Post-Ductility

Published by
Princeton Architectural Press
37 East Seventh Street
New York, New York 10003

For a free catalog of books, call 1.800.722.6657.
Visit our website at www.papress.com.

Printed and bound in China by 1010 Printing International
15 14 13 12 4 3 2 1 First edition

Front cover image: © Michael Moran

This book was made possible through the generous support of:
The Steel Institute of New York
The Ornamental Metal Institute of New York
The American Institute of Steel Construction

Editor: Megan Carey
Designer: Jan Haux

Special thanks to: Bree Anne Apperley, Sara Bader, Nicholas Beatty, Nicola Bednarek Brower, Janet Behning, Fannie Bushin, Carina Cha, Russell Fernandez, Linda Lee, Diane Levinson, Jennifer Lippert, Jacob Moore, Gina Morrow, John Myers, Katharine Myers, Margaret Rogalski, Elana Schlenker, Dan Simon, Sara Stemen, Andrew Stepanian, Paul Wagner, and Joseph Weston of Princeton Architectural Press —Kevin C. Lippert, publisher

Library of Congress Cataloging-in-Publication Data
Post-ductility : metals in architecture and engineering / Michael Bell and
Craig Buckley, editors. — 1st ed.
p. cm. — (Columbia books on architecture, engineering, and materials)
ISBN 978-1-61689-046-9 (alk. paper)
1. Building, Iron and steel. 2. Architecture and technology. I. Bell, Michael,
1960- II. Buckley, Craig. III. Title: Metals in architecture and engineering.
NA4135.P67 2012
721'.0447—dc23
2011029679

Columbia Books on Architecture, Engineering, and Materials
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Post-Ductility

Metals in Architecture and Engineering

Michael Bell and
Craig Buckley, editors

Princeton Architectural Press
New York

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Foreword

To think again about metal in architecture is to rethink the world around us and the world inside us. There are no buildings without metal. Metal is often the first thing we see—an aluminum facade catching the light—or the first thing we touch—as when grasping a brushed steel door handle. Yet most metal is hidden within or behind other materials in a secret world of hard-working structural frames, reinforcing bars, nails, screws, rivets, fittings, ducts, and endless wires snaking along every crevice. Countless metals collaborate in even the simplest of buildings. Each has its own performance characteristics, arrives on site by a different path, and has its own history. This is before we speak about all the metal that inhabits buildings in the circuitry of our computers, appliances, lighting fixtures, and furniture. Not only does the defining strength of every metal lie in its ductility, its inherent ability to be stretched, but there is a fundamental ductility to the whole world of metal, a remarkable flexibility in the alchemical capacity to forge unique metals and rework them for various tasks. Buildings are made possible by a symphony of different metals simultaneously flexing in different ways.

Metal is not just within the building itself. To retreat into an igloo made of nothing but ice yet leave your mobile phone in your pocket is to remain connected to the metal architecture of the nearest cell tower, the communication satellites orbiting far above, and everything they link. The phone acts as the portable tip of a global world of metal. Even if you throw the phone down a crevasse to go completely off the grid, think of the mobile metal in your clothing, watch, jewelry, and even the repairs of your teeth or the traces of metal in your bloodstream, bone, flesh, and organs. The human body has been filled with metals long before we learned how to forge metal into tools. The body itself is already a metal tool. It is literally built out of copper, zinc, iron, potassium, sodium, calcium, and magnesium. When thinking again about metal, it is important to remember that we are ourselves made of metal and live in a world of metal. Most of the core elements in the periodic table are metals, so the question here is not what is happening to metal in architecture but what is happening to architecture in metal. How is architecture taking form within the fluidity of metal? Out of what alloys is it being forged? How does architecture flex today?

In the standard historical narrative, modern architecture arrived in the early decades of the twentieth century as a belated response by architects to the introduction of mechanically manufactured iron in the bridges, towers, and exhibition buildings produced by engineers from the mid-nineteenth century on. In 1928, Sigfried Giedion, the most influential historian and promoter of modern architecture, argued in his first book that the unique molecular properties of metal allowed lean structural frames to act as "both muscular tissue and skeleton" in a building.[1] Heavy load-bearing walls could give way to a radical fluidity of both structure and the pulsating modern life it supports. Not only does the inner condition of metal "demand a more complex, more fluid balance of forces," but the outside world is now a set of fluids that "stream" through the newly "dematerialized" building. Metal acts as a dematerializing material. It allows building, light, air, and movement to melt into one another. The air "drawn into the interior" of the porous frame of the Eiffel Tower, for example, "now becomes, in an unprecedented way, a formative material."[2] Metal dissolves rigid buildings and gives birth to new material alloys, new concepts of space.

What is being dissolved, concentrated, or stretched today? What architecture is metal giving birth to? The research in this book is the third in a series reexamining our basic materials across a broad range of scales, from the nano to the global. It has been a privilege to invite such a density of remarkable minds to forge this picture of the state-of-the-art in metal.

1 | Sigfried Giedion, *Bauen in Frankreich, Eisen, Eisenbeton* (Leipzig: Klinkhardt & Biermann, 1928). Translated by J. Duncan Berry as *Building in France, Building in Iron, Building in Ferroconcrete* (Santa Monica, CA: Getty Center for the History of Art and the Humanities, 1995).

2 | Ibid.

—Mark Wigley

Preface

Post-Ductility: Metals in Architecture and Engineering is the third in a series of books that have emerged from conferences organized jointly by the Graduate School of Architecture, Planning and Preservation and the Department of Civil Engineering and Engineering Mechanics. While the first and second conferences dealt, respectively, with the use of structural glass and concrete in architecture and engineering, the focus of the third meeting was on metals, which means primarily steel, especially when we are talking about metal as a structural material.

The basic concept of our conference series was to bring together architects, engineers, and scientists to educate each other in new developments and novel uses of these materials. I would like to stress the words *educate each other*, because every one of us has something to bring to the table. I vividly remember the final panel discussion of our first conference between an architect, Mark Wigley, and an engineer, Werner Sobek, as they debated whether the architects are pushing the limits for the engineers or the engineers are pushing the architects. I came back from that discussion with the conclusion that there is both push and pull. So here we are, again, very fortunate in that we have been able to bring together a group of prominent engineers and architects who are quite familiar with the challenges involved and are ready to define what Wigley calls the big umbrella that covers materials, architects, and engineers.

In my introductory remarks for our first conference, I said my own Mudd Engineering building is only yards away from Avery Hall, yet it often seems as if an insurmountable gap separated engineers and architects. But we civil engineers are in the business of building bridges. So let us continue building that bridge from Mudd to Avery. And I am very grateful that we have in Dean Mark Wigley a willing and most supportive partner in this bridge-building project.

The gap we are trying to bridge is particularly apparent when we realize that we speak different languages, which brings me to the title of the conference and book: *Post-Ductility*. I am certain that our architectural colleagues understand something quite different under this term than I do as an engineer. The engineering definition of ductility is quite simple. In fact, it's one of the few definitions that I make sure all of our students understand and remember: Ductility is the capacity of a material to undergo large inelastic deformations without failure. Hence, the term *post-ductility* worries me. As an engineer, I hesitate to use that term, because after a material exhausts its ductility, it generally fails. As engineers we can't let that happen. It is our job to prevent failure.

On the other hand, the title for this conference is also an interesting one. Our first conference dealt with glass as a structural material, because glass is the quintessential brittle material—the exact opposite of a ductile material and it poses a special challenge to the engineer: namely how to incorporate a brittle material into a structure expected to behave in a ductile manner. When we work with metals, we don't face this problem, as metals—particularly structural steel—are very ductile and therefore an ideal material for structures. That leads me to the simple proposition, namely that post-ductility might define the challenges we face after the demand for ductility has been satisfied.

—Christian Meyer

Introduction

Post-Ductility: Limits of Form

Michael Bell

Assembled under the title *Post-Ductility*, this work is more precisely ascribed to what could be called a post-ductile era—one in which the elastic capacities of materials are inextricably lost as determining values. Yet materials remain nearly universal in their prevalence, and have, if anything, grown in complexity. Everywhere and nowhere in this equation, metals are ubiquitous, appearing in familiar roles such as facades, curtain walls, and frames, but they are also expanding in less visible arenas, from wiring to composite structural solutions to foams and films. We see this as a newly formed arena of dramatically extended material limits and orchestrations. The work of an architect, engineer, and materials scientist engaged in the urban world is to now trace the logic of decisions related to the deployment of metals in design and construction and to decipher the implications of material allocation. One must intuit the resulting spaces, those of contemporary architecture and urbanism, as well as the less tangible global network within which materials are produced, traded, discarded, or recycled.

Metals as surface or structure—as generators of space—play a role in nearly every strain of modernization in architecture, but they are also benchmark commodities that are central to labor and the changing patterns of employment before and after World War II. Metals define complete geographies of work, production, and political life. Nonarchitectural metals delivered in automobiles and hard goods (from AEG to General Electric to General Motors) in the United States and worldwide have been sourced as the engines of the sprawling late-twentieth-century city in all of its registrations and forms. But in the received aspects of architectural history, metals, steel in particular, remain something more segregate and less diluted; they are presented as intrinsic to key terms of the architectural and architectural engineering professions. As material, metals precede architectural concepts—they are instigators and carriers of architectural meaning.

The divide between what metals are as benchmark commodities and the stabilizing qualities they signify architecturally can be immense at times, but this gap, and its parameters, changes within historic circumstances. Much of *Post-Ductility* explores this divide as metals are traced to the economies of their production and to the urban economies of the buildings and infrastructure they form: metals are both a measure of financial activity and a foundation and strata of form and historical meaning. As material is increasingly viewed as one of many components in a delivery and control chain and more precisely monitored and recorded as such, metals are situated within a deeper set of organized techniques and seen less as an origin of content and more a conductor of all manner of forces. Metals, whose stature stems from rationalized structural or material foundation of twentieth-century architecture and economy, are presented in the work of *Post-Ductility*'s authors as progressively part of the ebb and flow of markets and of negotiated aspects of design, programs, or use. They seem far more conditional than they did even thirty years ago, when it was possible to see modernism as quintessentially stable against an emergent and more reflexive and semiotic postmodernism. In the work shown here, the structural uses of tension or other coefficients of material efficiency often appear less focused on the rationalization of spanning capabilities than on social or economic goals that are manifest or served by structure and material.

Material is conductive of social intention. In Steven Holl's Nanjing Museum of Art & Architecture, the use of cantilevered systems—with structural members usually reserved for infrastructure and bridges—allows a relatively small building to seamlessly span an open space far below, as a floating structure. Similarly, cable-stay systems for the San Francisco–Oakland Bay Bridge by Marwan Nader allow for reduced environmental impact on the San Francisco Bay. In both cases, engineering serves social and environmental goals. The complexity of the structural engineering and the degree of its tuned (i.e., computational) efficiency—its leaps in structural advancement—are discussed less, even as the forms enabled by this engineering are startling and new. The Holl building seems to levitate over its site. The new Bay Bridge adjacent to the existing bridge and its anchorage weaves into downtown San Francisco. With far less mass and the internal resolution of lateral force, the bridge hovers amidst the existing context and its demands.

Do such processes and new technical capabilities diminish the material's centrality in architecture and engineering? When material becomes less foundational, even as it is ever-present, does it indicate a shift away from engineering or a more global prevalence of engineered environments? In light of altered social dimensions that are both a reason for and result of new structural means, do metals, steel in particular, lose their iconic nature and instead become equivocated among forms of production and performance?

Without seeking to diminish the social, the social advancement seems to portray these aspects more fully than the engineering advancement. The work of

Smith-Miller + Hawkinson Architects is an example. In the Champlain border station, the boundary zone between the United States and Canada is dramatically extended in large part by increasing the spanning capability and spatial features through a structural steel shell and folded-plate canopy. Long known for innovative work in structural design, Smith-Miller + Hawkinson have nonetheless always fused structural and social aspects of design in ways that are inextricable. Structural engineering by Werner Sobek, Heiko Trumpf, and Craig Schwitter depicts a capacity for programmatic use and change largely through achievements in flexibility and environmental performance. Their work seems less connected with programming (and more with enabling flexibility) than the work of Smith-Miller + Hawkinson. Yet Sobek, Trumpf, and Schwitter, and the other authors assembled here, all thrive in pushing material limits, whether structural or social, with a compensatory drive to define these limits clearly. There is a search for what material can do, and for whom, but there is also a deep exploration into material capabilities in isolation of need or purpose. Much of *Post-Ductility* outlines these profiles.

In themselves, metals are a frontier of dynamic potentials: they have differing limits of ductility—the ability to be stretched or extended by plastic deformation—but they all inevitably recover more easily and with higher limits than other major building materials such as glass or concrete. *Post-Ductility* is not an avocation to alter these threshold limits needlessly or to suggest they do not continue to play a critical role in structural engineering—or life safety or coherent engineering practices. It is in many ways the opposite goal: the authors reaffirm material behavior as critical and its limits as generators of new conditions for design. Few concepts are as central in structural engineering as the known ability of a material to sustain plastic deformation under stress or strain. The standardization of historically established deformation limits or ductile properties of most materials allows architects and engineers to focus the structural analysis within given parameters of finite element analysis rather than materials science. If the material behavior is known (and has been for some time), the statics equations for its organization are predictable, and design thus follows standard parameters of statics. *Post-Ductility* refers to works that often push finite element analysis—statics—to the point of near failure in what seems an invocation or attempt to define a new material condition. In Sylvia Lavin's essay, "Metal Fatigue," metals are singled out as instigators. She describes metals that were "enticed to fail" in structural organizations that "flirted deliberately with fatigue, because failure was understood as an opportunity to bring down a totally exhausted architectural logic of modernist veracity and virtue." Indeed, much of the historical research included here points in this direction. Jorge Otero-Pailos portrays John Ruskin's condemnation of metals—first rejected by Ruskin as unworthy in the canon of architecture—and his proclamation that the material would require an entirely “new system of architectural laws.” These laws would be tested sixty years later in ways that Lavin reveals in her writing.

Similarly, Galia Solomonoff shows the limits of material strength in the vaults designed by Eladio Dieste as embedded in an economy that was ultimately vested in an ethics of distribution. The efficiency of Dieste’s structural mechanics was a mixture of high and low; the masonry’s mass, weight, and density are seen in contraposition to the lightness of the vaults and the potentials of the geometry and mechanics. In Solomonoff’s text, Dieste invokes the limits of both material and mechanics as thresholds that palpably reveal an ethical crisis in social economies. For many, Dieste’s work has become a sign of a local or regional modernism that carries the qualities of place within the universal aspects of the movement. However, in the context of Solomonoff’s writing, Dieste is instead a deeply critical architect whose work reflects not on the wholeness of place but on the violence imparted by a material economics based in lack.

Paola Antonelli, Theodore Prudon, and Mabel Wilson portray metals as both harbingers of social change and fundamental drivers and participants in new forms of manufacturing and labor. The semiotics of new forms, shapes, and figures in architectural and household metals is situated ultimately within the systems of labor and material capacities that metals carry. While it is difficult to recall a time when metals were a novelty in architecture or design, the materials did force, as Ruskin imagined, “a new system of architectural laws”—in that transition, a material, new in its molecular organization and materials science, invoked all forms of risk.

Recovering that productive risk is at the heart of much of the work in *Post-Ductility*. It is rare for architects and engineers in practice to encounter new material performance quotients that threaten known parameters; the boundaries are usually set (and tested) and the limits of ductility (or other material determinants) are observed for most materials today. Yet many projects in this book show an emergent series of practices and works that again place metals in a context where ductile limits are pushed and where material behavior is portrayed as near chaotic before it is stabilized. There is not a deep range of new metals presented here, but instead a use of statics to push metals toward new forms of behavior.

The term *post-ductility* refers to the literal aspects of material behavior—in this case, of metals—but also to aspects of architectural and urban space that are measured by less verifiable but nonetheless real quotients of stress. These include concepts of plasticity that have been common to architectural discourse for centuries, such as concepts of the plastic arts, as well as up-to-the-minute entities such as sprawling cities that exceed historic limits of "plastic" or formal coherence. The work collected in *Post-Ductility* often focuses on intricate structural detailing as much as urban or political circumstance. Rory McGowan's work and writing on the structural engineering of the CCTV headquarters in Beijing reveals a building within which public iconography and structural engineering are synthesized: the elastic aspects of the building's double cantilever are reconciled when anchored together at the precipice of the structure. The vivid image and essentially symbolic (if enigmatic) character of the building are upheld by this singular connection. While designed to sustain tremendous seismic, wind, and snow loads, the structure ultimately is balanced to a point of equipoise within a few centimeters; at final anchorage of the building, the expansion and contraction of metals had to be accounted for by month, day, and hour. The work of McGowan focuses on managing this expansion and contraction more so than any perceived building weight or torsion. McGowan's work essentially verifies the search for a new skyscraper, led by Rem Koolhaas and the Office for Metropolitan Architecture and Cecil Balmond, and inextricably fuses the scales of the building and its material behavior.

The authors and editors of *Post-Ductility* have sought a reciprocity by which the most essential aspects of material behavior have a capability to connote, if not outright take part in, larger urban issues without becoming overtly urban, even as the works change the urban by way of architecture and engineering. Material is at the core of this equation, but perhaps the common denominator in this body of work is material under highly controlled modes of stress and strain. It is reciprocity of tension and compression in statics but also within concepts of space that gives form (or coherence of form) to this work. In the domain of engineering and quantifiable limits, it is clear that formerly daunting degrees of material or structural risk often seem to have been diminished. New levels of sophistication in calculation raise the risk tolerance for failure in structural design because we know more about when fracture will occur; we get closer to failure because we understand it better. Yet more metaphoric readings of the tolerance levels or limits in architectural and urban space and its coherence seem to have been long surpassed. In recent years, financial risk in mortgage securities, housing development, and market liquidity has been exceeded with outright abandon, but what is known as urban sprawl has for decades connoted a city that was already beyond structural (and thereby social) capacity for governance. What then does the term *ductility* mean today if you seek material versus spatial limits? How do you measure limits, and to what degree do historically stable measurements of ductility still enable spatial organizations in architecture, engineering, or cities? How do we determine boundaries and when are they understood as having been crossed or defined irrevocably?

Since the 1970s, the architectural field has often appeared to abandon the subject of materials as a field in which to seek change or innovation, looking instead to the domains of computing and information management. The recent rush to issues of performance and capacities in design of all types has seen few attempts to define material performance within a broader social realm. However, there are several works here that show this direction with a limited but highly defined scope. Keith Kaseman, David Benjamin, and Hilary Sample all look to social- or site-based implications for new means of fabrication, while Mark Malekshahi's work on the thermal behavior in building systems is essentially unseen even as it allows the architecture of SANAA to chart startling new zones of experience. Such performance is intrinsic to material and its limitations but also to the wider questions of how material is allocated and distributed in the matrices of architecture and how architectural works are viewed as catalysts to new urban worlds. This architecture retroactively attempts to change the dysfunctional host—a city that is failing environmentally or socially here is less a cause for protest or upheaval than it is a capacitor to register and reveal energy as experience. From there, it's a social and technical realm that can be occupied and plied by many.

Architectural theory during the final decades of the twentieth century was often more focused on models drawn from linguistics than material or engineering. While not denying material importance, it positioned material as a conceit of modernism or strains of neomodernism. Materials seemed, in some sense, less real, even as they were omnipresent, and were typically financially, if not structurally, determinant. This is possible to suggest even with the work of firms such as Morphosis, where steel frames and metal sunscreens (made into overly visual elements) sometimes appeared more applied than fundamental. The work in this book often struggles to cut away what is not essential in design, or it forgoes design altogether as in the writing of John E. Fernández, where material territories supersede architectural production as zones of exchange, of political and financial change. Fernández's work on territories is essential here and points to a wider project in which the financial/material aspects of sprawling cities, while unsustainable, also hold the potential, if mined, to produce new forms of architecture. The expanse of territories and the immediacy of architecture and material are imbricated in most of the work presented here: architectural design by Juan Herreros is an example of a fusing of architecture and infrastructure that maintains detail and specificity amidst sprawling sites that are often thought to diminish architecture. Herreros does not see a cleft between these scales; his work is discrete from its milieu, a critique of it, but also made from it—material catalyzes this relationship and lessens its antagonistic nature.

Industrial Change: Imagined and Real

In the writings and architecture of Ludwig Mies van der Rohe, architects have typically found what they assumed was a drive toward the empirical aspects of building, yet the search for a renewed form of the building arts in Mies's work, while sustained in the facts of material, has more often been characterized by the phenomena of experience. The scholarship on this aspect of Mies's work by K. Michael Hays (among others) is well known, but the intricacy of what Hays called a "cleft" between the architectural experience and material reality of the building and its site could be expanded with a closer look at Mies's use of metals—in particular, chromium-plated columns and the polished nickel surfaces of his furniture.[1]

The optical qualities of Mies's chromium-plated cruciform column-cover, first used at the Tugendhat House (and later modified in the Barcelona Pavilion), has often been presented as both the figural and empirical signifier of a rationalized architecture; yet the chrome material, as discussed by Hays, becomes abstract when observed. It is liquefied into the surrounding light. A "temporal" participant in the world, the column-cover, with its geometry demonstratively described in architectural drawings, takes on visual characteristics and colors of the environment. Imparting a sense of flow, Hays saw this dissolution as a disruption of the otherwise factual materiality. The use of a chromium surface at the Barcelona Pavilion is the source of this optic dissolve, but what has been missed in discussions of Mies's work is the similar use of polished nickel in his steel furniture. The polished surface of the nickel seems more saturated and porous than the literally harder chromium surface of the column. This saturation of color and light conveys a palpably different sense of flow, giving the nickel and chromium surfaces a different sense of strength and flexibility. The immediacy in this reading of material is borne of the facts of industry but also the liquidity of experience. In some sense, the cleft that Hays enunciates and the severity of this work is opposite: how something is made and how it is experienced is not divided but integral. The imagined and the real are perhaps not easily resolvable but they are manifest in the same form.

During the first half of the twentieth century, real and imagined transformations in industrial capabilities and means had immense impacts on the aspirations of architecture and engineering. Early in the century, the rationalization of construction processes, techniques, and standards—those of labor but also of the subsets of professional practices and materials in building—reached levels of efficiency, analysis, and control that still persist as both empirically real and alternately imagined in scope. We see material as intrinsic to structure and the goals of that time. The elastic distance between the imaginary and the real is the zone in which much architectural and engineering ambition has been founded; the qualities of this zone are continually changed by way of received, and sometimes false, memories of the past.

But the radical aspects (both imagined and real) of the early century's avant-garde have nonetheless reinforced the discrete or finite terms of architecture's and structural engineering's impact within social or economic realms. Architecture, in this scenario, instigates social change by structurally freeing space (the free-plan, for example), and then is left behind as the focus shifts to new dimensions of social life. Alternatively, the structural design enabled by material innovation sustains a new form of social life in which architecture retreats (long span/clear span). New forms of spatial experience or the associated labor of new design and engineering capabilities at the core of the early century give way to a more automatic distribution of materials as commodities as a fusion of social and material/structural goals are eclipsed: design struggles to cohere the social dimension and eventually retreats.

The professional terms of architectural and engineering practices seem to have stayed within, and have often reinforced, disciplinary boundaries as the actual economics, geography, politics, and media forms of contemporary life rapidly change. A key aspect of this divide remains significant today as we reengage and escalate both the real and imagined aspects of our technological and material aspirations, regarding the tools we use and the world in which our realized works are made. The wide range of computation, design, and delivery means (e.g., BIM, IPD, etc.) that are gaining use in the building professions link localized small-scale firms across globalized sites. Materials and practices, now networked within architectural and engineering protocols, are reconceptualized and imagined, and are indeed newly "real" in what is believed possible. In this sense, the term *ductility* is an attribute of a material's physical limits, but also of its conceptual and economic limits. The extensive diagram of materials and practices as sites and zones, as areas of engagement, is changed by pushing boundaries previously thought closed. Material, then, is a component in a diagram of money, time, and delivery as much as precinct of physical properties and elastic limits. It is in this zone and its shifting parameters that the contributors to this book operate. Collectively, they begin to outline and diagnose the hidden architectural potentials of our time. Perhaps more than an origin for engineering advances, this mode of material exploration can be considered an immediate spatial engine; it is not something to critically engage or support but a milieu that has produced an environment of which we are subjects.

If the site of today's architectural and engineering work is the twenty-first-century *sprawling* city, how does one construct a value for materials? What is the ideal relation of engineering and architecture in this milieu? Is the city and its sprawling context an out-of-control economic engine that threatens the discrete terms of architectural and engineering practices (by overwhelming their boundaries), or does the city constitute a new form of material practice—a condition that is the source of conceptions of space and experience in which the gaps between the imagined and real are zones for new forms of urban life to emerge?

The Distribution of Metals: Beyond Architecture and Building

For most of the twentieth century, the automobile industry in the United States deployed metals in greater quantities than were used by architecture and building. Metals are indeed still everywhere but the architectural and engineering histories that sustained them, and provided importance to them, have never fully engaged the logics of finance and politics that also distribute metals into non-architectural uses. The complexity of materials in historically significant architecture is an underexplored project, if viewed in empirical terms. Metal structures, steel structures in particular, traditionally subtended the continual expansion of spanning capabilities in conjunction with the ever-growing dimensions of the postwar city. Yet these expansive tendencies are frequently portrayed as having inverse procedures that foreclose distances, exacting the tedium of daily life and instrumentally tracking or constructing our behavior patterns. The physical limits of the everyday are wide but often narrow with regards to how attention is parceled or how time is organized.

How we measure the building arts and their material allocations against the wider allocation of materials in other industries has become a central question for architects and engineers. To what extent has the precise territorial equation of discrete measure been irreversibly changed, such that the measure of statics, of components, and the relationship of part to assembly are able to be located within the broader deterritorialized aspects of material trade, emerging economies, and finance? These are not new questions, but as materials and development become inevitably global, we must consider how our work addresses the manufacturers and the markets that capitalize on them. In this realm, is there a new form of frame, structure, or enclosure—a new means of measurement? Or are these terms now malleable but not fundamentally changeable? Increasingly, the barometer of a material's meaning is the absence of its limits or finite formations rather than its ductile properties or the logics of its engineering. Space is at times radically unconstructed and almost randomly produced at the urban level, while its boundaries are just as often defined and driven by contravening social or economic constraints. As we see an increased attention to the logics and processes of fabrication again, it becomes more urgent to understand what the parameters are, and how we construct the value of materials in the equations of practice, urban space, and economic and social life.

As social life continues to be portrayed as untethered from the demands of immediate industrial production—from urban density, prewar factory life, and labor relations—materials have not ceased to be a determining factor in the spatial or economic engines of urban or suburban life. Yet when conflated within wider urban worlds, the industrial production of commodities such as cars, domestic equipment, and products merges with infrastructure such as freeways and bridges, and the limits of material performance and coherent social space become impossible to calculate. The dimensions, and discrete form, of professional practices fail to offer coherence to the broader experience of urban life. A measurement of raw steel as a benchmark commodity in the United States in relation to the gross national product shows a rapid and steady rise during the pre- and postwar eras, even as the metal simultaneously registered a persistent decline as a percentage of the overall economy. From the very origins of steel production's massive run-up, in the period from roughly World War II until 1970, steel was actually declining as a benchmark commodity in the United States and in Europe. Steel and metal production grew but not necessarily within architectural terms—or within our professional arena—and not within the larger economy. How are the material decisions of an industrial age adapted to the altered material economies that have developed since the 1970s?

The steel and glass towers associated with high modernism are received often as a story of rationalized or discrete production, yet they were never isolated from wider parameters. Political or social action could not be separated from material even as new forms of urban, social, and financial life emerged that increasingly relied on dispersed and bucolic forms of suburbia and media-based modes of social life—forms of private life that insulated subjects from overt forms of production. Yet production, by many accounts, has permeated the postwar suburban sprawl as fully as it has the prewar city.

Prior to the end of World War II, the goal of having full employment in a postwar United States was understood to require a dramatic rise in manufacturing and material exports. Metals were key to this equation, which was at the heart of the territorial and economic expansion of the country. Producing automobiles to meet that goal was also key, yet the need for exports could only occur against a stable exchange rate between the United States and Europe. Driven by production and finance, material commodities were never to be understood as discrete again. As they found their way into buildings as much as automobiles and airplanes, and into consumer products worldwide, metals became distributed and complex commodities.

The efficiencies of construction and engineering that produced new forms of architectural and subsequently social space on the cusp of the twentieth century operated within and were perhaps commensurate with the advances in economic production—efficiency in design was arguably on par with emerging economic practices. In this realm, material engineering innovations were often coupled with known forms of architectural language: columns, beams, and walls sustained their nomenclature while simultaneously achieving new spanning capabilities, greater lightness, and increased speed of construction. Traditional architectural elements maintained an operational value as they gained new material and economic qualities. Yet the material science that lies behind these renewed elements seems to have been rarely correlated to the new forms of social space that these innovations instigated. How do we look at these issues today? Do the nomenclatures and elements still hold—are the architectural and engineering terms commensurate with emerging material processes, and with the economics of global material practices?

Architectural and urban theory has persistently struggled to describe the material quality of the sprawling world of the megalopolis, privileging instead its economic, geographic, or social dimensions. From Manfredo Tafuri to Rem Koolhaas, there has been at times a seeming abandonment of material value or material goals for architecture that are nonetheless redescribed and pitted against a collapsing ability to sustain what we thought were venerable architectural practices. Architectural nomenclatures survive today despite the massive transformations in the substrate of our practices. The result is a divide between what is imagined as capable material techniques and what is witnessed as a debilitating, even reckless, urbanization that disallows material qualities in most building, while consuming ever greater amounts of material and producing an ever-widening detritus. Does the divide between quality and quantity circumvent a comprehension of often deeply organized processes of urban space and of urban life? How do we construct material's value in this realm? What is the level of ambition? What is imagined versus what is real and where do we try to locate, or, if necessary, create, the boundary between the two?

Spanning the Void

In clear-span or long-span structures, varying degrees of integration between framing and enclosure mean that volume, mass, and structure are often unified and undivided. Structural engineering, in this realm, takes on social aspects of what could only incrementally be called architectural space. In long-span structures, a threshold is passed, indicating that the space is fundamentally derived from engineering as much as or more so than architecture. At a large scale, the work becomes virtually infrastructural and perhaps supersedes any expected social readings of architecture or engineering. Within the evolution of metals, of steel framing in particular, the nature of clear- or long-span structures has also evolved. Spanning capacities reveal new functional potentials, new spaces whose uses were not conceived of in advance.

As either a pragmatic foundation or conceptual device, the structural frame, not as closure or volume but as its matrix, has often maintained a tight perimeter that keeps social aspects of use apart from overtly structural or material concerns. In the normative "modern" structural paradigm, the structural frame holds up the building as non-load-bearing walls, and, with the subsequent programming, affects social life and use. The stability of structure assures a datum for a segregate organization of social life—in this realm, a concrete office building essentially functions as a steel office building would. As a subset of structure, the social aspects of architectural space could occur as a concurrent or parallel project. In clear-span structures, or places where structure and space are synonymous, however, the degree to which social aspects of occupation are related to the very means of construction—to overt use of materials—implies that structure is a social entity. It is capable of instigating use. In other words, the social is overtly tied to material and engineering, even as space is often cast wide open and made to seem a-material in its newfound expansiveness. Quasi-endless interiors created by clear-span systems fascinated architects and engineers during the mid twentieth century, but also engendered countermovements and caused trepidation in other realms where spatial freedom became a source of anxiety.

To what degree have we seen counteracting tendencies to the capacities of spatial and structural extension—toward new models of privacy, intimacy, and interiority? Are examples such as the wide range of aedicular spaces common in postmodernism (as opposed to evolutions of the free-plan or Miesien open volumes within later forms of modernism), or even within new forms of networked communities and communication? What are the technical aspects of clear-span structures today? What aspects of spatial specificity versus universality affect its organization? New aspects of engineering in the structural design of bridges have led to crossover works and an architectural aesthetic of infrastructure. Coupled with recently developed computational tools that have allowed high levels of customization in structural design without compromising essential requirements of serviceability and economy, we are seeing a wide range of new forms of infrastructure as quasi-architecture. The professions of engineering and architecture merge in unique ways as new means of structural analysis open visual and aesthetic forms. In this collection, projects by Lise Anne Couture (Yas Hotel) and Hans Schober (several cable-stay bridges) mobilize immense works that are nonetheless fully customized. They also link infrastructure and design with an ease that suggests that this near-infrastructural scale will allow significant design and innovation in cities today. The designers are responsible for a wide range of scalar limits but also for working with the intricacy of relatively small-scale practices (this not Bechtel, for example). The spanning capabilities of this work also carry a tremendous degree of tuning and specialized design, in detail as well as programming. Couture and Schober revise the meaning of long-span structures. Similarly, Holl's Nanjing Museum also creates a new capacity for clear span, largely by building a rigid structure at a scale that is unusual for architecture but that is made possible by employing structure as mass—as counterbalance. Holl's work is almost certainly less efficient in use of material than Couture or Schober (in part because it is at a building scale), but like Couture and Schober, its scale of material and mechanics is between architecture and infrastructure. The degree of mechanical control is far higher than more normative construction, and despite its infrastructural size, it maintains a human-scale environment.

Schober's cable-stay bridge designs shown here are a delicate version of a cable-stay structure. In a cable-stay structure, the intricacy of the balance and the linear-planar control of forces reflect a mechanical invention that creates new forms of structure and monumentality. The works becomes iconic in part because of their startling forms. These structures rely on unprecedented levels of precision in the routing of forces to enable reductions in material weight: while the towers or pylons carry compression loads, the cables are arrayed in a way that essentially cantilevers the deck surfaces. The deck's ability to resist the horizontal components of the cable forces has the consequence of eliminating the need for heavy buttresses or anchorages. There are uncanny visual results as the expected visual mass of the suspension bridge's large anchorage is absent: the structure resolves itself internally. The concrete deck acts as a prestressed element and the structural composition becomes a matrix of linear and planar elements. It is visually light—the taut cables replace the parabolic form used in the suspension bridge.

Post-Ductility presents projects, historical research, and theory, although, at times, it also presents a still emerging form of architectural education and discourse. The authors were asked to respond to many shared questions, one of which inquired if architecture has the capacity to instigate change in material science or if instead it is bound to be a recipient of these changes? In writing, design, and research by Anna Dyson and Matthias Schuler, the book finds two strong replies that the editors shared and had hoped to foster. The first, as seen in Dyson's work, is a proposal that innovation will not happen upon a singular path—parallel and opposing forces all vie for play in a world driven by competing demands and unequal capacities. Change is a result of a conflation of forces. In this realm, Schuler has continually reminded us that there are consequences to change; otherwise, positive changes and new resources bear uneven results upon society, and this disequilibrium means that some suffer the results of change as others benefit. The divide is evident in the work presented here, yet much of the book shows highly capitalized and engineered projects backed by immense financial resources. What we have hoped to accomplish in bringing this work together, in the series as published to date, is to reveal a strata and complexity of means and operations that we believe is the zone where social change in engineering and architecture can happen. A simplification of the means, or a recoiling from the financial complexity of this work, would sever our ability to mine and better distribute its benefits. Few architects have plied this scenario more deeply than José Rafael Moneo, who has consistently placed innovation in a social context of history. But Moneo, whose new Northwest Corner Building at Columbia University is included in this book, is one of many here who have contributed work and ideas that try to outline a palpable and real enunciation of materials—of the built—that is as concerned with mediating the unreal (finance, economies, politics, and sites) as it is with the precision of knowing exactly the limits of exchange, and the tangible expression of how these means form a ductile, that is, visible world.

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1 | K. Michael Hays, "Critical Architecture: Between Culture and Form," *Perspecta* 21 (1984): 25. "The architectural reality takes its place alongside the real world, explicitly sharing temporal and spatial conditions of that world, but obstructing their absolute authority with an alternative of material, technical, and theoretical precision. A participant in the world and yet disjunctive with it, the Barcelona Pavilion tears a cleft in the continuous surface of reality."

History and Theory

Iron Cement: Material Limits of Historical Thought

Jorge Otero-Pailos

If the place that metals hold in discourse is an index of our knowledge of architecture, then the fact that textbooks categorize metals as either structural or decorative provides a basic understanding of architecture as that which carries load or that which expresses style. I would like to explore the history of a different categorization of metals in architectural discourse; one in which metals figured outside of the dyad of "skin" and "bones," and which is actually older than such a binary classification of the material.

Despite the fact that iron had been used to build bridges since the 1770s, neoclassical architectural theoreticians did not give metals any serious consideration as independent structural materials. For instance, Giuseppe Valadier's *L'architettura pratica*, which collected his lectures delivered at the Accademia di San Luca between 1828 and 1833 into five incredibly popular volumes, deals primarily with masonry and wood construction, and does not include metals as a separate category. This was not an omission due to a lack of familiarity with the material. Valadier was an expert on metals. He was the son of a goldsmith and oversaw a silver workshop, where he produced his own designs for chalices and silverware. Metals do appear in his textbook, but where least expected, in the section on the restoration of buildings, a subject in which Valadier was also an expert. In 1805, he had restored the ancient Milvian Bridge, originally built over Rome's Tiber River by consul Marcus Aemilius Scaurus in 115 BCE. Valadier also restored the Arch of Titus between 1819 and 1821. His knowledge of the behavior of metals and their alloys is clear in his discussions of how to properly repair a cracked column. According to Valadier, the workman was to first drill two holes on either side of the crack. Second, he had to manufacture a piece of iron in the shape of a staple whose cross section was equal to that of the holes. The staple was then to be fitted into the holes and the entire area heated. Molten lead was to be poured between the stone and the iron to fill in any remaining gaps. Valadier cautioned that workmen should take their time to do this job properly. Too much space between the iron and the stone would make the lead drip out, and too little would prevent the lead from entering the crevasses and bonding the materials. Also, if the stone was not heated properly, the lead would crystallize before reaching the back of the hole.[1] Valadier gave other examples for uses of metals in architecture, all of which involved metals holding other materials together, but never simply supporting them, and never supporting itself. He explained that iron worked best in tension, like a rope, which loses its structural properties when it is not being pulled.[2] So he

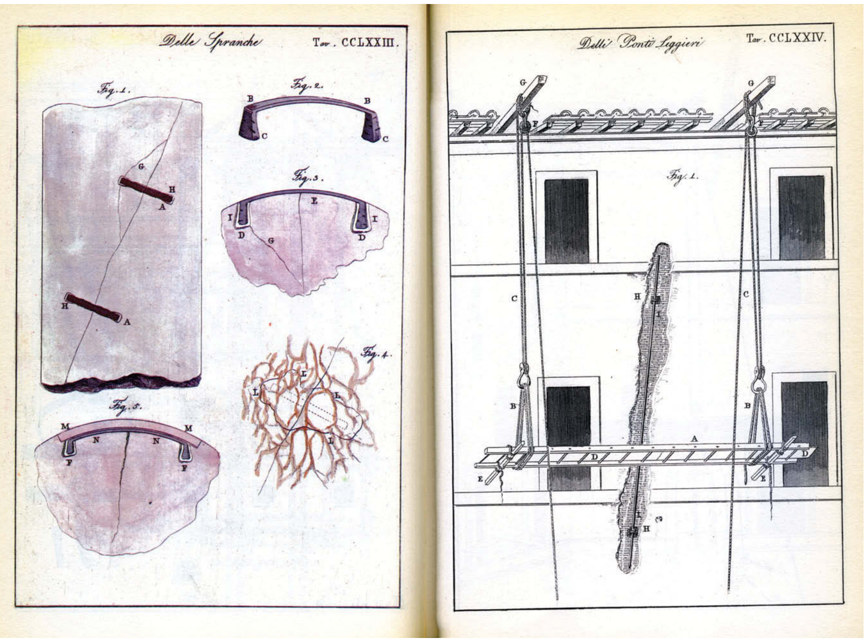


fig. 1 | Drawing demonstrating the use of iron as cement in the restoration of buildings, by Giuseppe Valadier, *L'architettura pratica*, 1833

recommended iron straps to keep walls from collapsing and tie-rods to prevent arches from deforming. **| fig. 1**

The prevailing assumption within neoclassical architectural theory that iron was a binding material sheds some light on the reasons why when James Bogardus and others introduced cast iron as a self-supporting structural building system in the 1840s they presented it in the image of masonry construction. It was more than merely an imitative gesture. No one was fooled into believing that cast-iron buildings were actually stone, quite the contrary. Cast-iron buildings were meant to be recognized as such. A more careful reading of these early cast-iron emulations of stone reveals that they were an attempt to challenge the discursive order of architecture. They were part of an intellectual effort to shift the classification of iron, from a binding to a supporting material, by symbolically usurping the place of stone, architecture's load-bearing material par excellence. **| fig. 2**

There was, not surprisingly, a great deal of resistance to this change. Writing in 1849, just at the time when the first cast-iron buildings were being erected in London and New York, John Ruskin recognized the threat that the reclassification of metals signified for the cultural order of architecture. Invoking the pronouncement of the ancient Delphic oracle, he defined iron as a "calamity upon calamity."[3] He acknowledged that the possibility of fully metallic construction would eventually require developing an entirely "new system of architectural laws," something that didn't happen for another fifty years.[4] For many architects today, schooled in the modernist tradition, the development of a "new system of

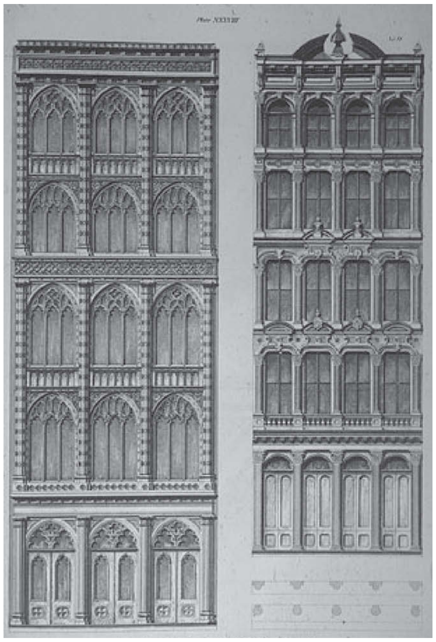
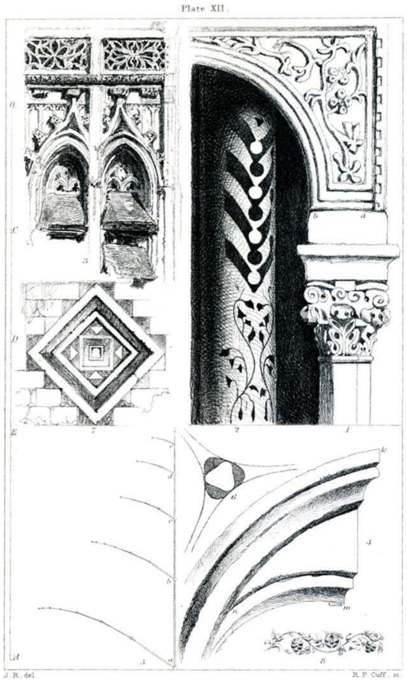


fig. 2 | Illustrations of iron architecture made by the architectural iron works of the city of New York, by Daniel Badger, 1856

laws" is aspirational. Not so for Ruskin, who insisted on the primacy of the laws of architecture that had evolved through the centuries out of the tradition of masonry construction. "[E]arly architecture," he wrote, referring to stone buildings, particularly early Gothic in style, "is a precious historical document."[5] But what was it, precisely, that allowed architecture to be understood as historical? Surprisingly, neither the architect's design nor the building's date of construction made the building historical in his eyes.[6] For Ruskin, materiality determined if a building was historical; it had to be made of masonry, preferably good stone, and the stone had to be rendered as such—made to appear as itself.

This idea of rendering stone as stone requires some explanation, if only to illustrate how much of the richness of Ruskin's theorization of material authenticity has been lost. For Ruskin, like for many Romantics, the source of all beauty was in nature. The work of architecture involved making buildings resemble nature, something that, he granted, was entirely superfluous to what was required of a building. Architecture "impresses on its [building's] form certain characters venerable or beautiful, but otherwise unnecessary."[7] In Ruskin's mind, "there are only two fine arts possible to the human race, sculpture and painting. What we call architecture is only the association of these noble masses or the placing them in fit places."[8] In particular, architecture involved arranging the noble masses of stone in such a painterly or sculptural way as to evoke their natural origin. But unlike painting and sculpture, which could represent all visible forms of nature, "The characters of natural objects which the architect can represent are few and abstract."[9] Stone was one of those few natural objects that the architect could represent. Architecture involved the daunting task of making stone, after it had been quarried, dressed, and assembled into a building, appear like a natural object once again. The architect, in other words, had to treat the stone in such a way as to reveal the inner nature of the material.

Scientifically speaking, the inner nature of stone was crystalline. Ruskin argued that the emergence of abstract decorative patterns in early Gothic architecture was an attempt by medieval masons to express the crystalline nature of stone. But more importantly for our purposes, Ruskin believed that the crystalline nature of stone also revealed its historical nature. He saw stone as a unique kind of material coming from dust that had crystallized eons ago, and which, through the weathering action of millennia, would eventually return to dust. The life of the material meant that its historical nature could not be reduced entirely to the present, nor simply to the moment of its assembly into buildings. In their comparatively short existence, the only insight humans could have into the historical nature of stone was to witness its slow deterioration. So in order to represent



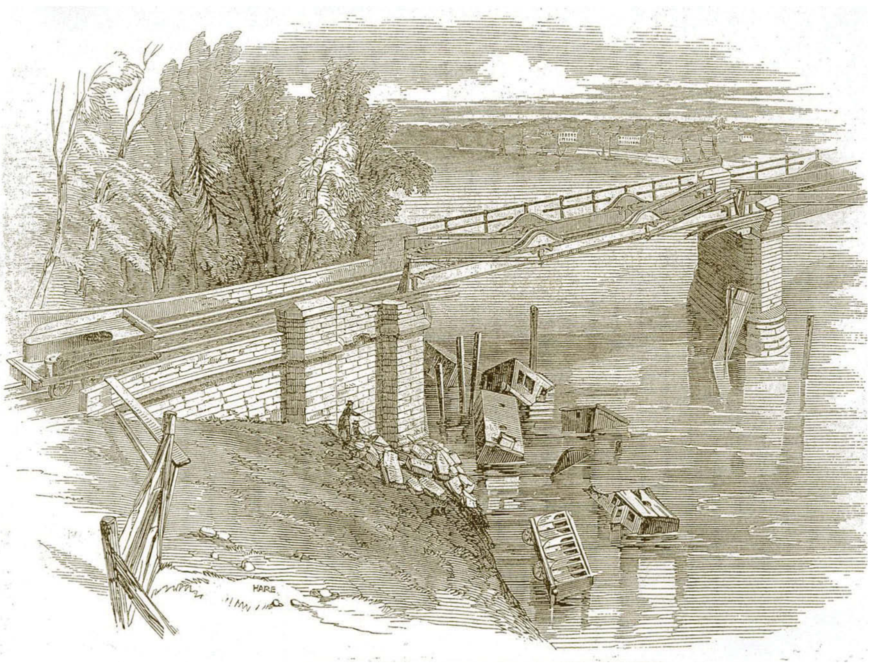


fig. 3 | Drawing of Lombard decoration, by John Ruskin, *The Seven Lamps of Architecture*, 1849 (left)

fig. 4 | Etching of Dee Bridge disaster, *The Illustrated London News*, 1847 (right)

building stones as natural objects, architects had two choices: either turn them into decorative patterns evoking nature or treat them in such a way as to make visible their slow transformation into dust. Ruskin opposed painting over stones, faux finishes, and other "deceptions" that would prevent the material from normal decay.[10] **|** **fig. 3**

Interestingly, what troubled Ruskin most about cast iron was not that it was being made to look deceptively like stone. Rather, it was the fact that cast iron was crystallized through artificial means and decayed unnaturally quickly when compared with stone. "No builder," he wrote, "has true command over the changes in the crystalline structure of iron, or over its modes of decay."[11] It was a man-made material, but paradoxically, it escaped man's comprehension, perhaps because it was too far removed from nature. When he defined iron as a "calamity upon calamity," he surely must have had in his mind the infamous 1847 collapse of the iron bridge over the River Dee at Chester just one year after its construction, which caused five deaths and was the object of one of the first major inquiries conducted by the newly formed Railway Inspectorate. **|** **fig. 4** If, as Ruskin maintained, the word *architecture* meant "authority over materials," then clearly the failure to control iron paired with the obstinate attempts to reclassify it as a support material could only undermine the cultural order of architecture.[12] Ruskin came down hard against the reclassification of iron: "metals may be used as a *cement*," he wrote, "but not as a *support*."[13]

fig. 5 | Test application of iron vitriol on the battlement walls of El Morro, San Juan, Puerto Rico (left)

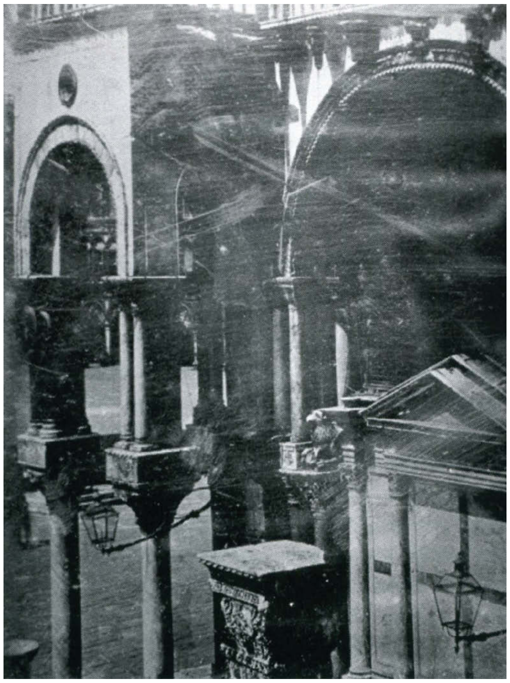


fig. 6 | Daguerreotype of the southern portico of St. Mark's Basilica, from the loggia of the Ducal Palace, by John Ruskin and George Hobbs, Venice, Italy, 1842 (right)

Today the classification of metals as either support or decorative cladding has entirely displaced their older classification as cement. But it is important to reconstruct the architectural knowledge that this former categorization presupposed. **| fig. 5** A cement is a substance used to bind others together, especially in the case of architecture, stones, or bricks. It is applied in a liquid or pasty state, which later hardens to become as strong as the materials it holds together. More broadly even, as defined by the *Oxford English Dictionary*, a cement is "any substance applied in a soft and glutinous state to the surfaces of solid bodies to make them cohere firmly."[14] As late as 1867, the popular *Ure's Dictionary of Arts, Manufactures and Mines* listed iron rust and white lead as names of cements. The latter was produced by grounding white lead with linseed oil varnish and keeping it out of contact with air. According to the volume, white lead cement was "capable of repairing fractured bodies of all kinds. It requires a few weeks to harden. When stone and iron are to be cemented together, a compound of equal parts sulphur and pitch answers very well."[15] The same source described iron-rust cement as:

> [M]ade from 50 to 100 parts of iron borings, pounded and sifted, mixed with one part of sal ammoniac, and when it is to be applied moistened with as much water as will give it a pasty consistency. Formerly flowers of sulphur were used, and much more sal ammoniac, in making this cement, but with a decided disadvantage, as the union is affected by the

> oxidisement, consequent expansion and solidification of the iron powder, and any heterogeneous matter obstructs the effect.[16]

The older formula for iron cement in all likelihood refers to the formula perfected by the Swedish pharmacist Johan Julius Salberg to prevent the decay of wooden buildings. In 1742, Salberg published a paper that proposed to improve on the traditional technique of coating wood with Falun red (red ochre) and tar by adding iron vitriol to it. Vitriol, from the Latin *vitrum* meaning glass, was the vulgar appellation of sulphuric acid, and of its many compounds, which in certain states have a glassy appearance. Iron vitriol, also known as Vitriol of Mars, is the red sulphate of iron. Salberg claimed that wooden buildings coated in iron vitriol would be preserved for "eternal times." It is possible that Salberg's application was inspired by the fact that iron vitriol was used commonly as a disinfectant at the time. A year later, he published a paper on the application of iron vitriol to stone buildings. The case for the preservation of stone seemed less urgent than wood, so Salberg tried to sell the idea by placing more emphasis on the aesthetic effects rather than the material conservation effects resulting from the treatment. When mixed with white lime, iron vitriol produced a nice ochre tint and could be used to replace the much more expensive imported ochre pigments then used to coat building facades in Stockholm. When applied directly on stones, iron vitriol darkened them, making them appear older than they really were, but also presumably protecting them from further decay.

We can appreciate the crux of Ruskin's abhorrence of iron as a "calamity upon calamity." Iron vitriol not only slowed the weathering of stones that Ruskin considered to be the source of their historical nature, it added insult to injury by artificially accelerating their aging through deceptive aesthetic means.

In the late 1870s, reports arrived in London that Giovanni Battista Meduno had been slowly restoring one of Ruskin's favorite buildings: St. Mark's Basilica. Since shortly after the 1866 incorporation of Venice into the Kingdom of Italy, Meduna had been quietly replacing the old, time-stained stones of the southern wall with new clean ones. Ruskin was appalled and William Morris embarked his British Society for the Protection of Ancient Buildings (SPAB) on its first international campaign, to shame the Italian government into stopping the restoration.[17] A reporter writing at the time for the *American Architect and Building News* could not understand all the fuss. If the new stonework "jars the sense of color," couldn't the problem be easily solved with a sulphate of iron wash over the new parts to "harmonize the color" with the old?[18] | **fig. 6**

In conclusion, if we extend Ruskin's idea that the ability to consider architecture historically depends on thinking through the manner in which materials such as stone decay, then we might ask what sort of historical thinking does the decay of metals in general, and iron in particular, make possible, and what kind of thinking does it restrict. In a sense, everything hinges on how we classify metals. If metals are considered as independent, self-contained systems, such as structure or cladding, then we will think through metals as if we were thinking through stone. Metals will appear historical in the same way of coming from dust and returning to dust, or rust to rust. But if we return to thinking through metals as cements and as binding agents, something contingent and dependent, then a whole different mode of historicization appears, one that we might properly call modern. In fact, one might even argue that what holds together all of Ruskin's ideas about stone is, precisely, iron-cement. For iron-cement is not the opposite of stone, but rather the negation of what is historical about stone in the name of making stone visible as history. The recovery of iron-cement reveals one of the central paradoxes of modern architectural historiography, which must negate what is historical about architecture—the fact that buildings are never the same and are constantly in flux—in order to present us with architectural history as a great dust cloud of moments or events cemented by narrative.

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1 | Giuseppe Valadier, *L'architettura pratica dettata nella scuola e cattedra dell'insigne Accademia di S. Luca* (Rome: Anastatica Sapere, 2000 [1833]) 84–85.

2 | "[...] il ferro devesi riguardare, come si disse colle medesime proprietà di una corda; una corda opera quando è rettamente teas, se vi sono nodi prima di tirare si stringono; ed ecco perduta una parte della sua forza; se la corda nel tirare viene a formare per qualche urto un angolo ottuso, o tortuosità, cedendo quei punti di appoggio si allenta e più non agisce, onde se queste non sono in linea retta ovvero in perfetto corpo rotondo agiranno sempre con incertezza e male, e però non si condanni il metodo di adoprare senza abuso le catene di ferro ma piuttosto il modo di adopalre se is wrisultati saranno cattivi." See Valadier, *L'architettura pratica*, 93.

3 | John Ruskin, *The Seven Lamps of Architecture* (Mineola, NY: Dover Publications, 1989), 42ff.

4 | Ibid., 39.

5 | Ibid., 218.

6 | Ibid., 217. Ruskin did not consider architects to be responsible for the building's historical nature. "I saw," he wrote, "that the idea of an independent architectural profession was a mere modern fallacy, the thought of which had never so much as entered the heads of the great nations of earlier times."

7 | Ibid., 9.

8 | Ibid., 217.

9 | Ibid., 117.

10 | Ruskin, "The Lamp of Truth," in *The Seven Lamps of Architecture*, 29–69.

11 | Ibid., 42ff.

12 | Ibid., 42.

13 | Ibid., 41.

14 | *Oxford English Dictionary*, 2nd ed., s.v. "cement."

15 | Andrew Ure, *Ure's Dictionary of Arts, Manufactures and Mines: Containing a Clear Exposition of Their Principles and Practice*, ed. Robert Hunt, 6th ed. (London: Longmans, Green, 1867), 681.

16 | Ibid., 680.

17 | Frank C. Sharp, "Exporting the Revolution: The Work of the SPAB outside Britain 1878–1914," in *From William Morris: Building Conservation and the Arts and Crafts Cult of Authenticity 1879–1939*, ed. Chris Miele (New Haven: Yale University Press, 2005), 187–212.

18 | "The Restoration of St. Mark's," *American Architect and Building News* 7, no. 215 (1880): 46–47.

Metal Fatigue

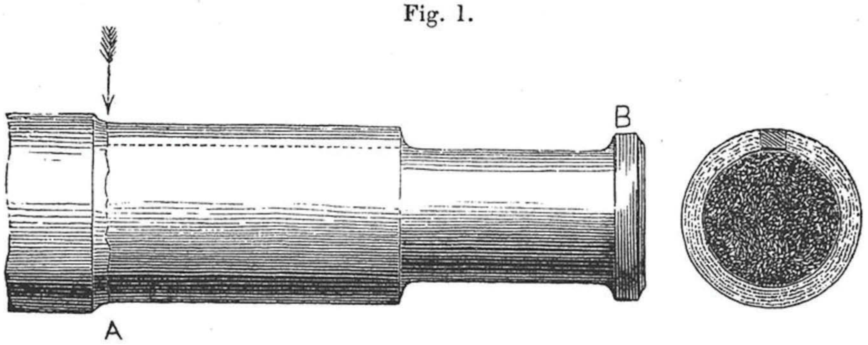
Sylvia Lavin

In 1842, a group of revelers were returning from Versailles where they had celebrated the birthday of Louis Philippe when the train upon which they rode suddenly came to a halt and burst into flames, killing scores of aristocrats.[1] After a lengthy investigation, the cause of the crash turned out to be exhaustion; not of the revelers, who may indeed have been spent, not of the train conductor, who too might have been asleep at the wheel, but rather of the train's metal axle. | fig. 1 Its iron was tired, stressed beyond its capacity like a toiling member of the proletariat, cracking under the strain of carrying around the noble supporters of the last king of France. So overworked and misunderstood, the iron collapsed as a material revolt against the monarchy and any last vestiges of the *ancien régime*.

