrane itself would fold into a neat bundle. This would come to rest in a large niche near the top of the tower. To extend the roof, the reverse process would be followed, using the secondary cables to draw the edge downwards while the main suspension cables were paid out. Once the lower edge of the membrane was attached to the permanent roof, the suspension cables would then be pulled taut to prestress the membrane and prevent flutter. To study the complicated kinematics of this process, the Stuttgart team started by constructing a realistic working model (7.13 – 7.16).

The original designer had faced a major problem in the enormous weight of snow which might accumulate on the membrane if a snow-storm struck while the roof was closed.

Roof in closed and prestressed position

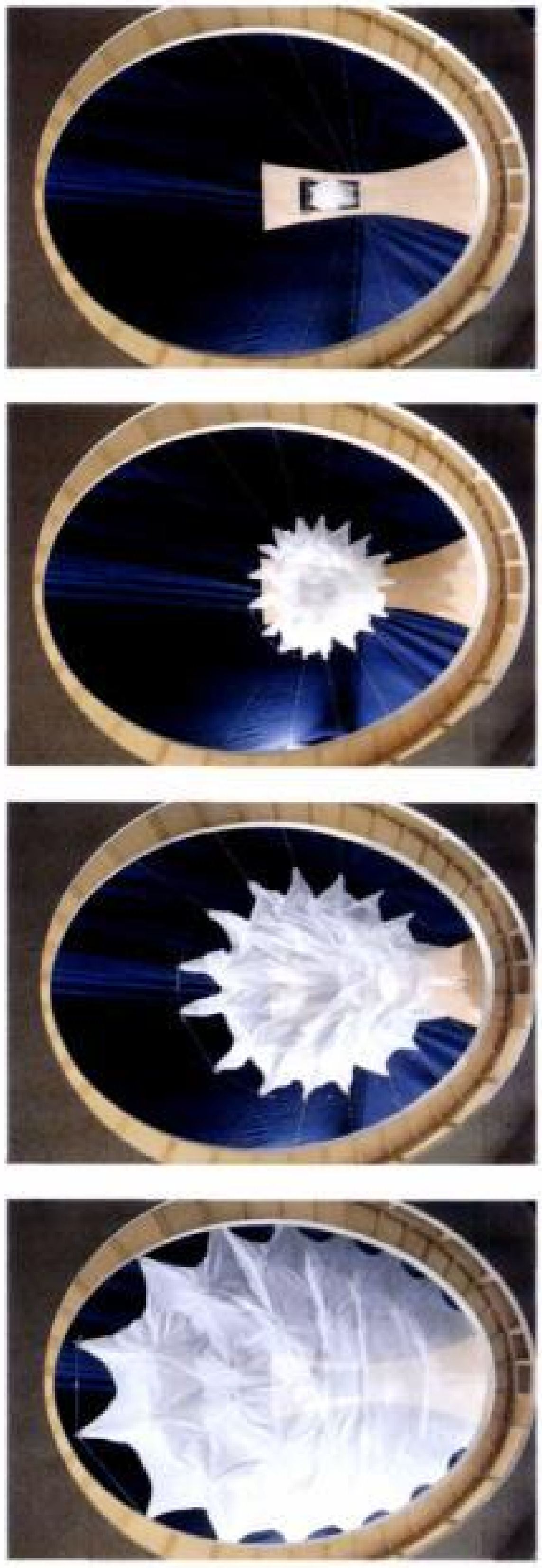
The prestress is released and the attachment bolts along the perimeter are removed



The roof is retracted.
Its movements are controlled with the "lasso" cable looped around its lower perimeter

7.17 – 7.19
Prestressing, releasing and retracting the roof

7.20
Cable anchorage at mast top: Prestressing and releasing is done by using hydraulic jacks which shift the sockets of the suspension cables. Separation of functions: The thick suspension cables are straight, when stressed. The lifting of the roof is done now by using thin hoisting cables



7.13 – 7.16
The kinematic model of the Montreal Stadium showing stages in the extension of the roof (view from below)

7.21
Transport of the membrane into the stadium (compare the size of the truck)

7.22
A large cast steel joint

7.23
Luc Lainey and Rudolf Bergermann watching the unfolding of the membrane from the mast top

7.24
What they saw

7.25
Close-up view of a suspension point

7.26
The same from below

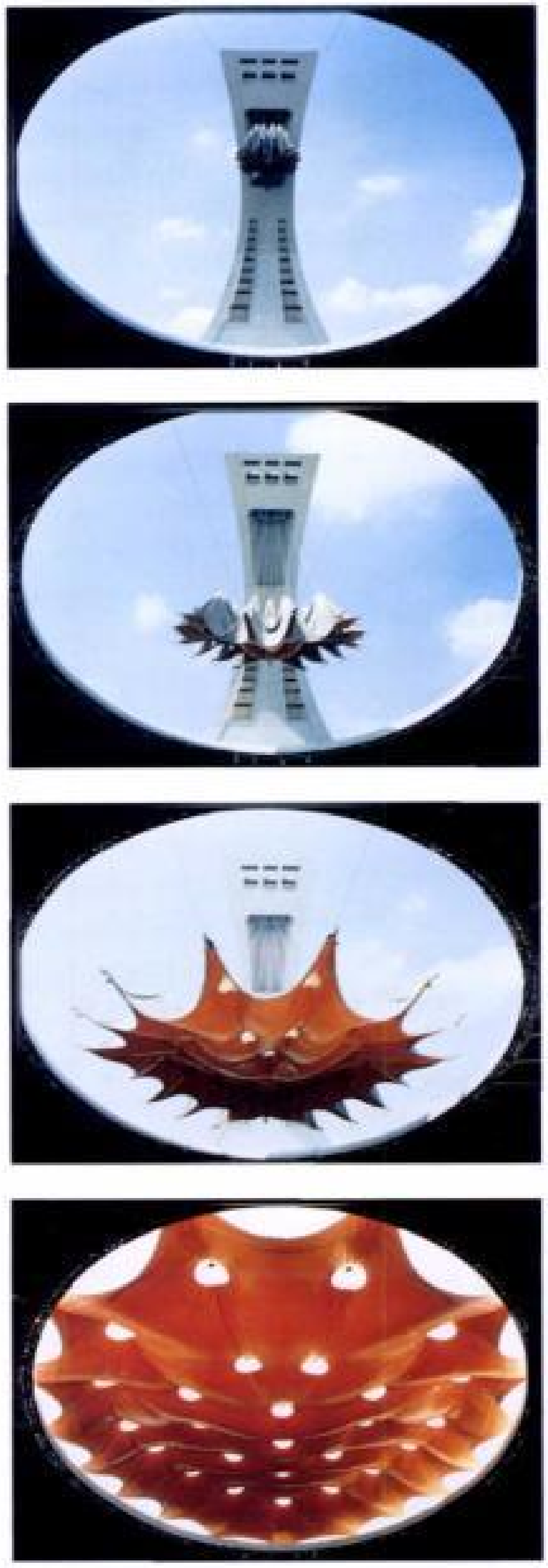
This would increase the force in the main cables which would be already heavily loaded by the prestress. The value of snow load normally used in design for Montreal is 1.35 kN per square metre of roof area. The cables required to support this load plus the prestress would have been massive and stiff. The minimum radius of curvature to which a loaded cable can be bent increases as its diameter increases. (Also, when a cable is required to move, the minimum radius of curvature is almost twice as large as when it is merely required to follow the curve of a saddle as on a fixed roof or on a bridge, thus, large diameter cables would have required large diameter drums for the winches and these could not possibly have been accommodated in the head of the tower.

In response to this problem, the original designer had envisaged a heating system for the membrane which would melt the snow as soon as it began to accumulate. As a safety measure the roof was however designed to carry a nominal snow load of 0.45kN/m^2. The justifications for using this lower figure were that the management of the stadium would retract the roof if snow storms were forecast; that the chance of a snow-storm striking while it was closed was therefore small; and that, if this did happen, the heating system would dissipate the snow. Based on these assumptions the designer arrived at a diameter for the main suspension cables of "only" 40 mm. This made it possible to accommodate 26 winches of the necessary size within the head of the tower. The overall dimensions of the tower were fixed on this basis and, just as importantly, its bending strength was determined to resist the pull of 40 mm cables supporting only a 0.45 kN/m^2 snow load.

The Stuttgart team was troubled, however, that the concept did not make enough allowance for the possibility of human error and mechanical failure. If the roof were to be subjected to a sudden snowstorm, the snow melting system might not be switched on soon enough. Even if it were, it might prove unable to control the accumulation of snow; it might melt the PVC covering of the fabric and reduce the strength of its seams; or there might be a total power failure. In this case, either the cables or the seams of the fabric could fail, leading to destruction of the roof. Schlaich Bergermann therefore stated that they could not share any responsibility unless the roof were designed for the full standard value of snow load. An analysis based on the original method of retraction showed that a diameter of 95 mm would be required for the main cables under full snow load and prestress. To accommodate them, and allow for the fact that a moving cable cannot be bent as sharply as a static cable, the winch drums would need to be six metres in diameter, rather than the one metre originally proposed. It was impossible to imagine a tower large enough at the top to hold 26 winches of this size. It appeared for a while that the design of the roof might have to be abandoned.

A solution to the problem was not easy to find, but the secret lay in the fact that the forces involved in retracting the roof were much less than those required to prestress it and support the snow load. Thus, when the roof was in position, the 95 mm diameter cables need run only from the edge of the permanent roof to the head of the tower. Here, each could be attached to a heavy jack which would react against a collar (7.20). A battery of jacks could thus perform the task of prestressing the membrane. To retract the roof, the jacks would first be released to relieve the tension and disengage them from their collars. They and the heavy cables would then be drawn back down, inside the hollow shaft of the tower (7.17 – 7.19). The cables would follow freely through the collars and be guided along curved tracks equipped with rollers to reduce the friction loss. To draw the jacks and main cables down the tower, smaller cables with an average diameter of 30 mm would suffice. These could be wrapped round drums of 1.2 metres diameter, and it would be possible to accommodate the necessary number in the broad base of the tower which was flared for mainly architectural reasons.

Once this major problem had been conquered there were many others to resolve. The first was to find a way of connecting the high-strength membrane to the large-diameter edge cables whilst ensuring the flexibility needed for the retraction process. A "lasso" cable was installed around the lower edge of the membrane so that it could be gathered up in a controlled fashion (7.19). Many cast blocks were designed for the cable connec-



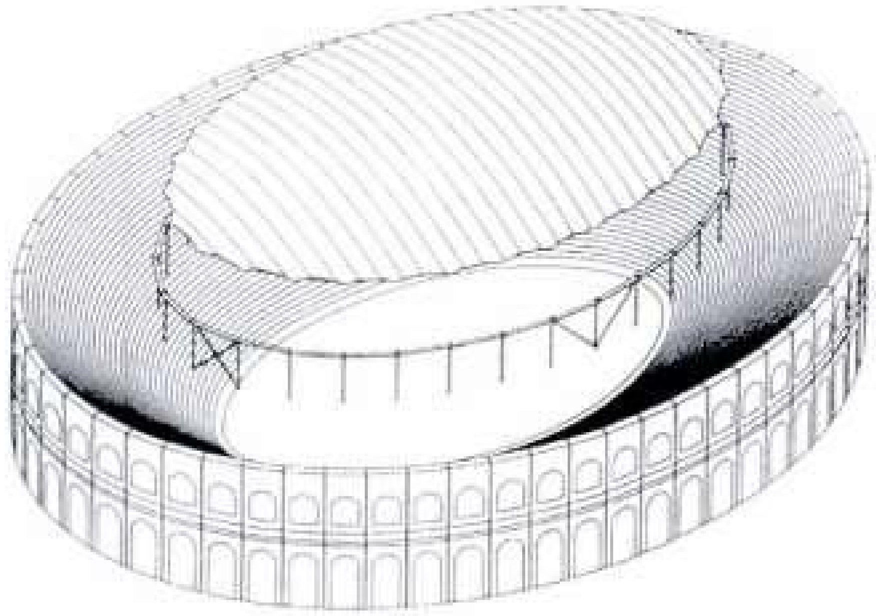
7.27–7.30
The roof in operation
[viewed from inside]

tions, some of them weighing several tonnes. As a result of the greatly increased forces which would be applied to the top of the tower its bending strength was now in question. The designers realized that some relief could be achieved by reducing its weight and thus the bending moments at its base. The upper part was therefore re-designed using steel instead of the originally intended concrete. This work was carried out by Lavalin who were also responsible for all the mechanical engineering and, as contractors, built the tower and manufactured and assembled the roof (7.21–7.26). It was completed in 1989.

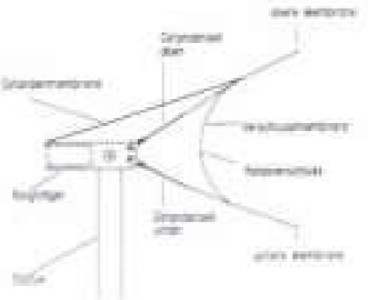
After some initial difficulties with the automatic release system of the anchorages, the roof was operated successfully for several years (7.27–7.31). It survived severe snow storms without damage although less violent storms and hot weather caused several minor tears in the seams. However, in 1993 the membrane suffered major damage which was repaired without consulting Schlaich and Bergermann. At the time of writing it appears, unfortunately, that the roof may even be dismantled and replaced with a rigid moveable covering.

Naturally, Schlaich has very mixed feelings about his involvement in this project. Even before the last damage occurred he wrote: "I got involved very reluctantly" and later "almost regret having been involved because it is bombastic architecture completely out of scale with its surroundings; an inefficient design from the beginning." He feels that his office never saw the full picture, being excluded from the manufacture and erection process – aspects which, as we have seen, he considers to be an integral part of design. This is often the lot of the specialist consultant, but is particularly difficult for an engineer who has a strong commitment to holistic design and who is accustomed to being in full control of his projects. On the other hand, Schlaich admits that he was drawn into the project because it represented his greatest technical challenge in recent years and he is still proud of his team's solution to the problem of retracting the strengthened cable system. He and Bergermann draw further comfort from the fact that they learned a great deal through "all the suffering" and so were ready for subsequent challenges in roofing the historic arenas at Nîmes and Zaragoza, where they enjoyed untrammelled responsibility for the engineering design.

7.31
The completed Montreal sports facilities (R. Taillibert, architect)



7.32
Nimes Roman Arena: schematic exploded view showing arrangement of the roof and its supports



7.33
Connection of the cushion to the compression ring. The ring is shown in cross section with one of its supporting columns

During the 1970s, the French architects Finn Geipel and Nicolas Michelin received a brief to design a **removable cover for the Roman arena in Nimes**.[5] The roof was to have minimum impact on the ancient structure and be designed so that erection and removal would take no longer than three weeks. The architects invited Schlaich Bergermann to act as consulting engineers, and the partnership put forward an imaginative idea it had conceived in response to a similar project for the Roman arena at Verona. The idea had been to make the roof in the form of a helium-filled cushion, rather like an airship. This was to be anchored low over the arena during the winter months, but floated high above it during the summer, or even flown outside the city to be put to some other purpose.

The Verona proposal had been ruled out by safety regulations, but it was decided to retain the idea of a cushion for the Nimes project, this time filling it with air and erecting it in a "conventional" way, rather than flying it in from elsewhere. The plan of the Nimes arena is an ellipse with main axes of 101 and 132 metres. The solution adopted was to erect a temporary auditorium within the old one, having axes of only 57 and 88 metres. When the roof is required, thirty steel columns, ten metres high, are erected in a ring within the grandstand. A box-section steel ring-beam, which is stored in one terrace of the grandstand during the summer, is assembled and hoisted to the top of the columns (7.32–7.41). It supports the cushion and resists the circumferential compression induced in it by the inward pull of the mem-

7.34
View of the facade from outside including the blowers and inflation tubes

7.35
The inclined translucent facade from inside

branes. The lower membrane of the cushion is given a curvature less than the optimum so that spectators seated in the upper rows are able to see those on the opposite side, thus preserving their sense of participation. It is allowed to sag only 4.2 metres at its centre, while the upper membrane rises an optimum 8.5 metres. As a result, high tensile forces are induced in the lower membrane by the air pressure and calculations showed that cable-net reinforcement would be necessary. These cables are exploited to provide extra stability for the ring beam, making it possible to limit its cross-section to 30 cm by 50 cm (7.33). As no functional restrictions limited the curvature of the upper membrane, it could be designed to adopt a greater curvature and thus needed no cable reinforcement. The temporary inclined facade of the auditorium, spanning between the compression ring and the steps of the grandstands, consists of 480 laminated plastic translucent elements each weighing only 30 kg (7.34 + 7.35). Hoisting of the roof, which has an area of 4,200 square metres and weighs about 40 tonnes, is carried out using 30 specially developed outriggers which are attached to the columns and raised by the same jacks used for lifting the compression ring (7.36 – 7.40). To avoid tearing there must be almost no wind during the erection process, which takes about five hours until the membrane is inflated. It is therefore carried out at night or in the early hours of the morning. The roof provides an excellent example of the strong tradition in the Schlaich Bergermann office of thoroughly integrating design and construction.

7.37 – 7.40
Hoisting and inflating the roof

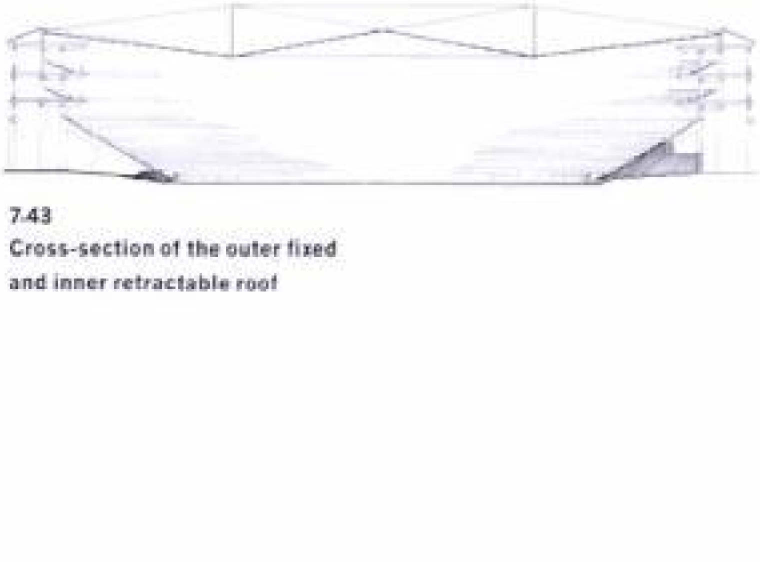
7.41 (overleaf)
The Roman arena at Nimes

A quite different solution was evolved to provide a partially-removable membrane roof for the 18th-century **bullring at Zaragoza** in Spain.[6] The building is circular in plan and has a diameter of 100 metres. Here, the Schlaich Bergermann team covered the grandstands with a permanent membrane roof having an outer diameter of 83 metres. Within this, the bullring proper is covered by a retractable inner roof 23 metres in diameter. The structural system of the outer part is based on the familiar theme of the

7.42
The roof over the bull-ring at Zaragoza showing only the outer permanent part of the roof

spoked wheel (7.42 – 7.45). The rim consists of a steel box-section compression ring, while the 16 spokes are as usual prestressed cables. These are anchored at their inner ends to two cable tension rings, situated one above the other and held apart by vertical tubular struts. There are thus two sets of cables radiating from the inner rings to the top of the grandstand: one sloping down and the other sloping up. The membrane of the permanent, annular roof is draped over the lower set.

The retractable inner roof is located entirely within the "hub" (7.43). The upper and lower tension rings serve as "rims" for two further "spoked wheel" systems meeting at a single common hub above the centre of the bull ring. The retractable membrane is draped over the lower cables of this inner system. When the roof is open, it hangs bunched up in the centre. When the roof is to be closed, 16 small electric motors draw the bottom edge of the membrane out to the lower rim to form a circular tent (7.46). Once the edge has been secured to the rim, a jack at the top applies the prestress necessary to establish rigidity and prevent flutter (7.47 + 7.48). Visitors greatly enjoy the magnificent spectacle of the opening and closing of the roof which has been likened to the unfolding and closing of a flower bud (7.49 – 7.54).



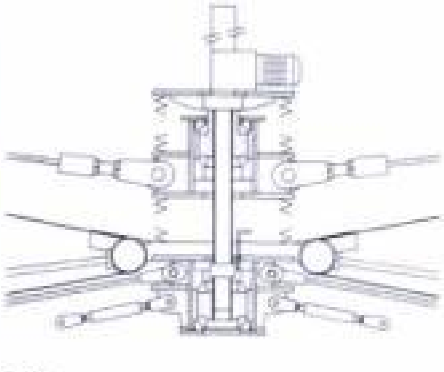
7.43
Cross-section of the outer fixed and inner retractable roof

7.44
Close-up of the outer roof viewed from inside the stadium

7.45
The outer roof seen from above with its cables and vertical struts

7.46
The retractable roof from above

7.47
View of the prestressing system



7.48
Cross-section through the prestressing system at the centre of the retractable roof

7.49 – 7.54
Closure of the Zaragoza roof
seen from inside the arena

7.55
The Gottlieb-Daimler Stadium roof at Stuttgart

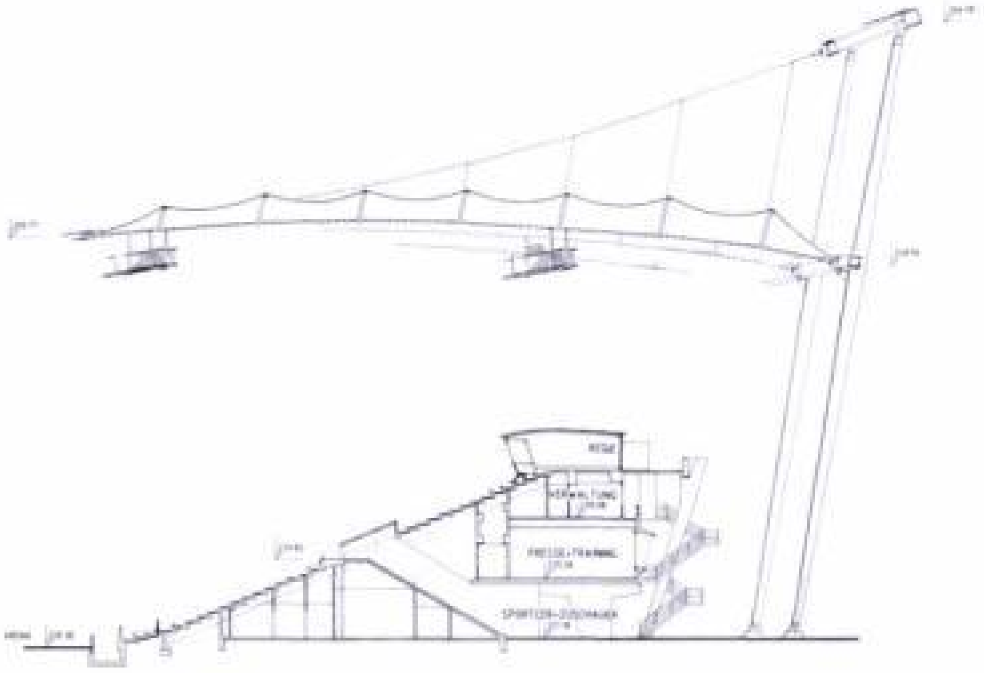
In August 1993 the Field and Track World Championships were held at the **Gottlieb-Daimler Stadium** (formerly the Neckar Stadium) in **Stuttgart**. For this event Schlaich and Bergermann together with the architects H. Siegel und Partner and Weidleplan were commissioned to design a roof to completely cover the grandstands. The task was challenging. Time and money were strictly limited, and it was required to interfere as little as possible with the continued functioning of the sports venue. The site near the river was composed of poor soil, but the conventional response of driving piled foundations was ruled out because of concern over the purity of the groundwater supplying the famous mineral water wells in the locality. The partnership chose to use a spoked-wheel type of structure because it was ideally suited to the situation, being entirely self-contained from a structural point of view and thus transferring only vertical loads to the ground. As a result, only small spread footings were needed at the bases of the columns, and there was no need for back-stays or ties which would have required bulky anchor blocks or tension pile anchorages. The sparse structural system of masts and cables was economical and simply erected. Within 18 months, the partnership had designed the largest membrane roof in Europe and construction had been completed on budget and on time (7.55 -7.66).

The outer edge of the roof is elliptical in plan with main axes of 280 and 200 metres and consists of two steel box compression rings supported by 40 steel box columns. The rings undulate in elevation to follow the varying heights of the grandstands. A steel-cable tension ring is suspended above the inner edges of the grandstands with 40 radial cable-girders stressed like spokes between the inner tension ring and the outer compression rings.

(The system is similar to that used at Zaragoza but inverted, because at Zaragoza there is one outer compression and two inner tension rings). The cable-girders consist of upper and lower cables which are connected and prestressed against each other by vertical suspender cables (7.56). The tension in the upper cables increases under snow load, while that in the lower cables increases under wind suction (uplift). The width of the roof between the outer and inner rings is a constant 58 metres. The roof is divided into 40 panels, each bounded by two adjacent lower radial cables, the lower compression ring, and the inner cable. The total area of membrane is 34,000 square metres. Each panel is supported by seven parallel tied arches running in the circumferential direction and spanning between the lower cables of adjacent cable-girders.

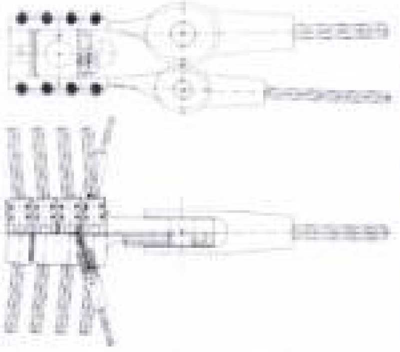
The columns and compression rings were first erected with the aid of cranes. The tension cable ring, consisting of eight locked coil ropes, was then laid out on the ground in the stadium and lifted into position using the (extended) radial cables of the cable girders. The tied arches could then be installed and the membrane laid over them (7.62–7.65). No temporary supports were needed for this process and there was no interruption to the scheduled sports activities in the stadium.

Shortly after the Daimler Stadium, Rudolf Bergermann and Knut Goppert (a former student of Schlaich and one of the coming younger generation of the practice) designed a similar roof for the Gerry Weber Centre Court at Halle Westfalen but with an additional convertible translucent central roof (completed in 1994) and another one, even larger than at Stuttgart, for Kuala Lumpur, which is now under construction.



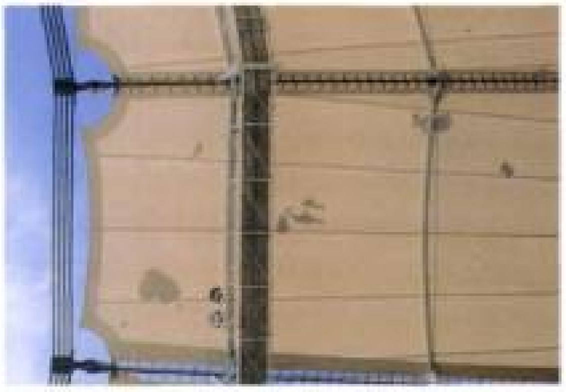
7.56
Section of the roof and grandstand

7.57–7.59
The stadium



The edge cable connection

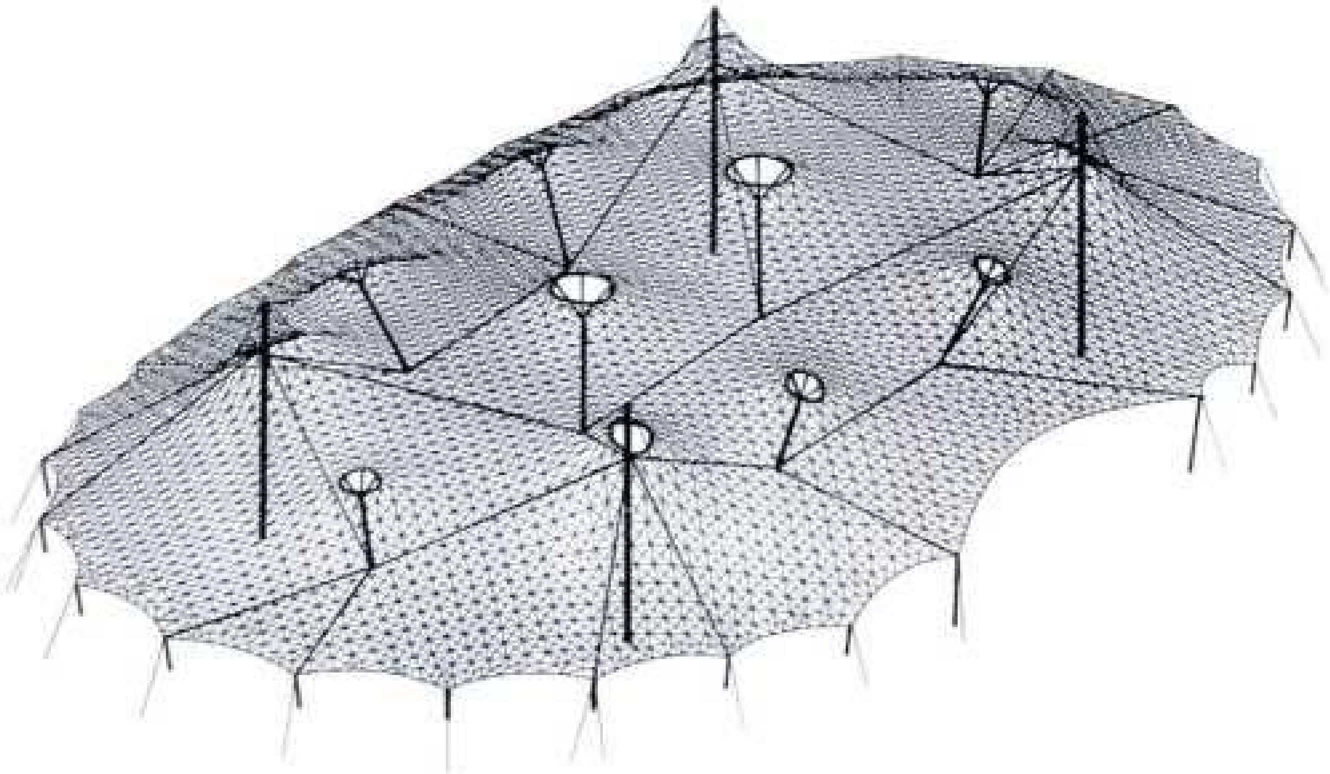
Two tied arches joining with a lower radial cable



7.60 – 7.65
Details of the edge cable. Installation of the membrane on arches spanning between the lower radial cables

7.66
The membrane roof


olivetti
olivetti



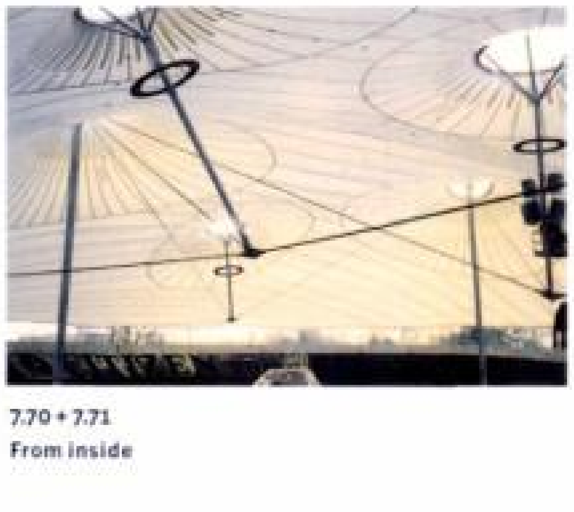
7.67
Ice-skating rink, Hamburg-Stellingen. Isometric view

Although Schlaich is the central figure of this book, he has constantly requested that proper recognition be given to all members of the team. He notes that this is particularly necessary in the case of the membrane structures, with Theodor Angelopoulos for the FEM-analysis and the cutting pattern of almost all cable net and membrane roofs and with project engineers Werner Sobek at Nîmes and Zaragoza, Knut Göppert at the Daimler Stadium and most recently two smaller but beautifully light and translucent roofs, at Hamburg with his junior partner Andreas Keil and with Michael Werwigk, and at Oldenburg again with Knut Göppert and with Kirsten Martin.

The roof over an **ice-skating rink at Hamburg-Stellingen** (7.67–7.71) was the outcome of a successful design competition in which Schlaich participated at the invitation of the architects Silcher and Werner. Covering an area in the form of an ellipse with main axes of 120 and 70 meters, the membrane is held up by 4 main masts and 8 cable supported props and tied down at its periphery by 26 short guyed masts. Whereas the Stuttgart roof in spite of its immense size retains a human scale through its lightness and simplicity the Hamburg roof convincingly uses the cutting pattern and arrangement of the membrane strips to show the flow of forces thus enhancing the natural beauty of membrane structures.

7.68
From outside, at night

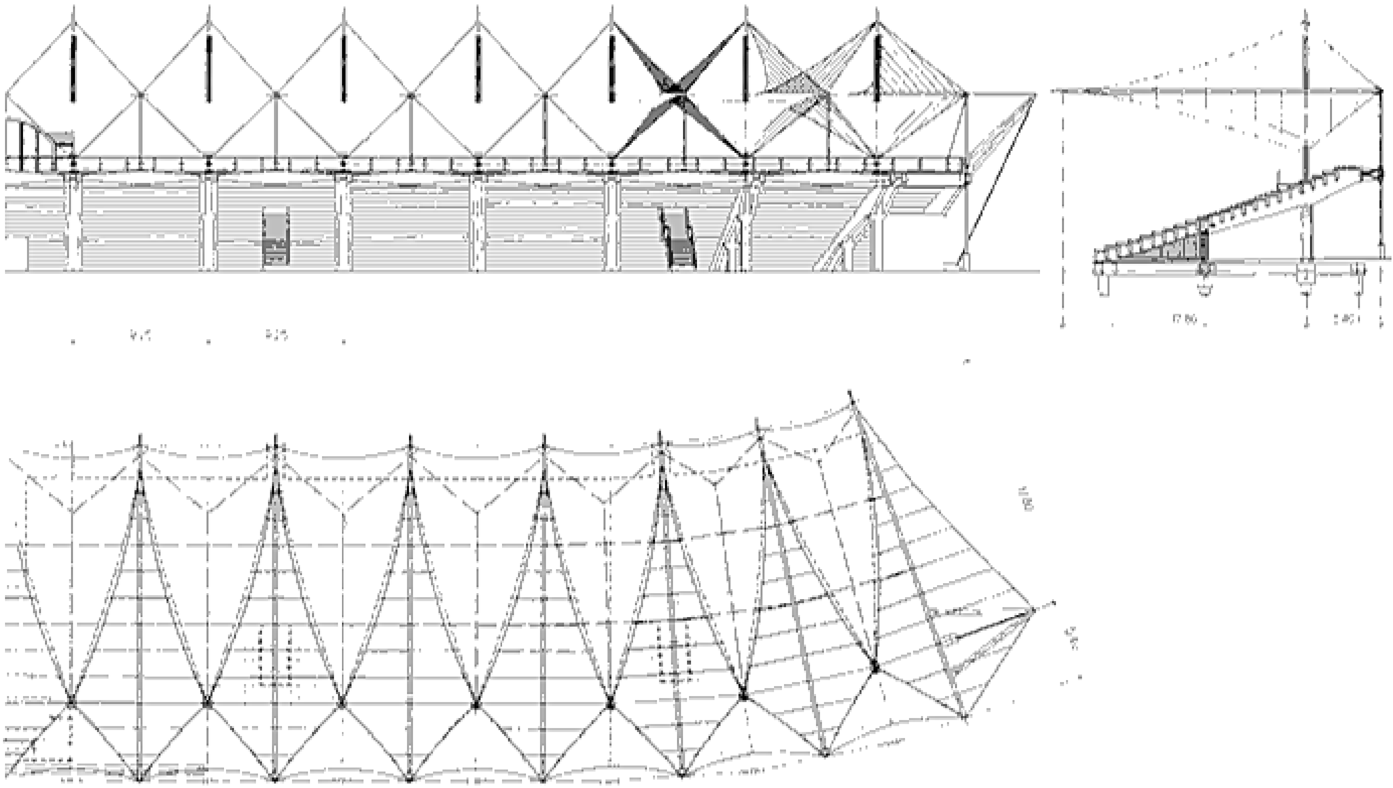
7.69
From outside, daytime



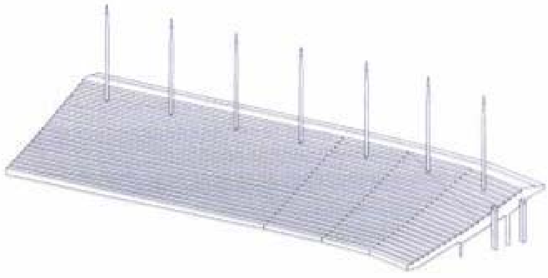
7.70 + 7.71
From inside

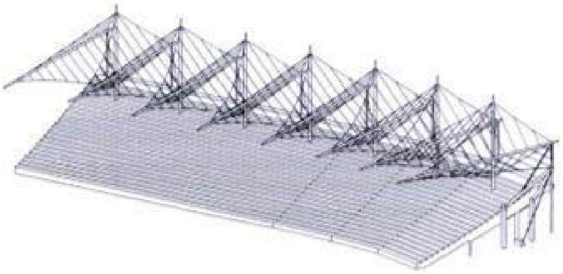
The roof over a **grand stand at Oldenburg** (7.72 –7.83) covers 5000 seats, arranged in 21 rows, 130 meters long. Though this design goes back to an earlier competition entry submitted by Schlaich and Bergermann at Karlsruhe, careful consideration was made of several alternative solutions - particularly of cantilevered roofs decked with trapezoidal steel sheeting suspended from steel cables, as frequently built in recent years. More satisfying aesthetically and costing little more, the present solution was chosen, using a steel tube, cable and membrane structure. Pretensioned membranes have to be strongly curved in order to take up loads economically. The anticlastic surface curvatures should be similar in both directions where, as here, roughly equal loadings from snow or wind suction can be expected. Under these boundary conditions the long form precluded a single membrane, thus there are 14 rectangular or trapezoidal elements, connected at upper horizontal level by their adjacent edges along radial struts and each tensioned downwards to a low point. The rectangles are 9.25 x 23 m in plan and their lower points are 4 m below the horizontal edges; roof projection is 17.6 m over seating area and 5.4 m behind. The horizontal struts are cable suspended from masts, 11.45 m high and held down by another set of cables. At each end of the whole roof a triangular cable truss in plan collects the horizontal forces to a point carried on steel trestle supports.

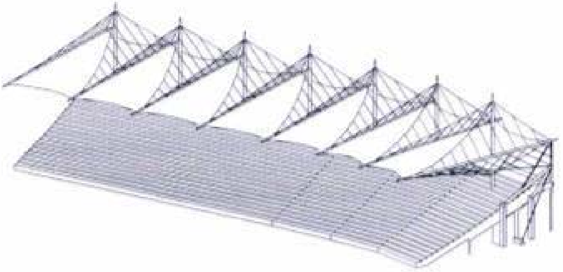
7.72 + 7.73
Oldenburg grand stand roof



7.74 – 7.76
Plan, section, view of
Oldenburg grand stand roof







7.77–7.80
Erection procedure

The assembly procedure was as follows (7.77–7.80):

- firstly the masts were erected with the cables exact in length, there being no adjustment devices (tolerances required for the reinforced concrete ± 10 mm and mast construction ± 5 mm);
- then pre-assembly of the membrane near site with compression struts and tension cables;
- lifting of pre-fabricated segments into position and securing support cables to masts;
- connection of end cable trusses between roof and trestles and gradual tensioning of cables (ca. 150 kN per cable) with continual monitoring of overall geometry and of prestressing forces,
- graduate tensioning of membranes at low points;
- final stressing of whole structure via end trusses and trestles);
- connection of stainless steel rainwater tubes to the low points.

7.81–7.83
Oldenburg grand stand roof

8 Highway and Railway Bridges

During his early years with the Leonhardt und Andra group, Schlaich did not become heavily involved in the design of large bridges because this was well catered for by established partners. However, in 1966 the group was engaged to provide expert advice to an Indian contractor in preparing a tender for a large bridge across the Ganges at Allahabad (8.1 and 8.2). Because of his strong personal interest in India, Schlaich was happy when Leonhardt accepted him as project engineer and he was able to commence work on the design with a group of Indian colleagues. Amongst these was Sharad Joshi and the two soon became firm friends. In 1968 he was sent to India to spend two weeks discussing the Allahabad project with the government, getting to know the country, and meeting its people. However, to the dismay of Leonhardt and Schlaich, the regional authorities considered the proposed use of high-quality suspension cables and partially prestressed concrete to be dangerously in advance of local practice, and he was unable to persuade them to accept Leonhardt's design for the bridge. However, his strong interest in India had been reinforced and whenever an opportunity arose Schlaich went there, "initially at a total financial loss", to seek involvement in projects for bridges.

About 1971, another Indian group suggested a collaboration with Leonhardt und Andra on a project for a bridge at Patna. In response, Schlaich established himself in Bombay where he and Joshi developed a special form of multiple cable-stayed bridge with decks in prestressed concrete (8.3). The Allahabad and Patna bridges were to be approximately four kilometres in length and Leonhardt and Schlaich had hoped to see them as prototypes for future bridges which would be suited to the special problems of India's wide rivers with their immense scour depths, when they rise rapidly during the monsoon season. (For further discussion of these two bridge types see "Prince Edward Island Link".)

It was during this period that the government of Bengal invited international consultants to submit tenders for the checking of the design of a large **second crossing over the Hooghly River at Calcutta**. This provided an opportunity for Schlaich to become involved on behalf of Leonhardt und Andra and so established him on a path which was to lead to the design of several large cable-stayed bridges. This aspect of his career developed parallel to, and almost independent of, his other work. It was of course precisely the field in which he could learn most from Leonhardt, whose achievements in bridge design, especially that of cable-stayed bridges, had brought world fame.

The first bridge across the Hooghly (a branch of the Ganges delta) consists of a series of massive trusses built under the British administration in 1943. In the 1960s a group of Indian contractors operating under the name BBCC tendered to construct a second bridge to a design by the renowned British consultants Freeman Fox and Partners. Their proposal was for a 457-metre cable-stayed bridge with two steel box-girders incorporated in the deck. BBCC won the contract to build the bridge but in 1971 the validity of the design principles then used for steel box girders came into question following failures in a number of countries. In Britain an investigatory committee recommended the adoption of revised guidelines and the strengthening of many recently-built box girder decks. The Indian government therefore decided that the design for the new Hooghly Bridge should be reviewed. The consultant responsible for supervision would also act as "proof engineer" and double-check the computations and drawings of the designers. The contract for these tasks was then opened to world-wide competition. The Government further specified that maximum use be made of local products, especially steel, in order to provide work for local industry, and that labour-intensive methods should be used where possible for fabrication and construction. The steel was to be rivetted rather than welded, to give maximum employment to local fabricators.

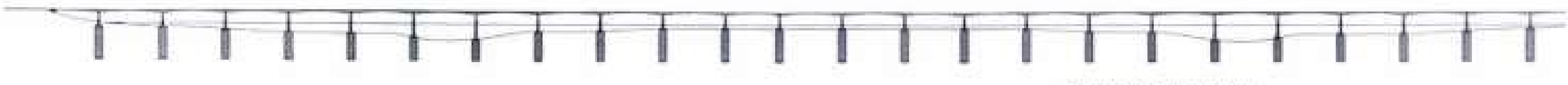
Because of his interest in India and in cable-stayed bridges, Schlaich was very keen to obtain the commission for Leonhardt und Andra to act as proof engineer for this design. His eventually successful negotiations with the authorities required several visits to Calcutta over a period of more than a year. As mentioned above, proof engineers take a large share of the ultimate responsibility for the structure and thus have a strong stake in having their own ideas accepted if they have a serious difference of opinion with the designers. At the time, the system was almost unknown in the anglo-saxon world. British engineers were accustomed to working entirely on their own and taking full and direct responsibility for their designs. It was inevitable that there would be friction between the two groups. Leonhardt and Schlaich suggested so many changes to the FFP design that they were in effect demanding a complete re-working. There was much lively disputation before the two groups of engineers began to develop a mutual respect which finally led to friendship. Later, in an exceptional development, the Indian government proposed that the two groups exchange roles. FFP would become the proof engineers for the design, while Leonhardt and Schlaich would put into effect their own design ideas and supervise the construction on site. This was accepted by both parties, and new contracts were signed.

In this context it is worth mentioning, that Schlaich and Bergermann some 15 years later employed Tony Freeman, the grandson of the founder of FFP, for the cable erection of the Hooghly bridge, since they had worked with him earlier and successfully at the inflated roof in Nîmes for which he designed and supervised the lifting equipment – a small world!

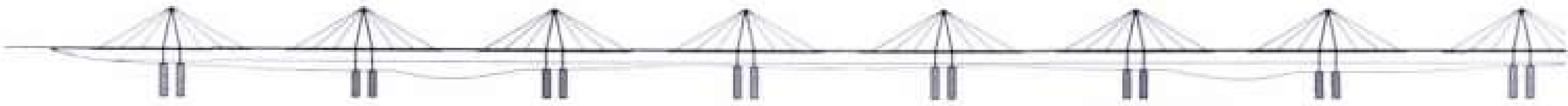
When Schlaich and Bergermann separated from the Leonhardt und Andra group early in 1980 they were content that their former colleagues were quite willing to get rid of what had by then become a "burdensome" project and were happy to take the Hooghly bridge with them into their new practice. It took a little longer for Schlaich to persuade the Indian authorities to agree that this major bridge should be handed over to the smaller and younger practice. It was at that time the only cable-stayed bridge in Southern Asia and in the 1970s still the largest in the world.

Rivers like the Ganges in India require caisson foundations 60 or more metres in depth to resist scour. Thus for standard girder bridges, requiring piers at frequent intervals, the foundations are extremely costly. Widely-spaced piers are more economical, and this leads to the use of large spans with cable-stayed decks

8.1–8.3
Cable-stayed bridges for rivers requiring deep caisson foundations



Standard girder bridge



Leonhardt's Allahabad proposal for a multiple-span cable-stayed bridge

The Patna proposal in 1981 – note the longitudinal cross-bracing between adjacent pylons

ability of the concrete. In addition to the promised cost savings due to simplicity of construction, the composite deck also offered improved distribution of concentrated vehicle loads, and increased damping of vibrations.[1]

In a further adaptation to local conditions, the cables were designed for highly simplified construction as parallel wire bundles built up from locally manufactured prestressing wire. To avoid the cost and maintenance problems associated with sliding bearings, the deck is not supported on the cross-girder where it passes through the pylons, but is suspended entirely from the cables. This system also eliminated the high bending moments which would have developed in the deep longitudinal girders if they had received knife-edge support from the pylon cross-girders. The legs of the pylons are sloped slightly inwards so that the cables may remain in the vertical plane (8.4). Schlaich spent several night-long sessions attempting to convince the West Bengal Minister for Public Works that his insistence on the use of steel for the pylons would result in unnecessary cost and delay, but without success.

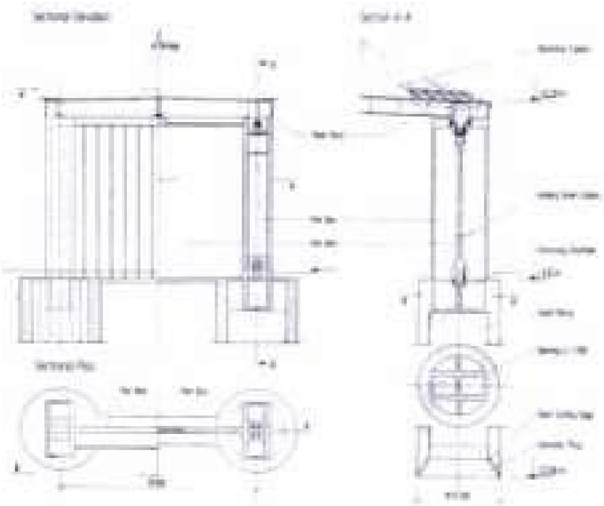
The deck is fastened to the abutment at one end only so that it is free to expand and contract over its full length with changes in temperature. Holding-down cables carry the vertical component of the tension in the backstay cables down into the well foundations (8.5). The end supports and the pylon frames are based on pairs of deep caisson foundations with a diameter of 24 metres, connected by massive cross-beams (8.6). Watertight steel caissons eight metres high were prefabricated on shore and launched into the river, to float there while their height was built up to 22 metres. They were sunk by admitting water until they penetrated the river bed. After this they were gradually filled with concrete to displace the water and form a solid foundation, an impressive operation by the contractor, Gammon India (8.6–8.9).