Of course, 1842 was just when metal was entering architecture as an object of cult adoration. Prior, metal itself had been present, but it became a matter of concern, an architectural principle, a theory of architecture, only in the mid-nineteenth century.[2] One could go so far as to say that it was the entry of metal into the architectural palette of construction that required materials as such to become theoretical objects. | fig. 2 Architecture had previously been interested in techniques demanded by particular materials—friable stone produced stereometry, the need to waterproof wood produced the vocabulary of classical ornament—but materials posed no problematic until metal appeared as a problem. In the form of cast iron, metal had neither form nor history but only a process of production. It was therefore an exception that proved the rule, that which resulted in the need for the invention of rules about materials. And it was this that caused materials—from concrete to glass to brick—to be thought of as having a nature, character, and capacity for being truthful, and thus for needing always to speak the truth, the whole truth, and nothing but the truth. There is nothing more exhausting than being the one responsible for holding it all together. It was such a tremendous burden that metal was no doubt already tired the very instant it got to architecture.

Metal fatigue is caused by the stress and pressure of trying to get architecture to behave as though it could know truth from falsehood. The moment metal entered architectural thought in the nineteenth century it shifted logically from fact to fiction, a change the field has worked hard to cover up ever since. Stories of metallic heroism are forgivably charming in the context of the nineteenth century, but today they must be rooted out as naive pseudopositivisms. One way to deal with this history of metal machismo is to celebrate metallic pseudonyms instead, by exploring those moments when metal was simply

Fig. 1.



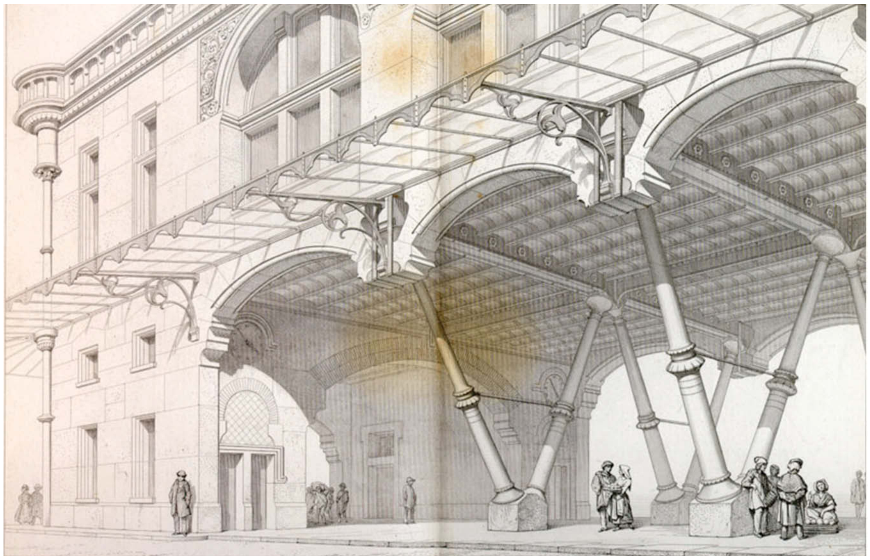


fig. 1 | Sketch of broken axle, by J. Glynn, *Proceedings of the Institution of Mechanical Engineers*, 1844 (top)

fig. 2 | Composition in masonry and iron, by Eugène-Emmanuel Viollet-le-Duc, *Entretiens sur l'architecture*, Paris, France, 1863 (bottom) excused from juridical duty, allowed to lie, liquefy, get soft and billowy, thin and delicate—moments when metals ignored the rules rather than simply breaking them. Metal, in fact, had a second phase shift, when, for a brief time, it was enticed to fail and flirted deliberately with fatigue, because failure was understood as an opportunity to bring down a totally exhausted architectural logic of modernist veracity and virtue.

Myra Breckinridge (1970) is considered by many to be the worst movie ever made. The film set, made with what you might call the essence of metal, was modeled on the aluminized Mylar-domed interior of the Pepsi Pavilion. Members of the Chrysalis Corporation, an experimental design group in Los Angeles, worked on both projects. As a part of Experiments in Art and Technology (E.A.T.), a collective of artists and engineers established by Billy Klüver, they were commissioned in 1968 to produce Pepsi Japan's pavilion for the 1970 Osaka Expo.[3] The group decided to build a structure in which reflections cast from a spherical surface coalesced in what they called "real images," or holograms, that floated untethered in free space. Pepsi viewed the multimedia extravaganza as a means to sell soda and intended to transport the pavilion throughout Japan. Klüver, however, considered it "the largest single most complex and difficult work of art produced in our time," one not to be "used in any other context, commercialized or reproduced." Whether being the source of inspiration for *Myra Breckinridge* constitutes a sign of influence (normally understood as a kind of success) or the reverse, the truth is, despite the recent interest in the pavilion brought about through Diller + Scofidio's Blur Building, the Pepsi Pavilion could be deemed a disappointment: the cloud only worked for a couple of days, and the project has failed to appear in any history of modern architecture. The associations with Whisky a Go Go and the Pepsi Corporation seem to have been a stretch for even the most open-minded critics, who themselves neglected to notice the pavilion's interior. A whole series of failures took place inside, the first being in 1969 when, just like the train on its way to Paris, too much pressure triggered an explosion. What began as twenty-foot models turned into a massive inflatable, ninety feet in diameter and fifty-five feet high. Made of thirteen thousand square feet of mirrorized Mylar, one-thousandth of an inch thick, and divided into sixty-four elliptical sections, the surface was geometrically intended to be true within a few millionths of an inch. | **fig. 3** Although fetishistically engineered, the metal was stretched so thin and put under so much air pressure that it became a metal surface with inadequate ductility, which, after twelve minutes in September of 1969, blew up.

The Pepsi Pavilion is the last of an extensive series of modern interiors in which metal was increasingly vaporized and turned into a flavorful essence. In the

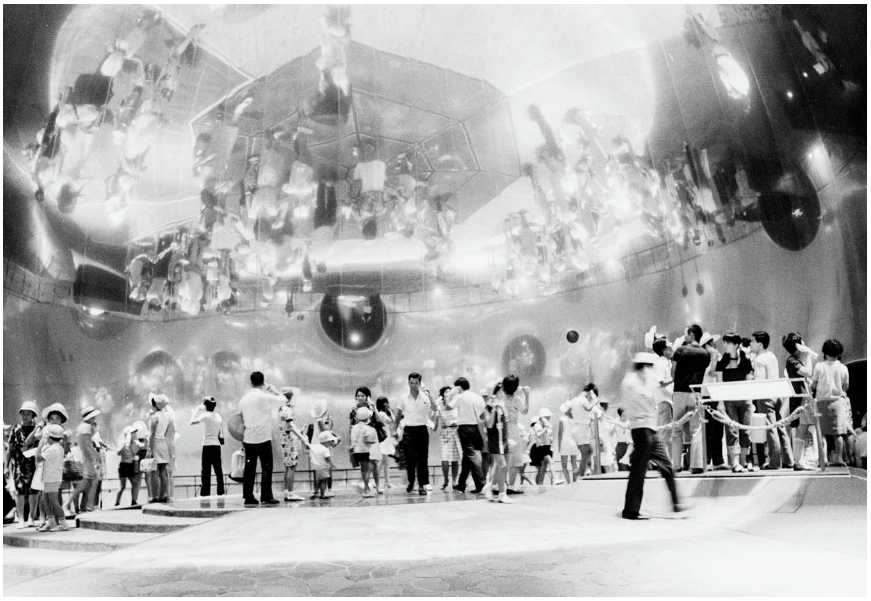


fig. 3 | Interior of Pepsi Pavilion, photograph by Fujiko Nakaya, Osaka, Japan, 1970 (top)

fig. 4 | *Morning Cleaning, Mies van der Rohe Foundation, Barcelona*, by Jeff Wall, transparency in lightbox, 1999 (bottom left)

fig. 5 | Wichita House, by Buckminster Fuller, Rose Hill, Kansas, 1948 (bottom right)

fig. 6 | Party at Andy Warhol's studio, the Factory, 231 East 47th Street, New York, August 31, 1965 (top)

fig. 7 | Interior of *La situazione antispettiva*, by Olafur Eliasson, 21st Century Museum of Contemporary Art, Kanazawa, Japan, 2003 (bottom left)

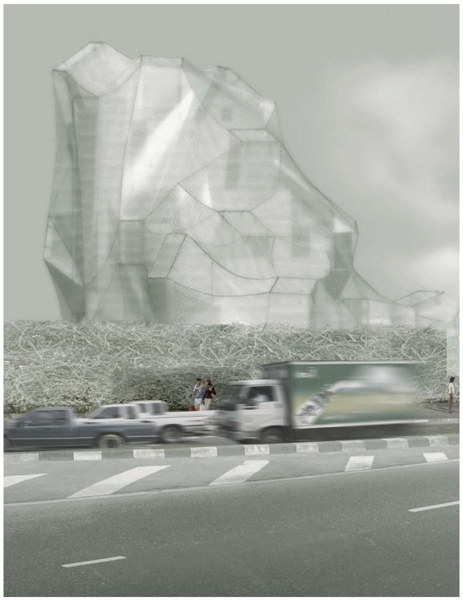
fig. 8 | Exterior of *La situazione antispettiva*, 2003 (bottom right)

fig. 9 | Forum Building, by Herzog & de Meuron, Barcelona, Spain, 2004 (left)

fig. 10 | *Balloon Dog*, by Jeff Koons, installation view at Château de Versailles, Versailles, France, 2008–9 (right)

early twentieth century, metal was large, meaty, and walked with a big stick—it was the architecture. Then it became what holds the architecture up, sort of, and then the appearance of what holds the architecture up. | **figs. 4, 5** Wall becomes column, becomes painted column, becomes painted room, becomes tin-foiled, aluminum-sheeted room of spectacle and metal as effect. | **fig. 6** At this point, metal's function was related to appearance alone, not to structure. It was pressed into service as a special-effects machine, not a representation but a tastable soupçon. Metal, which at first made architecture, began by the 1960s to remake architecture into something unarchitectural. The metallization of the interior not only invited the surface to behave in nonmetallic ways but also in nonarchitectural ways, requiring an entirely new set of descriptors such as ballooning, inflating, stretching, selling, shredding, drooping, hanging, bulging, and exploding. Metal began with a purpose: to bind architecture to the logic of the purposeful, a purpose that ultimately became exhausted. | **figs. 7, 8**

Building has traditionally been assigned the job of keeping the rain out, but architecture loves a cloud. Indeed, from Brunelleschi's perspective apparatus that captured the movement of a cloud in a burnished mirror to Heinrich Wölfflin's impassioned interest in the effects of chiaroscuro to the atmospheric spectacle in the work of contemporary architects such as Herzog & de Meuron and SANAA, the traces and animations of weather have permitted architecture to perform liveness on the otherwise inert stage of building materials. | **fig. 9** These programmable effects do not oppose or merely supplement architecture, they are not software to its hardware but rather architecture's inhabitants, spectatorial stand-ins,



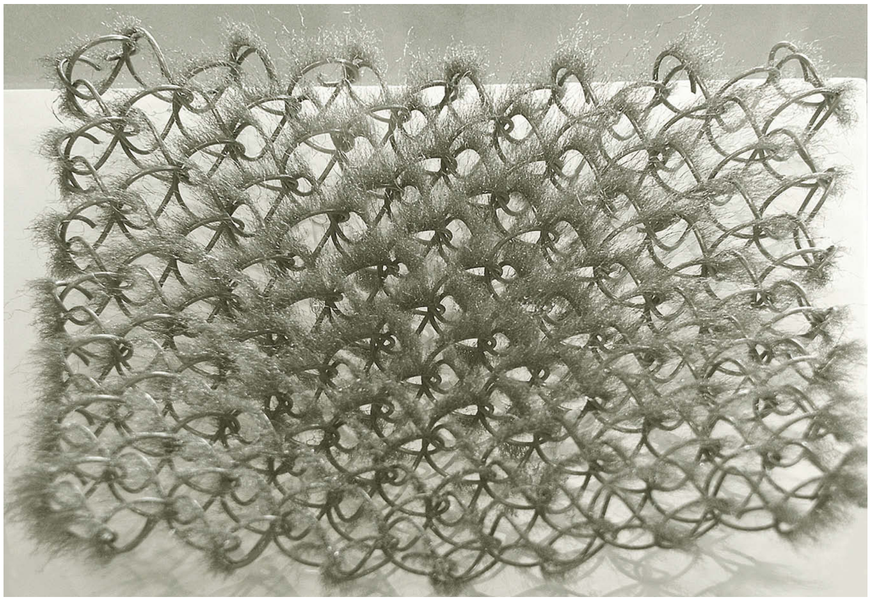


fig. 11 | Design for Contemporary Art Museum, Dustyrelief / B_mu, by R&Sie(n), Bangkok, Thailand, 2002 (left)

fig. 12 | Collecting particles of carbon monoxide, urban “dust,” by means of an aluminum envelope and electrostatics system, Dustyrelief / B_mu, 2002 (right)

witnesses to the passing cloud on Brunelleschi’s mirror and to that moment of animation that made perspective, like a hologram, seem true to life. The cloud, perhaps, was (and remains) beyond representation, but certainly more elusive was the demonstration, a staging that demanded the simultaneous participation of the drawing, apparatus, mirror, cloud, piazza, passerby, and spectacle. This was modern architecture’s original place, neither site nor region, but a landscape of events wherein the visibility of individual constituent objects became clouded by their performance within a manifold ecology. The still unrecognized atmospheric architecture at Osaka was not the cloud stuck to the structure but the idea of organizing the entire mise-en-scène as a system of nebulous animations.

The most interesting role of metal in architecture today derives from its interaction with this history of fatigue. Metal, thinned almost to the point of evaporation in the 1960s, has apparently redensified but it has not returned to the solidity of traditional architecture. This refusal is most visible in the degree to which metal remains separated from structure and in a state of semiautonomy—facets that exaggerate the historical role of the metal surface in the production of reflectivity now permit the surface to scrunch itself into incidental self-sufficiency. Metallized Mylar—now steel imitating plastic—is no longer droopy; it is taut but not volumetric. **|** fig. 10 In fact, metal, released from jury duty, isn’t tired any more but is springing to life—springing outside the interior volumes in which it was closeted in the 1960s and toward absolute exteriority. Out there, metal’s new challenge is most manifest because an architecture of pure exteriority, of vaporization rather than dematerialization, is an architecture without the capacity to shelter, house, or function in any traditional sense of the term. | **figs. 11, 12** It is an architecture without purpose. Metal is less useful today in terms of its material capabilities, which are many and a matter of ever-proliferating fact but not a matter of concern. Instead, just as it once achieved the transformation of fact into fiction, metal's value to architecture is in the way it converts the without purpose into more enveloping and conceptually expansive notions of the architecturally purposeful.

1 | Charles Francis Adams Jr., *Notes on Railroad Accidents* (New York: G. P. Putnam's Sons, 1879).

2 | Eugène-Emmanuel Viollet-le-Duc, *Entretiens sur l'architecture*, 2 vols. (Paris: Q. Morel, 1863–72). The tradition of French rationalism in architectural thought may be said to have completed its turn away from general questions of geometry and structure and toward materials with the publication of Eugène-Emmanuel Viollet-le-Duc's *Entretiens sur l'architecture*.

3 | Much of the following discussion is based on archival research I conducted at the Getty Research Institute Archives, where the papers of Experiments in Art and Technology are held. This research will form the basis of a chapter in my forthcoming book, *The Flash in the Pan and Other Forms of Architectural Contemporaneity*. For a basic account of the pavilion's history, however, see Barbara Rose, Billy Klüver, and J. Martin, eds., *Pavilion: Experiments in Art and Technology* (New York: E. P. Dutton, 1972).

Dieste and Serra, North and South, Material and Method

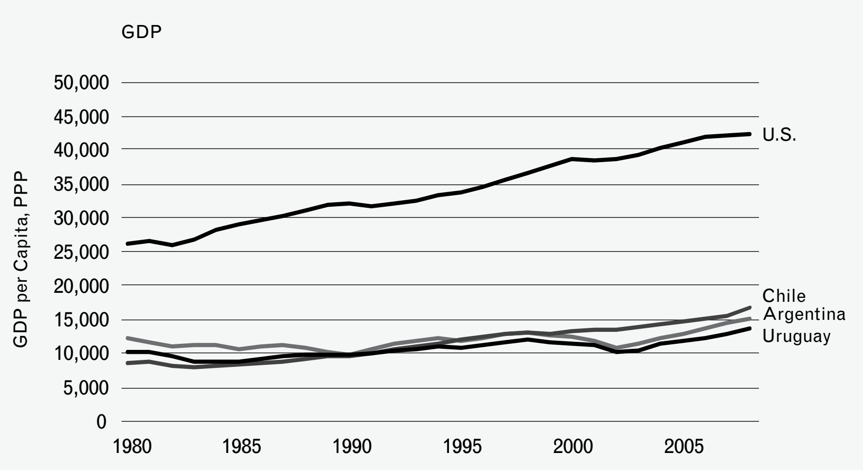
Galia Solomonoff

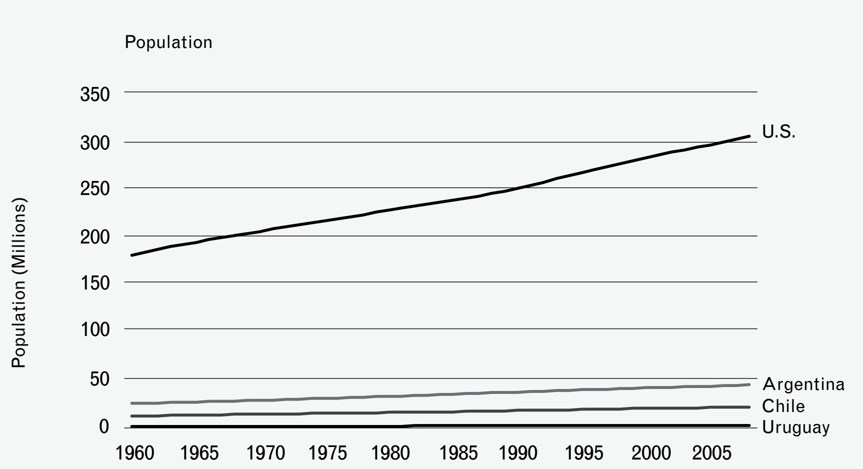
> The theorist who fails when faced with reality does so because he is not sufficiently theoretical.
>
> —Eduardo Garcia de Zuniga[1]

We often judge architecture by this equation: the longer and clearer the span, the better. Architectural spans signify inclusion, democracy, technology, modernity, and courageousness. To the question, What if it doesn't hold? the modern, western architect and engineer have consistently responded, Yes, it will! Long-span structures cover large groups of people at a time. To achieve these unsupported spans, both horizontal and vertical, architects need access to metal (and to engineering). Therefore, metal (and, by extension, engineering) is tied to matters of access, of means, and of methods. Metal, in particular, raises questions about the social dimension of structural engineering. In clear-span structures, where structure and space are synonymous, can we think of structure as having social agency? And, more broadly, how do we understand the links between materials and engineering and the social?

Metal has long been equated with wealth, even in the oldest and most literal sense: coins and jewelry. With the Industrial Revolution, the production of metal, first of iron and then of steel, was tied to transportation (trains and transatlantic shipping), then to infrastructure, and later to buildings. Joseph Paxton's Crystal Palace (1851) in London exhibited the potential of heavy industry as an instrument of regional pride.

Steel made American skyscrapers possible. In 1884, William LeBaron Jenney's Home Insurance Building in Chicago captured the scene. In architecture, towering heights and long spans are celebrated as achievements. Today, metal structures are everywhere, but they are rarely scrutinized in terms of the resources they required. If we focus on the correspondence of currency and metal, at its rates of exchange, we see a correspondence in gross domestic product (GDP) and purchasing power parity (PPP) growth. | fig. 1 In the United States, the growth in population is a steady line, following a more or less constant incline, yet a graph of steel consumption shows a line with more ups and downs, indicating that conditions other than an increase in buildings and infrastructure to accommodate an expanding population affect the consumption and pricing of steel. | figs. 2, 3





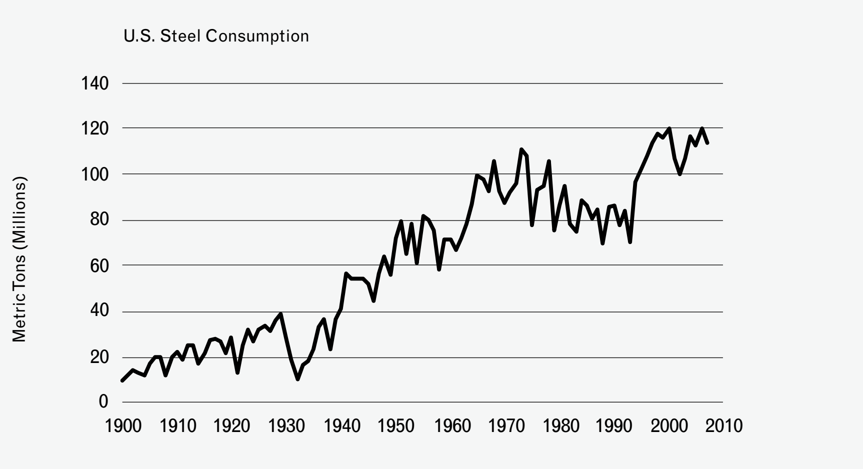


fig. 1 | GDP graph, adapted by Solomonoff Architecture Studio (SAS) from graphics created by A. Gurin with data from World Development Indicators (top)

fig. 2 | Population graph, adapted by SAS from graphics created by A. Gurin with data from World Development Indicators (middle)

fig. 3 | U.S. steel consumption graph, adapted by SAS from graphics created by A. Gurin with data from the U.S. Geological Survey (bottom)

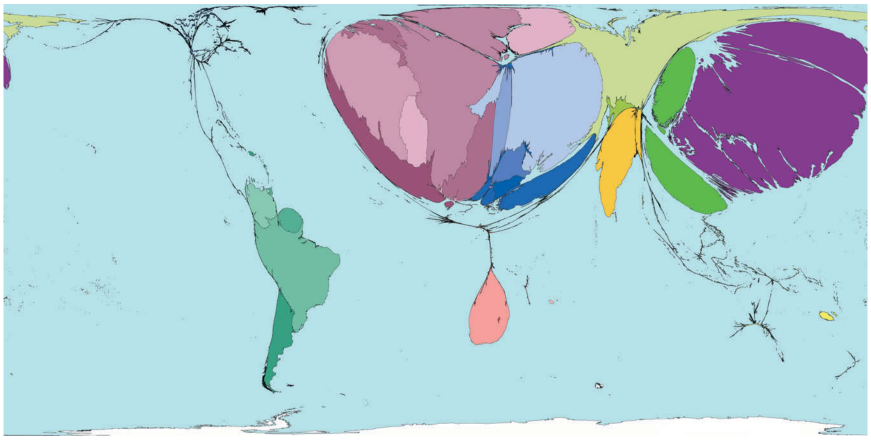


fig. 4 | World steel exports, 2006. Territory size indicates the proportion of worldwide net exports of steel (in USD). Net exports are exports minus imports. When imports are larger than exports, the territory is not shown. Source: Worldmapper.org (top)

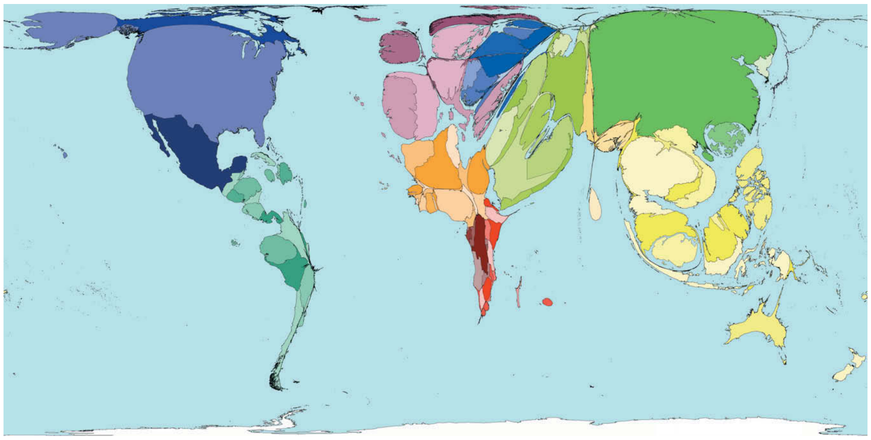


fig. 5 | World steel imports, 2006. Territory size indicates the proportion of worldwide net imports of steel (in USD). Net imports are imports minus exports. When exports are larger than imports, the territory is not shown. Source: Worldmapper.org (bottom)

Steel is a traded commodity, like soy, corn, coffee, gold, silver, or crude oil, and is traded on commodity markets where raw or primary products are exchanged and regulated in standardized contracts. China, Japan, the United States, Russia, and Germany are the biggest producers of steel, with China and the United States standing as the biggest consumers. Yet China maintains a positive trade balance, exporting more than it consumes. | **figs. 4, 5**

In reviewing two works, one by Eladio Dieste, an engineer from Uruguay, and one by Richard Serra, a U.S. artist, I investigate how each responds to the question of expression and to the availability of means and methods.

Dieste was born in Artigas, Uruguay, in 1917, studied engineering, and, until 2000, lived in Montevideo, Uruguay. Dieste invented reinforced ceramics and achieved 150-foot spans—the longest—with the least amount of metal by using reinforcement bars (rebars) on single-width hollow brick.

In a 1995 interview that I conducted with architect Sarah Dunn, Dieste noted, “This is what I can do here. If I was in Colorado, the things I could do!” He

fig. 6 | Church of Christ the Worker, by Eladio Dieste, Atlántida, Uruguay, 1958–60 (left)

fig. 7 | Port warehouse under construction, by Eladio Dieste, Montevideo, Uruguay, 1977–79 (right)

continued, “The soil in areas near the Colorado River has much higher iron content, making bricks stronger. There I could build 20, maybe 25 percent higher with the same method and width. It would be very elegant.”[2] Before it was understood as a contemporary imperative, finding the most efficient use of natural resources was an imperative for Dieste. In the Iglesia del Cristo Obrero (Church of Christ the Worker), in Atlántida, Uruguay, built for a liberation theology congregation—a South American Roman Catholic movement that advocates for a focus on solving poverty—Dieste used local clay and achieved long spans with single-width reinforced bricks threaded with rebars. | **fig. 6**

Ceramics, though much lighter, allow manufacturing tolerances similar to those of steel, reinforced concrete, or ferroconcrete. Other positive attributes include resistance to sudden temperature changes (which are frequent and of considerable importance in Uruguay), good maturing properties, good thermal properties, and low maintenance cost. Lastly, the adhesion between portland cement, mortar, and iron makes reinforced ceramics very efficient and cost effective.

Dieste achieved great efficiency by using double-curvature forms. He developed a sliding formwork that was relatively small, easy to handle, and easy to reuse in comparison with the total volume of the structure. | fig. 7 Since mortar and brick hardens in about a day, rather than the fourteen to twenty-one days it takes reinforced concrete, the formwork could be smaller, slide, and be used more quickly to create the overall structure. "The higher technical development in industrialized countries imposes uneven marketing conditions, yet lack of economic possibilities must not give rise to resignation or inefficiency," Dieste stated.

This declaration was consistent with geographer George Anglade's statement:

> If misery persists and even affects us, it is because we have not chosen a way out of poverty; we have followed, instead, the ways of working and thinking typical of others, the rich…a national architecture must take into account the habits of our people, our climate, the structural requirements, the construction aspects linked to our possibilities, the capacities of our workers and the imponderable expression of our light and landscape.…Intuition should be understood as something that can be proven experimentally: it must be based on a solid scientific education.[3]

As with the great Gothic masters, it was not due to calculi or computing that Dieste's work was built. Numerical analysis may be an ultimate and even necessary verification, yet it is not the essential basis of design. Dieste's understanding of the "workability" of structure was rooted in a solid scientific education that informed his intuitive comprehension of physics and numerical and mechanical analysis. A traditional conception of civil engineering assumes that all that can be calculated attains a scientific status. In the case of Dieste, there was a partial numerical understanding and a solid empirical method. "I have always thought that between morality, in the widest sense of the term, and economy, there is, or there should be, a common purpose, or basic coincidence. Economy is respect for the neighbor… respect for the gifts received." Deeply religious in terms of faith, yet incredibly progressive in terms of social issues, Dieste was concerned with what he called cosmic economy, a profound ethical and practical connection between resources and economy. He expressed, "I have never thought that an element, responding to its theoretical and mechanical context, could ever be ugly." He viewed the waste of resources with disdain and strived to create forms that adapted to the laws of matter with a sense of religious and cosmic austerity.

figs. 8, 9 | Scale models used to plan installation of Richard Serra's *Torqued Ellipses*, Dia:Beacon, Beacon, New York, 2003

When considering the use of metal, a very different yet peculiarly related take appears in the work of Richard Serra, with whom I became familiar while working as part of the architectural team that designed a museum for the Dia Foundation in Beacon, New York, between 1999 and 2003. I was then a principal of OpenOffice, an architecture firm dedicated to collaborations with artists. The task was to austerely convert a 292,000-square-foot Nabisco box factory into a museum for permanent installations of post-1960s minimal, conceptual, and land art. There was a strong parallel between the industrial process that gave rise to the building—box making and printing in this case—and the artwork the building was to contain—for example, serial plywood boxes in the work of Donald Judd, or the silkscreen shadow paintings of Andy Warhol. The factory plan was basically a set of two grids: a twenty-by-forty-foot grid on the upper level and a twenty-by-twenty grid on the lower level—to support the monumental weight of the box printing machines on the upper floor.

Our first charge as architects was to integrate the grid into the design, to work with it, to make the building look "long, expansive, clear, and modern," yet to do so with minimal expense. To achieve this, we devised a series of low-tech tricks: we swallowed columns into walls, allowed the roof to float over walls, and isolated certain key columns to let the space circulate around. Our method was rooted in a clear appreciation of modernism, yet, stylistically, we were embracing a pre-modern materiality. In many ways this attitude came from understanding Dieste and third-world modernism that adapted the modern method of space-making to the local and vernacular materiality and mode of production.

In addition to transforming the factory into a museum, we worked with the artists of the collection (or the artists' estates) in placing their works in permanent installations. We used Serra's lead models of the *Torqued Ellipses*—in which an inch is equal to a foot—to determine the work's placement in the building. | **figs. 8, 9**

figs. 10, 11 | Construction and installation of Richard Serra's *Torqued Ellipses*, Dia:Beacon, Beacon, New York, 2003

The *Torqued Ellipses* pieces are such strong forms that once their location was determined, the rest of the building organization easily followed. The Dia Collection had already acquired three *Torqued Ellipses*. From the thirty *Torqued Ellipses* variations, we, the artist, his aides, and the Dia curators selected a fourth to occupy the factory train shed that was converted into a Serra gallery. Leonard Riggio, Dia's primary benefactor for this project, paid for this fourth *Torqued Ellipse*.

When describing how it would be made, Serra, said, "it will be a single, continuous two-inch-thick COR-TEN steel form. It can only be formed in Germany (in a shipyard) and it will be shipped here to Elizabeth, New Jersey. It should cost about two million dollars and take about nine months to be produced."[4] **| fig. 10** As described, the *Torqued Ellipse* came from Germany to Port Elizabeth, New Jersey, in a ship and was then transported to Beacon on sixteen flatbed trucks. Each of the four *Torqued Ellipses* was made of four parts, each weighing approximately twenty tons.

Serra and Frank Gehry were at some point close friends and mutually influential in their artistic growth. When it comes to the *Torqued Ellipses*, I believe the method that brought the work from Serra's imagination to fully fleshed-out object was facilitated through this friendship and the assistance of Gehry and his team. Gehry, working with CATIA software, provided Serra with the technical and geometrical backbone as well as the approach to digital manipulation of geometric variables. As double-curvature forms, the *Torqued Ellipses* are impossible to describe on a single two-dimensional drawing. A three-dimensional model is needed to roll the double curvature of a *Torqued Ellipse* out of two-inch-thick COR-TEN steel plates. The sections, all of the same radii, are constructed in a sixteen-foot mill bed. The bearing capacity of the slab at Dia:Beacon is 320 tons, about a ton a square foot. **| fig. 11** The *Torqued Ellipses* are abutted but not attached to the ground. The concrete floor that supports these unattached structures has sixteen layers of rebar. My guess is that the steel in a few square feet of the supporting slab of the Serra Gallery is equivalent to the entire structure of Iglesia del Cristo Obrero in Atlántida.

When installing *Union of the Torus and the Sphere* in 2001, Serra expressed, "I want it to feel like if the sculpture was to fail, it would take the architecture with it."[5] Then, when Serra visited the construction site in 2001, he said, "I do not want it to be like what Gehry is doing for my space in Bilbao, I don't want anyone to see my work from above."[6] | **fig. 12**

From my experience and understanding of the work of Dieste in South America and from working with Serra in North America, my sense is that materials and methods are determinants to culture and the production of form. Materials dictate to a great extent what gets built and the normative methods of how something gets built. Original methods like Dieste's defy what a material can do and deliver forms that are unusually beautiful and extraordinarily plastic for a given place. The expansion of spatial possibilities and the delivery of expressive forms are most likely when a new method of arranging material arises. Method—more than material—is the territory that expands expression: originality is achieved when one has control and can extract precision of new techniques. In a sense, expression is the excessive quality of a given method.

fig. 12 | *Union of the Torus and the Sphere*, by Richard Serra, Dia:Beacon, Beacon, New York, 2001

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1 | Mariano Arana, "Eladio Dieste: Techniques and Poetics," in *Latin American Architecture: Six Voices*, ed. Malcolm Quantrill (College Station: Texas A&M University Press, 2000), 21. Eduardo Garcia de Zuniga (1867–1951) was Eladio Dieste's professor in 1945 at the National University in Montevideo, Uruguay.

2 | Interview with the author and Sarah Dunn, Montevideo, Uruguay, April 1995.

3 | Arana, "Eladio Dieste: Techniques and Poetics," 22.

4 | Construction site walk through with the artist at Dia:Beacon, February 2001.

5 | Ibid.

6 | Ibid.

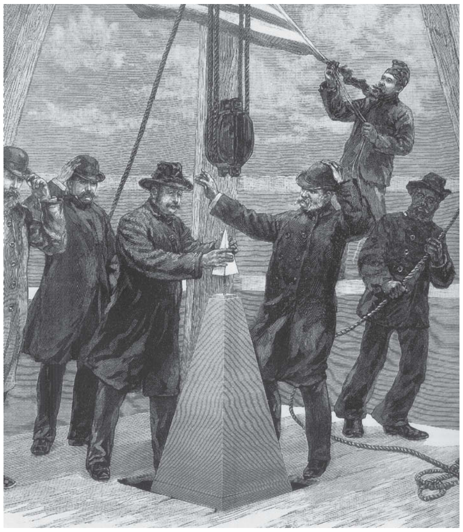

fig. 1 | One of the first examples of architectural use of aluminum is the pyramidion, or cap, installed on top of the Washington Monument, manufactured by William Frishmuth in Philadelphia, Pennsylvania, December 6, 1884

Metallic Reflections: The Rise and Fall of Aluminum

Theodore Prudon

Historically, metals have defined eras. Early periods such as the Bronze Age and, subsequently, the Iron Age demonstrate the important way in which metals have served as markers of historical changes, a trend that continues today. Regardless of a metal's appearance or strength, its relative rarity (or ubiquity), or its position in the periodic table, the role and perception of a particular metal or alloy will be modified over time. Bronze, for instance, has morphed from a quasi-precious material used for jewelry, tools, and weapons into a more common architectural material applied to masonry anchors, statues, and curtain walls. Steel, renowned early on for its strength, found a ready use in arms and armor. Often referred to as Damascus steel, it radically transformed our physical world with steel-framed buildings, following Henry Bessemer's invention of a commercial production process in the 1850s. Thus, it seems that every era has its own defining metal, the perception of which may evolve into something quite different. Yet, in our own time, the role and subsequent changes in perception related to metals have remained fundamentally unaltered, and, in many ways, are still like the Bronze and Iron Ages. If the name for the nineteenth century is the Age of Steel, recognizing the role of steel in the expansion of our built environment, then the first seventy-five years of the twentieth century could easily be called the Age of Aluminum.

Number thirteen in the periodic table, the element known as aluminum (referred to as aluminium outside the United States) evolved in the twentieth century into a material associated with progress in both building and lifestyle. Aluminum once had a value similar to gold; today, however, it has achieved an almost ubiquitous presence. It may be too early to tell what the dominant metal of the coming century will be—titanium may be the next best candidate—but it is clear that aluminum will continue to play an important role.

The story of the discovery and refinement of aluminum is well known and well published.[1] The cultural and perceptual development is, by contrast, much less appreciated. As early as 1807, Humphry Davy, whose name is largely associated with the invention of the miner's lamp, theoretically identified aluminum's existence, but it was not until 1825 that the Danish chemist Hans Christian Ørsted was able to produce a still impure sample of the actual metal. In 1827, German Friedrich Wöhler more or less repeated the experiment and has since been mainly credited with aluminum's initial production. In 1821, Pierre Berthier discovered bauxite—named after the town Les Baux de Provence—the ore from which he successfully extracted the pure metal. The extraction process remained extremely difficult, however, and only allowed for the production of very small quantities, making the metal scarce, desirable, and costly. Aluminum's characteristics—its noncorrosiveness, relative softness, light weight, and shine—initially added to its assumed preciousness. Not surprisingly, aluminum was used in jewelry and other objects for which traditionally nobler metals like gold had been used.

Another Frenchman, Henri-Étienne Sainte-Claire Deville, is credited with having conceived of electrolysis to extract aluminum from the ore in 1846. It is this concept of electrolysis that became the basis for the refining methods attributed to Charles Martin Hall, who developed a commercially viable method for the extraction of larger quantities of aluminum from bauxite in 1888.[2] With this discovery, like Bessemer's invention for making steel, the commercial industry as we know it today was born. As a result, in over just half a century, aluminum changed from a rare and precious metal to an all-purpose material used in a wide variety of applications in which weight, relative durability, and noncorrosiveness were important characteristics. As expected, the increased production capabilities caused a significant drop in price: in the seven years between 1885 and 1892, the price decreased from 11.33 dollars a pound to 0.57 dollars a pound.

In 1807, Davy referred to the then-theoretical metal as aluminium, deriving the name from the oxide alumina and using the suffix *ium*, as was customarily applied to other elements discovered in the nineteenth century. However, by 1812, when he published his *Elements of Chemical Philosophy*, he preferred the suffix *um*.[3] (In the nineteenth century, *aluminium* appears to have been most used.[4]) While Hall used the term *aluminium* in his patent drawings and when he first publicized his invention to the general public, when he and others formed the Pittsburgh Reduction Company in 1888, the spelling *aluminum* was used in the logo. By 1907, the company was renamed Aluminum Company of America (Alcoa). It seems that because the spelling *aluminum* was predominant in industry, in 1926 the American Chemical Society officially adopted that spelling, setting the United States apart from the rest of the world, which continued using the original nineteenth-century term, *aluminium*.

The history of the use of aluminum is filled with a number of significant milestones. The first is definitely the installation of a cast aluminum pyramidion, or cap, on the top of the Washington Monument in 1884. | fig. 1 Made by William Frishmuth from Philadelphia, the initial estimate for the piece of 75 dollars was inadequate due to the difficulties in casting; the final cost was closer to 225 dollars. Aluminum was selected because of its noncorrosive and nonstaining qualities.[5] These same physical characteristics combined with its shiny appearance and light weight led to a wide variety of divergent uses. From the end of the nineteenth century,

fig. 2 | Cast-aluminum spire, Smithfield United Church, by Henry Hornbostel, Pittsburgh, Pennsylvania, 1926 (left)

fig. 3 | The cast and extruded aluminum in the fireplace screen is finished and patinated to resemble traditional statuary bronze (at approximately 50 percent less weight), by Theodore Prudon, 2006 (right)

applications included *objets d'art*, sculptures (including castings of the Greek statue of the so-called Venus de Milo by the Frenchman Ferdinand Barbedienne in 1889, as well as a later statue of Hall himself on the Oberlin College campus), decorative boxes, household goods, and novelties.

Major changes in the use of aluminum and the expansion of the industry took place in the peacetime periods following both World Wars. Aside from its physical characteristics, the metal became a symbol of newness or modernity and was used particularly for transportation, furniture, household items, and other articles that not only benefited from a lower weight but also projected a contemporary, streamlined image. The opportunities and desires for aluminum before World War II are exemplified in two widely diverging works: the spire of the Smithfield United Church of Christ in Pittsburgh (1926), designed by Henry Hornbostel, and the Aluminaire House (1930), the demountable house designed by A. Lawrence Kocher and Albert Frey for the Allied Arts and Building Products Exhibition in New York City.

The spire demonstrated how the same level of detail previously achieved with cast iron could be accomplished with a lighter and more corrosion-resistant material. | fig. 2 Today, aluminum is still used to reproduce classic details, whether as a replacement for cast iron or another material, while benefiting from the lower weight. | fig. 3 Rather than replicating details of the past, however, the Aluminaire House sought to demonstrate a modern and streamlined way of living, and to show

fig. 4 | Aluminaire House, by A. Lawrence Kocher and Albert Frey, Syosset, New York, 1930

how mass-produced materials, not the least of which was aluminum—used in the house both as a structural pipe-and-beam frame and as exterior corrugated cladding—could create a new, more comfortable and more affordable architecture.[6] | fig. 4 These products reflected different manufacturing techniques, and much of the design innovation was made possible through the development of technology for shaping and forming aluminum from solid casting into thin metal foil. As an indication of how aluminum became synonymous with modern and easier living, the coffeemaker designed by Alfonso Bialetti in 1930 (and still for sale today) and Russel Wright's spun-aluminum drink sets of the same decade serve as excellent examples. | figs. 5, 6

While casting was the predominant technique during the nineteenth century, by the end of World War I, methods of fabrication included rolling, extruding, and spinning, and featured different alloys, along with annealing and tempering techniques—all of which affected the relative workability and strength of the material. One important development was the ability to manufacture aluminum sections and tubing, which, because of their light weight and rigidity, found their way into varied applications, ranging from dirigible or airplane struts to seating and furniture. | figs. 7, 8

Just as World War I stimulated the early growth and development of the aluminum industry, the expansion during and after World War II was even greater. Due to the wartime demands on the airplane industry, the overall capacity of refining

fig. 5 | Coffeemaker, by Alfonso Bialetti, 1930 (left)

fig. 6 | Spun Aluminum Group, by Russel Wright, ca. 1930 (right)

and fabrication grew exponentially. In the postwar era, the government divested itself of the various installations, which created a peacetime industry with a great deal of capacity and technical knowledge, but without a clear market. The result was an intensive industry marketing effort to introduce a wide variety of applications and uses of aluminum, both old and new, to the general public. Aside from the continued use of aluminum in furniture and other consumer goods, the focus was on architectural applications, transportation, and the beverage industry. The aluminum curtain wall and canned soda became quintessential postwar phenomena.

On an architectural level, the precision of the machine-manufactured material and its light weight made it ideal for items with repetitive parts and those requiring minimal tolerances. It is not surprising that the postwar airplane industry initially looked to housing, desperately needed by millions of GIs returning from the war, as an opportunity for prefabrication suited to their production capabilities.[7] Examples of this cross-disciplinary approach included Buckminster Fuller's work with Beech Aircraft in Wichita, Kansas, to develop the so-called Wichita House, and Edward Larrabee Barnes's collaboration with Vultee Aircraft Corporation. Neither of these projects, however, extended beyond the prototype stage. Aluminum's lightweight portability was also a core idea behind Jean Prouvé's Maison Tropicale of 1951.[8] **| fig. 9** Perhaps the most important growth for housing and aluminum was in the mobile home industry, which was building on prewar examples like the Airstream.[9]

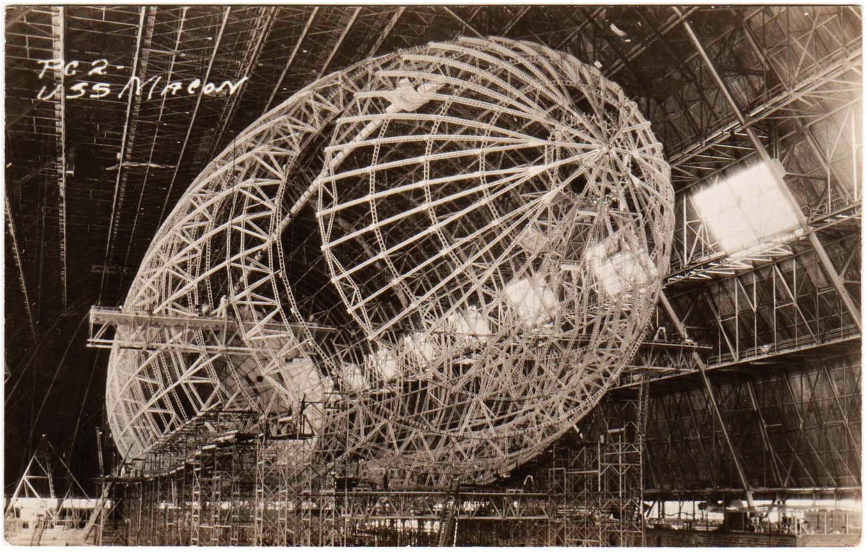

fig. 7 | Airship USS *Macon* (ZRS-5), under construction, 1933 (left)

fig. 8 | Aluminum Group Chair, by Charles and Ray Eames, 1958 (right)

The significance of the building trade to the aluminum industry in the postwar period can easily be gauged from the advertising and literature produced by manufacturers such as Alcoa, Reynolds Aluminum, or Kaiser Aluminum. Reynolds's two-volume *Aluminum in Modern Architecture* is probably the most extensive promotion effort, but is by no means the only example. Both Reynolds and Alcoa featured their products in their own buildings. In 1953, Alcoa hired the New York architecture firm Harrison and Abramovitz to design a new office in Pittsburgh, and in 1958, Reynolds commissioned Gordon Bunshaft of SOM to design its headquarters in Richmond, Virginia. The former was not only an example of aluminum but also a showcase of what could be done with a relatively thin-gauge panel spanning from floor to floor, incorporating openings for windows. **| fig. 10** Compared with the curtain wall of the United Nations Secretariat Building (1952), also constructed under the guidance of Harrison and Abramovitz a few years earlier, the Alcoa design represented one of the most advanced curtain walls in the early 1950s, and remains an example of the technical capabilities of aluminum and the modernity of the office building typology in particular and the postwar corporation in general.

Aluminum also provides one of the few instances in which two of the key areas of modernist innovation, household goods and architectural design, meet. One example is the Markel Building (1965) in Richmond, Virginia, a seeming amalgamation of aluminum foil, as it was used in kitchens, and the high style of Frank Lloyd Wright's Guggenheim Museum (1959). **| figs. 11, 12** According to the building's historical plaque, architect Haig Jamgochian's design was "inspired by a baked potato wrapped in foil" served to him at a dinner of the American

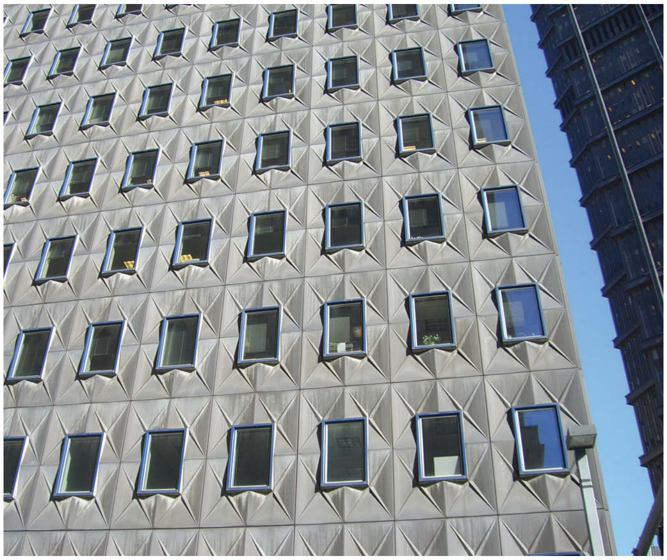

fig. 9 | Maison Tropicale, by Jean Prouvé, 1951 (left)

fig. 10 | Alcoa Building, by Harrison and Abramovitz, Pittsburgh, Pennsylvania, 1953 (right)

Institute of Architects. Each floor is a single piece of metal, some 555 feet long, and Jamgochian hammered the aluminum on the third story into its distinctive crinkles before the contractors were allowed to finish the remaining floors.[10] Aside from its remarkable exterior, the Markel Building introduced another interesting issue: how to repair or restore these unique structures—a dilemma vexing many buildings. Conventional techniques or philosophies about preservation and its materiality have advocated conserving as much of the original fabric as possible and replacing damaged areas with in-kind materials. However, it may not be an easy task to find and install a new 555-foot-long piece of aluminum. This one example indicates that the standard preservation theory may not suffice; certainly a Band-Aid approach does not offer a viable answer. | **fig. 13**

Perceptions change, and the ideas of aluminum have shifted. No longer considered precious or so strongly associated with modernity and progressiveness, the metal has become commonplace. A number of factors have precipitated that change. Its widespread availability and use has certainly dispelled any aura of rarity. Other advantages, such as its lightness relative to strength and durability, as well as its noncorrosiveness, are rapidly being overtaken by other materials that are lighter, stronger, and often less costly. This is a natural economic progression in architecture and business. For instance, the aluminum beverage can, which largely succeeded glass bottles and tin cans after World War II, has in turn been replaced to a great extent by plastic bottles. For structural applications, carbon fiber materials outperform aluminum in strength and weight characteristics.

In architecture, the story of aluminum's image-change may play out similarly. Early innovative curtain walls, for example, are gradually being replaced.

fig. 11 | Markel Building, by Haig Jamgochian, Richmond, Virginia, 1965 (left)

fig. 12 | The aluminum sheets for each floor of the Markel Building are some 555 feet long and were hand hammered in situ. (right)

They are often architecturally underappreciated, and, when measured against current standards of thermal and physical performance, are considered technically obsolete (mostly air and water infiltration). With energy costs continuing to rise, the pressure to substitute aluminum with more technologically advanced wall systems will only get more intense.

However, the challenges of preservation and environmental sustainability are particularly important today. Beyond the debate of authenticity, a number of broader questions are raised: How much of the modernity of architectural expression was associated with the material itself? Can the design be recreated visually in different materials and improved technically in a way that can still be called preservation? Was it all about its shiny newness? Is the recycling of the material (as is happening with most metals and certainly with aluminum) enough of a moral justification to forgo an adherence to the authenticity of the original material as a core principle?

History is full of replacements, substitutions, and reconstructions that are now considered worthy of preservation or have become authentic in their own right. In the process, improvements were made, materials were changed to achieve greater durability, and earlier technical mistakes were eliminated. Whatever the ultimate outcome of this dilemma for aluminum, it is fair to acknowledge that the Age of Aluminum as we knew it some decades ago is coming to an end and is being replaced with new materials. However, the age of preservation for the design and architecture of that early aluminum heritage has begun. The question of how it will be accomplished has yet to be fully resolved.

fig. 13 | Because the sheet material is one piece and quite thin, repairs are not easily accomplished.

1 | John Peter, ed., *Aluminum in Modern Architecture*, 2 vols. (Louisville, KY: Reynolds Metal Company, 1956). An interesting survey of the use of aluminum in the immediate post–WWII era can be found in *Aluminum in Modern Architecture*. While volume one represents a photo survey of projects in the United States as well as Europe and South America, volume two deals with the technical aspects of the use in building. This volume also contains a brief history of the metal, which forms the basis for several subsequent publications including the chapter by Stephen J. Kelley, “Aluminum,” in *Twentieth-Century Building Materials: History and Construction*, ed. Thomas Jester (New York: McGraw Hill, 1995), 47–51. A more comprehensive and recent overview is provided by Sarah Nicols, ed., *Aluminum by Design* (Pittsburgh, PA: Carnegie Museum of Art, 2000). The book is the outcome of an exhibit made possible largely through the support of the Alcoa Foundation and covers all uses of aluminum, including architectural from the beginning to the present. For a general discussion of the use of aluminum in twentieth-century architecture, see Theodore H. M. Prudon, *Preservation of Modern Architecture* (Hoboken, NJ: John Wiley & Sons, 2008), 115–19.

2 | Apparently the Frenchman Paul Héroult independently invented the same process at the same time.

3 | Humphry Davy, *Elements of Chemical Philosophy*, vol. 1, part 1 (Philadelphia: Bradford and Inskeep, 1812).

4 | An example is Henri-Étienne Sainte-Claire Deville, *De l’aluminium: ses propriétés, sa fabrication et ses applications* (Paris: Mallet-Bachelier, 1859).

5 | For a detailed description of the project, see George J. Binczewski, “The Point of a Monument: A History of the Aluminum Cap of the Washington Monument,” *JOM* 47, no. 11 (1995): 20–25.

6 | The house was intended to be dismantled after the exhibit and was moved to Long Island to the estate of the architect Wallace Harrison. The building has been moved twice since. For a more detailed discussion of the history and the current status of the Aluminaire house, see Prudon, *Preservation of Modern Architecture*, 194–203.

7 | See Prudon, *Preservation of Modern Architecture*, 144–45. Similarly in the UK, the AIROH house was developed and manufactured under the auspices of the Aircraft Industries Research Organization on Housing (AIROH) in the years directly following the war.

8 | Christian Enjolras, “Tropical Houses,” in *Jean Prouvé: The Poetics of the Technical Object*, by Jean Prouvé et al. (Weil am Rhein, Germany: Vitra Design Museum, 2006), 208–13.

9 | Colin Davies, *The Prefabricated Home* (London: Reaktion Books, 2005), 69–86.

10 | I am grateful to Patrick Ciccone, who brought this building first to my attention and who provided the photos accompanying this article. Some of these images may also be found on the front page of *The Architect’s Newspaper*, issue of October 23, 2009, with commentary on the Metals Conference held at Columbia University.

Empiricism and Abstraction: A Brief History of Metals in Architecture

Mabel Wilson

At the twilight of the Age of Enlightenment, Joseph Wright of Derby's painting *An Iron Forge Viewed from Without* (1773) is the last of his blacksmith series of works that anticipated the waves of industrialization about to inundate English society. | fig. 1 From within the iron forge, the viewer witnesses the process of smelting as the smithy heats pig iron over coal-based coke and then pounds its formless mass into the productive tools of the emerging commercial age. The employment of a water-powered tilt hammer, a common technology, mechanized one phase of the ironsmith's procedures. These discrete techniques would eventually be rationalized into large-scale industrial processes, wherein labor and material could be correlated according to efficiencies of time and cost. Here, already depicted by Wright, is the division of labor under industrial capitalism: the worker manning the forge, the manager overseeing his charge, and the owner surveying his enterprise. Joining the manager in watching this spectacle of production are his wife and child, who don trappings of their middle class status, exhibiting their new social role as the purchasers of the commodities being manufactured from the nation's lucrative cotton industries.[1]

Several significant innovations in metals followed in the decade after the completion of this final painting in Wright's series. In 1775, Thomas Pritchard would erect the first iron bridge over the Severn River at nearby Coalbrookdale. Its arch, spanning one hundred feet across a deep ravine, facilitated the carting of raw materials in and out of the burgeoning iron industries in the valley below. By 1785, cast-iron columns could be found shoring up the wooden beams of mills whose floors bore the weight of Richard Arkwright's massive, lurching cotton looms in factories around the Midlands and the North of England. By 1790, iron was fabricated into the first railroad tracks. Steam engines, powered by coal, soon darted across these rails, efficiently compressing the time it took to transport raw materials from ships just in from the colonies to the inland factories. By the nineteenth century, an intricate web of railroads would ferry finished goods to markets in towns and cities at the heart of the British Empire.

An Iron Forge Viewed from Without captures the dawn of what Lewis Mumford termed the "paleo-technic" age of iron and coal that rendered the era of wood and water obsolete.[2] The resplendent power of the luminous forge incites in the viewer a sublime moment of both fear and amazement. As architects, we may observe that Wright staged this scene of early industry within a primitive

fig. 1 | *An Iron Forge Viewed from Without*, by Joseph Wright of Derby, oil on canvas, 1773

fig. 2 | The Great Exhibition of the Works of Industry of All Continents, Crystal Palace, by Joseph Paxton, London, 1851

hut. Nestled in a picturesque landscape dense with twisted boughs and bounded by a rushing brook, the rustic hut, albeit in ruins, exemplifies the origins of classical architecture. Significantly, Wright framed this new age of iron through the column and the beam, rationalized structural components that would soon be abstracted into the logics of a modern language of classicism. As a syntax, these parts could be combined in a myriad of arrangements that responded to the programmatic needs of public buildings commissioned by the agencies charged with organizing the modern nation-state. Seventy years after Wright's parable, these combinatorial systems would find their full expression in the abstract expanses of the Crystal Palace's (1851) glazed facades, whose iron frame tested the metal's capacity to achieve long spans and accelerated the speed of production and erection. | fig. 2 Thousands of times larger than the intimate confines of the forge, the cacophonous interior of Joseph Paxton's hall didn't house the choreographed movements of the manual laborer; instead, its orderly aisles exhibited the bounty of industrialized society and disciplined the ambulatory gaze of the modern consumer.

It is obviously no longer the age of iron and coal. Nor do we reside in the century of steel—an era when the rationalization of the modern social order found its ideal milieu within the well-managed regional plan and its ideal postwar manifestation in the mute geometries of the glass curtain wall, behind which worked, of course, the massive bureaucracies of corporations and the State. In a photograph documenting construction at New York City's Ground Zero, the thirty-six-foot girder, weighing in at fifty-eight tons, no longer performs as a carefully sized

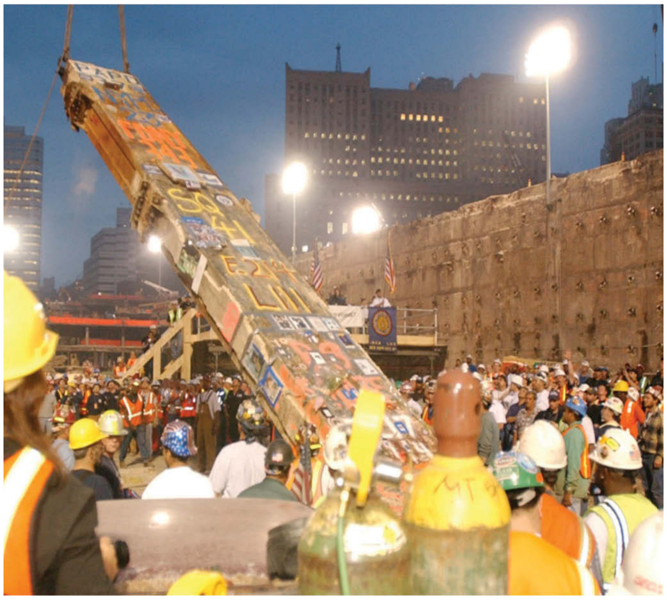

fig. 3 | World Trade Center, "Last Column," National September 11 Memorial and Museum, New York, New York, 2002 (left)

fig. 4 | World Trade Center, by Minoru Yamasaki, New York, New York, 1973 (right)

and milled load-bearing element of the World Trade Center's steel frame. | **figs. 3, 4** Now its role will symbolize the implosion of abstract space, the fall of what Michel De Certeau branded as "the tallest letters in the world."[3] The precious remains of the "last column" have become iconic, soon to be on display within the National September 11 Memorial and Museum.

Today, intermingling with these older irons and alloys are new metals—tantalum, lithium, platinum, palladium, and seventeen rare earth metals. These metals facilitate the continued compression of time and space, a process that is no longer powered by steam or dominated by jet propulsion but streamed by wavelengths through hertzian space, impulses of light and electric currents coded into zeros and ones. If Wright's painting anticipated an industrialized world fueled by coal and built by iron, how should we interpret Edward Burtynsky's digital photograph of cell production, *Manufacturing #16, Bird Mobile, Ningbo, Zhejiang Province* (2005), in which the facility's interior space travels toward an infinite horizon, modulating between the scales of the nano and the galactic? | **fig. 5** Microprocessing has bifurcated production into a network of flows, so that transnational corporations can shift any segment of production to almost anywhere in the world to maximize profit and optimize efficiency. Parametric analysis can dynamically calibrate material performance in relation to a host of other factors. The deployment of ubiquitous computing can orchestrate environments to respond to a range of human conditioning factors. In this regard, does the term *rationalization* aptly characterize these processes or is it one of "optimization," since the human capacity for reasoning, with all of its moral criteria and

fig. 5 | *Manufacturing #16, Bird Mobile, Ningbo, Zhejiang Province*, by Edward Burtynsky, 2005

Prins Hendrikkade
80/K
EUR 349000 K.K.,
Woonoppervlak: 165 m2
Afstand: 1323m
Makelaarskantoor Babs Persoons B.V.

fig. 6 | Layar Augmented Reality software, Layar, 2009

unexpected turns, is not yet intrinsic to digital computation (even though choice and desire are critical extrinsic forces)? And what happens in the gap, the lag time between empiricism and abstraction, the space for the creation of architecture, when new technologies can instantly re-present space, augment our reality? | **fig. 6**

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1 | David H. Solkin, "Joseph Wright of Derby and the Sublime Art of Labor," *Representations,* no. 83 (2003): 167–94.

2 | Lewis Mumford, *Technics and Civilization* (New York: Harcourt Brace & Company, 1963), 151.

3 | Michel de Certeau, *The Practice of Everyday Life*, trans. Steven Rendall (Berkeley: University of California Press, 1984), 91.

Projects

Northwest Corner Building

José Rafael Moneo with Jeffrey Brock

Northwest Corner Building, Columbia University, New York, New York
José Rafael Moneo

For most of the classic architectural histories of the twentieth century, the profound changes in building techniques, materials, and scientific knowledge during the late nineteenth and the early twentieth centuries have been the central means of explaining what architects achieved during that era.

At the risk of oversimplifying the matter, I would dare to say that Le Corbusier and Ludwig Mies van der Rohe have monopolized the narrative of twentieth-century architectural history by formally expressing the possibilities of building in concrete and steel. Frank Lloyd Wright and Alvar Aalto are recognized as remarkable architects, yet they were less directly engaged with methods of construction. It can be said that structure still prevails as the dominant factor in establishing a building's identity.

Despite being already well-known during the nineteenth century, materials such as concrete and steel were to become the substance for the most prominent chapters of architectural innovation in the twentieth century. From our own perspective at the beginning of the twenty-first century, it is difficult to identify materials and techniques that might have a commensurate impact. In other words, despite the present capacity to build at an unprecedented scale, I wouldn't say that we are witnessing a material revolution. Currently, it is the economy and issues of management and organization that seem to hold the interests of builders.

And yet, in the last two decades, new means of both calculation and representation introduced by computers have agitated the architectural waters. Computers, in addition to bringing advances in the manipulation and dissemination of information, have transformed architectural representation. This is a result not only of the precise and seductive renderings they produce but also because they enable architects access to much more complex architectural forms. Geometrical boundaries have been extended and the conception of architectural form in space has become easier with the computer's help. If Gothic architecture was the result of handling two-dimensional geometry, and the Cartesian grid led to spaces conceived by means of three-dimensional analytic geometry, today's computers have arguably forced architects to shy away from orthogonal geometry, drawing them instead to the undulating architecture celebrated in today's magazines. In addition, computer techniques have introduced radical changes in methods of calculation. Fastidious and laborious iterative procedures have given way to systems that allow us to predict structural behavior with much more clarity, often visualizing reactions under all types of circumstances. The field of building has improved dramatically with the advent of the computer, and we could add that we are on the brink of a broad new range of materials, capable of even changing their characteristics depending on the external conditions.

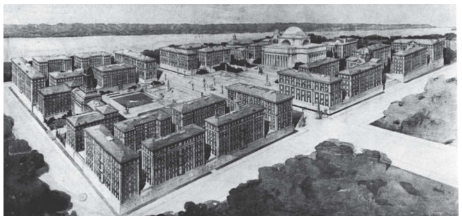
Faced with such a panorama, it isn't surprising that architects unleash their imaginations in pursuit of new images that conflict with the landscape of the cities in which we live. Visions abound of a built world in continuous movement, one struggling to capture the ever-changing reality of electronic screens, where new projects deliberately escape from the orthogonal geometry familiar to us in cities composed of buildings of known types. But the construction of these images often results in frustration and failure for the architect. Today's building industry does not offer the means to easily realize these much-desired architectural inventions. Even those architects who seem to successfully handle the new world of form pay a heavy toll when transforming their drawings into reality. While it may be possible to build almost any form, often these forms are cast with such artificiality that we perceive them, in the best case, with surprise, and, more often than not, with indulgence, ignoring their awkward inconsistencies.

Construction remains what it has been, and it will take time—I won't speculate how much—to see a built work that can eschew today's steel and concrete, or stone and wood. Indeed, the industry has an inertia that will be difficult to change. Yet the computer has endowed us with greater control over the materials we know, as well as new means of calculation and production, allowing architects to propose alternatives that challenge traditional practice.

Our project for the Northwest Corner Building (NWCB) for Columbia University makes a case for the role that might be played by new tools in structural analysis and architectural design, and their applications to a material condition: a real building in a real place. It is a project where traditional considerations of architectural form found a valuable partner in modern forms of analysis. I will try to explain what I mean by describing the major steps in the design process, indicating their significance for the design team.

The McKim, Mead & White Master Plan

The Columbia campus is a rich and unique architectural artifact within New York City. I began the NWCB project by studying the campus's master plan, conceived principally by Charles McKim of McKim, Mead & White at the turn of the twentieth century. What is remarkable to me about this plan is that it is embedded within



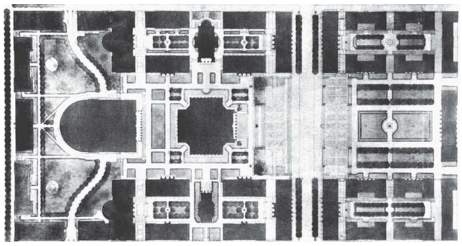


fig. 1 | Bird's-eye view of projected Columbia University campus built to full density, by McKim, Mead & White, 1903. Jules Crow, delineator (top)

fig. 2 | Plan of Columbia University campus, by McKim, Mead & White, 1903 (middle)

fig. 3 | Columbia University campus, showing the Morningside campus in relation to the planned Manhattanville expansion, 2009 (bottom)

the Manhattan grid without being a part of it. The greater context of Manhattan permeates the campus, but only anecdotally. The campus's architectural walls precisely protect and define the presence of the university while at the same time successfully merging domestic and public spaces. | figs. 1, 2

More than a century old, the plan invites us to ponder all the changes that have occurred since its conception. In the central area of the campus around 116th Street, the plan's original layout of buildings was not fully realized, leaving more open space than intended. Where a street once ran through the center of campus, we now enjoy the pedestrian walk, a pathway that has become determinant for the university's sense of community. While some of the buildings in the plan are missing and other aspects of the layout have been blurred, the essence of the campus conceived by McKim, Mead & White remains clear and forceful to this day. I believe this is due to the plan's fundamental integrity, and because construction began where it mattered most, at the perimeter. The buildings along 114th Street, Broadway, and Amsterdam Avenue are crucial to defining the character of the campus, whereas the buildings inside the perimeter are essentially optional. The variations in layout, scale, and orientation of the internal pieces all work within the framework provided by the perimeter structures.

Later, as the edge along 120th Street was developed, the original garden slope was transformed into a large platform, or plinth, for the campus, making the precinct ever clearer. Some of the construction in this area has not benefited the campus, and, indeed, the north end had come to be referred to as the university's "backyard"; a place that seemed to have been abandoned architecturally, where emergency generators and ad-hoc cooling towers were located—pure architectural residue. Our site at the northwest corner was the last remaining site on the perimeter of the main campus (known as the Morningside Heights campus), and our design responded from the outset to conditions established by the McKim, Mead & White plan. | fig. 3

This decision to abide by the master plan in defining the new building's footprint may seem simple, or even easy, but it was in fact a considerable challenge. While the slablike quality of the perimeter buildings (just sixty-five feet wide) reinforces the integrity of the campus precinct, we considered the gaps between the buildings as critical to the success of the McKim, Mead & White plan. It is through these gaps that we understand the campus in its relation to the surrounding city, not just because of the views they provide but through the solid-void-solid-void rhythm they establish, echoing the rhythm of the Manhattan gridiron on a smaller scale.[1] From the very beginning, we were attracted to the value of those interstitial spaces, which have the ability to enhance the value of the corners of the neighboring buildings: Pupin Physics Laboratory and Chandler Hall. We were interested in making those gaps into connectors between the campus and the city, carefully configuring the ground plane as it passed up from the street and into the campus.

Where other architects have proposed projects on this site for singular buildings, our approach was to think of this project very much as the completion of the perimeter structure established in the McKim, Mead & White plan.[2] Instead of simply enhancing and emphasizing the extraordinary quality of the corner in an expressionistic way, we sought to create a building that would, above all, form the corner of the campus. Rather than drawing attention to the singularity of its form, the building was designed to work in concert with its neighbors, reasserting the value of the campus as a total piece in the middle of the Manhattan grid.

Connecting the Campus to the City

The principal entries to the campus are currently at 116th Street on Broadway and on Amsterdam Avenue, with minor entries on both avenues at 117th Street and 115th Street, as well as along the south edge of the campus on 114th Street. To the north, across the width of the campus, comprising approximately half of the campus's perimeter, there is only one entry on 120th Street, and it is poorly conceived, with a forbidding flight of exterior stairs leading to an unseen destination. As it had gained a sense of architectural abandonment, the north end of the campus had also lost its sense of (and its real) connection to the city outside. This disconnection has been exacerbated by the sectional change that occurs between the campus level and the street, where the difference between them exceeds thirty feet.

With the university's plans to expand and develop the Manhattanville campus (located roughly nine blocks north of the main campus), the administration recognized the acutely problematic condition of the north edge of the Morningside campus. Manhattanville is to primarily house science buildings, bringing with it an impending need for an easy connection to Morningside (where the university's science buildings are concentrated today).

Here, then, the new building at the northwest corner assumed these greater responsibilities: to open the old campus to the north by forming a new gateway between the two campuses and to offer an easy way for people to climb the thirty-foot change in elevation from street to campus. But it was hoped that the project would do more than simply rectify the existing condition. We wanted to make an entry that could be seen as more inviting than any other on campus, where the life of the university and the life of the street might begin to blend, and where the classic "town and gown" tension might find some form of relief.

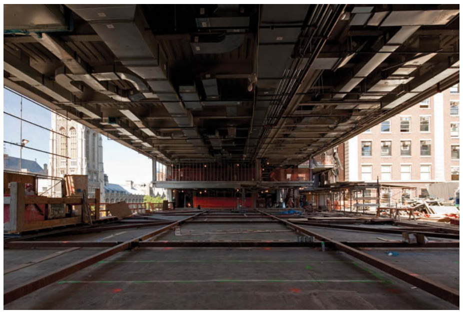


fig. 4 | Construction view; trusses span width of gymnasium

fig. 5 | Construction view of trusses being slid into place

The Gym and the Public Space

The complexity of the design problem can only be fully understood in relation to the most severe constraint presented by the existing condition: the fact that four-fifths of the area beneath the footprint of the NWCB was already occupied by another building, over which our project would have to be constructed. This building, the Levien Gymnasium, not only houses three contiguous basketball courts, and therefore could not admit columns at any point within its 120-foot span, but was also continuously occupied during the construction period except for a brief three-month hiatus each summer. This condition presented us, and the builder, with an all-important structural problem. | figs. 4, 5

The area of open ground left for the NWCB's structure was a narrow band at the south edge, just wide enough for a single line of columns, and a sixty-five-foot square area at the north end. In this very small area, we needed to bring down elevators, mechanical systems, and structure. In terms of program, the principal thrust of the remaining open space was to soften the hard climb up to campus level from the street, and to reach out to the street from the university.

With some difficulty, the spatial dispositions of the escalators, stairs, and café were made to fit so that the open space of the campus-level plaza remained visible from all key points along the path from the building's street entry to the café and up to the lobby. This view of the open space above is meant to draw the building's users through the sequence of spaces, providing exactly the sort of welcoming entry the campus needed. The café itself feels close to the street, located just twelve feet above it, but has its own ceiling much higher, about twenty-four feet.

At campus level, the remaining quasi-public spaces begin to unfold, with the library occupying practically the entire floor plate, except for the elevator and stair cores. The library and circulation spaces are by necessity completely free of columns where they sit atop the gymnasium. We decided to exploit this open condition by completely glazing the east and west library facades. This exposed the activity of the campus to the street, and vice versa—the connection attenuated by the thirty-foot difference in level. We felt this openness was critical to redefining the projected atmosphere of the existing architecture on the campus's north edge.

At campus level, circulating up and over the top of the café space at the north end of the building, is the lecture hall with its steeply raked floor. In order for this space to be column-free, and for the structural grid not to interfere with the layout of the café and other elements packed in below, the floor slabs of the café, lecture hall, and the above laboratory spaces were all hung from truss elements at the top of the building.

The use of hangers allowed us to configure the building's street entry in and under the great mass of the building's structure, with the doors set back below the suspended floor of the café. As a result of the hanging floor slabs, the building seems to hover above the street, revealing the strength of the structural solution to the visitors upon entry.

The slots of outdoor space between the NWCB and its neighbors, preserved from the McKim, Mead & White plan, provide a critical function. In addition to the views and light afforded to the ascending internal path, on the Pupin-side space, the slot offers an outdoor stair, connecting the campus with street level and allowing access to the campus without having to enter the building.

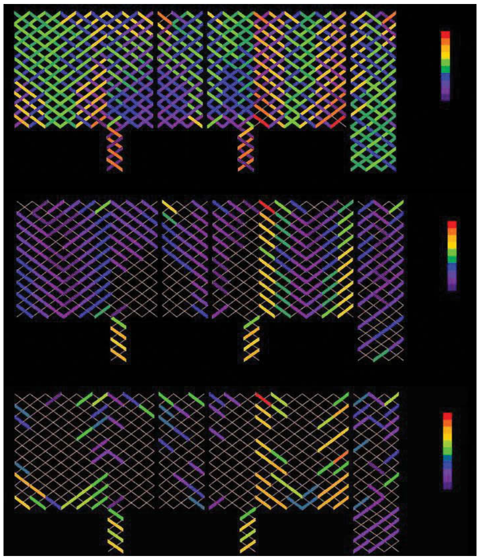
Structure

We quickly understood that the need to span over the gymnasium would require a prominent structural solution that would drive the overall architectural design. The seven double-height floors above the library are principally open laboratory spaces, requiring forty-foot clear spans and very stiff floor construction (to avoid shaking microscopes, for example).

With the help of Dan Brodkin at Arup, we weighed the economy and architectural merit of several different structural systems, ultimately pursuing the concept of bracing the facade plane in its entirety. This concept was not only the most efficient in its use of steel but also relied the least on monumental structural gestures. Most importantly, the solution of the braced frame integrated naturally with the architectural concept of the building as a prismatic form. In its final design, the structural bracing gives the impression of a texture laid on the prism. Although it appears as if it is a willful composition inspired by the work of Paul Klee, in fact it is the result of rigorous structural analyses: more a product of deductive reasoning and computer-aided analysis than artistic gesture.

The process devised by Brodkin for defining the arrangement of diagonal braces was at once straightforward and nuanced, open to a degree of manipulation. The method began with the construction of a detailed computer model including all structural elements identified during the architectural design process. This model incorporated the anomalies in the arrangement of columns, beams, slabs, cutouts, and cantilevers developed to accommodate the spatial configuration of the program. In its first iteration, each grid square on the facade was fully supported with diagonal cross-braces running in both directions. The model was then subjected to virtual dead and live loads and observed.

This virtual loading revealed that in each of the grid squares one diagonal was principally working in tension and the other principally in compression.



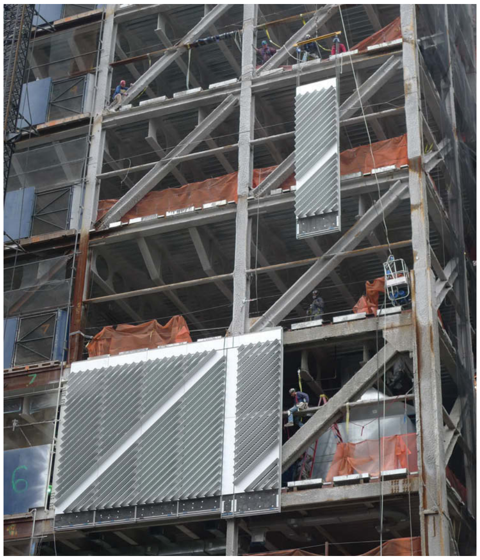


fig. 6 | Studies by Arup for steel structure on NWCB

fig. 7 | Installation of aluminum panels

To favor the efficiency of tension members, which do not have to carry extra steel to avoid buckling, the compression members were removed from the model. As a result, the frame took on an entirely different appearance. The drawing created by the tension-only members demonstrated the flow of forces around the facade. One could intuitively follow how the loads were being carried to the strongest columns and, from there, down to the ground. Out of what had been a static grid with a neutral pattern of braces had emerged a dynamic-looking diagram of structural flows. | fig. 6

In the next iteration, virtual loads were again applied and the relative stresses in the tension-only members observed. To save more cost in steel weight and piece count, we removed the diagonal braces that carried loads under a defined minimum. The loads that these elided braces had carried would be taken up by other members in the system; members already carrying a significant load could be fattened up to accommodate the extra load without exceeding the weight of what had been the independent member.

While studying the frame's behavior as members were removed and shifted, the "hand" of the architect and engineer became plainly active, making decisions about how much thinning should occur and, to some extent, where, as issues of daylighting and construction sequencing came into play. The modeling methodology could not, for example, account for the need to build the frame from the ground up; it would admit a design that was completely unstable until a steel member, some two hundred feet off the ground, was put in place. Obviously, the building would not be constructed entirely on scaffolding, and certain questions of common sense required more than a little user input. | fig. 7

Despite the rationality of advanced structural modeling, the facade also has a contingent quality. The irregularity of the facade's diagonals is to a great extent the direct consequence of the various distortions exerted upon the otherwise symmetrical loading pattern that the purely prismatic structure would have engendered. The cantilevered bridges to the neighboring buildings, the trusses for lateral bracing embedded in the plan, the suspension of the classroom and café spaces, and, importantly, the eccentricity of the central longitudinal column line all exerted influence on the perimeter frame. Here, we could say that the building's own architecture, the specific architectural responses made to accommodate the varied programmatic requirements, constituted the lion's share of the user input that gave the frame its final form. Beyond that, the capricious hand of the architect was, except in very minor instances, effectively silent. In a sense, I had not expected such a powerful and conspicuous structure, or that we might make of that structure the virtual substance of the NWCB's architecture.

The structure reflects all the nuances that the singular spatial organization of the building requests.

Diagonalization of the Facade

Structural diagonal bracing is not a new development, but the expression of diagonals on building facades has recently become much more prevalent. In creating NWCB's facade system, we made a very conscious decision that it should allude to the building's structure.

Considering an illustration from Carl Condit's history of Chicago's public and commercial building, we can see that the city's nineteenth-century builders knew how to make the structure independently from the floors.[3] This was not a discovery of the nineteenth century, however. Gothic builders all over Europe have arguably given us many examples of wood structures that, not unlike steel structures, were built independently of the building's enclosure. Looking at a Spanish *caserío* in the Basque Country, you can imagine how the builder erected the wood frame—visible on the facade along with the rest of the house's structure—and only later completed the outside wall with infill.

Obviously, this tradition of the Gothic spirit was very much embedded in steel practice. Mies van der Rohe was evidently aware of the distinction between structure and cladding. But even Mies was tempted by diagonals. In the Convention Hall (1953–54) in Chicago, he used diagonals while not allowing for any asymmetry. Mies continued to define a pure geometry, designing extremely well-balanced structures.

More recently, the diagonal can be said to have experienced a dramatic rebirth with the construction of the Hancock Tower (1969) in Chicago, engineered by the famous Fazlur Khan in the office of SOM. But it was not until the late 1990s that the overt demonstration of the use of diagonals became a more common sight in our cities, such that today it has become almost a cliché. The proliferation of diagonals is more and more evident, a situation for which the Arup engineers might be responsible.

Having accepted a structural frame characterized by the (judicious) use of diagonals as the virtual matter of the building's architecture, our first impulse was to construct the facade with infilling, even using brick. And yet, in making a twenty-first century facade, we recognized that we would be cladding more than infilling and selected a panelized curtain-wall construction system. The panelized system allowed us to proceed with more freedom, giving us the opportunity to develop the facade in any direction. And I would like to think that the memory of the infilling technique is still present in the final design.

The question of fenestration was primary. The relatively even dispersion of the diagonals across the facades allowed us to make quick decisions regarding the location of windows: modules without diagonals would have windows while those with bracing would be left opaque. To maximize daylight, we made the upper half of each windowed bay translucent, with a system of exterior louvers protecting the glass from excessive direct sun.

When designing the cladding for the facades, we chose a clear anodized aluminum panel with a deeply textured surface. The same extruded aluminum louvers that we used for the laboratories' windows were applied to the opaque sections of facade, expressing the repetitiveness of the industrialized curtain wall and the mechanical nature of the construction process, and, by implication, allowing people to think about the effects of science. The louver solution proved to be chameleonlike, adaptable to the various conditions around the building's four faces, admitting the introduction of grills for air conditioning, filtering daylight, and (most importantly for the current discussion) providing a means of representing the structural frame that had occupied the team for so many hours.

This representation, alluding to the structure hidden behind the curtain wall, was made by what can be called a "negative drawing." The aluminum louvers were applied at uniform intervals to flat aluminum panels. These panels then covered the entire facade *except* for in front of structural elements, where the regularity of the louvers is interrupted (to the observer on the street, an image of the building's structural frame can be discerned). The absent structural frame, hidden behind the facade panels, is defined precisely by another absence, the disruption of the texture of the louvers as they pass over the structure. This negative drawing references the infill, returning with the forceful, textured presence of the space between the structure; the heavy relief of the infill in turn makes visible the hidden structure.

In modules with bracing, the louvers were arranged parallel to the diagonal phantom structure, in contrast to the horizontally set louvers of the windowed modules. By this device, the variety of bracing orientation across the facades is emphasized, and the textured quality is enhanced as light reflects according to the varying louver direction.

Construction and Image

To look at our project alongside OMA's CCTV tower in Beijing will help clarify the relationship between frame and cladding. OMA, working with Cecil Balmond and Arup, have used diagonals everywhere in the structure. The perimeter framework is entrusted with the task of taking up all the eccentric dead loads generated by the building's radical form. The designs of both CCTV and the NWCB concentrate the buildings' most important musculatures in the planes of the facades. In this, they are not unlike any number of designs for tall buildings since the advent of the tube frame and the widespread use of diagonal trusswork in the facade plane for the absorption of lateral loads.

Seen together, the contrast between the different designs of the buildings' cladding systems becomes evident. Both projects exhibit pride in the work of their engineers, in the subtlety of the analysis of the structural system, through the application of diagonal bracing in a hyper-efficient manner, and finally in their demonstration of a level of finesse that engineers have recently acquired with the advent of new forms of computer analysis.

There is a distinction between the two projects that, while seemingly simple, I believe is of some importance. The primary structure—that of columns and floor slabs—has been completely suppressed in the CCTV tower, covered in a neutral curtain-wall skin; of the entire mass of the building's complex latticework structure, we are shown the diagonals alone. More than simply celebrating these diagonal members, the facades of the CCTV tower elevate them to the level of the building's overall iconography. At the NWCB, by contrast, we added texture. Distinguishing between windows and isolated modules, the texture makes evident the structure behind the cladding, while also allowing the building to recognize both the diagonals that take care of structural forces as well as the horizontal and vertical planes that together make up the substance of the architectural space. It is true that the cladding system is about allusion, about permitting the structure to be held behind the panels. But behind the panels, many other things could happen. I continue to be surprised by how fertile the device has been in interfacing with whatever condition of program, structure, or mechanical system arose behind it.

In the CCTV tower, there is instead a kind of repetition and redundancy that lets us say that the "diagonalization" of the structure is the iconic factor that characterizes the building. The diagonals are covered by several layers of enclosure systems, the outermost being a glass skin that slips in front of the structure. The building could easily have been finished with the glassy skin contrasted only to the powerful volume. But OMA was tempted by the structural diagonal and literally drew them on the surface with powerful lines that give testimony to the structural diagonals behind, adding to the singular volume a new layer of iconicity.

In the NWCB, we are trying to make image and construction coincide. It can be said that this approach is more traditional. But it could also be said that this approach absorbs more of the substance of the building. In our building, cladding and the memories of infilling are present at once. In the case of CCTV, it is only cladding that is present, without any reference to a possible infilling.

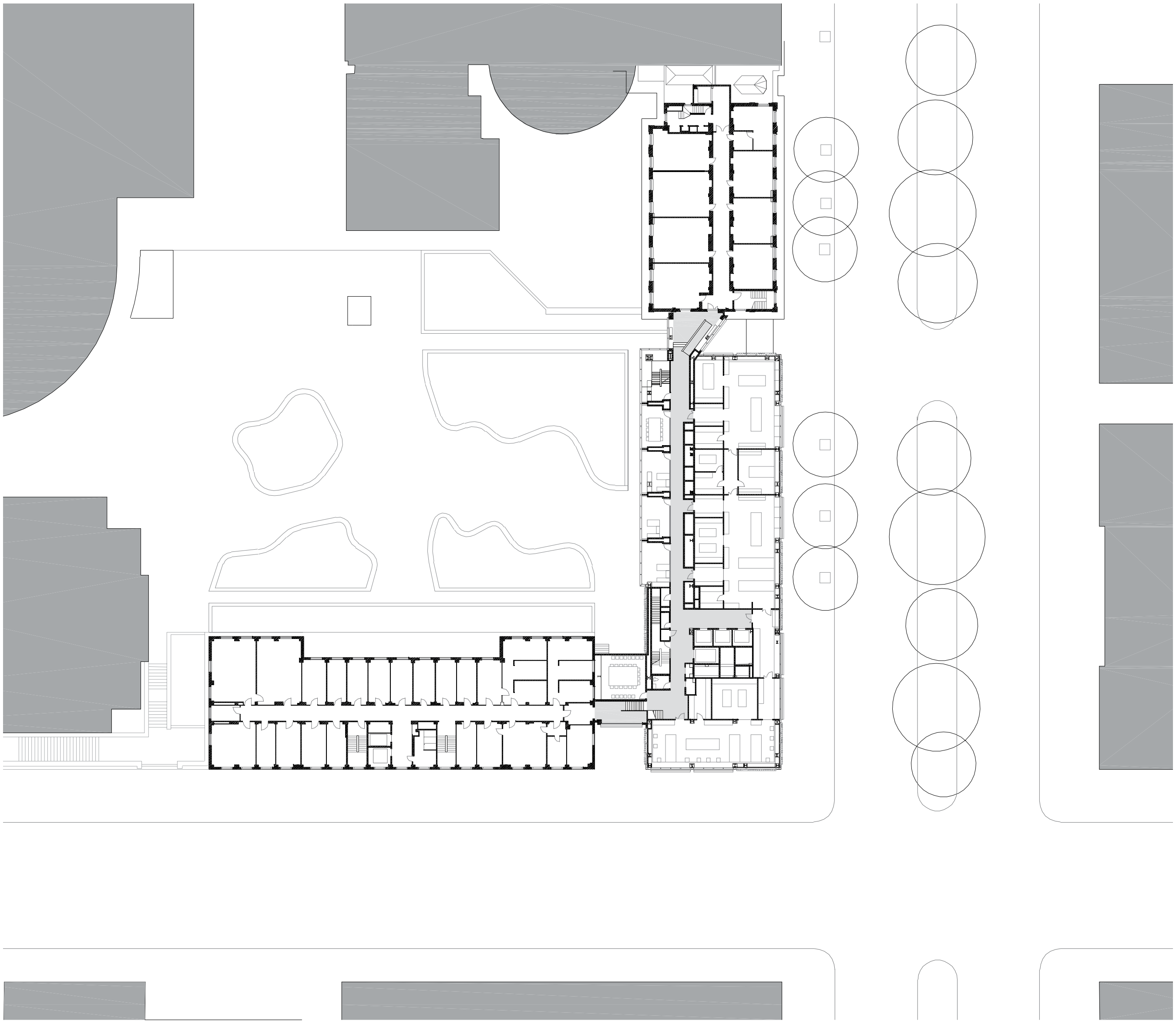
I like to think that we have achieved an integrated manner of relating all the means of architectural production, from the conception of the volume to its structural engineering to the detailing, as well as the issues of construction. I believe it is a kind of direction that starts from what I consider to be the most important and first condition for the building: the McKim, Mead & White campus. To see buildings not as isolated pieces able to absorb such abstraction but rather as capable of answering questions about the relationship between an institution and the city in which it is embedded, and, by an extension of this attitude, to offer an answer to the nuances and small details of construction: this is what I am indeed interested in.

For their help with this design and execution of the NWCB project, I would like to thank Belén Moneo and Jeffrey Brock of Moneo Brock Studio, our team at Davis Brody Bond Aedas, represented by William Paxson, David Haft, and Mayine Yu, and Daniel Brodkin from Arup.

1 | Of course, the question of scale is relative; the city around the campus has continued to grow, diminishing the towering aspect the campus may have had in its early days. At the same time, the formality of the campus architecture lends a different quality of scale; as a unified collection of buildings around large open pedestrian spaces, it enjoys the same kind of civic scale as, say, Rockefeller Center or Lincoln Center.

2 | See the James Stirling project for this same site of the mid 1980s.

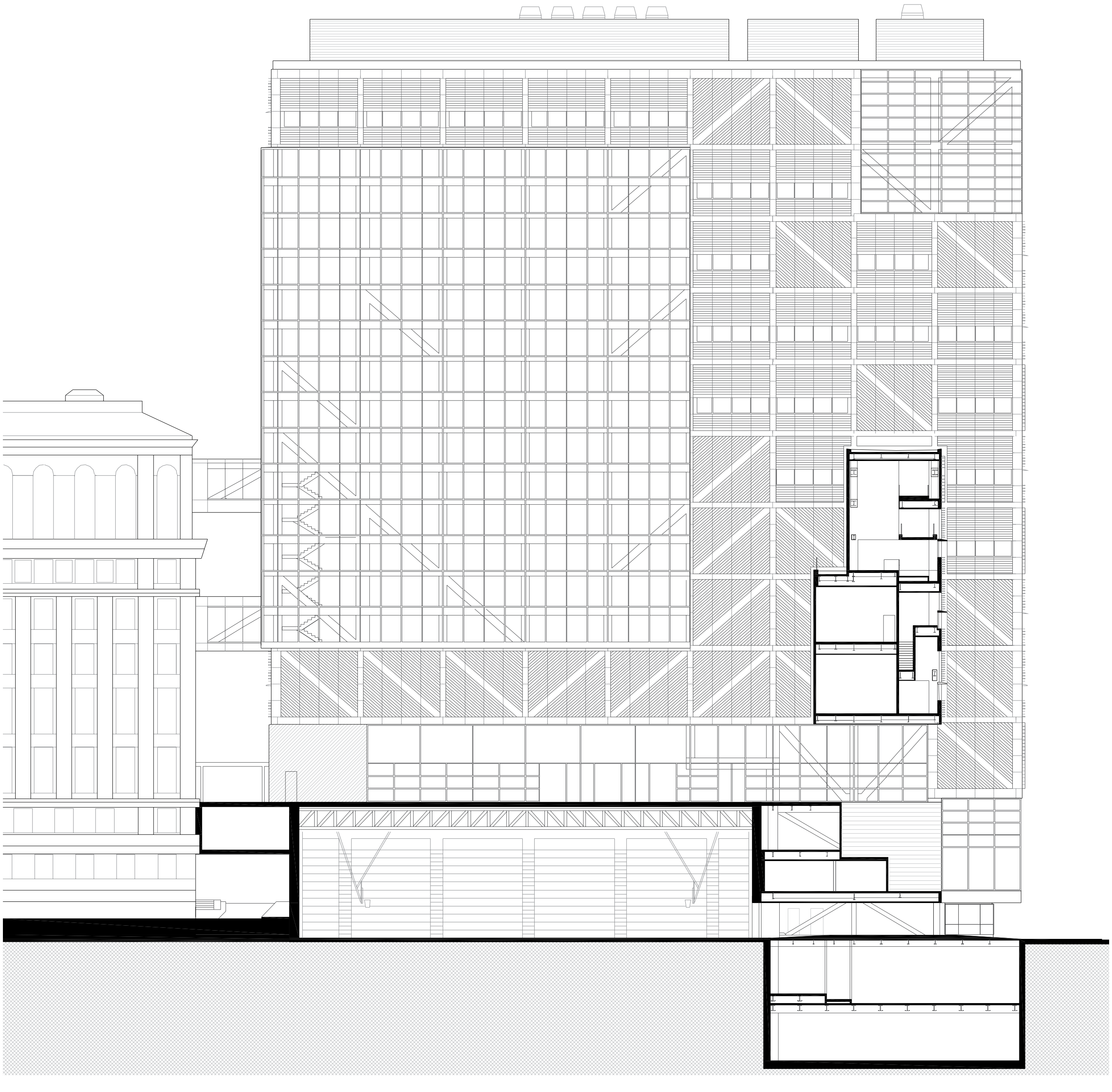
3 | Carl W. Condit, *The Chicago School of Architecture: A History of Commercial and Public Building in Chicago Area, 1875–1925* (Chicago: University of Chicago Press, 1964).



above: Lab level plan, showing connections to Pupin Physics Laboratory and Chandler Hall
opposite: View from the northwest

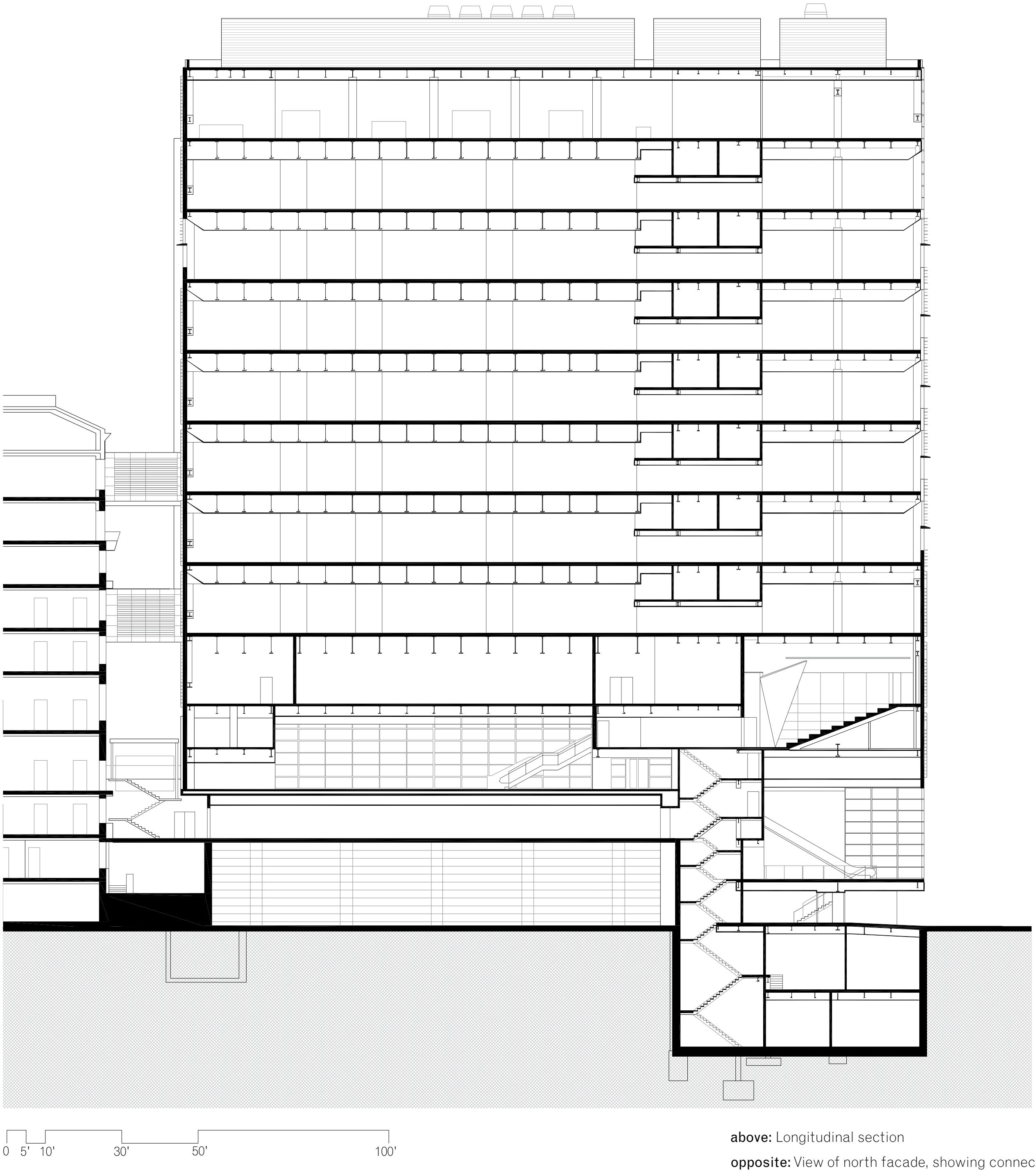
Northwest Corner Building, Columbia University, New York, New York

José Rafael Moneo



above: Section through gymnasium and connection to Pupin Physics Laboratory, revealing east elevation

opposite: West facade, showing café



above: Longitudinal section
opposite: View of north facade, showing connection to campus level


LEVIEN GYMNASIUM

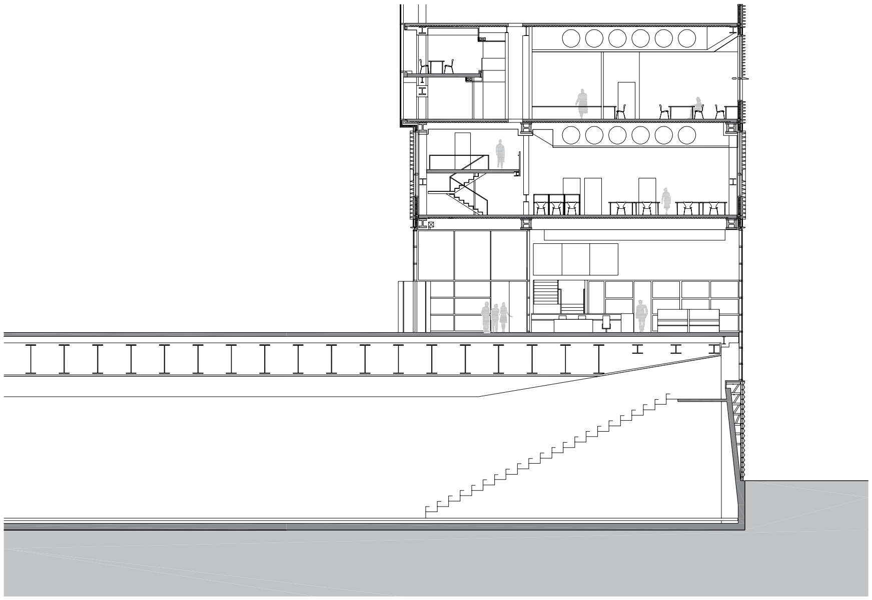
Northwest Corner Building, Columbia University, New York, New York

José Rafael Moneo

top: View through library

bottom: Cross section through gymnasium, library, and first lab level

opposite: Detail of aluminum infill panels



top: View of café and 120th Street entrance

bottom: Laboratory facilities

opposite: West elevation (partial)

overleaf: View south from elevated connection to Pupin Physics Laboratory

Yas Hotel

Lise Anne Couture

Yas Hotel, Abu Dhabi, United Arab Emirates
Asymptote Architecture

The Yas Hotel is an 85,000-square-meter (278,000-square-foot) structure made up of two twelve-story hotel towers linked together by a monocoque steel and glass bridge. A grid shell structure crosses above and over the Yas Marina Circuit F1 racetrack, making the Yas Hotel the first hotel to be built over an F1 race circuit. The hotel's exterior surface is designed as an environmentally responsive skin that by day reflects the sky and surroundings and by night is lit by a color-changing LED lighting system that incorporates video feeds transmitted over the entire surface of the building. F1 is the second most watched televised event globally, a fact that the client recognized as an opportunity to broadcast their image to the world. The hotel's direct proximity to the track became the site, or billboard, that the image was to be projected from. Because of the global television exposure, it is not just a hotel but also a kind of gateway. The cars literally go through it, but it is also a portal for many people to form ideas about the direction of and development in this part of the world.

The project had to be completed in less than two years, a constraint that helped determine a twofold strategy. The first was to build upon existing site work and certain procurements for steel and services, while the second was to develop another component that would in essence cloak the architecture. The use of steel for long spans was not necessarily about creating a volume or space but rather creating a surface that draped over two architectural volumes. We worked with the engineers Schlaich Bergermann and Partner to realize a grid shell structure, one that was neither a space frame nor geodesic. The grid shell is a two-dimensional surface in which all of the panels are potentially different, not unlike the skin of a snake or lizard. While it was important that the surface be successful from a distance, it also needed to succeed up close and from within. We wanted each cell to have a profile as it moved through space, allowing the two-dimensional surface to have thickness as well as a constantly changing perception due to the play of light and the varying conditions of reflectivity.

In developing the project, it was critical to be able to work parametrically so that we could move back and forth between what made sense structurally, economically, and in terms of material. We were interested in generating not only an overall geometry but also a pattern and texture. The use of parametric tools

Yas Hotel, Abu Dhabi, United Arab Emirates
Asymptote Architecture

essentially helped establish a balance between the standard and nonstandard. Initially, the structure had five thousand unique panels of glass. We reduced that number by setting a few rules that allowed for a tolerance between the size of the glass and the openings created by the steel. We determined that tolerance to be eight to twenty centimeters (3.1 to 7.9 inches) on either side, significantly limiting the quantity of panels that varied. The other technique that helped us rationalize the grid shell was to concentrate on corners and nodes. If all corners were standardized, on the glass panels and on the nodes on the structural panels, the remaining variable was the length of steel, both for the glass framing and the steel framing between nodes and corners.

Once design was finalized, almost the entire shell was fabricated off-site and arrived as a numbered kit of parts. The nodes were first assembled on the ground (the third dimension of the curvature was mimicked by holding up points in space with tripods using GPS). A similar exercise was employed for the glass panels. Assembly began with a limited range of corner shapes, followed by the steel strips. Since it is simpler to cut straight lengths any size, those lengths were varied, and subsequently were assembled to frame the glass planes. Finally, the anchors to the pieces of glass were adjusted, with six different angles possible within each diamond on the steel frame. The shell structure itself rests on supports connected to tension rods, which are then pulled in at key moments where they intersect with the floor slab, linking the overall load to that of the building. In its completed form, the pattern varies over the length of the structure. Manipulating surface in order to create texture, pattern, and movement can be seen as a further step in exploring this structural technology and the capabilities of long spans. This technique builds on earlier projects such as Gehry Partners' DZ Bank structure in Berlin and Foster + Partners's roof at the British Museum in London.

If this long-span structure creates a particular type of exterior surface, it also creates a particular type of interior experience. In this case, it forms an interstitial space between the building and the interior surface of the grid shell. On the environmental front, the fritted glass used in the shell acts as a solar shading device, which nonetheless appears transparent. Since the panels are not enclosed and are surrounded by gaps on all sides, they enable air to flow up the face of the building, creating a chimney effect that allows for both a draft and the escape of hot air.

The way the building would be experienced as the visitor moved through it was as important as the appearance of the structure on television. One of the interesting results of the interstitial space between the grid shell and the hotel structure was the disruption of the normal condition of balconied hotels, in which balconies are a projection of each individual space. Here, the continuous surface invites one to visually follow the line of the structure and to look over and observe a neighboring balcony (a neighboring hotel room)—pulling the gaze out and bringing it alongside and back in again.

The glass panels also contain five thousand points of light, allowing the entire long-span surface to become a light screen. Each node is programmable individually, both in terms of color intensity and animation path. We deliberately didn't want it to be a high-definition screen, since that would likely turn it into a billboard. Rather, the idea was that it would be controlled electronically in order to create a variety of constantly oscillating and changing atmospheres. The two-dimensional surface would thicken, acquiring a third, time-based dimension without ceasing to be a surface—creating a very slowly changing lightscape over the body of the hotel.

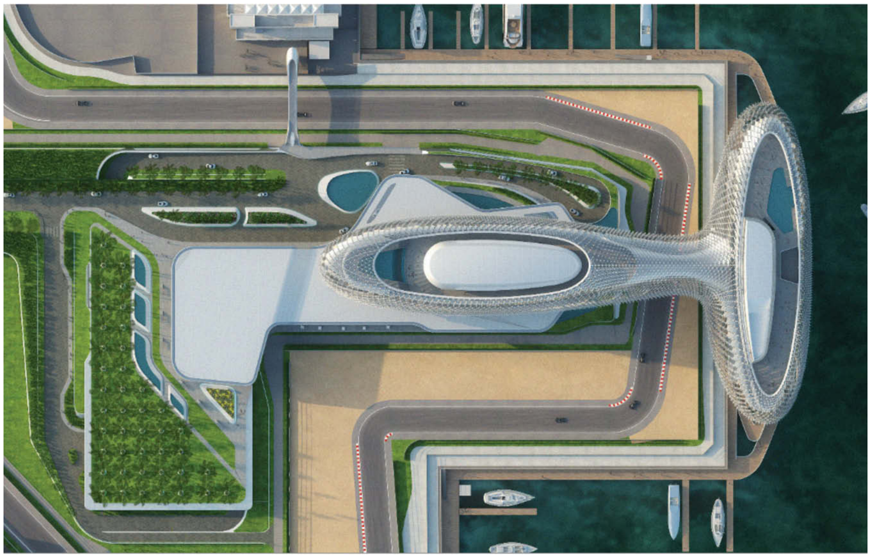
top: View of grid shell
bottom: View of grid shell at night with programmable LED lighting

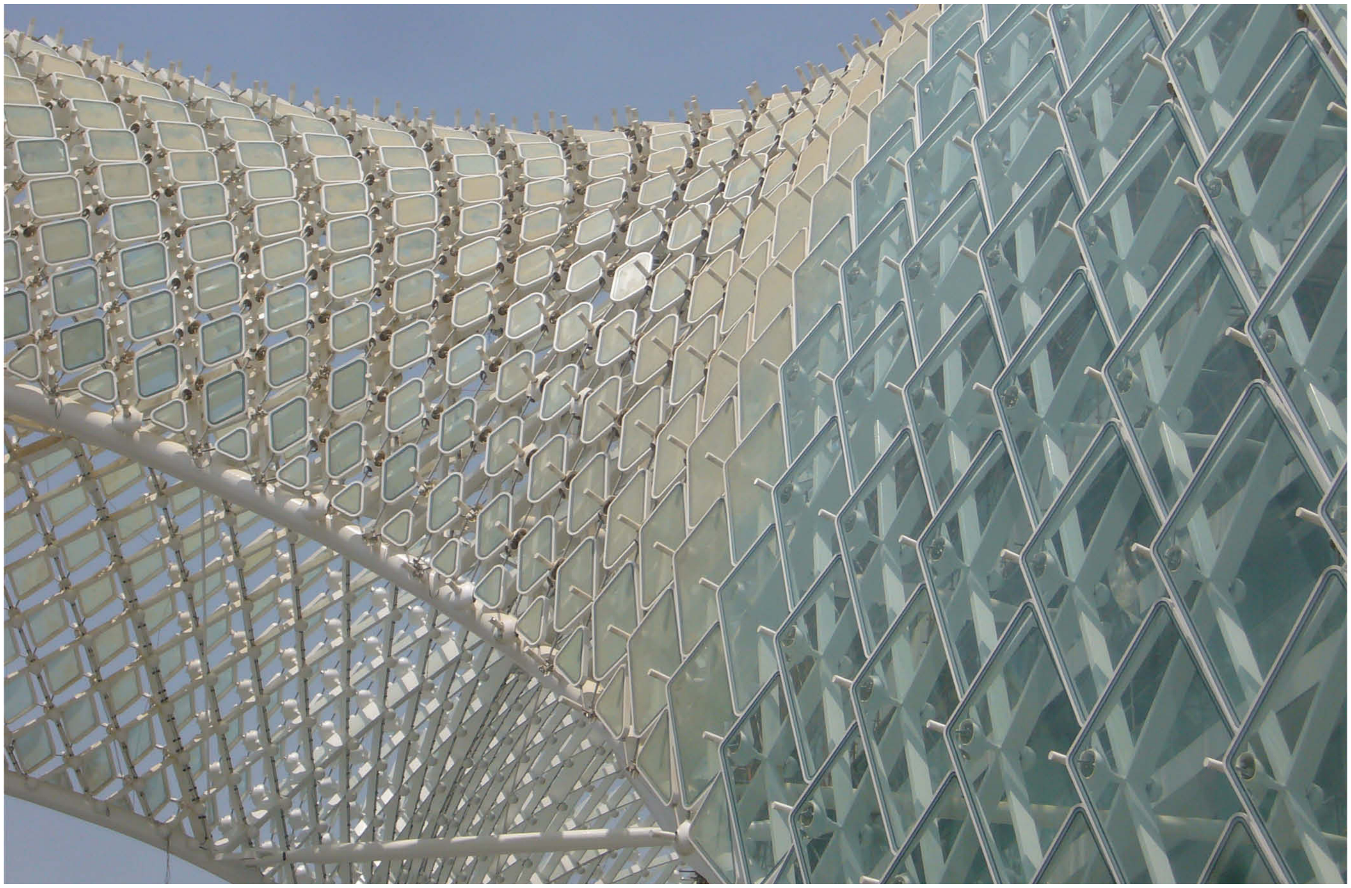
Yas Hotel, Abu Dhabi, United Arab Emirates

Asymptote Architecture

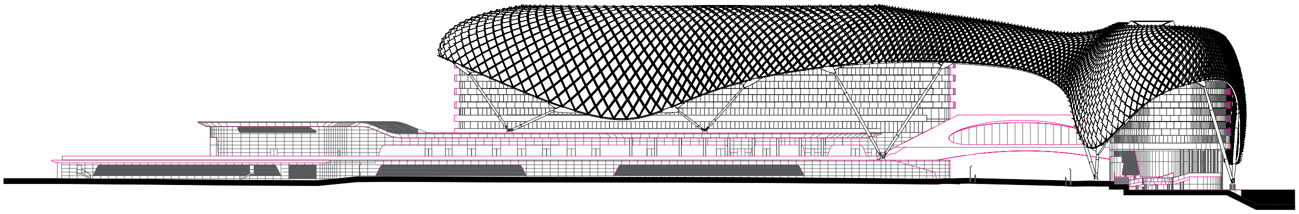
top: Site overview during construction

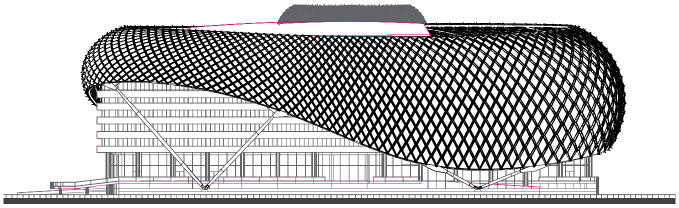
bottom: Rendering

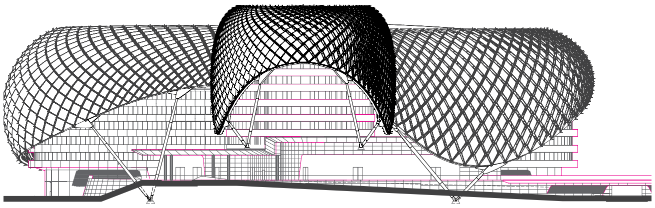




above: Detail of grid shell, spanning bridge
opposite: Construction view







top: South elevation

bottom left: East elevation

bottom right: West elevation

opposite: Installation views of individual panels

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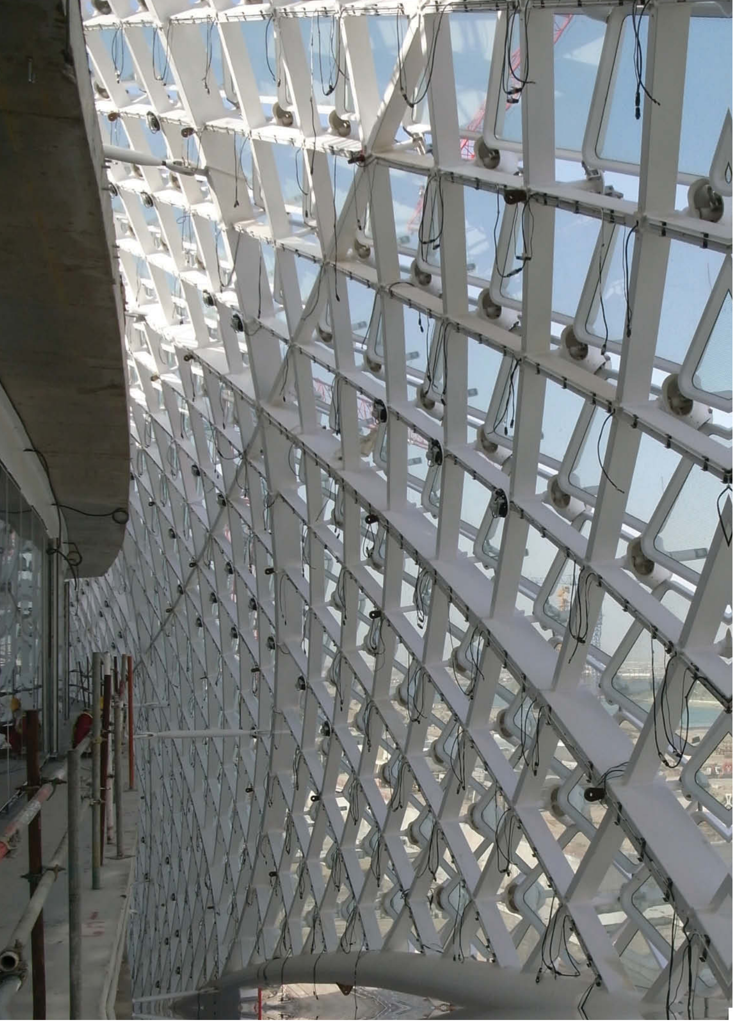

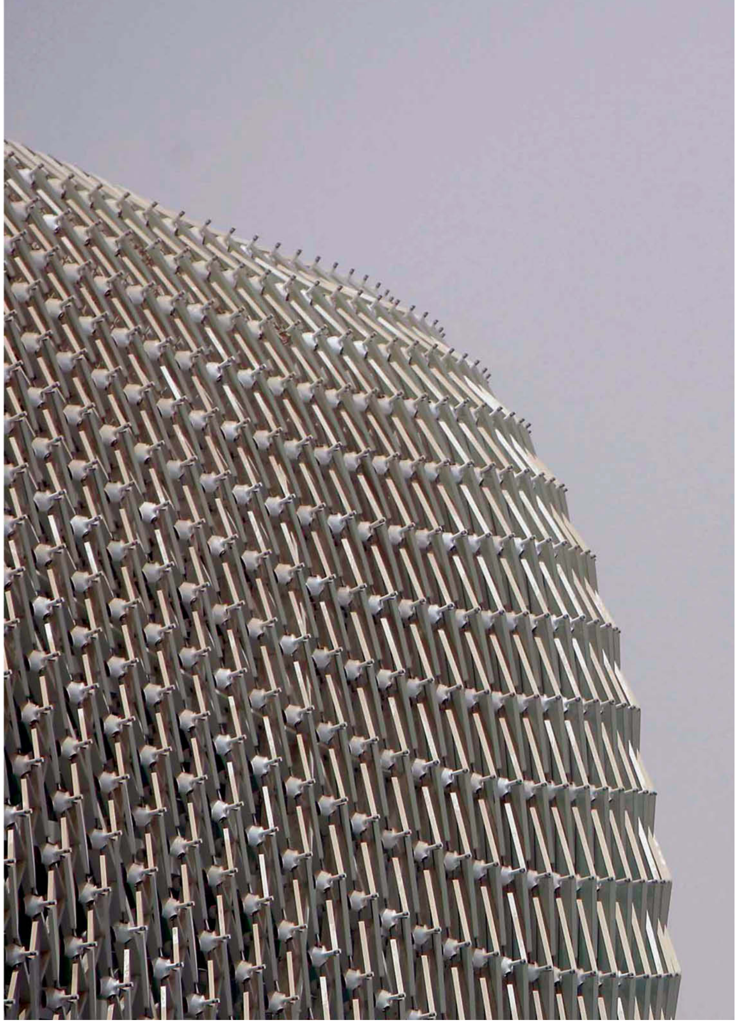

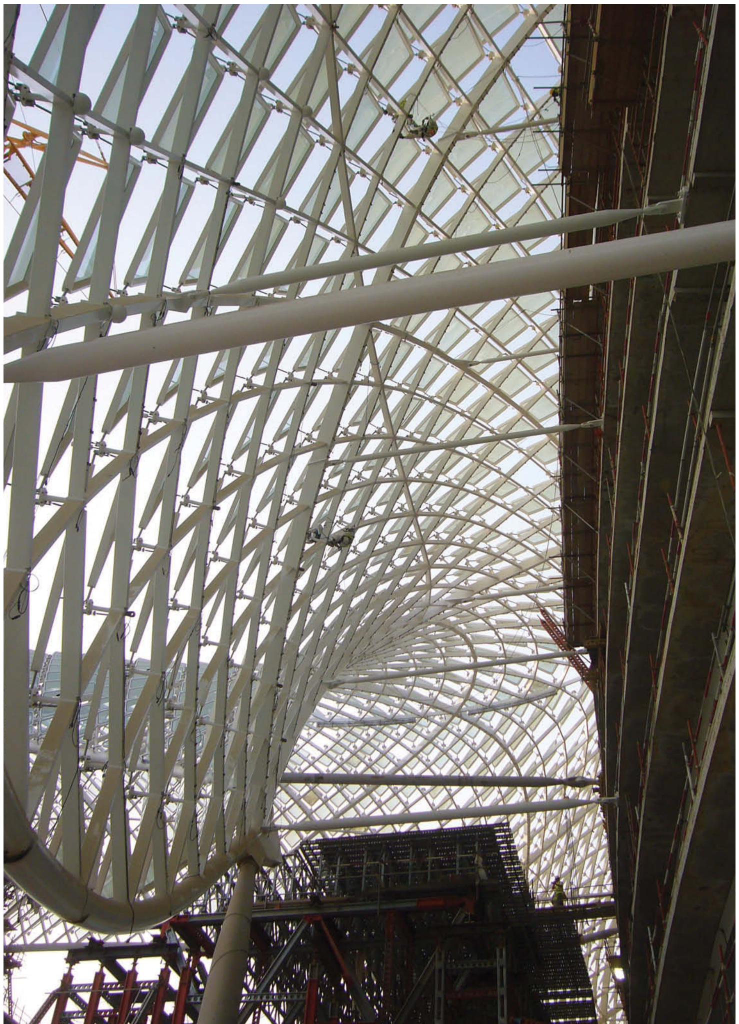

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Yas Hotel, Abu Dhabi, United Arab Emirates

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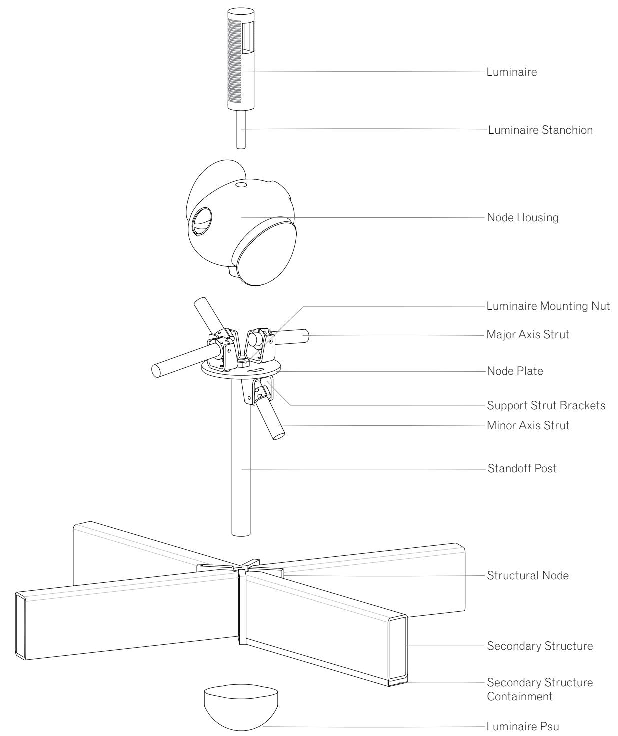
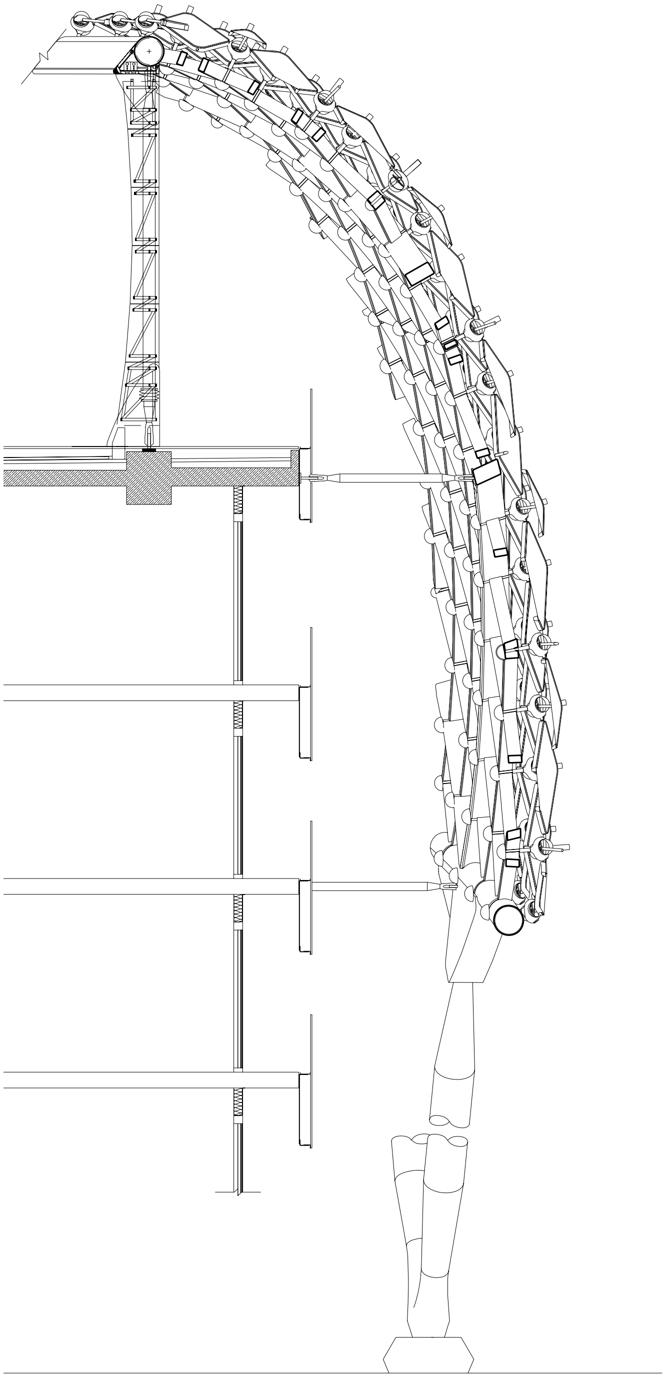




left: Detail of node

right: Section of grid shell

Invisible Steel Structure Structures Space

Juan Herreros

Bioclimatic Towers, Vitoria, Spain
Ábalos & Herreros

The Bioclimatic Towers, located in the Salburua Fens, Vitoria, Spain, is a complex of four fifteen-story towers including apartments and offices. The challenge was to incorporate these programs without a visible material change on the facade. To achieve this, a system was developed in which the apartments determined the habitable depth from the facade as well as the size and rhythm of the fenestration, and the offices established the clear height and open plan. Both programs are improved by their coexistence, while accepting some imposition. The initial consequence of this coexistence is the division of the program in the four 47-meter (154.2-foot) towers. The first seven floors are offices; the remaining floors are apartments. This shift occurs at the level where an occupant can see the promontory of the historic city of Vitoria and the surrounding wetlands. For the inhabitant, the view creates a sense of being in a central location while actually residing on the periphery.