8.7–8.9
Construction of the foundations started in 1978

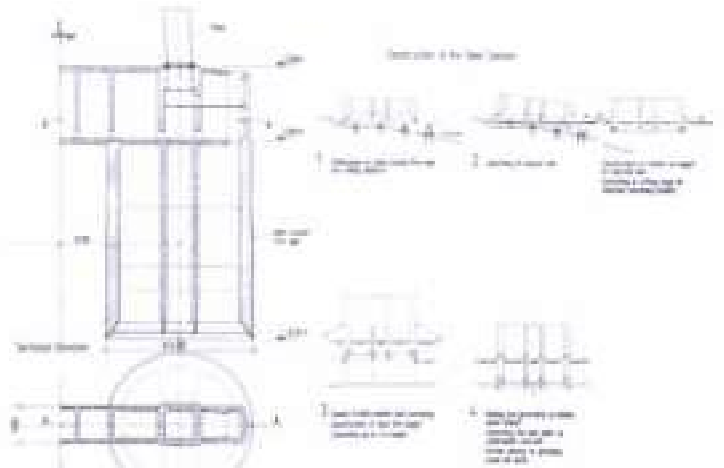
Concreting an end pier well

Launching the steel caisson of a pylon foundation

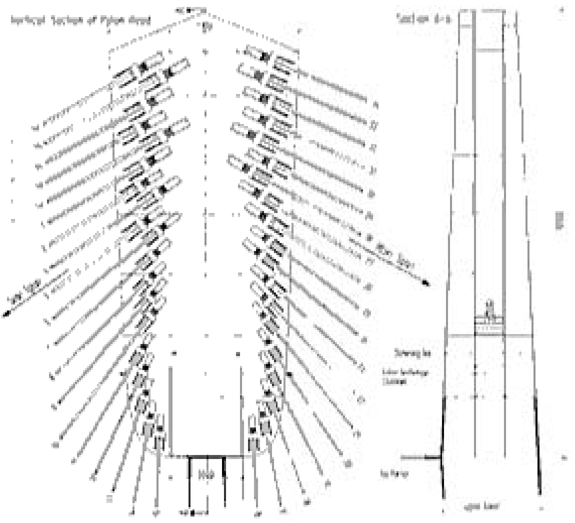
Concreting and sinking a pylon caisson



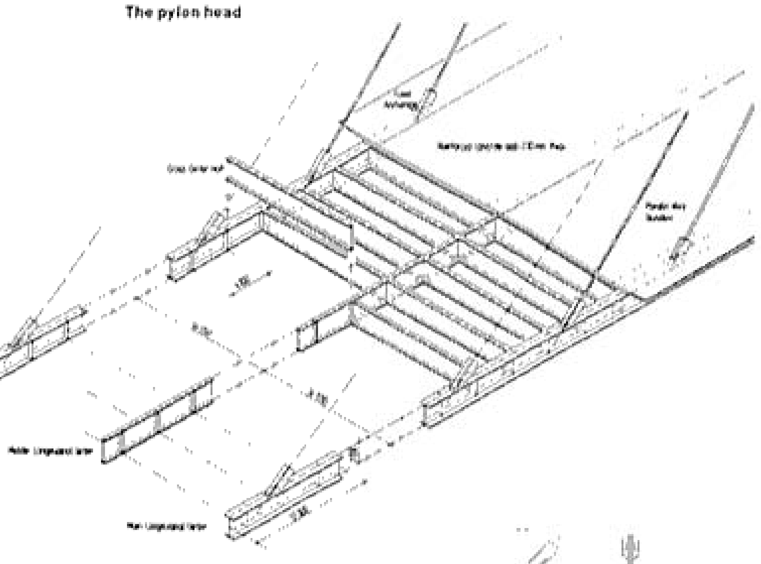
8.5
End piers and means of anchoring the backstay cables (detail see 8.13)



8.6
One of the four pylon foundations. Positioning of the caisson by flotation

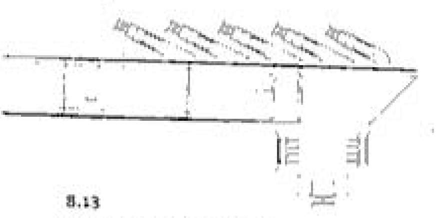


8.10
The pylon head



8.11
Arrangement of the deck – a steel grid with a composite concrete slab

8.12
Anchorage of the supporting stay cables at deck



8.13
Anchorage of the backstay cables at deck

Bridge cables are normally cut to an exact length to ensure that they carry their designed tension once the bridge is complete. However, some minor adjustment is usually needed, and this is done by applying jacks to the ends of the cables. This is a difficult task which can be dangerous in unskilled hands. Conventionally, it is carried out at the ends of the cables where they penetrate the deck and are anchored below it, often from platforms slung alongside or underneath. The work thus occurs at many locations, widely spread along the length of the bridge. Schlaich and Bergermann decided to use a simple fixed anchorage at these points transferring the cable force directly into the web of the I-beams and thus ensuring a smooth flow of forces (Fig 8.11 – 8.13). Because the cables are anchored to simple plate extensions of the webs, which protrude above deck level there is no weakening of the deck, the anchorages are easy to inspect and maintain, and they are well adapted for installation by labour with a medium level of skill. The more complex anchorages for the prestressing of the cables were placed at the top of the mast, in a specially widened housing. This means that the skilled work, and its supervision by engineers, is concentrated in a single location. A projection of the housing in the longitudinal direction solves the problem of anchoring the almost vertical cables that are required next to the pylon to support the deck as it passes through the legs (8.10). The characteristic shape of the housing defined by these functions has been nicknamed "the flowerpot" by Schlaich's close friend René Walther who is himself a highly gifted and experienced designer of cable stayed bridges. Schlaich considers that in addition to its practical advantages, this clearly defined termination of the cables at the pylon legs is better from an aesthetic point of view than the usual direct penetration into a plain box section leg.

Construction of the Hooghly bridge did not start until 1978 and suffered many delays, being finally completed in 1993 (8.14–8.38). To Schlaich's great pleasure, the composite deck system has proved advantageous for cable-stayed bridges in developed economies and has been used by other designers. (An example is the 462-metre Annacis Bridge in Vancouver.) Not surprisingly, he states that Bergermann and he, who carried the main burden of the project in its later years, could write an entire book about the Hooghly project: the initial battles with Freeman Fox over the design and their later friendship; his fights with the local bureaucracy; the battle against corruption; the evolution of the form, and the final design details; and then the lengthy period of construction. The meeting of two different cultures further enlivened proceedings. Engineers from Schlaich Bergermann und Partner, especially Ulrich Dillmann, Hermann Meier, and Ulrich Otto, were based in Calcutta for many years and some of them brought home Indian wives.

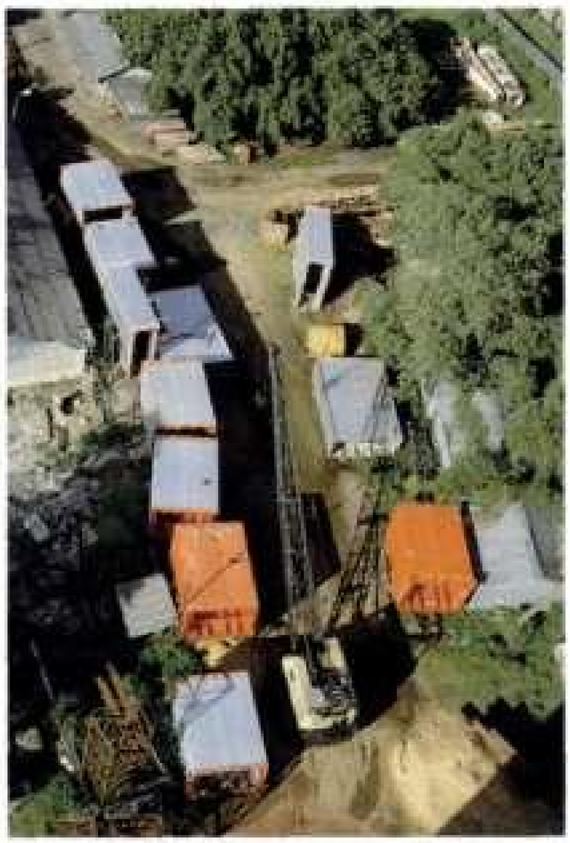
Schlaich took his family to India on many occasions once even all the way by car. He recalls, "we got to know India and got *involved* in the whole third world problem".[2] Amongst the Indians with whom he developed a special relationship was T. N. Subba Rao, one of the contractors on the bridge, who was in 1987 awarded an honorary doctorate by the University of Stuttgart. Sharad Joshi moved to live in Stuttgart for several years and played an active role in the design of the Hooghly bridge. Schlaich has a special love for this structure. He describes it as "a beautiful modern bridge [built] with indigenous third world technology" and declares "if I am proud of anything, and happy above that, then it is this bridge!" In 1993 his entire university Institut travelled to India to give a well-attended course on design of reinforced concrete using the strut-and-tie model.[3]

8.14+8.15
The steel grid of the side spans advances over temporay supports

8.16
Working on the steel grid

A pylon segment in the shop with Ulrich Dillmann in the green hat and Sharad Joshi at left

Pylon base in the workshop



Pylon segments on site as seen from deck level

Pylon assembly using a specially built derrick

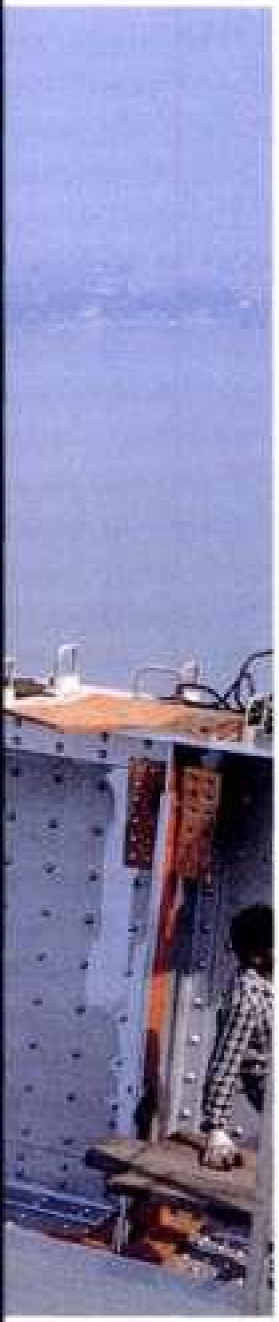
8.17–8.20
Pylon construction

8.21
A Pylon head during construction

8.22–8.30
Scenes of the construction of the main span composite deck

The freely cantilevering spans edge out over the river

Barges deliver segments of the grid to be lifted into position



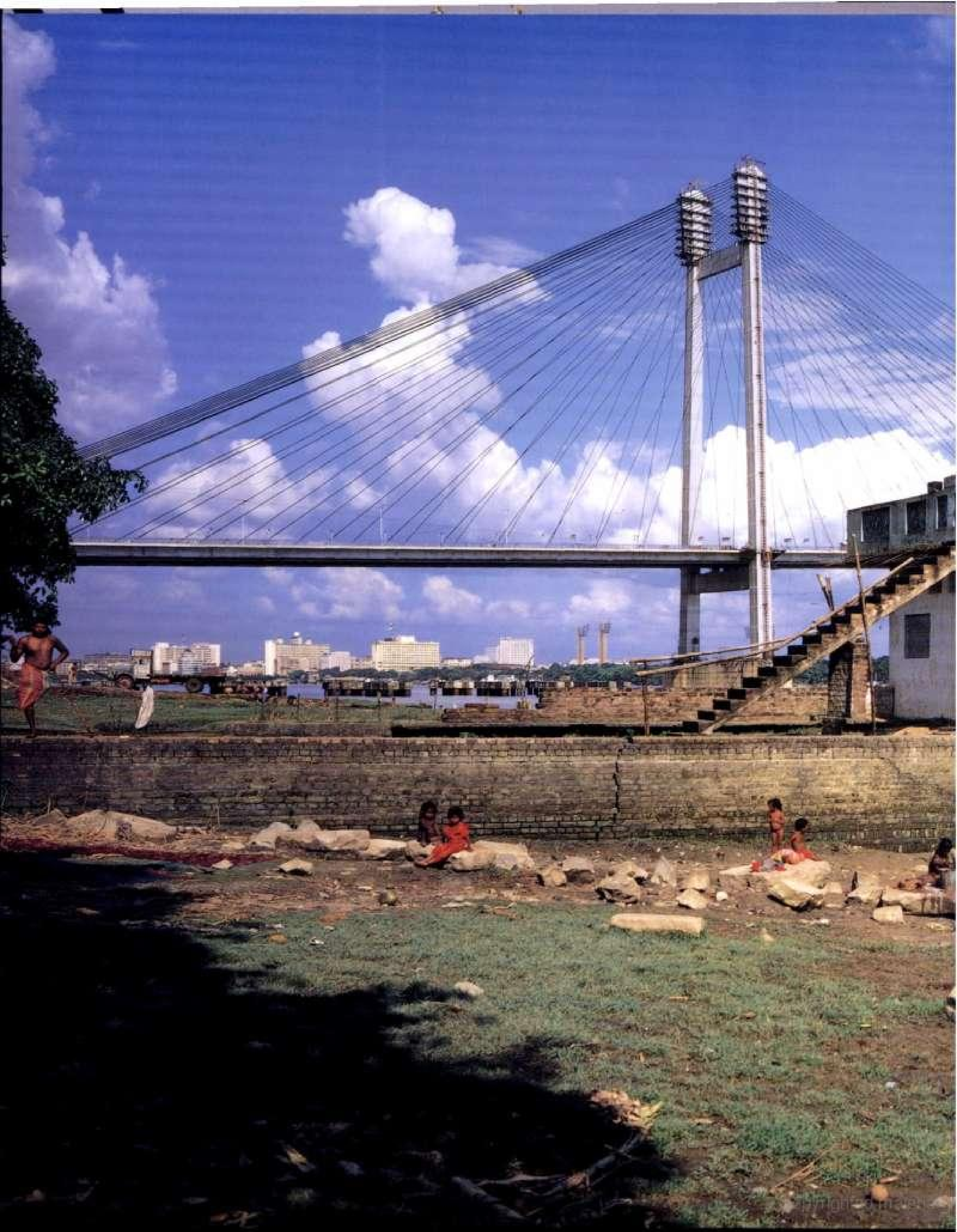
The workers' view of the deck and the river below

A carpenter preparing the formwork for the concrete slab

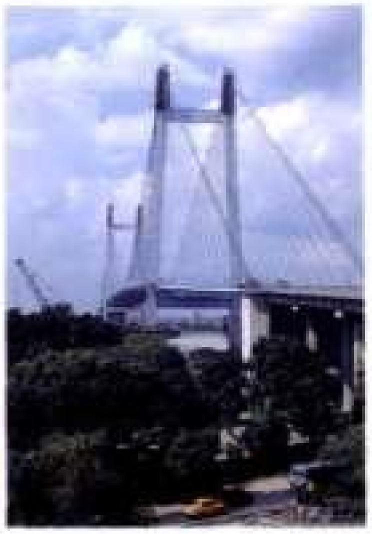
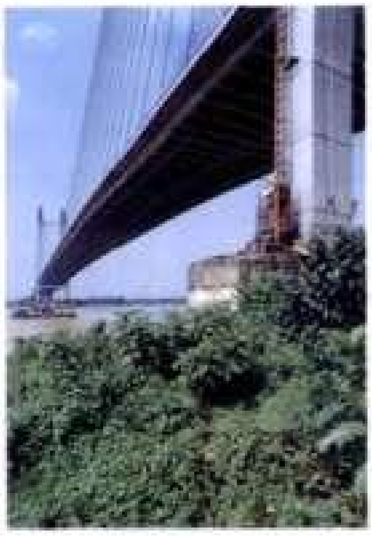
Cable anchorages

Rivetting of a connection in the freely cantilevering main longitudinal girder

R. Bergermann, H. Meier, and their Indian colleagues with a cable specimen delivered for inspection after testing to rupture



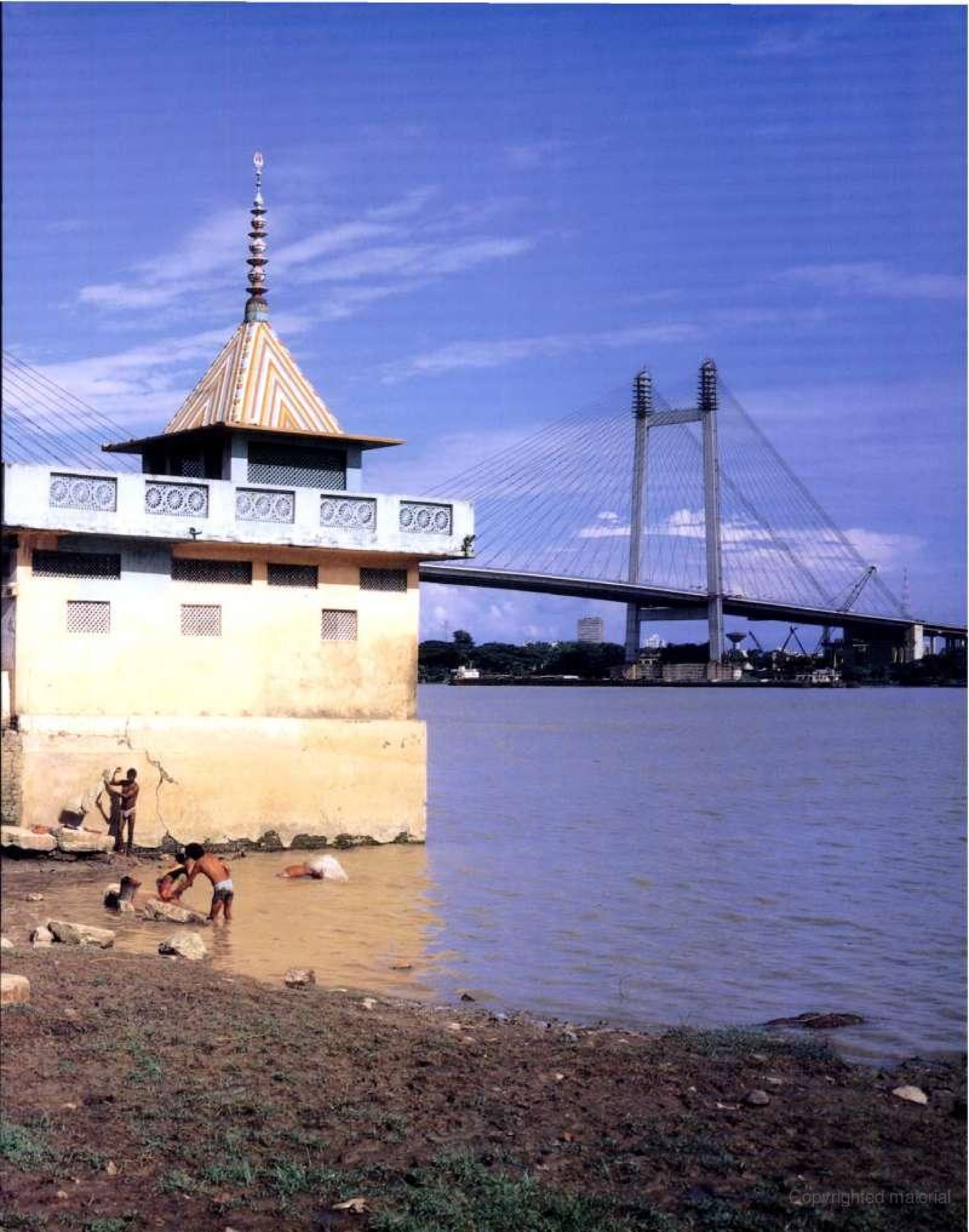


8.32–8.36
The completed bridge

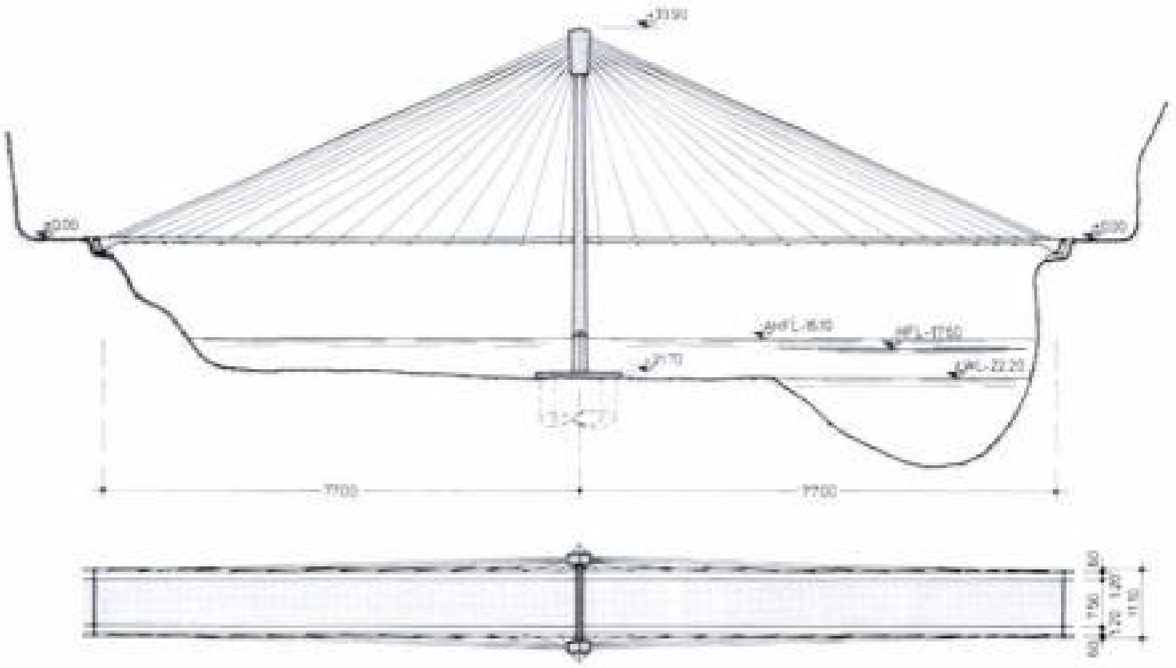
8.37
The heroes of the construction

8.38 (overleaf)
The second Hooghly bridge
in Calcutta

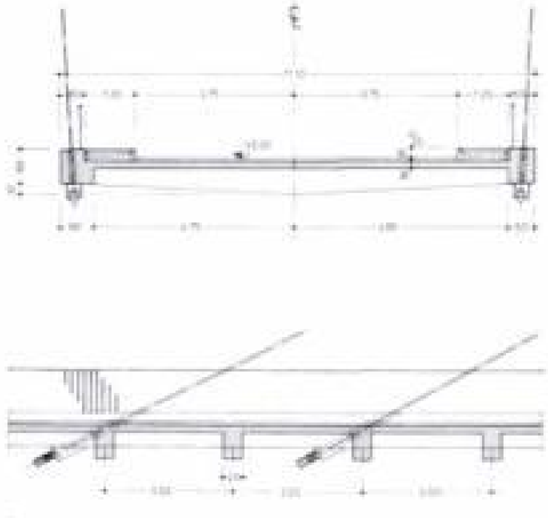


8.39
Akkar: the old suspension bridge sloping and listing heavily under the weight of a truck

In 1980, while the Hooghly saga was in progress, Subba Rao combined with Schlaich to design and build the **Akkar Bridge in Sikkim**, in the Himalayas, replacing the old suspension bridge (8.39). This was after the establishment of the Schlaich Bergermann partnership, and he felt able to take an uninhibited interest in bridge design. The aim in the Akkar project was once again to adapt the relatively advanced concept of the cable-stayed bridge to the special conditions of a third world country – with the added problem of a remote and mountainous location. To avoid the importation of large quantities of high quality steel, the deck and pylons were designed entirely in reinforced concrete: the first cable-stayed bridge of this type in Asia. A special type of cable was required, simple but strong, which could be manufactured in Sikkim. This was developed by Knut Gabriel who, since his involvement in the Munich Olympic roofs, had acquired many years of research experience in cable structures at the Institut in Stuttgart. It consisted of a simple bundle of parallel wires kept in shape by a long lay twist, so that the conventional sheath can be dispensed with. To protect the wires from corrosion, the cables are filled and painted with polyurethane. Connections at the ends are formed by pouring molten zinc into the sockets to fully bond the cables. The design team saw this project as an opportunity to demonstrate the feasibility of concrete cable-stayed bridges in Asia after the frustrating years spent trying to obtain acceptance of the projects for Allahabad and Patna (8.2 + 8.3). The bridge was completed in 1988 (8.40 – 8.47).



8.40
The Akkar Bridge in Sikkim General arrangement



8.41
Transversal and longitudinal section of the deck

8.42 + 8.43
Construction of the deck as balanced cantilevers using simple concreting gantries

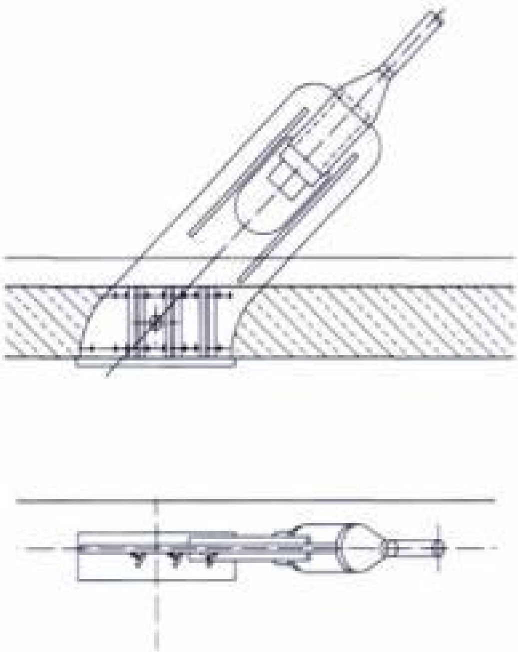
8.44–8.47
Manufacture of the parallel-wire cables on site

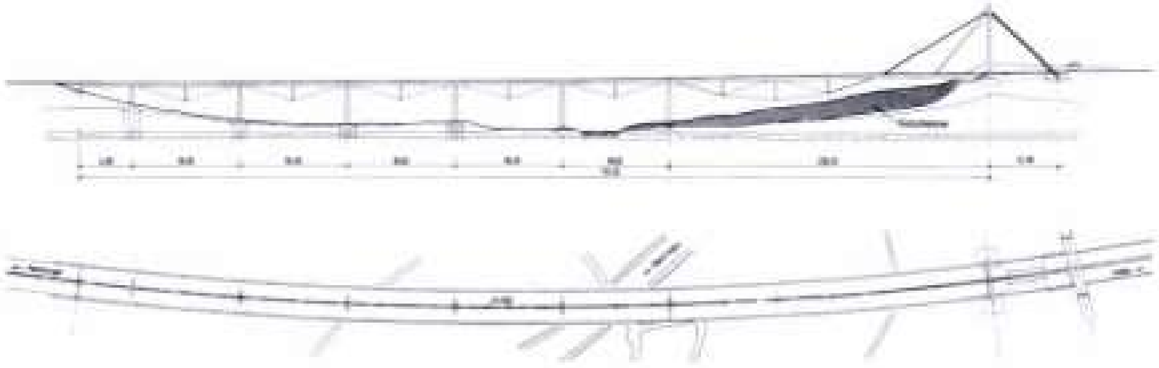
The flexibility of the thin deck permitted further elegance in design. As we have seen, the deck of the Hooghly bridge had been suspended from cables where it passed through the pylons to eliminate the need for sliding bearings and reduce bending stresses. These advantages had been "paid for" by a more complex pylon and an increased number of cables. The Evripos deck was so thin that it could flex more easily over the cross-girder, without developing high stresses. The more simple solution of supporting it directly on the cross-girders was thus indicated. However, this implied the use of sliding bearings which present major problems in maintenance and durability. In Schlaich's opinion, "the best bearing is *no* bearing". The idea was therefore conceived of simply connecting the deck monolithically to the cross-bars and pylon legs and making the pylons sufficiently slender to flex slightly in the direction of the span, thus permitting the movement necessary to accommodate changes in the length of the deck due to temperature change and shrinkage of the concrete. Thus in one stroke the design team was able to provide a system which was simpler, cheaper, and more durable than the conventional. The flexibility of the pylons in the longitudinal direction is carefully judged so that there is still enough stiffness and strength to cope with possible forces due to earthquakes – a major consideration in the design of bridges in Greece. In the other direction they are sufficiently strong to resist lateral forces due to wind load on the bridge. Because the Evripos deck slab was more slender than any yet built, the aerodynamics of the bridge were tested in a wind tunnel to check for the type of flutter which destroyed the Tacoma Narrows bridge.

The solid and flexible concrete slab was constructed together with the cables, starting from the pylons and working in both directions, using the classical free-cantilevering method. Although the contractor had never before built a bridge, this task was completed without problems. With the dedicated and practically-minded Andreas Keil as project engineer (now the youngest partner in the practice) the bridge was completed in 1992 (8.54–8.56). Schlaich sees this design as "the ultimate in simplification" and thus a major step forward in the partnership's quest to demonstrate that the cable-stayed bridge may one day prove to be the standard solution for developing countries such as India.

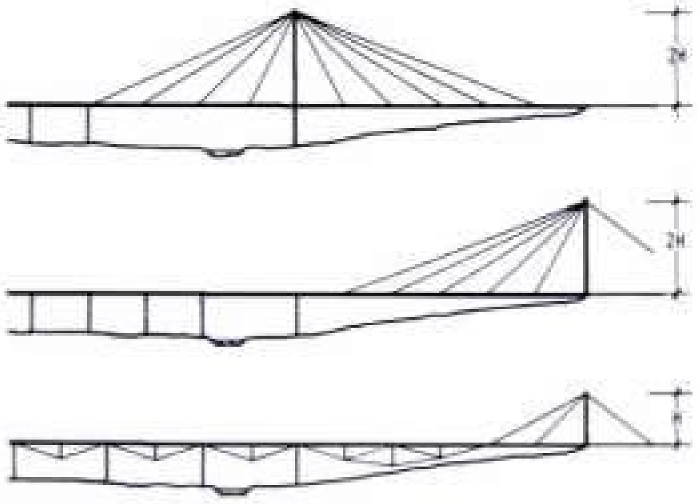
8.54–8.56
Views of Evripos bridge during free cantilevering construction and after completion in 1992

8.52 + 8.53
The cable anchorage at the deck



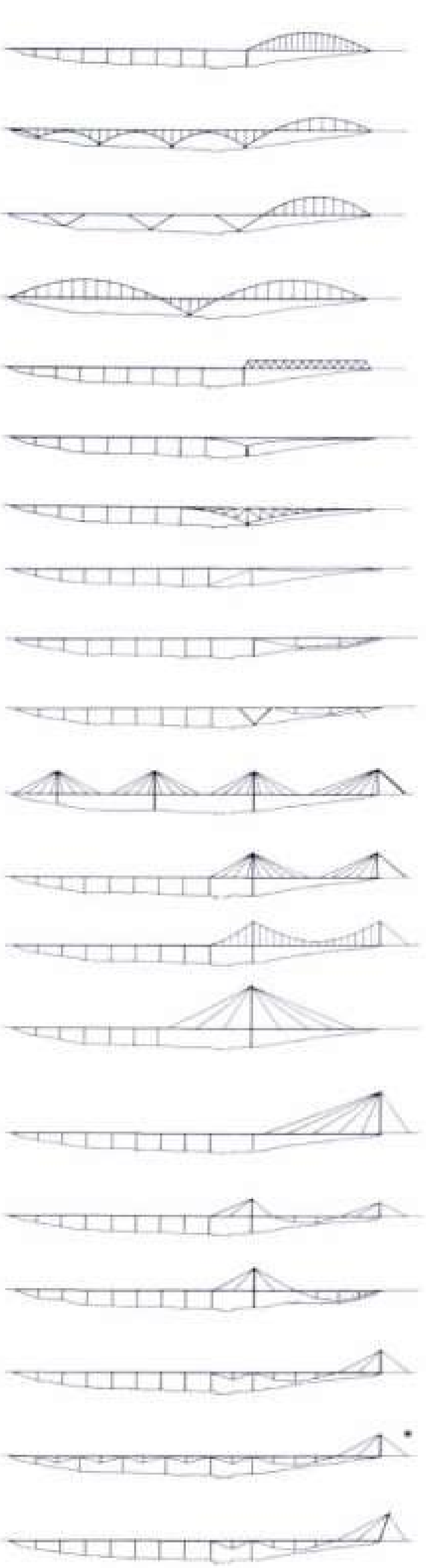


8.58
The proposal as submitted for the competition

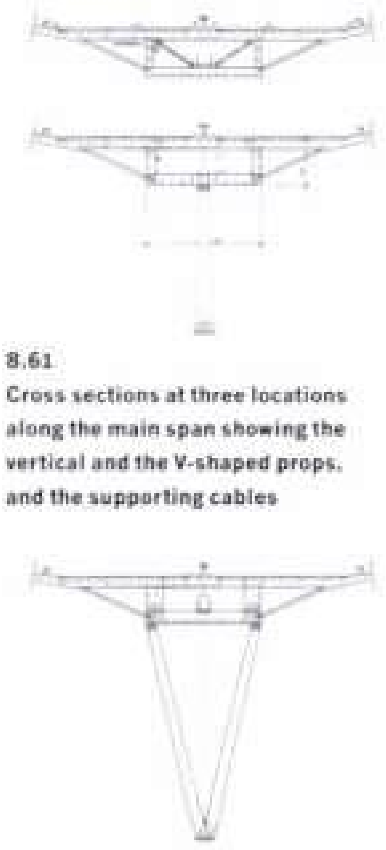


8.59
A study of alternative pylon locations and cable arrangements, and their influence on the height of the pylon. The combination of cable staying from above and propping from below (lowest diagram) halves the pylon height without increasing the cable forces

priate to place a heavily-loaded pylon at this end. The best solution was to suspend all the cables from a single pylon situated on the crest of the southern slope. Now, the forces generated in a cable-stayed bridge increase as the slope of the cables decreases, and the overall costs are roughly related to the magnitude of the forces. The mast of a single-pylon bridge should therefore be twice as high as the masts of a two-pylon bridge to keep the slope of the cables and thus the costs the same. However, this would have necessitated a mast projecting from the valley far above the trees and visually dominating the sensitive location (8.59). Once again the designers found that external factors were forcing them into a situation where the height of the structure must be less than the engineering optimum. To add to the difficulties, they were faced with the then novel problem of designing a cable-stayed bridge with a horizontally curved deck. Although the 3000-metre radius suggests a fairly gentle curve, it meant that the end of the bridge would be displaced 11 metres to the side of a line drawn straight through the portal of the pylon. However, as we shall see in the discussion of the partnership's footbridges, they find great satisfaction in tackling complex three-dimensional problems of this type.



8.60
The range of alternative solutions studied for the Obere Argen crossing



8.61
Cross sections at three locations along the main span showing the vertical and the V-shaped props, and the supporting cables

8.62
The inverted saddles at the lower end of the vertical and the V-shaped props

The eventual solution for the bridge was influenced by the design of the shorter viaduct spans on the northern side. Here, the designers' concern for the environment and their taste for minimalism and lightness led them to advocate a "trussed girder" form of construction (8.58). A span of 86 metres was chosen, using a single-cell hollow steel box for the superstructure, and enhancing its resistance to bending with a single underslung cable and prop. The latter provides a form of somewhat soft support to the middle of the girder dividing its span into two 43-metre intervals. The main span of the bridge was then set at 258 metres (a multiple of 86 and 43) so that it would be possible to use the same single-cell box deck by providing some form of support at the standard 43-metre intervals. This was achieved by running a cable under the length of the deck, starting at the end furthest from the pylon, to support three props with the desired spacing. From its lowest point the cable follows the natural slope as it begins to rise towards the mast. Where it passes through deck level it provides a fourth support. The fifth point is supported by a separate, conventional cable attached directly to the pylon head. With this solution, it became possible to use a low single pylon without incurring the penalty of increased forces in cables and deck (8.59). The single, centrally-placed cable and props proved well adapted to the three-dimensional play of forces. Because of the curvature, the main cables pull slightly to one side, producing lateral forces on the pylon. The pylon therefore has the form of a letter A which provides better resistance than the conventional H or portal shape (8.57 and 8.63). For the same reason a V-shaped prop was used under the deck of the main span, 86 metres from its far end (8.61).

Schlaich is content that the team achieved an overall design with a "continuous logic and rhythm" and avoided, in this location, the extensive fan of cables seen in conventional cable-stayed bridges. Only two cables and one back stay appear above deck level, discreetly close to the southern slope and pylon (8.63). Thus an overall impression of discretion, lightness and elegance is achieved in elevation. The deck of the bridge is identical to that of the northern viaduct thus ensuring visual continuity and harmony. The motorist, not really expecting a bridge because the shallow and flat valley is almost completely filled with trees, receives only a fleeting impression of an architectural (or structural) event on passing through the pylon. The hiker in the valley below is not disturbed by the many piers of a conventional viaduct and is, Schlaich hopes, reassured by the evident structural logic and discretion of the cable-propped girder.

The partnership won first prize for this design against competition which included Leonhardt und Andrä. Schlaich notes that he felt a mixture of pleasure and embarrassment at this success, recognizing that he owed much to his former partners in terms of his professional development. However, he feels that such situations can hardly be avoided. (This has been confirmed now that some of his own protegees have left him and are competing against *him* in a similar successful fashion!) He feels that this process is essential to the education of new generations of designers, but because of the unavoidable friction of such transitions it must remain a very special issue within the profession.

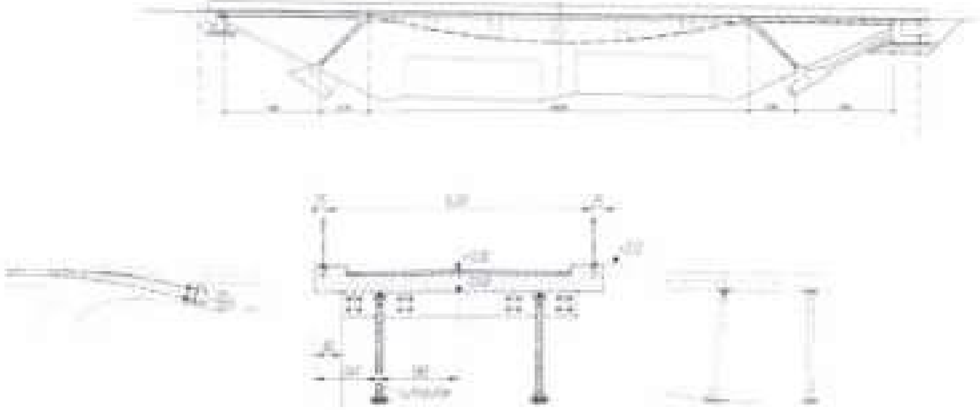
Unfortunately, the design was not to be realized as Schlaich and Bergermann had planned. Having awarded the prize, the *Verkehrsministerium* demanded significant changes. It is their policy that, wherever possible, the dual carriageways of the autobahns should be carried over bridges and viaducts on parallel and completely separate structures. The reason is that, if major maintenance or replacement works become necessary, it will be possible to direct traffic over one of the structures while the other is repaired or even replaced. The design team strongly defended their original concept, but the authority insisted on a re-design of the approach viaducts in the form of duplicate carriageways which were to be supported on conventional prestressed concrete box girders to achieve a certain economy by use of the "incremental launching" technique. It was agreed, however, that the original design should be retained for the main span. The designers felt that the homogeneity and lightness of the original concept had been lost, but the authorities argued ("rightly" as Schlaich had to admit) that due to the topography and the cover of the large trees, the bridge would never be seen as a whole; that from a distance, and for the motorist, the final design would appear no different from the original; and that only hikers close to it would be troubled by the increased number of piers.

Hans Kammerer, who was a member of the jury, was consulted as architectural adviser to alleviate the resulting aesthetic problems. He had considerable experience with bridges, especially in co-operation with Leonhardt in the design of a propped-girder bridge over the Neckar at Weitingen. However, he could do little more than assist in solving the problem of the formal transition from the single steel hollow box to the dual prestressed concrete girders.

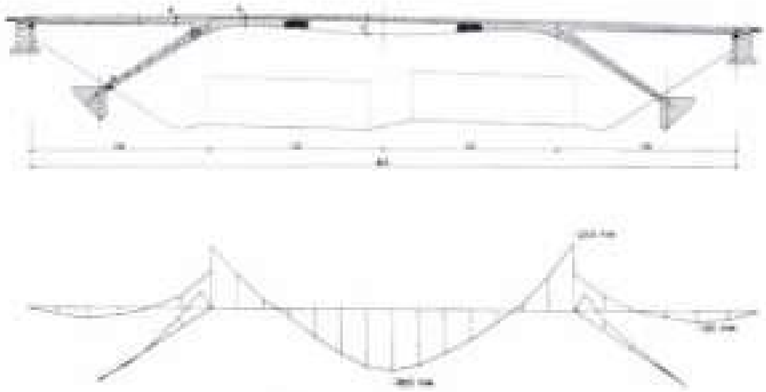
During the construction period, the complexity of the structure and the multi-national nature of the contracting team exacerbated the difficulties of cooperation between designer, client, and contractor. (Contract conditions and professional practices differ significantly from one country to another.) The contractor decided to diverge from the method of prestressing for which the designers had made provision, and a representative is quoted as stating that the bridge was "more difficult" than had been expected.[7] The resulting problems and cost overrun were unfortunate at a time when Schlaich and Bergermann were attempting to persuade German road and rail authorities to adopt a less conservative approach to the design of bridges. Despite these problems, they are happy with its overall conception. Schlaich writes that the propped girder solution makes the load-bearing behaviour evident to the observer. It appears lighter in comparison to a solid-web girder and appeals to the intellect. "We accept what we understand, and find agreeable what appears light."[8] He argues that we expect the form of a certain type of structure (in this case the cable-stayed bridge) to be modified to suit differing situations and requirements, and that we take an intellectual delight in the way the designer has responded to this challenge. He describes Obere Argen as "certainly a novel design, showing that difficult constraints offer opportunities for innovations". Jürgen Seidel, at that time a partner in the practice but recently appointed Professor at Munich, handled this difficult job. The bridge was opened to the public in 1990.

Schlaich was particularly concerned by the fact that such a complex bridge would not have been necessary if the traffic engineers had fully appreciated the problems posed by the instability of the southern slope. Having fixed the location of the road on the assumption that a conventional viaduct could be built, they committed the structural engineers to a complex and costly solution. This experience encouraged him and his colleagues to establish an interdisciplinary research team devoted to developing an holistic view of structural design.

8.63
The Obere Argen crossing in its environment. The conventional part starts at the right end of the picture



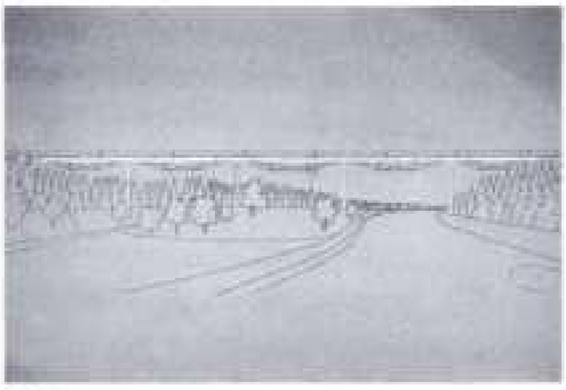
8.64
The original cable-supported scheme for the Kirchheim overpass



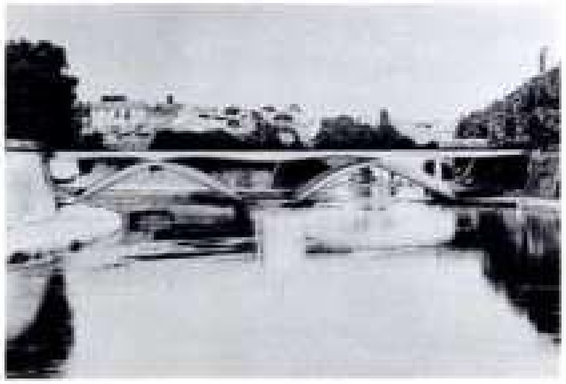
8.65
The prestressed concrete version overpass as built. Comparison of bending moment diagram and form of the bridge

As can be seen in his design for the Obere Argen bridge, Schlaich is fascinated by the technical and aesthetic qualities of the cable-supported girder (8.66). He sees this as a more efficient form of external prestressing than the common one (popular in France) where the cables are enclosed within a box-girder and are therefore limited in the distance to which they can descend below deck level and provide the leverage to resist high bending moments. He was encouraged by the fact that his colleague and friend Christian Menn had independently started research on this system at the ETH in Zurich and had clearly confirmed its efficiency.

Feeling that motorway **overpass** bridges urgently needed more variety and that this system could be one possible approach, he had held discussions with the state road authorities for some four years, urging them to let his office design one for them. Finally in 1987 the chief engineer E. Hoffmann announced that he had found a suitable opportunity in the widening of the autobahn near **Kirchheim**. The freeway here passes through a cutting, and a new farm access bridge was to be provided linking the fields on either side. The situation gave ample clearance over the road for the cables. The office therefore prepared a design in which inward-sloping legs supported a central span of about 42 metres (8.64). The deck was to be a solid slab only 40 cm in depth, stayed by two underslung cables each supporting five short props. The cables would be well clear of the legal limit on the height of lorry loads. Rosemarie Wagner, who had received her doctorate at the Institut working on just such "hybrid structures", was heavily involved in the design which was worked out in full detail.



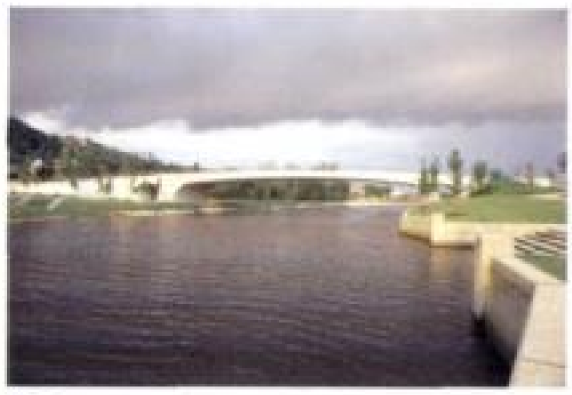
8.66
A design for a cable-supported rail bridge at Munich (1982)



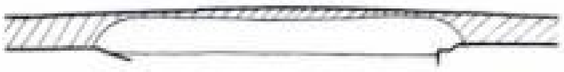
8.67
Myron Goldsmith's design for a bridge across the Tiber in Rome. Schlaich notes that this has been his "dream bridge" since Goldsmith gave him the photograph and all the drawings in 1955

8.70
The Kelheim Westtangente bridge during construction – general view

8.71
Falsework and formwork for the pedestrian tunnels through the abutments



8.72
Kelheim Westtangente: views of the completed bridge



8.73
A portal bridge shaped according to the bending moment diagram

The recently-completed canal joining the rivers Rhine, Main, and Danube passes along the former course of a stream called the Altmühl which ran by the old walls of **Kelheim** in Bavaria. The construction of the canal interrupted the former lines of communication, and a need arose for a new bridge to carry diverted traffic around the town centre on a by-pass road known as the **Westtangente**. Schlaich Bergermann and Ackermann und Partner were engaged as consultants because of the success of the suspension bridge which they had designed for a pedestrian crossing outside the town gate (Chapter 9). As in all overpass bridges, there were conflicting needs to provide adequate clearance underneath the deck and at the same time minimize the level of the road surface to limit the cost of the approach road embankments. Thus the economically optimum design would have a deck much more slender than usual. Conventional beam bridges were ruled out.

The design team prepared several structurally efficient designs including cable-stayed versions with slender decks, but the authorities were reluctant to accept any kind of superstructure above deck level. The team finally responded with a structure which in outward form is somewhat like a classic arched canal bridge, but structurally acts more as a frame composed of a slender prestressed deck cantilevering from heavy, integrated abutments (8.70–8.72). In this way it was possible to keep the depth of the deck to a mere 1.5 metres at the centre. The deck structure is a shallow hollow box with four compartments separated by three relatively wide webs. The total clear span is about 70 metres on the skew.

Although the massive appearance of the abutments is somewhat reduced by the circular pedestrian tunnels provided for the "towpaths", their weight and solidity conflicts with Schlaich's normal technical and aesthetic aims. He tried to improve its form by shaping it, as later in Kirchheim, according to the bending moment diagram, thus reducing its dead load and simultaneously adapting it better to the requirements for shipping clearance. However, this "pigbelly girder" was firmly rejected by Ackermann (8.73).

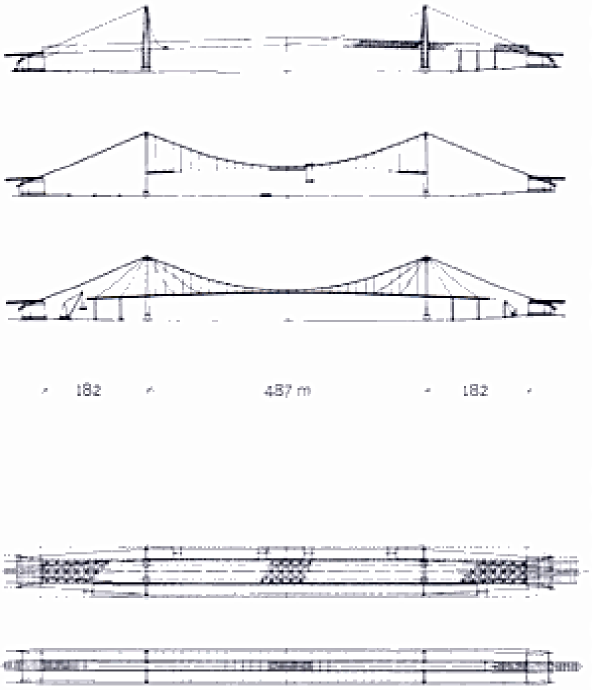
Schlaich finds comfort in the appealing sculptural qualities of the bridge as finally built, particularly the interesting visual effects created by the fact that the tunnels are skew to the abutments. He is also content with the extreme slenderness achieved in the deck and particularly with the fact that this is a bridge without any moveable bearing or expansion joint, making use of recent knowledge about the ductility of structural concrete, including what is technically described as its "softening" after forming hairline cracks. Nevertheless, he feels that this and Kirchheim is "at best a beginning, and not yet a satisfactory conclusion" of this line of development.

The project for the bridge over **Kämpfelbach near Pforzheim** is somewhat hard to place in the context of the office's other designs, but it is certainly close to Schlaich's heart. In the late 1980s, it became necessary to replace an existing bridge at the site to permit widening of the Stuttgart-Karlsruhe autobahn. As usual, two parallel structures were demanded, one for each carriageway. The freeway would at this point pass over a shallow valley containing a state highway and two railway lines. It would thus be a major feature in the landscape as seen from the local road. At the request of the City of Pforzheim, the Landesamt für Straßenwesen organized a competition amongst six selected design offices based in Stuttgart, including Schlaich Bergermann und Partner.

As usual, the team's main objective was to make the bridge as lightweight and unintrusive as possible. They rejected the idea of using an arch above the deck or a suspension system because, to motorists on the lower road, these would have had a "monumental" appearance, towering over the already elevated deck. Furthermore, they felt it would be hard to locate the four pylons needed for cable-supported decks on the tops of the embankments without giving the impression that they had been arbitrarily speared into the landscape. The proportions of the space beneath the decks posed further problems. The underside of the decks would be 36 metres above the lower road, while their combined width (in the direction of this road) would be 41 metres. The team felt that their

The bridge was to be built in two parallel halves, as though split down the middle, so that the old bridge could continue to function as long as possible during the construction period. The two halves would be built either side of the existing bridge without interrupting traffic, and then – within a few days – slid sideways into position after the old bridge had been dismantled. In their final position they would remain slightly apart and the intervening space would be covered by transparent grid-like decks which would support the rails for trains. This solution was conceived also because of its favourable aerodynamic characteristics.