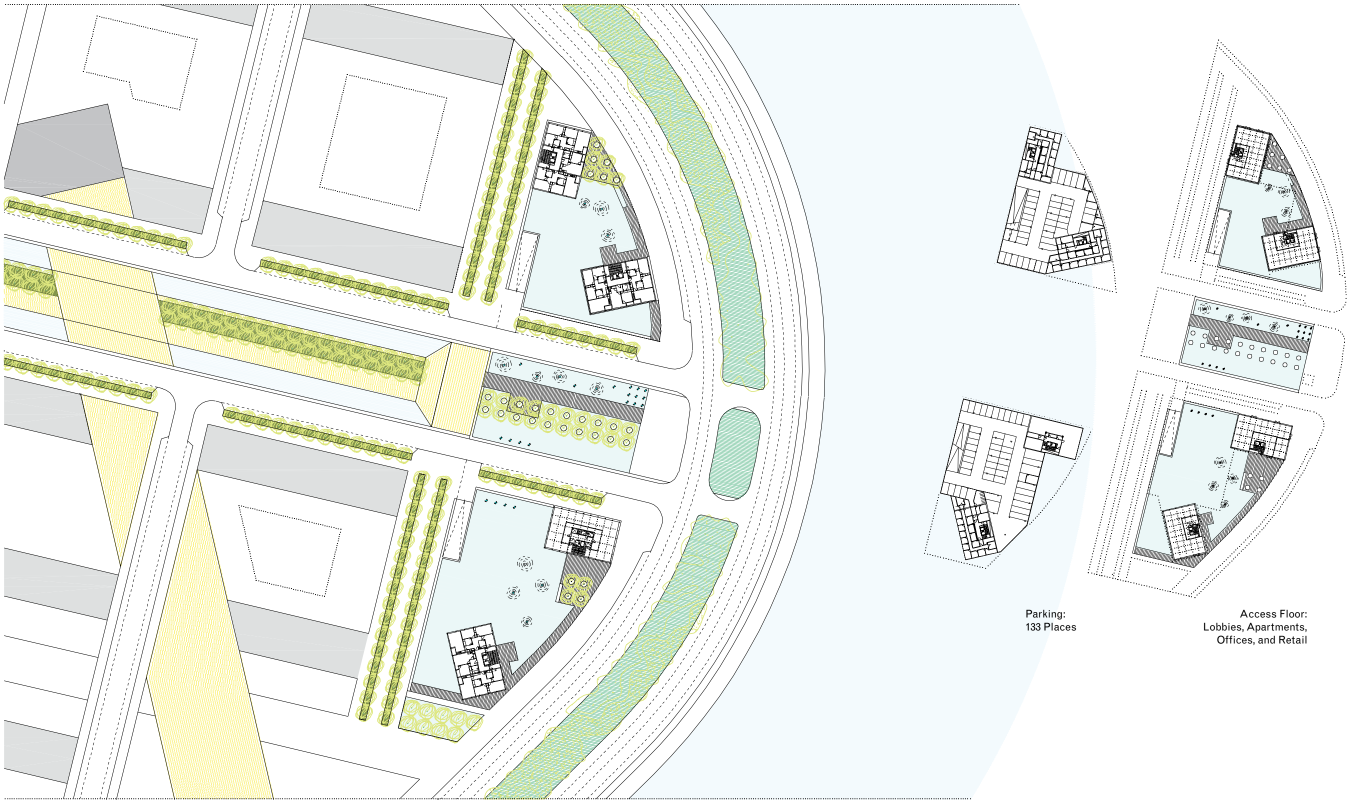
The project is defined as “bioclimatic,” a central concept from the beginning of the design process. In this case, the effort to reduce variables, such as sun exposure; ventilation; recovery, treatment, and reuse of water; and the pneumatic selective refuse collection system, goes further than strictly numerical efficiency and moves toward a conceptual and poetic simplicity, creating the true personality of the project. Following this principle, specific components of the structure are identified—slabs, facades, interior columns, half-walls—and resolved into a holistic architecture that intentionally mobilizes various types of energy. For example, the towers are positioned according to the movement of the sun in order to avoid obscuring one another, and each tower core is aligned with the least desirable portion of the facade—in this climate, the west or southwest facades are the most problematic orientations for sun exposure. The building form, the temperature differences between facades, the pools situated at the foot of the buildings, and the energy- and waste-management approaches are all parts of the same system: a structural typology, or a constructive discourse.

Due to the large number of technical requirements for each apartment, such as water, electricity, telecommunications, and sanitary equipment, the construction of the tower cores eschews a typical system of rigid concrete sheer walls. Instead, the cores are built of steel without the complicated stiffening systems, which were moved to the facade structure in the form of resistant belts composed

of commercial steel profiles and located in the half-wall below the sliding windows on each floor. Unlike the classic solution for office towers, in which a rigid core is surrounded by flexible walls, in the Bioclimatic Towers, the walls are rigid and the core is flexible, allowing little disruption to the openness of the space. By utilizing a poured-in-place concrete slab, the facades work as an exoskeleton stabilizing the building with the help of only two isolated interior shear columns.

These rigid facades, formed by large 120-centimeter-deep (47-inch-deep) beams with supports every 2.7 meters (8.9 feet), were divided into two-story-high sections that were prefabricated and moved to the building site to be placed in situ. The structures of the towers' short sides required only one facade module for every two floors, while the long sides required two. Once the facades had been erected, the continuous concrete slabs were poured while the six modules of the next two floors were installed. This procedure was repeated, alternating between towers, in a rhythm such that each week the two-story facade of a single tower was completed, which allowed four weeks for the pouring of two concrete slabs.

The systematization of the structure, which has just a single large repeated module, was extended to the whole construction process. This simple system has limited variables: the slabs and windows are uniform, a single material is used for the opaque parts of the facade, and the interior floors, ceilings, and cooling systems are all identical. It is only through this efficiency that the quality of social housing can be raised to a level comparable with that of the "domestic" office. In order to acquire a very desirable and competitive middle point between housing and office spaces, a readjustment of quality is made—the apartments are superior to social housing and the offices accept some imposition. The result is a mixed-use building that simultaneously reduces maintenance costs and intensifies the subjective experience of the building's use.

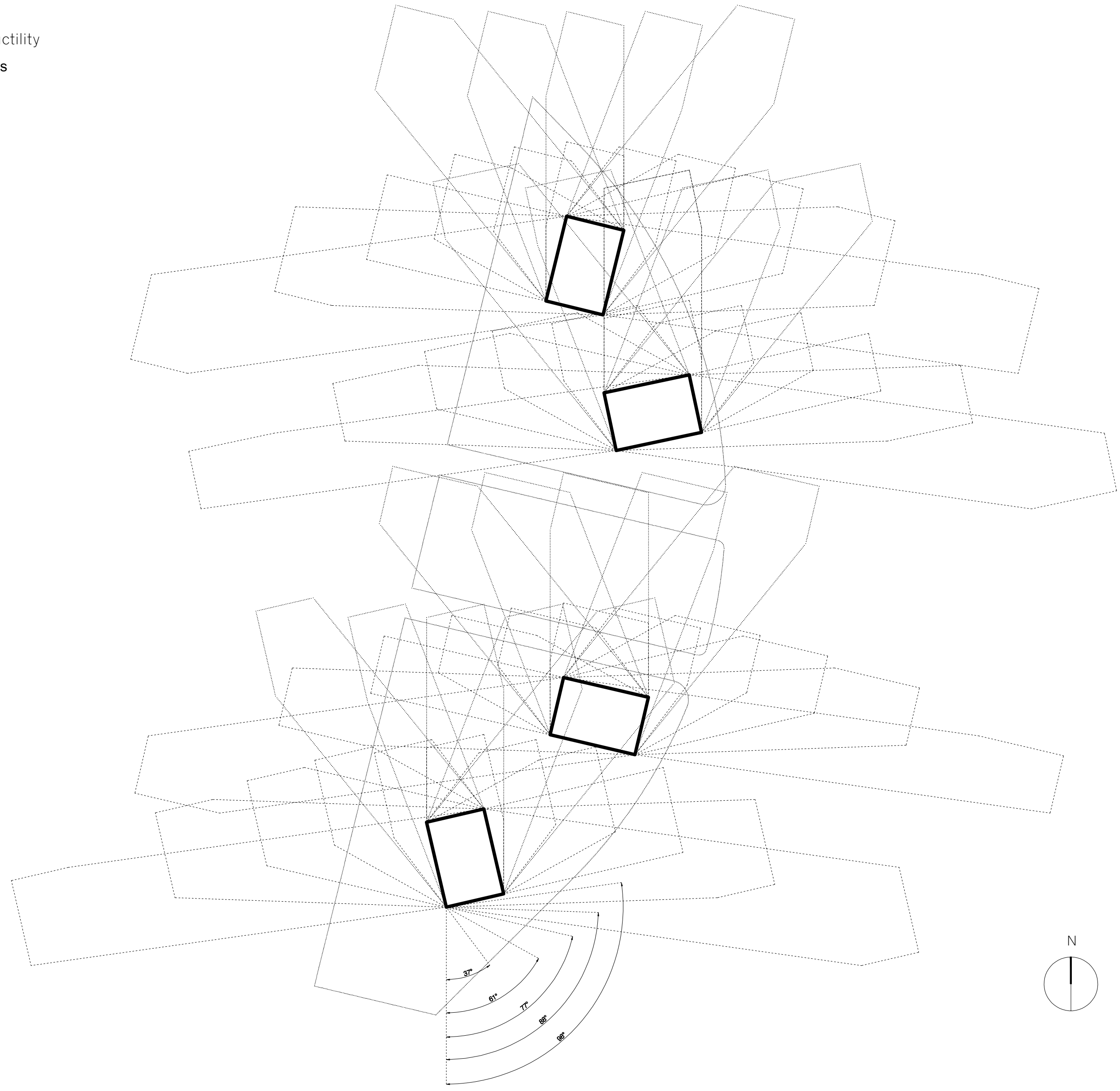


Site plan, with plan of subgrade parking and access floors

Bioclimatic Towers, Vitoria, Spain

Ábalos & Herreros

Floor plans for unprogrammed and residential uses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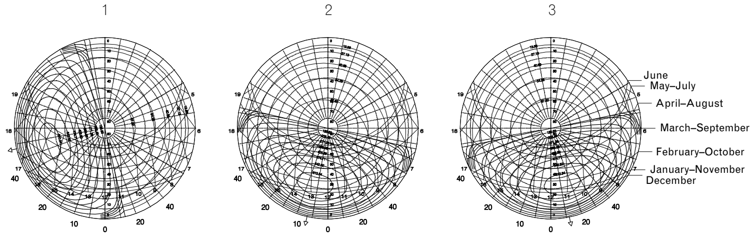
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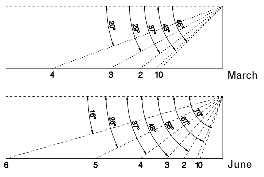
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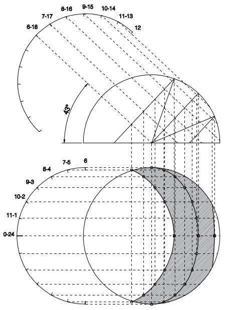
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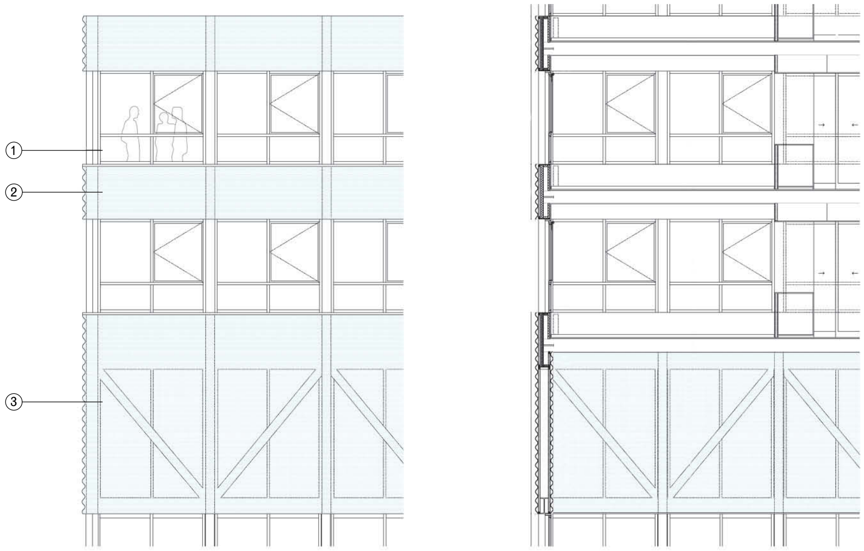
Bioclimatic Towers, Vitoria, Spain

Ábalos & Herreros

bottom: Facade detail. 1: transparent, glass; 2: opaque, foamboard and polycarbonate; 3: translucent polycarbonate and polycarbonate

opposite: Projection of shadows cast by towers and areas of solar energy harvesting



Nanjing Museum of Art & Architecture

Steven Holl

Nanjing Museum of Art & Architecture, Nanjing, China
Steven Holl Architects

Perspective is the fundamental historic difference between Western and Chinese painting. After the thirteenth century, Western painting developed vanishing points in fixed perspective. Chinese painters, although aware of perspective, rejected the single-vanishing point method, instead producing landscapes with "parallel perspectives" in which the viewer travels within the painting.

The Nanjing Museum of Art & Architecture is an exploration in parallel perspective. The new museum is sited at the gateway to the Contemporary International Practical Exhibition of Architecture in the lush green landscape of the Pearl Spring near Nanjing, China. The building explores the shifting viewpoints, layers of space, and expanses of mist and water that characterize the deep alternating spatial mysteries of early Chinese painting. The museum is formed by a field of parallel-perspective spaces and garden walls in black bamboo-formed concrete over which a light "figure" hovers. The straight passages on the ground level gradually turn into the winding passage of the figure above. The upper gallery, suspended high in the air, unwraps in a clockwise-turning sequence and culminates at "in-position" viewing of the city in the distance. The meaning of this rural site becomes urban through this visual axis to the great Ming Dynasty capital city, Nanjing.

Just as the spatial field moves from parallel perspective on grade to the distant perspective above, the construction moves from concrete to steel. Steel construction was crucial to the floating gallery. The engineering of the suspension trusses by Guy Nordenson was accomplished with a cost of approximately 10 percent of the construction of similar trusses elsewhere due to Chinese conditions.

In 1368 in Nanjing, the Ming Dynasty emperor Zhu Yuanzhang constructed the longest city wall in the world at the time. The work of two hundred thousand laborers took twenty-one years. The experience of a spatial urban frame can be felt in many existing sections of this wall.

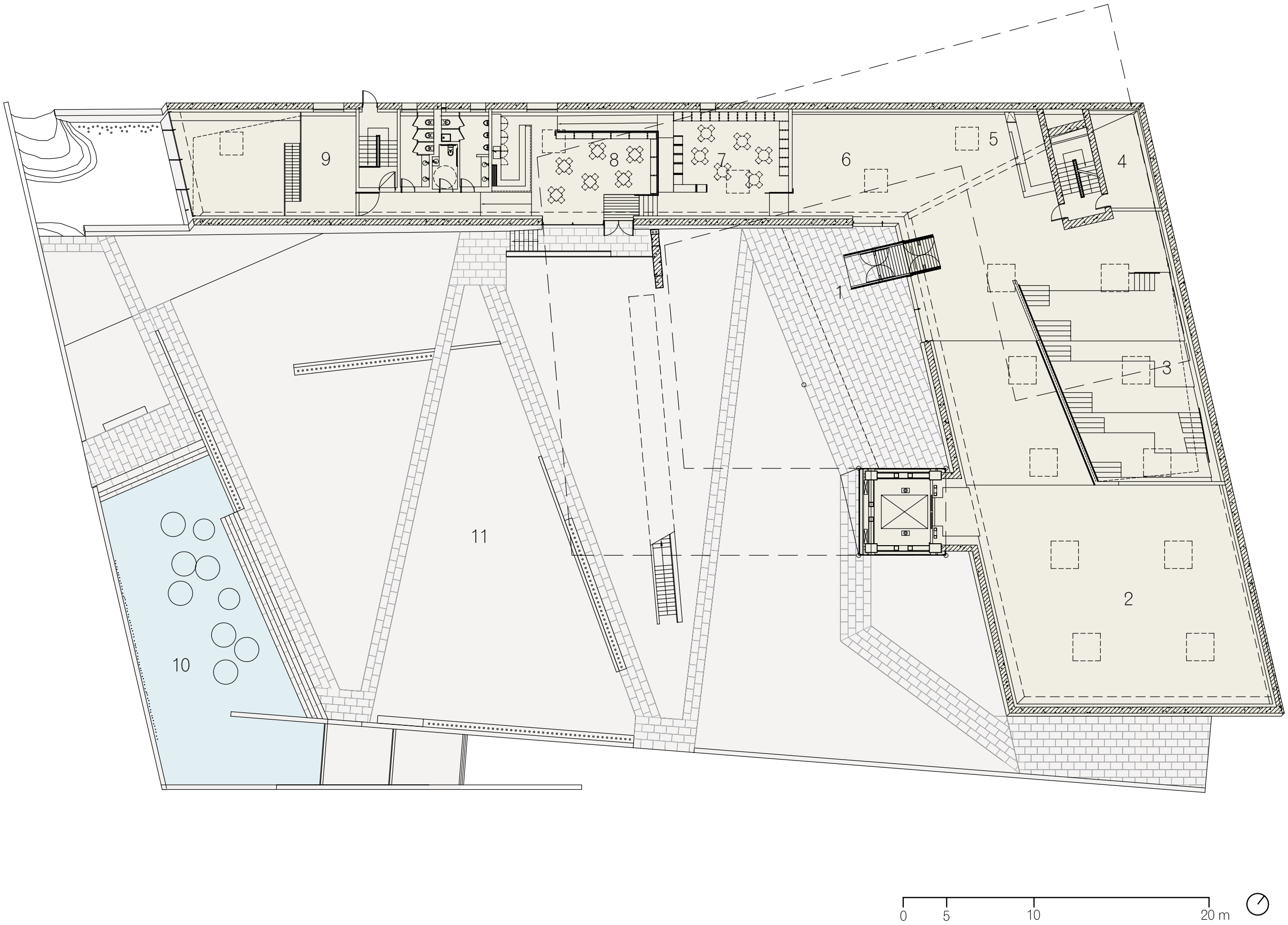
A material connection to Nanjing is made in the new museum's courtyard, which is paved in recycled gray bricks from the ongoing destruction of old *hutongs*. Large diameter bamboo, which previously grew on the site, was split to line the molds for the bamboo-formed concrete walls and covered with a penetrating black stain. This was the first use of this technique in China when construction

Watercolor sketch of Nanjing Museum

began in 2005. The museum is heated and cooled by twenty geothermal wells and has fully recycled water in the pools of the parallel-perspective courtyard.

As this is a museum that explores space in different ways, we limited the use of color to shades of black and white, in the spirit of ancient Chinese paintings. This monochromatic frame gives a neutral background to feature the colors and textures of the artwork to be exhibited in the future. However, as a study of space, foreground, middle ground, and distant views are more starkly present in the completed yet empty structure.

This project was our first in China, with the concept sketches made on-site in August 2003. An anomaly due to the client's trickling funding, it has been under construction for five years. At 98 percent complete, the space is fully present.



1 Entrance
2 Upper Gallery
3 Multipurpose Space
4 Coat Room/Storage
5 Reception
6 Informal Gallery
7 Shop
8 Café
9 Upper Office
10 Recycled Water Pond
11 Plaza

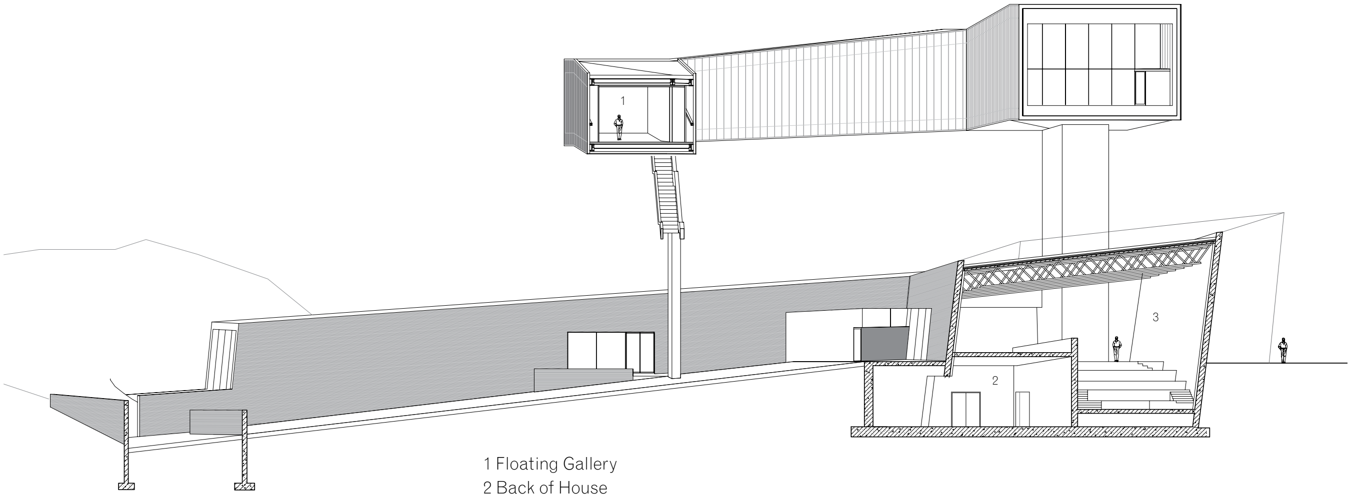
Ground level plan

Nanjing Museum of Art & Architecture, Nanjing, China
Steven Holl Architects

top: View of "floating gallery" in landscape
bottom: View of courtyard with "floating gallery" above

Nanjing Museum of Art & Architecture, Nanjing, China

Steven Holl Architects

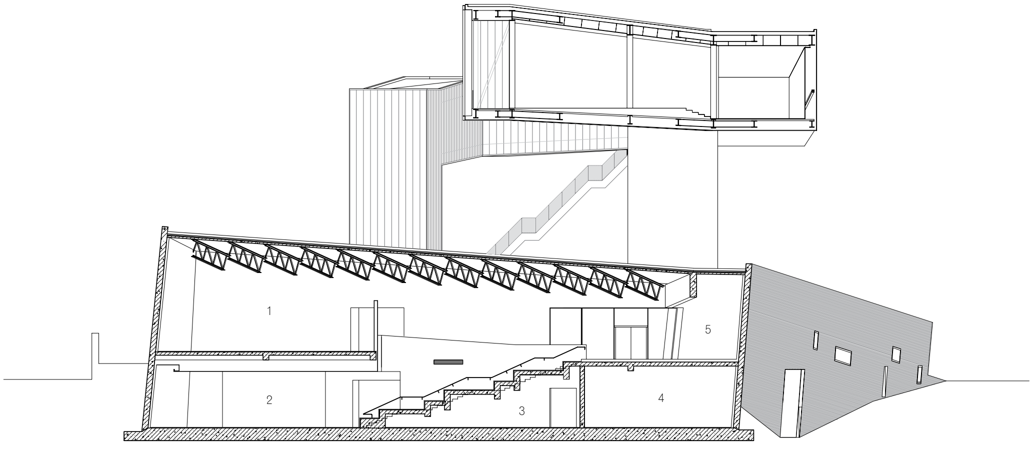


1 Floating Gallery
2 Back of House
3 Multipurpose Space

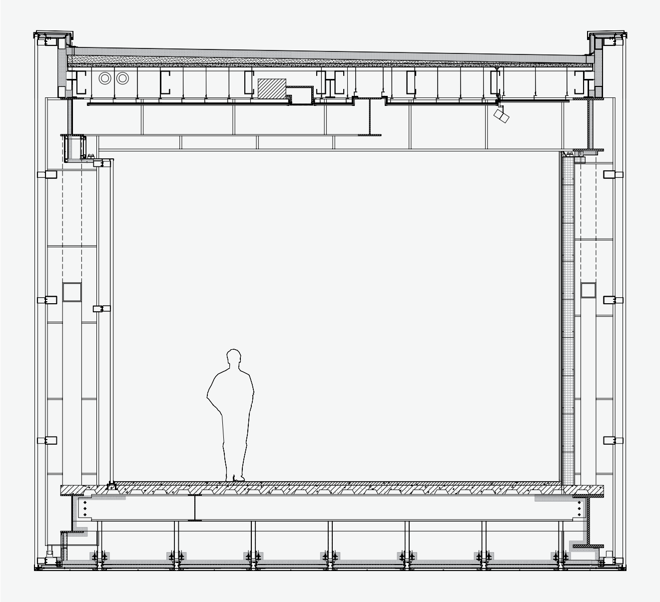
top: East-west section

bottom: North-south section

opposite: View of "floating gallery" from plaza

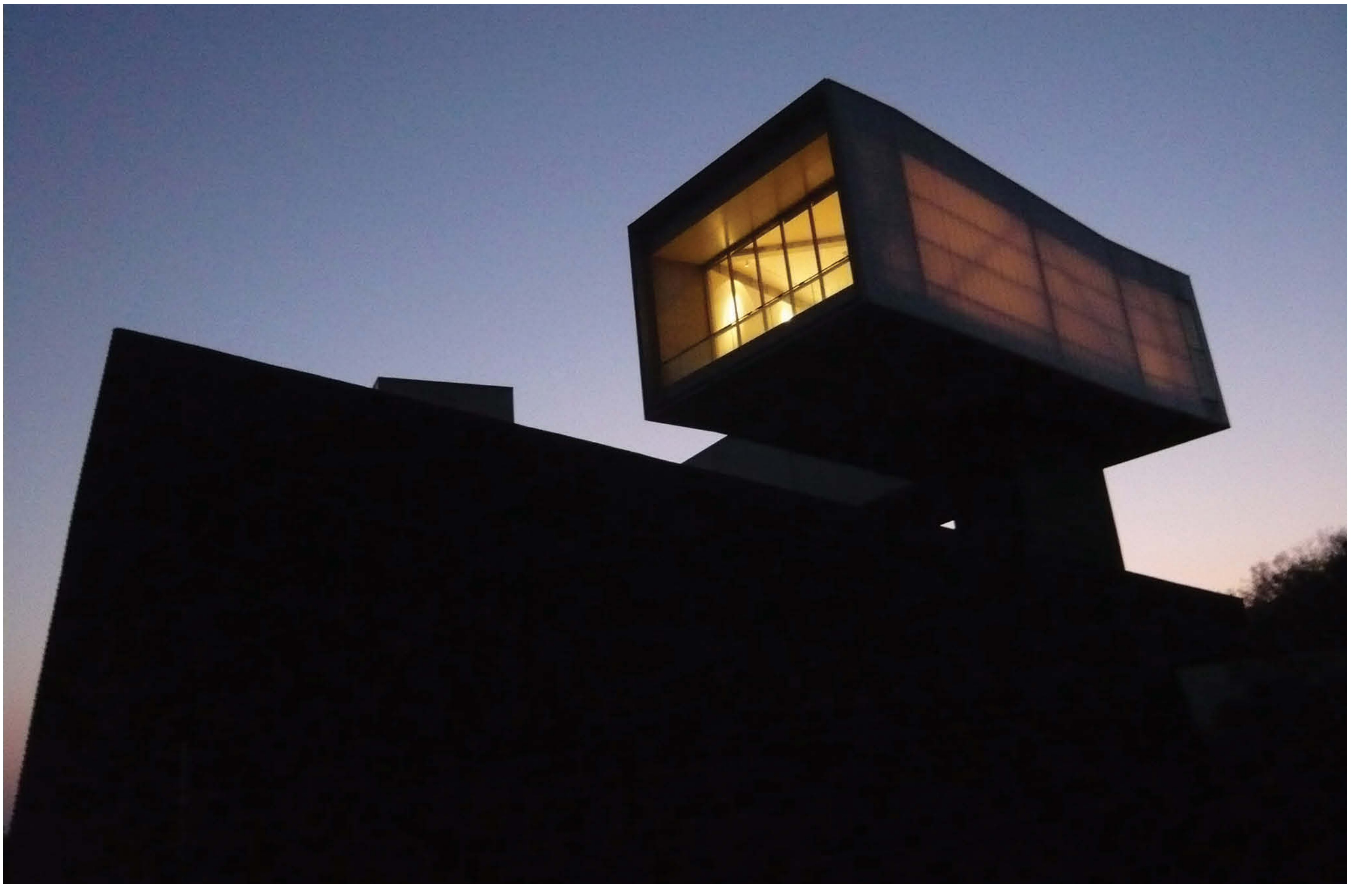


1 Upper Gallery
2 Lower Gallery
3 Storage
4 Mechanical Room
5 Reception



top left: Section through “floating gallery”
top right: Construction view
bottom: Steelwork detail

Nanjing Museum of Art & Architecture, Nanjing, China
Steven Holl Architects



top and bottom: Views of the “floating gallery”
overleaf: Southeast-facing view of museum, featuring winding upper gallery space

Architectural Detail and Motion

Michael Bell

Champlain Port of Entry, Champlain, New York
Smith-Miller + Hawkinson Architects

In the earliest stages of their work, Smith-Miller + Hawkinson Architects (SMH) offered a kind of mixed message. They seemed to fit well into a model of tectonic expression, aligned with contemporaries such as Thom Mayne and Michael Rotondi on the West Coast, but equally as well with Kenneth Frampton and the lineage of work he explicated, from Pierre Chareau and Bernard Bijvoet's Maison de Verre (1932) to the wider project of mechanical and material assemblage found in the architecture of Ludwig Mies van der Rohe, Walter Gropius, and other first generation modernists.

But SMH was never easy to see as overtly concerned with tectonics, in part because their spatial compositions (inclined planes, rotations, and oblique relations between surfaces) and material choices were not always anticipated or obvious. Materially, for instance, the firm has used aluminum for light structure where one might expect steel (in early loft projects and in House for a Film Producer). They also often employed multiple materials and profiles where one would have sufficed—resulting in work that was layered and sometimes doubled in its means. The relation to Mayne and Rotondi can be seen in the way they layered and doubled tectonic attributes, such as in the canopy structural elements at the Champlain border station. The relation is closer to Frampton, however, in the way material facts were driven by essential needs and tied to a wider set of architectural goals, such as circulation and movement; the layers are not a prime focus apart from what they abet. In early projects by Mayne and Rotondi (for example, the Kate Mantilini restaurant or the Cedars-Sinai Comprehensive Cancer Center), the tectonics were as ambitious in scope, but often seemingly more self-referential and less functional in their goals.

The work of SMH can be seen as suspended, while its reduced nomenclature is instrumental and precise spatial results are elastic and more active. This may have origins in the open lofts they designed at the outset of their career—a drive to make privacy but keep spatial continuity—but it is also relatable to a movement in the mid-1980s that included Morphosis, Frank Gehry, Frank Israel, and others, in which tectonics seemed as provisional as they were definite. For SMH, the enunciation of a detail or a mechanical connection was deeply linked to the West Coast ethos—a quasi-ethical drive to distribute material as structure, as surface, as budget and financial instrument—but, also like the work in the West,

Champlain Port of Entry, Champlain, New York
Smith-Miller + Hawkinson Architects

Precise yet expanded boundaries are revealed in layering, doubling of tectonic elements, and exacting placement of connections.

it embraced the commodity nature of common building supplies (aluminum windows, plywood, 2 x 4 studs and metal studs, and premanufactured surfaces from wood to polymers). The finitude and precision in the detailing of even everyday items was nonetheless undone in the spatial flows that were made possible by the mechanics—by the suspended joints. The real experience was human movement, evident in the ferry station for New York City and the Champlain border station but also in the early lofts and houses. SMH seemed then and now to be more spare than the West Coast architects in how they connect detail to movement and detail to space, but the issues are present in the wider generation and they represent a shift that spans the distance from Frampton's modern tectonics (and his desire to find value in the link between material, space, and labor) to a contemporary crisis of off-the-shelf components, the ubiquitous nature of often degraded construction commodities that are the material basis of most American building.

SMH frequently made a point of presenting the programmatic explorations in their work, as well as showing the diagrams of circulation and social connections. On the one hand, this made their architecture more overtly cultural than those of others who borrowed formalist means and mechanical tectonics from historical precedents. But this inclusion of program also incited a dynamism and movement linking their work critically to issues of perception and socially to a generation that includes Bernard Tschumi and Rem Koolhaas, for whom program was also a central driver of design—the motion of the subject was as important as the still volumetric work. A closer look at SMH's projects reveals that this dynamic aspect has perhaps always been what made them unique in relation to their peers—that is, the track of work that leads from loft renovations to two national border stations has been as consistent in its erasing of easy closure as it has been persistent in the push to material specificity. But the materials are themselves often suspended or made to carry several meanings and potentials: concrete in the Champlain border station is both radiation barrier and thermal mass; metals are surface, column, and beam, and are almost always multiple in type; curtain wall structure mimes or begins to fuse with building structure. In the end, the ductility of the materials becomes palpable in the differences exhibited, but also, in some sense, the materials are freed from reduced purpose—they have specific demands.

The extended passage of the border crossing is central to this assembly and array of parts and materials. SMH controls every relationship at Champlain: the slowing car as it approaches the station; the broadening asphalt skirt and its semiotics of stripes and signs; and the lengthening of distance and widening of visual breadth. All of this culminates in a thin and instant threshold. The metal details at the canopy are as explicit as the painted stripes and guide post—the entire environment is an expanded border that highlights and prolongs the experience of crossing as much as it states it with precision and detail. That this is all achieved with material detail and a keen sense of movement and a driver's/passenger's attention is remarkable.

A compression of sign, structure, and thermal envelope operates at the scale of the building and the quarter-mile-wide border zone.

The work is not ideologically driven in this regard; what might seem like structure becomes in the surreal sense "strange"—more present as it loses some of its functional alibi. The role of movement arises again as it is the experiencing subject that is revived at each step—reborn—as they find footing, touch a handrail, look through or around a surface, and discover the quality of a forward movement with its corollary reversal. In a recent interview, Richard Serra described his childhood curiosity about how a walk on the beach in one direction felt so different than the walk back. His tilted arc sculptures were affected by this memory, and the materiality and balance in that work was ultimately required to produce the experience.[1] In other words, the material and technical choice was about a subject's dynamic movement in time. In this sense, SMH's work is similar. The uses of metals, glass, concrete, or polymers all ultimately align them with many whose focus is not only on a new tectonic character but also on the eventual experience of space—as lived, as in time—casting the materials into a spatial ensemble with the occupants. It is as if the body is the counteragent force that keeps the entire structure up; the occupants are among the building components as much as within its architecture. The work has been a key moment in seeing a material sensibility for our time.

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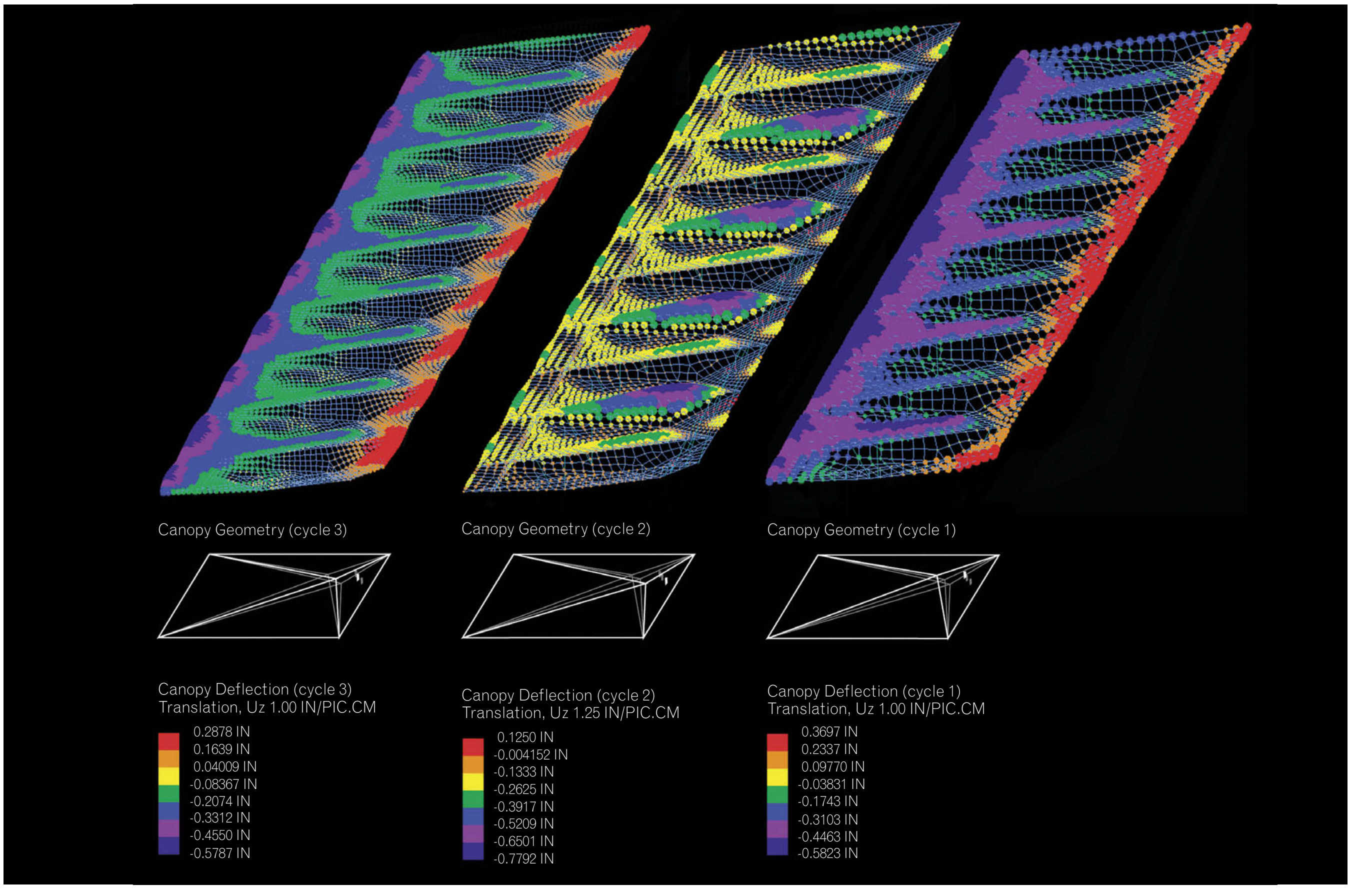
[1] Richard Serra, interview by Charlie Rose, *Charlie Rose Brain Series Episode Twelve: Creative Brain*, PBS, October 28, 2010.

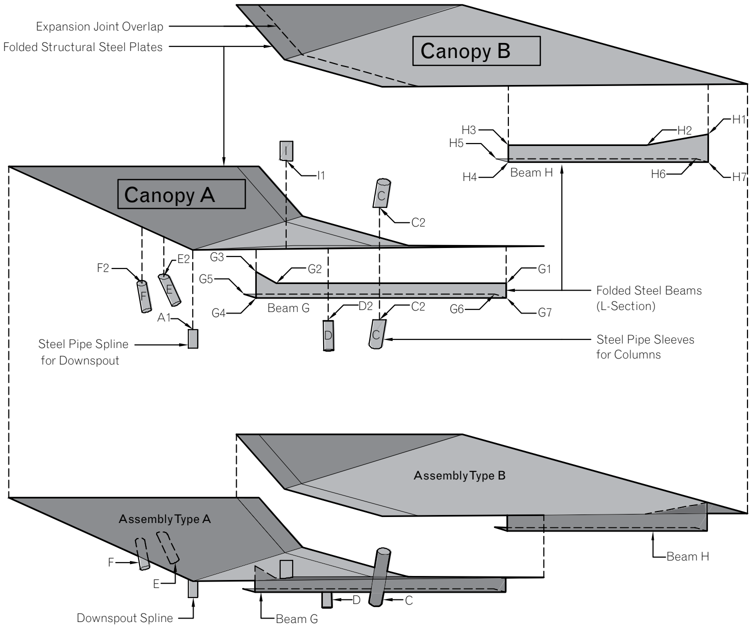
Champlain Port of Entry, Champlain, New York

Smith-Miller + Hawkinson Architects



top: Finite element analysis of street canopy

bottom: Axonometric key for canopy workpoints




UNITED STATES OF AMERICA
CLEARAN
16'-0" (5.0M) HIGH
CLEARAN
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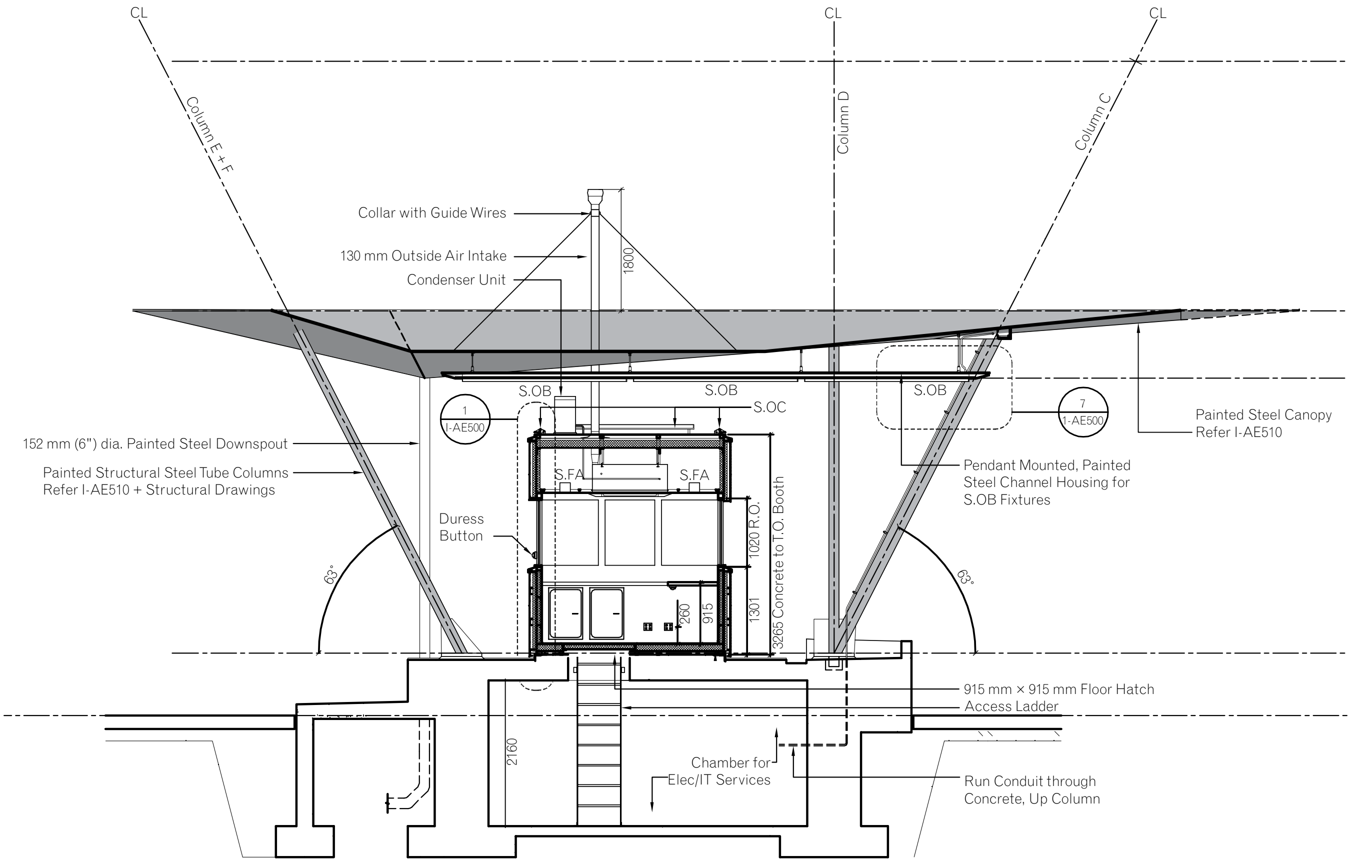
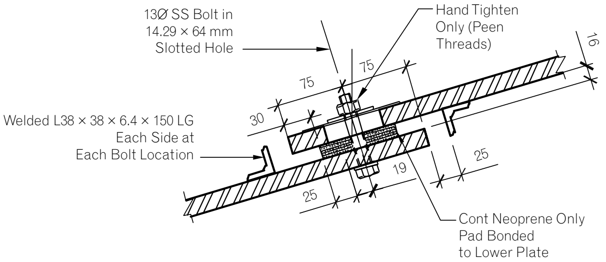
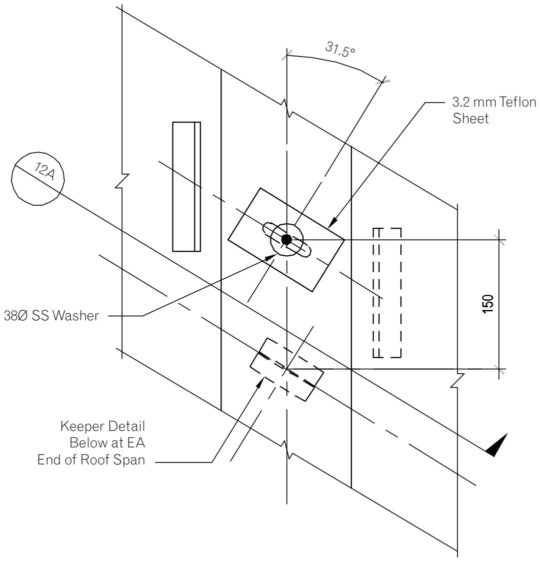






top: Inspection booth sections. The expansion joints occur where Canopy A and Canopy B overlap.
bottom left: Expansion joint section detail
bottom right: Expansion joint plan detail
opposite: Canopy as finite assembly and extension of border traffic flow. Paving and graphic codes direct traffic flow, tectonic assembly provides spanning capacity.

Champlain Port of Entry, Champlain, New York
Smith-Miller + Hawkinson Architects

top: View looking north, passenger inspection plaza
bottom: Export control
opposite: Folded steel canopy at passenger inspection


11
87 SOUTH
AZMAT
SPECTION

Structural Engineering

Adaptive Systems: New Materials and New Structures

Werner Sobek

How can new materials and structures change our ideas about the limitations and opportunities available when building? It is not enough to substitute existing building materials with different ones, or to fit together established structural elements to form new variations. In order to develop an architecture suited for the twenty-first century, the changes will need to be more far-reaching.

We build millions of houses every year. Why can't just a few of these be taken a step further? Instead, it seems that architects and engineers are barely moving forward with their designs—they are becoming lost in formalism, turning to decorative aspects without facing the integral problem of how to build attractive houses that also address sociocultural and geographical relationships. We should strive to build houses that do not consume energy or generate any emissions and that are also fully recyclable. We need houses that live up to the aspirations of cradle-to-cradle design: not downcycling, but recycling, according to the motto, "My house will be a Porsche next time 'round" or "I was once a tin can." | fig. 1 These environmental concerns should be given the same importance as questions of structural stability or facade technologies. I believe even more strongly that by addressing such issues we can break new ground in the field of architectural design. Unfortunately, we have made little progress in these areas. This is where we should learn from other industries whose practices are further advanced than ours—for example, the extremely high degree of recyclability achieved by the German automotive industry.

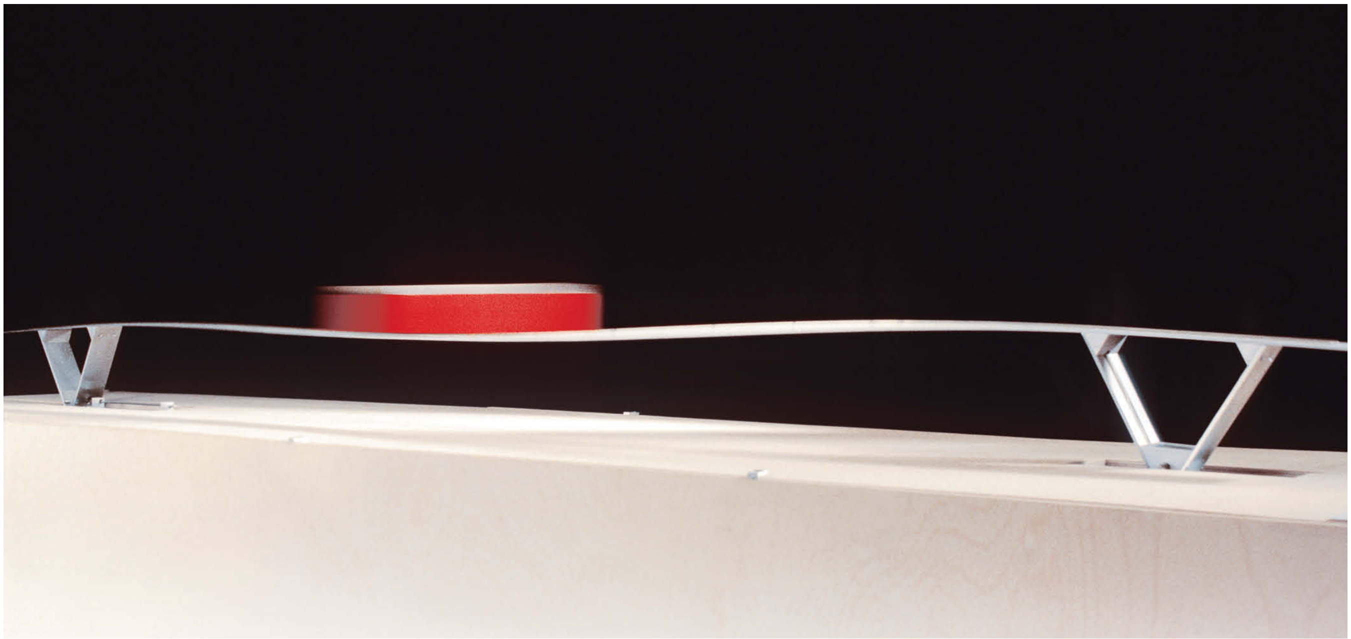
Innovative structures are the objective. However, when discussing new structures, one must ask, "What is considered new"? It is not enough to take known basic elements and put them together in a new configuration. Rather, we must learn to put the old ways of thinking and designing behind us and begin to consider ideas commensurate with recent technical advances. The understanding by structural engineers of the design and planning of load-bearing structures has never been based on the categorizations that are typically listed in textbooks (e.g., Chapter 1: The Strut, Chapter 2: The Beam, Chapter 3: The Plate, Chapter 4: The Truss, Chapter 5: Special Structures). This approach to design only combines basic elements of fixed geometric forms, and has nothing to do with the more complicated development of stress fields or force systems. Structural design should focus more on creating buildings that are three-dimensional, perfectly designed systems of stresses and forces. Of course, the knowledge required to understand, manipulate, and design in this way is rarely, if at all, taught in engineering.

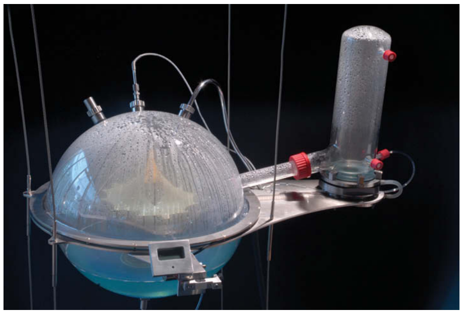
fig. 1 | R128 House, by Werner Sobek, Stuttgart, Germany, 2006. The Triple Zero® house consumes zero energy, produces zero emissions, and leaves zero waste.

Nevertheless, this is the only way to create structures that do not cause feelings of déjà vu, but instead have a high level of intrinsic logic, make very efficient use of materials, and radiate a special form of inherent beauty.

Adaptive systems are an important prerequisite for achieving new types of structures, and they are the key to efficient, ultralight constructions. However, in order to make full use of their potential, they must be integrated into the design process from the very beginning. The Stuttgarter Träger (Stuttgart Beam) is an impressive example of this approach, achieving minimum weight and serving as a model for an adaptive bridge. | **fig. 2** The single-span girder is 1,600 millimeters (5.25 feet) long, but has a structural height of only about 3 millimeters (0.12 inches); in other words, the structural height-to-length ratio is 1:600! The Stuttgarter Träger weighs 80 percent less than a comparable passive system. Moreover, adaptation achieves zero deformation below the wheel of the rolling load. This would be simply impossible for current structures to accomplish, since it would require an infinitely stiff (passive) system.

In addition to load-bearing structures, the principle of adaptivity can also be applied to other parts of a building, such as the facade. Research into breathable, multifunctional textile envelopes is being carried out at the Institute for Lightweight Structures and Conceptual Design (ILEK) at the University of Stuttgart, where agent systems integrated in the facade are also being researched. The latter actively react to varying light conditions, and in so doing are always able to guarantee the highest levels of comfort for the user.





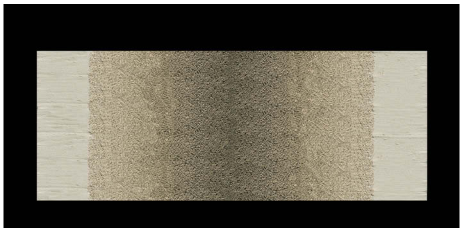


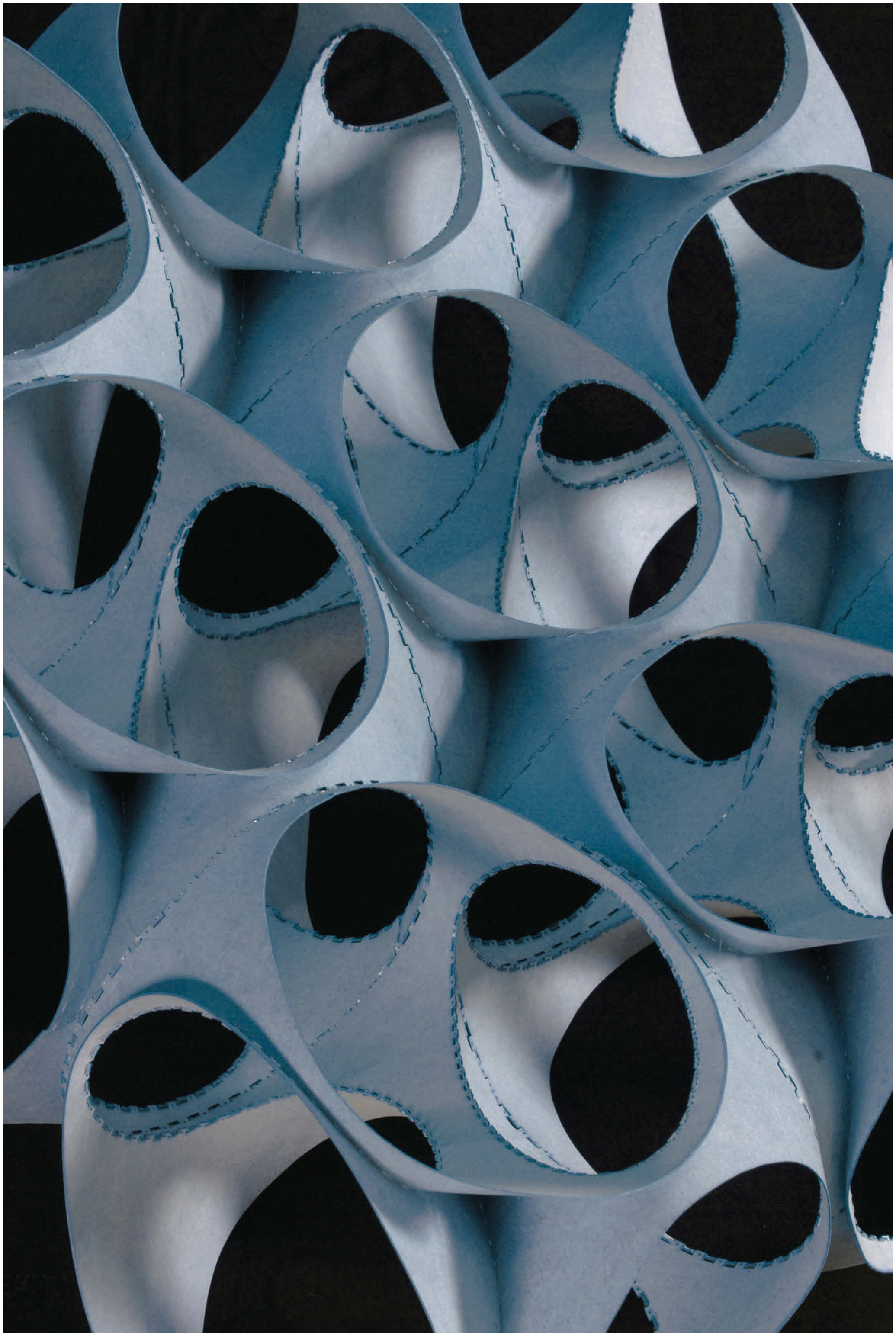
fig. 2 | Stuttgarter Träger stabilization of structure through specific temporary manipulation, by Institute for Lightweight Structures and Conceptual Design (ILEK), 2004 (top)

fig. 3 | Bioreactor used for tissue engineering, by ILEK, 2009 (middle)

fig. 4 | Functionally graded concrete, by ILEK, 2010 (bottom)

In addition to adaptivity, the creation of new building materials opens up a further path to innovative structures. For example, so-called tissue engineering makes it possible to design building components that are ideally adapted to the future instantaneous curvature in a building. Tissue engineering is being jointly researched by ILEK and the Center for Regenerative Biology and Medicine at the University Hospital Tübingen. Their objective is to develop techniques that will improve the mechanical characteristics of artificially cultivated fibers. In their studies, cell groups are mechanically stimulated in a specially developed bioreactor in a manner that causes them to increasingly locate their extracellular matrix along the force trajectories. | fig. 3 By transferring this principle to the engineering sciences, it becomes possible to develop materials that are ideally adapted to meet predicted load-transfer requirements. Initial tests with cellulose-synthesizing bacteria have already been carried out successfully.

Materials such as functionally graded concrete are a further important means toward creating a new architectural language. A concrete with flowing transition characteristics within its volume is illustrated in figure 4. | fig. 4 Utilizing graded-index materials makes it possible to precisely define characteristics on the inside of a component to meet local requirements, and the density can be adapted depending on the envisaged load conditions. Manipulable material parameters include porosity, fibrous content, and fiber alignment, as well as the composition of the different materials. In the near future, these experiments will make an important contribution toward ensuring that building materials are used much more efficiently than today.



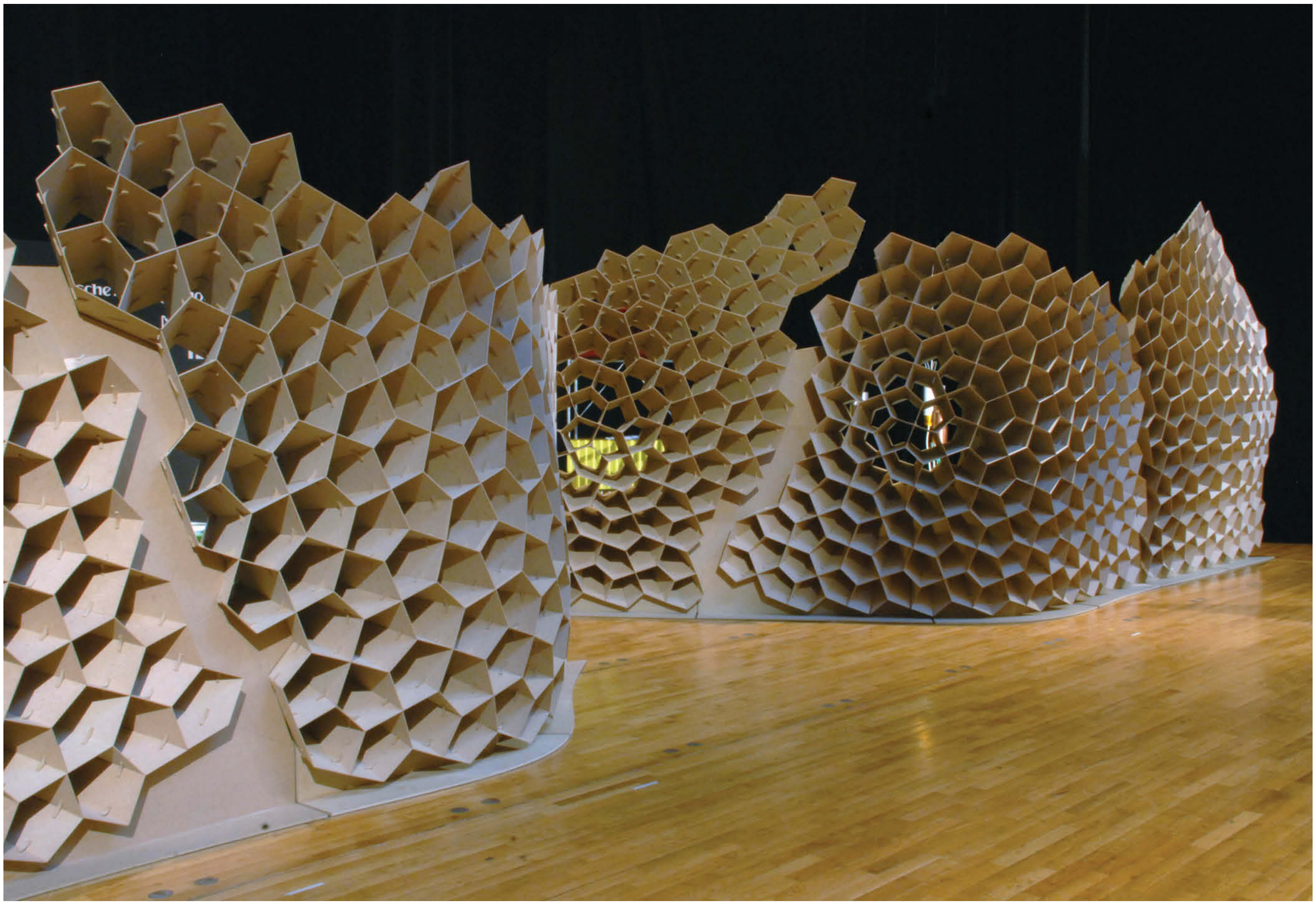


fig. 5 | Smart Structures, student project, by ILEK, 2009 (opposite)

fig. 6 | Blickfang, exhibition stand, by ILEK, 2009 (above)

If one continues this train of thought to contemplate ephemeral structures, the following question arises: How can a structure be made to take on any desired form while also being lightweight, stable, cheap, easy to produce, and suitable for repeated transport, assembly, and dismantling? The Smart Structures project offers one possible solution, with its easily realized cutout pieces—made from a flat material—that form a preprogrammed, three-dimensional shape when joined together. | **fig. 5** This system is defined by parameters that are controlled by internal, external, static, or dynamic input values, all of which allow it to be adapted to different kinds of structures, such as a piece of civic furniture, a pavilion, or even an exhibition stand for a trade fair. | **fig. 6** Smart Structures is a good example of the direction in which our work with new materials and new structures can develop in the future.

Engineering CCTV

Rory McGowan

While the 2010 China Central Television (CCTV) Headquarters in Beijing—designed by the Office for Metropolitan Architecture (OMA) and engineered by Arup—is a very well-known recent project, its engineering process has not been widely explained. | fig. 1 In this essay, as Arup's project director for the building, I will tell the story behind the structure and its relationship to the design environment in China.

First, it is worth noting that seven out of the nine standing members of China's politburo are engineers. In fact, the greatest surprise in announcing new members in 2009 was that for the first time they were not all engineers! I believe this has a huge impact on the way things happen in China. This can be seen in the astonishing speed at which construction projects progress once they are given the green light—for example, Foster + Partners's 2008 Beijing Capital International Airport was planned, designed, built, and opened in just over five years.

The 2002 competition for a new headquarters for CCTV, the Chinese state media broadcaster, called for a building to house its entire workings—including studios; production, sales, and management departments; and even mobile broadcast units—on a single, two-million-square-foot site. For me, the project's origins go back to the mid-1990s, when OMA's designs such as the Togok Towers and the Hyperbuilding investigated the possibility of megastructures propping each other up. | fig. 2 Another precedent was OMA's 1996 Universal Headquarters project, where four diverse fiefdoms of a major firm, each given its own tower, were skewered and united by a common program, with the ambition of potentially sparking a new, fifth business. | fig. 3

CCTV began as a sculptural piece. OMA's design for the building questioned the race for height and the monotony of the resultant circulation. When I first saw the form, it left me speechless, but I also understood that it was an absolutely serious proposition. Arup started studying the structure in April of 2002, and we quickly realized that the building's core would not play a role in its stability system, as in a traditional skyscraper. Instead, we would need to turn the building form into a tube frame. But how? Some early structural design schemes included a type of megaframe similar to I. M. Pei's 1989 Bank of China Tower in Hong Kong and a part-concrete, part-steel solution, but these options weren't appealing. Three weeks before the competition deadline, we decided to use a process that we had originally devised for OMA's (unrealized) Whitney Museum project, which consisted of examining the building's principal stress flows to determine where windows could go within a cantilevering concrete tube. | figs. 4, 5

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Engineering CCTV

Rory McGowan

fig. 1 | China Central Television (CCTV) Headquarters, by Office for Metropolitan Architecture (OMA), Beijing, China, 2010

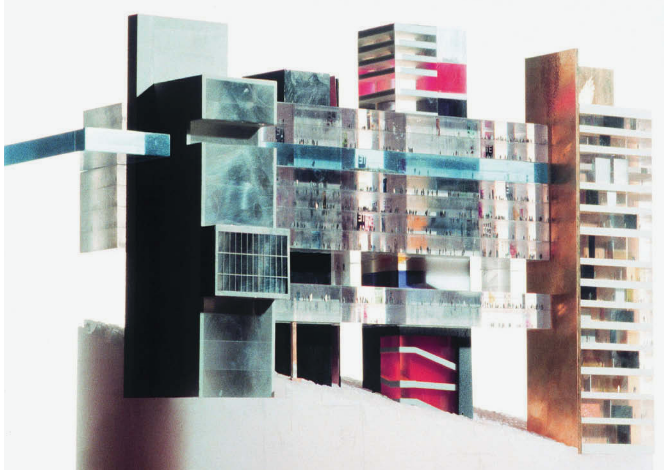


fig. 2 | Togok Towers, by OMA, Seoul, Korea, 1996 (left)

fig. 3 | Universal Headquarters, by OMA, Los Angeles, California, 1996 (right)

The competition model focused on the tube as a display screen that was almost hieroglyphic in quality, as if CCTV could be cut out from a pyramid. In the end, however, the model confused the client, and in twenty-four hours, a new one was made to explain more clearly the building to the "leaders," as well as clarify the structure. The building offers a major loop circulation and some alternatives to ambulation. Arup knew that the CCTV building's tube structure would need to have an open, triangulated surface to achieve the required stiffness. The initial modeled form showed large, seemingly random and chaotic variations of force distribution. Instead of adjusting member sizes to suit these widely ranging forces, we mapped zones of equal intensity, doubled and quadrupled structural density to deal with the level of force, and then reanalyzed the model. **| figs. 6, 7** The resulting randomized, triangulated pattern immediately grabbed OMA's attention, and Rem Koolhaas described it as an example of "apparent irrationality in what is scientifically correct." My first impression as an engineer was that the structural pattern seemed contrived to be eye-catching, but it was in fact based solely on the demands of the building. This apparently arbitrary force distribution subsequently inspired many students and artists.

Once Arup hit upon the randomized triangulation system for the building, we knew we had the solution, and the competition entry was sent to CCTV. **| figs. 8, 9** For the next twenty months, Arup used a painstaking iterative process to fine-tune the structure's arrangement. As we came to further understand the structure and its needs, additional advantages to its final triangulated pattern slowly revealed themselves: it was not tied formally or architecturally into a rigid structural diagram, and it allowed us to alter the arrangement without affecting the building's overall appearance. For instance, we could remove structural elements to save weight wherever we liked. We were also able to calibrate

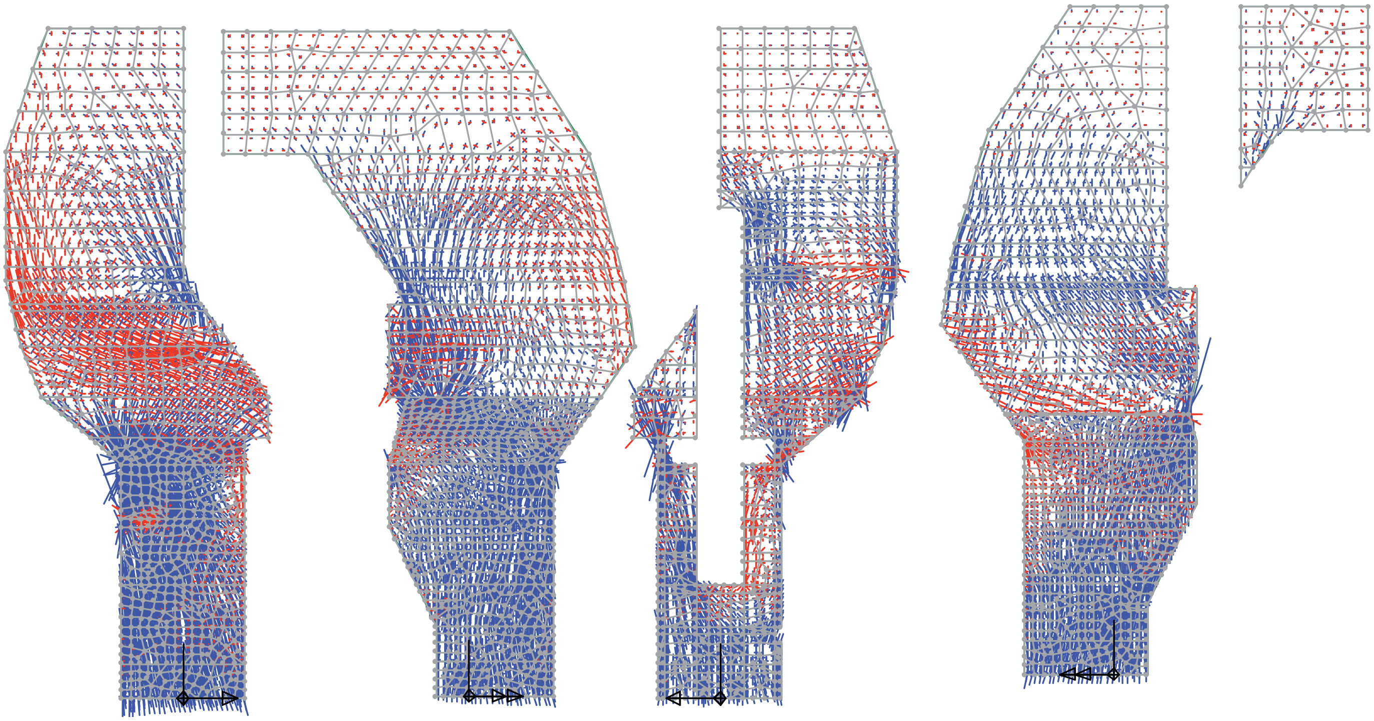
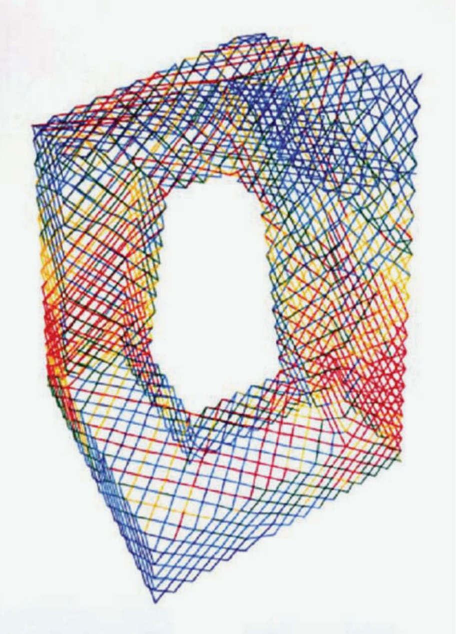


fig. 4 | Stress flow diagram, Whitney Museum extension, by OMA, New York, New York, 2001 (top)

fig. 5 | Whitney Museum extension, 2001 (bottom)



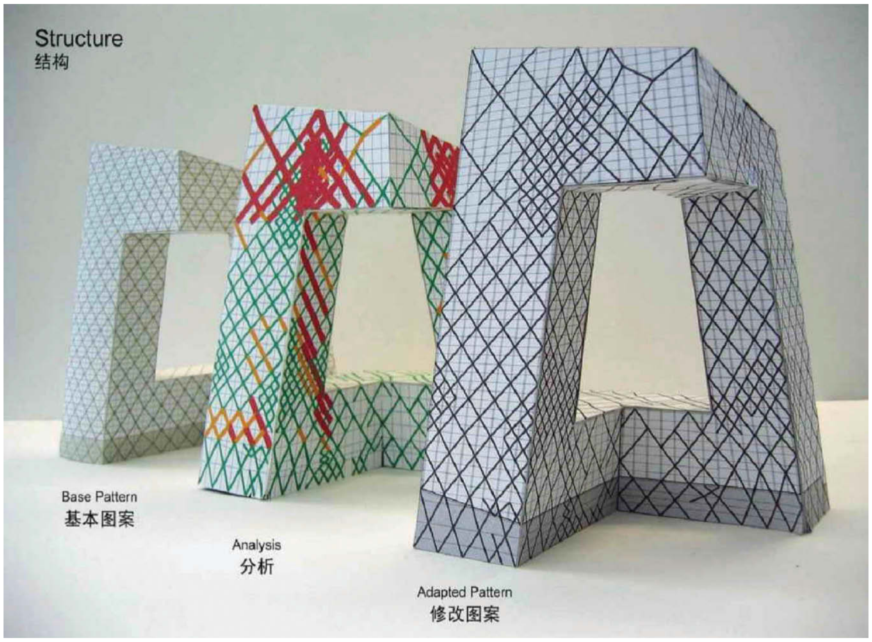


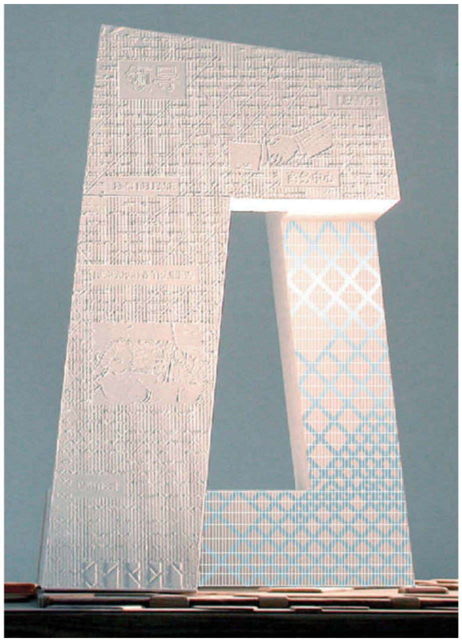
fig. 6 | Structure diagram, CCTV (left)

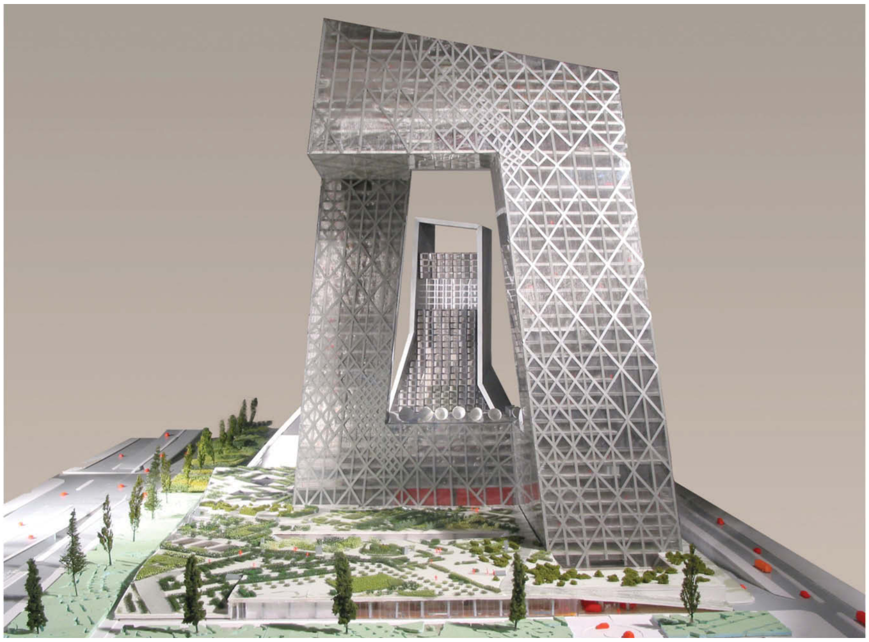
fig. 7 | Structure diagrams of iterative design process, CCTV (right)

stiffness, direct forces around the tube, and provide redundancy to protect the building in the event of a catastrophe.

When I heard that we won the competition, I had a feeling of 50 percent sheer exhilaration and 50 percent sheer terror. It's impossible to overestimate the public's fear of a seismic catastrophe. Our building fell outside the limits of applicable prescriptive codes, which allowed us to pursue a performance-based design philosophy for the CCTV building. If China's Ministry of Construction (MOC) hadn't allowed this best-current-practice approach, the building could not have been realized. We entered into a twelve-month-long expert panel review (EPR) with the MOC to gain approval for the structure's design. This involved numerous private meetings, official "unofficial" meetings, and one formal meeting. Arup was familiar with this process, having been through it in California and Japan, but CCTV was the first major use of an EPR in the new era of Chinese building development, and it set the precedent for the construction projects that followed.

We started the EPR by simply stating our objectives: to calculate and size the structure for the loads it would experience, but more importantly, to understand how it would perform both globally and locally at and beyond its elastic limit, into its ductile/plastic zone and—in the case of an extreme event—beyond. As we went through the EPR process, the building's seismic design criteria became more detailed and refined. Effectively, we wrote a code to design CCTV, got it approved, and then proceeded to analyze and design the building to the code while continuously reviewing and adjusting it in collaboration with the



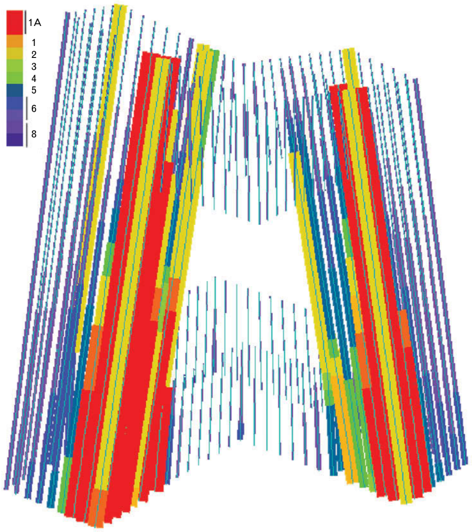


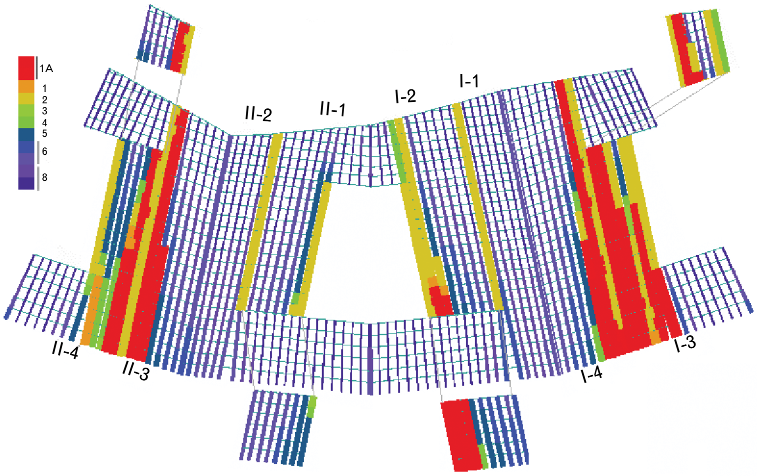
figs. 8, 9 | Presentation model, CCTV, 2002

expert panel. Through this process, the building became the most analyzed structure in Arup's history.

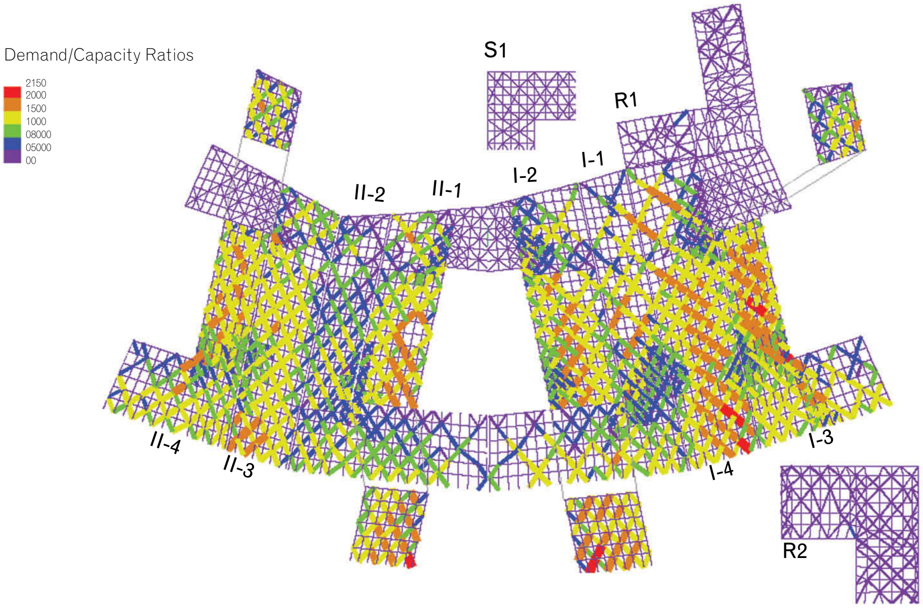
The CCTV building is a product of its time, as the tools and methodologies we used for it were unavailable only a few years earlier. We had conflicting requirements: to make the building stiff enough to limit deflections, but also to lower stiffness to reduce the seismic effects on the building. The nature of the bracing pattern meant we could add and subtract elements to fine-tune the stiffness against strength. The megacolumns also needed to be tuneable in some way. Arup's most powerful in-house analysis tool—Oasys LS-DYNA explicit nonlinear time history Finite Element analysis software—allowed us to build a virtual model containing every one of the building's 10,060 structural elements. This helped us understand—millisecond by millisecond—the elastic, ductile, and post-ductile behaviors of the building as a whole, as well as each individual structural part, as we subjected it to earthquake input. With such a complex analysis, we needed a simple way to present our results to the MOC, the architects, and the client, so we adopted a dress-pattern approach to clearly explain the structure visually. **| figs. 10, 11**

As the structural analysis of the CCTV building progressed, issues too numerous to cover here emerged, but one of the most challenging had to do with the structure's columns. Due to the design's geometry, we expected a huge variation in column forces between the inner (compression) and outer (almost-tension) faces of the tube. This discrepancy resulted in a large variety of column sizes on





figs. 10, 11 | Column variance configurations and dress-pattern visualizations, CCTV


Demand/Capacity Ratios

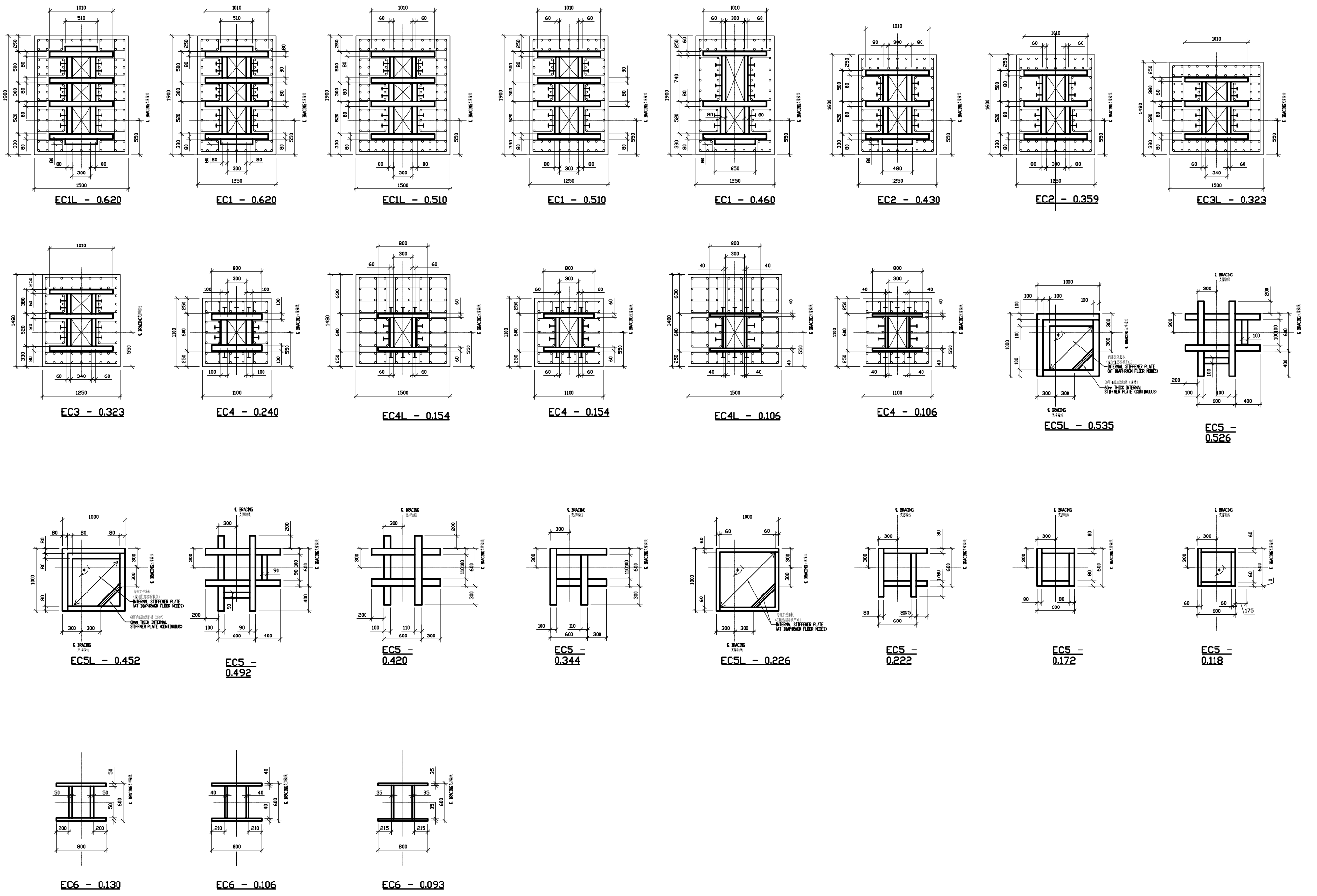


fig. 12 | Details of column variations, CCTV any one floor. | fig. 12 From the structural analysis model, we discovered that as we added steel to the compression-face columns, they increased in stiffness, and thus attracted significantly more seismic load. This was a worrying nonconvergence problem, and we tackled it in a number of ways. For the heaviest columns, we proposed using steel-reinforced concrete to heighten their load capacity. In an extreme earthquake scenario, the columns actually worked as fuses: above a certain loading point, the concrete would fail and deform, acting like a shock absorber. This would lower the stiffness of the building, thereby reducing the earthquake load it attracted. Understanding the columns' cyclic loading behaviors and their resultant capacity degradation was critical to the safe design of the structure. | fig. 13

During construction, the largest corner columns and braces were removed just below the overhang. These columns, due to the building's geometry, attracted the most load, and as they increased in size, they attracted even more gravity load and so on. Thus, to short fuse this, we decided to effectively take out the corner columns, throwing the loads they would have attracted to neighboring columns. After construction was completed, we added in these missing structural elements, which will be crucial in the case of a seismic event.

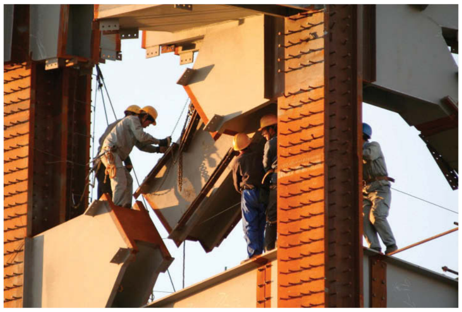


fig. 13 | Construction view, CCTV, 2008 (top)

fig. 14 | Earthquake test model, CCTV, 2008 (bottom)

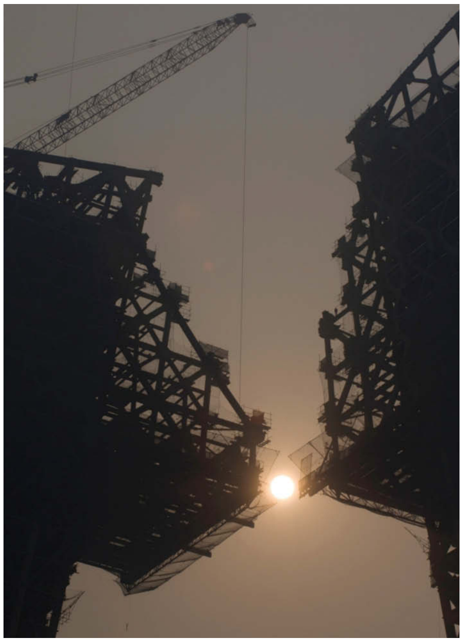
Another benefit of the CCTV building's structural arrangement was the robustness and redundancy of its bracing. We had to demonstrate to the MOC that even if a number of elements were removed from critical areas of the building, it would remain standing, and, in fact, our design would only suffer localized damage. This was made possible by the structure's bracing, which offered alternative load paths. One of the roles of the MOC is to comment on the material efficiency of a structure, a throwback to when they were seen as a check against overdesign and the waste of national resources. Many of the building's critics are stuck in a cost-and-steel-weight discussion, believing it to be extravagant in its abundant use of material, but this criticism has been disproven by built projects both in the vicinity of Beijing and in seismic zones worldwide. This issue was one of the earliest to be tackled by the team with the client and government authorities.

One of the scarier moments of the project occurred when a model of the building was tested under seismic conditions (i.e., a shaking table). The use of such a crude process to verify designs that are only possible because of the accuracy, power, and verification of current software is outdated. With such varying degrees of precision, anything was possible, and if there was a problem, it would set a hare running that would take a very long time to put back in its box. The model, built by a local university, helped subsidize the school and its professors. | fig. 14 Installed in the client's parking garage, the shaking-table model was a throwback to the old—and perhaps defunct—ways of proving a building's integrity.

figs. 15–17 | Construction views, CCTV, 2008

Excavation for the CCTV building's foundation began in September of 2004. The early stages of construction were relatively traditional and low-tech, and were carried out by an army of two to three thousand migrant laborers. By the time of the building's construction, China's steel industry had developed at an incredibly rapid pace, and we were able to source the highest strength steel required for the project (10 percent of total steel used) from within the country rather than importing it from the Czech Republic or Germany. The steelwork—100,000 tons in total, including 1,265 varying butterfly joints—arrived after twenty-four hours on the road from two major fabrication yards near Shanghai. The maximum lift was eighty-three tons, and the heavier columns took up to seventy-two hours to lift into place and weld. By 2006, the two towers of the building were going up at a rate of six floors per month. | **figs. 15–17**

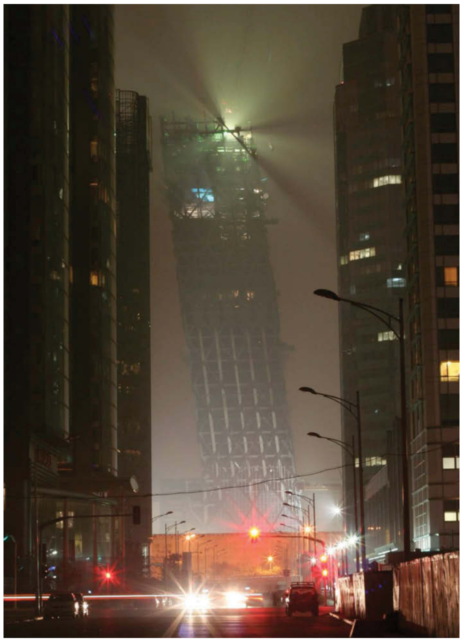
We had to consider the contractor's method of construction in our design, as this would have an impact on permanent, built-in stresses. Before construction began, Arup hypothesized that the contractor would need to cantilever out the horizontal link from the two towers instead of propping or lifting it. Each of the three competing contractors planned to use one of these methods, but the winner, China State Construction, chose our preference. We also had to assume upper- and lower-bound conditions of loading that the contractor would need to work within. If these constraints were neglected, the building would have to be reanalyzed to reconfirm all member sizes.



figs. 18, 19 | Connecting the cantilevers, CCTV, 2008

All buildings deform under their own weight, but for this structure, knowing exactly how much the towers would bend during construction was critical. Although hardly noticeable at the start, construction sequence time-history modeling showed that additional leaning due to the structure's weight became more and more significant as the tower reached its full height. Deflection during the construction of the cantilevered parts was even more pronounced. We had estimated that the tips of the cantilevers would bend 300 millimeters (11.8 inches) downward under their own weight, and we decided to precamber the entire tower upward and backward, so that as it deflected under gravity during construction, it would end up perfectly horizontal once the building was complete. Although this sounds simple in theory, it was an extremely complicated analysis and process. The contractor used a time-history construction model with fifty-eight stages to predict the structure's deflection and monitored its actual movements continuously during construction to make sure they corresponded to the predictions, making adjustments if necessary to keep the towers on course (adjustments were made by adding inches—even fractions of an inch—to columns, brace lengths, and weld gaps).

Another issue during the CCTV building's construction was thermal movement, and for this reason, a clause was added to the specifications that would require the connection of the cantilevers to take place before dawn. Because the sun passes to the south of the towers, they would both move as they heated up during the day. If we were to force the connection while they were in this deformed



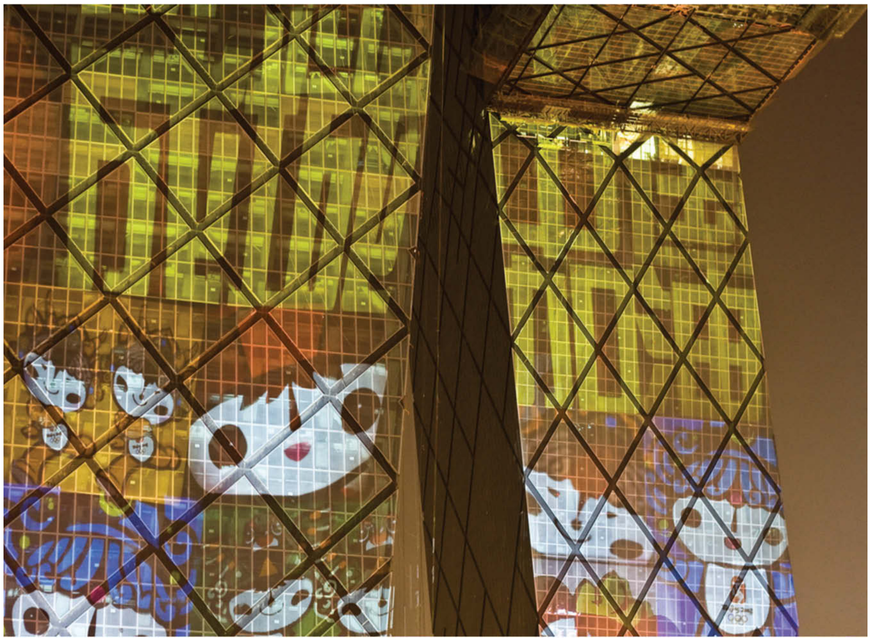


fig. 20 | CCTV, 2008 (left)

fig. 21 | View of facade with projected image during 2008 Olympics, CCTV (right)

state, we would permanently lock additional stresses into the elements. The contractor had to connect seven major joints in less than ninety minutes to ensure that they would be strong enough to withstand these thermal forces. China State Construction's solution was to monitor and measure the exact distance of the gap in the days leading up to the final connection, cut the bridging pieces to the precise dimensions twenty-four hours beforehand, join the towers in minutes with pin connections of minimum tolerance, and then weld up the joint at leisure for permanent connection. | **figs. 18, 19**

Even after all these years, I find the CCTV Headquarters a spectacular building to look at. I see it every day from my office, and yet I still sometimes find new angles, new views, that I never previously imagined. I just hope we're not responsible for a spate of crashes on the nearby Third Ring Road, as everyone takes their eyes off the road to look up at the building! | **figs. 20, 21**

Emerging and Merging: Liminal-Frame Structures and Beyond

Heiko Trumpf

The classic approach to the design of a building is to consider its load-bearing structure and its envelope separately. The designers in charge of the load-bearing structure, facade, mechanical engineering, and building physics typically become involved in later design phases, and usually don't participate in the overall architectural process. Interdisciplinary design mostly refers to coordination between these actors, not cooperation toward a common objective.

In this approach, the facade is regarded as a decorative architectural element, while the load-bearing structure—whose design is dictated by structural and installation requirements—is covered by the facade and is visually, if not entirely, subordinate to it. Steel-frame buildings, which usually consist of a skeleton structure with a bracing core, facilitate this classical approach of separating the building envelope and load-bearing structure.

Structure and Surface

Our goal at Werner Sobek Engineering & Design is to surmount design processes that are normally parallel to and separate from each other so as to merge the two crucial components of building envelope and load-bearing structure, with the aim of creating a symbiosis between decorative and supporting elements. By doing this, the design of the supporting elements becomes more important, and the building envelope can also serve as the load-bearing structure. The inventive use of different materials and hybrid construction components demands an intensive, integral design approach. New design and manufacturing methods, such as parametric design or computer-aided manufacturing (CAM), provide further fascinating possibilities for merging structural and decorative elements.

The 2010 Dornier Museum Friedrichshafen in Germany, which is devoted to the Dornier company's innovations in the field of aviation, was designed by Allmann Sattler Wappner Architekten and engineered by Werner Sobek. Its load-bearing structure consists primarily of classic framing components that geometrically break to form an aerodynamic wing shape. Consequently, the integrated design resolves the separation between structure and facade, connecting them architecturally. The load-bearing structure becomes visible at the periphery, merging with the building envelope and becoming the primary architectural elements. | fig. 1

For the 2007 Trumpf Gate House in Ditzingen, Germany—designed by Barkow Leibinger Architects and engineered by Werner Sobek—the facade fulfills

fig. 1 | Dornier Museum Friedrichshafen, by Allmann Sattler Wappner Architects, Friedrichshafen, Germany, 2010

structural requirements, whereas the load-bearing structure defines the visual character of the building. The Gate House's canopy structure consists of a support grid of welded-steel profiles, with all visible parts made of stainless steel (V4A quality). The roof is constructed from a flat, 16-meter (52.5-foot) cantilevering beam array, with a ceiling of patterned, laser-cut metal whose perforations correspond to strength- and stress-distribution requirements. **| figs. 2, 3**

Werner Sobek worked with Barkow Leibinger again on the 2008 Trumpf Canteen, also in Ditzingen, whose long-span steel beams—placed on seven pairs of diagonal columns—constitute the primary load-bearing structure of the building's canopy. This main structure forms nine triangles in plan, which are filled in with a network of glulam (glued-laminated timber) load-bearing honeycombs of different configurations and heights. The primary structure actually lies behind the wooden honeycombs, and therefore is perceived as a subordinate element. The predominant wooden honeycombs become the load-bearing structure of the roof. The building has a lively, joyful character, with its combination of smooth, exposed concrete forms, thin but distinctive steel columns, and concise wooden honeycombs creating a balanced and persuasive architectural expression. **| figs. 4, 5**

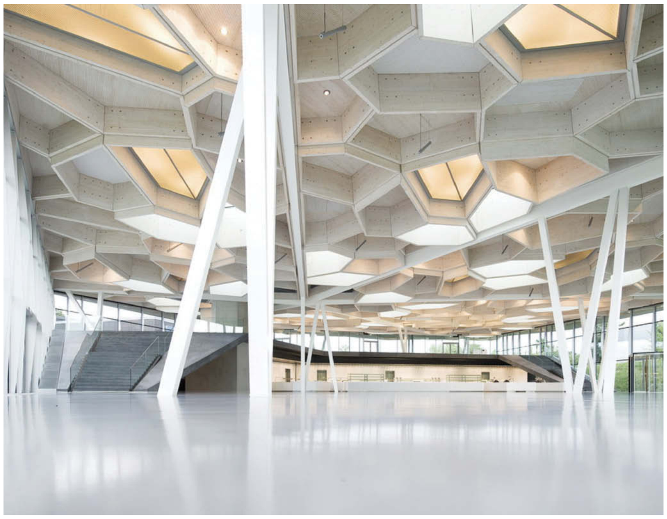
A final example of the successful merging of envelope and load-bearing structure is the Deutsches Architekturmuseum (German Architecture Museum) Pavilion in Frankfurt, also designed by Barkow Leibinger and Werner Sobek. The pavilion has a modular, curved structure made of thin steel tubes supporting alternating transparent and translucent load-bearing polycarbonate panels. These elements form both the envelope and structure, stepping forward visually

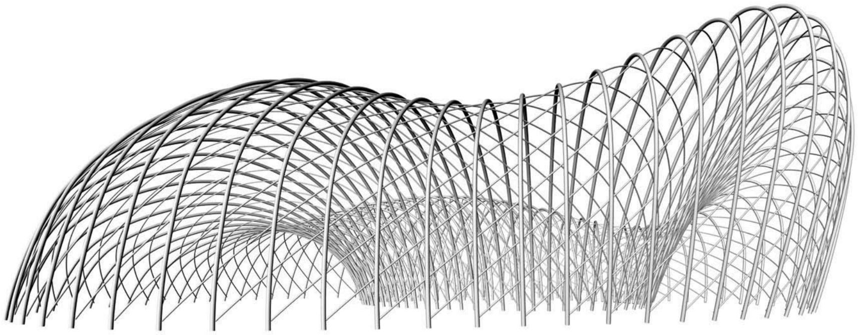
fig. 2 | Trumpf Gate House, by Barkow Leibinger Architects, Ditzingen, Germany, 2007 (top)

fig. 3 | Detail of exterior, Trumpf Gate House, 2007 (bottom)

fig. 4 | Trumpf Canteen, by Barkow Leibinger Architects, Ditzingen, Germany, 2008 (top)

fig. 5 | Interior view, Trumpf Canteen, 2008 (bottom)





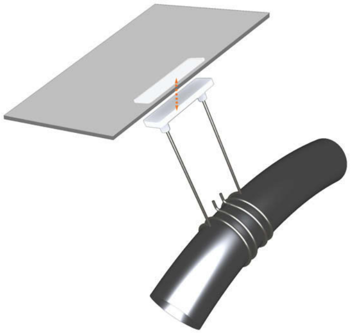


fig. 6 | DAM Pavilion, German Architecture Museum, by Barkow Leibinger Architects, Frankfurt, Germany (left)

fig. 7 | Detail of clasp joint, DAM Pavilion (right)

at every position. Werner Sobek developed innovative structural connection points that define the architectural appearance of the pavilion. | figs. 6, 7

Ultralightweight Metal Structures

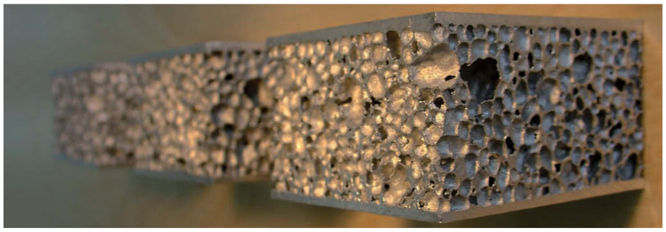
Ultralightweight metal structures are systems that—due to their composition and/or technical processing—have a much lower mass than comparative structures using standard basic materials with equal or greater weight. An example of such a system is a structure consisting of aluminum-foam panels sandwiched between two wafer-thin aluminum sheets to achieve maximum rigidity and load-bearing capacity. Ultralightweight materials and manufacturing technologies, adapted from the aerospace and automotive industries, have multiple physical properties that offer new architectural possibilities, including excellent U-values (heat-transfer capabilities), good sound-absorbency, and fascinating optical effects. They are also often made with pure and recyclable components. Ultralightweight metal structures include metallic fabrics and panels that—due to their deformation, perforation, or weave pattern—can significantly reduce empty weight and generate new capabilities through particular processing and implementation. Through digital fabrication processes such as CAM and computer numerical control (CNC), nearly any geometry is attainable for an ultralightweight metal structure. | figs. 8–10

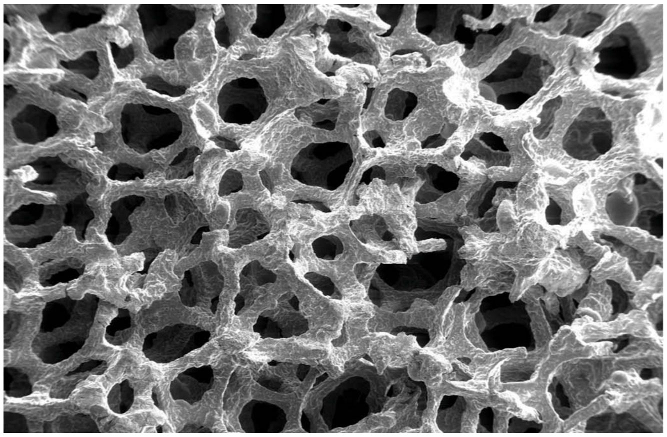
As part of the 2007 redesign of the plaza in front of the Swarovski factory building in Wattens, Austria, Designstudio Regina Dahmen-Ingenhoven and Werner Sobek created a mesh curtain that is 250 meters (820 feet) long and 10 meters (32.8 feet) high out of 12-millimeter-diameter (0.5-inch-diameter) stainless-steel rings. This striking steel curtain combines a high level of transparency with the lightness and flexibility of fabric. It separates the public space from the factory premises, and is held up by a series of conical and curved steel-tube columns. Before the Swarovski curtain, steel-ring mesh was mainly used for protective

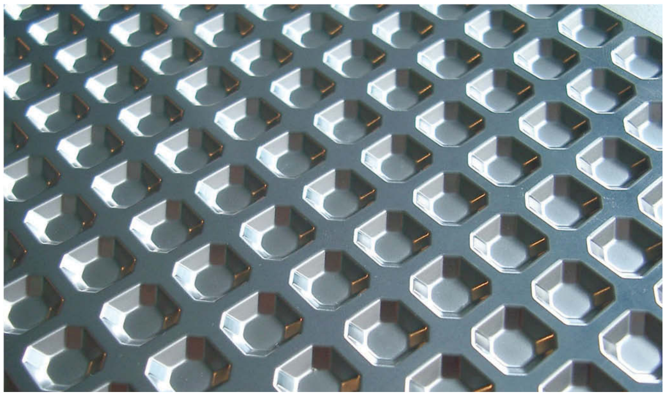
figs. 8, 9 | Aluminum-foam sandwich panel and detail (top)

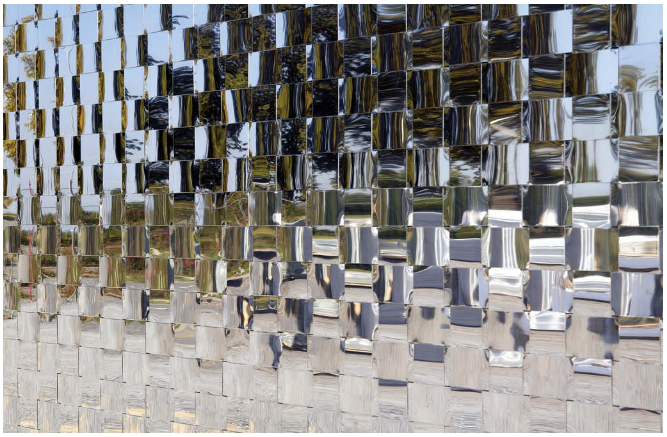
fig. 10 | Lightweight Borit panel (middle)

fig. 11 | Swarovski curtain, by Designstudio Regina Dahmen-Ingenhoven, Wattens, Austria, 2007 (bottom)









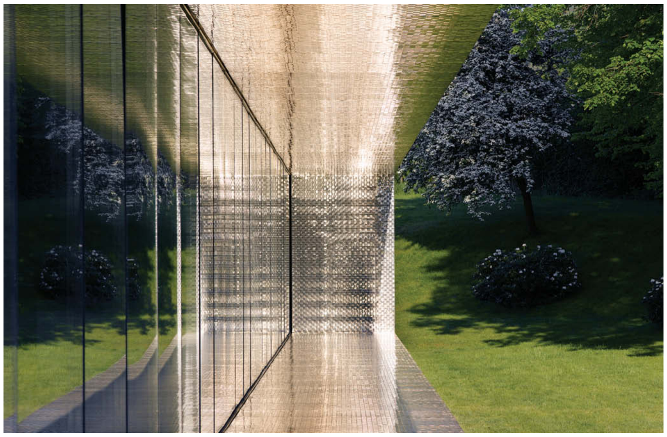


fig. 12 | Detail of woven stainless steel, Südwestmetall Branch Office, by Dominik Dreiner, Heilbronn, Germany, 2004 (left)

fig. 13 | Südwestmetall Branch Office, 2004 (right)

work clothing, and had not been tested at the larger scale of architecture. The mesh is suitable for long-term outdoor use and meets the area's demanding wind, snow, and ice load-bearing requirements. The construction of the steel columns pushed the engineers to the limit of what is technically feasible. | fig. 11

An even more spectacular separation between structure and surface appears at the 2004 Südwestmetall Branch Office in Heilbronn, Germany, designed by Dominik Dreiner and engineered by Werner Sobek. The structure of the building basically consists of a reinforced concrete construction. In the area of the floor-to-ceiling glazing on the longitudinal sides of the building, the ceiling rests on minimized stays of stainless steel. In order to underline the corporate identity of the employer association of the metalworking industry, the entire wall and roof surface of the reinforced concrete construction was clad with a woven fabric of filigree stainless-steel strips. | figs.12–14

Future Innovation

To meet the high demands of today's challenging and sophisticated building designs, architects and engineers need to focus on an integrated design process. The symbiosis of building envelope and load-bearing structure is a key element within a complex design process. Through the application of innovative building materials, hybrid material combinations, new and adaptive designs, and sophisticated production and manufacturing processes, such as digital fabrication and parametric design, including the use of CAM and CNC technologies, these extraordinary structures can be realized, while also meeting high quality standards and budget demands. Metal building materials offer an especially high potential through the necessary variety and changeability of optical and haptic qualities, as well as a range of construction demands.