Unfortunately, because of the financial problems of the city of New York, it has been necessary to shelve the project indefinitely and to repair the existing bridge.



After construction of the new pylons alongside the old bridge, the new main cable would be hung

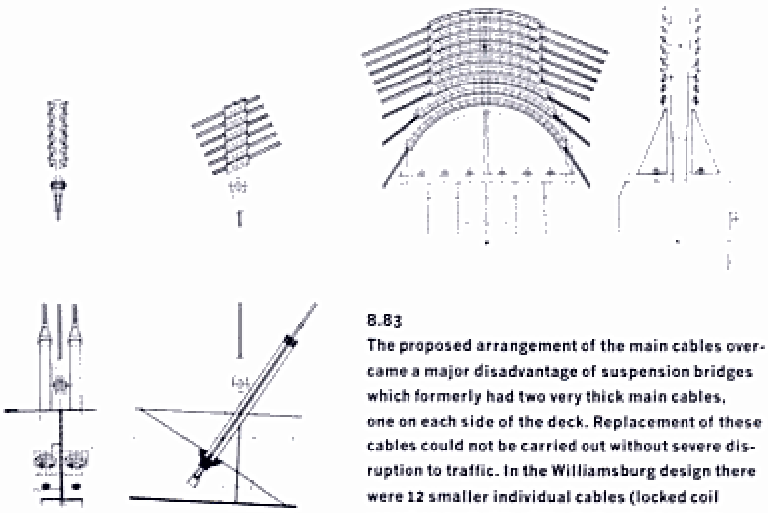
Sections of the girders for the new deck would be floated out and suspended at mid-span

Construction of the new deck for the side spans including installation of the inclined stay cables

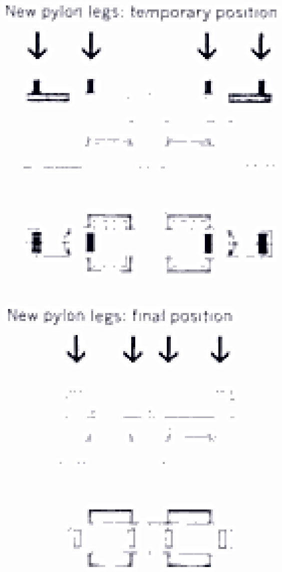
Plan of the two halves of the new bridge either side of the old, with the new main cables deviated and already attached to the old anchor blocks (8.85)

Plan of the completed new bridge. After the old bridge *had* been dismantled and the new halves slid into position the cables would have been straight

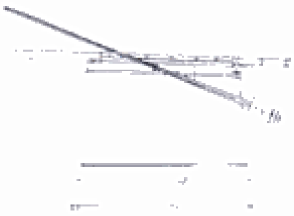
8.82
Construction procedure with minimum traffic interruption



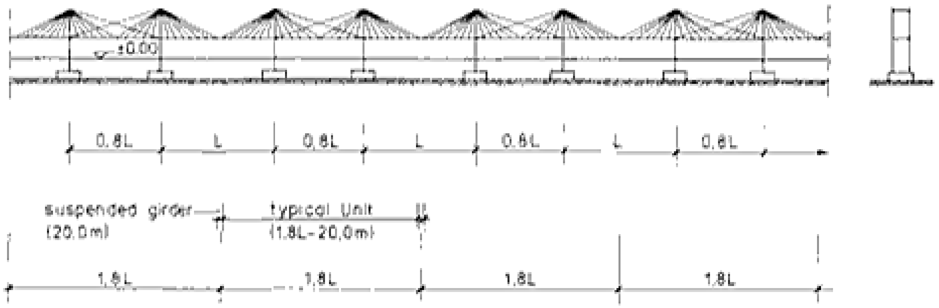
8.83
The proposed arrangement of the main cables overcame a major disadvantage of suspension bridges which formerly had two very thick main cables, one on each side of the deck. Replacement of these cables could not be carried out without severe disruption to traffic. In the Williamsburg design there were 12 smaller individual cables (locked coil ropes) on each side of the deck so that a single cable could be removed and replaced if necessary with a temporary loss of only one twelfth of the total strength, allowing normal traffic flow. Other advantages were that the main "cable" would appear transparent and lighter, and that the same type cables which make up the main cable could also be used for the hangers and inclined stays



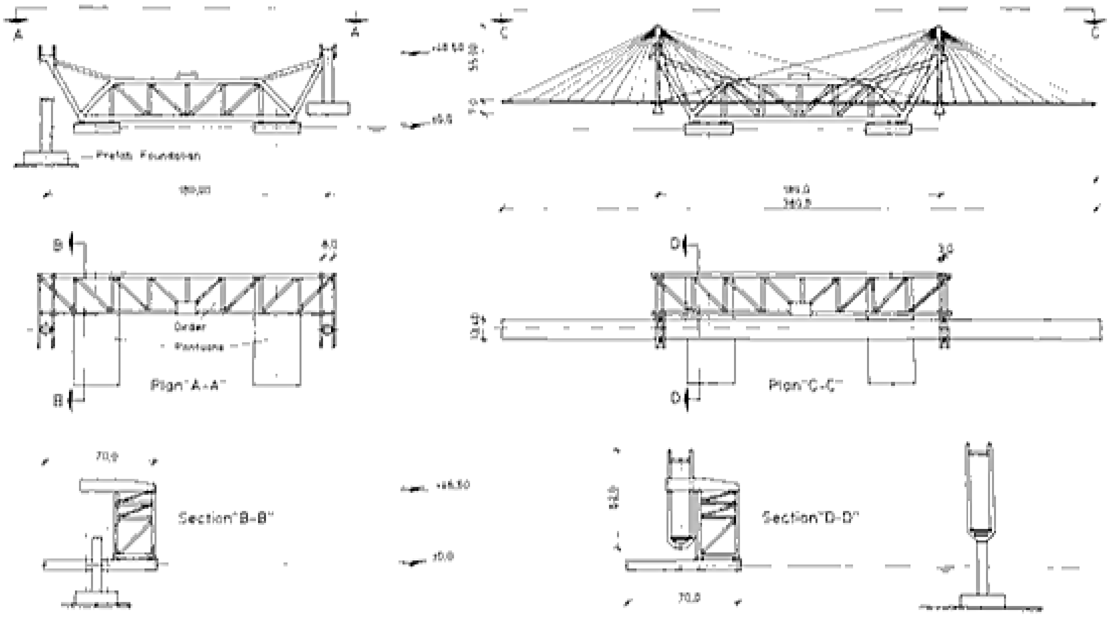
8.84
The proposed design of the re-use of the existing foundations for the pylons



8.85
The new main cables rest on the back of the old anchor blocks



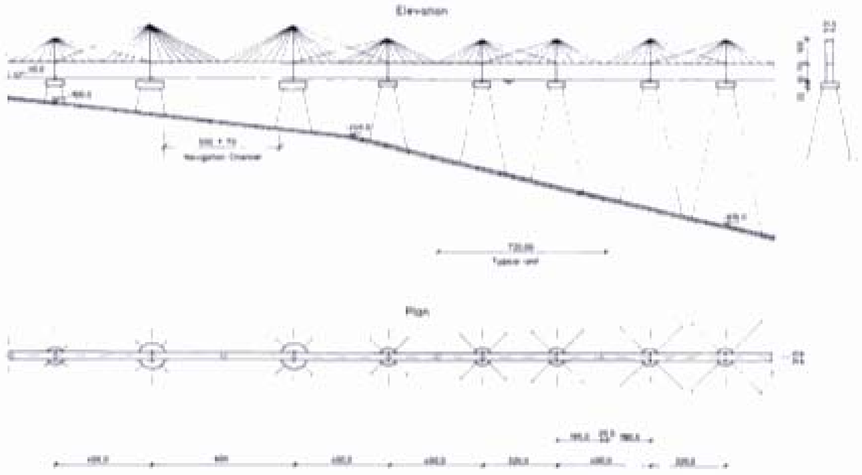
8.86
Prince Edward Island Link, cable stayed bridge proposal L + 0.8L = 400 m (not built)



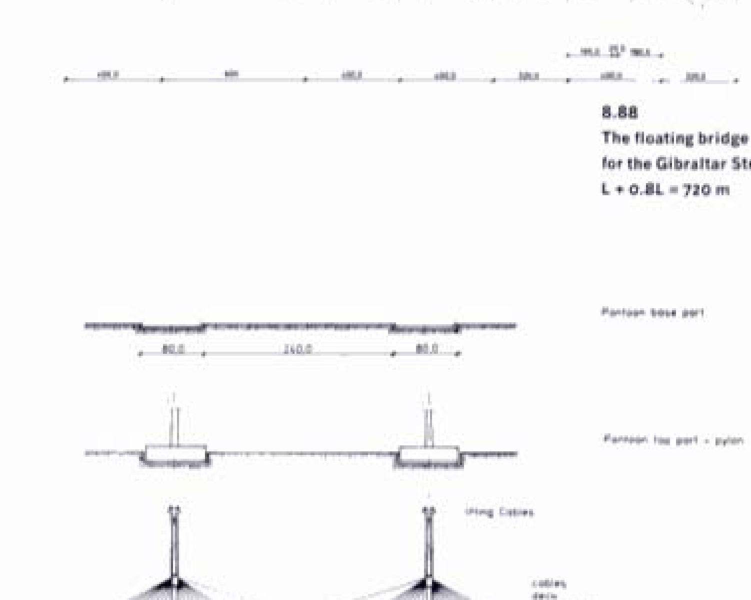
Elevation Pier Placing Rig

Elevation Bridge Erection Rig

8.87
Proposed construction procedure

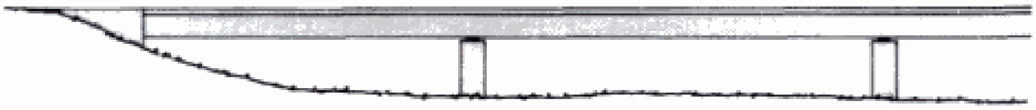


8.88
The floating bridge proposal for the Gibraltar Straits Crossing L + 0.8L = 720 m

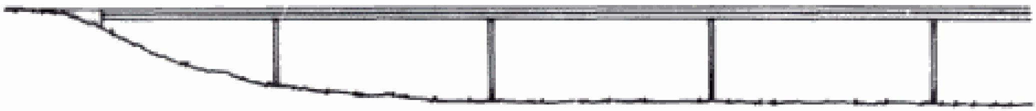


8.89
Proposed construction procedure

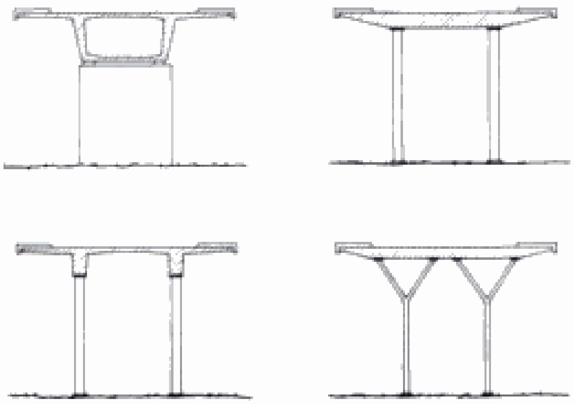
In a proposal for a 12 km **crossing to link Prince Edward Island** in Canada to the mainland (8.86), Schlaich and Bergermann revived the ideas developed for the two Ganges bridges in India dating back to the 1960s. The Allahabad design of Leonhardt (8.2) had been somewhat similar to Morandi's Lake Maracaibo Bridge in Venezuela, though much smaller and simpler and involved repeated units, each carrying two cable-supported cantilevering arms. In the Maracaibo and Allahabad designs, the legs of the pylons were spread in the direction of the spans in order to cater for the overturning effect when traffic was accumulated on only one of the arms. In their design for Patna in 1971, Schlaich and Joshi realised that stability in this direction could be achieved more simply by means of cables running from the top of each pylon and attached to the adjacent pylons at deck level (8.3). This had obviated the need for expensive splayed legs. An additional idea for Prince Edward Island, worked out in conjunction with Lavalin of Montreal, was to prefabricate 380-metre-long segments of deck and use a floating crane to lift them into position, so as to be able to build the bridge during the short period when the crossing is free of ice (8.87). That such ideas make sense was recently demonstrated by the construction of the Western Storebelt Bridge in Denmark. Schlaich and Berger-mann developed these ideas even further in a proposal for a **crossing of the Strait of Gibraltar**. The basic concept is similar, but the pylons in this case were to be mounted on their final submerged caissons, which would serve as pontoons and, after being floated with the 700-metre-bridge unit on top in their final position, would be anchored with cables to the seabed (8.88 + 8.89).



8.90 + 8.91
It makes no sense to exaggerate spans, especially for low-level bridges close to the ground



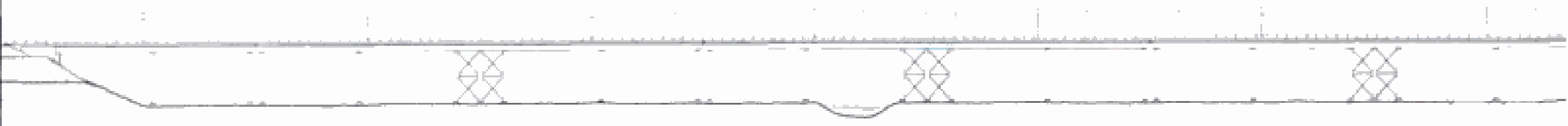
8.92
Shorter spans make it possible to reduce the depth of the deck, permitting the use of open sections, while flexible steel columns eliminate the need for bearings



8.93
Typical cross-section of a standard box girder bridge (8.90) and of short span bridges (8.92)

As a result of the construction of new lines for **high-speed trains**, the Bundesbahn has become involved in the design of many new rail bridges and viaducts.[12] For much of their length the new lines must be elevated only a few metres above the surrounding fields. Traditionally this has been achieved by placing the lines on earth embankments, but these form a continuous barrier across the countryside. There has therefore been a tendency in recent decades to use heavy prestressed concrete box girders resting on squat piers (8.90 + 8.91). Schlaich feels, predictably, that there is no need for such solidity of construction. He has argued his case forcefully through a number of channels.[13]

The design of the concrete **viaducts** is greatly influenced by the longitudinal expansion and contraction of the deck due to temperature change. Expansion joints must be provided – the very minimum being a single joint at one abutment. However, if long lengths of deck are made continuous, a large amount of movement is concentrated at a small number of joints. It is then difficult to make provision for this in the design of the rails and their immediate supports. The traditional solution was to provide an expansion joint at every pier so that limited movement would occur at a large number of joints. The technical "cost" of this solution was that the girders spanned simply from pier to pier and the bending stresses were higher than they would be in a continuous structure, thus requiring a deep girder. Also, each pier must alone resist the horizontal braking and acceleration forces caused by vehicles on the girder which was attached to it. In recent years the number of joints has been reduced to every third pier, thus relieving the problem but not really solving it.

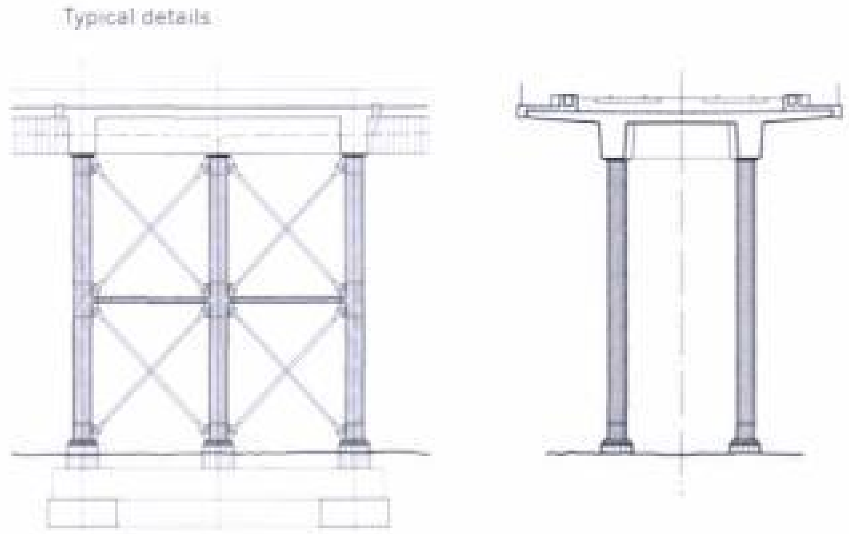


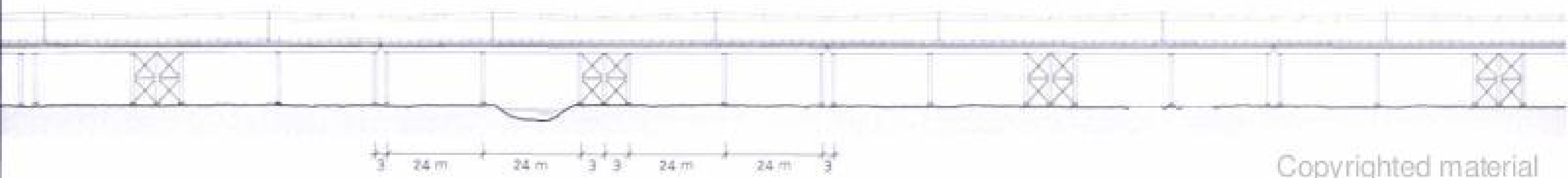
Further problems arise because the massive boxes must be cast in stages. The "floor" is cast first and hardens. Then the walls are added, and finally the deck. Each new portion shrinks after casting and tries to draw the previously-hardened portion with it. The latter is unable to follow this movement completely and so tension cracks are liable to develop in the new concrete. These must be controlled by heavy local reinforcement. Thus the massive nature of the boxes causes the material, in a manner of speaking, to work against itself. Although such situations cannot always be avoided, they offend the engineer's sense of what is appropriate and logical in structural form and highlight a need for drastic revision in design thinking.

Schlaich's counter-proposal to achieve a more lightweight and transparent structural solution starts with the fact that at low heights the spans may also be small, say half of the now standard 44 metres, and that the girders must be made continuous over a limited number of spans to reduce bending moments (8.92 + 8.93). These two measures permit the use of girders at least twice as slender and with open double-T cross sections, the webs supported directly by thin steel columns, thus eliminating torsion (8.94 – 8.97). The braking forces may then be transmitted horizontally to a steel trestle situated at the middle of each unit. All other piers in the section may be made as slender as possible, so that they can flex to follow the movements of the deck. The result is a highly transparent structure which ensures minimal intrusion in the visual environment. Hans Schober was responsible for working out this proposal with the help of Otl Aicher, a graphic designer and inventor of the logos of companies such as Braun, Lufthansa, and Erco. Aicher was an admired friend of Schlaich and teacher of his daughter Sibylle, the graphic-designer of this book, and his recent death following a traffic accident was a sad loss.

Artist's comparison of a bridge as presently built and as proposed

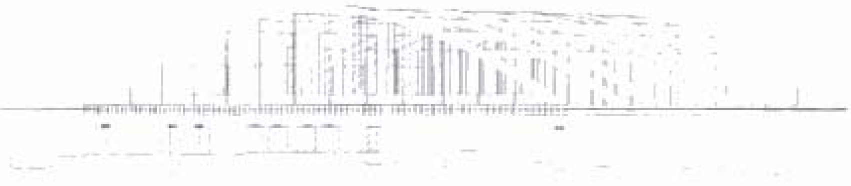
8.94 – 8.97
Proposals for bridges for the high-speed rail network with steel trestles and double columns at the joints (one pair each side of the joint)





Another interesting rail bridge in hand at the time of writing is the **Havel Bridge in Berlin**. This is a skew seven-track bridge of only 80 metres span – almost as wide as it is long. The original proposal was to use a series of tied arches side by side. The tied arch is in principle a visually "clean" structure, but when it was applied in this situation the result was a jungle of steel struts (8.98). The alternative proposal of Schlaich, a continuous girder with the height of the webs varying in accordance with the bending moments, makes a theme out of this "addition on the skew" (8.99) and may have a chance to be built thanks to the strong support of Heinz Durr, the president of the German Railroads and of M. von Gerkan, the architect of the adjacent Spandau railway station, on which they are working together. Hans Schober, Thomas Moschner and Jan Knippers are taking care of these projects.

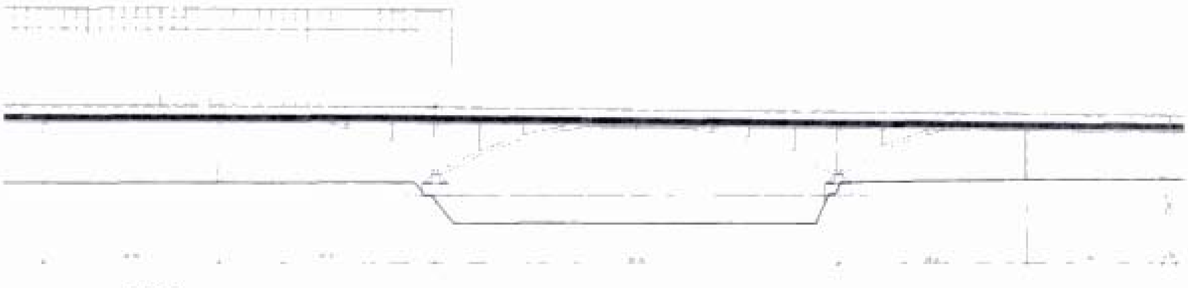
With the same architect, they are working on the Lehrter Bahnhof project at Berlin. This includes a seven-lane **railbridge over the Humboldthafen** which is to have a concrete deck supported on steel arches with cast steel nodes (8.100).



The initial proposal

The alternative proposal

8.98 + 8.99
The rail bridge over the Havel in Berlin

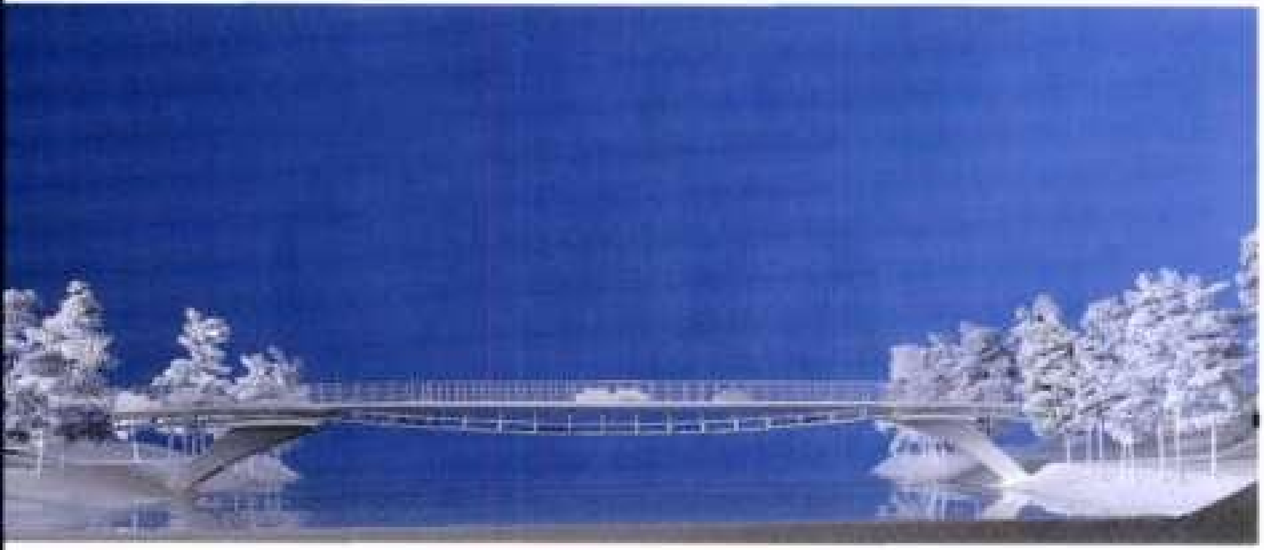


8.100
The rail bridge over the Humboldthafen adjacent to the Lehrter Bahnhof in Berlin (see 6.51–6.53)

As mentioned in Chapter 2, Schlaich was for many years a strong advocate of design competitions for bridges and other utilitarian structures, in the hope of inducing a more creative approach amongst engineers. Partly as a result of his efforts such competitions became popular in Germany in the early 1990s. Schlaich und Bergermann submitted a number of bridge designs, including projects at Schornbachtal (8.101), Wieslauftal, Heilbronn and Mannheim (8.102). It is ironic that the juries generally chose more conservative proposals. However, there have been successes on two recent occasions.

In January 1994 the partnership won a competition for another **bridge at Ingolstadt**, crossing the Danube and passing through beautiful parkland. Schlaich worked on this design with his son Mike Schlaich, also a structural engineer, who after studying in Zurich and working in Spain, recently joined the office for this auspicious start in company with Michael Werwigk. The engineers work in conjunction with Kurt Ackermann and the landscape architect Peter Kluska (8.103 + 8.104).

8.101 + 8.102
Two unsuccessful competition entries for highway bridges over the Schornbachtal and over the Neckar at Mannheim

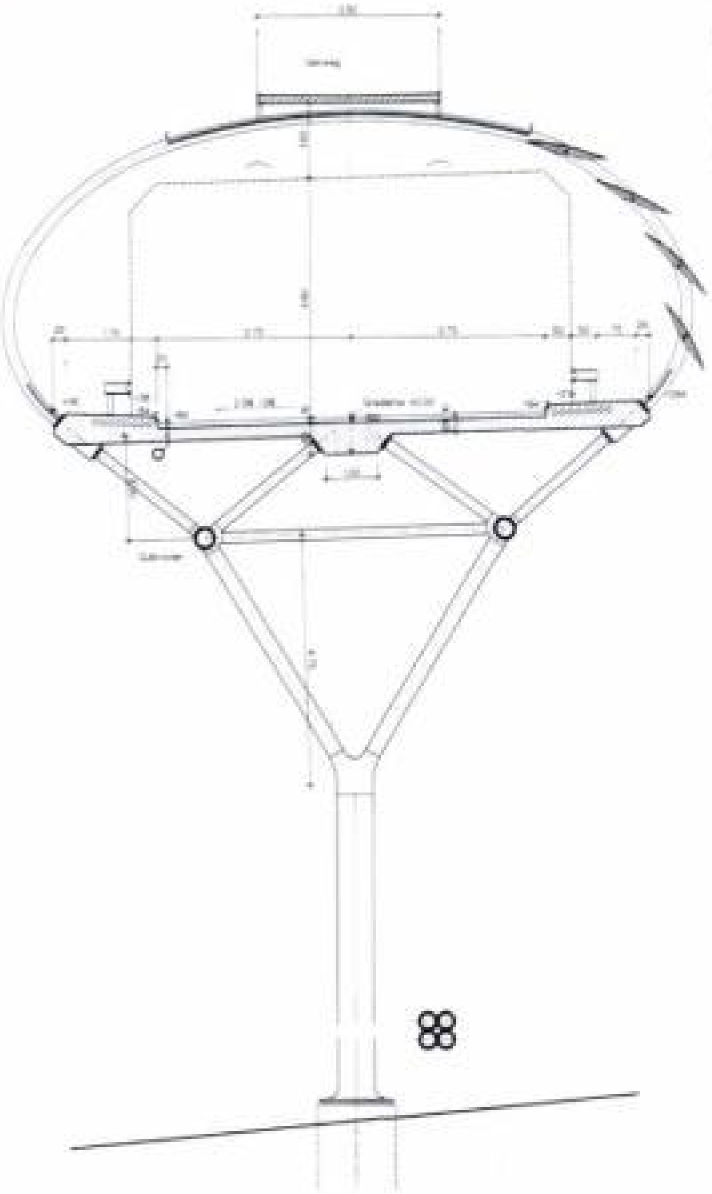


8.103 + 8.104
The road and pedestrian bridge over the Danube at Ingolstadt (under construction). The concrete deck of the roadway is supported by underslung cables and the footpaths follow the vertical curve of the cables.

In June 1994 the partnership together with Hans Luz, the landscape architect, won a competition for design of a bridge at **Stuttgart, crossing the Nesenbachtal** at a location where the road emerges from tunnels on either side of the valley. The bridge must carry a footpath above the road and sound barriers are required to provide protection on one side to people who live at the same level as the bridge and on the other to people who live at a higher level on the slopes of the valley. In addition, the designers had to allow for the visual competition provided by a modern heavy rail bridge close by. The cross-section of the bridge continues that of the tunnels (8.105 - 8.107). Michael Potzl who received his doctor's degree at Schlaich's institute, is the project engineer.

As we will see even more in the next chapter, Stuttgart appears to be an extremely favourable place for innovative bridge design, thanks to a very open-minded administration (see also note 5 in Chapter 9). Schlaich notes: "The client's contribution to the art of structural engineering would more often deserve to be emphasized."

8.105 - 8.107
The Nesenbach valley road and pedestrian bridge at Stuttgart (under design)

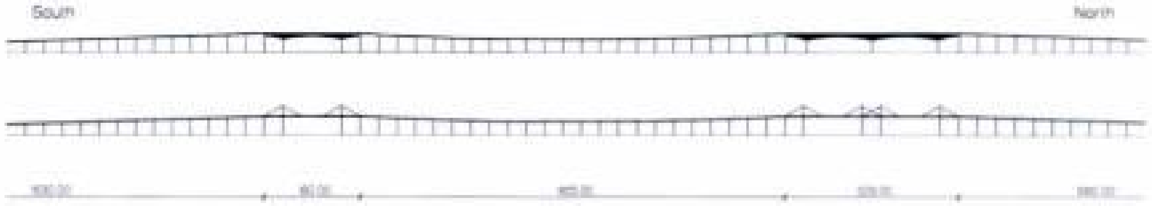


In 1989 Schlaich was approached by his Portuguese colleague I. L. Cancio Martins to advise him on an alternative design for a **second crossing**, several kilometres long, between the pensinsula of **Macau and its island Taipa**, over the South China Sea.

Martins himself was invited by the contractors Teixera Duarte/Construcoes Tecnicas in order to secure this job for them. The original tender, similar to the first Macau Taipa connection, handled the three approach sections on either side and between the two main openings for navigation with series of prefabricated prestressed I-girders of 35 m span and 1.7 m height. The navigation spans were to be formed with prestressed concrete box girders, completely different in character from the point of view of construction (8.108).

Since the key to economy was obviously the prefabricated girders, delivered extremely cheaply from casting yards in the People's Republic of China, Martins and Schlaich (once they had decided to "live" with them) proposed to use them for the full length, thus also creating a more homogeneous appearance for the bridge as whole. The main openings are multiples of 35m (i.e. ... 35 + 105 + 35 + 105 + 35 ... repeating ... 35 + 105 + 35 ...). For these the prefabricated beams are supported by a primary cable stayed structure of vertical masts, external horizontal struts at deck level and transverse beams spaced at 35 m with the cables replacing the "missing" piers. The prefabricated beams, of constant span and height throughout, are readily adapted to the regular short spans and the larger openings as it makes little difference whether their ends are supported by piers or by cables (8.108–8.111).

After the final design had been done in collaboration between Lisbon and Stuttgart, the bridge was completed in 1994. Schlaich felt that aesthetics had of necessity been sacrificed for economy and practical reasons, especially as the masts could not be well proportioned since the portion below deck, about 45 m high, was prescribed by the navigation clearance. However, when he was able to see the bridge recently together with Bergermann and his son Mike, they were happily surprised about the floating, even light appearance of this undulating white bridge against a blue sea and sky. "After all", he comments "what really counts in this less privileged part of the world – it was probably the cheapest bridge of such size ever built."



Original proposal and alternative design as built

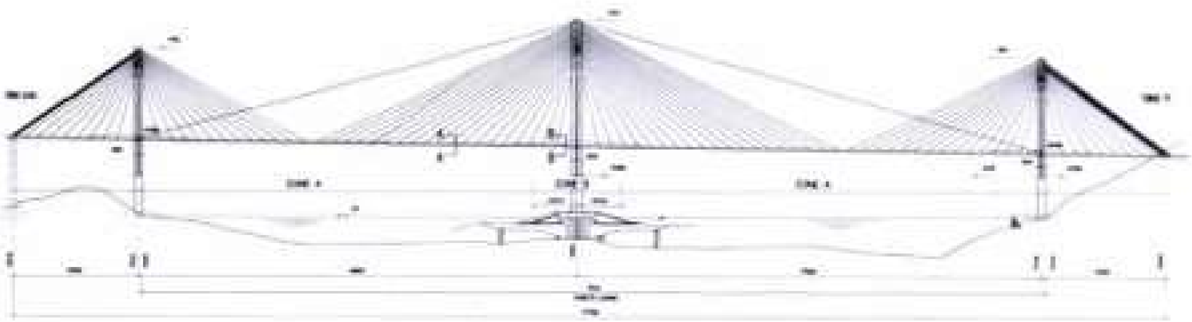
8.108–8.111
The second Macau-Taipa connection (completed in 1994)

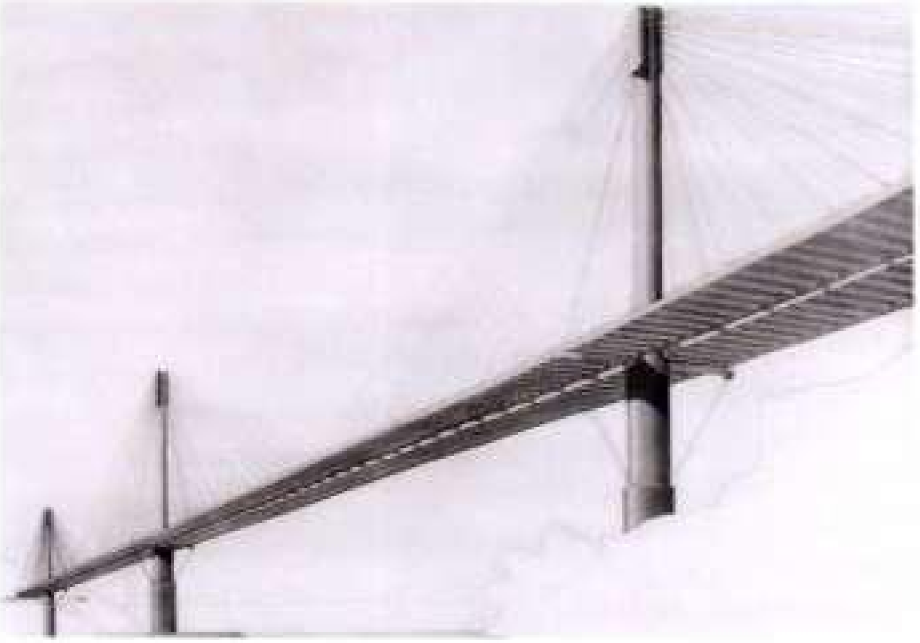
In 1992, Schlaich was approached by a New York artist James Carpenter to support him in the design of the Wabasha Street Bridge over the **Mississippi River in Saint Paul, Minnesota**. The commission was to replace an existing bridge with an innovative design. After several alternatives had been considered, a cable stayed bridge was selected with a V-shaped pylon situated on an island. The bridge takes a sharp bend in plan at this location and pedestrian access is provided to the island (8.112 – 8.114). This special design developed from Carpenter's idea of avoiding a straight connection between the two abutments on either side of the river, as happens with the existing bridge. (The latter bends when it leaves the north-western abutment.) The proposed bridge would continue in the direction defined by Wabasha Street and bend only on the island thus requiring and justifying the expressive pylon-cable layout which would now be seen through Wabasha Street, "bringing the river through its bridge (visually) into town".

8.112 – 8.114
The Wabasha Street bridge over the Mississippi in Saint Paul, Minnesota

In August 1994 the partnership was informed that its design for the **Ting Kau Bridge in Hong Kong** for a group of contractors had been successful. This large 6-lane, 1177 m long cable-stayed bridge will connect the New Territories and the Tsing Yi Island and join the new road cum rail link between Kowloon and the new airport on Lantau Island which includes the Tsing Ma suspension bridge and the Kap Shui Mun cable-stayed bridge. The innovative design of the Ting Kau Bridge (8.115 to 8.116), which convinced the client not only as the lowest bid but also visually, resulted from Bergermann's idea of utilizing a shallow in the middle of the Rambler Channel for support. Thus only one costly pile foundation exposed to ship impact is needed rather than two closer to the banks for a "standard" cable stayed bridge design or two piers onshore with a costly 1000 m span between them. The longitudinal bracing of the central 194 m high tower is reminiscent of the Patna bridge design (8.3). In the transverse direction the three masts are braced like the masts of a sailing ship (8.116). The total 384 stay cables fan out from the top of the three masts in four inclined cable planes. They carry a composite deck. Since the bridge is to be completed in time for the return of Hong Kong to China in 1997, Bergermann's design team with Mike Schlaich as project engineer and a large crew have no time to waste.

In these later bridge designs, in addition of course to Rudolf Bergermann, leading roles have been played by Hans Schober, Andreas Keil, Thomas Fackler, El-Araby El-Schenawy, Dorothea Krebs, Jan Knippers, Thomas Moschner, Michael Pötzl and Mike Schlaich; while Jochen Bettermann, Volkwin Schlosser, Peter Schulze and Thorsten Helbig, the "Konstrukteure" are an integral part of any bridge project.





8.115 + 8.116
The Ting Kau Bridge, Hong Kong with two main spans of 475 and 448 metres and two side spans of 127 metres each

Notes for Chapter 8

[1] As a result of the changes introduced by Leonhardt and Schlaich the contractors argued that their original contract was no longer applicable and brought claims for extra payments. This was one of the major reasons for the long delay in completing construction.

[2] On 4 June 1992, the *Suddeutscher Rundfunk* broadcast a TV documentary on the Hooghly bridge and on Schlaich's crusade in the cause of Solar Energy.

[3] The Strut-and-Tie Model course was held in New Dehli.

[4] Schlaich notes that the only real alternative is to overlap the cables, anchoring each one on the far side of the mast to that from which it comes. However, this requires that the cables be distributed widely over the height of the mast, resulting in the "semi-harp" arrangement, as at the Sunshine Skyway Bridge at Tampe, with its "unfavourable cable angles and high bending moments in the mast".

[5] See J. Schlaich: "On the Detailing of cable-stayed Bridges", Seminar on Cable-Stayed Bridges, Yokohama, Japan, Dec. 1991.

[6] The responsible authority was the *Landesamt fur Straßenwesen* of Baden-Wurttemberg, under the supervision of E. Hoffmann.

[7] An account of these problems is given in an article in *New Civil Engineer (NCE)*, 23 March 1989, p. 31 to 34. The Schlaich/Bergermann design envisaged that the deck would be built on basically horizontal falsework. The under-slung cable would then be prestressed to raise the props and cause them to take a share of the weight. During this process the cable would stretch and the lower ends of the props would move horizontally. With this in mind, and also to ensure a clear visual separation of the props from the box, the designers therefore provided carefully detailed steel hinges at their upper ends to accomodate the resulting rotation. However, the contractor preferred to develop the prestress in the cable by a totally different procedure which, amongst other things, would eliminate the need for the hinges. The deck was constructed on falsework which had a pronounced, calculated, downward curvature. In this condition the tip of the deck, at the end farthest from the pylon, was several metres below its final position. The cable was then installed and secured, and the end of the deck was jacked upwards. This caused the deck to straighten and extended the cable, inducing the required prestress in cable and struts. However, this process was itself complex, partly because it was necessary for the end surfaces of the deck segments be non-planar.

[8] "Der ,... unterspannte Trager macht das Tragverhalten anschaulich und erscheint im Vergleich zum Vollwandtrager schlanker. Man akzeptiert, was man versteht, und empfindet als angenehm, was leicht wirkt. Man erwartet, daß ein Bauwerk auf sich andernde Randbedingungen angemessen reagiert." J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61, 1986, p. 51.

[9] These ideas are summarized in J. Schlaich: "Bruckenbau - Baukultur?", *Die Bautechnik*, 70 (1993), Heft 1, editorial, p. 1.

[10] See J. Schlaich: "Robert Maillart - und wir?", E. Schunck and E. Ramm: *Robert Maillart 1872 to 1940*, exhibition catalogue, Fachgebiet Planung und Konstruktion im Hochbau, Institut fur Baustatik, University of Stuttgart, 1991.

[11] See for example M. Bill: *Robert Maillart*, Girsberger, Zurich, 1955. Published in English as *Robert Maillart: Bridges and Constructions*.

[12] See for example *Structural Engineering International*, 2/1992.

[13] See, e.g., J. Schlaich: "Zur Gestaltung der Ingenieurbauten oder Die Baukunst ist unteilbar", *Der Bauingenieur*, 61, 1986, p. 49, or J. Schlaich: "Bruckenbau - Baukultur?", *Die Bautechnik*, 70 (1993), Heft 1, editorial, p. 1.

Selected Publications by Jorg Schlaich and co-authors (if given) up to 1995 to Chapter 8: **Highway and Railway Bridges**

month/year

01/82: "Betonhohlkastenbrucken" (German edition) "Concrete Box Girder Bridges" (English edition), with H. Scheel, *IVBH-Structural Engineering Documents 1d und e.*

09/82: "Cable-stayed Bridges with Composite Stiffening Girders – The Second Hooghly Bridge in Calcutta", with R. Bergermann, *Proc. of the Sino-American Symp. on Bridge and Structural Engineering, Peking 1982.*

09/84: "Die Hooghly-Brucke in Kalkutta – Eine Schragkabelbrucke in Verbundbauweise", with R. Bergermann, *Festschrift Roik*, 1984

05/88: "New Parallel Wire Bundle for Cable-stayed Bridges", with R. Bergermann, *Cable Stayed Bridges, Proceedings ASCE Convention, Nashville, Tennessee.*

05/88: "Some Subjective Remarks on Cable Bridge Design", with R. Bergermann, *Proceedings ASCE Spring Seminar 1988, Bridges, New York City.*

06/88: "Teilweise unterspannte Schragkabelbrucke uber die Obere Argen", mit J. Seidel and D. Sandner, *Prereport: 13th Congress of IABSE, June 1988, Helsinki, Finnland.*

06/88: "Some Recent Cable Stayed Bridges", Intern. Congress Major Engineering Projects in the World, Nice, France.

09/88: "Variety in Cable-bridge design", with R. Bergermann, *The Indian Concrete Journal.*

10/88: "Geometrics and Dimensioning – Maintenance and Inspection of Cable-Stayed Bridges", keynote address, with R. Walther; "Structural Detailing and other practical Aspects", keynote address, Seminar on Cable-Stayed Bridges, Bangalore, India.

12/88: "Entwurfswettbewerb Williamsburgbrucke New York", *Stahlbau*, 57.

05/90: "Cable-Stayed Floating Bridge for the Gibraltar Link", with R. Bergermann, IIIe Colloque International sur la liaison fixe Europe–Afrique travers le d'Étroit de Gibraltar, *Marrakech.*

08/90: "Some thoughts on Cable Bridge Design", *Proceedings of the Forth Rail Bridge Centenary Conference, Edinburgh, Scotland.*

04/91: "Cable-Stayed Floating Bridges", with R. Bergermann, ASCE Congress, Indianapolis, Indiana.

06/91: "Maillart – und wir?", *Beitrage zur Geschichte des Bauingenieurwesens*, Heft 2, Universitat Stuttgart.

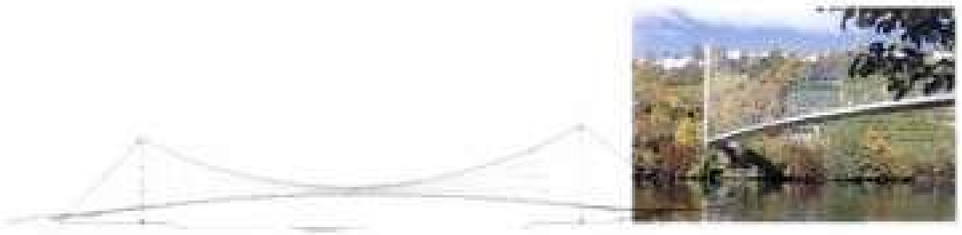
12/91: "On the Detailing of cable-stayed Bridges", Seminar on Cable-Stayed Bridges, Recent Developments and their Future, Yokohama, Japan.

12/91: "Der Entwurf der Talbrucke Obere Argen", *Baukultur*, 6/91

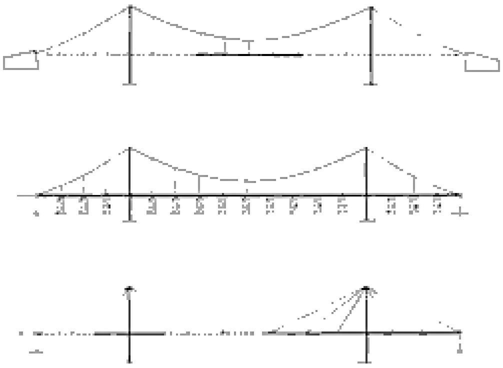
06/93: "The Bridges of Robert Maillart", *Concrete International, The Magazine of the ACI.*

03/95: "Grundlagen fur den Entwurf, die Berechnung und konstruktive Durchbildung lager- und fugenloser Brucken", with M. Potzl and K. Schafer, *Kurzberichte aus der Bauforschung*, 36 (1995).

10/95: "Variety in Bridge Design", *Proceedings Conference "Bridges into the 21st Century", Hong Kong.*



9 Pedestrian Bridges



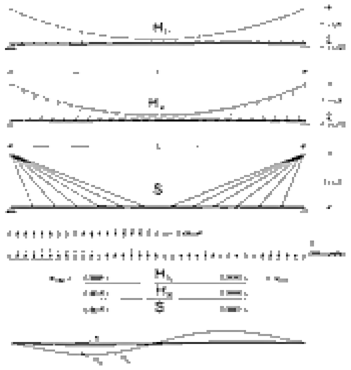
9.1
Comparison of the erection of back-anchored and self-anchored suspension bridges with that of cable-stayed bridges

The footbridge is one of the jewels of the art of the structural engineer. Generally, form and structure are one. In design, the engineer is often free to work alone, or at least take the leading role in defining form. Trade-offs between engineering factors and aesthetics may be made consciously and with reasonable foreknowledge of their effects on technical complexity and cost. There is less pressure to accept clumsiness in structural action or detail for the sake of harmony within the design group.

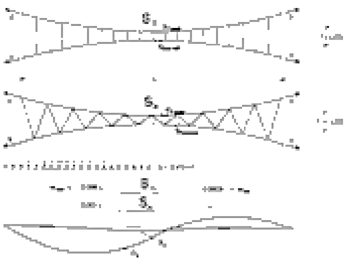
Schlaich and his colleagues have made a major contribution to the development of this particular art-form in recent decades. Their quest for lightness and transparency, and their favoured means of design and construction, have given their footbridges a clearly-defined, almost personal signature. The forms they use are not always the cheapest for the small spans of footbridges, but they have ensured that the additional cost is always justifiable on the grounds of increased elegance, visual and technical interest, and adaptability to topography and functional requirements including durability. In Schlaich's words: "Whoever masters these load-bearing systems is able to adjust them to all requirements of location and function (stairs, ramps, and approaches) and is able to make these bridges increasingly slender, light, and transparent."[1] The design team has developed a skill in combining slender reinforced concrete slabs with high strength steel cables which has allowed them to achieve extreme freedom of form – curved outlines in plan and elevation; constantly changing widths; and bifurcating elevated walkways. In addition to the cable stayed bridge they have employed both types of suspension bridge: the "back-anchored" and the "self-anchored". In the former, the ends of the main cables are usually anchored to massive concrete blocks capable of resisting the inward pull. The masts and main cables are erected first, and as the deck is progressively assembled its elements may be immediately supported from the main cables. In the self-anchored version the ends of the main cables are attached to the ends of the deck. The deck serves as a horizontal strut, resisting the inward pull of the cables and obviating the need for anchor blocks. However, this means that the main cables cannot support any weight until the deck has been assembled, so that the deck must be supported from below during its construction. The cable-stayed bridge combines the best features of both types of suspension bridge. Once the masts have been erected, the deck may be constructed by a cantilevering process (Chapter 8), with cables being progressively installed as the deck grows outward from the pylons. The bridge is self-anchored at all times during this process. If supports for the deck construction are feasible, the self-anchored suspension bridge is equivalent to the cable-stayed bridge (9.1).

There is a general perception that cable-supported bridges are suited only to medium to large spans, greater than about 200 metres. We shall see that this limit is somewhat arbitrary and should at least not be applied to pedestrian bridges.