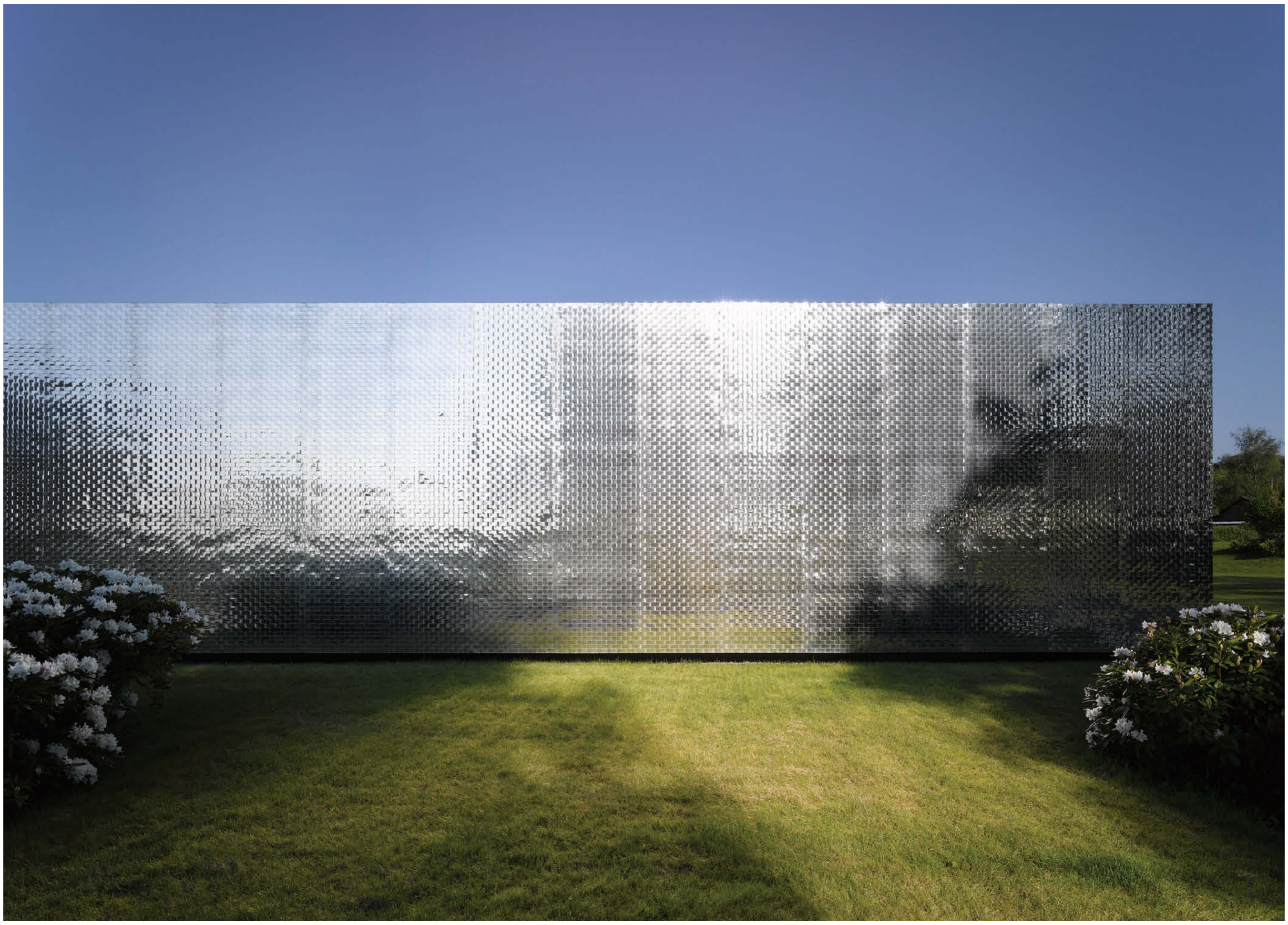


fig. 14 | Südwestmetall Branch Office, 2004

The Aesthetics of Minimal Structures

Hans Schober

Lightweight and efficient structures are sustainable because of their minimized consumption of materials and resources. This materials savings often results in additional mental and physical labor, which can be seen as another type of sustainability. The design, fabrication, and installation of efficient strut-and-tie structures require more manpower and skill—but less material—than a standard, bulky beam. Additionally, this method of building offers the chance to create a beautiful structure whose form makes the flow of forces in the building apparent and understandable. The following principles might serve as a short guide to effective, lightweight bridge design:

1. Avoid bending

Lightweight structures can be achieved by avoiding elements that are under bending stresses in favor of bars that act axially in tension or compression. Connections in tension perform better than struts prone to buckling in compression. Tension-stressed elements become even more efficient with increasing tension strength. For example, high-strength cables are flexible and allow for a structure to have simple, standardized connections. | fig. 1

The common rule that cable bridges are adequate only for spans greater than one thousand feet does not apply to pedestrian bridges. Schlaich Bergermann and Partner (SBP) have designed a multitude of cable-supported pedestrian bridges with spans ranging from two hundred feet to one thousand feet.

2. Create variety through knowledge and creativity

Structural designers must apply all of their skills and imagination to add more variety to bridge designs, in order to avoid the monotonous girders that are now so common and which rarely reflect their natural or urban environments. A wide range of spatial shapes is made possible for bridges by using one or two masts that are either vertical or tilted. Alternatively, by cutting a regular structure in half, a delicate shape is created where the hanger cables provide an inviting gesture for pedestrians. | figs. 2–5 Turning a structure upside down is another way to create new forms. For example, inverting a suspension structure yields an arch. | figs. 6, 7 For every project, there are countless distinctive structural designs possible.

3. Seize the opportunities offered by curvature

It is in our nature to prefer walking on a meandering path instead of one with

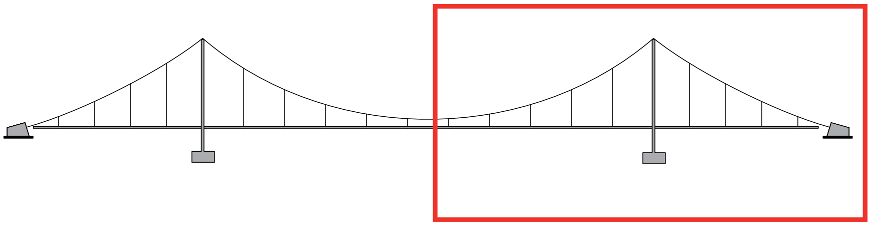


fig. 1 | Pedestrian bridge at Max-Eyth-See, by SBP, Stuttgart, Germany, 1988 (top left)

fig. 2 | Pedestrian bridge at Enzauen I and II, by SBP, Pforzheim, Germany, 1991 (top right)

figs. 3, 4 | Pedestrian bridge over River Enz, by SBP, Pforzheim, Germany, 1992 (middle)

fig. 5 | Suspension bridge cut in half (bottom)

figs. 6, 7 | The inversion of a suspension bridge results in an arch bridge, Pragsattel I, by SBP, Stuttgart, Germany, 1992

sharp corners. | **fig. 8** Curved bridges offer more design options, as they open up a new world for efficient spatial structures, effectively utilizing human nature as well as the nature of the structure. Flexible suspension cables with standardized connections also allow designers to create complex spatial structures with relative ease. Local conditions give unique qualities to each bridge design, leading to a wide range of beautiful, three-dimensional structures where form and structure are a cohesive unit. | **figs. 9, 10**

In 1987, SBP designed a semicircular suspension bridge in Kelheim, Germany, with hangers only on one side (hangers on both sides would have restricted the clearance for pedestrians). | **fig. 11** Using similar principles, in 1998 SBP designed a circular footbridge inside the Deutsches Museum in Munich, which provided access to some special exhibits while simultaneously illustrating to museum visitors the “art of bridge engineering.” | **fig. 12** As already demonstrated with the semicircular footbridge and its prestressed deck at Kelheim, a circular bridge deck only needs to be suspended from one side, and is able to counteract the resulting torsion with an inner pair of radial forces. In the Deutsches Museum bridge, these forces are physically represented by three continuous cables that run beneath its glass deck. | **fig. 13** The radial forces create compression in the lower chord and tension in the upper chord. By turning both members in the vertical direction, one may recognize at once the well-known structural elements of an arch and a suspension cable. This bridge clearly demonstrates that innovation is often based on prior knowledge as well as creativity, and that a pure structure has its own aesthetic. | **fig. 14**

The Liberty Bridge (2004) in Greenville, South Carolina, follows the same principle as the Deutsches Museum bridge: the overturning moment caused by hangers on one side of the bridge is counteracted by a compression arch and a suspension cable in the horizontal position. In this case, the hangers are on the “outer side” of the bridge, so the forces in the chords from the overturning moment switch places: the

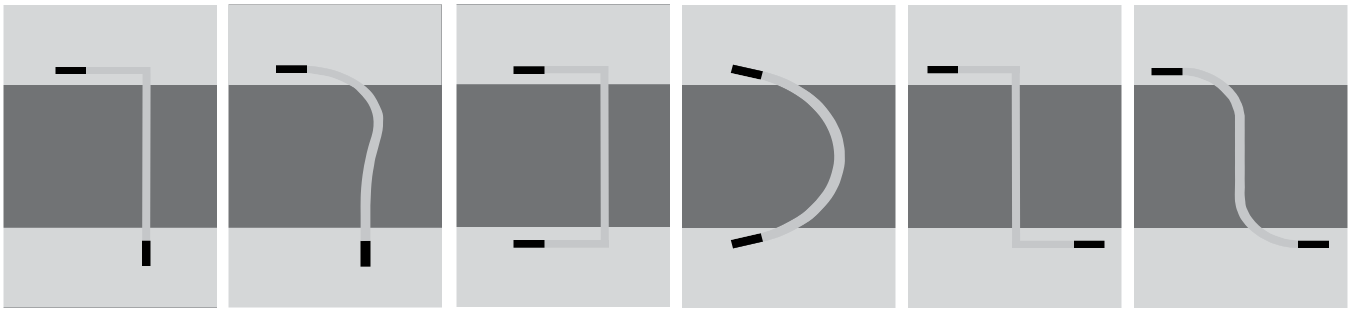
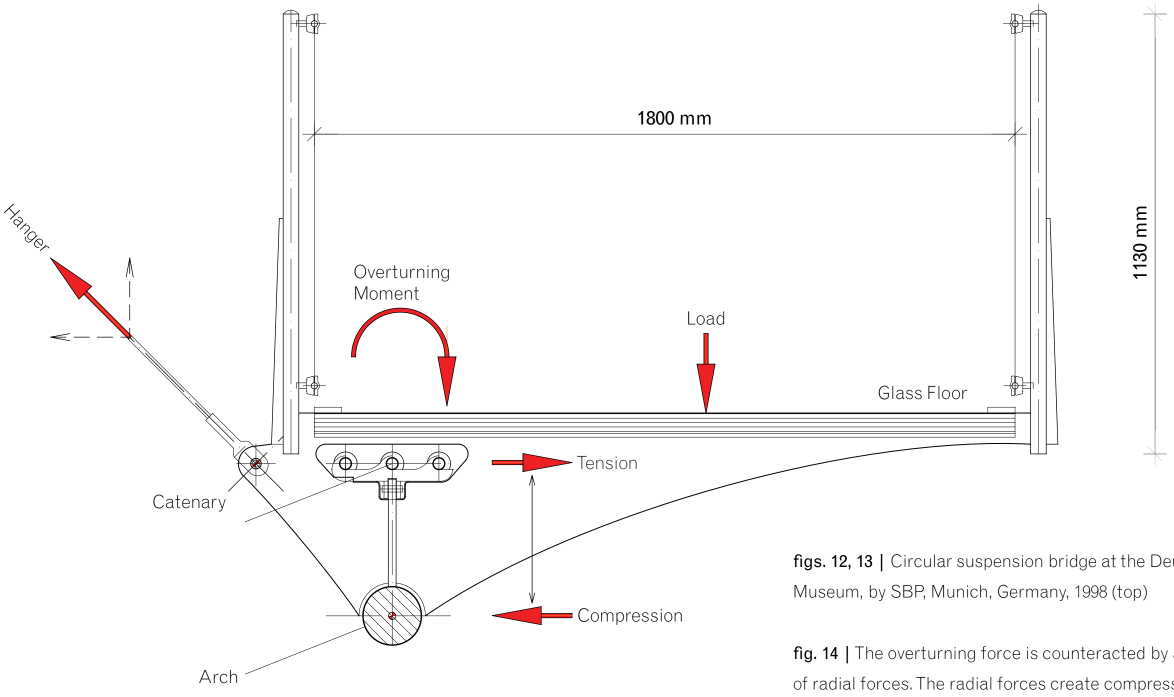


fig. 8 | People prefer walking on a flowing path. (top)

fig. 9 | Suspension bridge over Rhein-Herne Canal, by SBP, Gelsenkirchen, Germany, 2009 (middle left)

fig. 10 | Curved suspension bridge, by SBP, Sassnitz, Germany, 2007 (middle right)

fig. 11 | Semicircular suspension bridge, by SBP, Kelheim, Germany, 1987 (bottom)



figs. 12, 13 | Circular suspension bridge at the Deutsches Museum, by SBP, Munich, Germany, 1998 (top)

fig. 14 | The overturning force is counteracted by a pair of radial forces. The radial forces create compression in the lower chord and tension in the upper chord. (bottom)

figs. 15–17 | Circular suspension bridge with carefully shaped details, Liberty Bridge, by Miguel Rosales (architect) and SBP, Greenville, South Carolina, 2004

upper chord works in compression and can be formed by the bridge deck, while the lower chord is under tension. | fig. 15 Since people can see and touch most of a pedestrian bridge's structure, its detailing is very important and should be shaped carefully according to the flow of forces. | figs. 16, 17

In 2003, SBP designed an S-shaped suspension bridge on Gahlensche Strasse in Bochum, Germany, with hangers on its inner side. | fig. 18 The hangers switch at the center of each curve to the opposite side, creating a pleasing, winding-cable geometry. The three-dimensional shape of the cables and the tilt angles of the masts were determined using computer analysis and cannot be altered without ruining the bridge's balance. This careful arrangement allows for the hinged masts to hold up the suspension cables, while the suspension cables in turn keep the masts in position.

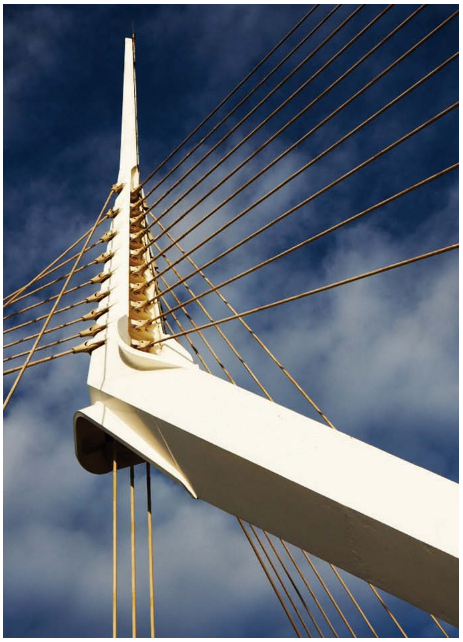
fig. 18 | S-shaped suspension bridge over Gahlensche Strasse, by SBP, Bochum, Germany, 2003 (opposite)

4. Going beyond pure and minimal structures

The primary duty of architects and engineers is to produce structures of the highest overall quality, which includes aesthetic considerations. Engineers are responsible for the design of structures, and with knowledge and creativity, they are capable of developing innovative and unique forms that clearly and efficiently materialize the flow of forces.

Santiago Calatrava's Petah Tikva footbridge (2005) in Tel Aviv demonstrates that good aesthetics in engineering can be achieved even when in excess of the most efficient technical solution. The shortest possible load path for the bridge's mast would have been a straight line, but Calatrava added a "kink" to the mast to give the bridge an iconic form. | figs. 19, 20 By redirecting the most efficient load path, Calatrava created a new and interesting structure whose form still materializes the bridge's flow of forces, in contrast with purely sculptural approaches where the load paths have no impact on the design.

The 2010 Sheikh Zayed Bridge in Abu Dhabi, designed by Zaha Hadid Architects, is an example of a sculptural structure, where the striking form comes first and the flow of forces second. | fig. 21 As a result, the role of the engineer in this project was reduced to sizing a given structure and resolving the many structural problems that came up during the design and construction phases. Hence, architects should welcome technical discipline and order through structural intelligence, especially in the case of infrastructure projects, which, unlike multifunctional building projects, are focused on a specific function and primarily concerned with load resistance.



figs. 19, 20 | Cable-stayed pedestrian bridge, Petah Tikvah footbridge, by Santiago Calatrava, Tel Aviv, Israel, 2005

fig. 21 | Construction of the Sheikh Zayed Bridge, by Zaha Hadid Architects, Abu Dhabi, United Arab Emirates, 2010

The New San Francisco–Oakland Bay Bridge

Marwan Nader and Man-Chung Tang

The seismically vulnerable east span of the San Francisco–Oakland Bay Bridge will soon be replaced by a 3.6-kilometer-long (2.24-mile-long) parallel structure, due to be completed in 2013. Initially constructed in the mid-1930s, the eight-mile-long Bay Bridge was one of the longest high-level bridges in the world at the time. Today, the bridge is a primary route between the San Francisco Peninsula and the East Bay, carrying nearly 280,000 vehicles daily. | fig. 1

In 1989, the Loma Prieta earthquake—measuring 7.1 on the Richter scale, with an epicenter seventy miles south of San Francisco—caused a 15-meter (49-foot) section of the upper deck of the bridge's east span to collapse. | fig. 2 The Bay Bridge lies between the Hayward and San Andreas faults, which are capable of generating earthquakes with magnitudes of 7.5 and 8.1 on the Richter scale, respectively. Performance criteria require that the bridge must be operational immediately following a 1,500-year return-period earthquake from either of these two faults.

Four distinct structures make up the new design for the east span: a low-rise, posttensioned concrete box girder near the Oakland shore; a 2.4-kilometer (1.5-mile) precast segmental-concrete box girder; a single-tower, self-anchored suspension span; and a posttensioned concrete box girder that connects to the east portal of the Yerba Buena Island tunnel. | fig. 3 This new section of the Bay Bridge accommodates five lanes of traffic in each direction and can be reconfigured in the future to accommodate a light-rail transit system. The bridge also has a pedestrian-and-bike path on the south side of the eastbound deck.

Selecting a Bridge Type

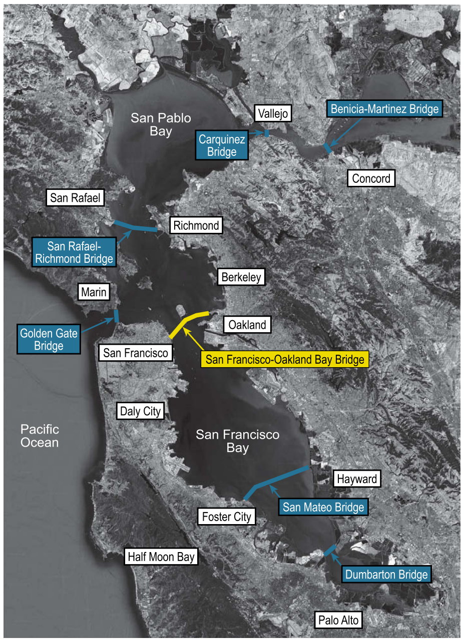
After the 1989 earthquake, the California Department of Transportation recommended replacing the Bay Bridge's seismically vulnerable eastern spans with a multiple-span concrete viaduct. This suggestion was based on the desire to provide the cheapest seismically safe structure possible. However, the Bay Area community wanted a new bridge that would give the East Bay neighborhoods of Oakland and Berkeley a signature structure to rival the iconic Golden Gate Bridge.

Public outreach meetings were held in which the community was invited to share its vision of what the new bridge should look like. After several meetings, an Engineering and Design Advisory Panel (EDAP), appointed by the Bay Area's Metropolitan Transportation Commission, made the following recommendations:

1. The new bridge should have a signature span near Yerba Buena Island.
2. The signature span should be cable-supported.

The New San Francisco–Oakland Bay Bridge

Marwan Nader and Man-Chung Tang



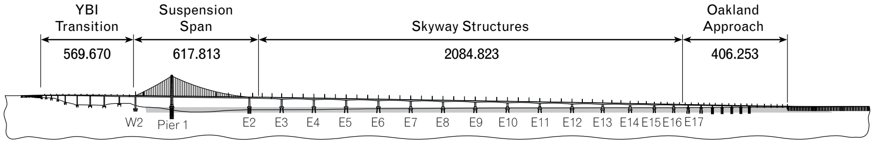


fig. 1 | Geographical location of the San Francisco–Oakland Bay Bridge, California (top left)

fig. 2 | Twilight image looking east from Yerba Buena Island in San Francisco Bay, showing the temporary support structure and the new span in the background; existing Bay Bridge is shown on right. (top right)

fig. 3 | The new San Francisco–Oakland Bay Bridge, California, 2013 (bottom)

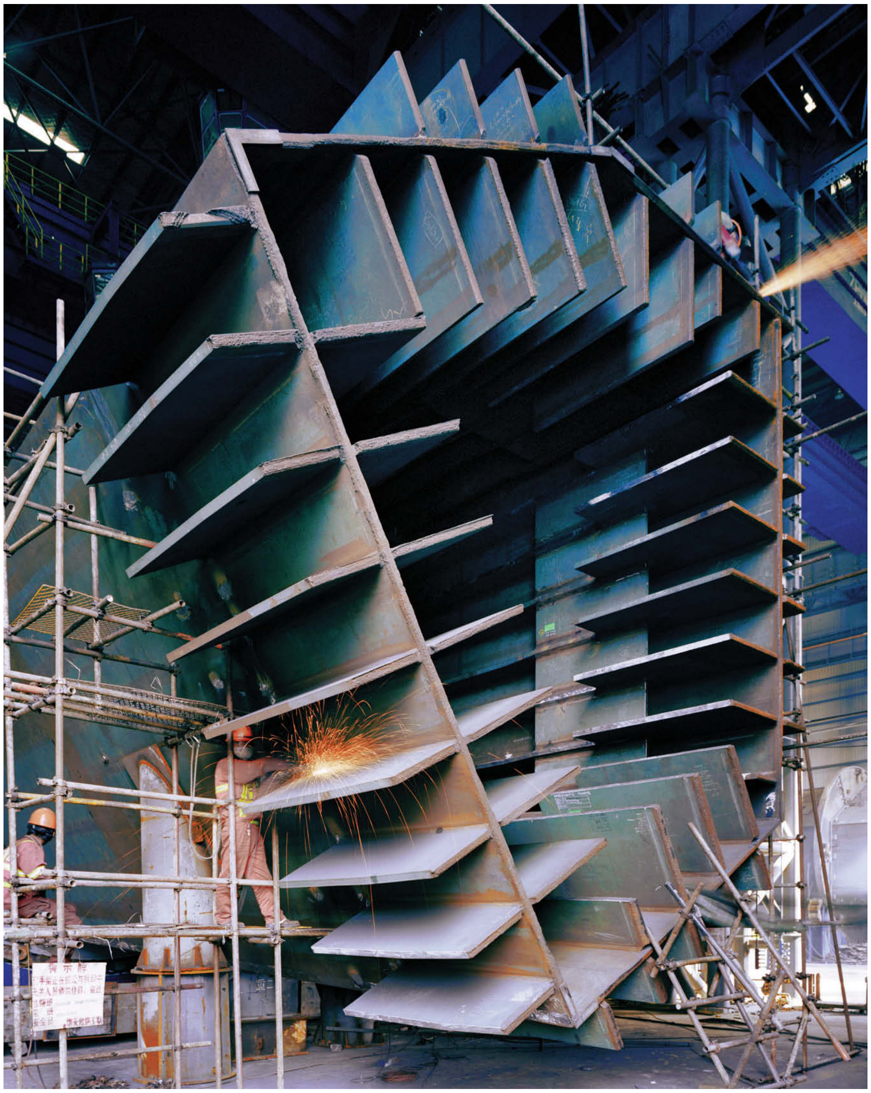
3. The signature span tower's height should not be taller than the towers of the west spans of the Bay Bridge, with a maximum height of 160 meters (525 feet).
4. The remainder of the new bridge should be a parallel structure (not a double-deck bridge), in order to provide eastbound traffic with sweeping views of the Berkeley Hills.
5. The new bridge should provide access to pedestrians and bicycles.
6. The new bridge should be located north of the existing bridge to provide the westbound traffic with sweeping views of San Francisco.
7. The bridge should have aesthetic night-lighting and should be painted white.

From a total of four design options developed for the signature main span, the EDAP evaluated and eventually selected a single-tower, self-anchored, asymmetrical suspension span with a steel tower and orthotropic deck. | fig. 4 Aesthetics was the driving force behind the selection of the final design, which would provide the Bay Area with a structure not found anywhere else in the world. Its catenary cables resonate with both the Golden Gate Bridge and the west spans of the Bay Bridge. The chosen design's single tower, along with its three-dimensional cable profile, will give the new east span a powerful cathedral-like feeling. The EDAP also selected the final design for the east span's segmental-concrete haunched girder—with a length of 160 meters (525 feet) for the skyway—from three possible solutions.

A Self-Anchored Suspension (SAS) Bridge

The SAS bridge would not be feasible if it were to be built using another material, such as prestressed concrete. The high-performance steel used for the SAS, representing between 30 and 35 percent of the bridge's total cost, provides high yield strength and toughness unmatched by other materials available today. The self-anchored suspension portion of the Bay Bridge's new east span consists of dual box girders held up by cables that are supported by the 160-meter-tall (525-foot-tall) tower located off of the eastern shore of Yerba Buena Island. The self-anchored suspension spans 565 meters (1,854 feet) between the piers E2 and W2 (as illustrated), with a 385-meter (1,263-foot) main span over the navigational channel, and a 180-meter (591-foot) back span. Once completed, this bridge will be the longest single-tower, self-anchored suspension bridge in the world. Its asymmetry subjects pier W2 to vertical uplift, while the bridge is lightly supported on pier E2. The main tower therefore carries most of the bridge's dead load. The uplift at pier W2 is fully counterbalanced by a prestressed-concrete bent cap beam.

fig. 4 | One of four footings of the tower section, at fabrication plant in Shanghai, China



The box girders are not directly supported by the tower, and are therefore “floating” at the tower; the suspenders provide the only connection between the box girders and the vertical structure. This implies that while the tower carries most of the bridge’s dead load, it is not the primary element carrying the bridge’s seismic loads.

The 0.78-meter-diameter (2.6-foot-diameter) cables are secured to the east anchorage and looped around the west bent through deviation saddles. The cables do not cross at the main tower and are secured in a single saddle. The suspenders are splayed to the outer sides of the box girders and are spaced 10 meters (32.8 feet) apart.

The east span’s superstructure consists of dual hollow-steel orthotropic box girders (OBGs) that are in longitudinal compression (reacting against the tension forces of the cables) and are a part of the gravity load system. | figs. 5, 6 Each box girder is 29 meters (95 feet) wide and 5.5 meters (18 feet) deep. Transverse diaphragms spaced at 5 meters (16.4 feet) support the orthotropic deck and distribute the suspender loads to the entire box. The OBGs are connected together by 10-meter-wide (32.8-foot-wide), 5.5-meter-deep (18-foot-deep) crossbeams spaced at 30 meters (98.4 feet) on center.

The single tower consists of four interconnected steel pentagonal box-shafts that taper toward the top and are held together with shear links. The shafts are provided with diaphragms spaced 4 meters (13 feet) apart and are rigidly connected at the top and bottom by a tower saddle grillage and a tower base grillage, respectively. | figs. 7, 8

Seismic Performance

Seismic analysis of the new Bay Bridge span was performed using the ADINA (Automatic Dynamic Incremental Nonlinear Analysis) computer program. In addition to the main span structure, the model includes boundary frames representing the skyway and the transition structure on Yerba Buena Island. The model is largely inelastic and consists of nonlinear truss and beam elements.

The bridge is a limited-ductility design, in which plastic deformations are clearly defined and predetermined. The bridge is meant to be largely elastic with the exception of the east and west piers, which are designed to form plastic hinges. The shear links between the tower shafts are also designed to yield in shear during the safety evaluation earthquake (SEE). The piles were designed to sustain minimal damage (strains less than 0.01mm/mm for concrete and 0.02 mm/mm for steel) when subjected to the SEE displacement demands. The tie-down at the west pier was designed with a safety factor of two.

References

The San Francisco–Oakland Bay Bridge East Span Seismic Safety Project, 30% Design Report, May 11, 1998, prepared by TY Lin International, Moffatt & Nichol Joint Venture, for the State of California Business, Transportation, and Housing Agency.

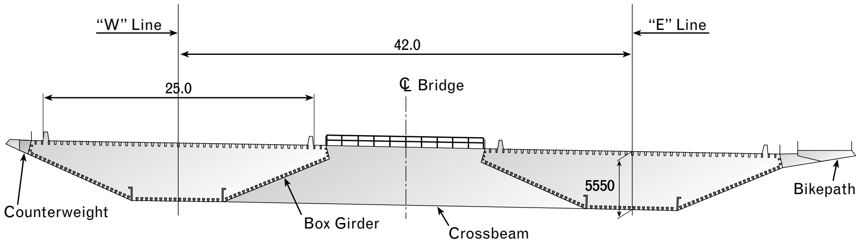
The San Francisco–Oakland Bay Bridge East Span Seismic Safety Project, Supplement to Final 30% Design Report, June 22, 1998, prepared by TY Lin International, Moffatt & Nichol Joint Venture, for the State of California Business, Transportation, and Housing Agency.

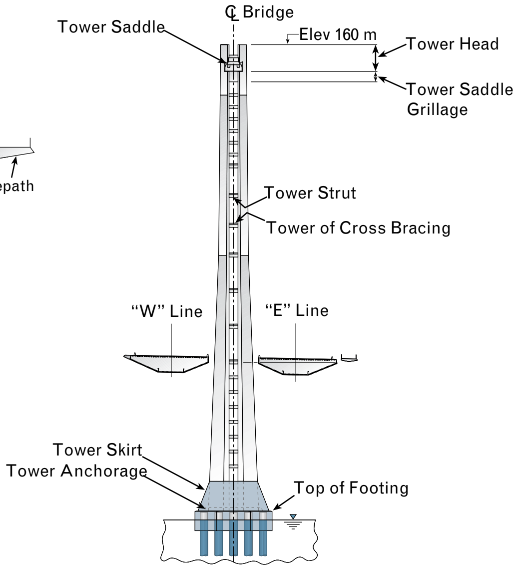
Design Criteria of the San Francisco–Oakland Bay Bridge East Span Seismic Safety Project (1999), prepared by TY Lin International, Moffatt & Nichol Joint Venture.

First Annual Progress Report San Francisco–Oakland Bay Bridge, July 1934.

Fugro/EMI Geotechnical & Seismic Report, May 1999.

Vulnerability Reports on the Seismic Performance of the Existing East Span of the San Francisco–Oakland Bay Bridge, California Department of Transportation.

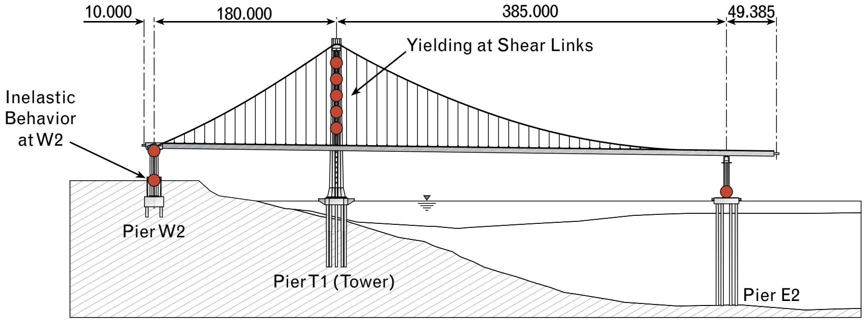


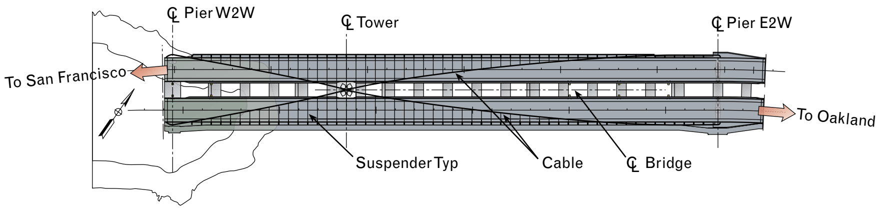


figs. 5, 6 | Typical cross section of bridge with dual box girders with crossbeam, San Francisco–Oakland Bay Bridge, California, 2013 (top left and right)

fig. 7 | Single tower of four shafts interconnected with shear links, San Francisco–Oakland Bay Bridge, California, 2013 (middle)

fig. 8 | Plan of self-anchored suspension bridge, San Francisco–Oakland Bay Bridge, California, 2013 (bottom)





Energy and Sustainability

All Inclusive: On the True Value of Materials

Anja Thierfelder and Matthias Schuler

Measuring the Impact of Materials

In recent years, *globalization* has become part of our everyday language. Along with other terms such as *sustainability*, *holism*, *ecology*, and *networking*, this vocabulary reflects how a concern for complex interrelationships and the overall whole has come to dominate discussions—whether the subject is climate, modern work environments, medicine, culture, or production. Increasingly, these dialogues apply to the realm of materials as well.

With a rapidly growing population and an escalating high standard of living for more and more people, the demand for natural resources and energy has risen sharply and continues to skyrocket. It comes as no surprise that all the major issues currently at hand—climate change, preservation of biodiversity, providing for a growing global population, and world peace—are directly related to our planet's available resources. GEO-4—the fourth Global Environment Outlook report by the United Nations Environment Programme—recalls that the world does not face separate crises, and in fact, the "environmental crisis," "development crisis," and "energy crisis" are all one. | fig. 1

Energy production and the exploitation of raw materials strongly impact politics, the economy, and the environment, resulting in side effects with tremendous local *and* global repercussions. A few brief examples, significant but by no means exhaustive, illustrate the range of ramifications stemming from raw materials extraction.

With the advent of industrial crude oil drilling roughly a century ago, hydrocarbons have made their way into the sea through extraction, transportation, and ocean dumping. They are the main causes of marine pollution and severely upset the marine ecosystem, where they enter the food chain. The extraction of crude oil in the Niger Delta, for example, has led to an ecological disaster with catastrophic consequences for the traditional farming and fishing industries—and this has caused social upheaval throughout the country.

Since the 1920s, more than two hundred German villages, especially in the east, have had to make way for excavators and open-pit mines in which brown coal is removed from seams lying just below the earth's surface. The call for "energy for all" overrides the demand for "*heimat* for a few." This trade-off takes place quietly with limited media coverage and thus limited public awareness. Large-scale relocations, however, have made the news, including the 2007 move of the 750-year-old Emmaus church in Heuersdorf in order to keep it from being destroyed by coal excavation.

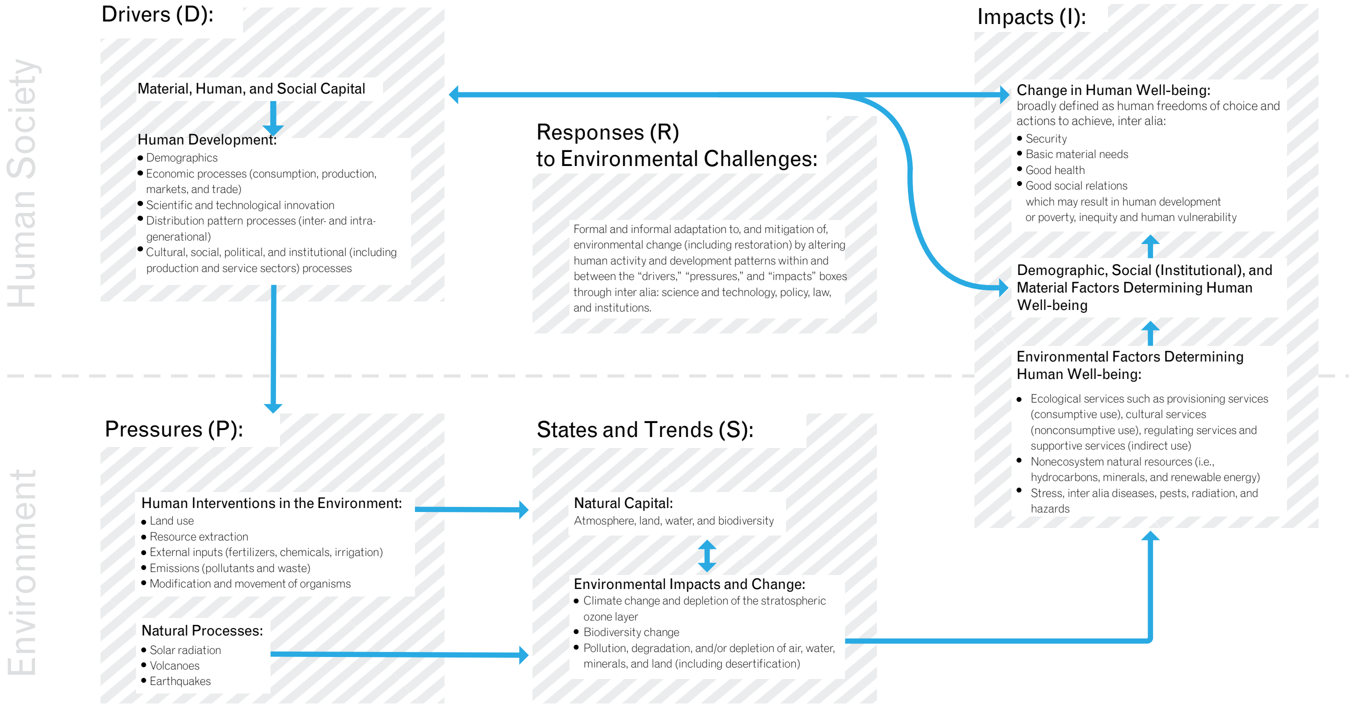


fig. 1 | The fourth Global Environmental Outlook report by the United Nations Environment Programme

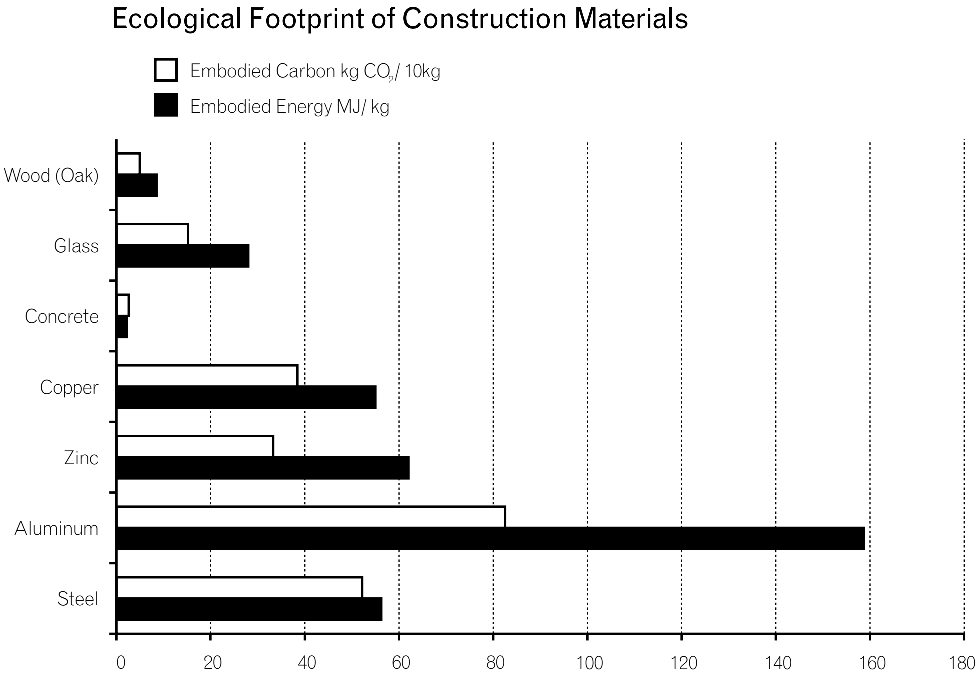
In another devastating, well-documented example, enormous amounts of radioactivity were released in the explosion of Reactor 4 at the Chernobyl Nuclear Power Plant in 1986. By 1996, 30,000 people had died from the effects of this accident, 400,000 had been relocated from the 30-kilometer (18.65-mile) exclusion zone around the plant, and five million people in Ukraine, Belarus, and Russia still live on radiation-contaminated land. Given the 24,100-year half life of the plutonium-239 released in the accident, this will be the case for a long time to come.

For more than a decade, the Republic of Congo has been ravaged by a bloody war primarily fought over the profits from the world's largest columbite-tantalite (coltan) reserves, which are, incidentally, located in one of the last natural habitats for mountain gorillas. The metal coltan is commonly found in mobile phones.

Initiatives

Architecture is also well on its way to redefining itself in this global, highly charged discourse about energy and resources. In the future, a house will be more than a house—rated today by its architecture and energy performance—and building materials will be considered beyond simple forms, such as wooden beams, bags of cement, pieces of marble, or steel girders. | **fig. 2** Assessment tools such as LEED (Leadership in Energy and Environmental Design) in the United States, HQE

fig. 2 | Ecological footprint measures of different building materials



(Haute qualité environnementale) in France, and DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) in Germany provide frameworks for rating newly constructed and refurbished buildings according to their ecological compatibilities. At the United Nations Climate Change Conference in Copenhagen, Denmark, in December 2009, the global community failed to agree on general rules for handling raw materials and energy or to set a limit for global warming. Whereas high-level politics, burdened by economic and national interests, are unable to progress past declarations of intent, there are indeed a number of future-oriented approaches on a smaller scale.

Hardly has any other region been so strongly influenced by its history of coal mining and steel production as the Ruhr Area in Germany, which is neither a landscape nor a political, historical entity. Extending over an area of 4,434 square kilometers (1,712 square miles), the Ruhr Area comprises 53 cities and communities and has a population of 5.4 million people, making it the largest economic/geographical region in Europe. Since the mid-eighteenth century, coal mining has been a central industry of the area, with new technologies for producing iron and extracting coal in continual development.

Commercial extraction of coal along the Ruhr River from the early nineteenth century marked the beginning of industrialization in the Ruhr Area. Coking plants converted coal into the coke needed for steel production in the blast furnaces of the on-site iron- and steelworks. With economic expansion, the plants enlisted more and more laborers. The population increased sharply, rising sixfold from 1871 to 1961. In 1957, the coal crisis hit and suddenly the global market controlled the raw materials market, dropping the price and demand for coal from the Ruhr Area. Coal mines closed, and by late 2008, there were only four active mines in the entire region.

Today these abandoned complexes of the past are impressive relics of the industrial age. The Zollverein Coal Mine Industrial Complex in Essen, Germany, for example, once the largest and most modern black-coal mine in the world, was named a UNESCO World Heritage site in 2002. | fig. 3 Based on a master plan by Rem Koolhaas, the site was converted into an art and design monument. The new building for the Zollverein School of Management and Design, by SANAA, was erected nearby in 2006. In 2010, the Ruhr Area was the European Capital of Culture—putting its best face forward and presenting itself to a large audience with a wide range of events. On an everyday level, however, the Ruhr Area is a region that must rethink its future and restructure itself. Converting the many lost jobs in the coal-mining and steel-making industries to employment in promising new branches and the service sector is a long and arduous process—within Germany, the Ruhr Area is regarded as an economically weak region.

The futuristic project Innovation City Ruhr might be a chance to give the Ruhr Area a strong new identity. The aim is to create an energy-efficient pilot region, an eco-city in the former industrial area—something like the internationally renowned plans for the carbon-free city of Masdar in Abu Dhabi. The region is currently searching for a city, community, or district with a social and structural fabric representative of the Ruhr Area. Ideally, the model plot would have fifty thousand inhabitants. Two-thirds of the region would consist of residential buildings, and the remaining one-third of industrial, commercial, and public structures. Innovative energy and traffic concepts would be in place within ten years. The extant structures would be renovated with high-quality materials and thermal insulation; energy would be supplied from a decentralized mix of sources including photovoltaics, biogas, and geothermal power. In the near future, electric cars would drive through the streets of the eco-city. The initiators, sixty companies who have joined forces as the Initiativkreis Ruhr, estimate the costs for this large-scale experiment at 3.5 billion dollars and hope to gain insight about sustainable urban development that they will be able to market globally in the future.

In Zürich, very concrete and ambitious plans for a 2,000-watt society were proposed by the city and approved by 76 percent of its inhabitants in 2008—with a target year of 2050. Currently, Switzerland's continuous energy use for living,

fig. 3 | Aerial view of the Zollverein Coal Mine Industrial Complex with Zollverein School of Management and Design in the background, by SANAA, Essen, Germany, 2006

including transportation and material embedded energy, is equivalent to roughly 5,000–6,000 watts per capita. According to specialists at the Swiss Federal Institute of Technology in Zürich (ETHZ), it is possible to effect a medium-term reduction of that amount to 2,000 watts by increasing efficiency in material consumption, building construction, device performance, and vehicle mobility without lowering living standards. Of that amount, 1,500 watts should be produced by regenerative energy sources. The remaining 500 watts, which would be derived from fossil fuels, would amount to one ton of CO_2 emissions. One clearly expressed goal of these measures is sustainable development, which is, according to the Brundtland definition, “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” With this in mind, it is essential that we work with a finer-grained understanding of the total cost of materials, in economic, social, urban, and environmental terms.

References

GEO-4, the fourth Global Environment Outlook: environment for development assessment is a comprehensive and authoritative United Nations report on environment, development, and human well-being, providing incisive analysis and information for decision making. http://www.unep.org/geo/geo4/media/.

Inventory of Carbon & Energy (ICE), version 1.6a, University of Bath, embodied energy and embodied carbon database, 2009.

Eberhard Jochem, Daniel Spreng, Marco Semadeni, *Steps Toward a 2,000-Watt Society: Challenges for the Technological Development in Switzerland*, Partners, ETHZ (Ph. Rudolf v. Rohr, K. Hungerbühler); EPFL (D. Favrat); PSI (A. Wolkaun), EMPA (M. Zimmermann), 2002.

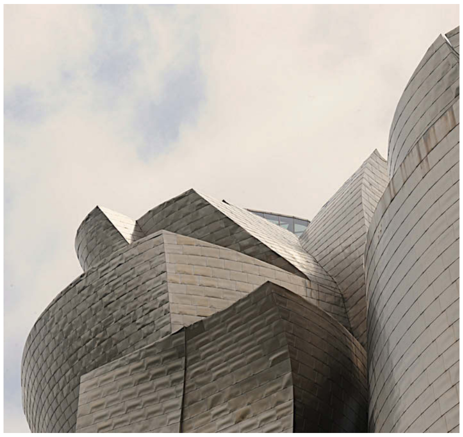


fig. 4 | Guggenheim Museum, by Frank O. Gehry, Bilbao, Spain, 1997 (left)

fig. 5 | De Young Museum, by Herzog & de Meuron, San Francisco, 2005 (middle)

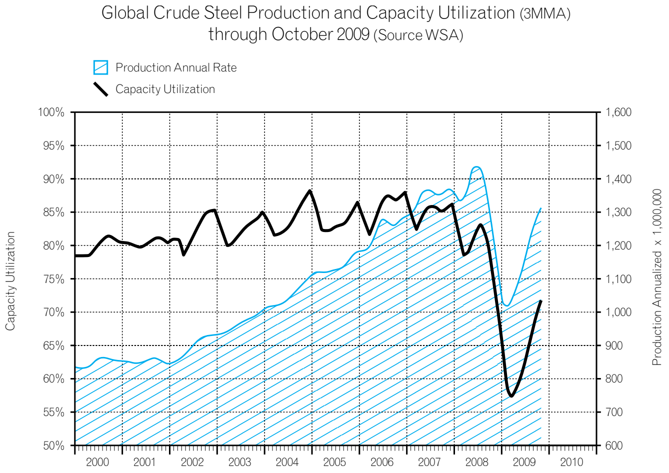
fig. 6 | New Philharmonie, by Ateliers Jean Nouvel, Paris, France, 2012 (right)

Metals

Zinc (Zn; density: 7,000 kg/m³; embodied energy: 61.9 MJ/kg; embodied carbon: 3.31 kg CO_2/kg; light, soft, and ductile)
Frank Gehry's hallmark building material is a titanium-zinc alloy that was used in the Guggenheim Museum in Bilbao, the small but striking Vitra Design Museum in Weil am Rhein, and many of his other buildings. | fig. 4

Copper (Cu; density: 8,600 kg/m³; embodied energy: 40–55 MJ/kg; embodied carbon: 2.2–3.8 kg CO_2/kg; infinitely recyclable, soft, tough, and easy to process)
This extremely weather-resistant metal is known by its distinctive colors: copper red or copper green (caused by oxidation), which is a defining characteristic of many familiar old structures. The Swiss architects Herzog & de Meuron have also clad icons of modern architecture in copper: the Switchtower in Basel and the De Young Museum in San Francisco. | fig. 5

Aluminum (Al; density: 2,700 kg/m³; embodied energy: 155 MJ/kg; embodied carbon: 8.3 kg CO_2/kg; light, soft, malleable, and easy to process)
Aluminum can be turned into sheets, window and door profiles, and fixtures and fittings, and is used in furniture construction. In the 1980s, colored anodized aluminum profiles and facade elements were trendy; today, aluminum is popular in its natural color. Due to be completed in 2012, Jean Nouvel's expressive new Philharmonie de Paris in Parc de la Villette will be fully clad in a shell of cast-aluminum elements. | fig. 6



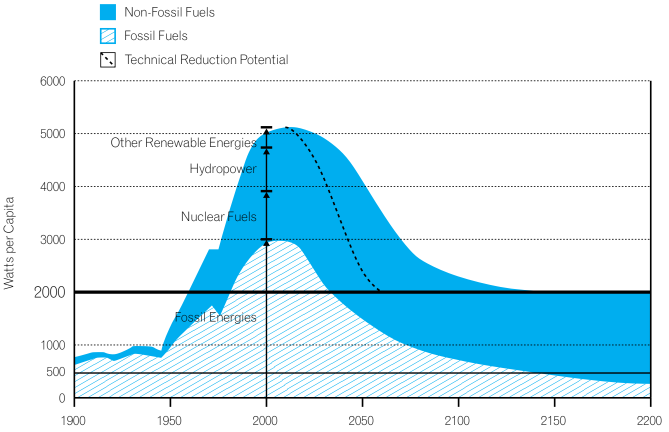


fig. 7 | World crude steel production, 2000–9

fig. 8 | World crude steel capacity utilization, 1900–2000

Steel (Fe + 2–3 percent C; density: 2,700–7,800 kg/m^3; embodied energy: 24–56 MJ/kg; embodied carbon: 1.7–6.15 kg CO_2/kg; strong, flexible, adaptable by tempering, and recyclable)

Producing steel from scrap metal saves a lot of energy and resources—roughly 1,100 kilograms of iron ore, 630 kilograms of coal, and 55 kilograms of limestone per ton of recycled steel. Steel, an alloy from iron, which contains 2 to 3 percent carbon, is much more than just a metal. Steel consumption has become a telling indicator of the global economic situation because key industries—such as the building and the automobile construction sectors—require huge amounts of steel. China's rise to economic power, for example, is strikingly reflected in its use of steel: in just a few years, steel consumption in China rose by 100 percent from 2003 to 2008 and dropped sharply by 10 percent in 2009 during the economic crisis.

| **figs. 7, 8**

Post-Ductility: From Manipulation to Cultivation of Material Behavior

Anna Dyson

Forming a continuous "genetic" thread since the Bronze Age, the essential core logic of our architectural systems has been defined by the ductile property of metals through forming tools and, subsequently, within building components themselves. With the application of ever more concentrated forms of heat energy, the quest for control and mastery over the behavior of metallic compounds has accrued with dexterity in morphing matter at the smallest scales. Our increasing ability to manage *metal flow* sustains the innovation of more exacting precision instruments in a direct trajectory from the earliest weaponry to contemporary semiconductor materials that must be heated to more than one thousand degrees and then cooled within the span of a few seconds. Within this paradigm of material formation, the embodiment of energetic processes into engineered materials increases as we travel down the scales into the nanosphere, in direct contrast to the phenomenon of self-organizing natural processes that require very low energy fluxes in their formations.

In characterizing desired properties and relative performance in design, the potential for manipulation of material structure intersects our evolving capacity to visualize and communicate the phenomena of interest to us. In our current quest for multiscalar design intelligence, there is a poignant parallel to the mid-twentieth century moment as captured in *Powers of Ten* (1968), Charles and Ray Eameses' film adaptation of the 1957 book *Cosmic View* by Kees Boeke. Reinterpreting the author's sketches of matter at different scales, the film stitches together stills in logarithmic intervals—from the nanoscale of human anatomy to the infinity of the universe—linking a series of photographic frames that depict various patterns of occurrences at each scale. The precision-machined stainless-steel instruments that manipulate light in order to register phenomena through photography comprise the unseen material framework underpinning the revolutionary imagery of the era. Yet the Eameses set up an extremely affecting array for the designer—the fascination with examining the diverse morphology of matter at each scale elicits the question of what comes in between these stills. In other words, at what point, in what way, and for what reason does one geometric pattern morph into another?

These questions inevitably rest outside our singular methods of characterizing and manipulating materials that fit into the componentry of our persistent mechanical and electrical frameworks—frameworks that are enabled and defined by the culture of manipulating metals and semimetals with their concomitant economies and means. Within figure 1, the frames below the scale of the light spectrum illustrate this phenomenon. The photographs are taken from the constituent components of a contemporary solar facade system and they incorporate a broad range of examples of modern processes of material production—from the semiconductors to the fabrication of metal dyes for precision optics. Yet all these geometries result from the conceptualization of materials within single-scale models. Even when the materials themselves exhibit a form of multifunctionality, as in the case of the switching of semimetals or the responsiveness of a shape memory alloy, they are incorporated into an assembly whereby they operate within singular scales. The interdependency across scales, as recalled through the biological and atmospheric imagery in the Eameses' stills, is reduced within mechanical assemblies to the controlled intersecting joinery of component parts, whereby the clear delineation of materials is assigned to categorically identified functions and scales. In contrast, the *Powers of Ten* array depicts a living continuum—if the geometric property of the atmospheric scale changes even slightly, there is an interdependent shift in the geometric properties of the human cellular structure. Part of what makes the film so compelling is this degree of continuity keenly felt even through its absence in the actual representation (due to technical limitations).

There is a direct parallel between the Eameses' film, which connects single-scale photographic stills and zooms across them within the motion picture, and our struggles within contemporary design practices in the production of material assemblies. Even within the most accomplished multiscalar modeling of the aerospace and automotive industries, for example, we still take single-scale models from various disciplines and stitch them together for interoperability. Can we develop viable ways to computationally exchange information and material criteria across scales within and from the inception of design procedures in order to incorporate biotic or biocompatible intelligence within built environments?

The ability to translate recent advances in the understanding of material phenomena interactions across the atomic, molecular, microscopic, and macroscopic scales into a means of expression that is unbound by the projective manipulative stance inherent to our current material methods requires a profound transformation in the methodologies of modeling, simulation, and design.[1] The conventional means of protecting authorship and identity through the leveraging of codifed inscriptions within highly regimented silos of hyperspecialization need to be reconsidered. The production of knowledge has been institutionalized to the extent that parallel and unidentifiable streams of information exchange across

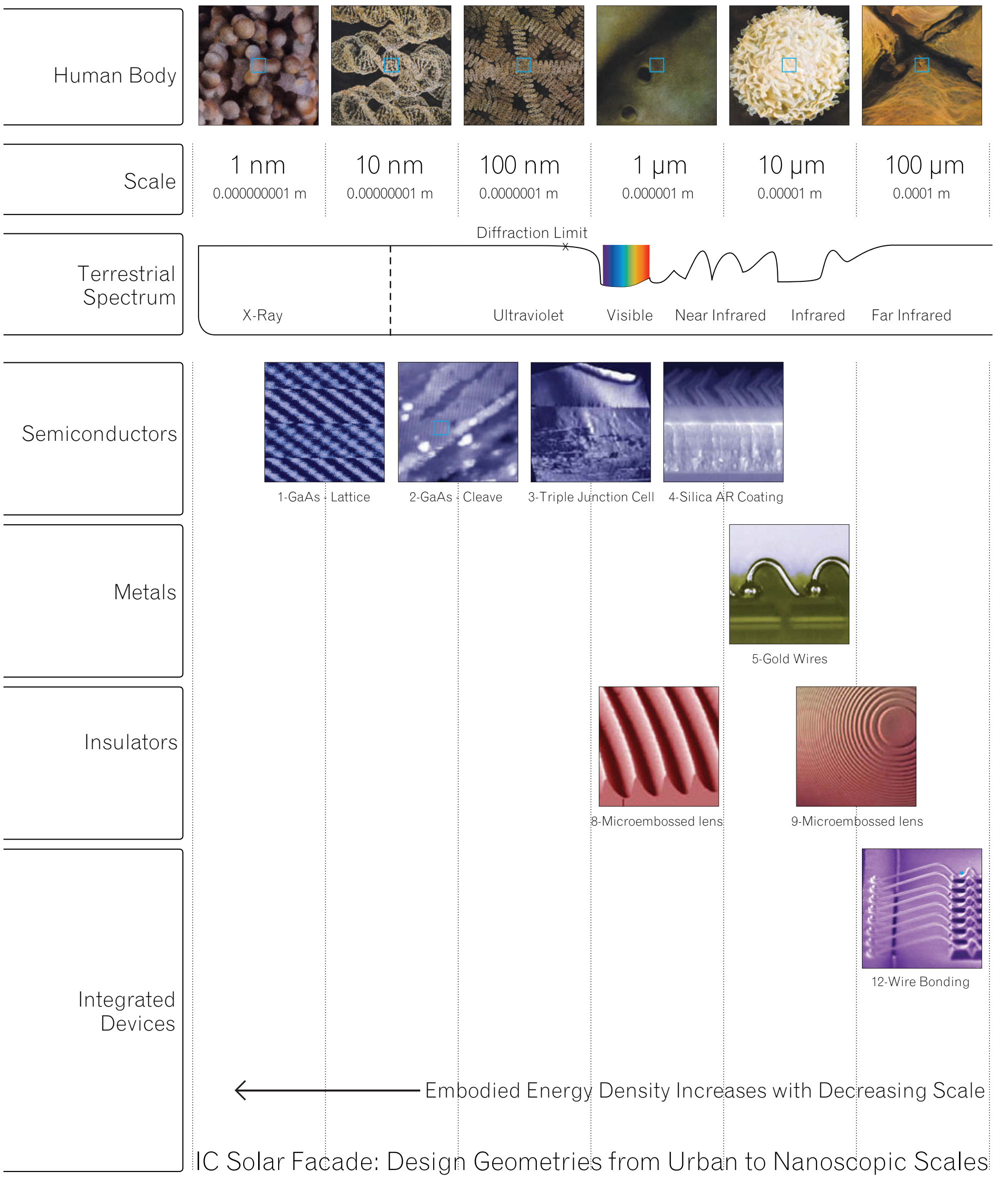
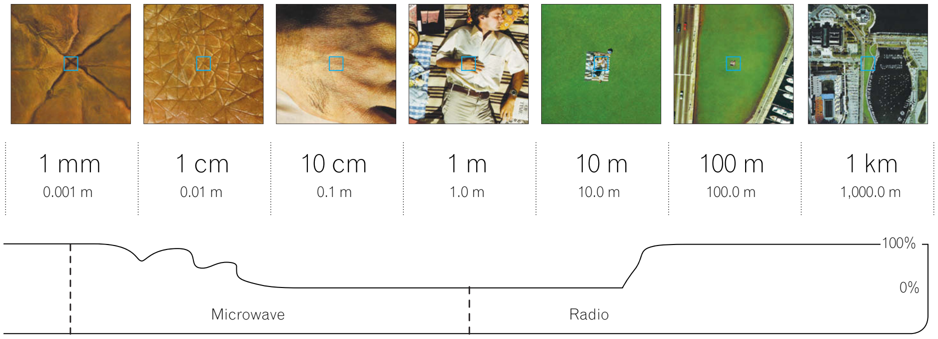
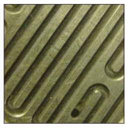
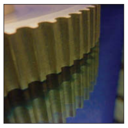


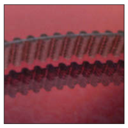
Chart examining the diverse morphology of matter at each scale, in order to understand resultant geometries from the conceptualization of materials

multiple actors may not be socially viable under the current dictates for protecting academic and industrial intellectual property. The strict means of interchanging information, combined with the necessity to protect format, boundaries, and identities, militates against the development of the continuous frameworks that are necessary for the generation of complex biocompatible assemblies that range from the material to the infrastructural scale. We are robbed of our mandate to convince "when deprived of the graphisms through which mobility and immutability are increased," as we cannot be identified as an author/owner.[2]

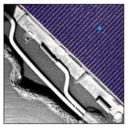


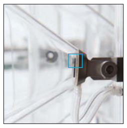

6-Heatsink


7-Timing Pulley

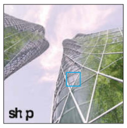

10-Timing Belt


11-Fresnel Lens


13-PV Cell and Wiring


14-IC Solar Module

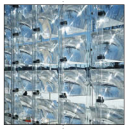
15-Housing Interior

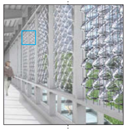


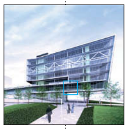
16-Mixed-Use Towers

17-Busan, S. Korea


18-Tracking Accuracy Testing


19-IC Solar Facade Panel


20-IC Solar Facade


21-Center of Excellence

The problem of the control of the format and means of information exchange directly parallels the cognitive mindset emerging from the metal-based fabrication paradigms. (This includes all materials formed through metal tooling frameworks using energy-intensive procedures—i.e., almost all noncultivation procedures.) In contrast to the elusive quest for control and stasis within our constructed systems, which rely on vast quantities of concentrated energy for manufacturing and maintenance, natural systems have evolved myriad adaptive strategies for self-assembly that effectively convert, utilize, and transport energy and material resources through dynamic processes at comparatively insignificant energy fluxes. Balanced by the processes of metabolism and thermoregulation, a range of biotic interdependent scales, from very small organisms to vast ecosystems, has grown to thrive in even the most extreme climates. These interactions across multiple scales have resulted in complex, dynamic, self-organized ecosystems that make optimum use of ambient energy flows. Built ecologies have increasingly moved toward a model of escalating dependence on internally driven mechanical and electrical systems for environmental control. The current model seeks to completely isolate built environments from the fluctuating bioclimatic energy resources surrounding them.

Ecosystems self-organize to increase their abilities to degrade incoming solar exergy. As such, they can be considered as the biotic, physical, and chemical components of nonequilibrium, self-organizing, dissipative systems that could serve as radically different models for the metabolism of natural energy flows throughout building systems.[3] While ecosystems are most resilient when cross-scale interactions reinforce one another to create redundancy at multiple scales, built ecologies can also be most adaptive to fluctuating conditions when local responsiveness is distributed throughout material systems. Recent advances in the study of ecological energetics suggest new approaches that take on the complexity of interconnected resource and demand flows, rather than decoupling them, to develop a more adaptable and robust "building metabolism."[4]

Throughout the modern era, building typologies have increasingly moved away from passively harnessing and directing natural energy flows and toward a model of escalating dependence on internally driven mechanical and electrical systems for environmental controls. Motivated by principals derived from the first law of thermodynamics—that energy may be transformed, but neither created nor destroyed—the development of building technologies has tended toward the optimization of energy conservation by resisting the flow of energy into or out of building membranes. Unfortunately, this mechanical approach to entropy minimization is more appropriate to the steam engine than urban systems, which are, as per the *Powers of Ten* opera, essentially open ended, whether we choose to model them as such or not. If considered through a framework of ecosystems energetics based on the second law of thermodynamics—that in any chemical or physical process, the entropy of the universe tends to increase—the concept of managing and directing the flow of entropy generation is more applicable and effective for built ecologies, which are essentially open-ended, as entropy increases in time in closed systems. However, in open biotic systems, inputs such as food and energy cause these systems to self-organize in an endless series of exchanges. Natural systems have evolved a web of metabolic pathways to make optimal use of exogenic energy degradation through the storage, distribution, and transformation of energy for purposeful endogenic tasks until the ability to do work is exhausted. Can we develop an informational framework that aligns with the emergence of a network of systems that degrade available energy as biotic systems do, extracting as much work from each step by matching each stratum of quality?[5] If so, the question here would be, what is our collective tolerance for "live" dynamics within our constructed environments? Given the history of our illusory quest for technological control, as exemplified by the manipulation of metals, when combined with the current inundation of environmental uncertainties surrounding the impact of that quest, we may be increasingly receptive to procedures that relinquish it.

It was the forging of metal and our reliance on combustion technologies that produced the aforementioned changes in atmospheric composition, with their cascading resonant effects all the way down to the restructuring of our DNA. However, the specter of biotically cultivated and infused built environments suggests a far deeper and perhaps more direct engagement with (out of control) technology in understanding the interdependent reactions that we are creating with our built ecologies. In the context of design, how is the complexity of such informational engagement possible within current practices? The reduction of variables has been mandated and facilitated by the legacy of methods within the intersecting spheres of academic and commercial knowledge, so the reconstitution of continuity within the academy between large networks of individuals constitutes a Herculean ambition that may be rendered vulnerable by our current attachments.

1 | M. S. Shephard et al., "Component Software for Multiscale Simulation," in *Multiscale Methods: Bridging the Scales in Science and Engineering*, ed. Jacob Fish (New York: Oxford University Press, 2009).

2 | Bruno Latour, "Visualization and Cognition: Drawing Things Together," *Knowledge and Society: Studies in the Sociology of Culture and Present*, 6 (1989): 1–40.

3 | Robert E. Ulanowicz, *Ecology, the Ascendent Perspective* (New York: Columbia University Press, 1997); S. E. Jorgensen, and James J. Kay.

4 | *Thermodynamics and Ecology* (Boca Raton, FL: Lewis Publishers, 1999); Eric D. Schneider and Dorion Sagan, *Into the Cool: Energy Flow, Thermodynamics, and Life* (Chicago: The University of Chicago Press, 2005).

5 | Eric D. Schneider and James J. Kay, "Complexity and Thermodynamics: Towards a New Ecology," *Futures* 24 (August 1994): 626–47.

Metallic Flows of the Built Environment

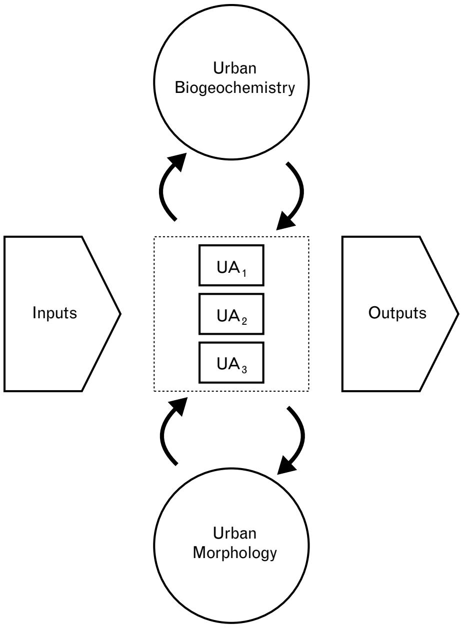
John E. Fernández

The last several decades have witnessed an explosion of data regarding the material intensity and environmental consequences of our societal metabolism. This work includes measuring intensity over time and through space at regional, national, and global scales. Studies focused on assessing the resource consumption of our contemporary world have provided some clues about the various futures that we may be making for ourselves. For example, it is now well known that the built environment accounts for a majority—upward of 70 percent by weight—of the material flow in the anthroposphere of contemporary society. This heavy material flow devoted to construction has led to shortages in rapidly urbanizing cities such as Singapore and Beijing.

Infrastructure systems—road, power, and water networks—and buildings—those that house both people and the processes and products of industrial production—demand that the vast majority of mineral ores on the earth be extracted and converted into useful metals and alloys. Our built environment is literally the largest in-use repository, or stock, of minerals that humans have gathered, and this accumulation is estimated to reach several hundred tons per capita in some developed regions.[1] To serve this demand, we have extracted minerals from relatively evenly and widely distributed global sources, and then directed their flows into a small number of dense urban population centers. In fact, 25 percent of in-use primary metals are concentrated in just three large urban regions: the eastern coast of the United States, from Washington, DC, to Boston; England to Germany and northern Italy; and in South Korea and Japan.[2]

In addition, material extraction is proceeding at ever-increasing rates. Never before has there been a more frantic period of resource prospecting, extraction, and processing than in the last one hundred years. A recent study found that global-materials use during the twentieth century increased eightfold and the GDP ballooned twentyfold, while the population only grew fourfold.[3] The half century after World War II—especially the years between 1945 and the oil crisis of 1973—saw the largest acceleration in the extraction of natural resources, and eventually led to a global per-capita materials use double that of 1900, as well as a 340 percent increase in the use of nonrenewable materials.[4] This last figure reflects the fact that many economies decreased the amount of relatively low-value, renewable biomass and replaced these with high-value, nonrenewable metals and other minerals.

Humans now use approximately sixty billion tons of material every year, an amount that rivals the total natural production of all plants on earth.[5] At the



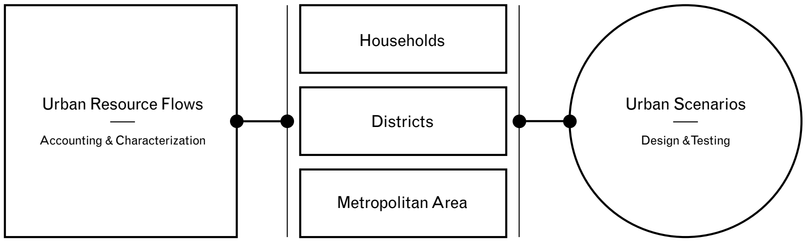


fig. 1 | Material flow analysis, urban biogeochemical and morphology relationship (left)

fig. 2 | Scope of urban metabolism research activities (right)

same time, the worrisome prospect of vastly increased natural resource use with the development of India and China looms large in many academic and governmental circles. Over the past century, the rise in energy and materials consumption closely correlated to population increases in the developing regions of the world, but in the coming decades, industrial development accompanied by massive urbanization and the spread of middle-class affluence will drive resource use to rates significantly higher than population growth. The study of this societal metabolism holds special importance for cities, leading to the emergence and significance of *urban metabolism*.

The framework of urban metabolism analyzes the behavior of contemporary cities for the purpose of developing an alternative infrastructure that delivers the provisions we have come to expect at vastly reduced resource costs. It attempts to map linkages between resource flows and socioeconomic activities in cities and looks at regional and global biogeochemical processes. Urban metabolism studies the resource requirements of cities, additions to material stocks, and the formulation of pathways toward a sustainable urban future. The physical structure of cities—their extent and growth patterns, network configuration, density, and other aspects of urban morphology—are also part of urban metabolism research. **| fig. 1**

Studies in urban metabolism can be categorized as either urban resource flows—highly aggregated assessments of the major material flows that enter, are consumed by, and then dispersed by cities—or urban scenarios—the delineation and “testing” of alternative urban scenarios based on proposals for resource efficiency and decentralized city infrastructure. These two sets of research activities can be conducted at three distinct scales: the household (individual), the district (neighborhood), and the metropolitan area (extended urban region). **| fig. 2** At each of these three levels, the demand for resources serves distinct urban activities.

Urban metabolism associates active and passive material flows with the actions that depend on them. All urban socioeconomic processes can be grouped into three general activities: the provision of shelter (the built environment), the production of goods (all industry, service, and other business activities, as well as

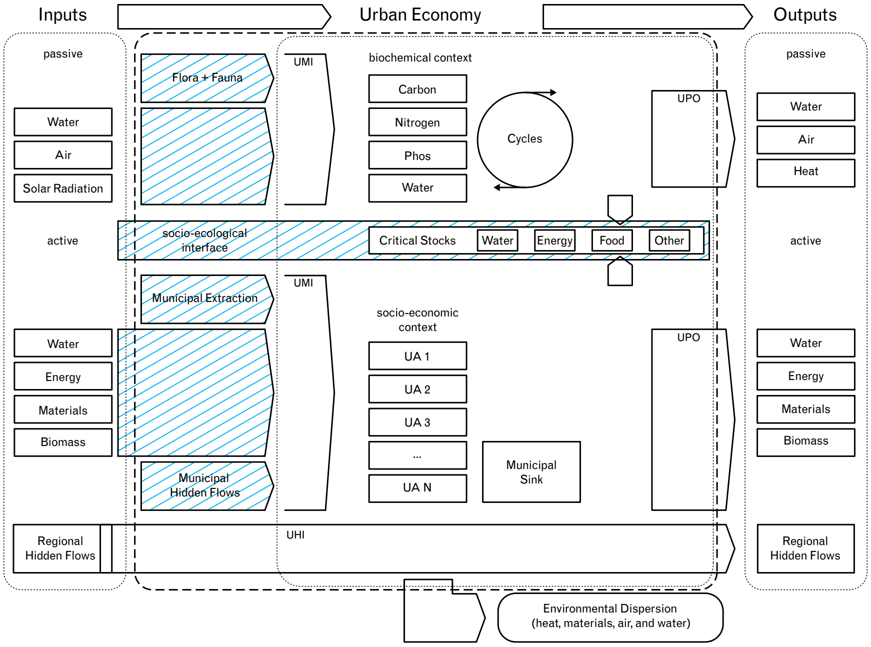


fig. 3 | Urban metabolism material flow analysis framework

cultural and educational "products"), and the transportation of goods and people. Natural or biogeochemical processes are linked to urban socioeconomic activities through passive inputs and other attributes of the metropolitan spatial zone such as primary net production from photosynthesis and carbon exchange with soil. | fig. 3

More research into urban resource use is needed, for two reasons. First, studies that establish a comprehensive, let alone holistic, understanding of the materials consumption of actual cities number fewer than a dozen. The primary method currently used to assess resource flows is material flow analysis (MFA). Founded on the principle of establishing verifiable mass balance between inputs, outputs, additions to stock, and other sinks, MFA has most often been used at a national or regional scale. A small group of researchers are making an ongoing effort to adapt MFA to the urban context. As a result, there is a sense that recommendations for improving urban resource consumption are being proposed and considered in a decidedly uninformed context. In fact, municipal policy makers regularly admit that the decision-making process in evaluating "green" city initiatives is being conducted with only an intuitive understanding of their effects and a very limited awareness of the unintended consequences of such policies. The second reason that further research into resource consumption in cities is necessary is that the level of interest from a variety of stakeholders in urban decision-making positions has grown dramatically. The evidence for this increase is found in the number of city environmental plans that highlight green technologies as a major pathway not only for a sustainable future but also for economic growth and job creation. Though the consulting community is also increasingly interested in these concepts, concern is growing that these services are creating profitable ventures at the expense of rigorous analysis and actual reduction in carbon emissions.

The multidisciplinary community of researchers involved in the study of resource consumption in cities has identified three critical goals for urban metabolism studies:

1. Resource efficiency: identifying potentials and formulating practical strategies for decreasing urban resource consumption per unit of economic activity
2. Resilience and security: researching critical stocks and proposing implementation strategies for increasing the resistance of city systems against natural and man-made disruptions in resource flows serving these stocks
3. Pollution minimization: formulating integrated solutions that drive economically robust closing of material loops, especially to reduce pollution

These goals are set within two interlinking methodologies: MFA and system dynamics (SD). As described before, MFA literally tracks the path of all physical units serving all urban activities. SD, which is derived from general system theory, seeks to map and describe the various linkages between components of a complex situation.[6]

SD is not a panacea for solving complex problems. The primary intent of the SD approach is to develop an overall architecture of components that can be used to model a question rather than reality. In doing so, the developer may need to describe large swaths of a situation, but only the relevant components. That is, if an element is part of the reality of a situation, but clearly plays no role within the question at hand, then there is no reason for its inclusion in the model. SD assists in a methodical process of identifying the parts of a system and describing, as specifically as possible, the nature of the links between these components. Often, the goal is to derive a quantitative or mathematical relationship that describes the interdependence between elements of a system. Sometimes that is impossible to do, in which case a qualitative description is sought.

MFA and SD can be used together to model various aspects of the behavior of contemporary cities. Figure 4 illustrates the relationship between material flows (as inputs), activities (as urban activities 1-n), and elements of the urban system including both critical resources—such as water, energy, and food—and system attributes, including its ability to respond to emergencies, potential for adaptation and symbiotic adjustment, and behavior that results in structural shifts. | **fig. 4** While this diagram is highly abstract, it can be resolved through the connections between

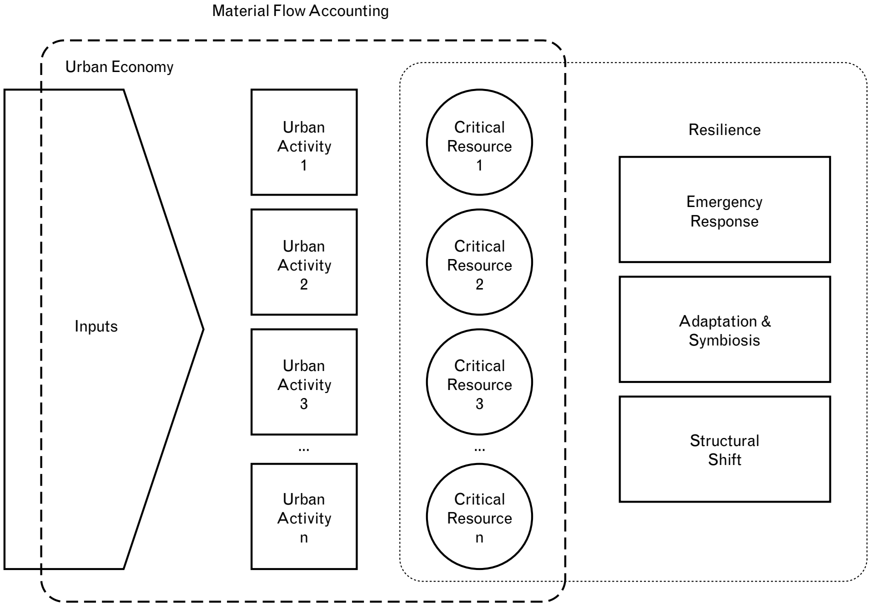


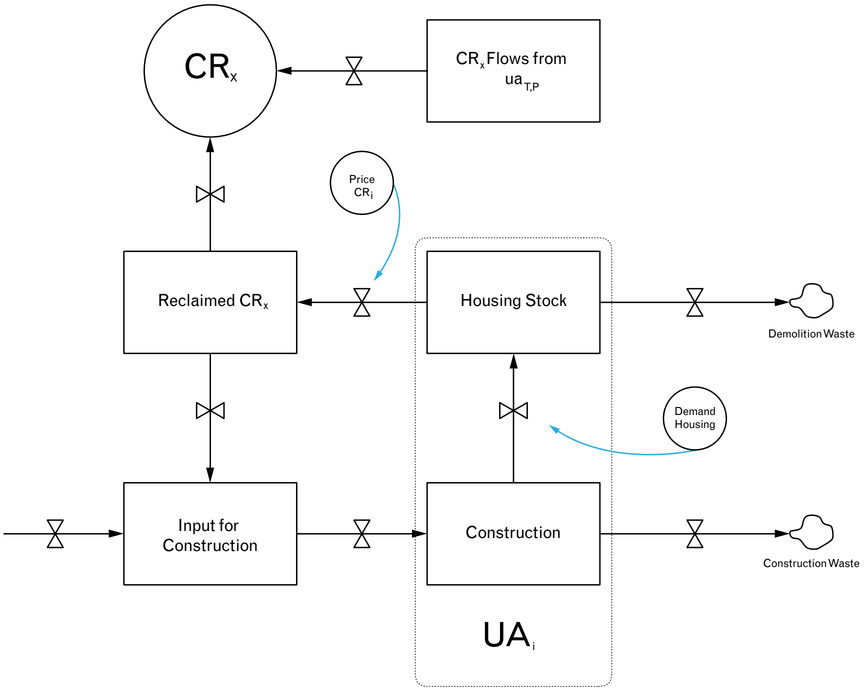
fig. 4 | Material flow analysis and system dynamics, urban activities and critical resources

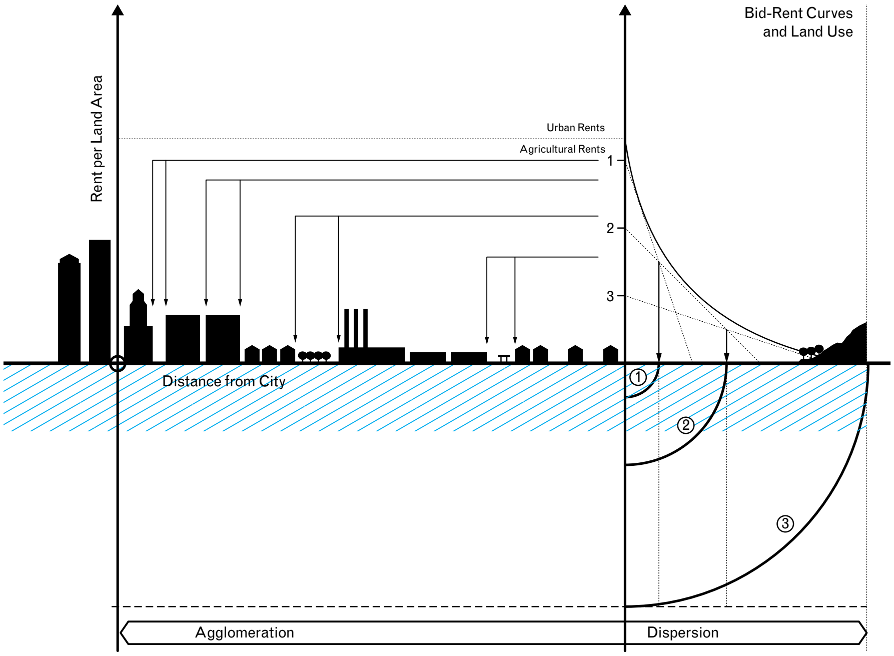
assessing the rate of flow of a specific resource—say water—and the ability of a city to adopt conservation policies and design and construct water harvesting infrastructure to improve emergency response, provide for adaptation, and generally increase the resilience of the urban water system.

Conceptually, MFA is easier to implement in a rigorous, empirically derived mode than SD, which requires that the modeler establish an architecture of relationships while also considering the link to the physical flows of the situation. For example, figure 5 shows a schematic of metal flows that serve urban housing. **| fig. 5** The lower left-hand portion of the diagram shows extraction as the primary input to construction, which then continues to the right to feed the subsystem, UA_i. This is the urban activity of the built environment. That is, UA_i represents the provision of housing in an urban context. The only physical flow mapped here is metal (specifically iron). Arrows to the right of UA_i delineate the output of metal from construction and after demolition at the end of the service life of the housing unit. Metal recoverd after disassembly flows into the reclaimed critical resource stock, CR_x. The secondary input of metals into urban housing construction originates from this reclaimed stock, which is also fed by the recovery of metals from other urban economic sectors such as transportation (CR_x flows from $ua_{T,P}$). Levers in the system are shown as the price of iron (price of CR_i) and the demand for housing. This limited scenario attempts to delineate the interaction between the various system components that determine the flow of a critical resource. Reclaiming that resource can be promoted or discouraged by various policies that affect the

fig. 5 | Urban metabolism material flow analysis framework (top)

fig. 6 | Urban agglomeration and dispersion (bottom)





price of the metal or the demand for housing. Clearly, the complexity of the diagram is highly dependent on the scope of the question.

Urban resource planning—especially within the emerging modes of green city design and eco-planning—must account for the complexity inherent in achieving desired effects in multiple economic, social, and physical realms. Economic dynamics and resource dynamics—the location and nature of value and the intensity and character of resource flows in an urban context—are inextricably linked in both time and space. Urban metabolism has begun to delineate these links while also aiming to reveal the holistic map of materials consumption in cities. | fig. 6 Large-scale integrated modeling efforts, such as the U.S. Long Term Ecological Research Network, aim to bring to light the important, though often ephemeral, dynamics that connect socioeconomic activities with ecological and biogeochemical processes. In the next few years, urban metabolism will serve to elucidate the various links between urban activities and resources while focusing on the creation of practical and rigorous urban sustainability indicators.

1 | Seiji Hashimoto, Hiroki Tanikawa, and Yuichi Moriguchi, "Where Will Large Amounts of Materials Accumulated Within the Economy Go?—A Material Flow Analysis of Construction Minerals for Japan," *Waste Management* 27 (2007): 1725–38.

2 | J. Rauch, "Global Mapping of Al, Cu, Fe, and Zn In-use Stocks and In-ground Resources," *Proceedings of the National Academy of Sciences* 106, no. 45 (2009): 18920–25.

3 | Fridolin Krausmann et al., "Growth in Global Materials Use, GDP and Population during the 20th Century," *Ecological Economics* 68, no. 10 (2009), doi: 10.1016/j.ecolecon.2009.05.007.

4 | Fridolin Krausmann et al., "The Global Sociometabolic Transition: Past and Present Metabolic Profiles and Their Future Trajectories," *Journal of Industrial Ecology* 12, no. 5–6 (2008): 637–56.

5 | Helmut Haberl et al., "Quantifying and Mapping the Human Appropriation of Net Primary Production in Earth's Terrestrial Ecosystems," *Proceedings of the National Academy of Sciences* 104, no. 31 (2007): 12942–47.

6 | Ludwig von Bertalanffy, *General System Theory: Foundations, Development, Applications* (New York: George Braziller, 1969).

References

Alberti, Marina, and John M. Marzluff. "Ecological Resilience in Urban Ecosystems: Linking Urban Patterns to Human Ecological Functions." *Urban Ecosystems* 7, no. 3 (2004): 241–65.

Brunner, P. H. "Beyond Materials Flow Analysis." *Journal of Industrial Ecology* 6, no. 1 (2002): 8–10.

Glaeser, Edward L. "The Economic Approach to Cities." Discussion Paper no. 2149, Harvard Institute of Economic Research, Harvard University, Cambridge, MA, 2008. http://www.economics.harvard.edu/pub/hier/2008/HIER2149.pdf.

Gordon, R. B., M. Bertram, and T. E. Graedel, "Metal Stocks and Sustainability." *Proceedings of the National Academy of Sciences* 103, no. 5 (2006): 1209–14.

Grimm, Nancy B. et al. "Global Change and the Ecology of Cities." *Science* 319, no. 5864 (2008): 756–60.

McDonnell, Mark J. et al. "Ecosystem Processes Along an Urban-to-Rural Gradient." *Urban Ecosystem* 1, no. 1 (1997): 21–36.

Vitousek, Peter M. et al. "Human Domination of Earth's Ecosystems." *Science* 277, no. 5325 (1997): 494–99.

World Urban Forum—an organization of the UN-Habitat. http://www.unhabitat.org/.

Adaptation in Structure

Craig Schwitter

The concept of post-ductility for metal as a construction material raises many issues that engineers are grappling with today, as technological advances in analysis and manufacturing continue to evolve. Thinness, or the minimization of materials, has been a constant goal in engineering for most of the twentieth century, manifest in the lighter and longer bridges, leaner and higher towers, and seemingly weightless roof constructions built over the past century. Driven by innovations in materials and structural systems, architecture embraced the edict of lightness and rational form from the modernist explorations of the 1950s through to the high-tech movement of the 1980s and '90s. As a member of the engineering field, which is inherently concerned with minimizing energy and materials, the firm Buro Happold has always worked to get more out of less.

Steel has been, and continues to be, a transformative metal in the construction industry. To achieve both minimization of materials and maximization of architectural expression beyond simple shapes, engineers look to highly developed forms such as shells, cable nets, and other geometrically efficient systems. An example of this ideal of structural thinness is the 1999 Millennium Dome in London, whose cable and metal structure supports a roof with an external diameter of nearly twelve hundred feet. | fig. 1 After many achievements over the past fifty years in building design, structural engineers must shift their focus. To use an analogy from the automotive industry, making an efficient chassis for a car is no longer enough. A strong and elegant structure may be dependable, but buildings must respond to more in the next wave of architecture. Strength and dependability are prerequisites, but performance drives solutions.

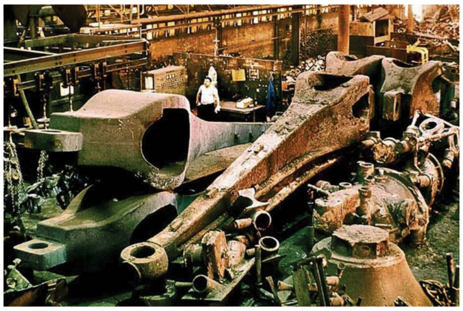
Public expectations contribute to the rapid regeneration and upgrading of buildings. The idea of post-ductility implies extending the limits of metals as materials, but in a more general sense, metals must allow for greater flexibility of form, surface, and space, as well as for adaptability in structure. Dynamic structures, either in the form-finding process or when used in construction, will need to function as more than just static frames and envelopes. As environmental issues become more urgent, the transient nature of buildings will develop in more sophisticated ways. Transience—for the purpose of beauty, marketing, performance, comfort, or energy reduction—will be paramount to the architect and engineer. Buildings, conceived as immovable objects or monuments of stone in the past, will start to change. | fig. 2

Arguably the most influential and earliest structure of the high-tech movement, the 1977 Centre Georges Pompidou in Paris uses frame components created

from cast metal, and it remains an icon of a building-as-machine. Except for the large-scale castings—such as the gerberettes—most of the structure's components exist in a static condition: despite the fact that they aesthetically express a fluidity of shape and form, they are ultimately immovable. From a material standpoint, the museum's structure speaks of craft, of each component in a machine doing its job properly. But its pieces remain frozen in time, an effort to maximize a structural framework for future flexibility. Even though it is static, the Centre Pompidou's structure serves as a rational, efficient, and beautiful system for the building. | fig. 3

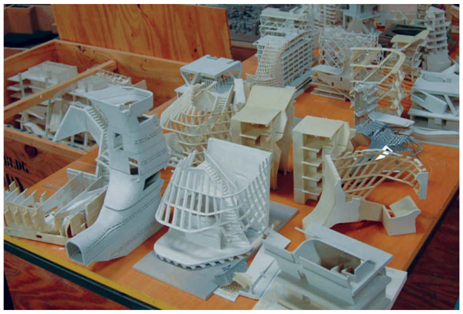
For the 2009 Cooper Union academic building in New York City, designed by Morphosis Architects, Buro Happold created a frame to clad an internal circulation and atrium space. Developed directly with the architects and contractors, the structure was essentially built from kits of scaffolding parts. Its geometries were laid out three-dimensionally, and early discussions with fabricators ensured an economical yet lightweight structure. The joints of the system informed the end structure and allowed for certain rotations. Buro Happold digitally "molded" a final form, which was then detailed and fabricated. While static in its built form, the complex framework acts as both screen and object, speaking to the fluidity of the atrium within the building and the ever-changing perspectives it opens up to occupants. | figs. 4–6

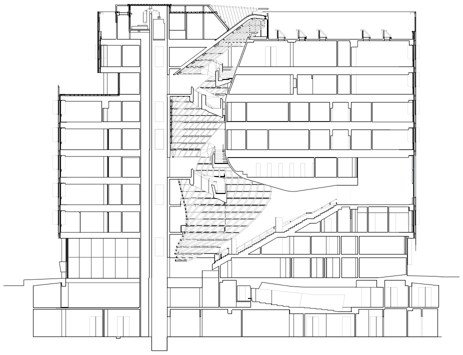
The King Abdulaziz Center for World Culture in Saudi Arabia, designed by Snøhetta, continues the theme of complex surfaces developed to meet programmatic and functional requirements. Buro Happold developed the center's structural and building services systems, as well as the facade system's detailed geometries. The firm envisions the facade as a shield against the intense desert environment, designed to cover the complex curvatures of the buildings with a network of exposed stainless-steel, two-inch-diameter pipes.



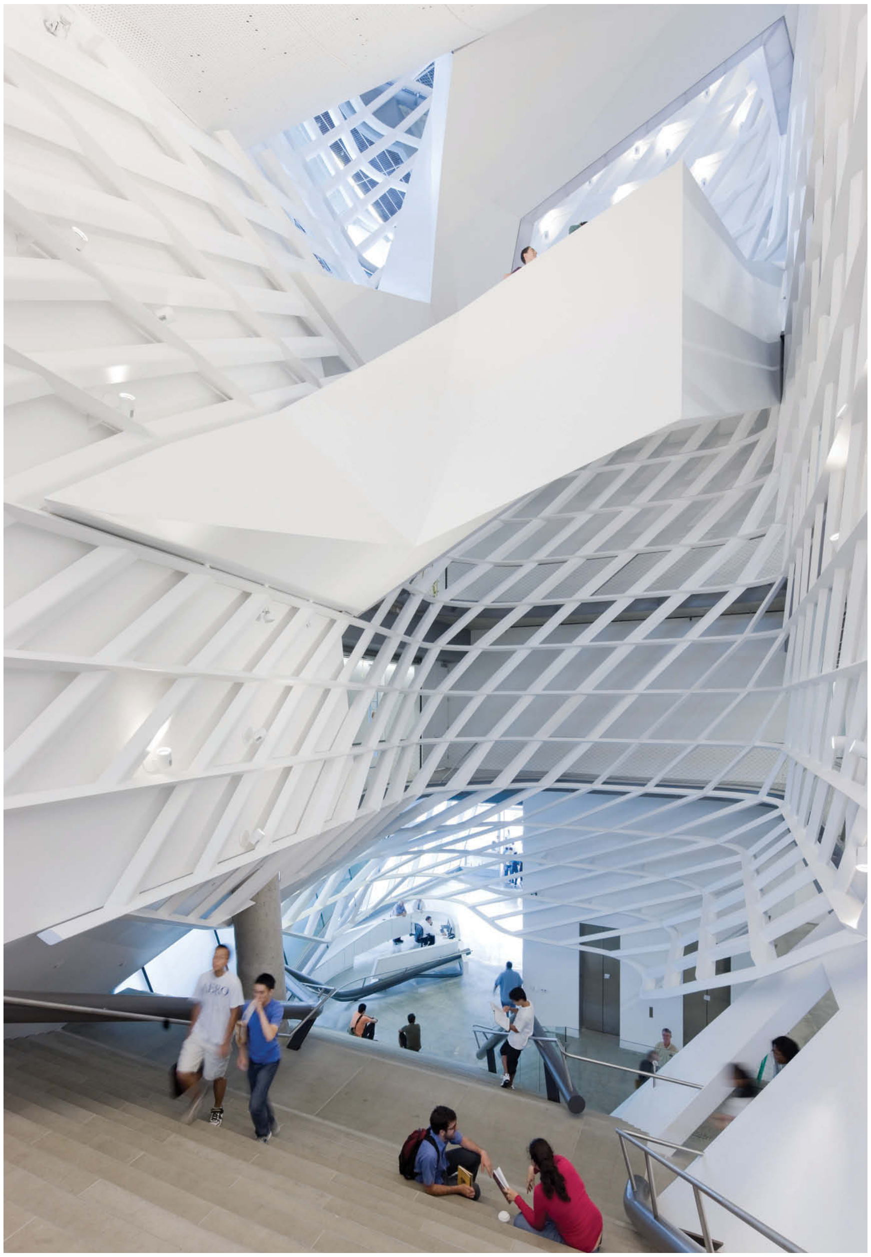
figs. 1, 2 | Views of construction, Millennium Dome, by Foster + Partners, London, England, 1999 (top and middle)

fig. 3 | Castings for Centre Georges Pompidou, by Renzo Piano and Richard Rogers, Paris, France, 1977 (bottom)





figs. 4–6 | Spiral in central atrium, shown in model studies, section, and completed structure, Cooper Union Science Building (41 Cooper Square), by Morphosis Architects, New York, New York, 2009

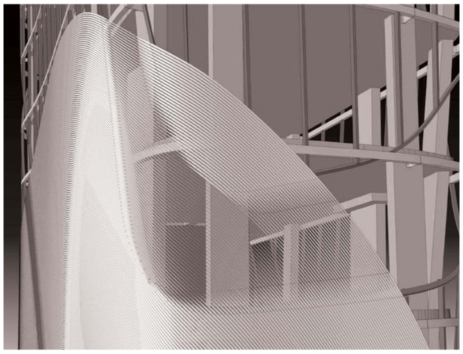


The pipes were mapped onto the surfaces of the building and individually bent based on fabrication information provided to the contractors. In the areas where windows exist behind the cladding screen, the tubes have been flattened, allowing daylight to penetrate the interior. The center's facade has a fluid form both in its overall system geometry, but also in the mapping of its surface. The pipes are bent by a programmable machine, deforming to continually changing radii in order to satisfy the layouts of the surface map. As a result, the piping does not need to conform to simple curvatures, but can be developed to any shape. This flexibility of form, coupled with a performance-based design for the facade, serves as an example of a static system that can be considered transient. A snapshot in time for the building form, there are a myriad of forms that could take hold, and a wide range of apertures to satisfy the building's internal performance. | **figs. 7–9**

Buro Happold also worked with Foster + Partners to create grid shell structures for two recent projects: the Great Court at the British Museum in London and the Robert and Arlene Kogod Courtyard for the Smithsonian Institution in Washington, DC. The Great Court, completed in 2000, was an early expression of a minimal-material grid shell, developed to enclose a nonsymmetrical courtyard in the museum. An expression of pure lightness, the courtyard space contrasts with the surrounding historic stone structures of the museum. The roof, consisting of custom-cut, welded-steel nodes, is approximately 3.9 inches deep with spans of up to 82 feet. The design was intended to make minimal use of the curvature of the shell, and develop a thin expression of the triangulated surface. | **fig. 10**

In comparison, the shell for the 2007 Kogod Courtyard enclosure functions more as an environmental filter for the space. The shell's depth, with more structural material, was designed specifically to allow for a maximum amount of surface area to be coated with an acoustically absorbent material, creating better performance characteristics in the space. The blades of the shell are also tilted, and their depth is used to provide natural sunlight shading and allow the enclosure's glass to be more transparent. | **figs. 11–13**

These two grid shell projects express the ongoing development of performance-related elements in building design. The Great Court could be seen as a response to the old maxim of minimum material use, while the Kogod Courtyard is more attentive to issues of sound, light, and environment. Although they are static in their final constructions, both structures speak to the adaptivity of form inherent in surface structures such as grid shells. The two courtyard enclosures respond to the boundary conditions of the existing buildings, as well as to height restrictions to meet historic preservation requirements. But these skin



figs. 7–9 | Model, detailed rendering, and facade fabrication, King Abdulaziz Center for World Culture, by Snøhetta, Saudi Arabia, 2011

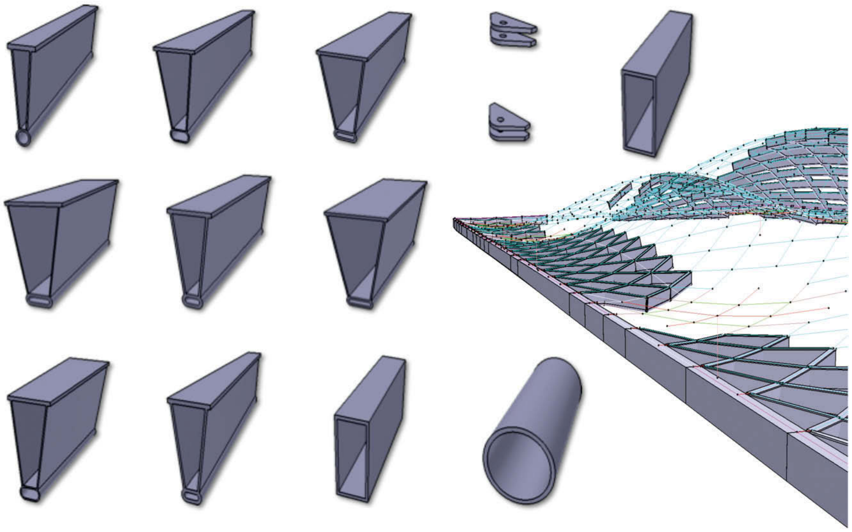


fig. 10 | Great Court, British Museum, by Foster + Partners, London, England, 2000 (top left)

fig. 11 | Smithsonian Institution, Patent Office Building, by Foster + Partners, Washington, DC, 2007 (top right)

figs. 12, 13 | Roof details, Smithsonian Institution, Patent Office Building, 2007 (bottom) structures do even more—they allow interior spaces to adapt to changing external conditions.

While the previous examples alluded to the adaptive nature of metals associated with formed surfaces, a screen system that is part of the center stage for the band U2's 360° tour—developed by inventor Chuck Hoberman and Buro Happold—is a structure that changes in real time. Hoberman and Buro Happold have long worked together in developing such systems, of which the project for U2 is but one in a series. The U2 system is an expanding group of connected screens—approximately sixty-five feet tall with a radius of roughly thirty feet at the top—that hangs from the stage constructed for the band's tour. In its compressed state, it is a series of struts and nodes that allow the screen to expand. When compressed, each node has a screen forming a complete image, but when expanded, the screens develop a single, large, pixelated image. The screen system is both an object and a communication device: it acts as a theatrical lighting fixture for the show and also displays large-scale images for the audience. Inherently adaptable, the screen adjusts in size and pixilation throughout the show. | fig. 14

Moving and transient construction systems are the true machine structures of our age. Although we do not often see large-scale moving elements like the U2 screen system in building form, we can and will see more structural and enclosure systems that develop a transient response to the end user. As people demand greater performances from the buildings they occupy, architects and engineers will need to push metal elements to new uses. These innovations will probably not be dominated by minimization of materials or the structural rationalization of form. Rather, they will more likely address energy consumption, user comfort, and risk reduction for unforeseen conditions. Adaptation is not a new concept, but it is one that, in its widest sense, the next wave of building engineering solutions must address.

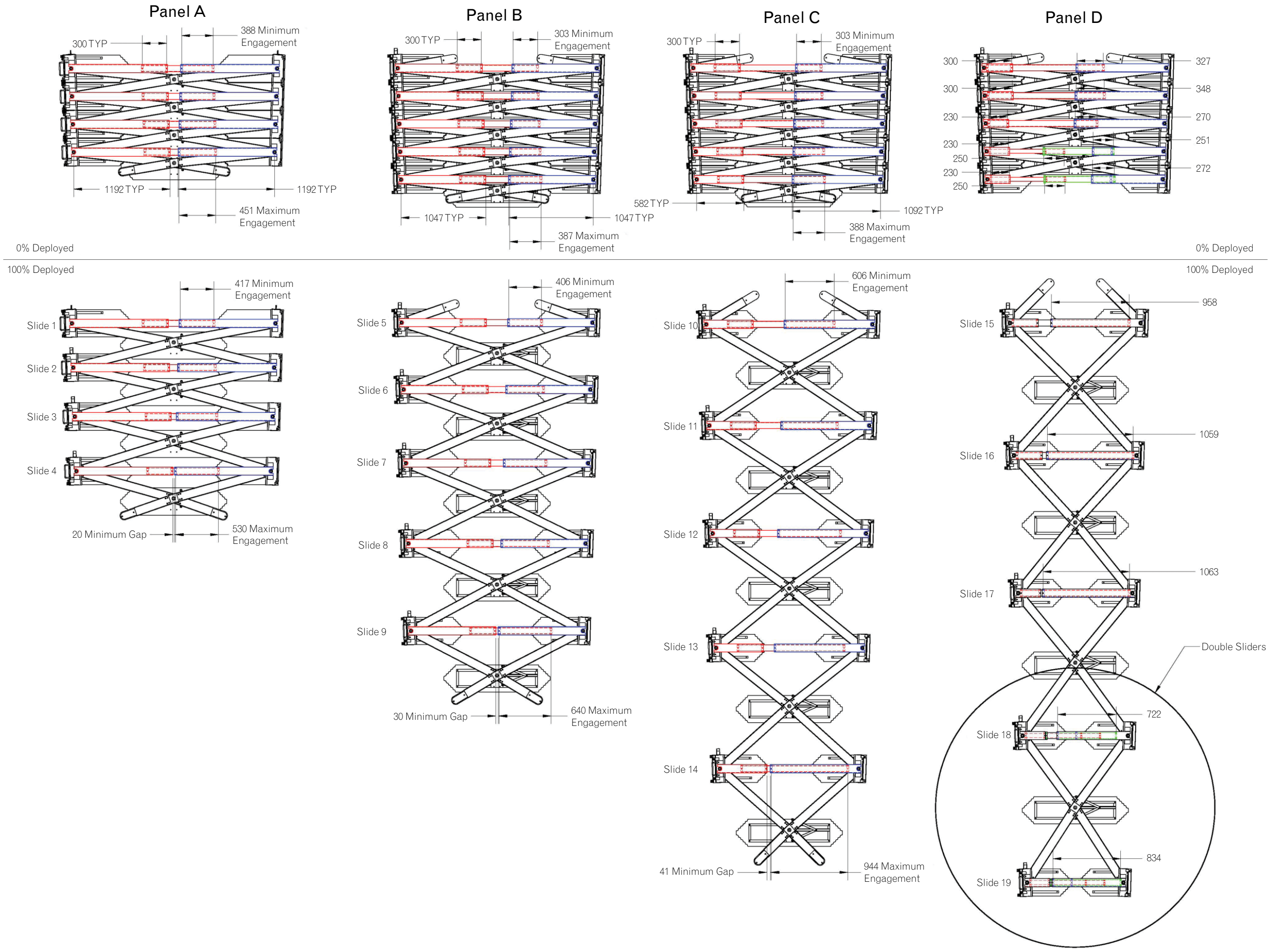


fig. 14 | Hub stabilizers used on columns, U2 360° Center Stage Screen, by Chuck Hoberman, 2009–10

Inside Out: Climate Engineering for Exposed Structure

Mark Malekshahi

Much of this book deals with the effect of the natural environment on ductile materials and the resulting challenges and benefits. This essay moves away from those external impacts to concentrate on mediating the effects of the interior environment on ductile materials, both through climate control and through architectural solutions. At their first glance into the design and program of a project, architects and engineers often consider the impact of humidity and thermal variation on the building's structure, and particularly on its exposed elements. As these unprotected parts of the structure become more common in a variety of building designs, long- and short-term impacts on them will need to be closely studied.

COR-TEN, or weathering steel, became an interesting structural element in the design of a series of buildings in the 1970s. Perhaps the best-known example is Roche and Dinkeloo's Ford Foundation Headquarters (1967). The use of exposed structure both for interior and exterior of the building provided a challenge for the climate engineers and the architects. Employing weathering steel in the interior is an issue to which climate engineers must be sensitive and respond carefully.

Unprotected weathering steel has certain design and code restrictions. An exposed steel structure treated for fire protection will provide more freedom for the design team to showcase the steel. For the purpose of this discussion, I would like to review three of our past projects that dealt with the issue of climate control and exposed interior structure.

Most commercial building design requires climate control that is within the standard range of human (occupant) comfort of 60 to 80 degrees Fahrenheit, with a relative humidity (RH) of 20 to 60 percent. In addition, the interior conditions of a building fluctuate according to the number of occupants, outdoor ventilation, or potential greenery. The challenge is to minimize the impact of these fluctuations on the structure.

Traditionally, building climate engineering tends to gravitate toward solutions that require the isolation of exterior from interior. However, this methodology conflicts with the design intent of modern transparent exterior walls, which are frequently integrated with an exposed structure. Furthermore, this approach limits the envelope options for buildings with tight climate-control tolerances, such as museums or semi-industrial structures. When working on these types of buildings, we evaluate the potentials for zoning the program and building, moving sensitive areas to the center of the building and locating the open, more active parts of the program toward the exterior envelope, even if it is a glass enclosure. With

fig. 1 | Glass Pavilion, Toledo Museum of Art, by SANAA, Toledo, Ohio, 2006

this approach, energy consumption is reduced and appropriate climate control is more easily achieved, and the architect's vision of a more transparent building can also be realized.

The Glass Pavilion at the Toledo Museum of Art (2006), designed by SANAA, is an example of such an approach. | fig. 1 The design directive from the museum was to integrate as much transparent skin as possible, and SANAA's original intent was to provide a clear, single-pane glass wall. We undertook the project with this method in mind and incorporated a cavity wall that provided a tempered buffer zone between the interior gallery climate of 72 degrees Fahrenheit and 50 percent RH and the ambient set point of -3 degrees Fahrenheit based on winter temperatures in Toledo, Ohio.

During our initial investigations into a climate-control solution that would satisfy the pavilion's program as well as provide comfort for its occupants, we determined that an all-air system could not be fully integrated with the architectural design. Therefore, we concentrated on a hybrid solution that would utilize radiant heating and cooling for both the ceiling and floor to reduce the overall airflow requirements. We supplemented this with a reduced local airflow system to lower any chance of condensation forming in the glass wall cavity or on the steel columns and other steel surfaces. The lower airflow rate saves fan energy and reduced the number of supply-air diffusers needed. In addition, a tempered

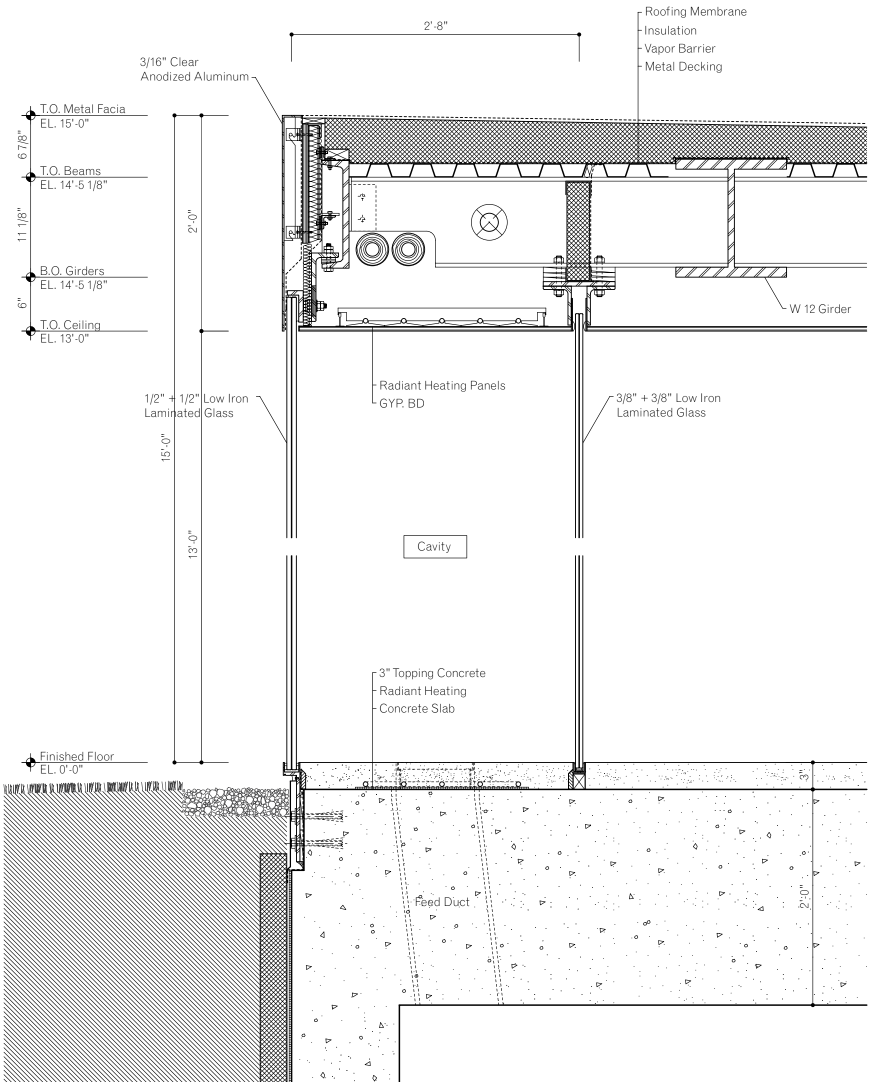


fig. 2 | Section diagram of curtain wall, Toledo Museum of Art, 2006

exterior airflow supply protects the quarter-inch-thick steel plates that serve as shear walls from temperature fluctuations with changing climate conditions. The hybrid system was an optimal solution that maintained the architectural concept while keeping the overall mechanical costs within budget. | fig. 2

Gund Hall at Harvard University, designed in 1972 by John Andrews to house the Graduate School of Design, is a good example of a building whose exposed structure has a strong negative impact on the interior climate. At the time of its construction, the predominate form of climate control was all-air systems. The building's supply air is introduced overhead and the return intakes are located at the top of an upper platform level. This system's performance was compromised by Gund Hall's exposed structure, which had almost no insulation coverage and acted as a thermal bridge from inside to outside. From the start, the interior conditions were unbearable in a climate that requires heating for much of the year. The steel structure acted as a conduit that transferred cold air from the upper ceiling down to the lower platform. In some areas, the steel was so cold that condensation was running down the beams and onto the students' work. The condition was also damaging to the structure. The university's facilities management team was forced to compensate for the climatic conditions of the space, implementing some remedial heating measures for the occupants in the lower platform.

As part of our search for an energy-efficient alternative system for upgrading Gund Hall, we proposed multiple schemes that would increase the R-values of the glass facade and roof. We understood that the increase in envelope performance could only be part of the solution. However, given the structural capacity of the roof, improving the roof's thermal performance proved too costly. Still, we were able to reduce the air infiltration and thermal bridging in the facade. We proposed altering the climate-control system to provide a more uniform temperature between lower and higher platforms, settling on central VAV—a fan-powered box system with heat recovery—as the solution that would utilize most of the interior mechanical system with modest alterations and minimal impact on the structural load or occupants. The integration of the fan-powered box provides more local control and better airflow. It will also break into the air stratification occurring at the ceiling, interrupting the downward flow of cold air that had made conditions so unpleasant. A computational fluid dynamics (CFD) analysis of the modified system concluded that the expected temperature at the occupant level will stabilize at approximately 69 degrees Fahrenheit during the winter months, with better control of airflow and more even temperatures throughout the building. The energy savings with the improved envelope and system modifications will reduce Gund Hall's energy use by about 28 percent a year.

A third case study involves issues that are typical in semi-industrial buildings, for which climate control is critical for the operations within and infrastructure maintenance. In 2009, Buro Happold designed a water-processing plant for the town of Framingham, Massachusetts, with a roof structure of exposed steel and wood beams. The climate parameters called for an upper limit of 50 percent RH, which is a normal criteria for a commercial building. In this case, we were challenged with a processing program that included open water-filtration tanks and minimum air changes. Additionally, the client was interested in registering the project as a LEED-rated, energy-efficient, sustainable design.