9.2 + 9.3
Comparison of deflection of different cable bridges with partial live load



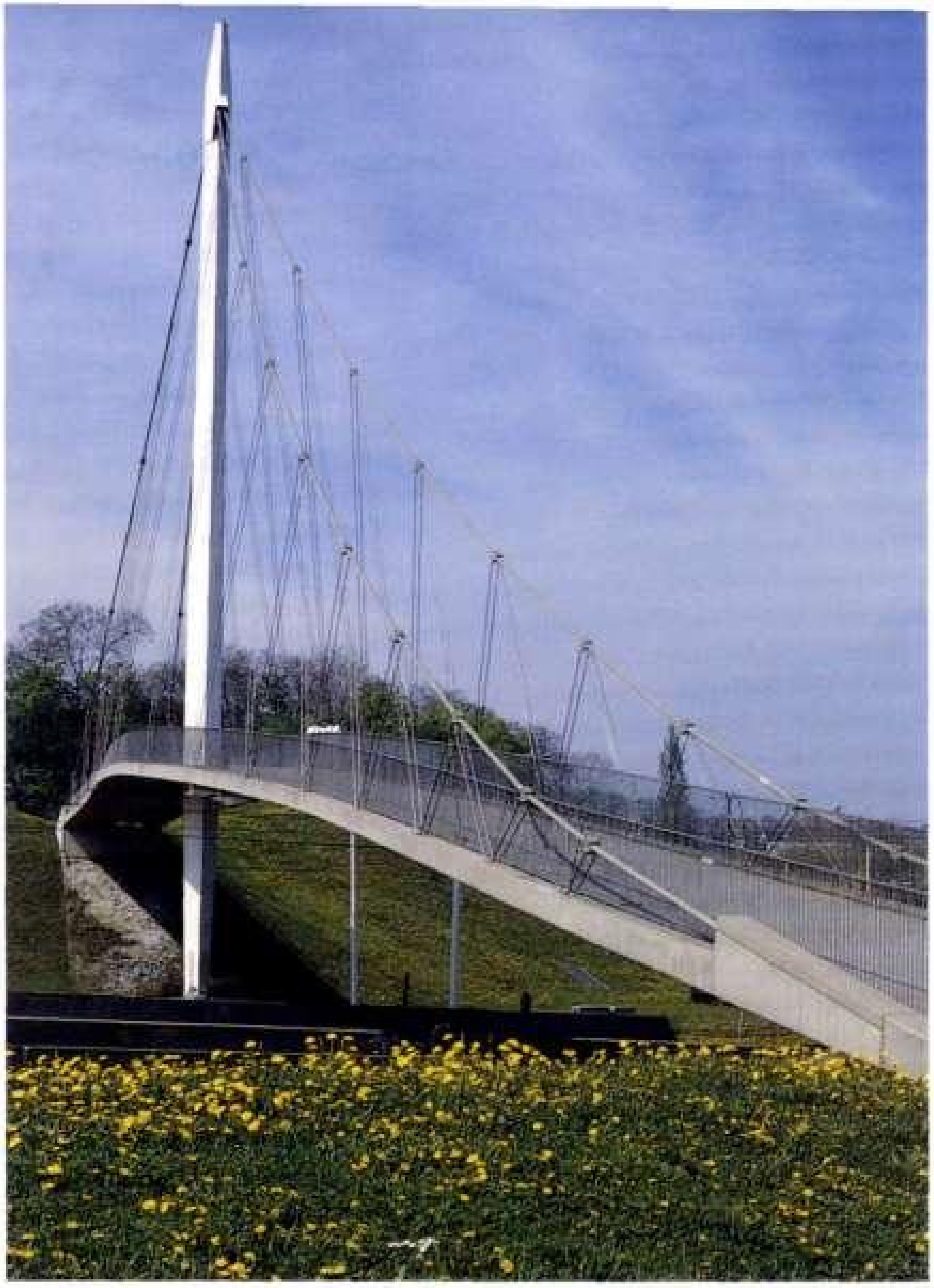
Deck suspended from parallel hangers $H_{||}$, deck suspended from inclined hangers H_x, and cable-stayed deck S.

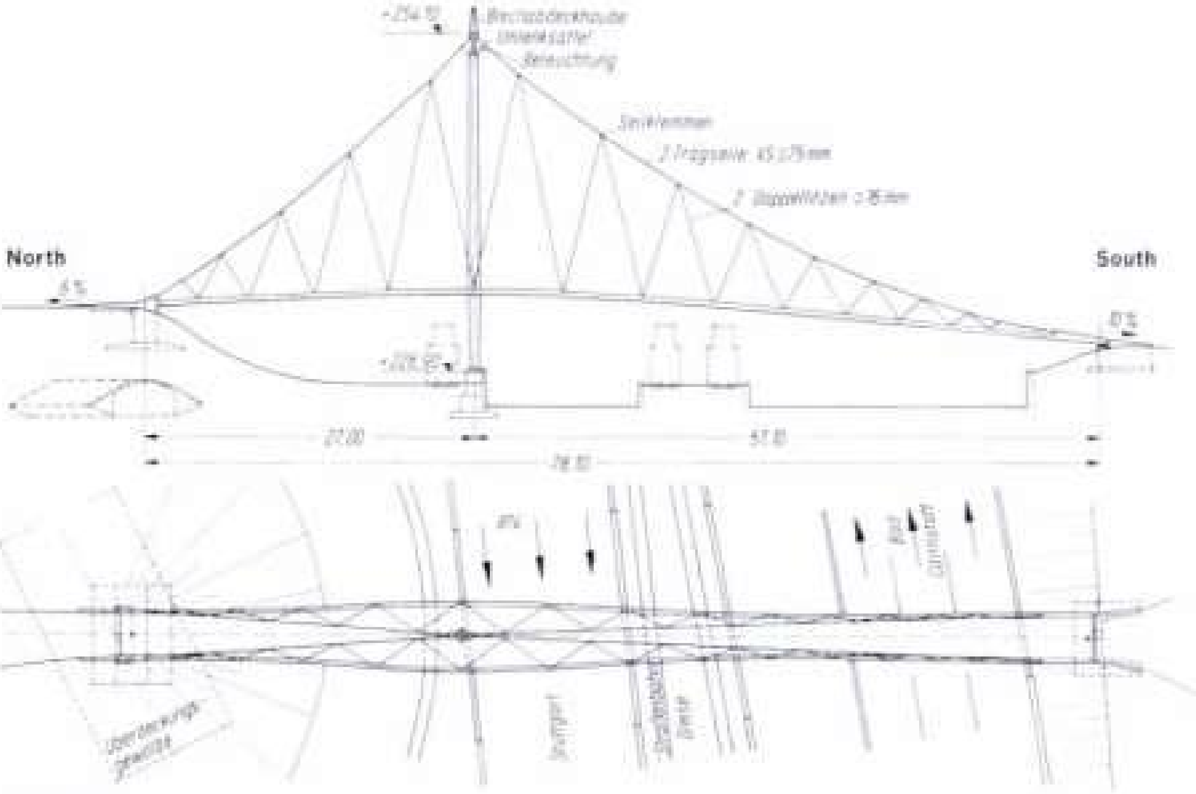


Cable truss with parallel hangers $S_{||}$
Cable truss with inclined hangers S_x

Once again, the **1977 Bundesgartenschau (BGS) in Stuttgart** provided Schlaich, at that time still a partner with Leonhardt und Andra, with an opportunity to put his ideas into practice. The city has many beautiful parks and gardens which were once isolated from each other by busy thoroughfares including multi-lane roads, railways, and tram lines. Hans Luz, the landscape architect for this occasion, conceived the idea of linking the gardens by a series of footbridges. Being the cousin of Schlaich's wife, Luz turned to him for advice on the practicability of the scheme. It was decided that four bridges could advantageously be built to provide improved access to a park called the Lower Schloßgarten. Two of them connected this with another park, the Rosensteinpark, and they therefore became known in the office as the **Rosenstein-park I** and "Rosenstein-park II" (pedestrian) bridges (9.4, 9.15).

At the southern boundary of the park, a dual-carriageway, having crossed the Neckar river on the König-Karl-Bridge, descends abruptly into a tunnel. Between the carriageways is a dual tram track. For a short distance yet another tramline loops alongside the road as it approaches the tunnel (9.5). This was the area to be bridged: a maze of retaining walls, light poles, masts, overhead cables, footpaths, rail lines, and traffic lanes. To further complicate matters, two service tunnels carrying sewage, electricity, and telephone links run parallel to the road, one of them directly beneath the southern end of the proposed bridge. As a result, it was essential to support most of the weight of the bridge at the other side of the road. At the same time it was important to impose some sort of aesthetic unity on the visual chaos below. Schlaich and Luz realized that both technical and aesthetic factors favoured the use of a single relatively tall mast, situated at the northern end, which could visually dominate the light poles and tramway standards. On this occasion there was no restriction on the height of the structure. As we have seen,





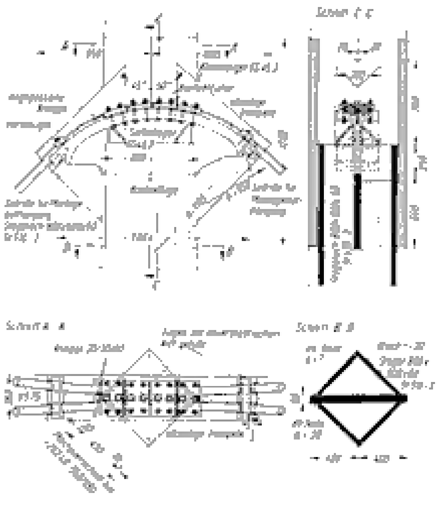
9.4 + 9.5
Rosenstein I pedestrian bridge
1977

the horizontal cable force in a single-sided back-anchored bridge would be larger than that for a symmetrical bridge. It was therefore decided to use the self-anchored system, taking account of the fact that the deck could conveniently be propped from road level during construction. Once the mast and cables were installed, the whole system could then be prestressed by jacking upwards at the base of the mast (9.12 + 9.13). This method of prestressing has become a characteristic of Schlaich Bergermann self-anchored suspension structures.

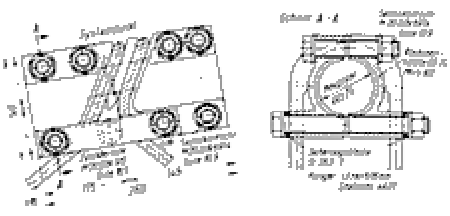
The elegance of the structural conception requires some explanation. In cable supported bridges, the most common system is to arrange the cables in two vertical planes, one each side of the deck, as in the Hooghly bridge. These may be suspended from independent masts either side of the deck, or from the legs of portal frames. Less frequently, single masts are placed on the centreline of the bridge, with a single vertical plane of cables anchored along the centreline of the deck (as in the Brotonne Bridge). For Rosenstein I, in the interests of structural and visual simplicity, the designers adopted the concept of the single mast but attached the lower ends of the cables to the edges of the deck. The two cable systems thus have a slope in the lateral direction (9.4 + 9.5, as in Ting Kau Bridge, 8.116). The main cables are clamped to the saddle at the top of the mast, and this enables them to hold the top of the mast in position in all directions, reducing its tendency to buckle, and thus permitting a more slender profile (9.6). In the region of the mast, the deck is widened to flow around it. In addition to satisfying a functional need, this increases the lateral slope of the cables at this critical point, and provides more positive support to the top of the mast. When they are serving this function, the cables exert a sideways pull on the deck tending to bend it horizontally. The stiffness of the deck in the horizontal plane is thus an important factor in stabilizing the entire system. To reduce vertical deflection under non-uniform load, and to minimize vibrations, the hanger cables are also inclined in the longitudinal direction (9.2).

The deck is elegantly arched in profile to provide the required clearance for the tram tracks without necessitating the expense of building up the approaches. The slight arch also serves to reduce bending moments in the deck as it spans between hanger support points. Compressive stresses induced in the deck by the inward pull of the main cable from both ends counteract the undesirable tensile stresses induced by bending. The problem of temperature change is solved by anchoring the deck to the abutment at one end only. To permit the necessary movement, the mast is hinged at its base so that it is free to rotate slightly in the longitudinal direction. The main cables clamped to its top prevent it from overturning. For reasons of economy, it was decided not to use a cylindrical tubular mast, but to make a square hollow cross-section by welding four plates together. The mast is tapered in both directions, being widest at deck level. This gives it a better appearance than a straight mast and is technically more efficient in terms of material usage although somewhat more expensive because of the added complexity of fabrication.

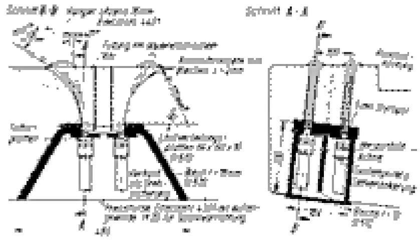
Because one span of the bridge is longer than the other, there is a tendency for the northern end to lift under most conditions of loading. This problem was solved by shaping the abutment in the form of a concrete box which was filled with soil as the bank was restored to its former shape. With crowd loading on the northern span, there would also be a danger of the southern end lifting. However, the forces involved here are much smaller, and an articulated link is used which allows free horizontal movement.



Details of the mast top (see 9.9)



The main cable clamps (see 9.10)



Anchorage of the inclined hangers at the deck

9.6–9.8
Rosenstein I, details

Already in this, his first pedestrian bridge, Schlaich and his colleagues paid particular attention to the technical and visual details. These were made very simple for economy. Standard clamps were developed for the connection of the hangers to the main cables at changing angles (9.7). The hangers penetrate the slab that they could be anchored beneath it and stressed from below (9.8). At later bridges that idea was abandoned for a combination of reasons connected with appearance and inspection and maintenance. Hangers within easy reach of passers-by are formed from stainless steel strands. The mast was painted white to distinguish it from the deck and increase its visual dominance. The incidence of natural light on the square cross-section, which is oriented diagonally to the main axis, produces a two-tone effect due to shading. This heightens the impression of slenderness, while the sharpened outline lends it an austere classicism. A cover placed over the saddle at the top of the mast to protect it from weather is used to house lights to illuminate the bridge (9.4+9.6) and creates a feature at the top of the mast, further reinforcing its visual importance. Handrails present a major aesthetic problem in the design of light footbridges. The conventional balustrade, even when made of steel sections, can visually dominate the real structure. The Rosensteinpark I handrail, while more visually intrusive than in later bridges, is successfully overshadowed by the grand scale of the mast and suspension system.

This bridge exemplifies Schlaich's gift for conceptualization and analysis of three-dimensional static systems and architectonic form, and his readiness to move away from conventional solutions. Although it was probably the first suspension footbridge to be built in recent times, there is a fine balance amongst competing technical considerations and between the technical and the visual. The balance is tilted more in favour of the technical than in the later footbridges where there was an obligation to keep the masts low and hidden by trees. Thus the more efficient Rosensteinpark I profile seems more "heaped up" in comparison: the mast is higher in relation to the span, and the main cables have a steeper slope in the longitudinal direction. Schlaich knew this was a "test case": an opportunity to prove that a light, elegant, and functional suspension bridge could be designed and constructed for not much more cost than a conventional one. As Rosemarie Wagner puts it, this was when he "built bridges rather than designed them".[2]

The mast top during construction

Cable clamps

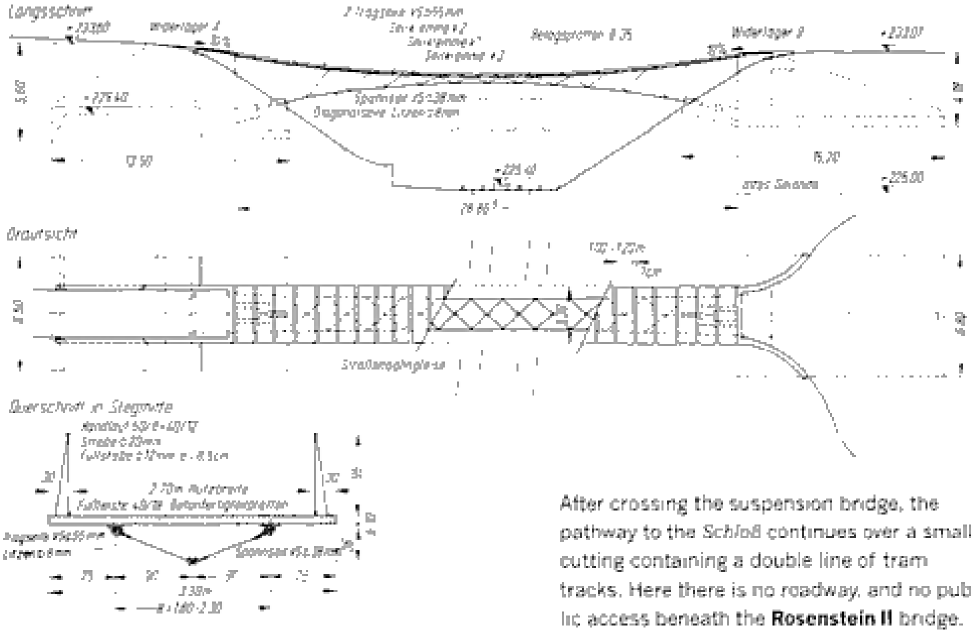
9.9 – 9.13

Rosenstein I: Details of construction

Concreting the deck on formwork

Jacking the mast base ...

to lift the deck from the formwork



9.14
Rosenstein II bridge

After crossing the suspension bridge, the pathway to the *Schloß* continues over a small cutting containing a double line of tram tracks. Here there is no roadway, and no public access beneath the **Rosenstein II** bridge. The designers were therefore able to adopt a totally different solution to bridging the gap while making it technically and visually consistent with the larger bridge. They decided to support a concrete deck directly on two sagging cables (9.14). It is desirable to choose a length of cable which permits a reasonable amount of sag because the force generated by a given weight of deck decreases as the sag increases. However, in this case the sag possible was limited by the level of the abutments in relation to that of the high tension wires for the trams, and the need to limit the slope of the deck to the six per cent required to permit access by the disabled.[3] It was therefore necessary to accept relatively high tensile forces, and resist them with massive abutments on the same principle as those used in the other bridge: large concrete boxes weighted down by the earth they enclose. There is, however, an aesthetic advantage in that the flat slope at the end of the bridge is in harmony with the slope of the natural ground as it rises towards the Rosenstein palace.

The flexibility of simple cable suspension systems presents a challenge for the designer. A cable carrying a uniformly distributed load adopts a shape known as the catenary which is near its apex close to a parabola. However, if it is loaded on only a part of its length, by a single vehicle or a crowd, its shape will change dramatically, and continue to change as the weight moves across the span. This can be most alarming to anyone walking across this simplest form of suspension bridge. The designers realized that a continuous concrete deck slab would significantly stiffen the bridge but would be subjected to high bending stresses as a result. These could be countered only by increasing its thickness and hence its weight, and thus increasing the forces in the cables and abutments. Worse, the increased stiffness would in turn cause increased bending stresses so that, as often happens in design, a vicious circle of increasing weight and stress would be set up. If this went far enough, the bridge would change in nature from a light suspension bridge to a heavy girder bridge, resulting in the very clumsiness which Schlaich abhors. It was therefore decided to take the opposite track: to ensure that the deck was completely flexible, and to use other means to reduce deflection.

The deck would be formed from individual precast concrete slabs 100 mm thick and 1 metre wide separated from each other by a 10 mm gap. Construction would be much simpler, drainage would be free, and the slight friction between the units and their connections to the cables would provide some damping of vibrations. To further control deflection and vibration an additional cable was included, running under the centreline of the bridge, and curved in the opposite direction to the main cables, using pairs of diagonal ties (9.3). This cable could be anchored part way down the sides of the cutting, and pretensioned to hold the deck down at several points along its length. The result is a three-dimensional "cable truss" situated beneath the deck. The tensile prestress is carefully calculated to ensure that, with about 60 per cent of maximum pedestrian load and maximum temperature expansion of the cables, all remain taut. For reasons of economy, the designers decided not to prestress the bridge to ensure tautness under the full 5 kN-per-square-metre live load specified in the German code of practice.

9.15+9.16

Rosenstein II

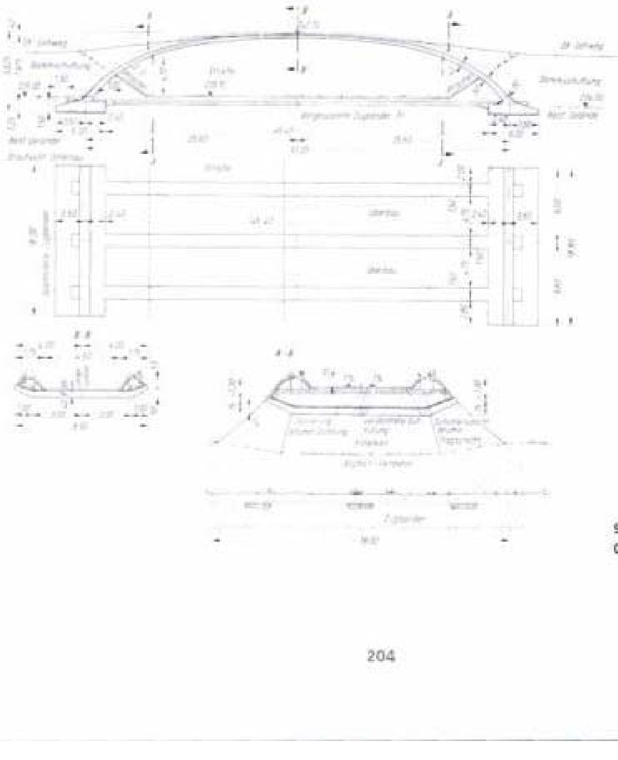
They reasoned that this would be rather improbable because it implies seven people standing on each square metre and that in any case, with such congestion, nobody would be able to move, so the danger of vibration would be negligible! Special clamps were developed to connect the main cables to the diagonal ties.

Visually, this is a very self-effacing structure (9.15+9.16). No mast rises above the level of the adjacent parkland and the deck dips discreetly beneath it. When the bridge is viewed from an oblique approach at deck level, the most prominent feature is its handrail. This is of conventional design, with vertical railings cantilevered upwards from the ends of the deck slabs and propped at regular intervals. In the middle of the span it is deeper than the structural system. Technically, the cable structure is a masterpiece: a fascinating three-dimensional system, striking in its lightness. It is ideally suited to resist the lateral force of winds blowing along the cutting, and the torsional effects arising from one-sided pedestrian load, as well as the more obvious symmetrical forces due to self weight and full crowd loading. The bridge does vibrate more than is customary, and in an unusual manner, especially when loaded at the quarter points of the span. However, as Schlaich predicted, the citizens of Stuttgart have come to accept this, and tourist information maps of the park include their nick-name for Rosensteinpark II – "the swinging bridge".

9.17

Rosenstein II with Rosenstein I in the background

During the first year, with vegetation still scarce



9.18–9.23
Cannstatter Straße bridge

The third bridge required for the Bundesgartenschau (BGS) 1977 was to cross the **Cannstatter Straße**, a multi-lane arterial route which swings across the linear garden of the old palace, the Schloßgarten, and separates its "central" from its "lower" part. The idea was to bridge this road in as unobtrusive a manner as possible so that the garden would appear to flow over it in a continuous fashion. However, the site presented major problems. The top of the deck was to be kept as low as possible to avoid expensive raising of the pathways leading from the gardens. The level of the soffit was determined by the need to provide clearance for vehicles on the road beneath. Thus, as usual, there was a need to minimize the depth of the deck while still providing the necessary strength in bending. Also, to avoid contamination of Stuttgart's renowned mineral springs which flow close beneath the road surface at this point, the foundations were to be kept very shallow, while the water-logged nature of the soil would permit high settlement, calculated to be about 60 cm.

To meet these exacting conditions, Schlaich and Luz in collaboration with B. Winkler devised a bridge in the form of what was essentially a wide, thin sheet of concrete, arching over a span of 50 metres with a thickness of only 400 mm (9.18–9.23). To increase its stiffness and strength its longer edges are folded slightly upward. The structure thus consists of three curved planes joined along their sides. The width of the central surface is six metres at the crown, splaying out to 11 metres at the abutments. The canted planes on either side also splay out as they near the abutments. The whole structure thus behaves more like a complex doubly-curved shell than a simple arch, and this form provides the necessary strength despite the small thickness of construction. The arch is covered in earth which forms the walking surface and helps stabilize its shape.

The most efficient shape for a simple arch with a uniformly spread load (due to its self weight and full crowd loading) is a parabola. However, the most important load on the Canstatter Straße arch is the weight of the earth it carries, and this is much greater at the ends than in the centre. Crowd loadings even at mid-span have little effect in comparison. The most efficient profile for the bridge thus has a flatter curve near the crown and a much steeper curve at the abutments than does a parabola, and this corresponds very well with the requirements for traffic clearance. Thus, the designers were able once again to conceive a scheme in which, right from the start of the design process, harmony existed between the technical, functional, and aesthetic determinants of form. The poor foundation conditions were overcome by preloading the area to induce settlement prior to installation of the bridge and by joining the feet of the shell with prestressing tendons, buried under the road and encased in concrete.

The arch looks good when seen obliquely from the gardens, but it is possible, as was planned, to pass over it from one part of the Schloßgarten to the other without the normal feeling of crossing a bridge. On either side of the walkway, troughs are integrated into the folded-up part of the slab and plants have been encouraged to grow over the sides. Schlaich is pleased to be able to describe it as the "green bridge".[4]

The fourth bridge built to provide access to the Schloßgarten for the Bundesgartenschau (BGS) of 1977, the Heinrich-Baumann-Straße bridge, belongs to quite a different family of structural forms and is described later in this chapter.


The formwork

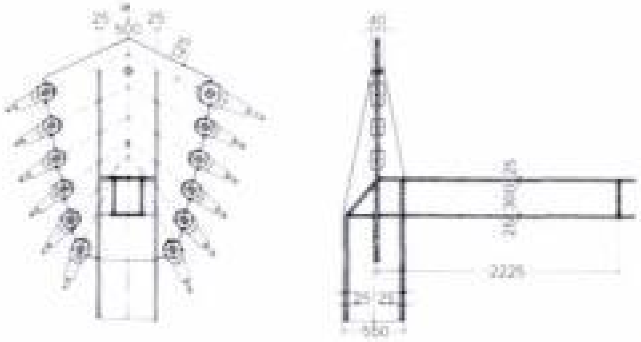

The pure arch


In summer: the green bridge

9.24–9.29
Neckarsulm bridge I

In the early 1980s a need arose for two light bridges to carry pipelines over the Neckar River and the adjacent Neckar canal supplying hot water for the community heating system of **Neckarsulm**. The larger, with a total length of 142.5 metres carries two 80 cm pipelines and a footpath over both the river and the canal. The smaller, with a length of 102.5 metres, has no footpath and crosses only the canal and an adjacent road. It is typical of Schlaich's approach that the bridges, being in the same vicinity, are similar in general layout in the interests of harmony, but differ significantly in important details to reflect their different functions and locations (9.24–9.30).

In both cases it was possible to place a support near the middle of the total length of the bridge, the eccentricity being just enough to avoid slackness of the backstays when only the smaller span is loaded. The designers thus chose to use a single pylon in each case. For the narrower **bridge II**, they selected the elegant single-mast solution, with the mast placed between the two pipelines (9.30). This has the disadvantage that if one of the pipes is emptied for maintenance purposes, while the other remains operative and full of water, the load is unbalanced in the lateral direction. The structural system is able to resist this because the cables slope inwards from deck level to masthead, as on the Rosenstein I bridge. However, there is some "cost" in that the mast must be strengthened to cope with lateral bending moments. As at Rosenstein I, it is built from welded plates to form an uncompromising sharp-edged square section oriented diagonally to the longitudinal axis. Once again, the lateral inclination of the cables enhances stability and permits a narrower cross-section than would otherwise have been possible.



View and section of mast top

The mast tops before being painted white

Section through deck: Walkway in between pipes

Backstay tie down

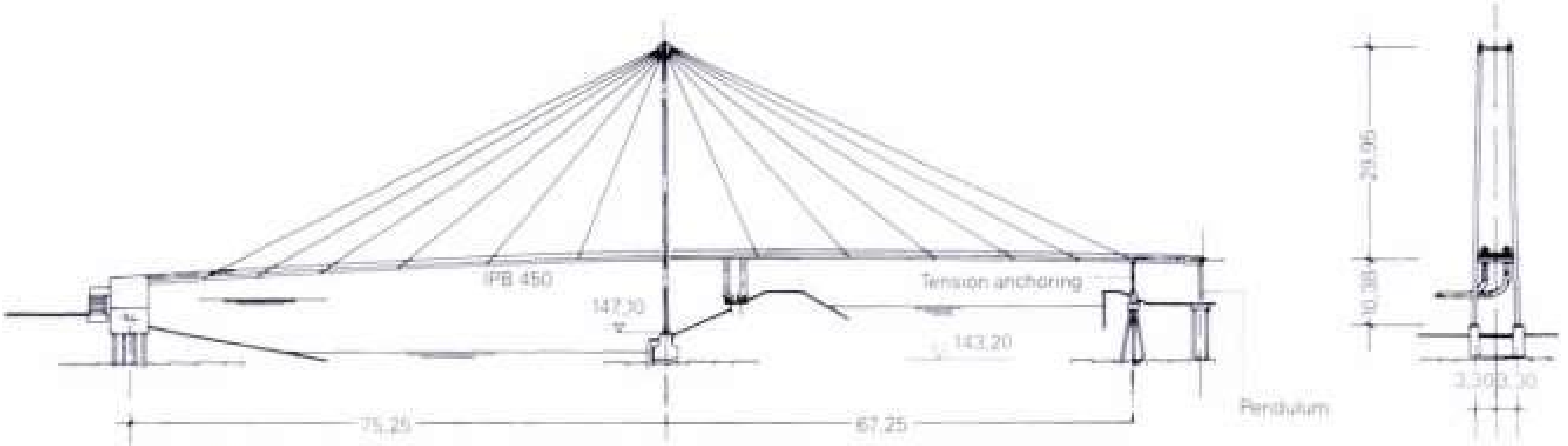
For the wider **bridge I**, where the pipelines are separated by the footpath, the twisting moment due to the emptying of one pipe is much greater. The design team therefore chose to use two distinct, vertical planes of cables and a conventional portal-frame pylon (9.24–9.29). The out-of-balance load on one side of the bridge may thus be carried almost directly by the cables and mast on that side and the masts and cross-piece may be extremely slender.

For the decks, the aim was once again to achieve a minimum thickness. Closely-spaced cables support two simple, standard rolled-steel I-sections which in turn carry a concrete slab. In both bridges steel beams and concrete deck act compositely to resist bending. The decks also serve as horizontal girders, spanning from abutment to abutment to resist lateral wind forces and, through the cables, brace the mast in the lateral direction. Once again, the ends of the bridges are tied down using "pendulum" links (9.28).

The need to adjust the tension in each cable on site was eliminated in an experiment which the designers were encouraged to try because of the relatively short span of the bridges. While still in the fabrication shop, the cables were prestressed to overcome their non-linear behaviour at low load. They were then cut to the exact length required by the geometry of the bridge, to an accuracy of 1 in 10,000. As a result, there was no need for turnbuckles or other expensive means of adjustment on site, and the connections at deck and pylon head were greatly simplified using standard open spelter sockets. The mast heads have an outline somewhat reminiscent of the "flowerpot" heads of Evripos, Hooghly, and Akkar. The whole system was prestressed by pulling down on the pendulum tension anchor at one end.

Much thought was given to colour schemes for the two bridges. The cables and pylon of the larger bridge are coloured white-grey to minimize their intrusion in the skyline. Because the pipes are deeper in side elevation than the deck, they tend from a distance to rob the bridge of its slender appearance. They are therefore painted silver grey to make clear that they are a load imposed on, and distinct from, the girders which are dark grey. The smaller bridge follows in colour the adjacent Audi-car factory. For this industrial environment, the designers gave both bridges an appropriately purposive air. Although they have a certain functional severity, they are slender and classic in line. From certain angles, fascinating and probably unintended visual plays of form and lighting appear. Construction was completed in 1985.

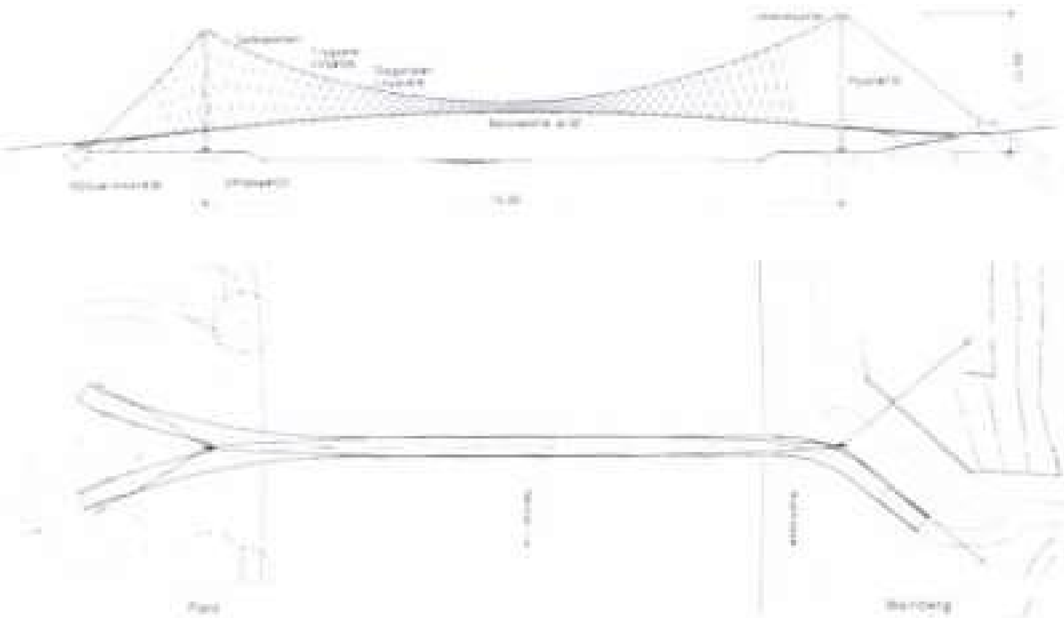
9.30
Neckarsulm bridge II (the smaller one)



Neckarsulm Bridge I

Looking up river, with the park at left and the vineyards at right

The bridge across the Neckar near the **Max-Eyth-See** recreation park in **Stuttgart** is one of Schlaich's personal favourites. The topographical setting presented both technical and aesthetic problems. On one side of the river are steep vineyards which slope directly to the river bank. On the other lies a relatively flat, wooded portion of the recreation area surrounding the lake. The bridge was needed to provide a direct link from the suburbs above the vineyards to the recreation area. Detailed functional requirements were as usual challenging. A clear span over the Neckar and the adjacent footpaths would amount to 114 metres. The bridge had to be high enough to provide clearance for river traffic, including freight barges plying between the North Sea and the Stuttgart quays upstream of the bridge, and for large sight-seeing launches. At the same time it must provide access down to the footpaths on either bank, connect with a steep path in a gully running down through the vineyards, and join a path leading towards the bank from the recreation area.



9.31+9.32
Max-Eyth-See bridge

Schlaich was entrusted by the City of Stuttgart with the project in this environmentally-sensitive area on the understanding that he would maintain a reasonable balance between aesthetics and cost.[5] He carried out the early conceptual work on the bridge in 1978, but it was not until 1987 that the City finally allocated the funds for its construction.

Given the objectives of minimizing the impact on the scenery and respecting the differing topography and greenery on either side of the river, Schlaich's natural response was to envisage a light and transparent structure, which meant either a cable-stayed or a suspension bridge. To demonstrate the aesthetic benefits, J. Bettermann in the office prepared photomontages comparing this solution with the more conventional and somewhat cheaper alternative of an unstayed hollow prestressed concrete girder of substantially reduced span (9.33+9.34). The requirement for river clearance meant that the deck of any bridge would appear prominently against the background of the vineyards, and even the slender prestressed concrete beam appeared unacceptably intrusive.

No architect was formally involved in the project, but Schlaich discussed it at length with his sister, Brigitte Schlaich-Peterhans, when she paid a timely visit to Stuttgart. She paid careful attention to the placement of the bridge and of the approach paths so that the visitor descending through the vineyards would be able to appreciate the entire form of the structure. It was agreed that the sweeping lines of a suspension bridge would be more suited to the location than the angular form of a cable-stayed bridge, even though it would be somewhat more expensive. As a result Schlaich felt it incumbent on him to justify this choice by a particularly fine design in both aesthetic and technical terms.[6] He and his sister felt at first that the bridge should respond in some way to its highly unsymmetrical setting: the steep vineyards on the one side and the flat park-like recreation area on the other. One way to achieve this would be to make the profile of the bridge also unsymmetrical by using a pylon at one end only. This presented two further alternatives. If the mast were placed on the vineyard side, it would be overshadowed by the cliff and the main cables would slope in the same direction as the vineyards. If the mast were placed on the opposite side the reverse slope of the cables would act as a counterpoint to that of the vineyards and it might be possible to conceal the mast in a grove of trees which was conveniently located near the bank.

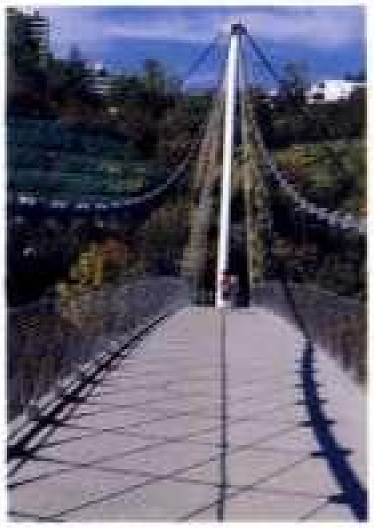
Schlaich employed a simple survey technique to study the situation. He went to the site with his young sons, taking helium-filled balloons and long pieces of string. The boys let out the string until the balloons reached the height of the trees, and then tied a knot when Schlaich gave the signal. This allowed him to build models and study the visual effects of pylons of varying heights. He tried out a number of arrangements for the cable system and finally came to the conclusion that a symmetrical suspension bridge offered the best solution. This decision was based mainly on technical grounds. "Luckily we engineers are not, in such a situation, left depending only on our intuitive understanding of form. We can (and must) follow reason, supported by our specialist knowledge. A bridge suspended from only one side needs a pylon twice as high, and cables twice as strong, as one which has a mast on both banks and a main cable spanning the river symmetrically. People can grasp what is logical, and find it more agreeable than that which is difficult to understand and appears forced. And so, that is how it was done!"[7] The mast on the park bank is almost concealed in a grove of trees. The mast on the other side shows its strong, straight lines against the background of the vineyards, contrasting with the delicate tracery of the cable system. The mast colour, almost white but with a slight tinge of grey, was chosen to enhance these contrasts so that the mast looks more substantial. The main cables were also painted white, a decision which Schlaich considers unfortunate because it results in a surprisingly strong contrast with the background (9.35+9.36).

9.33+9.34
Competitive photomontages of:
- **a box girder bridge of only 75 m span**
- **a suspension bridge of 114 m span**

9.35+9.36
The bridge as built with its main cable not yet painted white and after painting it white.

9.37–9.39
Details: cable clamps and handrail

9.40
Approaching the bridge through the park



9.41 + 9.42
The vineyard side

9.43
The park side

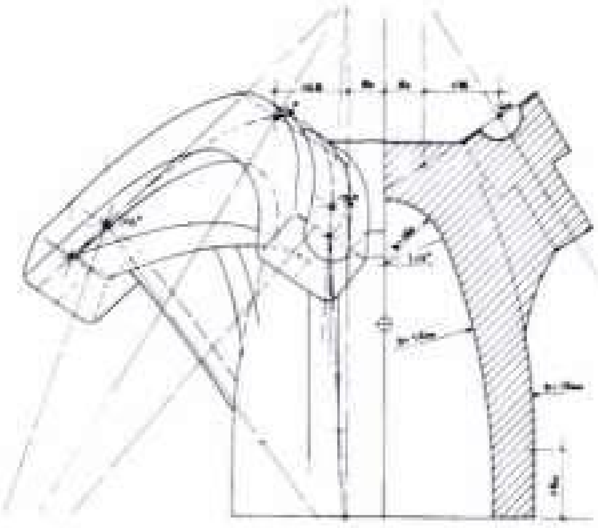
In order to minimize the required thickness of the deck slab and control static and dynamic deformations, the design team adopted a criss-crossed arrangement of diagonal hanger cables at very close spacing (9.32). This permitted a slab thickness of only 300 mm and allowed the use of small-diameter, and thus less-visible, cables. To ensure that the visual impact of the handrail was not greater than that of the deck it was conceived as a wire mesh clamped to two longitudinal tensioned cables, one strung at handrail height, and the other at deck level (9.37 – 9.39).

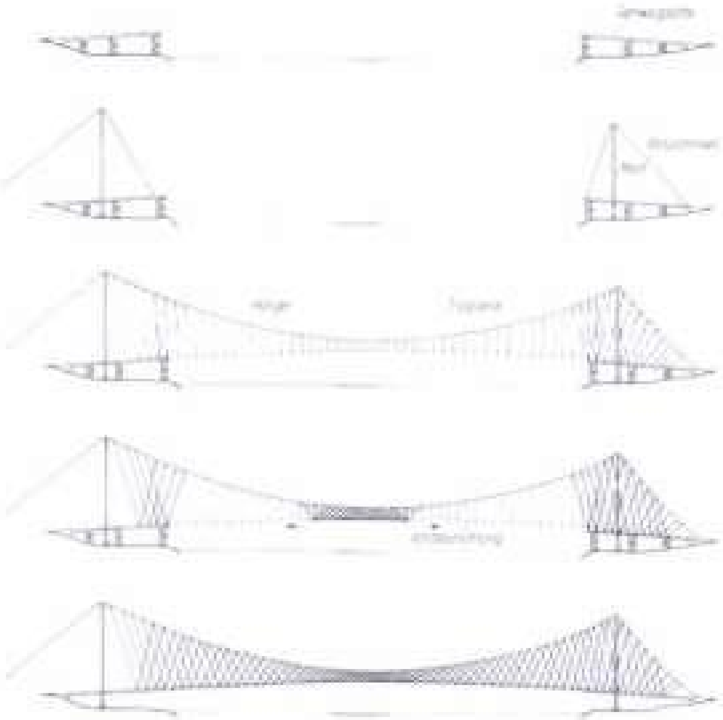
Whereas the bridge is symmetrical between its two masts, as is the river itself, the treatment of the two ends of the deck beyond the masts is quite different, responding to the complex requirements regarding access, and the differing scenic qualities of the approaches (9.32, 9.40 – 9.43). These features exemplify the freedom of formal conception and its relation to mastery of structural action which characterize the partnership. The team exploited the fact that the deck of a back-anchored suspension bridge does not balance the cable tension and therefore may curve quite freely in elevation or plan. This contrasts with the self-anchored variety where there are strong reasons for keeping the deck completely straight.[8]

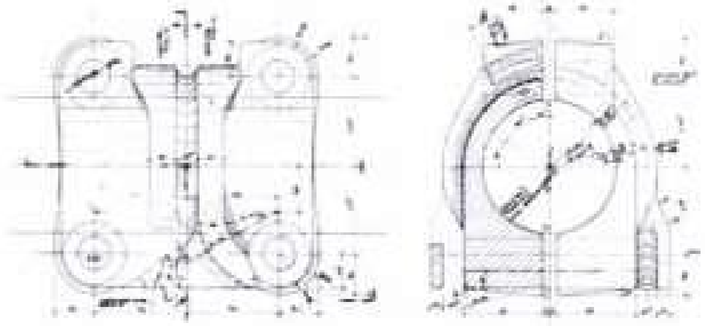

Lifting the units from a barge


The centre section installed, its concentrated weight causing temporary sagging


The last unit is lifted


9.44
The cast steel mast top


9.46 – 9.49
The construction sequence


9.45
Cable clamps

On the vineyard side, the end of the deck is curved quickly away from the centreline just before it reaches the mast, so that it can pass over the tow-path without losing too much height and join the path through the vineyards (9.41 + 9.42) on a convenient promontory of earth. The fact that the hangers are inclined makes it possible to dispense with them at this point, so that the deck can curve outwards, spanning between the last hangers and the concrete abutment. The absence of the hangers reveals the mast clearly on this side, and permits an unrestricted view of the vineyards. As usual, it was necessary to cater for movement at one end of the deck and in this case the vineyard end was chosen. To prevent the end of the deck from rotating in the vertical direction at the support, in order to reduce the bending moments and hence the thickness required for the span to the first hanger, the deck was made integral with a large wedge-shaped block of concrete. In the initial conceptual stages it was envisaged that the deck could be made flexible enough in plan to accommodate change in length by horizontal bending. This proved not to be the case, and the designers were obliged to allow the concrete block to move in the longitudinal direction on sliding bearings: a detail with which Schlaich is not fully satisfied.

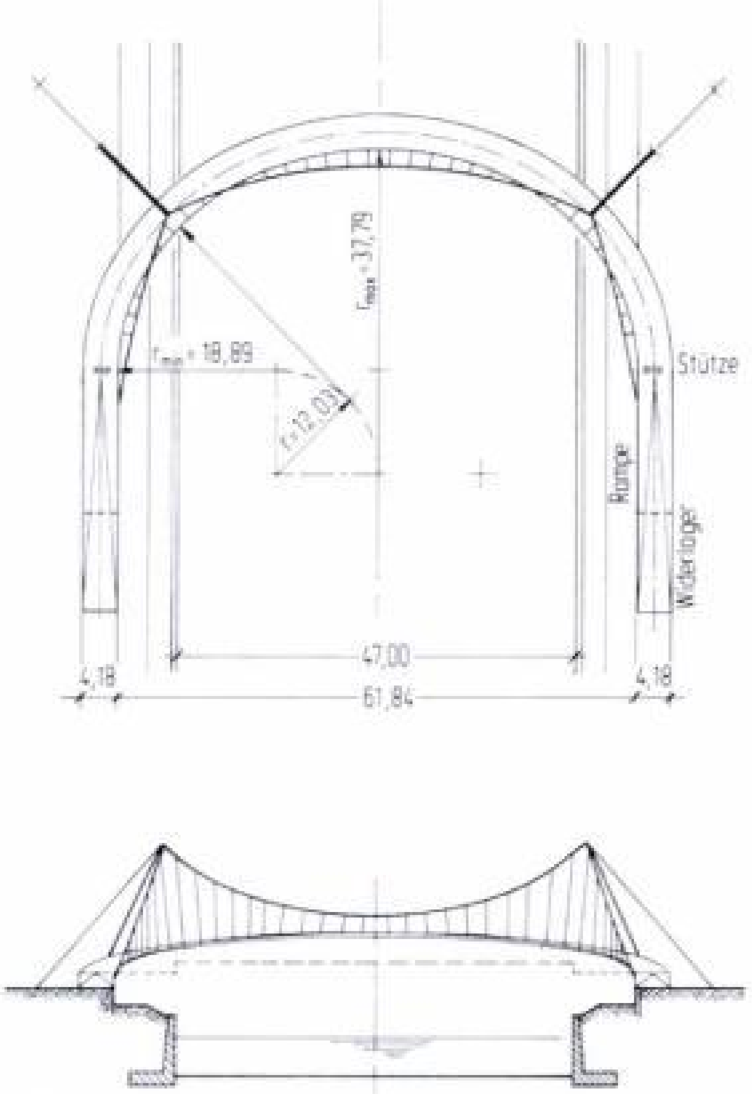
On the meadow or park side, the deck is bifurcated just before reaching the mast and passes on either side of it (9.43). There it is possible to continue the hangers almost to the end of the deck and, because this part of the bridge is partially concealed by trees, there is no need to provide a free view. Most engineers would baulk at the complexity of designing and constructing a beam which is curved in plan. Schlaich and his team have not only done this at both ends, but have created a fine and complex three-dimension balance of forms and forces. The construction of the bridge (9.46 – 9.49) attracted a great deal of public interest, including a four day opening ceremony, and it received continiuous newspaper coverage – hopefully in the interest of the profession.

By the time the Max-Eyth-See bridge was built, it was possible to take advantage of experience gained at Rosensteinpark with respect to maintenance and durability. There is improved corrosion protection and provision for replacement of cables.

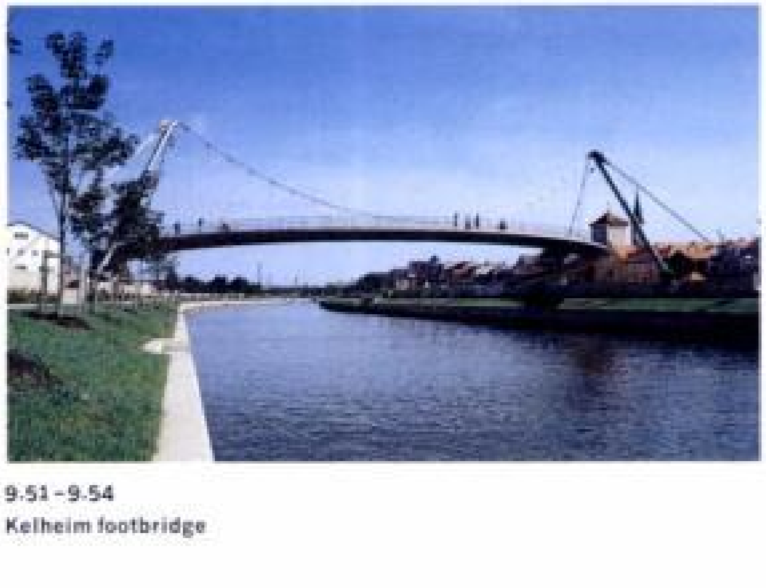
Hans Schober and Thomas Fackler, as members of the design team, were adept at dealing with these complex problems.

From the aesthetic point of view, this is a beautiful structure which clearly displays the love bestowed on it by its designers. It is an amiable bridge: in current terminology it is "user friendly" because it is so obviously adapted to suit those who cross it, view it, and live with it. The deck splits and curves, at considerable cost in terms of design and construction effort, to make the approach easier and more welcoming for the pedestrian. The structure nestles discreetly below the slope of the hill. From most viewpoints one mast is lost in the trees and the other disappears against the visual complexity of the vineyards (9.31). The same discretion is also evident in the fine tracery of the cables, and the low depth of construction at mid-span. However, when one finally comes upon the bridge in the clear, its beauty of form is striking and self-sufficient. From the technical point of view these features have been "bought" (as Schlaich would say) at the cost of disadvantages elsewhere.[9] The forces in the main cables are greater than if higher masts had been used, and the small depth of construction at mid-span has caused localized distortion of the cables. However, these minor problems are a small price to pay for the beauty of the Max-Eyth-See bridge.

9.50
Max-Eyth-See bridge, 1989
Seen from the vineyards



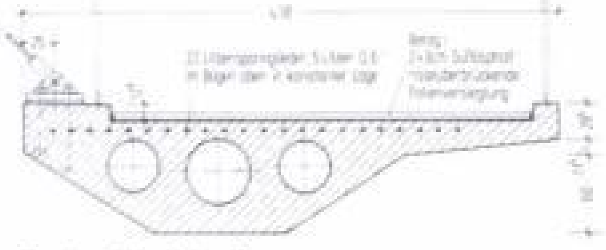
Plan, elevation



9.51 - 9.54
Kelheim footbridge

The cable-supported footbridge at **Kelheim**, completed in 1987, is the partnership's most dramatic in terms of form and technical conception (9.51 - 9.59). As we saw in the previous chapter, the need for a new bridge arose with the construction of the 47 m-wide Rhine-Main-Danube Canal along the course of the Altmühl right outside the city walls (8.70). The medieval town centre was formerly connected to an adjoining suburb by a road which ran straight through the old city gate and crossed the Altmühl by means of a small bridge. Traffic was now to be diverted around the town centre, and the former traffic bridge was to be replaced by a footbridge which would span the canal proper and the two towpaths either side. Clearance requirements for barges travelling on the canal meant that the deck of the new bridge must be well above ground level. To provide access for the disabled, lengthy approach ramps would be required.

In 1981 a competition was called for design of the new structure. Ackermann and Schlaich were amongst those invited to take part. They agreed that the bridge should be a lightweight "high-tech" structure which would reflect the contrast between the old town and the modern canal. The situation was somewhat unusual in that the bridge would be built before the canal was excavated. Thus during construction it would be possible to support the deck from ground-level using simple props. This suggested that a self-anchored cable suspended bridge with a cast-in-situ, post-tensioned prestressed deck would be both practical and economic. The immediately obvious way to meet the functional requirements was to place the bridge, with associated spiral ramps and stairs, on the line of the old traffic bridge directly in front of the city gate. Most other entries to the competition adopted this solution, using

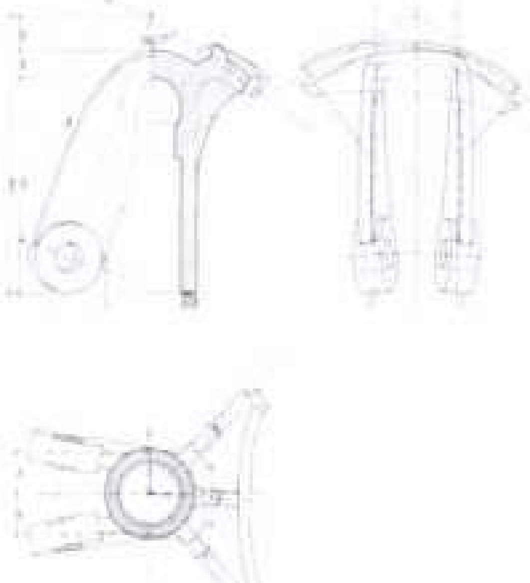


Section of deck at midspan

a conventional girder system. In contrast, Ackermann conceived the idea of running the access ramps parallel to the canal until they gained a sufficient height to clear the barge traffic, thus shifting the bridge deck away from this important architectural axis. To keep the deck thin, in order to keep the ramps as short as possible, a conventional self-anchored suspension bridge was initially envisaged with a pylon at each end and a straight deck joined to the tops of the ramps in an abrupt 90-degree turn.

Schlaich however, was not happy with the sudden change in direction. He recounts that he was working on the problem at home one evening with rough sketches spread out on the floor, trying to "round off the corners in some way", when his son Mike, who had just commenced studying engineering said to him "why don't you make it an arc in plan and suspend it?" This "naive" suggestion would have been dismissed immediately by many engineers because of a preconception that a self-anchored suspension or cable-stayed bridge must be straight to resist the cable thrust through its deck and because of the extremely daunting theoretical challenge of conceiving and analysing a three-dimensional cable system capable of supporting a deck in the form of a semi-circular horizontal arc.[10] Also, conventional wisdom holds that girders curved in plan are always subjected to high torsional forces which are difficult to calculate and must be resisted by massive box-like cross-sections.

Schlaich knew that in this case the scheme could be made to work. He had earlier made a special theoretical study of curved beams in connection with his work on circular TV-towers.[11] He realized that the semi-circular deck could be suspended from hangers located on one side only. This eccentric



9.55+9.56
Details of the mast and cables

support would ensure that when the structure was carrying full uniform crowd loading (and its own weight) it would be subjected to a state of completely pure bending in the circumferential direction. There would be no torsion at all, and the deck would need only nominal torsional strength to cater for minor non-uniformities of loading in the longitudinal direction. Analysis would still be complex, but torsion (which is especially critical for concrete structures following routine crack formation in service) would not dominate design. With hangers attached to only one edge of the deck, the cable system would be greatly simplified both visually and technically. The mast heads could be situated over the quarter-points of the circle, and a single main cable could be anchored on the inside of the curve at the tangent points. It would then "cut the corners", curving slightly in plan under the variously inclined pull of the hangers. Thus as happens surprisingly often, a naive suggestion inspired a creative response in someone who was mentally prepared to respond to it. The scheme was discussed with Ackermann who agreed on its architectural merit.

In order to reduce the weight of the deck, a hollowed out cross-section was chosen which combines high resistance to longitudinal bending moment with good torsional resistance (9.53). Its overall depth is 880 mm – relatively thick for a Schlaich Bergermann footbridge – with kerbs at either side to contain a walking surface of paving blocks. A thickening adjacent to the inside kerb serves as an anchorage for the hanger cables. The outer edge is carefully shaped to reduce its apparent depth. The soffit slopes up at a shallow angle and the deck is cantilevered sideways to provide a narrow vertical face only 280 mm in depth.

The scheme was submitted in this form and won first prize in the competition. However, "as often happens in these cases", subsequent events impaired the purity of the original concept. Urged by conservationists, the authorities decreed that the slender masts must not be higher than the ancient and massive tower in the town wall (9.57). This was a full four metres lower than Schlaich had wanted them for a combination of technical and aesthetic reasons. Because the location of the feet of the masts could not be varied, the angle between the sloped masts and their backstays became very small and the forces therefore very large. The resulting reduction in the sag of the main cable generated much higher forces in all members. This in turn required more bulky clamps, anchorages and suspension points. To obtain as much sag as possible between the level of the mast-head and the deck, the hangers at midspan were made extremely short. As a result, they must incline at an angle of 45 degrees in order to reach the edge of the deck: much steeper than the structurally desirable optimum (9.58).

Schlaich feels that the curve of the main cable is now too flat from an aesthetic, as well as a technical point of view. The contrast between the original design ideas and the final nature of this suspension system, so susceptible to changes in geometry, are obvious. To make matters worse, he is not at all happy with the shape of the cast heads of the masts (the saddles) (9.56+9.59). He said in 1987 that he would give a great deal to be able to change them because, being so prominent, they spoil the whole effect for him. He was thus by no means completely happy with the bridge immediately after its completion. Such feelings are common in creative people, especially when they have just completed a work, because they are all too conscious of the difference between their original vision and what it proved possible to achieve in reality. This is especially true when, as must happen frequently in architecture and engineering, many of the major differences are due to the fact that the designer did not have total control of the process of creation. Nevertheless, the international community of structural engineers have no such qualms, and this bridge is recognized as the technical and aesthetic masterpiece that it is.

The full semi-circle of the curved deck is internally prestressed in the circumferential direction. The prestressing tendons are eccentric in the vertical direction to counteract the vertical bending moment in the cantilever (9.53). The three-dimensional suspension system, the elegant minimal support of the deck, the complex studies of bending versus torsional moments, and of wind effects and vibration, the development of high-quality cables, castings, and other details make this indeed a "high-tech" structure. Schlaich notes that much credit is due to Jürgen Seidel who was project engineer in the design office.

To turn to aesthetics, the saddle at the mast heads does look a little awkward in comparison to the rest, particularly as the profile of the fin on its back is for some reason not smooth. Observers with a heightened imagination might see the heads of two primeval beasts looming over the deck (9.56). The ramps seem unnecessarily heavy. They are out of keeping with the lightness of the bridge itself, and block the view of the canal over some distance (9.54). The bridge itself is quite another matter. The first glimpse of the arc of the deck is startling. It seems to leap from the abutments and soar weightlessly above the canal. The sense of movement is beautifully counterpointed by the inward inclination of the pylons. There is a further counterpoint between the thin, but emphatic white band of the deck, and the even more slender black lines of the masts and back stays. The third element of the composition is the complex arc of the main suspension cable and the regularly varying angles of the hangers. The full aesthetic value cannot be conveyed by photography. It is a heady experience for the pedestrian to follow the curve of the deck. There is a wonderful sense of freedom, almost of wheeling through the air like a bird: rising, turning, and descending. To delight the eye and the intellect, there is the constantly-changing visual interplay of masts, stays, suspension cable and hangers, both within themselves and against the backdrop of the city and surrounding countryside.

The spatial balance of the suspension system has a unique effect when we compare it with the flat fan-shape and earnest directness of the cables of a conventional bridge. The interplay between cable forces and the bending strength of the deck is so complex that it is difficult even for an engineer to grasp the mode of structural action. Thus the cables at Kelheim seem destined more to define space than to support the load. There is an apparent nonchalance in their attachment to only one side of the deck. These factors combine to give the impression that the solid concrete deck hovers above the canal almost without external assistance. The design team put a great deal of time and effort into detailing the handrail in order to ensure that it would not detract from the lightness of the deck. However, the bridge will never look quite as wonderful as it did just before the handrail was installed!

9.57–9.59
Kelheim footbridge (with Kurt Ackermann, architect)

Schlaich noticed however that in the architectural model and drawings of the future building there happened to be, for architectural effect, large columns located at either side of the first-floor opening in the facade (9.64 and 9.65). These would provide excellent anchorage for the main suspension cables. After he had explained his concept to the architects, they managed to persuade the client that it should be adopted, despite the latter's concern that the cables might spoil the view from two of the hotel rooms. The dimensions of the columns and reinforced concrete frame of the building could not be changed at this late stage, but calculations showed that it would be possible to reinforce them to withstand the extra load. The suspension cables splay out near the hotel because the width of the opening between the columns is much greater than that of the footpath. As a result, the hanger cables are inclined inwards towards the edge of the deck. This makes for good lateral stability and provides the pedestrian with a sense of security inside a "cradle" of cables. At the hotel end, the hanger cables are cut away, and a secondary suspension cable is provided which runs back to deck level. This avoids the extreme differences in the length of hangers that would otherwise have occurred, and so avoids certain technical problems of load-sharing. Making the far ends of the suspension cables almost tangential to the deck provided a beneficial compressive prestress to the concrete, permitting a thickness of only 260 mm.

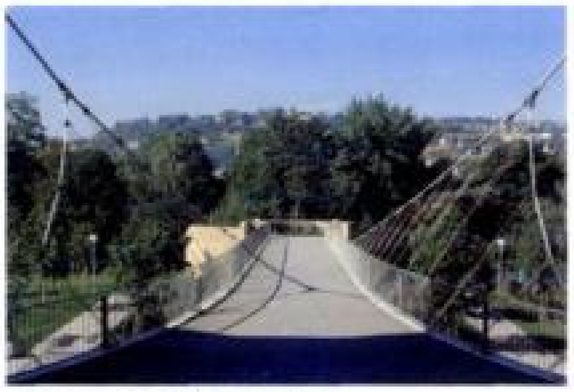
As usual, it was necessary to provide slender linkages at the far end of the deck, hinged at top and bottom to permit longitudinal expansion and, though normally subjected to tension, capable of carrying an occasional small compressive load. Architectonic arrangements at this end of the bridge led to the linkages being unusually long and fully exposed to the observer. They are therefore made from thin flat steel plates with eye-bar hinges and are pretensioned to pull down against the main cables under all loading conditions except full crowd loading, when they resist a slight compression (9.62). Because of their slenderness they are equipped with vertical stiffener plates to increase resistance to buckling in this situation. An extension of the deck spans from here to the massive stair structure which leads the pedestrian to ground level on the park side.

Once more, great thought was given to the design of the lighting and handrails, and to a number of innovative details. For the first time all anchorages and nodes were made from stainless steel plates or cast steel to avoid the need for maintenance, especially painting. In Schlaich's experience, coats of liberally applied paint can very soon blur the crispness of his office's precise detailing. However, normal stainless steel develops extremely dangerous intercrystalline corrosion due to the chlorides used for de-icing roads. Special attention was therefore paid to the choice of alloy. There is insufficient space to discuss fully the finer points of design, but it must be mentioned that the Stuttgart strut-and-tie theory of reinforced concrete played a special role, facilitating creative detailing of the anchorages which connect the cables to the deck by means of a toothed connector and of the reinforcement of the deck slab in this vicinity (9.61 + 9.62). These anchorages were forerunners of those used on the Evripos bridge (8.52 + 8.53).

This bridge is yet another excellent example of its designers' art on both the technical and architectural level. From a distance it is almost invisible against the visual clutter of the streetscape. Viewed from nearby, its sweeping horizontal and vertical outlines seem to grow naturally out of the hotel, like the limb of a tree. The deck also serves as a canopy and provides extensive protection to guests arriving at the kerbside below. The only unfortunate aspect is the stair structure at the Schloßgarten end. A massive, squat cylinder of brick and concrete, it is intended to reflect the constructional materials and surface characteristics of the hotel, and provide a visual counterbalance to it. However, it is out of keeping with the lightness of the bridge, and greatly detracts from it.

9.64 – 9.66
The Neckarstraße footbridge

As seen with the hotel in the background



As seen by pedestrians walking through the first floor of the hotel

A similarly transparent bridge crosses the **Kochenhofstraße in Stuttgart** to link a large car-park with the fairgrounds of the Killesberg. For once, the site offered many advantages: on both sides of the road the approach paths lie on high earthen embankments. Although clearance requirements precluded the use of an arch, the deck of a suspension bridge could be located well above the traffic, with its main cables economically back-anchored using the familiar concrete "boxes" buried in soil. The designers therefore chose to use two main cables, supporting the deck along both edges (9.67 to 9.73). Masts were placed at one end only and, as usual, concealed as much as possible in nearby trees. Mainly for aesthetic reasons, the masts were leaned slightly outwards. This causes the main cables and hangers to slope inwards towards the deck. To maintain stability the tops of the masts are tied together with a lateral cable, creating a symbolic entrance to the bridge, although it is doubtful whether this was a conscious intent. The high clearance over the road made it possible to use inverted prestressing cables under the deck, as at Rosensteinpark II, but in this case anchored on one side only, part way down the embankment. These stabilize the system and reduce deflections and vibrations. As a result, it was possible to keep the thickness of the slab to 130 mm. A very simple form of composite steel and concrete deck was used to simplify fabrication. At 2.5 metre intervals, cross girders are suspended from the main cables by hangers attached to their ends. Resting on the cross girders are two longitudinal steel angle sections which form the edges of the deck and corrugated metal sheeting spans from one cross-girder to the next. Thus a shallow steel box was formed into which the concrete could be poured.

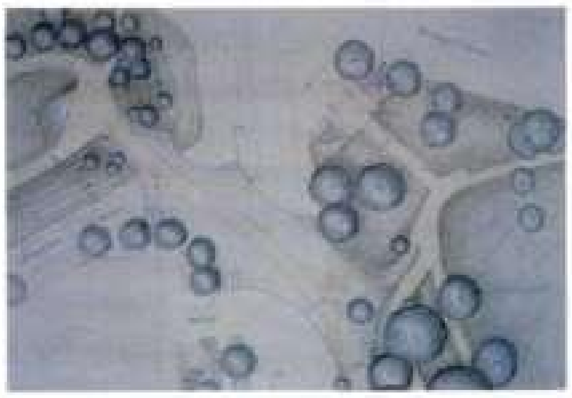
9.67+9.68
The Kochenhofstraße footbridge

Seen from the adjacent high-rise building with the ramp leading to the tram station at left

With the Nordbahnhof crossing in the background

9.81 – 9.86
The Heilbronner Straße crossing

The design of the adjacent similar, but smaller bridge over the **Heilbronner Straße** was also heavily influenced by external factors, especially with regard to access (9.81 to 9.86). In this case, the main span is almost straight and its support cables are unable to provide the tension in the northerly direction needed to stabilize the mast against the southward pull of the cables carrying the spur. The balance of forces in plan has therefore been achieved in quite a different manner. The main span is a self-anchored suspension bridge, while the spur is supported by a back-anchored system. The single mast is placed completely to one side of the main deck, to the north. This removes the need for the problematic hole in the deck. Near the tram stop, the cables supporting the spur are attached at ground level to a concrete block concealed below the deck. The southward



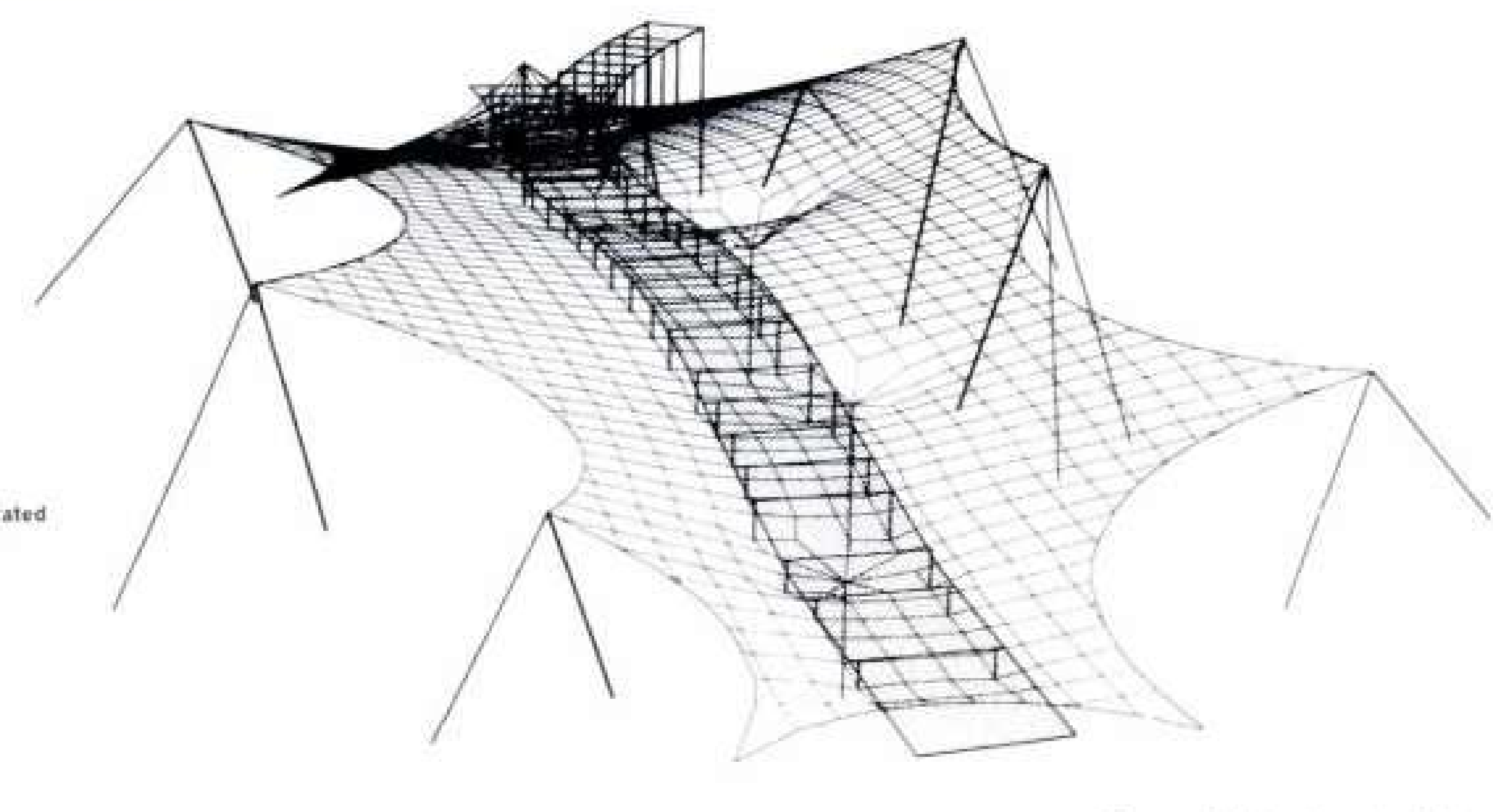
9.87
Plan prepared by the landscape architect Professor Hans Luz

9.88+9.89
Löwentor cable-net footbridge

Another facility required for the 1993 International Garden Exhibition was a footbridge to cross the busy Nordbahnhofstraße near the **Löwentor** gate and connect the Rosensteinpark to the Leibfried'schen Garten. The construction of a tunnel was considered but found to be too expensive. Once more, Hans Luz and Schlaich aimed to intrude as little as possible on the landscape, but in this case decided to reflect the nearby terrain in the "hills" and "valleys" of a point-supported cable-net surface which would stretch across the road, suspended between two rows of masts (9.87-9.92). Climbing plants would be encouraged to cover the net and provide a form of artificial landscaping, obscuring the view of the road below and giving the impression of a continuous strip of garden. From a technical point of view, the net would allow a certain degree of freedom in the placement of the supports – an important consideration in a highly congested site. The footpath would take the form of a thin concrete slab supported just above the net on short props.

Once the basic idea had been formulated there was much developmental and detailed work to be done by Thomas Fackler in the design office. Despite the power of modern computers, it was found preferable in the initial stages to work towards an optimum structural system by means of physical models. Because a cable net is flexible and adapts to partial crowd loading by changes in shape, great care was required to ensure that these would not overstress the stiffer concrete slab. Much effort went into the design of the saddles for the tops of the masts and the nodes at the low points, where the net is pulled downwards against concrete foundations, to ensure that it remains taut under all conditions of loading. A special support – a short prop designed to rest on the cable nodes – was developed to carry the concrete slab.

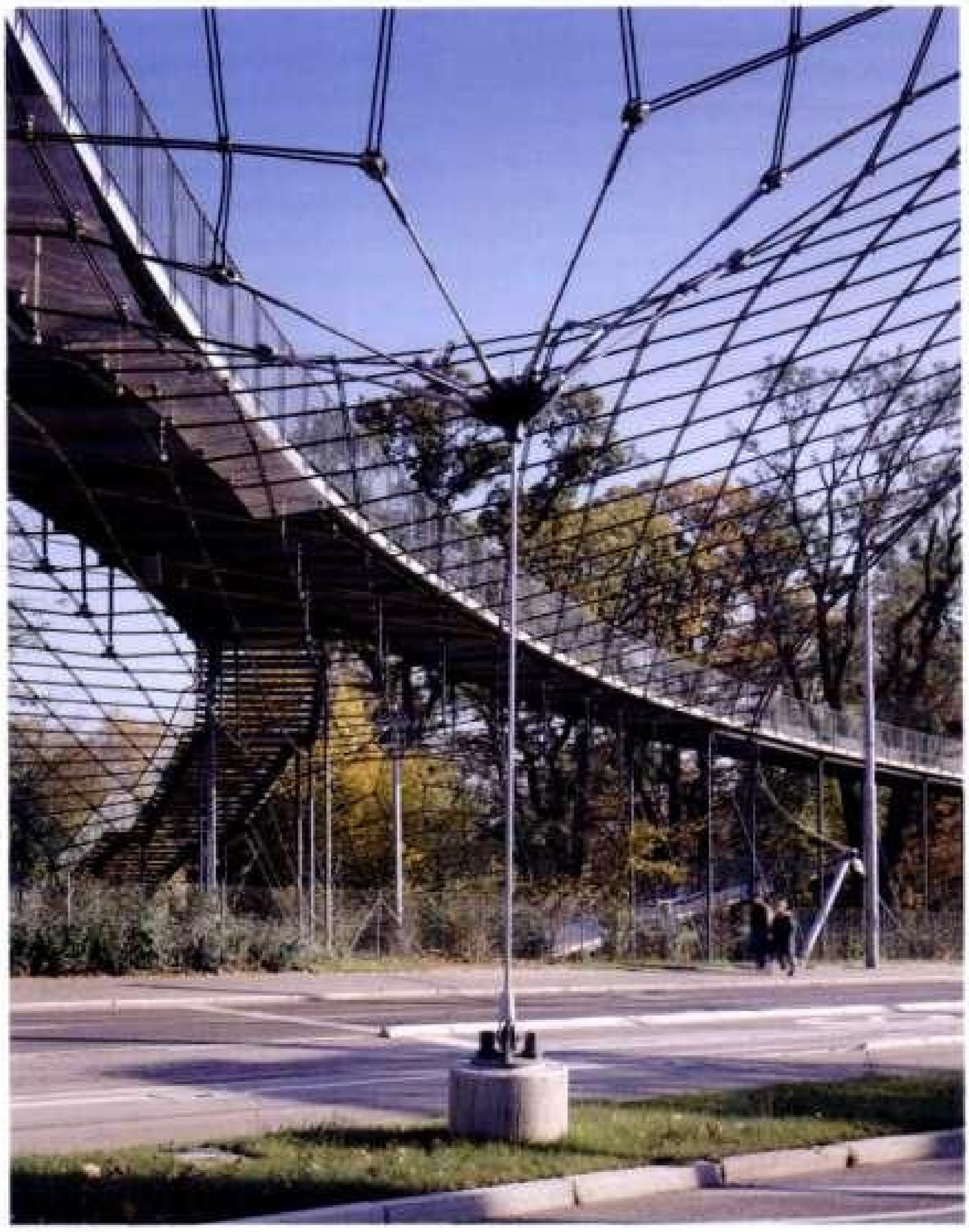
Schlaich is happy to have had the chance to build such a bridge, but he would have preferred to have utilized the concept in a more congenial location. The Lowentor net is cramped by the excessively restricted nature of the site. Once again there was a limitation on height imposed by the level of the approaches and the six per cent limit on the slope of ramps. It was necessary to fit the net just below deck level, but just above the high tension wires for the trams, and to avoid the horizontal arms of numerous street lights. It is woven over some of these and under others. To provide clearance for trams and heavy goods vehicles while avoiding these other obstacles, sudden changes of direction are necessary and the flowing form characteristic of cable nets is lost. Because of the shortage of points suitable for footings, one mast is located close to the wall of a nearby house where its inclination is limited and it appears somewhat incongruously surrounded by parked cars. Advantage is taken of a narrow median strip to locate the footing of another mast and the ground anchor for its associated stay cable. The force in

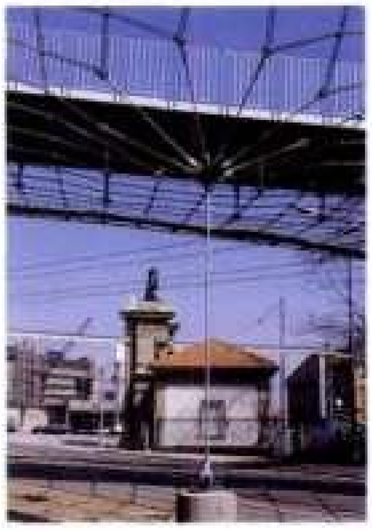


9.90
A view generated by computer

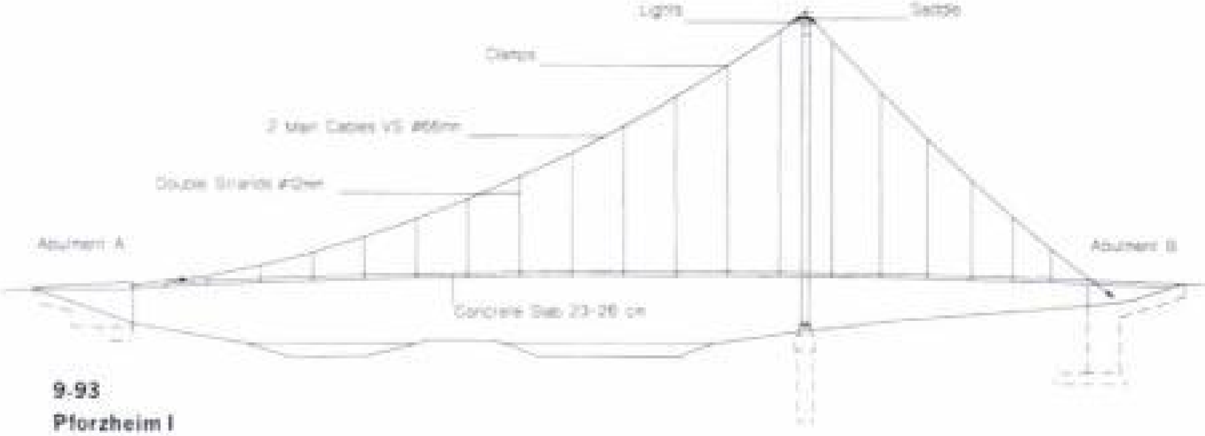
the stay cable must thus follow the line of the median strip and this does not suit the balance of forces at the head of the mast. This means that the edge cables of the net at that point cannot be placed in their optimum position and must carry much higher forces. To avoid encroaching on clearance limits, the "low point" of the net is pulled down much more sharply, and is much more localized, than would have been desirable for best aesthetic effect. Thus the brilliance of conception and execution cannot be fully expressed because of the severe constraints of the site. Nevertheless the cable-net bridge is exciting visually and technically. Its full effect will not be evident until it has been covered with vegetation.

Schlaich was aware of the limitations of the site when he conceived the scheme, but felt he ought to seize the opportunity to give some indication of its potential: "If we can get the idea across to people, perhaps we shall get a chance to do it elsewhere." It is interesting to speculate whether the cable-net bridge concept was inspired by his experience of walking over the roofs of the Munich Olympic Stadiums while they were under construction. Non-engineers who use the bridge are surprised to note how stiff and inflexible such a light cable net can be when shaped into an appropriate form and pretensioned.

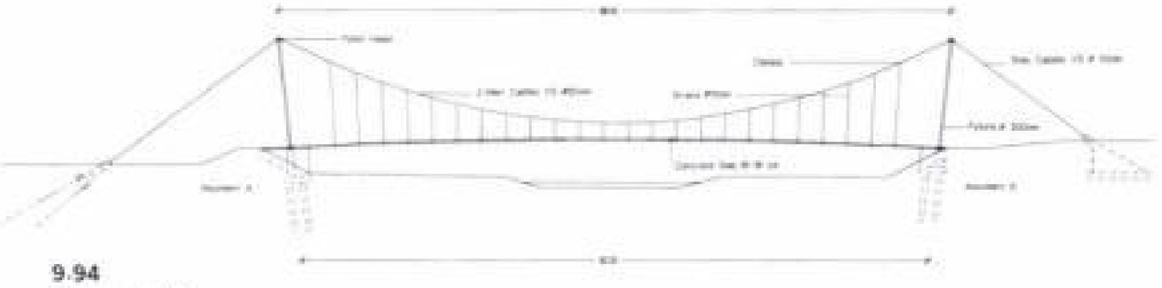




9.91+9.92
A low-point in the net where it is pulled down by a tensioned anchor rod. A row of deck props may be seen

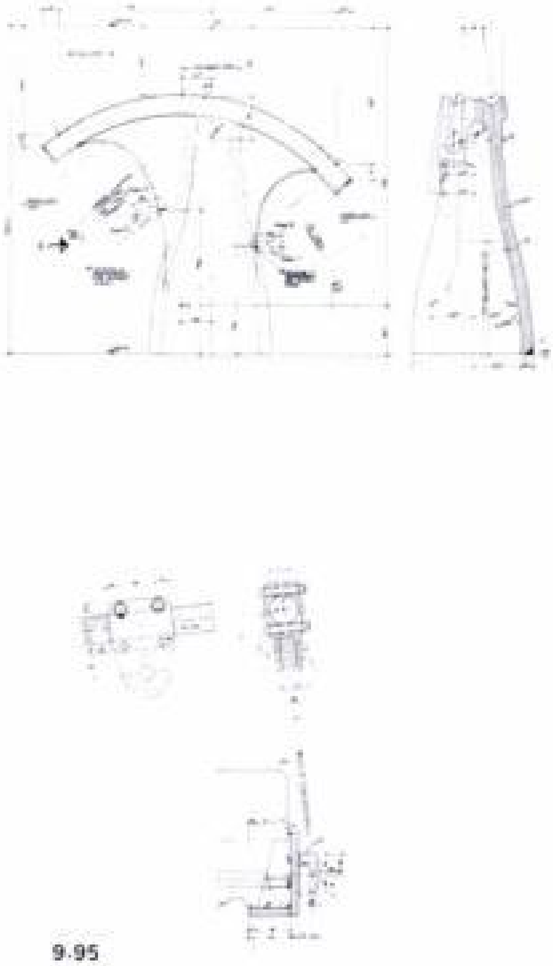


9.93
Pforzheim I

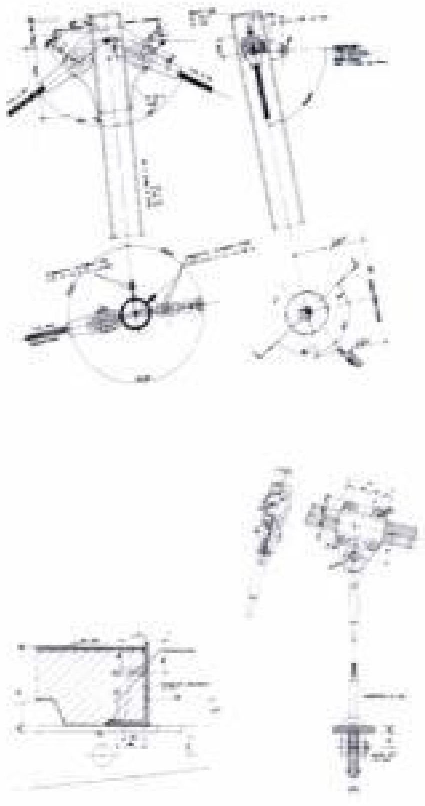


9.94
Pforzheim II

A pair of cable-supported pedestrian bridges built across the River Enz at Pforzheim for the city's **1992 Landesgartenschau (LGS)** hark back to Schlaich's earlier designs. **Pforzheim I** (9.93+9.95+9.97+9.98) is closely related to Rosensteinpark I though with quite different detail. **Pforzheim II** (9.94+9.96+9.99 to 9.103) is a development of the Kochenhof bridge but is more than double the length (88.4 m) and symmetrical, with masts at each end. The lower prestressing cables used to hold the Kochenhof deck down have been omitted. Even so, Pforzheim II has a slender concrete deck with a maximum thickness of 180 mm. The masts, now again simple tubes, were leaned out markedly, to provide visual interest and simplify the anchorage of the hanger cables to the deck, and were stiffened by the addition of bracing cables. A test carried out with a group of "volunteer pedestrians" showed a build-up of lateral vibrations which some of them found uncomfortable. This type of lateral vibration is very unusual and had rarely been seen before. It increases with the number of users because they tend to synchronize their steps to accord with the motion of the bridge. In fact this vibration was only observed once more at Pforzheim, and that was during the opening ceremony when the bridge was full of people.



9.95
Details I



9.96
Details II

9.97+9.98
Pforzheim I

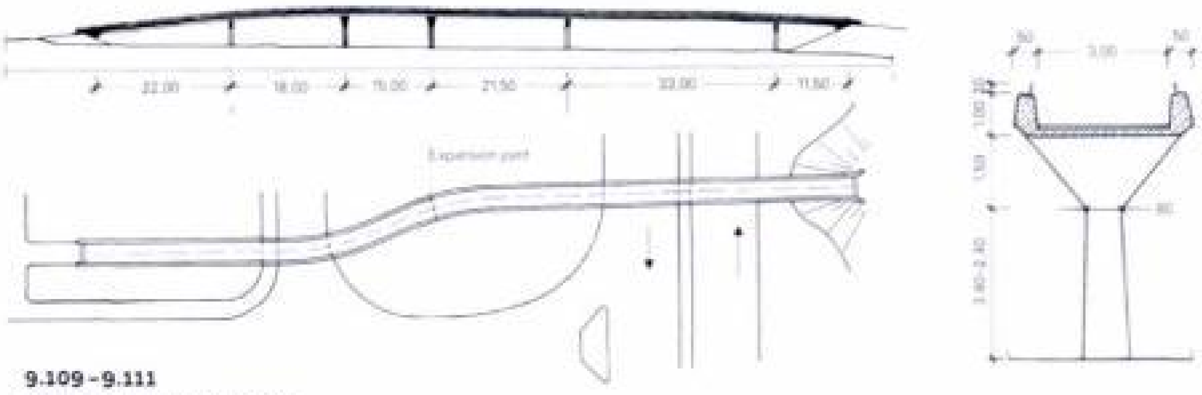
9.99
Pforzheim II: Before the railing was unfortunately painted white

9.99 – 9.103
Pforzheim II footbridge
(continued overleaf)

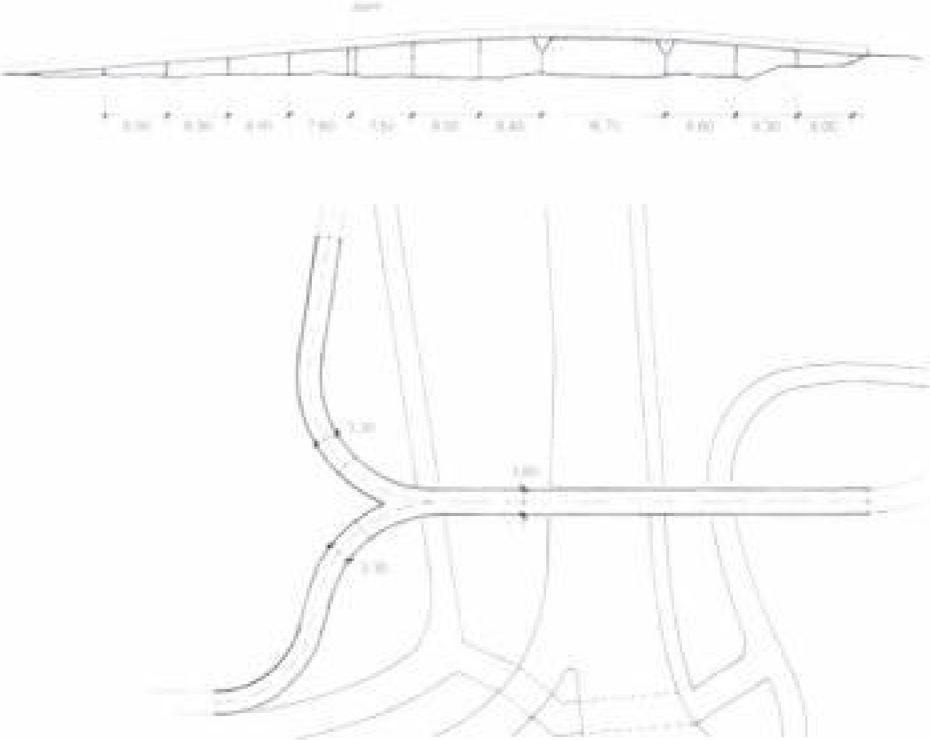
In a line of development which parallels that of the cable-supported footbridge, the partnership's quest for minimalism has led them to refine the art of supporting thin multi-span strips of concrete above the traffic on delicate tubular steel props which branch like the boughs of a tree (9.117). There are certain urban environments which call definitely for one form rather than the other. The decks of propped-slab bridges must have greater bending strength than those of cable-supported bridges, because it is neither convenient nor economic to provide support from below as frequently as it may be provided by cables from above. It would be possible to throw a simple girder bridge clear across a wide road and its adjoining pavements, but the girders would be extremely deep and therefore oppressive. Schlaich's solution has been to provide slender unobtrusive supports at relatively frequent intervals, as conditions allow, and adopt a "high-tech" approach to design and construction to achieve a similarly slender deck (see also the high speed rail bridges mentioned in Chapter 8 and illustrated in 8.94 – 8.97).

There is a technical advantage in making the columns as slender as possible. The deck may be made continuous over the whole length of the bridge and anchored at one end only. As the deck lengthens and contracts with temperature change, the tops of the columns move with it. The columns flex and develop bending stresses. However, slender columns offer less resistance to this movement and develop lower stresses. The thickness of such a column is determined only by the need to prevent buckling under the weight of the deck and crowd loading. The continuity of the deck over the tops of the columns has another advantage: it reduces the bending stresses in the slab, permitting an even thinner cross-section. The closer the supports, the thinner the deck may be. Thus we arrive at a concept of a very thin deck supported on slender columns which is totally in keeping with Schlaich's personal philosophy of structural design.

The pedigree of this family of footbridges starts with the **Heinrich-Baumann-Straße** bridge, connecting a residential area of **Stuttgart** with the lower Schloßgarten, and built for the Bundesgartenschau (BGS) of 1977 (9.109 – 9.111). A similar bridge was also built at Stetten. The maximum span in the first bridge is 33 metres across two lanes of traffic. To obtain maximum resistance to bending, the "handrails" are low concrete walls, made integral with the deck slab to form a beam of trough-shaped cross-section. With the aid of prestressing, it was possible to keep the total depth to 1 metre, giving a span-to-depth ratio of 33. There are six spans, and the deck is fixed to the abutments at each end with the expansion joint placed in the middle of the bridge. The columns are longest at this point, where the greatest movement takes place, and so the maximum flexibility occurs where it is most needed. The facets of the side walls are elegantly shaped, however in reality the weathered concrete appears heavy and something of the desired lightness is lost.



9.109 – 9.111
Heinrich-Baumann-Straße footbridge



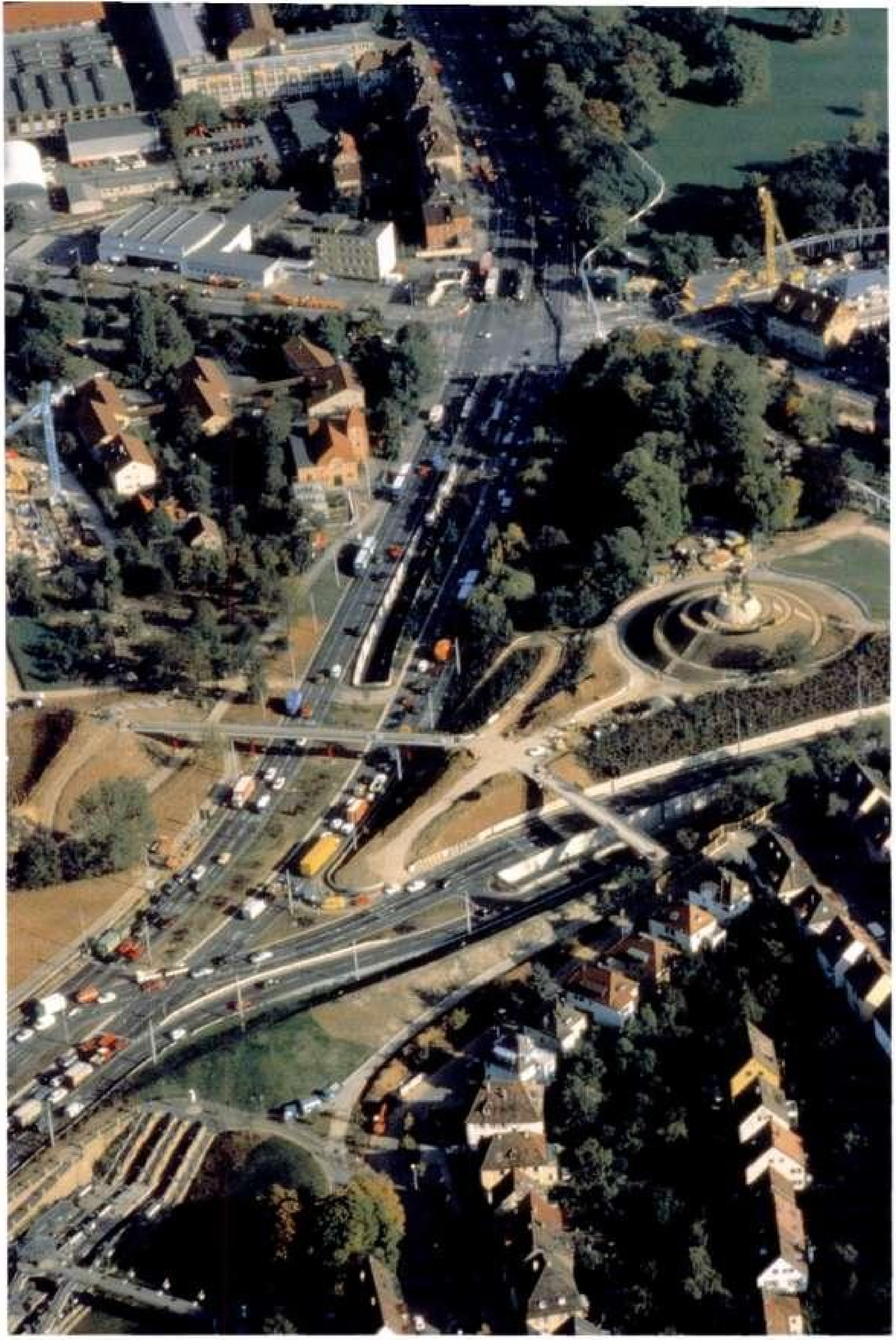
cast steel joint

9.112 – 9.114
The Sindelfingen footbridge

For a footbridge at **Sindelfingen** with a similar function, built in 1986, Schlaich abandoned the upturned concrete walls, and reduced the height of the deck by providing more frequent support (9.112 – 9.114). The longest distance between columns is 16.7 metres, and the shortest is 7.5 metres. The columns themselves are slender pipe sections with a maximum diameter of 267 mm. Those adjacent to the main span have four branching arms which further reduce the effective span of the slab. Advanced cast-steel technology was employed to produce the joints which make the branching form possible, and the flanges which connect the tubes to foundations and deck. Schlaich was concerned at one stage that the supports, like the fingers of an upturned hand, looked somewhat "childish" on the engineering drawings. However, he is content that they work really well in reality. The concrete slab is prestressed, with a thickness of only 300 mm and has a single expansion joint not quite at the middle of the bridge. In appearance, the bridge is very light and simple, set in a section of suburban greenery which it tries in no way to dominate. It is an excellent example of the reticence of Schlaich Bergermann architecture.

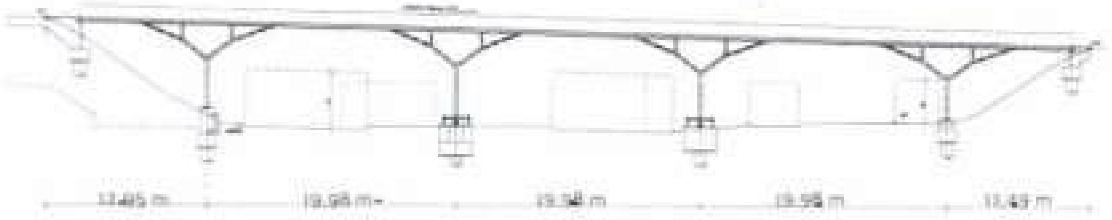
The two footbridges at the Karl-Benz Platz in **Untertürkheim**, built in 1981, are a development of the Sindelfingen bridge to suit an urban streetscape (9.115). Here, the thin supports, and even the ribbon of the footpath, become lost in the visual jungle. Once again, the structure is as unobtrusive as possible. The approach paths trace curves in three dimensions, another hallmark of the partnership's designs. Hans Schober was in charge of these projects.

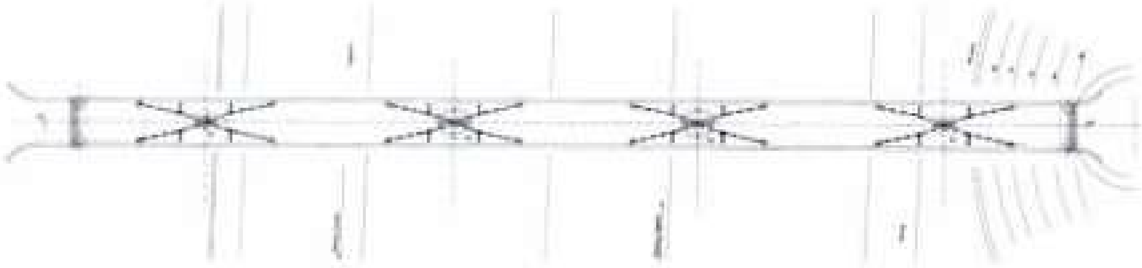
9.115
One of the two Untertürkheim footbridges



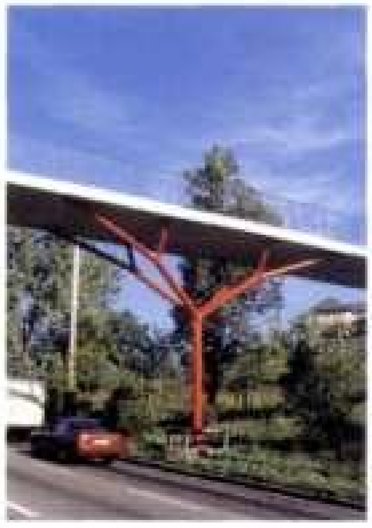
9.116
An aerial view of the Pragsattel (see also 9.74) with its two bridges (9.117–9.124) at the centre and the Löwentor cable-net bridge (9.87 to 9.92) – with the yellow crane – in the background

A recent, further development of this theme is a footbridge designated **Pragsattel II**, built across the Pragstraße for the 1993 International Garden Exhibition in **Stuttgart** (9.117 to 9.121). Here, the deck is straight and therefore somewhat less interesting than in the other two cases. The columns, with their branching arms, have become veritable trees with many complex cast joints. In side elevation, they appear to arch over the roadway to support the deck, so that the profile intentionally echoes the arch of the adjacent Pragsattel I footbridge over the Heilbronner Straße. (see also 9.116)





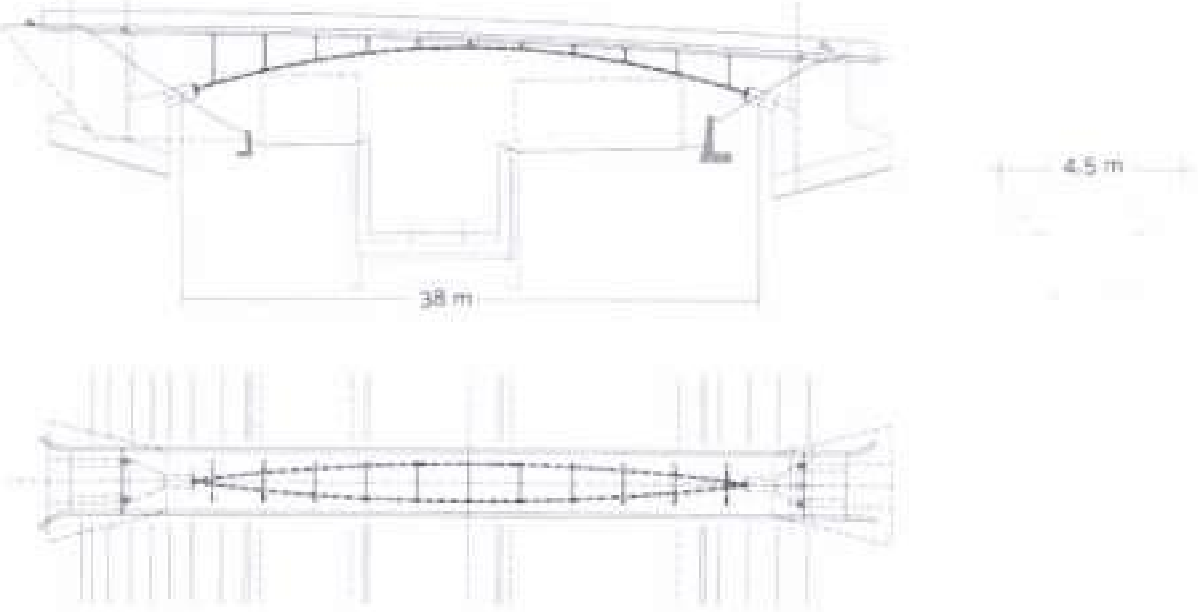
Pre-assembly of a tree-column from tubes with cast steel joints



9.117–9.121
Pragsattel II footbridge

The **Pragsattel I** footbridge, also built for the 1993 Exhibition, spans the Heilbronner Straße where it passes through a deep cutting, providing an ideal site for an arch (9.122–9.124). The span is 38 metres and the form chosen is known as a Stabbogen, similar in principle to Maillart's famous concrete road bridge at Schwandbach in Switzerland.[13] The structural concept is elegant because the two major structural elements provide each other with mutual support. The arch helps carry the weight of the deck and its loads, while the deck provides most of the stiffness required to prevent the arch from buckling under axial compressive force. Schlaich likens the Stabbogen to an inverted suspension bridge. Comparing Pragsattel I and Pragsattel II, we can see that, as in so many of their projects, the partnership has approached the same structural form from two opposite directions. In the Pragsattel I bridge, the solidity of the earlier arch forms has been dissolved into a pair of thin steel pipes, while in Pragsattel II the thin vertical columns of the beam bridges have grown branches and are tending to become filigree arches.

The structural concept of Pragsattel I is ingenious. Schlaich had been fascinated by it for many years, playing with various possibilities and refining it in his mind until the right opportunity occurred to put it into effect. Once again, there is a subtle three-dimensional play of form and force. The arch is composed of two tubular steel members meeting at the supports, but splayed out towards mid-span. The deck is supported from these by props which appear vertical in the elevation, but are inclined at varying angles when the bridge is seen in cross-section. It is allowed to expand and contract outwards from mid-span, its far ends supported on sliding bearings. The props have sufficient flexibility to accommodate the movement, while the arch itself adjusts to expansion and contraction by a slight rising and falling. The white deck slab, whose extent is determined by functional requirements, dominates the form, and the dark red metal substructure which supports it seems insubstantial in comparison. Pragsattel I and II were designed by Ulrich Otto in the office.



9.122–9.124
The Pragsattel I footbridge

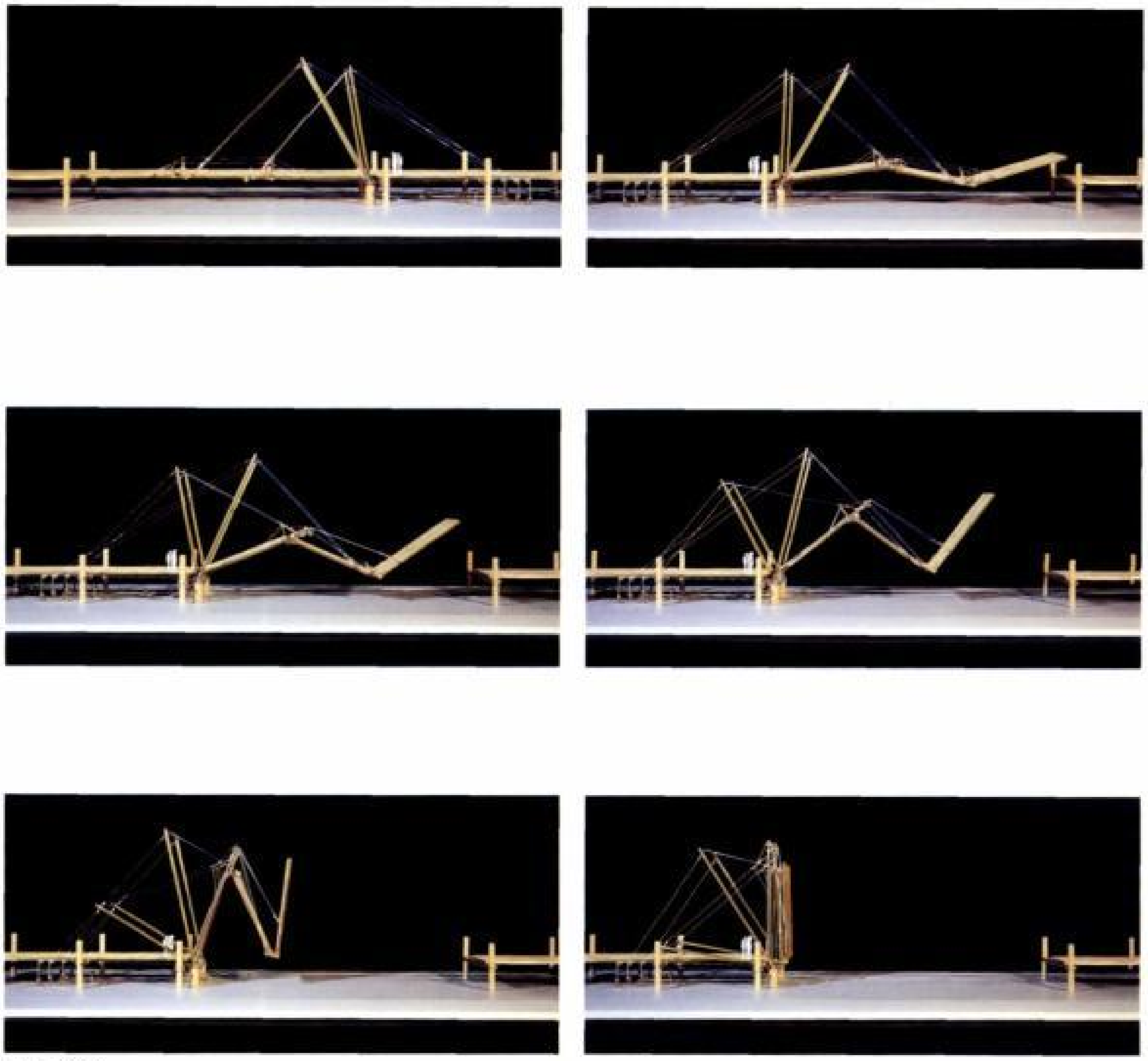
9.128
The Bad Windsheim footbridge

It would be possible to devote an entire book to the Schlaich Bergermann footbridges.[14] Some more have been completed during the coming into being of this book, such as at Minden over the Weser, close in character to the Max-Eyth-See bridge. Beyond those already mentioned, Thomas Moschner, Xavier de Nettancourt and Kirsten Martin were the designers. Two of these bridges deserve special mention because their utilitarian aesthetic sets them apart from most of the other suspended footbridges. A small access bridge ("only 32.5 m long") at **Bad Windsheim** spans the tracks near the railway station to connect the car-park to the spa gardens (9.128). This bridge was designed in cooperation with the architect Eberhard Schunck, a former colleague of Schlaich's at Stuttgart University, and was built in 1988. The suspension system here is composed of steel flats rather than cables, and is somewhat reminiscent of the "link chains" of early nineteenth century bridges. However, the linkages are few in number and change direction abruptly, in a direct display of the equilibrium of forces. As usual, the end of the shorter span must be held down by a pendulum link so that it does not lift when the longer span is fully loaded. The deck of this bridge is so slender that when this situation occurs, the shorter span bends visibly upwards. It is therefore tied down by special linkages attached at its mid-point and anchored to the ground. The workmanlike form of this bridge and the sparsity of material employed relate well to the utilitarian nature of its immediate surroundings: the station and the railway yards.

A small bridge at **Herrenberg** is of quite a different nature. It crosses a main road to connect a shopping centre to a car park and is therefore covered and provided at one end with a lift and stair. The design concept was to make the bridge as transparent as possible so as to interfere as little as possible with the medieval townscape (9.129 - 9.131). The bridge was designed with the architect Hans-Georg Reinhardt and the engineer responsible in the design office for both bridges was Dietger Weischede.

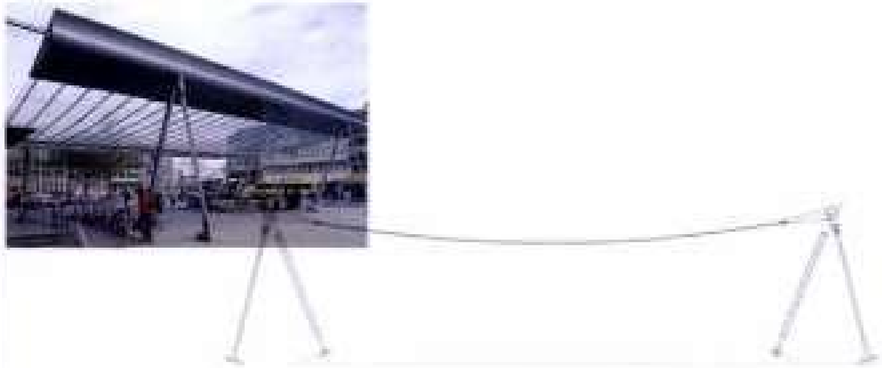
9.129 - 9.131
The Herrenberg enclosed footbridge

Finally, a small drawbridge which is under design at the time of writing, provides a fascinating new branch of development. Schlaich is cooperating on this project with Volkwin Marg, the architect of the Hamburg glass roof. The bridge is to cross the Forde, the natural harbour fjord at **Kiel** on the Baltic Sea and its moveable part alone has a span of 26 metres. After studying numerous alternatives and shunning clichés ("no nostalgic van Gogh, no invisible hydraulics") the team arrived at the idea of a folding deck supported by cable stays. Jan Knippers contributed many good ideas to this develop-



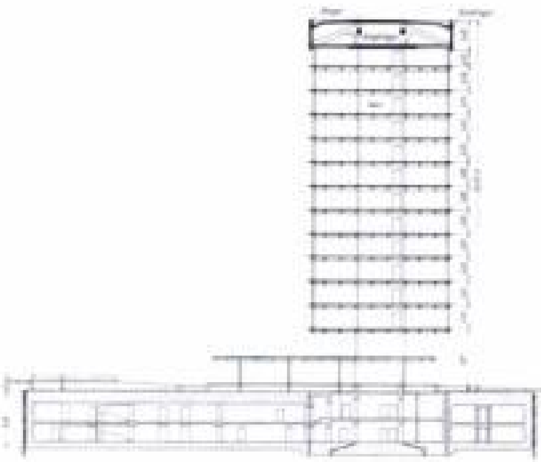
9.132 – 9.143
The moveable bridge at Kiel (under design)

ment. As the deck "concertinas", the two supporting masts tilt and the cables follow the movement. This should, Schlaich hopes, make the process of opening and closing "a delightful event" (9.132 – 9.143).



10 Suspended Buildings and Roofs

10.1–10.4
The Finnlandhaus in Hamburg



Many structural engineers have some interest in architecture, but when this goes further and extends to dedicated collaboration with architects in the shaping of architectonic form, they can make a substantial contribution to the holistic quality of buildings which goes far beyond their conventional duties of structural design. Although mention is made of fruitful collaboration between the Schlaich Bergermann practice and various architects in the different chapters of this book including Chapter 12, it would be beyond the scope of this book to delve into this aspect of the partnership's work in detail. However, brief mention is made below of a number of projects in which the structure is more dominant than in conventional small- to medium-sized buildings and which may be summarized under the title "Suspended Buildings".

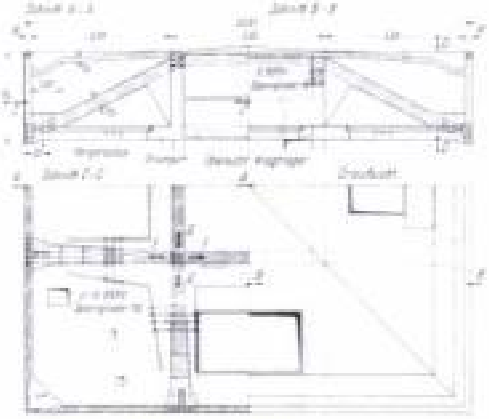
An episode which Schlaich now sees as being of somewhat minor importance was his involvement in the design of suspended multi-storey buildings in the 1960s and 1970s. The concept appeared to offer great advantages to both architects and engineers. It arose because the size of the columns in a normal building is governed by the need to provide sufficient stiffness to prevent buckling under compressive load. As a result, their cross-section is rarely stressed to the full capacity of the material. However the core of many buildings consists of a large rectangular or circular concrete shaft whose overall dimensions are determined by the need to enclose the stair wells and lifts. The central shaft thus has stiffness and strength to spare. Designers realized that by projecting massive arms from the top of such a shaft and suspending the outer edges of the floors from them on hangers, the full weight of the building could be thrown onto the core (10.1). Because the hangers would be in tension there would be no danger of buckling and the strength of the material could be fully utilized.

The concept also simplified the problem of thinning out the columns on the ground floor. In prestige offices and hotels it is conventional to provide grand entrance halls with tall, widely-spaced columns. With a conventional structural system this creates difficulties for the engineer. The closely-spaced columns of the upper floors must be supported on heavy "spreader beams" or trusses at first-floor level to distribute their load to the fewer columns available to carry it to the ground.

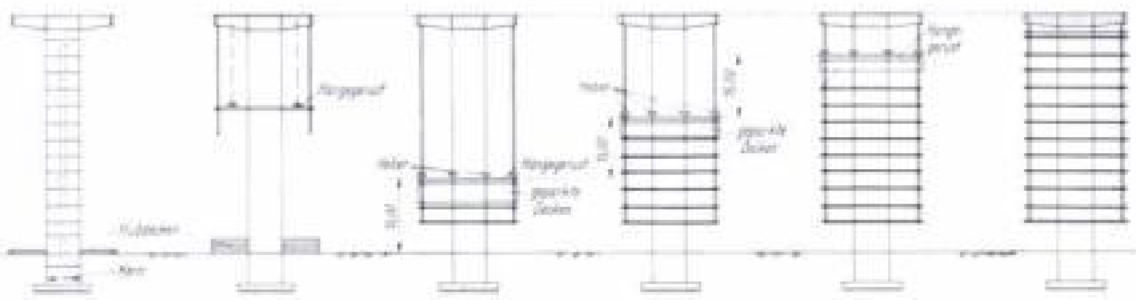
There were also advantages in construction. The core could be erected speedily using the slipform technique. Working surfaces and formwork for the slabs could then be assembled conveniently on the ground and hoisted to the desired level to hang suspended from the outriggers. The site at the bottom of the building could be less cluttered, providing free access to delivery trucks and eliminating the need to annex local streets and land for storage of materials and parking.

Schlaich's involvement in such buildings started in 1963 with the **Finnland-Haus in Hamburg**, his first project with Leonhardt und Andra (10.1–10.4.). The partner in charge was Kuno Boll (under whom Schlaich also later tackled the Olympic Competition, 5.2), and the architects Hentrich and Petschnigg. Their justification for employing the system was that the congested nature of the surrounding streets would have seriously interfered with construction work on a conventional building.

Although the promise of this form of construction was not fulfilled, Schlaich is happy about one aspect. The roof structure of the Finnland-Haus incorporated large concrete shear walls cantilevered out to support the



The cantilevering structure on top of the core



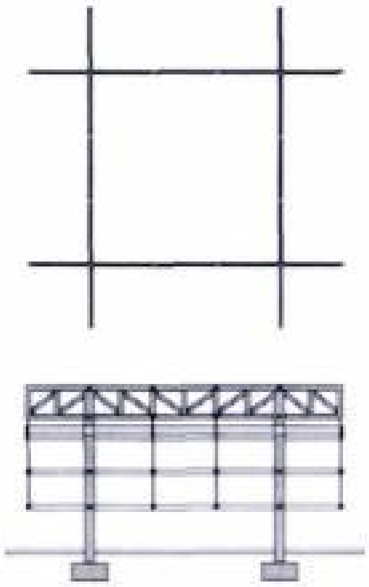
A proposed construction process

tension members. Their design provided an early opportunity to use the "strut-and-tie" concept as later developed at the Institut in Stuttgart (12.1). The walls were assumed to contain a series of diagonal members carrying tension, while the ceiling slab and parts of the walls acted as compression members. It was then possible to calculate the forces in the theoretical tension members, and position prestressing cables to carry them. Finally the team used the concept as a tool for design in changing the physical form of the wall to accord with the envisaged flow of forces and thus create a truss comprised of a strut and a tie (10.3).

In a series of buildings for the **Hochschule der Bundeswehr in Hamburg**, built between 1974 and 1978, the justification was a need for flexibility. With the rapid expansion of tertiary education in the 1970s, the authorities demanded buildings which could be easily adapted and extended. The architects, Heinle, Wischer & Partner, responded with a design for a series of isolated blocks, square in plan, with sides of 36 metres. The structural engineer's contribution is clearly evident (10.5 + 10.6). Each pavilion stands on four columns, spaced 21.6 metres apart. The two upper stories are borne primarily by four large truss girders above the roof surface. Suspended from these is a secondary grid from which the two floors are in turn suspended by steel tie rods at 7.2 metre intervals. The ground floor is free of loadbearing components except for the four main columns.

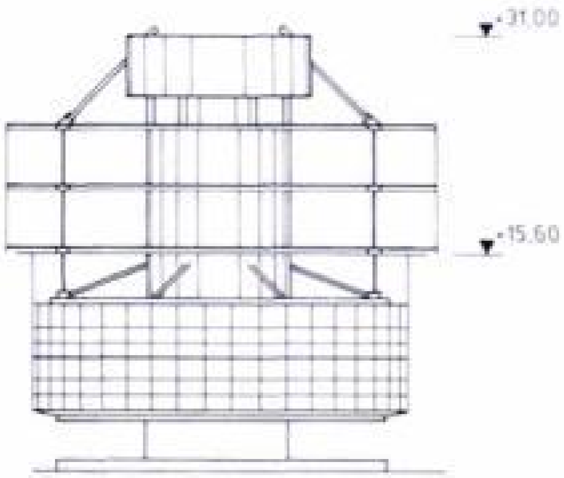
An office block designed by the architect Uwe Kiessler for a **Munich** insurance company, the **Bayerische Rückversicherung** was erected in 1976 and later extended (10.7 and 10.8). The rationale here was that because of the restricted site, the entrance tunnel to the underground carpark encroached on the plan area of the building, making it difficult to position conventional columns.

10.5 + 10.6
Hochschule der Bundeswehr in Hamburg



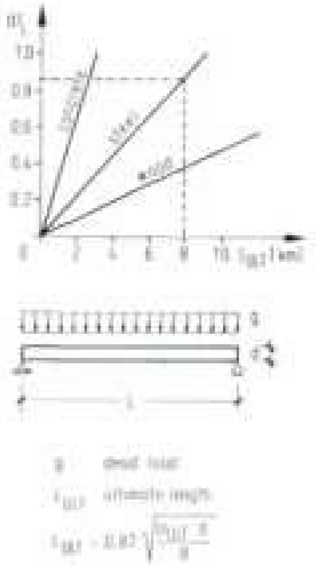
Plan and section

10.7 + 10.8
The Bayerische Rückversicherung offices in Munich



Section/View with later extension

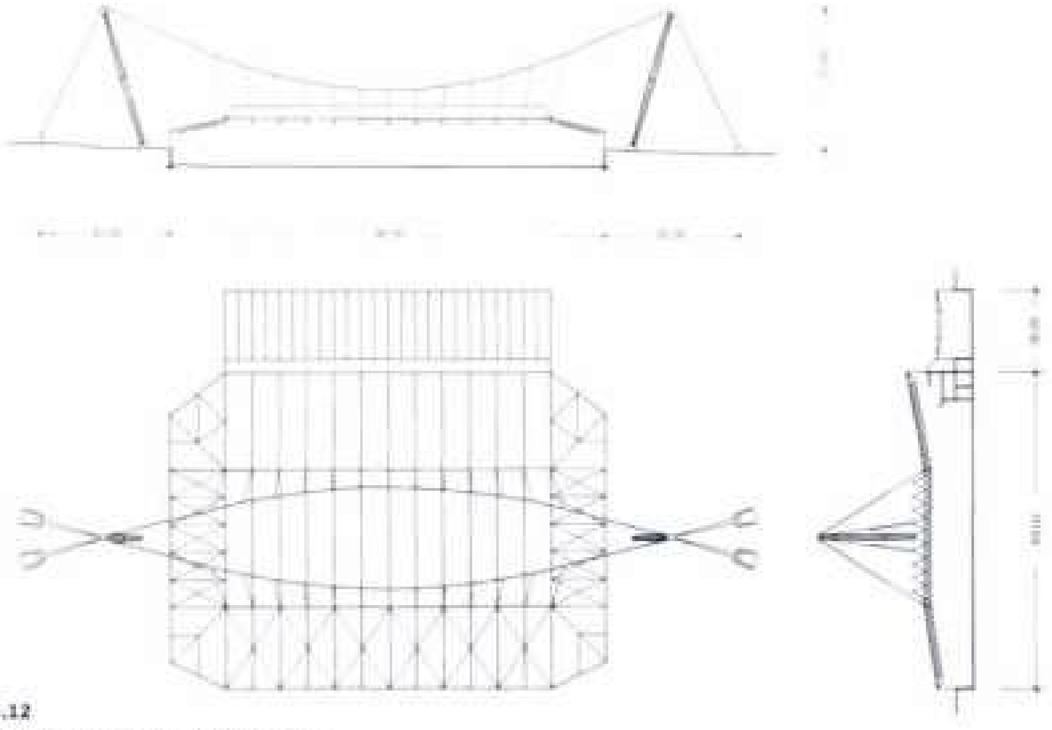
10.9
Nature tells us, that with increasing size a structure becomes more clumsy



10.10
Ultimate span of a beam carrying its own weight and required ratio of depth "d" to span "L"

10.11
The Europahalle in Karlsruhe

A more successful story in recent decades has been the development of suspended roofs for large-span buildings. To ensure sufficient strength and stiffness, the depth "d" of a beam must increase with its span "L" and the required ratio of d/L is by no means constant, as is usually assumed in the "rules of thumb" used for preliminary design (10.9 and 10.10).[1] In wide buildings such as factories and sports arenas, roof beams tend to be heavy, clumsy-looking, and expensive. There is a large volume of space below the roof, within the depth of the beams, which is heated and air-conditioned to no advantage. One solution to these problems is to extend the columns above the roof line to form masts. Sloping tie rods, attached to the tops of the masts, provide the roof beams with additional points of support. This greatly



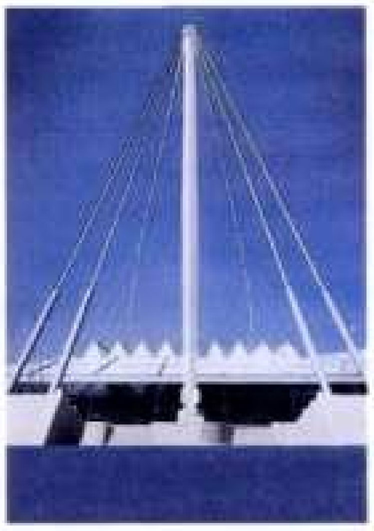
10.12
Plan and sections (the transverse section already shows the roof lifted at the right hand side)

reduces their effective span and hence their required depth. The system has been much favoured by architects in recent years. As often happens, its adoption has created a style, and this has been taken up and used by some architects in cases where there is no economic justification for it. Unfortunately, many architectural critics are unaware of this, or are unconcerned by it, and are happy to classify all such buildings as "high-tech".[2]

In 1978 the city of **Karlsruhe** selected a group of local architects to take part in a limited competition for the design of a large multi-purpose hall known as the **Europahalle**. Schlaich and Bergermann were asked by one of the entrants, G. Kasimir, to join him as structural engineer. The requirement was for an approximately rectangular column-free space of 96 m x 69 m. The influence of the partnership's experience with bridges is immediately evident in the two large masts at each end of the building and in the sweeping lines of the two main cables (10.11 - 10.15). The roof members take the form of trusses, spaced at intervals of 6 metres. Because they are supported by secondary cables at two intermediate points along their 72-metre span, they need be only 1.25 metres deep. Borrowing another concept from their footbridges, the engineers tensioned the whole roof system by jacking the masts upward, against the restraining force of the cables, before packing their bases. (Their first use of this technique was in the Rosensteinpark footbridge, Chapter 9) The architect insisted that the brackets needed at the base of the mast to facilitate jacking should be kept as a permanent feature (10.15).

Unfortunately, the building was not to retain its planned form. In the original design the roof sloped downwards on all sides. This was in keeping with the line of the stay cables and permitted a clear view of the cable system from all approaches to the building, making it possible for the public to understand how the clear internal space had been created. Shortly before construction was due to commence, the client decided that extra seating should be provided. Kasimir responded by tilting the roof of one of the longer sides so that it sloped upwards instead of down, allowing him to tuck a second tier of seats directly underneath the slope. The increased height of the eaves now obscured the suspension system from view on the very side of the building from which most visitors would approach it.

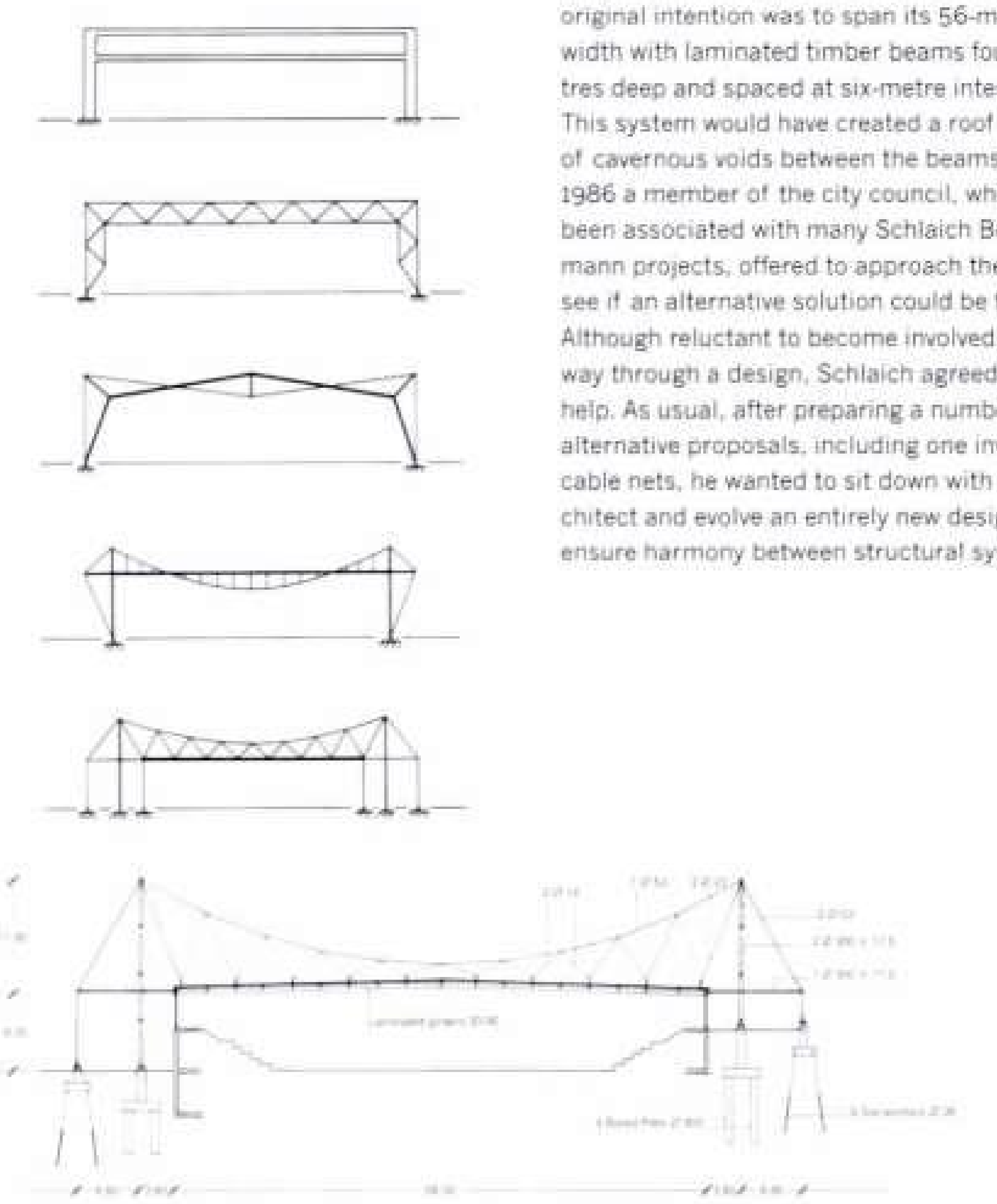
In Schlaich's opinion, the unity of the concept had been spoiled and most of its visual impact lost. He argued that architect and engineer should sit down and start all over again, conceiving a suspension system and envelope properly adapted to the new functional requirements. He felt it would now be more logical to run the main suspension cables across the width of the arena rather than along its length. But all alternative proposals were ruled out by the client because of the limited time available for completion of the project. Despite this, the image of the building, usually photographed from its better sides, has become very popular with the public.



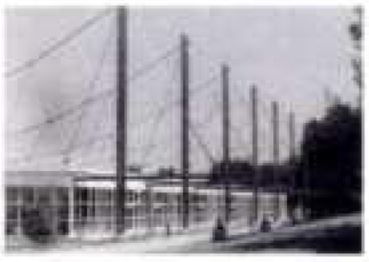
10.13 – 10.15
Details of mast and cables

The structure of the **ice-rink in Memmingen** clearly shows the technical advantages of suspension roofs appropriately applied. The original intention was to span its 56-metre width with laminated timber beams four metres deep and spaced at six-metre intervals. This system would have created a roof space of cavernous voids between the beams. In 1986 a member of the city council, who had been associated with many Schlaich Bergermann projects, offered to approach them to see if an alternative solution could be found. Although reluctant to become involved part way through a design, Schlaich agreed to help. As usual, after preparing a number of alternative proposals, including one involving cable nets, he wanted to sit down with the architect and evolve an entirely new design to ensure harmony between structural system and architecture.[3] Once again, the client and the architects were (understandably) unwilling to abandon all of their completed work. It was therefore accepted that the basic form of the architectural envelope should remain unchanged. After a study of several alternative structural systems (10.16) the design team settled for a series of bridge-like main suspension cables running across the width of the building. These have sloping hangers which support roof girders only 80 cm deep. Thus the external appearance of the roof was improved and the internal volume greatly reduced, with consequent savings in heating costs and lighter appearance (10.17 + 10.18).

Schlaich still feels that the bland, box-like form of the building envelope clashes with the bold lines of the structure. There is indeed a strange contrast. It is obvious that when the height of the roof was lowered by some four metres, the walls lost much in stature. No attempt seems to have been made to compensate for this, and the masts



Development of the concept and final cross section



10.16 – 10.18
The suspended roof of the ice-rink in Memmingen, 1988

Details of the masts, booms and cables

tower above them. The conventional detailing of the façade, though suited to the original timber roof structure, cannot compete on visual terms with the austere metal suspension system. Schlaich comments that he would rather not have been involved, but feels that "the final building is a lot better than an absolutely blunt box. You just have to do what you can". This is a situation over which he and his friend the architect Kurt Ackermann have agreed to disagree. Whereas Ackermann insists that one should get involved in a project only if complete control is assured to guarantee overall quality, Schlaich can imagine being satisfied - as in this case - if he has helped to improve a project, even if the final result is much less than it could have been. Schlaich summarizes Ackermann's position as "*Alles oder nichts* - all or nothing" and his own as "*Mehr als nichts* - more than nothing!" He sees in this an existentialist choice which must confront every designer.

When it was decided to erect a roof over the existing **grandstand** at the Bökelberg soccer **stadium in Mönchengladbach**, the municipal design office responsible for the project found itself facing major problems. For obvious reasons, the front edge of the roof could not be supported by heavy columns. An alternative was to cantilever it out from the back of the old grandstand. However, calculations showed that the existing structure would be unable to resist the additional forces. There would be high leverage due to the weight of the roof and wind forces in the upward and downward direction. It was therefore necessary to design a lightweight roof which would impose minimum gravity load on the substructure and would somehow be prevented from "taking-off" in strong winds. Schlaich, still with Leonhardt und Andrä but already working with Bergermann, was called in for advice. Working without architectural input, they devised a system consisting of two large masts placed clear of either end of the grandstand, with a suspension cable and hangers to resist the gravity load of the front of the roof (10.19). The masts would serve also to carry the floodlights required for night games. To deal with wind uplift, they employed a mirror-image system, throwing a downward-curving cable along the front of the stand. This causes a minimum of interference with the view of spectators.

At this point, mention should be made of some minor structures where the engineer's contribution is visible. Schlaich notes that although these are less spectacular than some of the larger structures with which we have dealt, they are in many ways more important because they are so close to the people. They include a **factory at Dachwig** for a client who wanted a large-span structure for functional reasons but also of distinctive form to provide corporate identity. These dual aims were achieved employing the same flat steel members as had been used at the Windsheim footbridge. Fritz Bacher was the project engineer (10.20 + 10.21).

10.19
The grandstand roof at Mönchengladbach, 1977

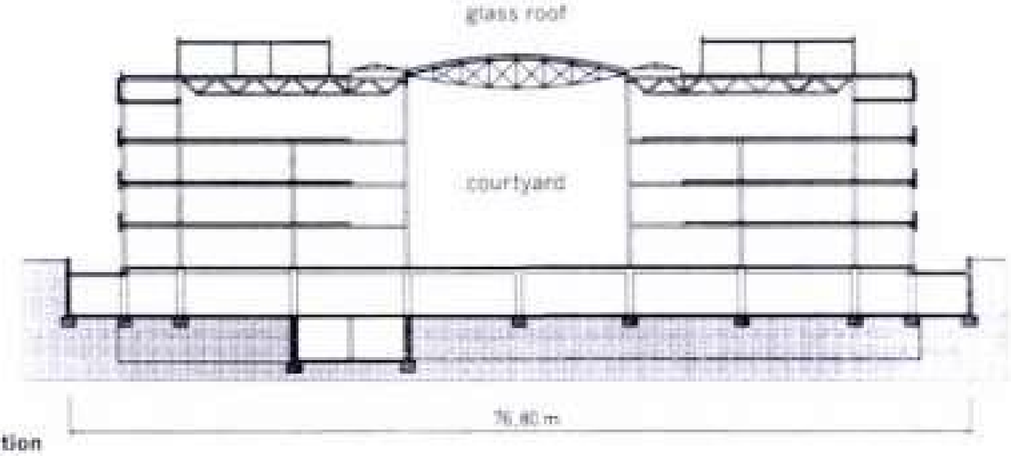
10.20 + 10.21
The Dachwig factory roof during erection, 1993

Two suspended glass roofs are worthy of mention. The **courtyard** of the new entrance-hall and multi-purpose building of the **Katharinenhospital in Stuttgart**, designed by architect R. Wischer and completed in 1992, has a glass roof with a span of about 20 metres. Schlaich sees the building as "imposing in its clean and restrained approach which makes it, in these days of 'post-modern' junk, one of the best built in Stuttgart in recent years" (10.26 – 10.28). The structure of the central roof, engineered by Hans Schober, consists of a composite deck and a "floating" stiffening system. Its cable girders are pretensioned using the slab of the surrounding roof as a tensioning frame. Because the members of these "trusses" are thus subjected to minimum compression, they can have extremely light sections combined with cables. The resulting transparency of the roof contributes to a pleasant ambience for patients and staff.

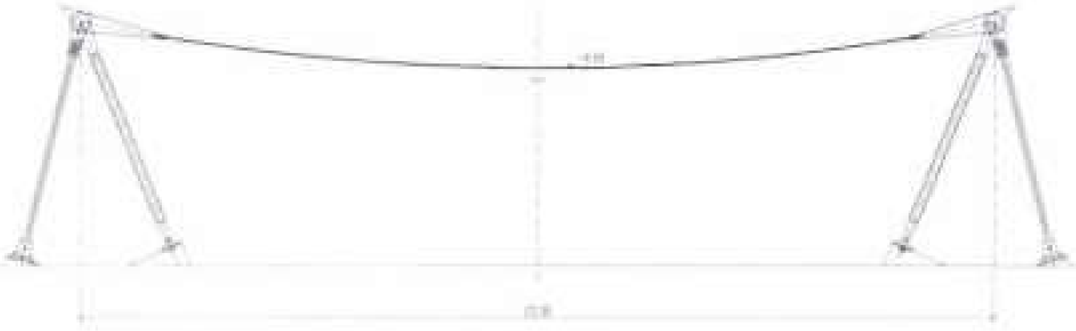
10.26 – 10.28
The Katharinenhospital, Stuttgart 1992


The courtyard with its glass roof


The front of the building



Cross section



The structural scheme
in cross-section

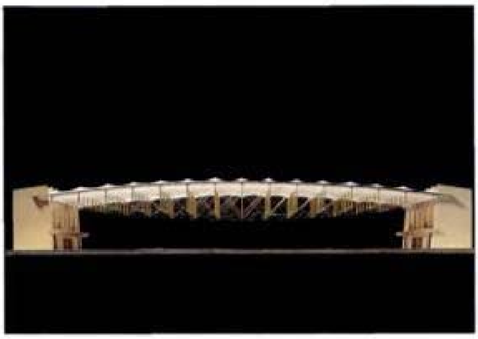
The **railway station at Ulm** was completely destroyed in the war and has recently been refurbished by the architect H. Gaupp in a restrained modern idiom which respects the historic cathedral and its 162-metre spire, the highest Gothic-style spire in the world, and harmonizes with the modern town hall designed by the New York architect Richard Meier. Gaupp's design included an extensive **canopy** in front of the main doors of the station to provide protection for passengers in transit (10.29 - 10.32). The structure proposed by Schlaich, with K. Friedrich and F. Simon as project engineers, is a pure, unstiffened hanging roof, similar in principle to the Pforzheim III footbridge, stabilized only by the dead load of its 10 mm thick glass panels which rest on 60 x 40 mm steel strips spaced at one-metre intervals. Edge beams with a wing-like cross-section collect the forces from the strips and distribute them to A-shaped strut and tie supports.

10.29 - 10.32
The suspended glass canopy in front of the Ulm railway station, 1992

The fairgrounds at Hannover will provide the setting for the **Expo 2000**. Compared with former events, there will be only very few temporary pavilions built specifically for the purpose. Rather, the **Hannover Fair** plans to provide permanent facilities which will be available to different nations or large industrial exhibitors as required. In that context Schlaich Bergermann und Partner became involved in two large exhibition halls, which were both nearing completion at the time of writing.

Hall 4, received first prize in a competition with the architect Volkwin Marg of Gerkan Marg und Partner of Hamburg. The Schlaich Bergermann office was represented by Sven Plieninger as project engineer, with Thorsten Helbig as designer. The hall covers a rectangular area of 112/184 m² without supports, using 18 cable girders of 122 m span and 9 m maximum depth, resting on parallel concrete walls (10.33 - 10.35). Initially it was intended to prestress the girders between the walls, as for the Katharinenhospital, but this had to be abandoned for cost reasons. Also, in this case the lightness of the girders would not have paid off, because for exhibition purposes such roofs should only be partially transparent. The compression members of these girders are made from steel tubes and the tension members from ropes, the tension members from ropes, the joints mostly from cast steel. The roof is partially covered with corrugated sheet, arching between the steel tubes, and partially with glass, lending this huge space a surprisingly light and transparent atmosphere.

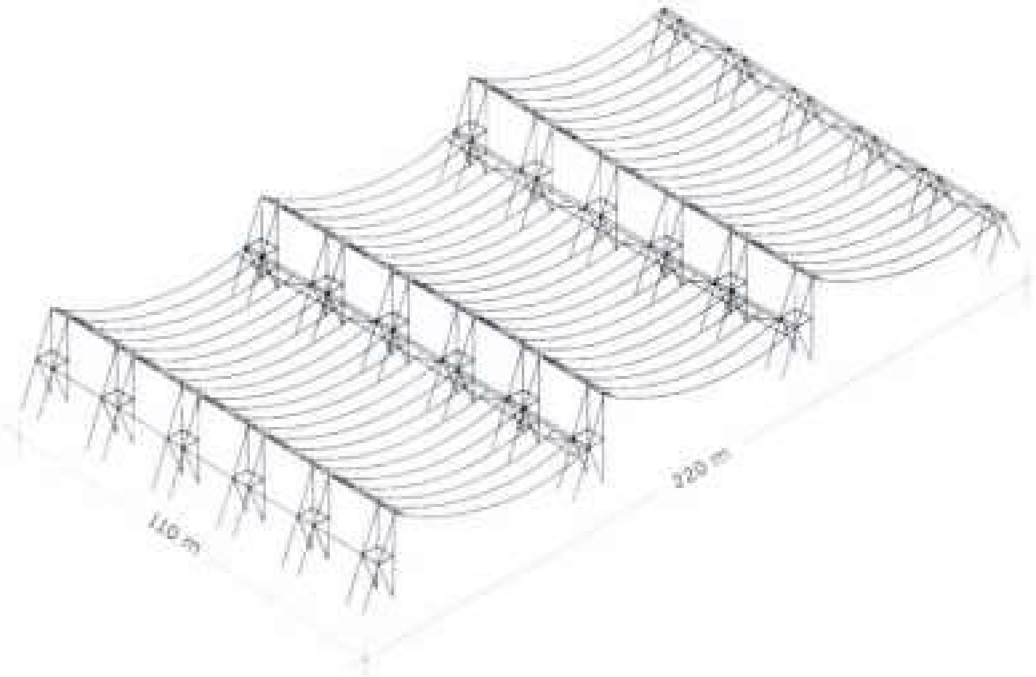
During construction



Competition model

Interior view

10.33 - 10.35
Exhibition Hall 4, Hannover Fair

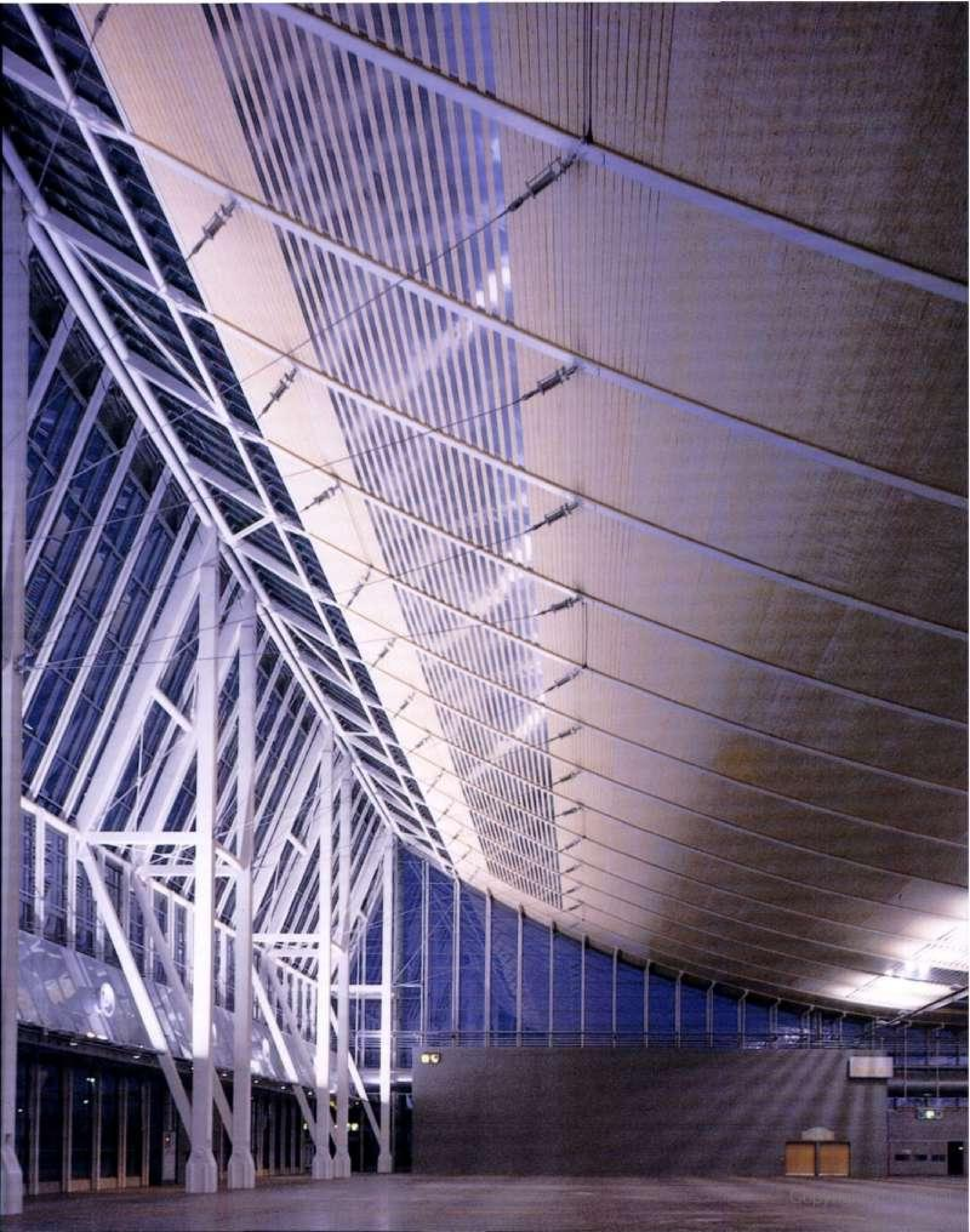


The architect of the other **Hannover Fair exhibition hall, Hall 26**, is Thomas Herzog and Partner of Munich. Frank Simon was the project engineer, with Hansmartin Fritz as designer. Covering a total area of 220/110 m², its three equal bays are covered with unstiffened suspended roofs, hanging between A-shaped strut-and-tie supports (10.36 to 10.39), similar in principle to the Ulm canopy. Steel strips 30 mm thick and 400 mm wide at intervals of 5.5 meters span 55 meters with a sag of 7 meters. Wooden panes rest on these steel strips and are expected to avoid aerodynamic exitation through their weight and natural damping. Wind tunnel tests were carried out to confirm predictions of wind loads on this unusual roof shape which was also chosen to provide natural ventilation.

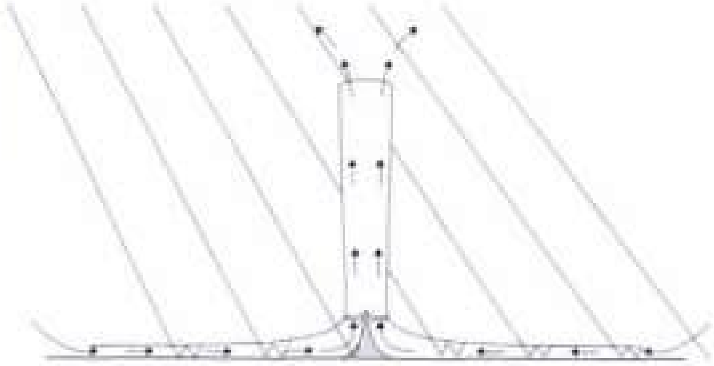
A suspended roof is predestined for wide spans: it creates a functional internal height and permits large glazed areas for daylight whilst excluding direct sunlight. The main column-free spaces are separated by narrow planted areas under the steel pylons which will provide access and recreation.

Despite its size and striking form, this hall is not monumental and has a bright and atmospheric interior. Structure and form are a clearly recognizable entity.

10.36 – 10.39
Exhibition Hall 26, Hannover Fair



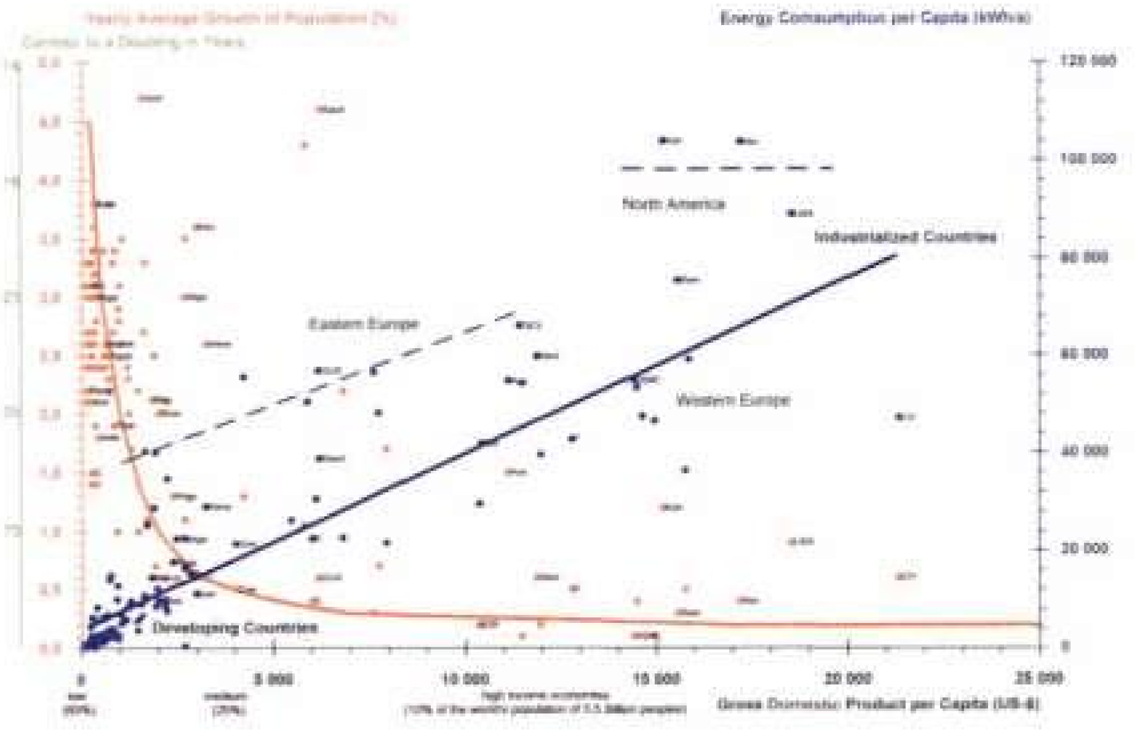
11 Solar Power Plants



As we saw in an earlier chapter, Schlaich is greatly concerned by the poverty of underdeveloped countries and by the threats to world peace and the environment posed by the population explosion and our reckless pursuit of economic growth. He sees the industrialized powers unable to make a rational analysis of the situation and lacking the will and determination to make significant efforts to avert disaster. His frustration is evident in the forceful language he used in an editorial for the journal *Die Bautechnik* in 1992.[1] Choosing as his starting point the latest preoccupation of the business world – "Lean Production" – he sees technology becoming a goal in itself and asks: "Are we out of our minds? Have we nothing better to do after the fall of communism and the end of the cold war than to further stimulate a damaging trade war in consumer goods? Will no one see that we are further alienating the Third World – depriving three quarters of mankind of their only capital which is their cheap labour and that through this madness we shall ruin the earth?" "... When we think of the emaciated children of Africa, it is pure cynicism to concern ourselves with 'Lean Production' when we should be working out how to help their parents achieve jobs and human dignity through a world-wide partition of work." He points out that people in underdeveloped countries must see children as a form of provision for their old age. The poorer they are, the more children they feel they need. Since coal, oil, and other fossil fuels are too expensive for the vast majority, and we may not export atomic power stations, they must cut down their forests to satisfy their immediate needs for energy. Thus a vicious cycle is established (11.1). Third World countries are forced into a new form of colonial dependency to ensure jobs for their people and a minimum of economic security. However, they cannot be expected to accept a situation of increasing misery indefinitely, and are likely one day to decide to take by force what is currently denied to them.

Schlaich sees the potential of solar energy as one way of breaking out of the cycle. It offers the technical and economic prerequisites for a new world energy economy. "In the Third World there are adequate dry, unutilized areas and three times the quantity of sunlight as here [in Germany]. With a fraction of the resources which have been expended so far on, for example, nuclear energy or manned space-flight, we could have attained a much higher stage of development of solar-energy use. However, we still have only small prototypes. In Germany ... all the development occurred in the 1970s." Since then, he notes, initiative has failed and a door has been slammed. However, it remains essential to build prototypes of a size approaching full scale. Schlaich asks, why does this not happen? The expense would be small in comparison to that of many other developmental projects, so our inactivity cannot be due to a shortage of money. "Is it because the idea of an explosive doubling of the world population within 35 years and its resulting impact on nature and climate exceeds the limits of our comprehension – so that we go and stick our heads in the sand? Is it impossible to understand the simple and obvious connection between population explosion, living standard, environment and energy – or do people simply not make time to consider the status and opportunities of solar technology?" "Has parliamentary democracy reached its end in the same way as communism? ... Is it incapable of tackling long-term problems: producing mere politicians rather than statesmen with imagination, courage and a sense of long-term global responsibility?"

11.1
The higher the standard of living in a country the more energy it consumes and the smaller is its population increase. Therefore a poor country needs energy to slow down its population increase. The graph compiled from World Bank Statistics '93 is taken from J. Schlaich, Das Aufwindkraftwerk, Deutsche Verlagsanstalt, 1994 (English: The Solar Chimney, Edition Menges, 1995)

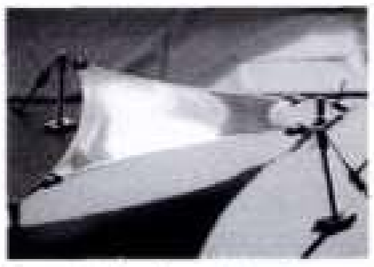


"It is incumbent upon us engineers to come out of our shells and bring our technical competence to bear where today the politicians rule in a vacuum, tied to the apron-strings of an irresponsible [energy] lobby." "There can be no more excuses ... The misery is there and the consequences are irreversible. Facing this challenge, and demanding that society show its credentials in making the necessary effort, is a pressing task for politics." Spurred by these considerations, Schlaich has visited many politicians and rulers at home and abroad to convince them of the need to invest money in solar energy, and above all to act before time runs out. This he was able to do following his involvement, at a practical level and over a long period, in the development of two promising types of solar power plant. He has not only guided the evolution of efficient and economical forms of construction, but has invested a great deal of energy and enthusiasm in working with mechanical engineers and economists on the overall concepts. The **two types of plant** lie at opposite ends of the spectrum. The first takes the form of a reflector dish which concentrates the sun's rays on a Stirling motor supported at its focal point. The idea here was to develop a plant which would be cheap, sturdy, and simple, so that it could be owned and operated by at least the wealthier farmers in underdeveloped countries. The second type exploits the phenomenon of natural thermal updraft in a chimney to drive wind turbines which generate electricity. This principle may be applied at varying scales, but for greatest efficiency the chimneys should be as large as is practicable.

The form of the solar concentrators grew out of Schlaich's desire to find improved means of constructing **membrane roof structures**. He felt that for certain applications where translucence was not required, **thin metal sheet** promised greater durability than fabrics and a mode of structural behaviour which would be more consistent with classical theory and thus easier for the design engineer to grasp intuitively. However, there were still major problems to be solved. Metal membranes cannot be folded like fabric membranes (7.1). It is therefore difficult to fabricate doubly-curved surfaces from them and to transport and erect them. As a result, only a small number of such roofs had to that date been built. These were formed from relatively narrow sheets of thin metal which could be rolled up for transport. However, when they were unrolled and joined along their edges, the structure still consisted of a series of flat strips with the seams appearing as awkward discontinuities. In 1968 Ludkovsky had erected an experimental dished metal roof with a diameter of 26 metres in which he had found a solution to this problem. He smoothed out the joints by preloading the roof to the extent that the metal yielded and stretched. (Mild steel will "yield" at high stress and flow almost like plasticine to a considerable extent before it ruptures.) By exploiting this property, Ludkovsky was able to attain a smooth, almost ideal shape approximating a segment of a sphere. Significant work in this field was also done by Yeremeyew, especially in connection with the Moscow Olympic structures and by Kawaguchi in Japan.

This suggested that a similar result could be achieved by applying forces from the edges of thin metal sheet to form a "sail" or strong internal pressure to inflate a "cushion" made of thin steel sheet (11.2–11.4). However, it would be necessary to choose a steel which could stretch a great deal after yielding without rupturing. The research was carried out by Switbert Greiner at what was still called the Institut fur Massivbau. He used metal sheet 0.3 mm thick joined by a specially developed welding technique (11.5). From this, an experimental "pneumatic cushion" five metres in diameter was built for testing purposes (11.6–11.8). It was discovered that, with sufficient pressure, the membranes

11.2–11.4
Small scale model tests on forming doubly-curved surfaces from plane metal sheet utilizing the plasticity of thin stainless steel sheet



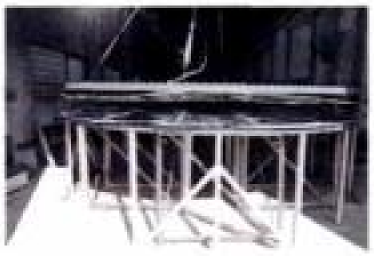
By mechanically applying forces from the edges of an open surface a plane steel sheet assumes a saddle shape

By pneumatically applying forces from the inside of a closed surface a polyhedron becomes a sphere

11.5–11.8
Larger scale model test on forming a cushion from flat steel sheet 5 m in diameter

Welding 0.2 to 0.5 mm stainless steel sheet

A 0.3 mm stainless steel sheet five metres in diameter welded from strips (and thus heavily wrinkled)



Two sheets are clamped between two steel rings

The interior is inflated and the two sheets deform plastically.
The cushion, with a small interior pressure is easily able to carry Switbert Greiner and his girl friend

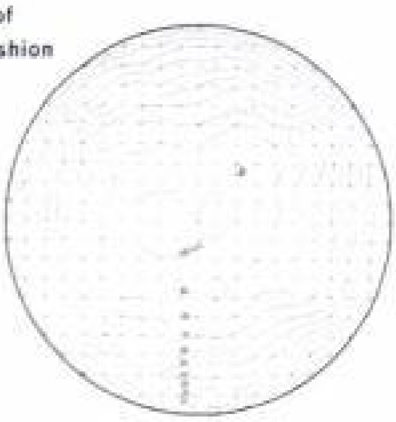
forming the cushion adopted an extremely precise "surface of rotation" with exactly circular contours (11.9 + 11.10).

Schlaich felt that there must be more rewarding applications for such precision which would, in a way, be "wasted" on conventional roofs. The dished shape would be ideal for the reflectors used in telecommunications and radar, but he was particularly attracted by the thought that it could be used to support the spherical mirrors used in **solar concentrators** (11.11–11.14). At the time, these were composed of many individual facets laboriously attached to a complex framework (11.15). In contrast, the thin metal dome formed by the inflation process was extremely simple and economical.

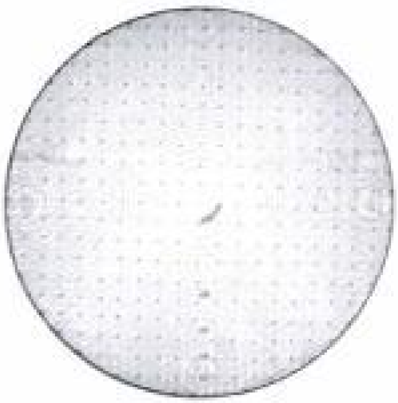
Thus began another of Schlaich's often lonely missions to convince others of the potential of his ideas. He had a useful contact in M. Simon of the engineering firm MAN, and in 1979 parts of the Stuttgart "cushion" were used to construct a prototype solar concentrator in the grounds of MAN's head office in Munich (11.16). Unfortunately, the firm did not see sufficient commercial promise in the collectors and later withdrew its support. Nevertheless, Schlaich was able to build a number of prototype plants (11.17–11.18). These included a complete generating system for the European Research Centre in Ispra using photovoltaic cells to convert the solar energy into electricity. Construction was carried out in collaboration with the famous Zeppelin metalworks in Friedrichshafen.

A major breakthrough occurred early in this process with the realization that the photovoltaic cells could be replaced by the robust Stirling engine directly coupled to a generator and mounted at the focal point of the mirror.[2] This idea was tested in the USA using conventional 12-metre mirrors built from facets (11.15). The success of these trials encouraged the design team to refine the scheme. The most challenging problem was to suspend the heavy motor and generator exactly at the focal point of the mirror with some form of structure which would be strong and rigid but would not throw significant shadows. The whole assembly – mirror, power plant, and support system – must be sufficiently light to be tilted and rotated about horizontal and vertical axes to follow the movements of the sun. In addition it had to be cheap and capable of resisting the harsh conditions of a desert environment.

11.9 + 11.10
Contour lines of the 5 metre cushion

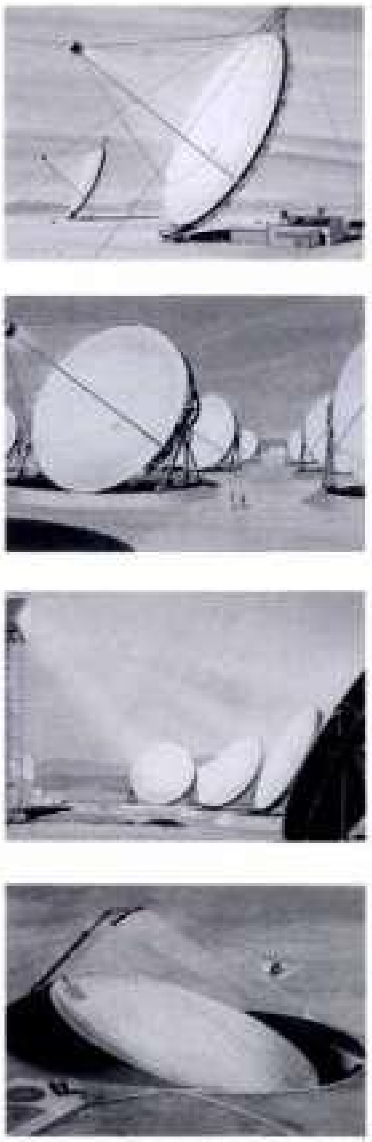


Contour lines at an internal pressure of 0.2 kPa. The wrinkles are still reflected in the poor shape. The sag and rise are 100 mm

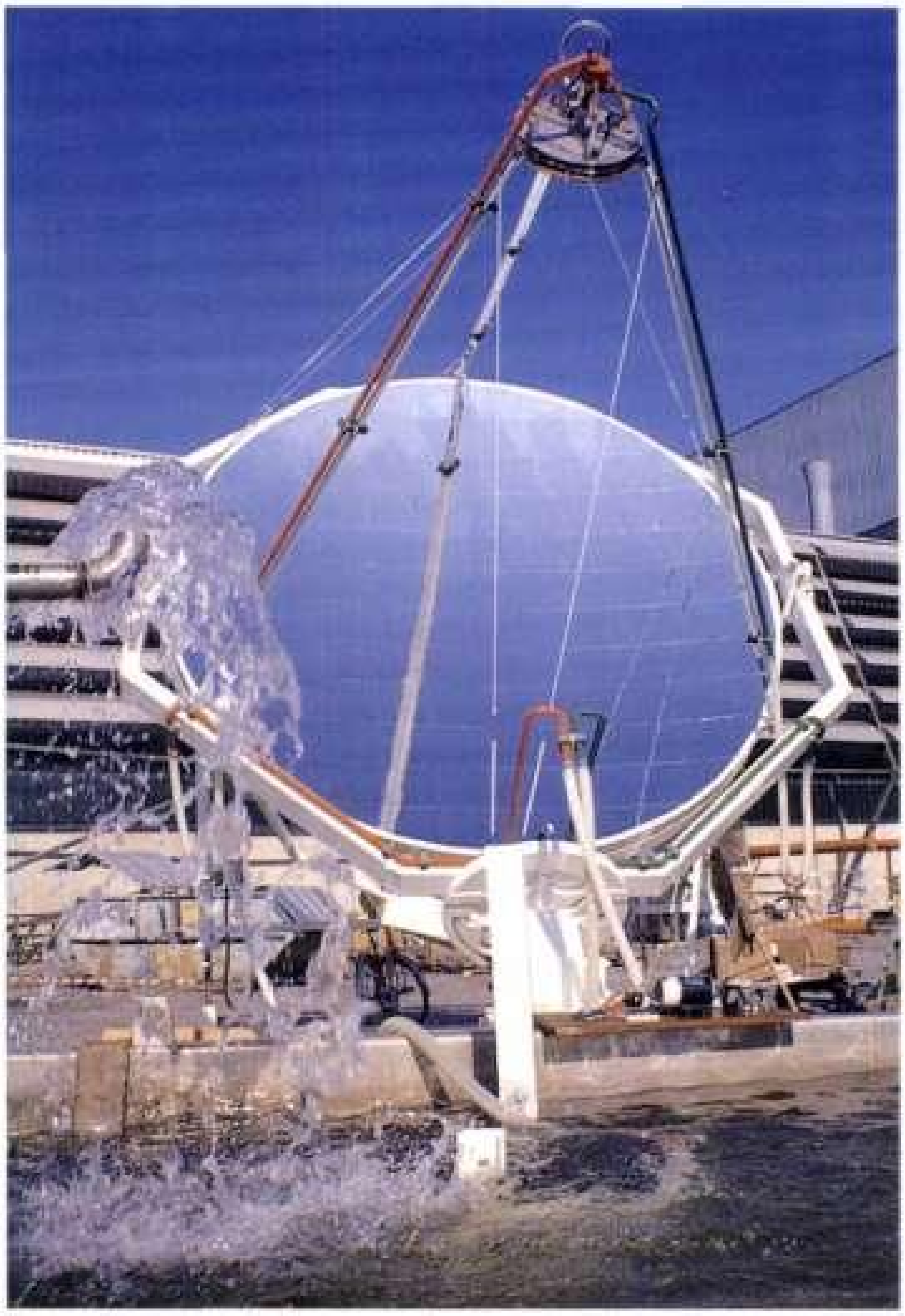


Contour lines at a pressure of 30 kPa and with sag and rise of 500 mm. The contour lines are perfectly circular

11.11 – 11.14
Drawings prepared in 1979 to demonstrate and propagate membrane technology



11.16 – 11.18
The first experimental metal-membrane sun-tracking concentrators



11.18
A water pump utilizing solar cells for conversion of light energy to electricity (the first complete version of the system built with the Zeppelin company in 1981)

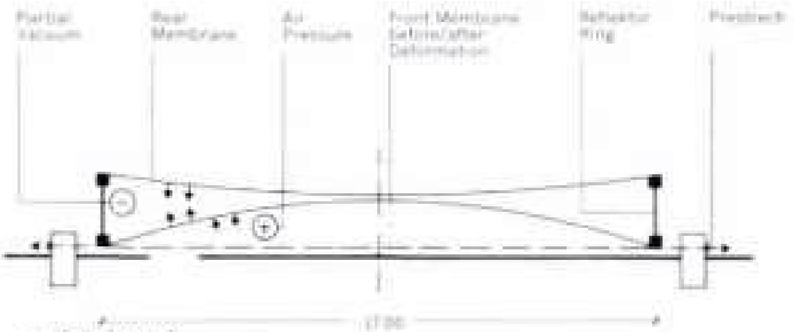
11.15
A facetted type of solar concentrator (built by Jet Propulsion Laboratory/USA)

11.16
A five-metre dish built for the firm MAN

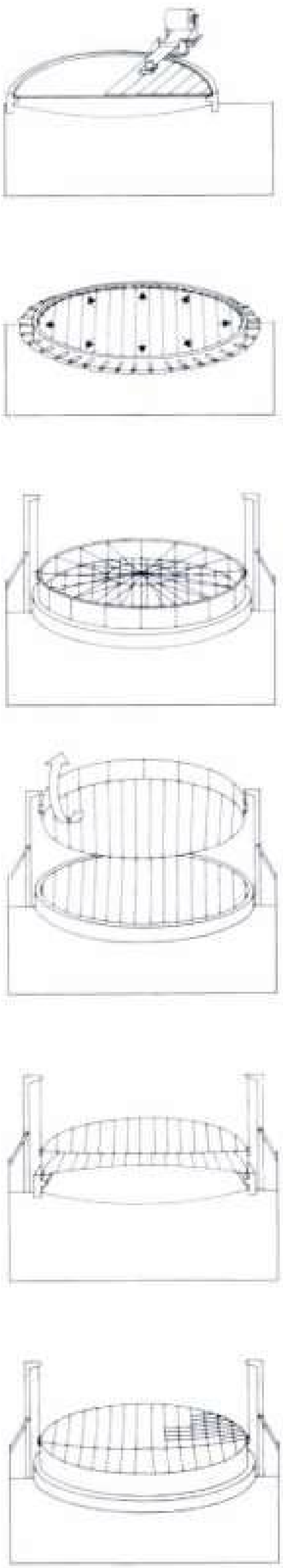
11.17
Brick burners with a secondary dish

11.19–11.22
Fabrication of 17 m diameter dish concentrators

Turning the concentrator housing



section through concentrator box

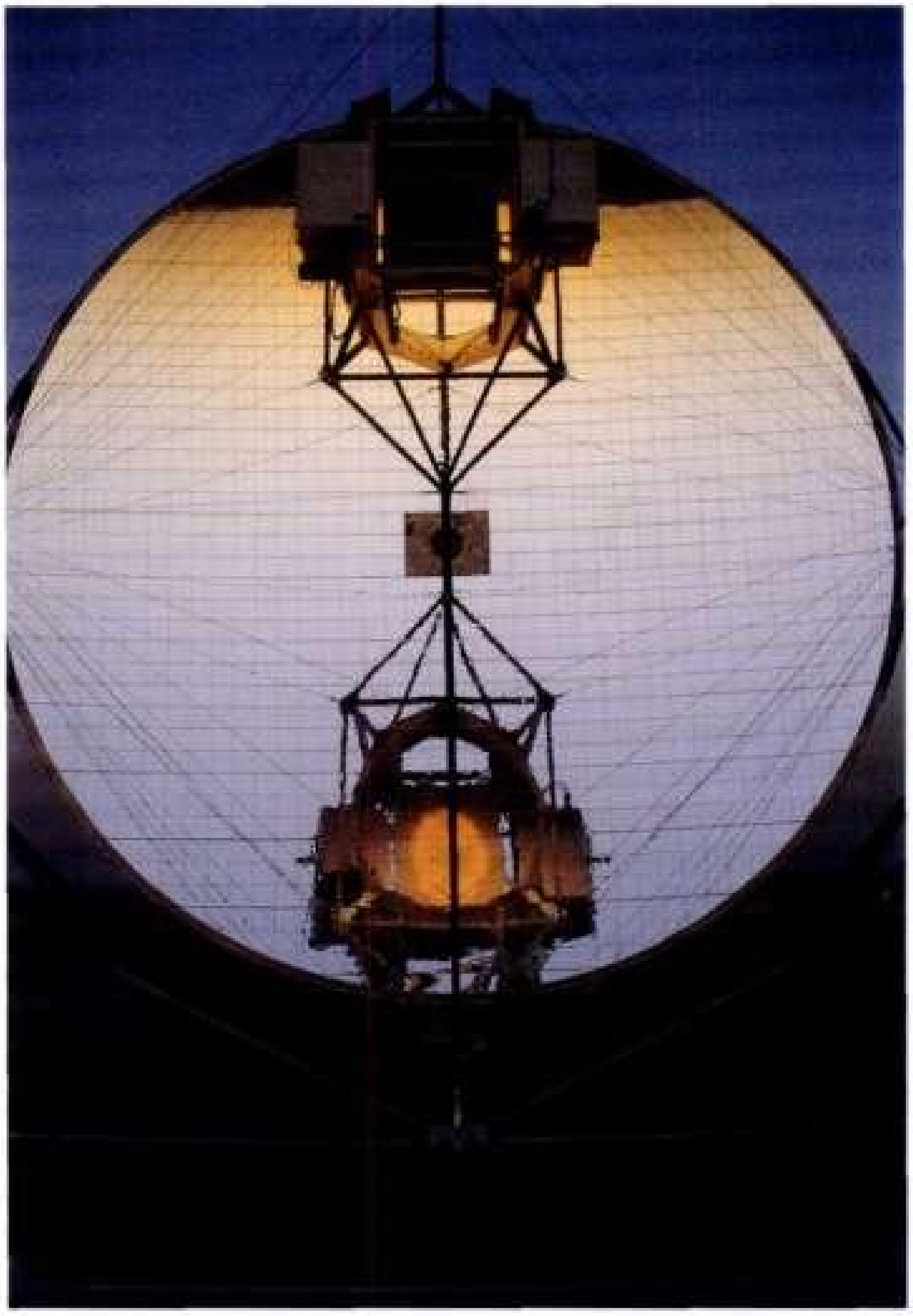


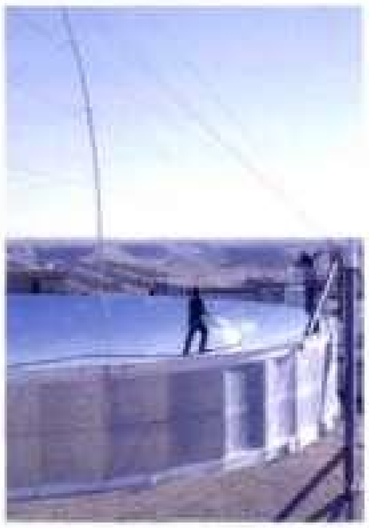
Pneumatic forming of metal-membrane concentrators

With assistance from the German Federal Ministry of Research and Technology and the King Abdul Aziz City for Science and Technology in Saudi Arabia, and after many weeks of negotiations in Riyadh and Bonn from 1981 onwards, Schlaich was finally able to see a large scale realization of this dream (11.19–11.22).

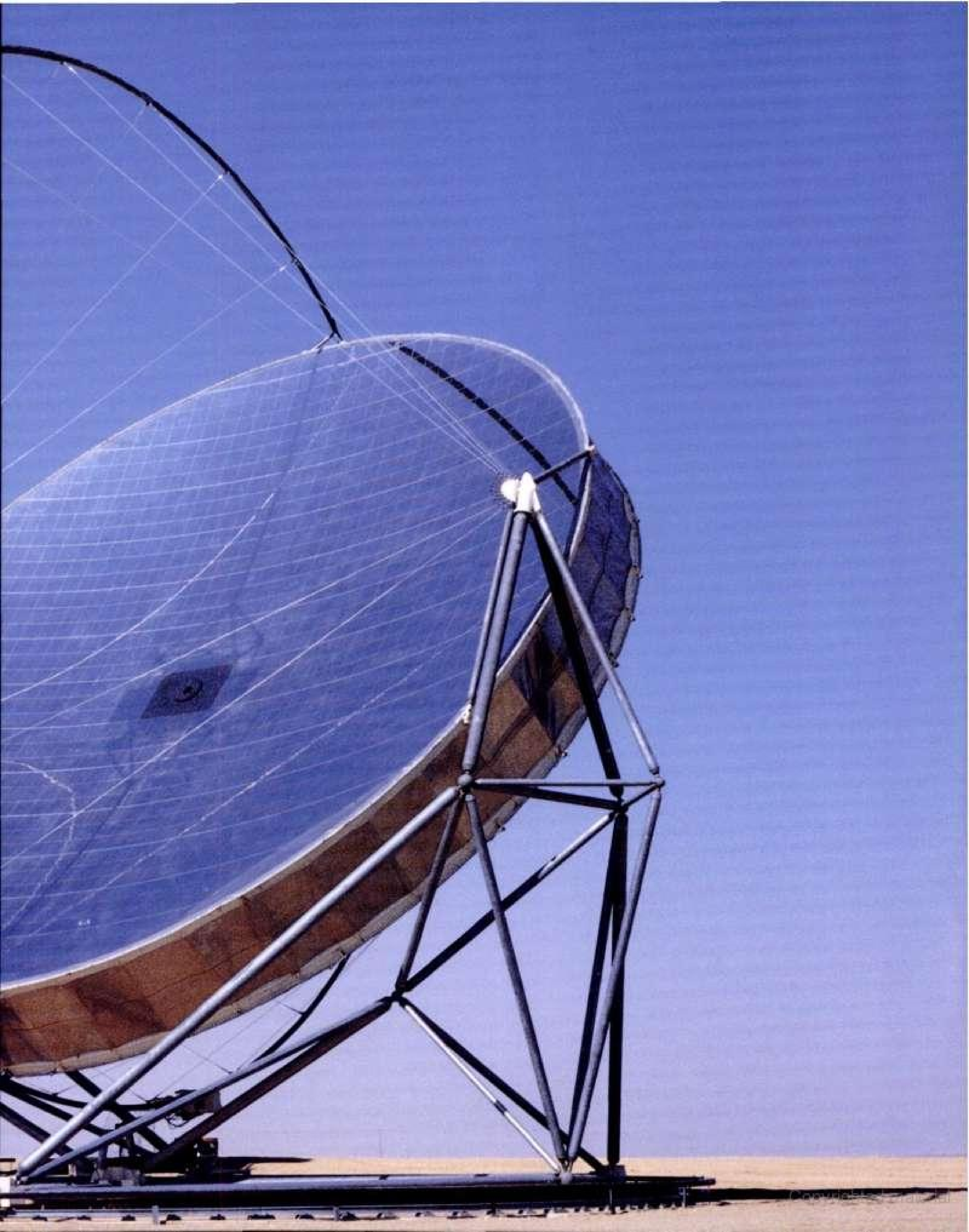
The brilliance with which the stringent criteria were met can be seen in the structure illustrated in 11.23–11.26. The principle of the bicycle wheel is again employed. The rim, comprised of steel tubing, supports the power plant and is braced by spoke-like prestressed cables which prevent it from buckling under the load. The mirror is suspended by tubular steel arms from the hubs and these in turn are supported on a slender tubular framework with a circular base which permits horizontal rotation. Perhaps the most fascinating part of the design is the way in which a thin sheet of metal is formed into a spherical surface strong enough to support the elements of mirror glass. The sheet is in fact the upper surface of a shallow drum. In the workshop, a flat circular sheet of metal is clamped to the floor around its periphery by a strong circular rim and gasket. Air pressure is applied underneath the sheet to cause the metal to yield and flow, to take up the form of a shallow dome. The rim and curved membrane then become one surface of the drum with the membrane dished inwards. Air is pumped out to establish a vacuum, and this preserves the exact shape of the membrane and gives it the stability to resist the weight of the mirror glass, wind loads, and stresses due to routine handling. The mirror glass is finally attached in the form of thin strips bonded to the metal surface.

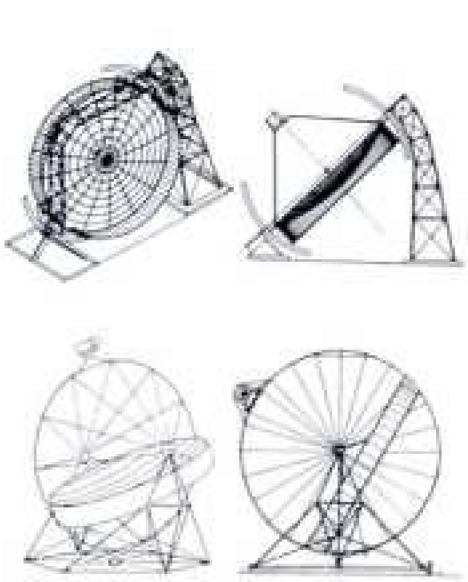
The first of this new breed of solar concentrator was built at Lampoldshausen near Heilbronn in 1983, mainly to test the assembly procedures. Its mirror **concentrator diameter** was **17 m** and its 2.5 tonne energy converter provided an output of **50 kW**. Two further units were installed in Saudi Arabia in 1985 to check the efficiency of the mirrors and the mechanical plant. A self-contained control system governed the level of the vacuum in the drum, the production of electricity, and the movements of the mirror necessary to follow the sun.





11.23 – 11.25
11.26 (overleaf)
Two 17 m diameter metal-membrane dish concentrators with Stirling engines and generators operating in the Solar Village near Riyadh, Saudi Arabia since 1985. The electrical output is 50 kw per unit

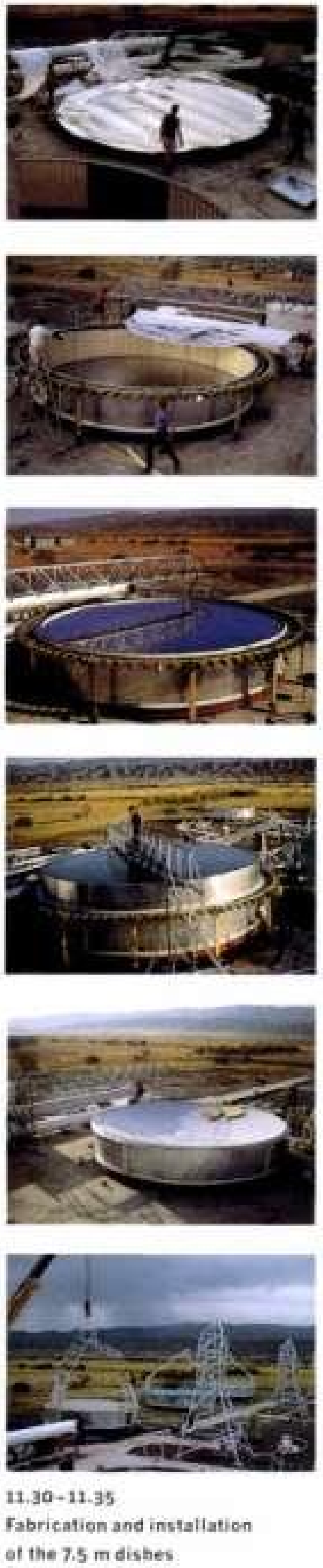




11.27
Comparison of simplified polar (above) with azimuthal tracking (below)

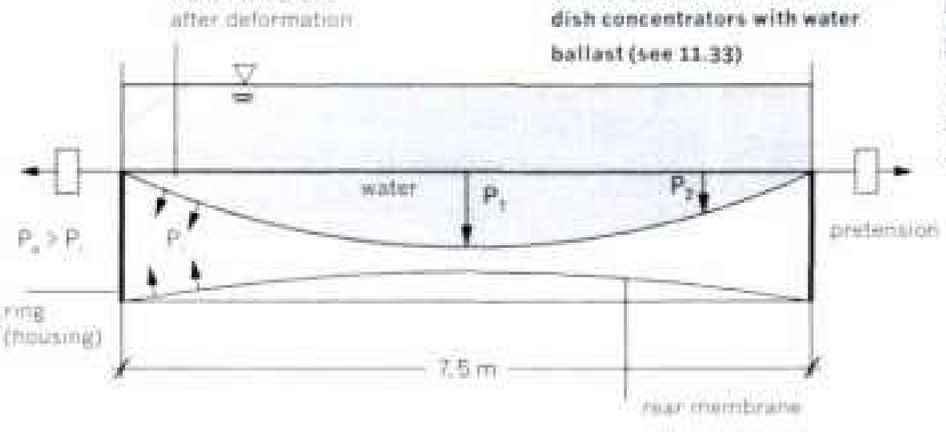
The Saudi-Arabian experience showed that, for use in remote areas, a simplified method of control and a very robust engine are required, even if the latter suffers some reduction in efficiency. A prototype unit was built to these specifications in 1988 on the grounds of the University in Stuttgart-Vaihingen, with a **7.5 metre diameter concentrator** and a **9 kW V160 Stirling engine** produced by SSPS of Ann Arbor, Michigan. Adjustments necessary to follow the annual variation in the path of the sun were kept quite separate from those necessary to follow its daily cycle. This permits a simpler rotational system at the expense of a more complex and rigid suspension system (11.27). Following the demise of SSPS, Schlaich Bergermann und Partner have acquired all the drawings and the production licence and are developing the engines in cooperation with SOLO, a local engine manufacturer (11.28) Following a first trial in Stuttgart (11.36), three prototypes of this new version have already been operating successfully in Almeria, Spain for several years and have received widespread recognition. (11.30 – 11.35, 11.37 + 11.38). Further steps in development will be to "hybridize" the system so that when sunlight is insufficient, or at night, the farmer will be able to utilize bio-gas to heat the Stirling engine, thus avoiding the requirement for expensive storage batteries. It would be far beyond the scope of this book to report on developments in more detail.

Metal membrane technology is also useful to build cheap and precise **heliostats** which are needed in large numbers for solar power (11.39 + 11.40). In the partnership, development and design in this area is carried out under the guidance of Wolfgang Schiel, a physicist, by Rainer Benz, Brian Hunt, Thomas Keck, Jurgen Kern and Axel Schweitzer. This highly committed team also supervises construction in the field. At the time of writing, a major power plant manufacturer L.C. Steinmuller of Gummersbach has joined in for further development and production, providing a very positive synergy.



11.30 – 11.35
Fabrication and installation of the 7.5 m dishes

11.28
The V160 Stirling engine with its solar receiver to be suspended at the focal point of the concentrator



11.29
The improved fabrication principle of the 7.5 m diameter dish concentrators with water ballast (see 11.33)

11.36
The first complete 7.5 m-system with Stirling engine and generator installed at Stuttgart 1989

11.37 + 11.38
Three 7.5 m-systems operating at Almeria, Spain since 1992

11.39 + 11.40
The first metal-membrane heliostat built in 1991 (ø = 7.5 m) (right) and a more advanced type, built with Steinmüller in 1994 (ø = 14 m) (left)

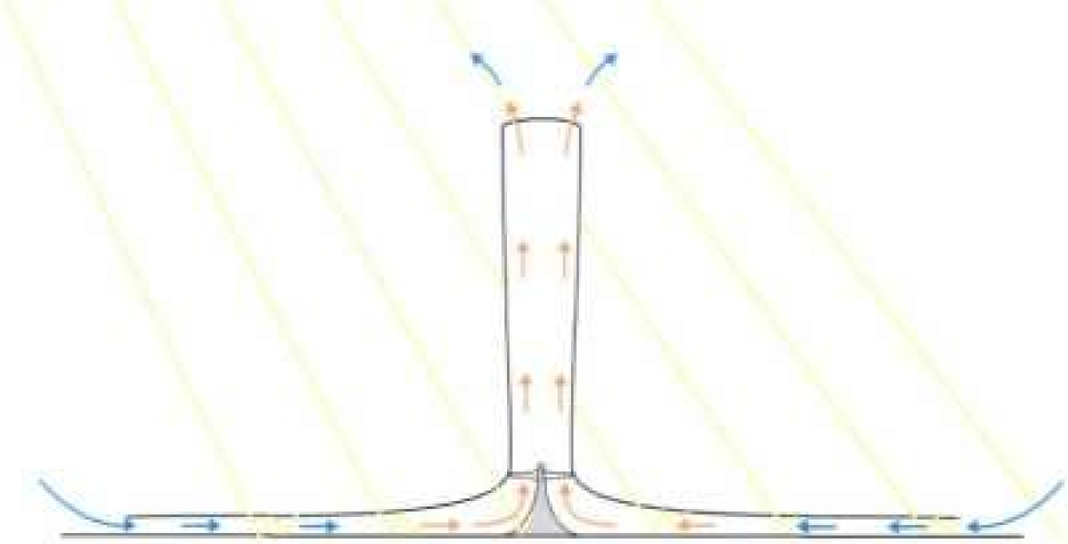
11.41
Drawing of a 100 MW plant with a cable-net or membrane skin chimney

11.42
Drawing of a 100 MW plant with a concrete chimney

Several years after the design of the Schmehausen cooling tower (see Chapter 5), a French engineer named Edgar Nazare approached Schlaich to suggest that the technique could be modified to form tall chimneys whose natural updraught could be used to drive wind turbines and generate electricity. Schlaich realized that chimneys of great height could be made by placing a number of "cooling towers" on top of each other, the whole being stabilized laterally by guy ropes, and became enthusiastically involved in the project. The scheme was stalled for a while when detailed investigation of its thermodynamics by Günther Schwarz at the University of Stuttgart showed that the updraft of a simple chimney would be insufficient for economic power generation. However, by a fortunate coincidence, Simon of MAN had independently approached the team with a similar proposal which included a sort of large greenhouse (a circular area covered by a low roof of transparent foil or glass) at ground level to heat the surrounding air before it entered the bottom of the chimney.[3] Preliminary calculations of what they called a solar chimney suggested that the cost of the electricity would decrease exponentially with increasing size of the facility. A 100 MW plant with a chimney about 1000 metres high would require a "greenhouse", or collector area, of 10 square kilometres (11.41–11.43).[4]

After much persuasive effort, the Bundesministerium für Forschung und Technologie agreed in 1979 to allocate DM 3.5 million so that a prototype could be erected for testing purposes. The design team were anxious to build the largest prototype possible with this sum of money in order to provide accurate modelling of conditions in a large plant and to give the best proof of the viability of the concept. Their aim was therefore to develop a simple, cheap, and lightweight structure which could be assembled and dismantled quickly and easily, with a minimum of skilled labour. Plastic was chosen for the roof of the greenhouse, and the exposed metalwork was provided with only nominal corrosion protection, aiming for a "design life" of between three and five years. With these economies, it was possible to build a chimney 195 metres high with a collector some 250 metres in diameter (11.58 + 11.59, 11.61). The chimney had a diameter of 10 metres, and the collector roof was 1.85 metres above ground level. Schlaich found a suitable site at Manzanares, in Spain, where sunshine was reliable and a sufficiently large area of reasonably cheap land could be obtained, devoid of houses. Construction took place over the years 1980 and 1981 (11.44–11.54).

Many problems of detail were encountered and overcome during the operation of the plant. One of these was that wind vortices near the base of the chimney ripped the plastic roof panels of the collector.



11.43
The principle of a solar chimney. The sun heats the air under a large circular glass-roofed "collector" – a sort of greenhouse. Convection causes the air to be sucked into the chimney, creating a vertical draught. This drives turbines and hence a generator installed at the base of the chimney

11.44 + 11.45
The plastic collector. The soil underneath is sprayed black

11.48 + 11.49
Erecting the 195 metre high 10 metre diameter guyed tube from corrugated sheet using an incremental lifting method

11.46 + 11.47
Fabrication of the initial plastic collector roof (diameter 250 m) by unskilled labour.

11.50
Fabrication of the later glass collector roof

11.51
The glass collector roof from underneath

11.52
Looking from the top down into the chimney

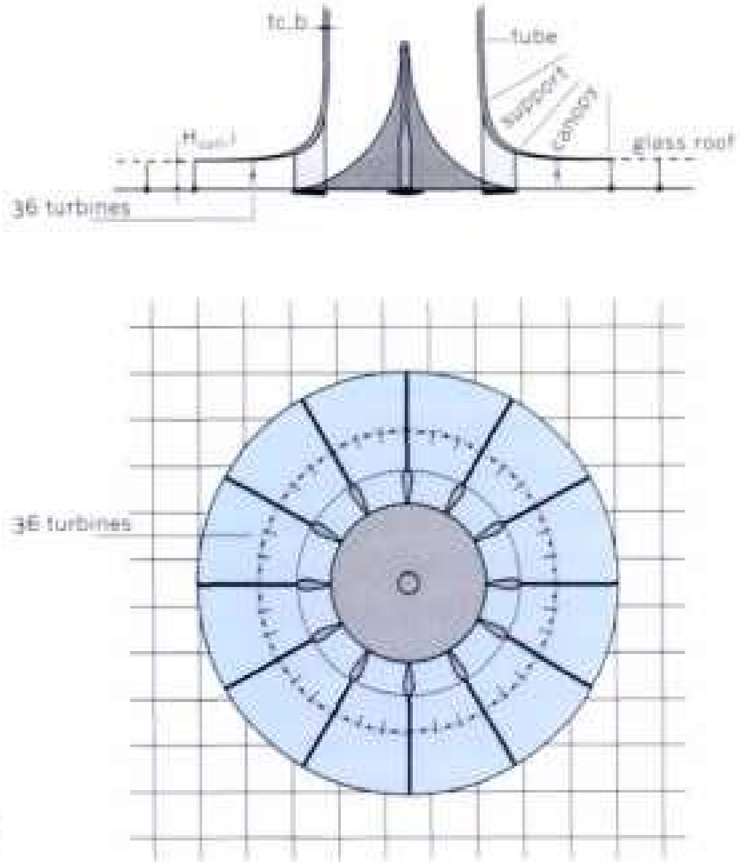
11.53
The transition between collector roof and chimney

11.54
A view into the chimney from the base looking up (showing also the turbine with the four adjustable blades)

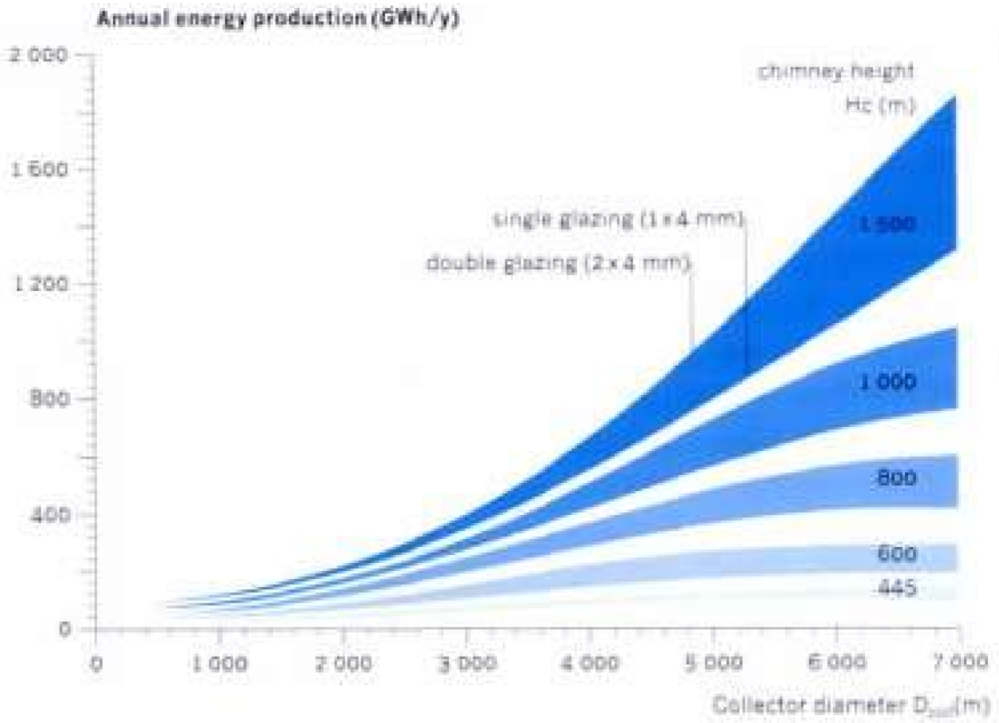
After a few years exposure to sunlight, the plastic became brittle and lost some of its translucency. These problems were solved by replacing the critical sections with glass, which performed very well, so that glass will be the final solution for large scale application (11.50–11.51). Occasional rain showers proved sufficient to clean the roof.

Schlaich successfully applied for a number of additional grants which made it possible to keep the plant functioning for eight years: roughly twice as long as had originally been planned. The observed behaviour of the system, including the maximum output of 50 kW, was in good agreement with theoretical predictions. This was to the credit of a number of dedicated engineers in the office, mainly Gunter Mayr, Karl Friedrich, Wilfried Haaf, and Jurgen Kern, in a later stage under the guidance of Wolfgang Schiel – and to Leonhardt's enthusiastic support.

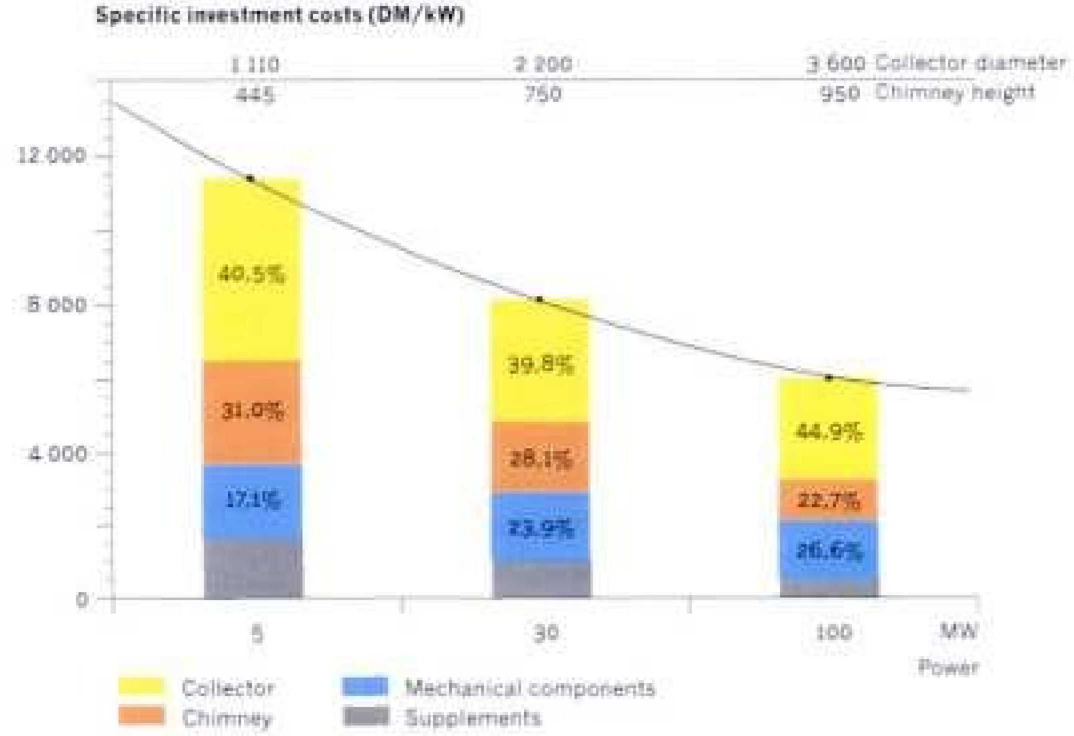
Finally, corrosion began to make serious inroads on the unprotected guys, and the pipe collapsed during heavy storms in the spring of 1989. However, the measurements taken proved the robustness and the dependability of the system and confirmed the thermodynamic calculations. Detailed thermodynamic, structural, mechanical, and above all financial analysis based on this experience suggested that very large solar chimneys could be an economic proposition, especially in desert areas (11.55–11.57). Major advantages of the solar chimney are that brilliant sunshine is not required for its operation (it works well on cloudy-bright days), it has a natural thermal storage capacity within the soil under the "greenhouse" roof, and it can be built by local industries in developing countries, thus providing increased employment as well as cheap energy. The project and its rationale are reported in detail in Schlaich's latest book *Das Aufwindkraftwerk/ The Solar Chimney*, and there is no need to present further details here.



11.57
Structural details of the base of a solar chimmney

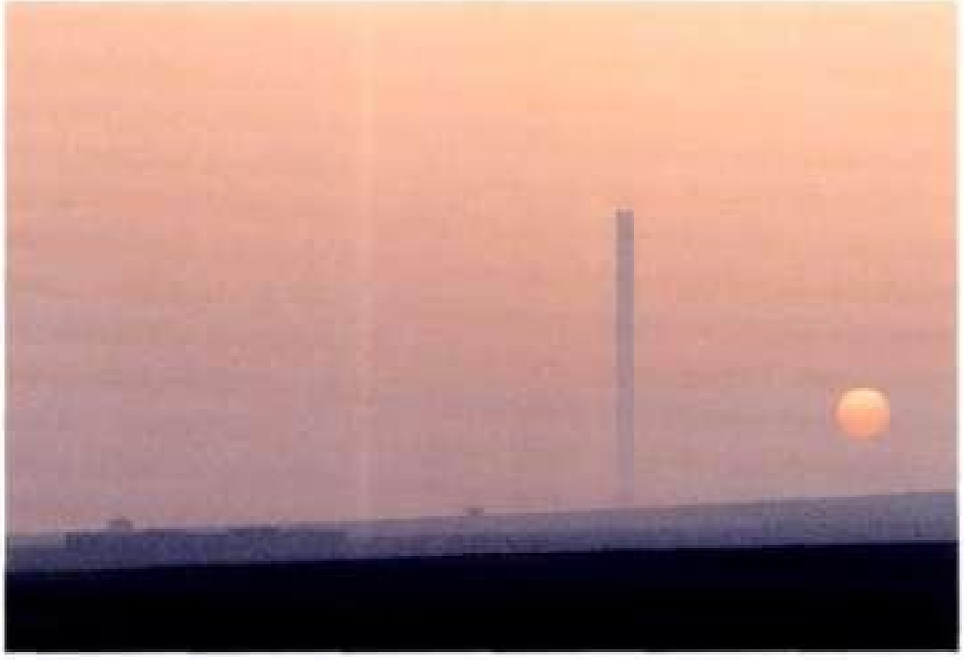


11.55
Annual energy production by solar chimneys (at 2 300 kWh/m²y global radiation) dependent on collector diameter Dcoll and chimney height Hc



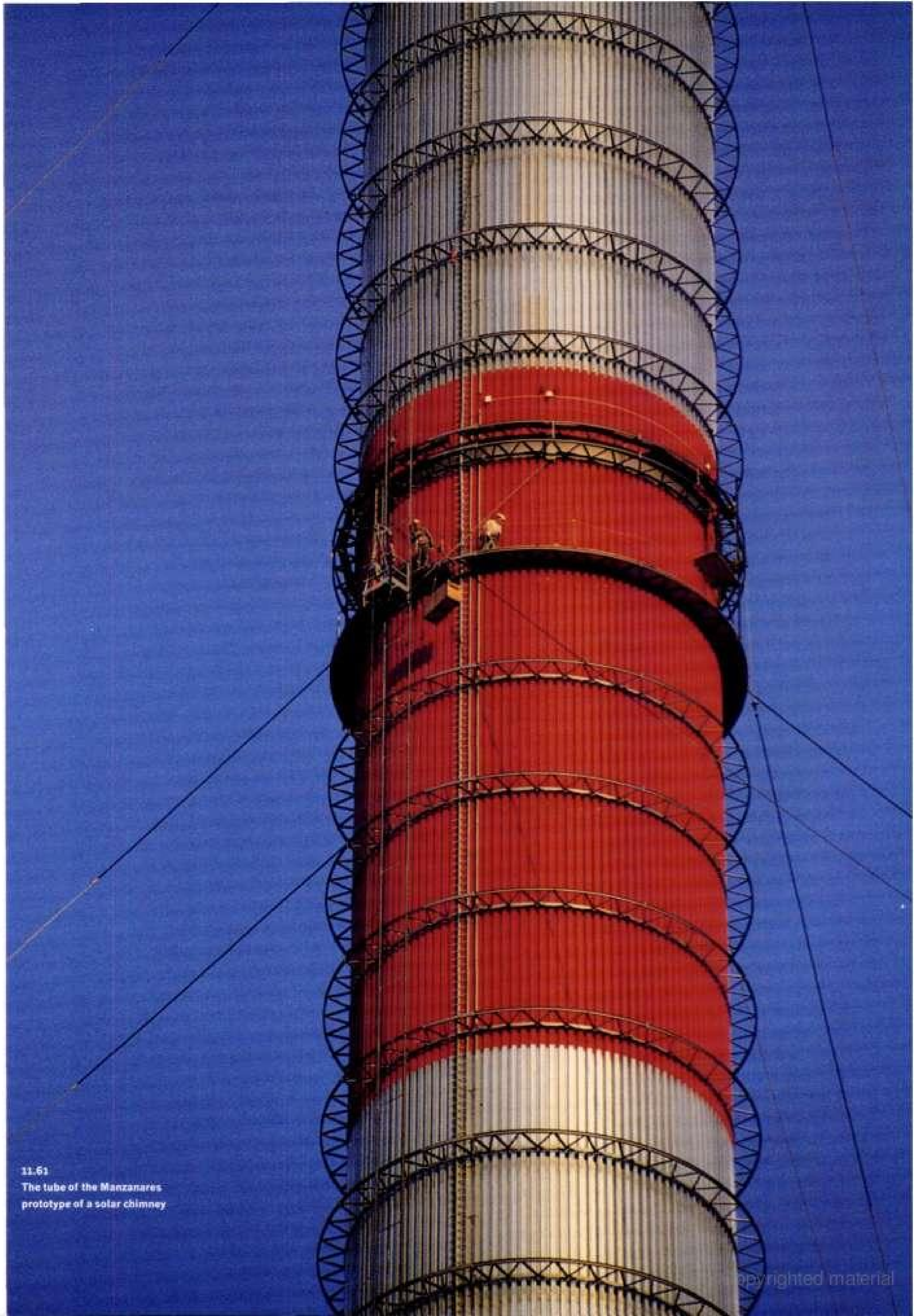
11.56
Specific investment costs for solar chimneys dependent on power block size

Unfortunately, the passing of the oil-crisis of the 1970s has led governments to return to their normal short-term view of planning, and the money available for solar energy research in the technically advanced world has been greatly reduced. Despite this, Schlaich still strives ardently to convince governments and those directly in control of research funding to invest in the bright future of this form of solar energy. One part of this battle is the attractive small book *Erneuerbare Energien nutzen* (Werner Verlag) which he and his daughter Sibylle produced in 1991 to advance the cause of all forms of solar energy.



11.58 + 11.59
View of the completed 50 kW prototype in Manzanares, Spain, 1982

11.60
Presentation to the Saudi Arabian government officials of a functional model of a solar chimney, 1980



11.61
The tube of the Manzanares prototype of a solar chimney

Notes to Chapter 11

[1] J. Schleich: "Bevölkerungsexplosion, Energie und Umwelt", *Die Bautechnik*, 1992, Heft 5.

[2] The Stirling engine was invented in 1816 by the Scotsman Robert Stirling and was used widely in the 19th Century. It works with a constant gas volume (usually helium or hydrogen) which moves back and forth between two chambers during operation, applying pressure to a pair of pistons. In its solar-energy application, the gas in one cylinder is expanded by the heat concentrated by the mirror which raises its temperature to between 700 and 1000 degrees. Movement of the pistons compresses the gas in the other chamber and this is cooled by a regenerator as it moves from the hot to the cold side. The process is then reversed. An independent control sys-tem is necessary to govern the exchange of heat, the production of electricity, and the movement of the mirror. See e. g. G. Walker: *Stirling-cycle Machines*, Clarendon Press, Oxford, 1973.

[3] It was discovered later that, like many good ideas, this one been described 60 years before, but had not been exploited because the necessary technology was not available. See H. Gunther: *In 100 Jahren: Die künftige Energieversorgung der Welt*, Franckh'sche Verlagshandlung, Stuttgart, 1931.

[4] J. Schlaich: "Solar Chimneys: The principle – The pilot plant – Prospects for the future", *IABSE Periodica*, 3/1983, and *IABSE Structures*, C-26/83 (August); J. Schlaich: *The Solar Chimney – Electricity from the Sun*, Edition Axel Menges, Stuttgart, 1995.

Selected Publications by Jorg Schlaich and co-authors (if given) up to 1995 to Chapter 11:
Metal-membrane structures, solar-energy utilization

month/year

03/78: "Vorgespannte Flächentragwerke aus Metallmembranen", with S. Greiner, *Der Bauingenieur*.

05/79: "Die Nutzung der plastischen Verformbarkeit von Metallen beim Bauen zugbeanspruchter Flächentragwerke", with S. Greiner, 2. Internationales Symposium des SFB 64, Stuttgart.

08/81: "Atmosphärenthermische Aufwindkraftwerke", with W. Haaf und G. Mayr, *Bundesministerium fur Forschung und Technologie, Bonn, Forschungsbericht T 81–11*.

04/82: "Solar Chimneys – The Concept – The Prototype in Spain – Prospects for the Future", with G. Mayr and K. Friedrich, *IASS-Bulletin, no. 78*.

04/82: "Neue und erneuerbare Energiequellen", *Beton- und Stahlbetonbau* and *Festschrift 75 Jahre Deutscher Ausschuß fur Stahlbeton*.

10/82: "Atmosphärenthermische Aufwindkraftwerke – Bau der Demonstrationsanlage Manzanares und Ergebnisse", with G. Mayr and W. Haaf, *Statusreport Windenergie des BMFT*.

04/83: "Solar Chimneys. Part I: Principle and Construction of the Pilot Plant in Manzanares", with W. Haaf, K. Friedrich and G. Mayr, "Part II: Preliminary Test Results from the Manzanares Pilot Plant", with W. Haaf. *International Journal Solar Energy*.

08/83: "Solar chimneys – the principle – the pilot plant – prospects for the future". *IABSE Structures*, C-26/83.

02/84: "Das Aufwindkraftwerk Manzanares – Zusammenfassung der bisherigen Ergebnisse. Stand Febr. 1984", with W. Haaf and H. Lautenschlager.

09/84: "Ergebnisse vom Aufwindkraftwerk Manzanares", with W. Haaf, H. Lautenschlager and R. Bergermann

"Solar Power Plant with a Membrane Concave Mirror, 50 kW", with R. Benz, *DGS: 5. Internationales Sonnenforum, Berlin 1984*.

12/86: "Baureife Planung und Bau einer Demonstrationsanlage eines atmosphärenthermischen Aufwindkraftwerkes. Anwendungsnahe Auslegung großerer Einheiten und erweitertes Meßprogramm", with R. Bergermann, K. Friedrich, W. Haaf and H. Lautenschlager, *BMFT-Forschungsbericht T 86-208*.

08/89: *Wieviel Wuste braucht ein Auto?*, published by the author.

01/90: "Solar Chimneys", with W. Schiel and K. Friedrich, *Encyclopedia of Physical Science and Technology, 1990 Yearbook*.

05/90: "How much desert does a car need? The case for more intensive research into the utilization of solar energy", *IABSE Proceedings P-144/90*.

03/91: "Studie zum Vergleich von Solarthermischen Anlagen zur Stromerzeugung (Dish/Stirling)", with W. Schiel, Final report for Deutsche Forschungsanstalt fur Luft- und Raumfahrt e.V.

04/91: *Erneuerbare Energien nutzen*, with Sibylle Schlaich, Werner Verlag, Düsseldorf.

05/91: "World energy demand, population explosion and pollution: could solar energy utilization become a solution?", *The Structural Engineer*.

09/91: "Stahlmembran-Parabolspiegel mit Stirlingmotor zur Sonnenenergienutzung", with R. Bergermann and R. Benz, *Der Bauingenieur*.

05/92: "Bevölkerungsexplosion, Energie und Umwelt", *Die Bautechnik*, editorial.

09/92: "Aktueller Stand der Dish/Stirling-Technik – Erste Ergebnisse der Feldtests in Almeria", with W. Schiel, Th. Keck and A. Schweitzer, Arbeitsgemeinschaft Stirling, Zentrum fur Sonnenenergie- und Wasserstoff-Forschung, seminar report *Angewandte Stirlingmotor-Technik*.

11/92: "Thesen zur Notwendigkeit Solarkraftwerke fur die Dritte Welt zu entwickeln", VBI Symposium, Bonn.

02/93: "Population Explosion, Energy and Environment", *Structural Engineering International*, vol. 3, no. 1; also Discussion in vol. 3, no. 3

12/93: "Sonnenergie", *Brockhaus-Enzyklopädie*, Bd. 20.

05/94: "Solar Thermal Electricity Generation", *Structural Engineering International*, vol. 4, No. 2, and *Festschrift zum 60. Geburtstag von Prof. Jorg Schneider*, ETH Zurich.

09/94: *Das Aufwindkraftwerk*. Deutsche Verlags-Anstalt, Stuttgart.

05/95: "Strom aus der Sonne", *Deutsches Architektenblatt*.

09/95: *The Solar Chimney – Electricity from the Sun*, Edition Axel Menges, Stuttgart, 1995.

10/95 "Das Aufwindkraftwerk – Strom aus der Sonne: einfach – erschwinglich – unerschöpflich", with J. Kern, *Solarthermische Kraftwerke II, VDI-Berichte 1200*.

The aim of this chapter is to discuss some of the special qualities which are characteristic of Jörg Schlaich's approach to engineering and in the process learn something more about the art of structural design. As has become apparent in preceding chapters, the physical laws which govern the behaviour of materials and structures leave plenty of room for individuality in design. The situation may be summarized as follows.

- Engineering is by no means simply a matter of function and technology. Politics, economics, and the dynamics of human relationships within the design team play a large part in shaping outcomes.
- On the technical side, the body of knowledge available is vast and is continually changing and developing. Each engineer must chart his or her own path of discovery and learning.
- Design engineers must grapple with the physical world as they find it, in all its complexity. They cannot dissect it in the laboratory as does the research engineer or scientist. Each structure is "an invention followed by a prototype". Scientists primarily occupy themselves with what exists; engineers develop something new and then supervise its fabrication and construction.
- There is a great need for competently-designed conventional structures and considerable commercial, bureaucratic, and social pressure to remain within the confines of established practice.

It is pertinent to ask what qualities and attitudes mark the sort of engineer who is willing to break through the many constraints and do something different – to tackle the analysis and design of unconventional structures; to develop new theoretical and practical techniques; and to attempt to alter the perceptions of a whole industry, of government, and of the general public regarding structures. Obviously, there must be strong motivation. Ambition is an important factor, but there must be much more: a sense of mission, often inspired by ethical and moral principles; a lively sense of curiosity; a fascination with structures as objects; and a dissatisfaction with conventional ways of doing things. These are often accompanied by strong convictions, forcefully expressed and courageously defended, which must of course be backed up by a high level of knowledge and expertise. Engineering is an unforgiving discipline. An architect may choose to ignore the "rules" of classical proportion, or even design a building which is inconvenient to its users, and no irreparable harm is done. An engineer cannot infringe the "laws" of nature. If a structure collapses the result may be death or heavy financial loss. Engineers who are innovative must be prepared to carry the resulting burden of responsibility. They must thus prepare themselves well for their chosen role and be secure in the background knowledge and experience passed on to them by their predecessors, teachers, and mentors. They must continue to amass information and experience assiduously during their careers through simple observation and experience in design and construction, and through reading, research, and interaction with colleagues. They must fulfil their responsibility to improve technology through innovation, and yet avoid undue risk for the users of their structures. It is obvious from the foregoing account of his projects that Jörg Schlaich is just such an engineer.

Amongst the most noticeable qualities of leading designers in any field are strength of character and self-confidence. This gives them the ability to lead teams; to motivate others, to sift conflicting information and advice, and to set clear goals towards which others can work with efficiency. In engineering design, conviction alone is not enough: leaders must be *right* in absolute terms on issues of safety and reasonable economy. Even so there is room for wide differences of opinion on less critical matters. Schlaich's convictions about the social and professional obligations of designers have led him into a number of conflicts with engineers in government and industry and with prominent architects. Inspired perhaps by the example of his crusading father, he confronts an issue (and the people concerned) head on and has been charged by at least one of his adversaries with arrogance and insensitivity. However, he does not enter conflict willingly. He respects sincerity, technical competence, and rational argument, and moderates his comments if he feels the person concerned is particularly sensitive to criticism. His moral and aesthetic principles, his concern with minimalism and his delight in making his structures barely visible are hardly those of an egoist. The footbridges at the Kochenhofsteg, Sindelfingen, and Pragsattel, and his project for the look-out tower on the Killesberg are good examples. His views are tempered also by an awareness that self-confidence in design must be bought with a lifetime's patient study and experience and a familiar respect for the laws of nature. He declares that engineers must be around 50 years old before they can conceive structural form with the same freedom and confidence that architects bring to their proposals.[1] He is ready to criticize his own work, pointing out aspects that he feels with hindsight could have been improved and is unusually willing to discuss the origin of his ideas and give credit to others for providing some initial spark which he was able to turn to advantage. He says, with genuine conviction: "I am just a normal engineer – there is nothing special about me. And that is good, because if I achieved something useful and beautiful, then many more structural engineers – all of them – can, if they only want and strive for it, and that could be to the best interest of society."

Schlaich is particularly keen to acknowledge that the high reputation of the practice depends greatly on the work of his long-standing partners and the many talented engineers, designers and office staff who have participated for varying periods (some throughout the entire life of the practice and Schlaich's tenure of the chair at the Institut). Many specialist consultants have also contributed greatly. The names of most of these have appeared in preceding chapters. However, at the end of the day, the leaders of the practice must weigh the sometimes conflicting advice offered by colleagues, specialists, subordinates, politicians, regulators, and critics, make decisions on intangible matters, and accept final responsibility for the form, cost, and final performance of the project. At this point it may be necessary to override opposition, if diplomacy and persuasion do not work.

Research into the personalities of creative people suggests that an important factor is a certain psychological toughness which makes it possible to cope with intellectual tension. This shows itself in an holistic view of design in all its complexity: taking account of and weighing disparate factors such as mechanical properties, fabrication, and construction alongside function, economics, and aesthetics; an acceptance that conflicts of evidence and values can never be completely resolved: and a drive to continue exploring alternative possibilities long after others have given up. The less creative designer tends to cut short the process and make premature decisions in order to relieve the mental strain of coping with the vastness and complexity of the problem and the information which might be brought to bear on it.

Schlaich's interest in aesthetics and his work with architects will be considered later in this chapter. On the purely technical side, his holistic approach is evident in his determination to win a more general appellation for the Institut, and his insistence that structural form, load-bearing behaviour, and fabrication and construction procedures (Form – Tragverhalten – Fertigung) should be considered together in the conceptual stages of design. Construction methods are described in all the papers and brochures concerning the partnership's structures. Being actively involved in research, Schlaich enjoys the complexity of an intricate theory, but at the same time has an extremely practical approach to construction. (A result, he says, practitioners think he is too theoretical, while theorists regard him as a practitioner.[2]) His broader approach makes him willing and able to cross the traditional boundaries which compartmentalize the theory and practice of engineering. This is unusual in a country where many designers and researchers specialize in one material and even in one form of construction only. Schlaich feels that too many of these specialists burn out their brilliant ideas within a period of about 15 years, and then go on to refine and polish them without making further major advances. He feels that designers who take up the challenges of different construction materials (such as steel, concrete, and timber) and different forms (cables, shells, grids) are better able to maintain active production of innovative ideas. In his work on solar energy Schlaich has (of course through collaboration) crossed the more formidable boundaries between structural and mechanical and electrical engineering. This adaptability allows him to transfer knowledge and experience from one field to another as in the case of his movement from the design of shells to that of cable nets and on through membrane structures to grid roofs. The process is assisted by his ability to grasp the essential nature of complex problems, extracting simplified concepts which are sufficiently correct, if applied with understanding, to serve as a tool in the initial conception of original structures.

It should be mentioned that Schlaich's holistic approach encompasses the details of his structures: an aspect to which he devotes great care and innovative effort. The great pioneer of modern architecture, Mies van der Rohe, said that "God is in the details", and most engineers would agree with him. Occasionally, an inspired structural form – a brilliant general solution to a given problem – fails because it is impossible to resolve the questions of detailing which are inherent in the overall concept. In his paper on the detailing of cable stayed bridges, Schlaich writes: "This by the way is the cardinal point of systematic detailing: don't start arbitrarily but look out for the most crucial detail, burdening it with as few boundary conditions as possible, and derive from its solution the less critical ones."[3] Expanding on this, he states: "This means that if the most crucial, difficult detail in the whole structure is not burdened with boundary conditions resulting from other details, it has a chance to become simple. The less difficult details may be able to bear some 'burden' from other details, without themselves becoming overly complicated." He cites as examples the cable-to-girder and cable-to-tower connections developed by the partnership for their bridges.

A willingness to face the full complexity of significant factors and value-judgements in engineering problems leads most prominent designers to the opinion that there is very rarely a single optimum solution. Schlaich shares this view. "It appears to be forgotten that for every engineering task there are a practically unlimited number of solutions and that, because of this, it is never possible to make a choice according to purely functional considerations. Of necessity, it must be hit upon subjectively."[4]

Thus he argues that designers should discard the principle that form must uniquely follow function in its narrowest sense. If structures were adapted to suit a broader range of needs and accommodated to the local environment in each case, the natural and inevitable result would be the variety of form which he considers so desirable.[5]

In practical design, the opportunity for individuality stems as much from the profusion of conflicting requirements as from the wealth of equally economical solutions. Any solution must contain trade-offs. As Schlaich puts it: advantages must often be "bought" (erkauft) at the cost of disadvantages elsewhere in the structure. In discussing the relative merits of harp and fan-shaped arrangements of cables on cable-stayed bridges he states: "The harp which is more beautiful in the case of two cable planes must be paid for with 'unnecessary' bending [stresses] in the pylon and, in contrast to the fan, with greater compressive forces in the beams and a greater amount of cabling."[6] If the "optimum" solution is one in which the "value" of the advantages is maximized, and that of the disadvantages is minimized, the designer must use a sort of "creative accountancy" to compare the merits of alternative solutions.[7] Such accounting will depend largely on the individual's system of values, and this introduces a fair measure of subjectivity into engineering design and its criticism. It is the manner in which good designers keep their personal accounts which distinguishes the work of one from that of another.

Schlaich tends to see in tensions of opposites only a further opportunity for creativity. An example is the paradox that structures which operate efficiently in (mechanical) tension, such as cable nets and membranes, must generally be supported by masts which act in compression and must be stabilized against vibrations with perimeter beams or a stiffening girder. All of these last act in bending which is the least efficient way of resisting load and their cost and appearance detract from the overall effect. However, in his words: "It is just this combination, this antithesis, which results in a creative challenge for the designer and which rewards him, if he succeeds, with a natural and aesthetic structure."[8] Of course, a creative designer confronted with a conflict of requirements is often able to conceive of a radically different way of doing things which circumvents all the major problems without introducing new ones. Schlaich is a master of this sort of "conflict resolution". It also requires a certain mental toughness to combine a sense of adventure and a desire for variety with the responsibilities of an engineer. Many engineers believe that unconventional and untried solutions should not be used unless unusual circumstances make this unavoidable. Schlaich is convinced, however, that it is the duty of the designer – to society and to the profession – to advance the art of structural engineering even in small steps by introducing and testing innovations, cautiously pushing current techniques to their limits. Discussions with colleagues about proposed initiatives in design, after all considerations have been carefully weighed, are often concluded with the comment "Warum eigentlich nicht?" – "Well, after all, why not give it a try?" Convinced that the goal of total optimization is unachievable, he declares "Long live variety ... uniformity is boring!"[9] Naturally, he introduces his innovations in a responsible fashion, with great forethought and careful prior investigation and testing. He feels that designers should be willing to accept a small degree of risk, provided that possible adverse consequences will be minor, and economical remedial measures can be foreseen to deal with them should they arise.

An important factor in creativity is the ability to make full use of the subconscious part of the mind. In the initial, conceptual stages, when designers are searching to define a form which can be subjected to rigorous qualitative and quantitative analysis, they must be guided by intuition based, if it is to be effective, on years of experience. Psychologists say, however, that the conscious mind can store only "seven items plus or minus three". Thus, when design engineers bring their mental resources to bear on complex problems they must place great reliance on subconscious thought processes. The results reveal themselves as "hunches" or "feelings". A designer will say that a suggested solution "does not feel right", or that another "just clicks". Thus the experienced designer is able to postulate solutions which at least have a high chance of success. No solution works perfectly in its raw state, and the process of "ironing out" inherent difficulties is arduous and time-consuming. It is the chief designer's innate sense of appropriateness that minimizes the effort lost on proposals which eventually prove fruitless.

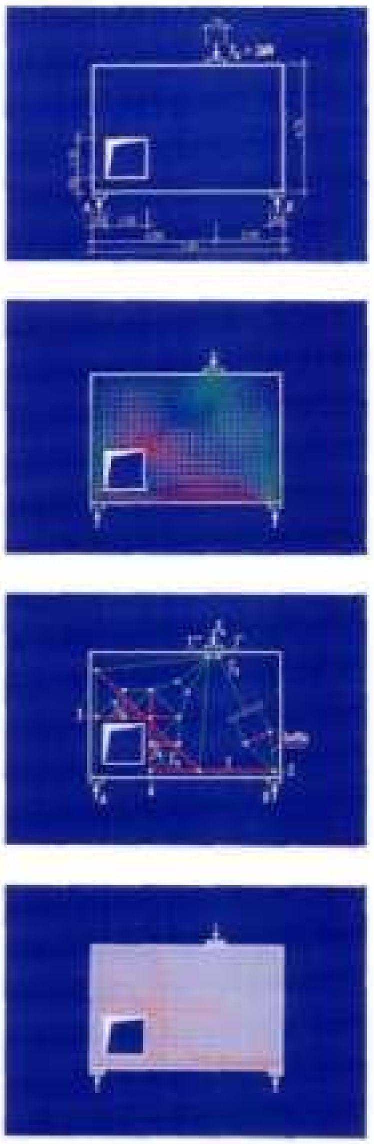
Many designers see the initial stages of conception as a sort of dialogue between themselves and their artefact. When a particular line of approach proves fruitless, or a new possibility is revealed by their investigations, they feel that the building or structure is trying to "tell them something". The famous architect Louis I Kahn felt that when he was designing a building it was "telling him what it wanted to be".[10] Schlaich has a similar attitude to materials and their associated forms of construction, though he feels that some tell him more than others. He notes that cable structures are especially good in this regard. A high degree of discipline is imposed on the designer by the fact that the cables and their attachments are fully exposed (whereas conventional prestressing cables are buried in concrete) and must be largely standardized to achieve simplicity and economy in fabrication. Within this discipline Schlaich tries different schemes, alters various parameters, and then finds: "Suddenly everything seems to fall into place – the spacing of cable sockets, and thus that of the cables. Even the handrail fits in. It all seems to fit together beautifully. It just goes like that. [He snaps his fingers]. I like the discipline of steel. I like order. The discipline imposes an order." He remarks that the footbridge at Pforzheim "told" him not to lean the masts outwards again.

These structures are "very unforgiving" and net structures in particular let you know exactly when they are just right. A square net is very easy to mould into the desired shape, but the designer must pay a heavy price in the high deformability of the finished structure. The Munich roof is an example, undergoing very large deformations under load. "With cable nets – as with no other type of structure – are form, construction, load-bearing behaviour and deformation so closely linked that the slightest clumsiness [of design] in one area must in all certainty be paid for in another. On the other hand, cable-net structures reward the persistent designer in that they audibly 'click into place' when the correct solution is found in terms of constructibility and form."[11] What Schlaich is describing here is an abstract version of the close relationship between the potter and the clay. On the other hand, some materials and forms of construction do not permit such a close relationship between designer and material. "Other types of structure always leave you with the feeling that there might somehow be a better way to do it."[12] Schlaich regrets that reinforced and prestressed concrete tend to fall into this category, at least in the "unnecessarily massive" forms in which they are mostly used at present. The solid webs and flanges of box girder bridges tell the observer little about the flow of stresses within them. The T-beam (especially when prestressed) is somewhat better because there is a clearly-defined division of "labour" between the top flange, which carries most of the compression; the web which carries most of the shear; and the lower region of the stem which carries the tension and sometimes takes a distinctive bulbous form to accommodate the tendons. Schlaich finds it strange that the monolithic nature of concrete and its mouldability – which should be its greatest advantages – allow us to use it in such a way that we lose touch with its natural modes of structural action; and that to control its internal stresses, we insert hinges and cut it up with contraction and expansion joints.[13] Naturally he regards shell roofs as a good example of the proper use of concrete: they make correct use of its mouldability, they are cast on site, and they are able to accommodate shrinkage and expansion without a need for unsightly and inappropriate joints.

It is thus no accident that Stuttgart is a leading centre of research into the strut-and-tie model for the analysis and design of reinforced and prestressed concrete. As we have seen, the continuous planes and volumes of concrete are visualized as containing discrete linear compression members, while the steel reinforcement acts as a series of ties. Masses of reinforced or prestressed concrete are thus transformed, mentally, into planar or spatial trusses similar to their equivalents in steel construction. (There is of course adequate experimental evidence that something like this does occur in reality, and that the method gives good prediction of the strength and behaviour of concrete structures and components.) What is most interesting is that this abstraction also has real consequences in design, because, for example, a next rational step is to omit those portions of the concrete which are seen to be playing no significant role in transmitting force. The result can be observed in the French extrapolation from box-girder bridges in which the webs have been dissolved into concrete trusses, and in the outriggers of the Finnlandhaus.[14] Schlaich notes: "Strut-and-tie models are a very useful tool for really understanding the complex material reinforced concrete. The method is simple, but not too simple: it supplies sufficient information, but no more. You can work with a material only if you understand it, and there can be no novel design without such understanding." (12.1)

An important element of Schlaich's sense of what is appropriate in structure is his perception of scale.[15] Commenting on the massive Kochertal Bridge, which was the highest in the world when it was completed in 1987 (the spire of Ulm cathedral would fit comfortably underneath it), he writes: "Though there is no question that this bridge is a fantastic achievement and though it looks good (slender and elegant) from a distance, one should not do anything like that – those massive beams on those tremendous columns. Cables supporting a continuous double-T beam at close intervals would be better. When a car on a bridge becomes almost invisibly small compared to the deck itself you know something is wrong. When a structure is doing little more than hold up its own weight and resist wind loads, it cannot be efficient." He feels uneasy that the recent leap in the span of cable-stayed bridges has been achieved by a simple increase in scale, rather than correspondingly radical developments in technique.[16]

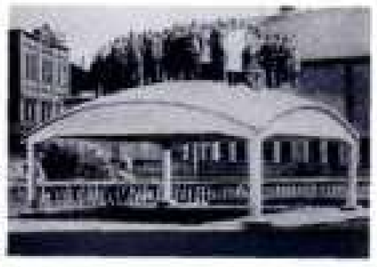
A major challenge for the design engineer is the constant need to take "decisions under uncertainty". As we have seen, researchers may to some extent study a phenomenon by stripping away factors which are unpredictable or difficult to quantify, or not yet properly understood. The theories they derive thus apply only to a part of reality. The design engineer must accept the full complexity of the real world and use whatever theories and concepts are available as helpful but not entirely dependable guides. The most common way to cope with the "grey areas" is to be conservative in decision-making. This approach is of course enshrined in the universal use of "factors of safety" in design. However, the designer must balance the need to ensure adequate structural safety on the one hand against the requirement for an economic solution on the other. The mechanical engineer and industrial designer have the advantage that they may build and test prototypes to destruction, but the structural engineer is normally concerned with "one-off" constructions. Thus the likelihood is far greater of making expensive provision for theoretically possible situations which later prove not to occur or, on the other hand, trying to economize with eventually expensive or disastrous consequences. Hunches, based on a fundamen-



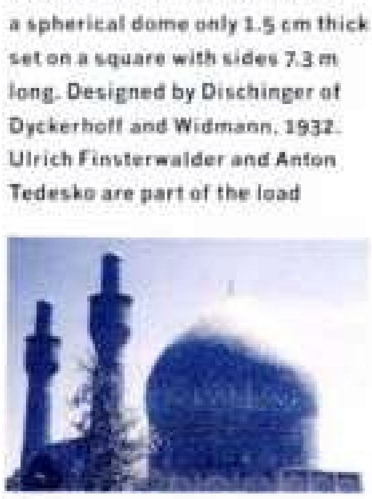
12.1
A typical strut-and-tie model design procedure:
– the problem
– elastic stresses by FEM
– strut and tie model
– reinforcement

tal understanding of available theory, a wide experience of practice, and a great deal of subconscious reasoning, play an important role in steering a course between these extremes.

As we saw above, one method of doing this (which is not often used) is to assess the likely consequences of "getting it wrong" and to make some provision for modification of the structure while it is in service, if this proves necessary. Wind effects on buildings provide a good example. The wind is random and unpredictable and although our experience gives a reasonable understanding of its behaviour, our theory must be couched in statistical (or "stochastic") terms. Schlaich regrets that these "tell you nothing – you cannot get a feel for what is going on". Treating the wind as a series of discrete gusts of variable number, as he did in an early paper, allows the designer to get a feel for the sensitivity of the structure. Then, as Schlaich says "depending on how you feel about it – how confident you are of the situation, and what the consequences are likely to be, you can choose and vary the number of gusts and their intervals which you think are important and proceed. (After such an initial and transparent design analysis, a confirmation with the stochastic black-box approach is of course appropriate.)" A similar technique may be applied to study the sensitivity of a structure to the minor defects in geometry which cause collapse due to buckling. Modern computer programs are able to simulate the increasing deformation of a structure as it buckles and to repeat this procedure many times for different initial values of the size of defects. Thus the designer of a shell may postulate defects of gradually increasing magnitude and check whether it becomes highly sensitive within this range. The result shows what level of tolerance must be specified to the builder or, if this degree of accuracy is not economically achievable, indicates that the form of the structure must be modified to achieve the necessary stiffness by other means. Although Schlaich has strong reservations about excessive dependence on computers, he says that, in cases such as this, they are "a blessing".



12.2
One of the first concrete shells, a spherical dome only 1.5 cm thick set on a square with sides 7.3 m long. Designed by Dischinger of Dyckerhoff and Widmann, 1932. Ulrich Finsterwalder and Anton Tedesko are part of the load



12.3
Friday's Mosque, Isfahan, 12th century. A challenge for tower and shell designers

We saw how Schlaich put such intuition to good use in the early stages of design of the Munich Olympic roofs. There was a strong body of opinion that the roof would suffer excessive vibrations in strong winds. The expert committee advised that because rigorous analysis could not then be carried out, the roofs should not be built. Schlaich's hunch was that the cable net was so complex, with so many different curvatures, different areas, and different lengths of cables, guys, stays, and masts, that any excitation applied at one point would be reflected back from a nearby edge at a quite different frequency. Excitation by a large number of random, localized gusts would thus result, as he puts it, in a "frequency salad" in which conflicting vibrations would cancel rather than reinforce each other and the cumulative vibrations would remain small and safe. After making the decision to go ahead, Schlaich was careful to confirm this intuitive approach by conducting tests on a model panel of the roof and to provide for additional stiffening cables should they prove necessary. The actual roof has lived up to his expectations.

An important characteristic of Schlaich's approach to design and research is his commitment to fundamental theory.[17] Many researchers start to explore a topic by making a large number of tests and then by studying the relationships between the parameters observed, make generalizations to arrive at a hypothesis. While there must be some reasoning in the choice of the tests – one cannot devise tests without at least a vague idea of what one might be looking for – it is indeed possible to arrive at a new vision of phenomena fortuitously in this way. However, Schlaich feels that the strategy is wasteful and advocates the Popperian approach of developing a clear theoretical position and then attempting to prove it wrong. As examples, he quotes the development of the strut-and-tie model (which has resulted in "translucent, general models" and "consistent design"); the triumph of theory in the design of the Hamburg hyperbolic paraboloid shell roof; and his fight for a uniform European code of practice for concrete which works from the general to the specific. He declares "case-by-case solutions are dangerous" and commends the wisdom of the old saying that "nothing is more practical than a theory". At the same time, his theoretical stance is by no means elitist, as is shown by the practicality of his designs, his interest in the skill of the technician, and the homely analogies which he uses to illustrate his lectures at the University.

Schlaich shares with many leading designers, past and present, a passion for certain techniques and forms of construction which is not entirely rational.[18] Innovations in engineering are usually introduced and perfected because an individual or group of people develops a fascination with some new or unusual form of construction and, for no clear economic reason, invests the time and effort necessary to solve its particular problems and overcome its drawbacks. Eventually, the new form must indeed be put to the test in the market-place where clients and the general public will weigh its practical and aesthetic qualities against its cost. However, without the initial somewhat irrational enthusiasm there would be no chance for this test to take place.

An example of this is Schlaich's attempt to revitalize the design and construction of the concrete shell roof. As we have seen, he became enamoured of it during his student days in Berlin, attracted like so many other engineers to the beauty of its mathematical complexity and the purity of its structural action, as well as its architectonic qualities. The concrete shell was pioneered in the 1920s, flourished in the 1950s and 1960s when it enjoyed great popularity with architects, and has now almost disappeared, apart from the brilliant projects of Heinz Isler in Switzerland (2.9).[19] In 1989 Schlaich wrote of this trend: "Without shells we abandon one very essential way of building, and the concrete industry gives away, perhaps not its basis of existence, but one way of making friends, which today means a great deal. With shells the concrete worker learns his handicraft, without which there is no quality."[20] Having listed new possibilities offered by pneumatic formwork, improved handling of timber, or use of new materials like glass-fibre reinforced concrete, he continued "adding to these advantages a little vision and the will to construct light and graceful structures, and with the concurrence of clients who evaluate a project in the light of quality and not only direct price, one can hope for a new evaluation of concrete shells ... Happily, clients now accept the price of inspiration, knowing that the authorities give their approval more readily to projects with a pleasing appearance ... Concrete shells with a thickness of a few centimetres are genuine lightweight structures. It is a pity to have to say that this technique is no longer used. *We must correct this situation.* [Author's emphasis]."[21] (12.2 + 12.3)

Like other pioneers, Schlaich is willing to pay for the intellectual and emotional rewards of tackling unconventional and challenging projects. Consulting firms rarely make a cash profit on these jobs and, as Schlaich says ruefully, "must do some 'bread-and-butter' projects to survive".[22] He is happy that his office is now so well established that it can afford the satisfaction of tackling more projects of intrinsic interest and investigating all projects more thoroughly than is usual.

The way in which engineers interact with architects provides an interesting insight into their approach to a number of central issues. It reveals the depth of their commitment to sound engineering principles and their interest in matters of architecture and aesthetics. The balance achieved depends to a considerable extent on their organizational and social skills. In previous chapters, we have seen Schlaich at work in the area of bridge design: a field in which the engineer is either in complete control of the project, or takes a leading role in form-finding.[23] However, in the design of habitable structures, the architect is universally recognized as the principal partner. The resulting interaction offers many rewards for the engineer, but these are combined with many challenges and, quite often, a great deal of frustration. With his interest in form and aesthetics and his strong ideas on the moral duty of the engineer, Schlaich is keen to make a positive input as a partner, rather than a servant. He particularly feels that on questions of structure and materials, the architect should take the advice of the engineer. Of course, architects are not always happy about this.[24] Schlaich prefers to work with an architect who is willing to look initially at the larger issues and explain in broad terms the functional and aesthetic effects desired, then leave the engineer free to devise about five proposals broadly consistent with these. If none of the proposals meets the architect's needs, it is up to the engineer to invent more until one is found which is broadly satisfactory to both and can form a starting point for refinement. Schlaich sees excellent examples of this sort of cooperation in his collaboration with Volkwin Marg on the Hamburg Museum roof design, with Kurt Ackermann in the design of the Kelheim bridges, and more recently with Meinhard von Gerkan on the Berlin railway stations. However, other experiences have not been so happy, as he has been approached by architects who wished to present him with a predetermined form in the hope that he would be able and willing simply to "make it stand up". Schlaich finds this particularly galling in the case of bridge design, a field in which architects are asserting themselves in competitions. He notes that architects who try to "design" a bridge, can gain inspiration only by leafing through journals and looking at previous examples. They cannot, like an engineer, examine the constraints and opportunities offered by the location in the light of fundamental knowledge and experience of bridge engineering and devise an original form which responds properly to a unique situation in all its aspects.[25] In this case they should limit themselves to providing comment and criticism on the architectural aspects of the bridge and on its refinement.

In the design of buildings, Schlaich has gained much satisfaction from working with architects for whom he has great respect (12.4 - 12.7, and Chapter 10). Nevertheless Schlaich still feels that, in many of the projects on which he has worked, no real integration of structure and architecture was achieved.

In particular, he thinks that German architects and engineers have not achieved the same results with suspended roofs as their British counterparts because cooperation between the two professions in this area has been less effective.[26] (Schlaich's view may be coloured by the fact that he normally has freedom to combine structure and "architecture" in projects such as bridges and cooling towers. In comparison, the design of buildings in conjunction with an architect must involve compromise and restriction. Many engineers work only in the field of building and so have no such yardstick against which to judge.)

When things go seriously wrong engineers are placed in a difficult position. Is their duty to try to achieve whatever the architect desires, or should they stand by their principles – particularly if they think that the architect is not acting in the best interests of the client? Withdrawing from the project is always an option, but there are contractual problems, and much effort may have been invested in design, analysis, and

12.4

The Hochschule der Bundeswehr, Munich, 1980. Architects: Heinle, Wischer und Partner

12.5

Spa visitor center Bad Salzuflen, 1982. Architects: Fritz Auer and Carlo Weber

12.6

The new Bundestag at Bonn, 1992. Architects: Günter Behnisch und Partner

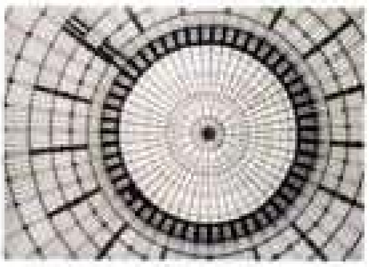
12.7

The Bioverfahrenstechnik laboratories at Stuttgart, 1993. Architects: Kurt Ackermann und Partner

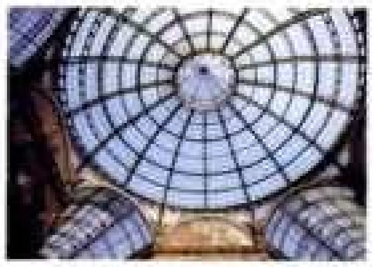
drawing by both parties. Architects meet similar problems with clients who wish to overrule their decisions and Kurt Ackermann tells Schlaich that the designer must be ruthless and pull out at any time rather than compromise his principles. Of course this is preferably done as early as possible. Schlaich has himself taken this extreme step when he found it impossible to work with an architect on an entry for a competition for a bridge in Paris. On the other hand, he sees nothing wrong in helping colleagues out, if asked to do so, in order to ensure that an important structure will work, as in the case of the huge hangar at Changi airport in Singapore (12.8).

12.8
Changi Airport, Singapore, 1981. Hangar roof designed by Y. S. Law

Like many members of both professions, Schlaich has given much thought to what can be done to improve collaboration. His ideas have been published widely.[27] It seems obvious that matters would be greatly simplified if both tasks could be handled by the same person, but Schlaich is sure that we shall never again see the "master builder" of the middle ages. He writes: "Whoever wishes to practice his profession as engineer in earnest must acquire so much knowledge, and constantly renew it, that it is impossible for him also to acquire the knowledge of the architect. There are already too many dilettantes."[28] He has great respect for the architect's social responsibility and "would never dare to enter his field" by, for example, trying to undertake the planning of a house.



12.9
The glass dome of the Bourse in Paris, 1811



12.10
The glass dome of the Galleria Vittorio Emanuele II in Milan, 1867

Schlaich shares with many leading designers a disinclination to talk about the way in which his aesthetic values appear in his projects, perhaps feeling that intellectual analysis may destroy the very quality it is trying to grasp. He has, however, included some mention of the subject in his writings.

"Obviously, when it comes to design of form, nothing can be proved, and there are few rules. Good form is above all a subjective challenge to each individual engineer, an appeal to his sense of responsibility, his industry, and his imagination. Because even if there are no learnable rules for good design of form – if art can not be learned – there are nevertheless clear pathways that everyone can follow: to make the load-carrying system 'readable'; to have the building respond appropriately to its natural surroundings; [to choose] variety instead of monotony of form; lightness instead of clumsiness; and the correct use of materials in accordance with their properties rather than pure efficiency of production (Materialgerechtigkeit statt reiner Fertigungstechnik)."[29] Elsewhere he wrote: "There are means accessible to all civil engineers to orient [conceptual] design in the right direction because no one can doubt that all that is light, transparent, and filigree evokes a more positive response than that which is heavy, massive and awkward.[30] All that is varied and yet harmonious, and possesses elan, attracts people more than monotony, uniformity and confusion."[31] Schlaich sees this principle exemplified in the lightness of grid domes such as that of the Hamburg Museum. Related to shells, cable nets and membranes they developed from his admiration of the glass architecture of the nineteenth century (12.9 + 12.10) and his study of the work of designers like B. Fuller and Frei Otto, inspired by "an extreme displeasure with all that is associated with ungainly, awkward buildings".[32] It can be seen that his design philosophy, with its moral overtones, blends with his aesthetic principles. Considering the wider meaning of the term "aesthetics" (the appreciation of what is "good") this is as it should be. He says that he "physically suffers" from the "architectural junk-yard" that his home town of Stuttgart has become in recent years and is at a loss to understand how this has happened when it possesses one of the best architecture schools in the country.

One formulation of the functionalist aesthetic (albeit a narrow one) is that rigorous adherence to principles of engineering efficiency will automatically lead to visual beauty. Schlaich's position on this is complex. Like most experienced engineers, he knows that it is not true, but wishes that it were. He points out that his solar reflector power plants, designed to be as cheap as possible and light in weight, have an appealing sculptural quality. They look good "even though, or rather because" formal considerations played no role in their design. Is this a lucky coincidence, he asks, or could it be that it is impossible to design without paying at least subconscious attention to conformation?[33] His Rosensteinpark I footbridge and the bridge at Nantenbach both suggest that a reduced emphasis on formal qualities can give rise to a severe form of beauty, even though it cannot guarantee it.

On the other hand, he recognizes that beauty can exist at some remove from function. In the design of the Schmehausen cooling tower Schlaich was happy to find that the more aesthetic solution could be shown to be the more functional. When low, heavy road bridges were proposed to cross the Neckar near Heilbronn, he fought to show that a solution which corresponded with his aesthetic principles could be made as economical as the conventional one. His favourite example of a structure which is irrational but visually pleasing is a viaduct at Schwieberdingen whose arch is shaved off at the top by the deck (12.11). From a structural point of view this is neither frame, propped girder, nor arch – but he finds it beautiful all the same! However, he feels it is imperative that the designer take care not to lose touch with the essential discipline of the medium in which he works and is torn between the desire to create beautiful form and the responsibility of building rationally and economically.

Schlaich's populist sentiments combine with his aesthetic principles to demand that the load-bearing behaviour of a structure should be clearly expressed so that the average person can understand or "read" it without difficulty. An example at the level of detail is his articulation of the ground

The office of Schlaich, Bergermann und Partner has a world-wide reputation for its innovative structures of striking aesthetic quality. The work ranges from cable-net and membrane roofs through bridges of a unique inventiveness to new devices for the utilization of solar energy. This account of their work concentrates on their leader Jorg Schlaich without losing sight of his partnership with Rudolf Bergermann and a steadfast team of designers and researchers based in his consulting office and in his Institute for Conceptual and Structural Design at the University of Stuttgart.

Schlaich's holistic approach to structural engineering combines science, pragmatism, and meticulous attention to detail with concern for the natural and built environment. It embraces the theoretical "Berlin" tradition of Franz Dischinger and the pragamatic "Stuttgart" tradition of Emil Morsch, maintained by Schlaich's mentor and teacher Fritz Leonhardt. Schlaich's drive to combine scientific theory, engineering design, and aesthetic art has links to the great German tradition of the Werkbund and the Bauhaus.

The range of structures is impressively wide and varied. In the design of utilitarian structures Schlaich and his team have made a major contribution to the art of structural engineering, taking responsibility for all aspects of design and achieving close integration of its technical and aesthetic components. In architectural design Schlaich is increasingly sought by prominent architects who value a spirited advocacy of the engineer's point of view.

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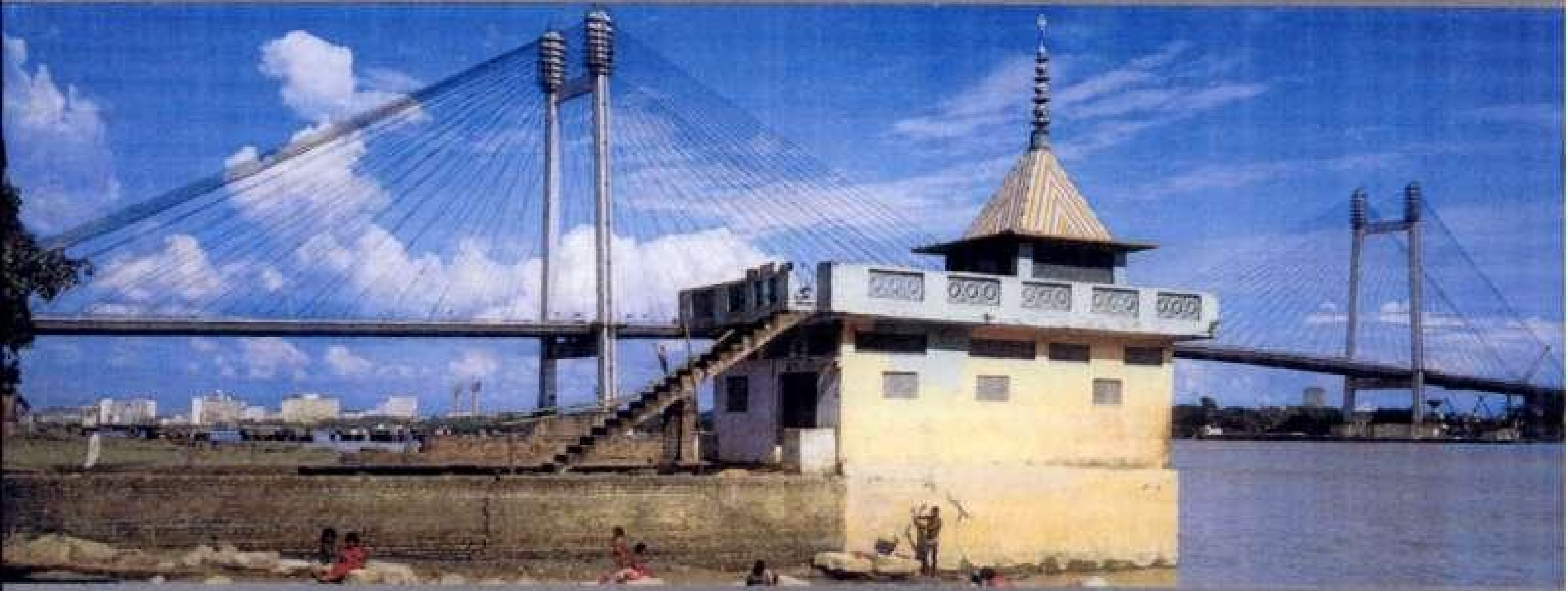

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