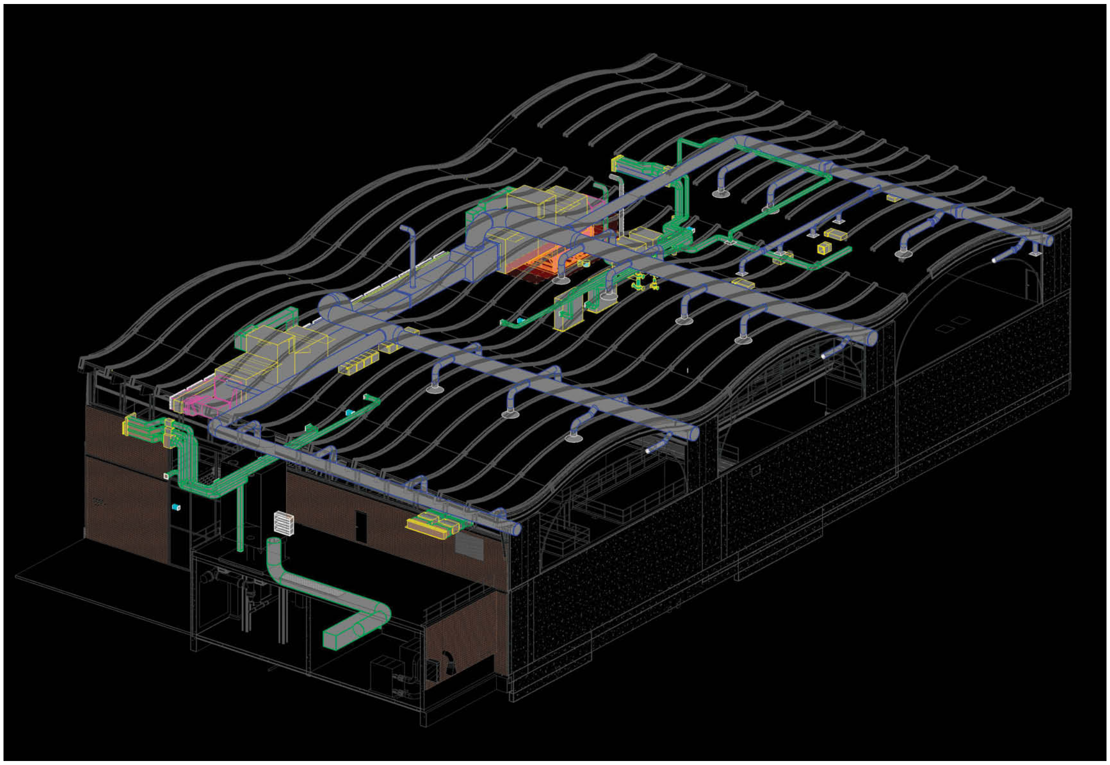
To achieve these goals, we had to make sure that the climate-control system not only provided air-conditioning for the plant operators, but also maintained

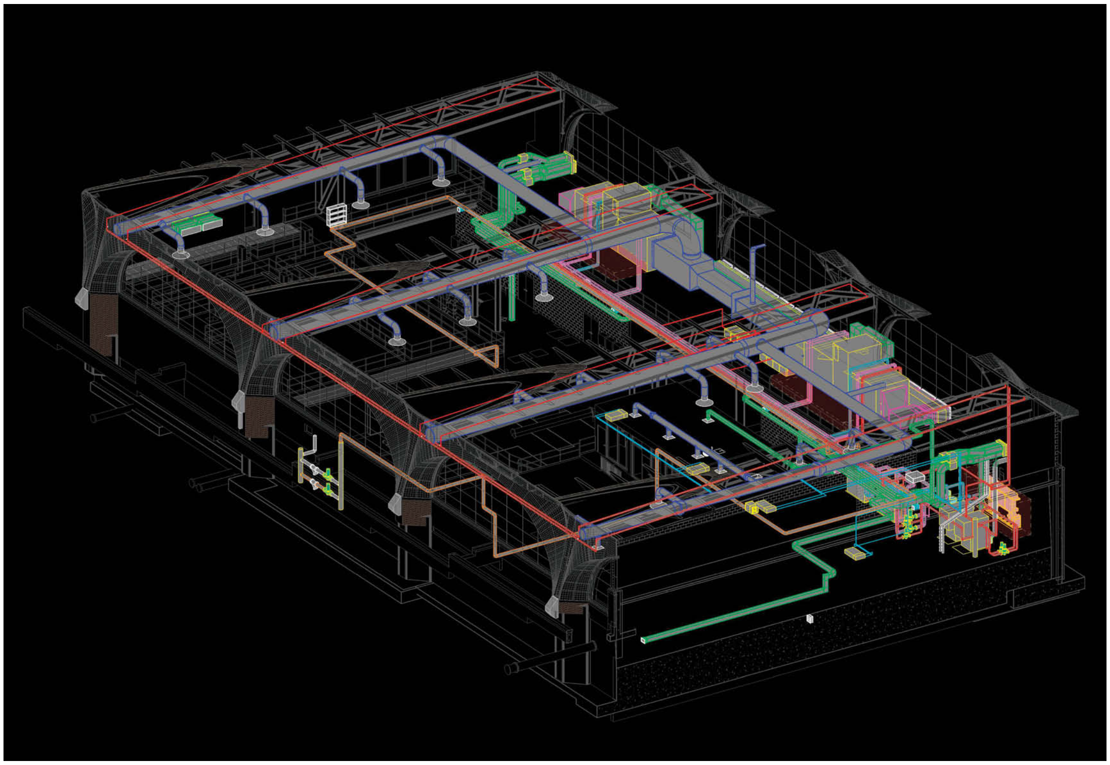
figs. 3, 4 | Water-processing plant, by Buro Happold, Framingham, Massachusetts, 2009

thermal control for the exposed roof structure. We started under the premise that thermal comfort could be extended to accommodate a wider range of temperatures. This would reduce the overall energy consumption, and potentially allow for more natural ventilation in the plant. We also sought to take advantage of the natural thermal energy available from the building's water supply by installing a closed water circuit system. The water utilized for the primary circuit of the cooling plant was up to 25 percent of overall water processing. The goal was to limit the maximum temperature increase to 3 to 5 degrees Fahrenheit on the plant discharge water. This is a minimal water temperature increase that, even during the summer season, would not be considered too high for potable water distribution. We achieved another major energy savings for the building by using central air-handling units with double-heat recovery from the exhaust air. Since the plant has high-ventilation air requirements, it needs a lot of energy for cooling or heating. By recovering energy from the ventilation exhaust, we were able to reduce waste energy by more than 25 percent. In addition, the plant was able to take advantage of natural ventilation when the ambient air was suitable for full or partial air economizer cycle.

We carefully integrated the Framingham plant's air-distribution system with the building's internal and external architectural layouts. The ducts and pipes were designed to run close to the main steel beams to mitigate humidity and moisture accumulation. | **figs. 3, 4** All piping and duct distribution was coordinated above the main steel beams and secondary glulam beams. This coordinated layout provided a clear interior design and the desired thermal control. In order to further reduce the energy consumption of the plant, we proposed a direct outside air unit with radiant systems for the administration and operation area, which was approximately one-third of the overall building but accommodated 99 percent of the occupants.

A well-designed climate-control system can provide a comfortable thermal environment while also reducing the maintenance of the facility by lowering the overall degradation of its infrastructure. While a structure fully exposed to the elements such as the Eiffel Tower or the New York City subway system requires constant maintenance, an indoor structure subjected to extreme conditions can be treated with care to reduce energy and maintenance costs. To conclude, we can summarize our objectives as the following: inclusion of climate-control issues at the programming and diagrammatic stages of design; integration of interior building systems with the structure and program of a building; and close collaboration of the interior and exterior climates in the selection of materials.





Experimental Fabrications

fig. 1 | Cast aluminum model of teeth, early nineteenth century (top)

fig. 2 | Aluminum beverage can, ca. 1965 (bottom)

Precious Industrial Metals

Paola Antonelli

Are metals really worth our while? Except for soft, warm, gentle, docile aluminum, is all the energy and the effort that it takes to shape them into architecture really worth it? What are we hoping for? Are metals and architecture only one step in the evolution of mankind, or are they here to stay? Are they where we are going to be in the future? Or, are we just waiting for the Boeing 787's maiden voyage to be at last freed from metal and its tyranny, from the dry air and weird pressure that metal condemns us to? Are metals really necessary in this day and age?

In 1995, I worked on an exhibition at the Museum of Modern Art (MoMA) called *Mutant Materials in Contemporary Design*. The exhibition was divided into seven groups of materials. I have to confess that among all the sections—from glass, plastics, foams, ceramics, and even wood (the most traditional)—the metals section was the least interesting to work on. At that time, somehow—and structural engineer Guy Nordenson confirmed this hunch when I interviewed him for the exhibition catalogue—metals had not really been pushed toward their limits. Granted, it was 1995, the age of fibers and composites. Today, however, we hear that Werner Sobek is trying to engineer foam out of metal; he is trying to push it far beyond its physical limits. Though I hope that he will achieve this goal, so far metals in architecture have remained resistant to that kind of systemic innovation.

Aluminum, for instance, has a very distinct personality compared with other metals. Because it is so malleable and versatile, aluminum stands alone among metals in architecture and design. Seemingly humble, aluminum began as a very precious metal: witness the exquisite aluminum ring from the beginning of the nineteenth century, shaped to reproduce the dentures of a dead loved one. **| fig. 1** During the first part of the twentieth century, aluminum became available and affordable, but was still relatively exotic, and in search of its own expressive freedom. The gorgeous experiments in spun aluminum by Russel Wright in the 1950s are a good example of this. Another milestone in this super-compact history of aluminum is, of course, the aluminum beverage can from the 1960s: inexpensive, light, hygienic, and eternally recyclable. **| fig. 2** Profiles, extrusions, modules—aluminum was the champion of economy. But in a recent reversal, some designers, such as Hisanori Masuda in the 1990s, have tried to make aluminum precious again. Masuda's beautiful boxes, shaped like pebbles, are made from cast aluminum with the texture of the sand still visible on the inside. Gilded and polished on the outside, Masuda's boxes are a flight away from the automation and standardization that aluminum had come to signify.

Designers have always had an intense and troubled relationship with standardization. At the beginning of the twentieth century, there was a moment when standardization represented hope and enlightenment, the possibility of true justice and betterment of all society. But it then became only a matter of economy and systemic concordance, and sometimes even cheapness. Designers have moved away from standardization in the attempt to achieve diversity, if not uniqueness. The holy grail in the 1970s was the "diversified series," first attained conceptually by designers like Ettore Sottsass and Gaetano Pesce in the 1980s, and widely available today thanks to the introduction of rapid manufacturing.

The diversified series relies on the capability of injecting difference and uniqueness into a manufacturing process without "stopping the presses" and breaking its economy and integrity. One of the first designers to think in these terms was Marcello Nizzoli. While working for Olivetti in the 1930s, he tried to apply the methods and processes of car manufacturing to home and office equipment. His famous—and gorgeous—Lexikon and Lettera 22 typewriters, designed in 1937 and 1949 respectively, were among the first examples of aluminum *pressofusione*, or die-casting, applied to objects. | **figs. 3, 4**

*La vita
della casa
scrivetela a macchina*

*Perchè la casa sia bella, basta spesso il buon gusto. E perchè nella eleganza degli ambienti, ci sia il segno di una presenza intelligente, ci vuole una portatile Lettera 22.
I suoi colori si accorderanno con i colori che avete preferiti, la sua forma con quella degli strumenti della vita moderna che vi aiutano ogni giorno.
Non solo la vostra corrispondenza si comporrà facilmente su questa macchina, che è di precisione e di resistenza; ma vi darà note, appunti, elenchi, documenti domestici, in più copie. (E ai vostri figliuoli, insegnate a scrivere a macchina).*

*Olivetti
Lettera 22*

modello **LL** lire **42.000** I.O.R.

fig. 3 | Lettera 22 typewriter, by Marcello Nizzoli for Olivetti, ca. 1949 (top)

fig. 4 | Advertisement for Lettera 22 typewriter (bottom)

Are metals in architecture just a means to an end, a way to achieve a wider span or a larger view? When we find a better way to achieve those results, will we move on? Maybe in the future, metals will not be a necessity, but rather a stylistic and aesthetic choice. By removing necessity and obligation, it is easy to slip into expressionism. Ron Arad's exhibition at MoMA in 2009 included an indigestion-provoking series of metallic follies. Arad, an Israeli-born and London-reared architect and designer, loves steel and has used it in all its forms, from tubes, sheets, and mesh to wires with aluminum and a little copper thrown in for good measure. Arad approaches metals playfully, without trying to push their technology or to innovate. He looks instead for the most expressive way to exploit the aesthetic potential of metal. Yet, along the way, he has created several new seating typologies as well as larger-scale structures, including the installation system for his exhibition, a work titled *Cage sans Frontières*.

In Arad's work metal is used in every way possible, from ribbons and sheets to hand-hammered, polished, oxidized, or brushed steel. Nothing is spared in his career-long exploration of this one material. The objects in the exhibition made from other materials almost seem to be accidents. Steel is his obsession. A manufacturer might have visited his office or an exhibition and seen a steel piece, and then decided to make it in fiberglass, polyurethane, polyethylene, or aluminum. But it was first realized in steel. One particular shape, for instance, can be repeated in three different forms or applications of steel: patinated and oxidized, completely

fig. 5 | PizzaKobra, by Ron Arad, 2007

reflective (like an artwork by Jeff Koons), or as a steel skeleton painstakingly covered with little, hand-applied steel rods. His approach tries to understand all the possibilities of one metal. The same designer who lovingly treated steel as a precious art material can also use it as an industrial means, as for instance in the case of his PizzaKobra lamp. **| fig. 5** Playfulness and a light hand in using this heavy metal is an inspiring attitude for the future, when metals will not be an obligation, but rather a conscious aesthetic choice.

The value of metal in the future will become increasingly connected to the uniqueness of its choice, a uniqueness allowed by the manufacturer in processes that we are perfecting; manufacturing processes with privilege, rather than standardization as an ideal, and which consider the application, flexibility, and response to local context of every structure and every object that we design. I want to conclude with gold, the most mysterious of all metals. Most mysterious to me, at least, since I had to leave economics school because I couldn't understand how the value and the richness of the world could be connected to a yellow parallelepiped. Here was a real clash, between adamant standardization—of size and weight in ingot, the king of quantitative value—and uniqueness; the same matter, once cast or manipulated into an object, revealed its qualitative preciousness. But in a way, the uniqueness of the jewel is almost completely obliterated when you are in a moment of need and you sell the same piece for its weight. The standard reveals, in this particular case, the value of the metal itself and of life.

An Old Glossary for the New Metallurgists

Ana Miljački

Ductility

Flows of metals describe geographical territories that have been controlled and contested throughout history. Not only can we think of these flows (economies of extraction, trade, taste, etc.) as constitutive of material limits of metals, but material properties historically have also been territories controlled through advancements in technology and science. Once material limits and material territories begin to redefine one other, ductility also expands from a singular property of metals to a property of discursive and disciplinary definitions. Relying on this slippery collapse of material and discursive properties of metals, the glossary that follows revisits some of the oldest terms from the metallurgical lexicon in light of contemporary architectural practice. The main purpose of this glossary is not just to assess the capacity of antiquated terms that correspond to contemporary material or disciplinary processes but, more importantly, to highlight the coexistence of old and new in contemporary work as an important and historically specific characteristic of it.

The work and research of several design practices—The Living, KBAS, MOS, and John Fernández—frame many of the questions involving metals as a material with particular properties and architectural applications. From their own project descriptions, KBAS and Fernández have contributed to a conversation regarding the networks and economies of expertise. KBAS's Pentagon Memorial is repeatedly described in the context of the enormously complex and spatially dispersed network of people, materials, and knowledge that made it possible. The core of Fernández's work, which is the examination of the metabolism of material urban systems, involves an organized effort in re-extracting metals from the architecture of cities—what may be the most bountiful site of future ore deposits. Each of these practices can thus be seen in terms of territories that literally involve geography, exchange, and collective behaviors. On the other hand, The Living and MOS both tinker (or test) at the edge of material and design limits, invoking a territory of operation when that tinkering becomes a type of project. Similarly, an economy and network of expertise are meaningful only insofar as particularly valuable properties of a material are at their centers. Thus, it should come as no surprise that tests and hypotheses involving metal as an architectural material offered here ultimately reflect on the state of contemporary architectural practice in general.

This group's engagement with metals as a set of architectural materials, and their engagement with material reality in general, frame a number of issues particularly relevant to the contemporary practice of architecture: control, optimization, archaism, and radical scarcity. To call these architects metallurgists is in part a nod to the recognition that metallurgy received in Gilles Deleuze and Félix Guattari's shifty, multiplied world of *A Thousand Plateaus*. Architecture's favorite philosophers of the 1990s described a world of continuous battle between the forces of stratification, striation, and sedimentation and wild jumps, ingenious moves, and freeing agents, nearly always making their appearance in relationship to the forces of control that preceded them. Their model of constant takeover of the sedentary (e.g., state and bureaucratic apparatuses) by the nomadic (literally nomadic tribes), and vice versa, applied to large historical processes, to life in general, and to every form of creativity—whether they found proof of it in the life of plants, or in the life and work of great novelists, painters, and war strategists. But, characteristically exploding their own binaries, Deleuze and Guatarri claim: "There are no nomadic or sedentary smiths."[1] For these "materialist" philosophers, always interested in extracting abstract models from material evidence, metallurgy was a core metaphor for nonorganic life, and the metallurgists' position even more privileged than the nomads'. Neither nomads nor sedentaries, the metallurgists are able to deal with and contain both extremes. As Deleuze and Guatarri set forth, "They are in themselves double: a hybrid, an alloy, a twin formation."[2] Although this brief reading on the metallurgist will not do justice to the texts that inspire it, my use of the term metallurgist serves to call out a slippery hybridity, a condition relevant to a type of disciplinary ductility discernible in the projects and research of The Living, KBAS, MOS, and John Fernández.

That this glossary of definitions is old and new simultaneously is of particular importance. The coexistence of the archaic and the digital in each of the four projects explored here is a symptom of a particularly contemporary condition of practicing architecture. The history and future are simultaneously present for us. The consensus is that we no longer inhabit the relatively simple modernist temporal paradigm in which forward was always equal to progress. Whether we call our contemporary moment "premodern" (Latour), "late style" (Eisenman via Said), or "altermodern" (Bourriaud), instead of anguishing over the loss of clarity that was constitutive of modernism's narrative of progress, we may be better served today by concentrating on the computing power and intellectual agility that allow us to simulate our history and our future at the same time.[3]

Mining

John Fernández's research on urban metabolism anticipates a world of radical scarcity in which a more or less benevolent species of architectural cannibalism is imaginable. Fernández's story starts like all good apocalyptic narratives, by invoking a time when the supply of metal from mines will be exhausted. But he quickly assures us that there is no reason to panic, or at least that there is enough reason to be hopeful given the amount of metals already embedded in our cities. Even though Fernández doesn't specifically endorse this condition as a reality beyond his research, the radical scarcity of a finite material like metal would be a "game changer" for the discipline of architecture, literally and conceptually. Mining, reimagined as an extraction of ore from the new synthetic ground of dead cities and defunct structures, inevitably invites architects—whose task is fundamentally anticipatory—to reposition their conceptions of buildings within this retrospective paradigm. If urban metabolism were to transcend research and fulfill a dream not unlike that first forged in the utopian projects of 1950s Japanese Metabolism, it would involve an unprecedented amount of control and optimization of resources.

Melting Point

Control and optimization are at the core of the work produced by The Living, KBAS, and MOS. Enabled by new software, new levels of precision and versioning engage material realities, and often engage historically older techniques for shaping metal. MOS has perforated, sheathed, inflated, and stretched metal in their projects. When Hilary Sample, a partner at MOS, suggests that they "look at the resistance of materials—formless resistance—as a way to think about and frustrate architectural propositions," she is both acknowledging the particular material reality of metals and placing it within a disciplinary description of MOS's practice. Claiming repeatedly that they are interested in recuperating an avant-garde project, though not at the expense of the vast contemporary architectural intelligence, nor at the expense of the gritty, down-to-earth reality of architectural production and use, MOS dissolves an old definition of the architectural avant-garde in favor of a radically heteronomous, hybrid one—one which perhaps does not imagine a particular future as much as it culls it into existence by whatever means available. In their formal games, the material reality (of metals, plastic, or wood) "frustrates" the parametric formal research, just as their desire for certain effects (such as the chimney effect of passive cooling used in Afterparty, their project for the PS1/MoMA Young Architects Program) might inform other aspects of the research. Radical inclusionism or heteronomy are about a kind of discursive and disciplinary dirt. As is the case with metals, for which the inclusion of dirt and impurities lowers the melting point, by lowering the "melting point" of disciplinary definitions (of material limits, the avant-garde, or the medium), MOS rewires the connections to the history and the future of the field. It is in this sense, that we should understand the deliberate primitivism of Afterparty, or the 2007 PS1 entry Prehistoric Future. Both projects begin to augment author William Gibson's often-cited notion that the future is already with us, just simply unevenly distributed, with its logical counterargument: *history* is always with us, just unevenly distributed.[4]

Casting

The melting and pouring of 184 benches of KBAS's Pentagon Memorial required a vast network of experts in load engineering, metal mixing, and casting. The number of people responsible for the production of the actual units of the memorial was in fact larger than the number of units that constitute the memorial. According to KBAS, the production of the Pentagon Memorial benches directly involved over two hundred people and indirectly over a thousand people. They initially projected five thousand pounds per unit, but through modeling, prototyping, and adjusting were able to reduce the unit weight to one thousand pounds. The KBAS team not only managed to convince their patrons of the aesthetic effect produced by a twinkling field of elongated benches, they supervised the master models of all components and information flows required for CNC fabrication of the molds. The Pentagon Memorial impressively closes the gap between architectural imagination and production, an achievement made possible in part through the sophistication of the digital models used in the process of designing and developing the project. Indeed, the economy of labor involved in closing that gap imbued the Pentagon Memorial with an appropriate human energy, pointing to both its galvanizing program and to the deep pockets of its patrons. The robust network of experts, whose communication may indeed have been made possible via new digital tools (with the architect as the master of information flows), is also indicative of an unprecedented necessity for collaboration. The encounter between digital design processes and the most archaic method for shaping metals—casting—could be seen as another case of material properties frustrating the digital. In this project, the potential of new tools confronts an archaic material, shaping intelligence to produce a contemporary aesthetic whose task in the Pentagon Memorial is precisely to function as a link between future and past.

Alchemy

Through a set of directed tests and a number of lab accidents, several families of shape memory alloys (SMA) were developed over the latter course of the twentieth century. A little bit of electrical current, exposure to heat, or exposure to the effects of a magnetic field make some alloys "remember" an earlier configuration of atoms. The architects who make a glass membrane breathe with the use of SMAs are treading in unknown, or previously undescribed territory. The Living explain their project as one of constantly redefining a design territory appropriate for the issue at stake. With the constant redefinition of their territory of operation, material limits are challenged in every project. Fascinated by rules of thumb, The Living precisely seeks out design territories that don't yet have commonsensical solutions. Instead of frustrating their formal propositions by the old definitions of material, the testing (the only rule of thumb that The Living subscribes to) seems to frustrate the materials they work with. The two types of testing described by David Benjamin of The Living—the multiobjective optimization software and the full-scale physical test—clearly operate on different registers, but they are productive only in tandem. In the hands of The Living, both of these lines of inquiry, a highly computational method and a direct physical test, inhabit a particular retro-aesthetic of an alchemist's lab. Just like video footage of materials at their limits, the numbers and formulas nod to the postwar research at some "mechy" lab at MIT, if not to the middle ages and the quest to turn metals into gold or to Dr. Frankenstein's lab (consider "The Living" as a name). If the group's "archival" footage showing a low-tech hammer on a piece of metal, or their installation rendering aesthetic of the local pollution levels of your air and water, simulate a narrative link to a historical era characterized by a more naive desire to control organic and nonorganic life, they also suggest the emerging forces seeking to capitalize on such control. Although their aesthetic traffics in both nostalgia and legitimation, it also announces The Living as the inheritors and the possible contemporary corrective to that naïveté simultaneously.

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1 | Gilles Deleuze and Félix Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia* (Minneapolis: University of Minnesota Press, 1987), 413.

2 | Ibid., 415.

3 | See Bruno Latour, *We Have Never Been Modern*, trans. Catherine Porter (Cambridge, MA: Harvard University Press, 1993); on Eisenman's notion of Lateness, see Peter Eisenman, ed., "Lateness: A Critique of the Metaphysics of Presence," *Thresholds*, no. 33 (2007): 10–15; Nicolas Bourriaud, *Altermodern* (London: Tate Museum, 2009).

4 | William Gibson, "The Science in Science Fiction," *Talk of the Nation* (NPR radio broadcast, November 30, 1999).

Pliability

Hilary Sample

Pliability negotiates the relationship between flexibility and resistance. Being pliable suggests the potential of a material to be unyielding; this differentiates metals from other materials. No material seemingly bridges greater extremes. When thinking about the architectural properties of metals, words like "soft," "mutable," "receptive," and "ephemeral" may not immediately come to mind. However, recent projects have proven that metal is capable of transcending its well-known conventional properties when engaged by a pliable architecture—an architecture that applies pressure to the soft spots of received ideas in an effort to produce alternative design methodologies. One needs fantasy and science to work with metals.

In the midst of comparing the tasks of building and weaving, Anni Albers introduced the term "pliability" to contemporary architecture in the mid-1950s.[1] If architecture is conceived of as grounded, fixed, and permanent, then producing textiles, producing pliability, is its antithesis. Albers pointed to the role of textiles as the enclosing skin placed over the structure of the nomadic tent. This recalls Gottfried Semper's concept of *Bekleidung* (dressing), a practice that celebrated the application of covering and, more importantly, that was dismissed by the form-follows-function arguments for visible, undressed structure favored by the modernist polemicists of the early twentieth century.[2] Despite the modernist rejection of pliable coverings, Albers argued that building and weaving are fundamentally similar: they both involve the joining of disparate parts that retain their individual identities. However, Albers suggested that the techniques of fabrication that were developing in her time—in both architecture and textiles—were leading toward a "fusion" of these parts "as opposed to linkage."[3] In other words, new means of making introduced new possibilities, or outcomes, that were not tied to mere surface nor to mere structure. This fusion resonates even more today as the surface versus structure debate has reached expiration. As our projects attest, skin can become frame and, likewise, structure can become surface, while the whole ensemble is challenged to perform structurally, environmentally, and sensorially.

If anything, the emerging manipulability of metal has produced a tendency toward spectacle not unlike the novelty of plastics over half a century ago. Upon discovering the transformative means of its production, Roland Barthes notably described plastic as "a spectacle to be deciphered: the very spectacle of its end-products."[4] He continued, "At the site of each terminal form (suitcase, brush, car body, toy, fabric, tube, basin or paper)" resulting from the extreme pliability of the productive process, the consumer understands plastic only as a "'shaped' substance" that expresses the control of humanity over nature.[5] Similarly, the newfound pliability of metals—from worked and folded surfaces to metallic textiles and aluminized fabrics—is at once a state that supports flexible technological performance, as well as a reflection of the ruthless demand for continual adaptability required by capital, progress, and other contingencies.

In our practice, we are interested in "pliability" as an operative and disciplinary term. Experimentation shapes our thinking about each project. Projects are designed in parallel—kept separate but on similar timetables—with research contributing to both built and speculative work. Our method involves repetitive testing, pushing designs to the limits of structural failure. We work alchemically, inventing and creating rather than merely uncovering, fusing *and* linking rather than choosing one or the other.

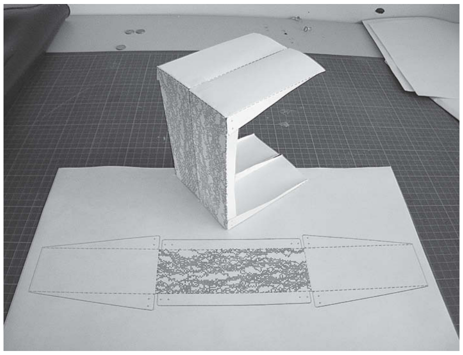


fig. 1 | Model of panel for Perforated Storage Shed, by MOS, Columbia County, New York, 2005 (above)

figs. 2, 3 | Constructed perforated panels, Perforated Storage Shed, 2005 (opposite)

Perforated Storage Shed, Columbia County, New York

This aluminum storage shed is a small-scale insertion in a remote and densely wooded landscape. A practical consideration for this type of storage is continual airflow to keep the wood dry, which requires openings on the inner face of the shed. An inexpensive, lightweight system was devised to hold the cut wood. Experimenting with folded paper models while developing scripting software for other projects in the office, these two practices were combined in studies for the shed. **| fig. 1** Scripting was ultimately used to generate a pattern of randomly distributed holes simulating the shadows of the surrounding trees. This pattern was applied locally to each panel and worked across the surface of the storage shed. The panels of thin aluminum sheets, like the paper models, were easily folded. The perforations of both the cut pattern and folded edges were achieved through the water-jet process. The final aluminum panels (two feet wide by six feet tall) were fabricated in Vermont and brought to the site in a van. **| figs. 2, 3** Folded and bolted together, the thirty-foot-long shed was constructed in one day. The reflectivity of the panels changes with the seasons: in the summer the surface appears to have a greenish tint, and in winter it takes on a whitish vibrancy of the snow.

Artist Studio, Columbia County, New York

This artist studio was introduced to a site already inhabited by a Quonset hut and an Airstream trailer—both constructed of metal. Although not in close physical proximity, the existing structures (one used for work and the other for temporary living) and their distinctly similar shapes acted as a background for our design. The Quonset hut, a lightweight prefabricated structure made of corrugated galvanized steel, and the Airstream, constructed of aluminum, both have a semi-circular

Pliability

Hilary Sample

fig. 4 | Artist Studio, by MOS, Columbia County, New York, 2007

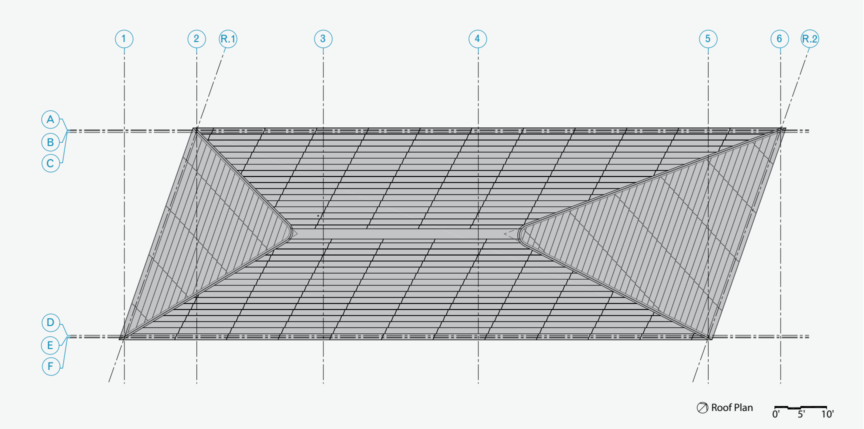
section. The new artist studio was to provide necessary space for painting and drawing, with additional space for storage, cooking, bathing, and mechanical equipment. We conceived of this building as a similar shed-type structure—this time hollowed out for art practice. **| fig. 4** The idea to cover the entire studio from ground to roof in a continuous surface was influenced by the existing structures but also allowed for easy maintenance. Weathering, another important factor, led to the selection of zinc: a durable material with a two-hundred-year life span and a dark gray finish that will deepen over time. **| figs. 5–7**

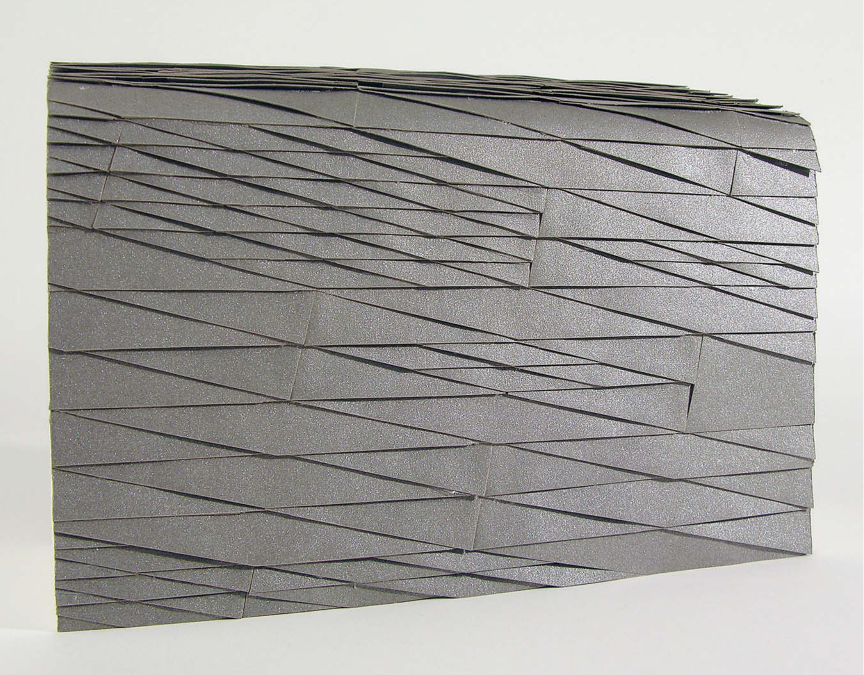
PS1/MoMA Prehistoric Future, Long Island City, New York

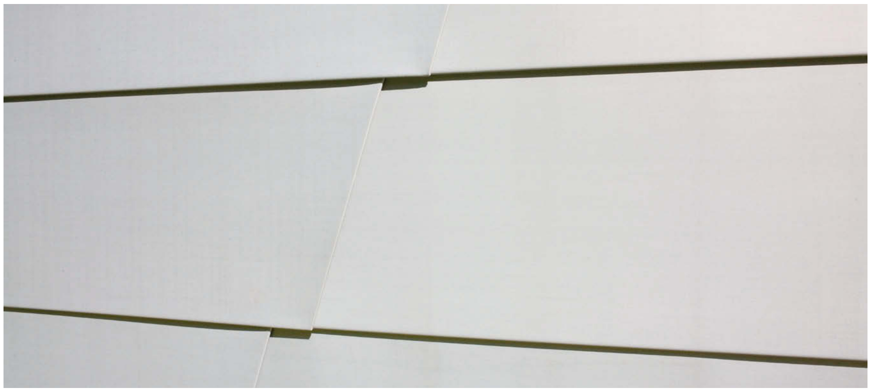
The inflatable pavilion, a temporary structure for the PS1 Warm Up parties, covered five thousand square feet within the main exterior courtyard of the gallery. **| figs. 8, 9** Structurally innovative, the project used a three-dimensional aluminized fabric as the skin of an inflatable cell. The experimental textile was made by sandwiching a fibrous structure between two layers of aluminized fabric, with the inflated internal membrane supporting the outer surfaces. The ability to create the form with discrete modules, as opposed to one large structure, allowed for an aggregation of separate cells (two feet in width and roughly sixty feet across) that were heat-welded to each other, a technique similar to seaming a dress. Each cell remained structurally independent, so if one cell was damaged the entire structure would not collapse. The cells were fabricated as individual units then connected together in the factory. Through scripting, we devised a pattern of large- and small-scale apertures that were formed by separating the cells along

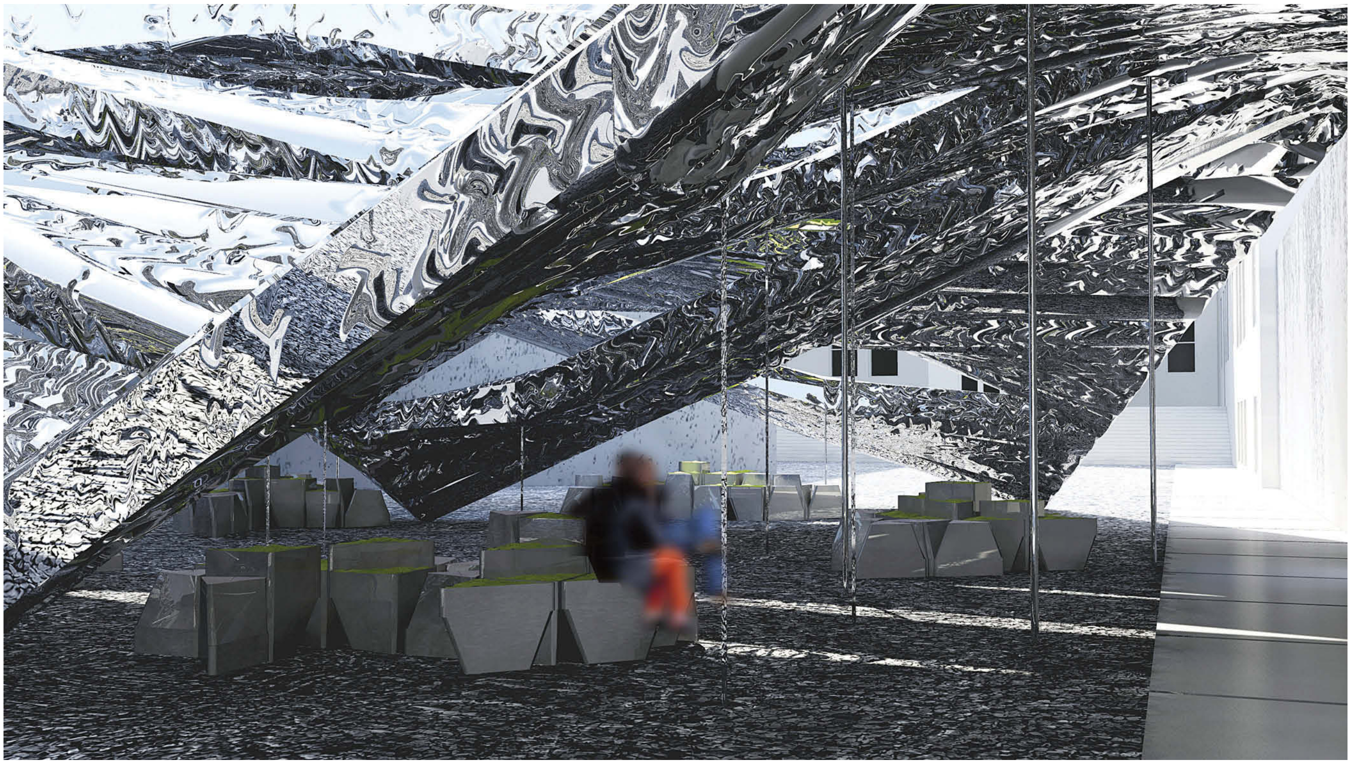
fig. 5 | Roof plan, Artist Studio, 2007 (top)

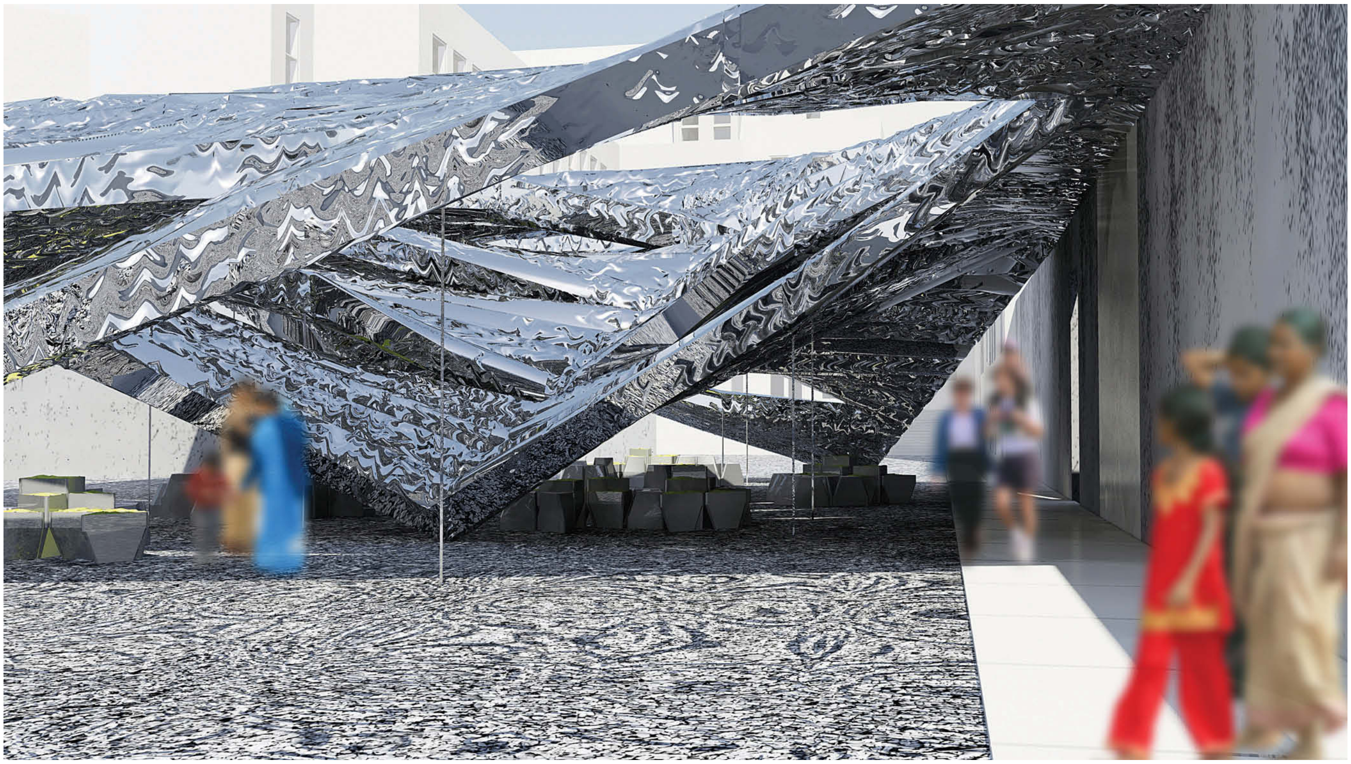
figs. 6, 7 | Model and detail of zinc panels, Artist Studio, 2007 (middle and bottom)

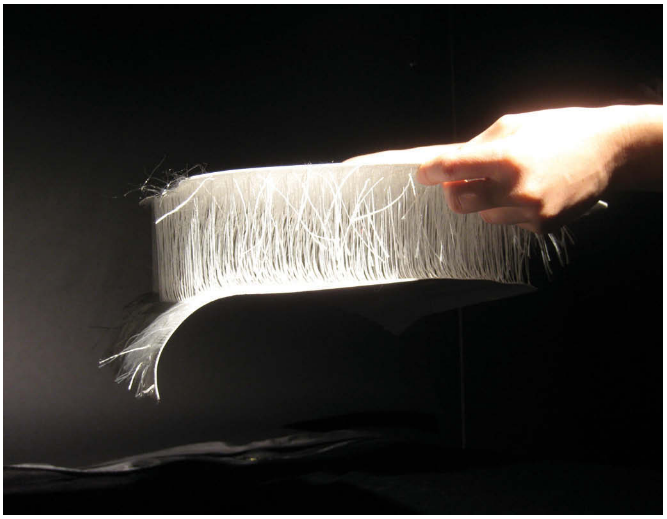


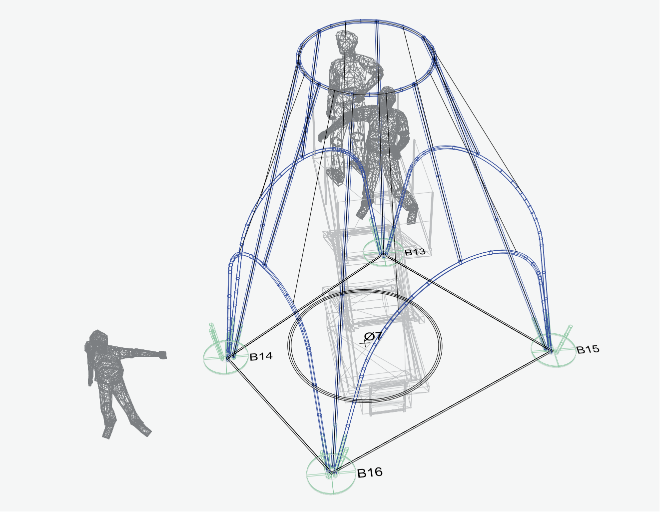












figs. 8, 9 | Inflatable pavilion, PS1 Prehistoric Future, by MOS, Long Island City, New York, 2007 (opposite)

fig. 10 | Three-dimensional woven aluminized fabric, PS1 Prehistoric Future, 2007 (top left)

fig. 11 | Construction drawing, PS1 Afterparty, by MOS, Long Island City, New York, 2009 (top right)

their seams. **| fig. 10** The finish of the fabric was mirrorlike and produced effects more mesmerizing than a fun house—creating an environment that reflected the surroundings and blurred the atmosphere of mist and moss.

PS1/MoMA Afterparty, Long Island City, New York

Both of the PS1 projects grew out of research into the properties of metal fabrics and fibers. Whereas the Prehistoric Future project from 2007 was an exploration into a rugged and thick fabric, Afterparty employed a thin and delicate fabric to contrast with the coarse thatch of a natural raw fiber from Indonesia—a choice inspired by the promise and potential of textiles as put forth by Albers in her essay “Pliable Plane.” Afterparty is a collection of sixteen domes and cones used to connect the three disparate external courtyards at PS1. The ambition was to produce as much shade as possible while maintaining a bright atmosphere underneath. Aluminet, typically used in hydroponic farming, is a knitted and woven metal net made from high-density polyethylene, a recyclable material. The fibers are durable and undergo a metallization process during which they are treated with an anti-oxidation coating. The ability to customize the knitting pattern of the Aluminet allowed us to create three different perforation densities. The smallest domes had the densest fabric with 40 percent perforation, and the largest domes and tallest cones had the most perforation at 60 percent. **| fig. 11** The variety of perforations reduced the amount of fabric weight on the aluminum frames, an essential consideration because the Ijuk palm thatch weight was unknown. **| fig. 12** The fabric also served as a structural skin providing a taut and rigid surface stretched across the forms. The aluminized fabric reflected both light and radiation, and its fineness allowed diffused light to pass through and bounce around the reflective interior

fig. 12 | Construction of aluminum and steel structure and Aluminet, PS1 Afterparty, 2009 (top)

fig. 13 | Completed structure, PS1 Afterparty, 2009 (bottom)

fig. 14 | PS1 Afterparty, 2009 (left)

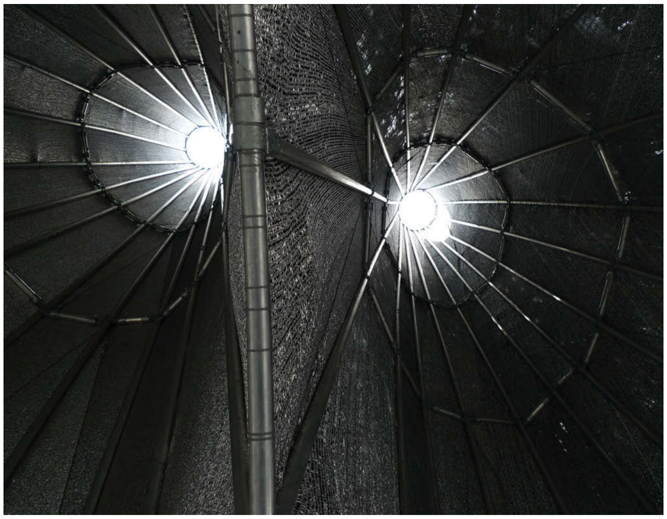


fig. 15 | View looking upward through towers, PS1 Afterparty, 2009 (right)

underneath the rough, dark-colored thatch. The nearly ten thousand square feet of Aluminet fabric arrived on site pre-sewn into large-scale skirts that were carefully moved to the top of each form—some carried by hand up ladders, others lifted in an assembly line up scaffolds, and the largest raised by a mechanical lift. The seamed fabric was then slipped over the aluminum-framed skeleton of each shape, trimmed in place, and attached with gray plastic zip ties. | **figs. 13–15**

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1 | Anni Albers, "The Pliable Plane: Textiles in Architecture," *Perspecta* 4 (1957): 36–41.

2 | Gottfried Semper, *Der Stil in den technischen und tektonischen Künsten*, Erster Band, "Textile Kunst" (Munich: F. Bruckmann, 1878), 204–17. Translated by Harry Francis Mallgrave and Michael Robinson as *Style in the Technical and Tectonic Arts* (Los Angeles: Getty Research Institute, 2004).

3 | Albers, "The Pliable Plane," 36.

4 | Roland Barthes, *Mythologies*, trans. Annette Lavers (New York: Hill and Wang, 1972), 97.

5 | Ibid., 97–98.

Oblique Frames

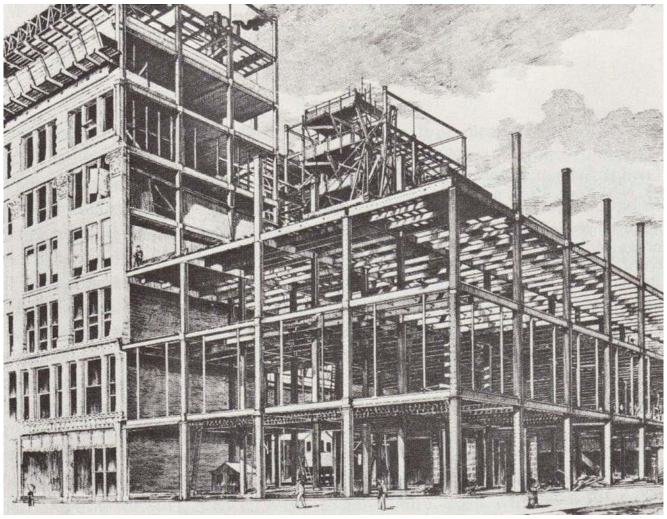
Jesse Reiser

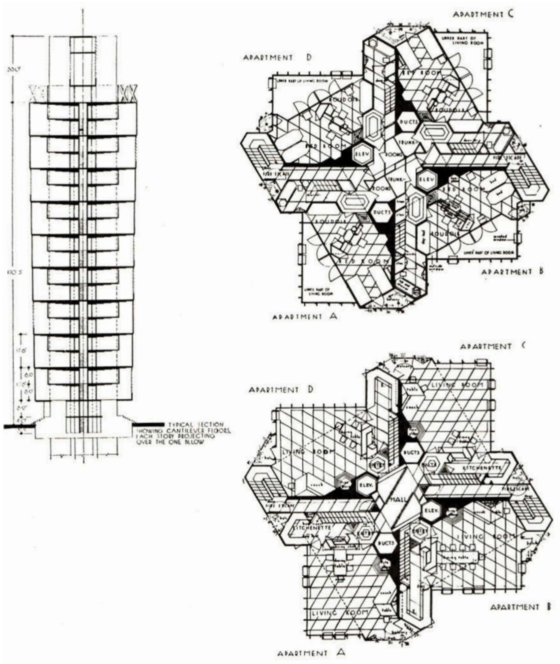
My focus is not steel-frame projects, in the sense of buildings that utilize steel frames; rather my focus is in projecting or extending the logic of the steel frame, or more precisely, our reactions to it. This essay provides a retrospective look at the steel-frame project, by way of Colin Rowe's well-known text "Chicago Frame," and its relationship to some of the recent work in our office in order to try to clarify our actions and the context in which we worked.[1] | fig. 1

Rowe distinguishes between the pragmatism of the developer-led Chicago projects in the nineteenth century and the highly charged polemic of an architect such as Le Corbusier. The Chicago frame is neither a spatial polemic nor an architectural polemic, but simply the creation and appropriation of a new technology toward economical, efficient ends. Today, when we compare the steel frame to the Dom-ino concrete frame, I think the parallel still holds, but with a twist. | fig. 2 We find ourselves suspended between the two issues: influenced by the economic pressures of building and interested in developing the work (and our polemic) within that tension.

The notion of developer pragmatism, especially in the Dubai of four years ago, occupies a very different universe than mercantile Chicago; Dubai is part of a post-Bilbao universe where excess has its own peculiar economy and cannot be easily separated from architectural expression or polemics. The iconic imperative found in Dubai is a standard as free of polemics as the Chicago frame. So our project was posed in a context where architectural excess was a practical norm—a riot of architectural gymnastics where icons were to stand cheek by jowl. For us, it was not a question of refusing the icon, or attempting to create the anti-icon, but to explore other means of producing one, and in doing so to derive another polemic.

In "Chicago Frame," Rowe deviates from his initial comparison to include Frank Lloyd Wright, who essentially developed the anti-frame. With St. Mark's Tower, Wright undermined the prominence of traditional column-and-slab relationships by basing the building structure on a core and a treelike form in which trays carry the apartments. In a simple sense, our O-14 tower project, recently completed in Dubai, is an inversion of St. Mark's Tower—the structure was moved to the exterior, making the core very light and allowing for a column-free interior. | fig. 3 Though this evacuation of structure inverts Wright's project, it is still sympathetic to his kind of organicism—in other words, a conflation of structure and space. For O-14, this meant a movement toward the development and elaboration of the envelope. In this way, O-14 evolved out of historic and pragmatic logics but attempted to push them in a slightly different direction. | fig. 4





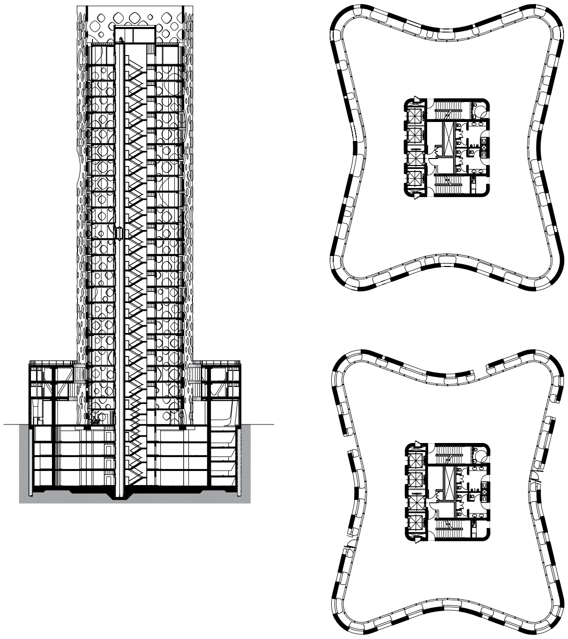


fig. 1 | Fair Store, by William LeBaron Jenney, Chicago, Illinois, 1890–91 (top left)

fig. 2 | Aerial view, O-14, by Reiser + Umemoto, Dubai, UAE, 2009 (top right)

fig. 3 | Plan and elevation, St. Mark's Tower, by Frank Lloyd Wright, New York, New York, 1952–56 (bottom left)

fig. 4 | Plan and section, O-14, 2009 (bottom right)

Interestingly, the first iteration of O-14 was a concrete-frame building with a curtain wall and an amorphic plan. From there, it slowly developed into a structural evacuation to create a column-free space, thereby eliminating the frame, simplifying the plan form, and allowing fenestration and structure to be more or less on the same plane. Thus, we were able to fundamentally transform the tower typology from a standard column structure into one that utilizes a concrete exoskeleton. We were following that old nineteenth-century directive, or accepting the conditions as imposed by the speculator, but toward different ends.

fig. 5 | Rendering, O-14, 2009

Working with the issue of iconic building—working in a supercharged market environment in which every building is trying to call attention to itself—is vastly different from the restricted economic logics of the Chicago frame. Although this new building environment is perhaps most strikingly manifest in Dubai, the city is certainly not unique. Rather, it can be seen as a more extreme version of the development of the globalized city typical in the Far East, where the grafting of market-driven economies quickly outpaces and leaves behind the evolution of culture. From a polemical standpoint, this globalized city is the new reality, the new context. As such, we imagine that our O-14 project could be deployed in any city with a similar context of growth and with the type of developer pressure to create icons. Paradoxically, iconicity seems to have become ubiquitous; so for us, the question becomes how to reformulate the notion of icon itself.

The client's desire for iconic buildings is what brought us to Dubai in the first place. In a competition to design a central tower for the development of Business Bay, our Aeon project stood against entries from OMA, Zaha Hadid, and Morphosis. Koolhaas's polemical argument was that there was already a plethora of difference; so much so that in effect it became a sea of sameness. His proposal, a deadpan modernist building, worked in contrast to that context—precisely the type of the thing that would call attention to itself, a kind of anti-difference argument. Both during and after the competition, we felt that this was absolutely the wrong move. In our practice, we are very invested in architectural expression, and, most significantly, how to deal with the expression. **| fig. 5**

When considering our building's relationship to this new context, we attempted to formulate a different notion of how a building could meet the skyline. This led us to explore the diagonal grid as an expressive structural system, and, more importantly, to investigate its architectural effects. **| fig. 6** The diagonal fenestration of the shell counteracts the stratification of most layered tower structures in the area, and, in a quasi-sublime way, is more assimilable to the sky and the ground. **| fig. 7** From a distance, the overall gradient in the

fig. 6 | Construction, O-14, 2009 (left)

fig. 7 | Customized formwork, O-14, 2009 (right)

field of holes renders the tower as a solitary chunk of moon come to Earth. Driving past O-14 in Dubai's skyline is like watching the moon follow you as you drive past a horizon of trees. There is a strange and unexpected uncanniness to the building. It is contextual, yet not of the place; it is radically different from the contextualism most foreign architects try to assimilate. We term this typical integration the "Zelig" phenomenon (referring to the Woody Allen character Leonard Zelig): a good example is Renzo Piano's Tjibaou Cultural Center, which attempts to relate to the context of the local building culture.

O-14's basket-weave structure is often read as an attempt to relate to the local context, though arts like basket weaving are common to nearly every culture. In fact, most of the inspiration for the tower's structure (and for a series of our previous projects) derives from the field of aviation design rather than from local culture. However, with O-14, the design is contextualized immediately in that manner. Of course, other projections are made on the building, too, which are out of our control. But that's what we would term the "Chauncey Gardner effect," referring to Peter Sellers's *Being There* character, a cipher onto whom meaning is projected. The meanings projected onto O-14 appear contextualist, but in fact, the building remains somewhat indifferent to the specifics of site, and, in a certain way, to materials.

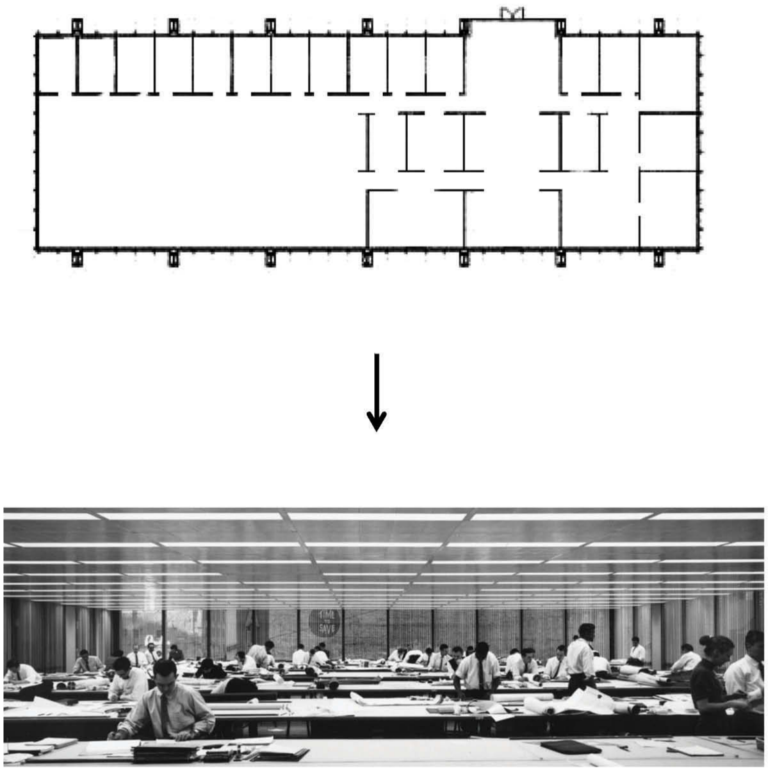
The frame in Mies van der Rohe's photomontage of the Adam Building (1928) was depicted as a crystal from the future landing amidst the historical eclecticism left over from the nineteenth-century city. Today, one has to deal with a context of super-spectacular versions of frames, so there is no longer such a play against that type of foil. Other sets of tactics or techniques need to be employed. By producing effects that have qualities of both the artificial and the natural, we are able to

fig. 8 | Against clouds, O-14, 2009

design a building that can simultaneously attach and detach itself from the city. This may be considered a strange or artificial nature—it is not evident whether it is something new or something old, natural or artificial. In O-14, one way we were able to create this perception, which is also a technical issue, was to take a simple, monolithic volume and apply a disruptive pattern, similar to a camouflage pattern, through which to read the form. **| fig. 8** This wasn't meant to make the building visually blend with its surroundings but rather to defeat easy readings of scale; effectively, the diagrid subverts the layered legibility of the traditional tower.

On a technical level, we began with the underlying uniform diagrid, but vertically offset it from the building's slab edges. By making the fenestration pattern independent from the slabs, O-14 has random or irregular sets of connections from slab to shell. From the outside, it is difficult to discern the number of floors. The issue of perspective is also a crucial concern in the design of the building. For instance, we had to consider our approach from different angles to the changing speeds of diminution and expansion on the facade. An image from the Beatles' *Yellow Submarine* (stuck in my head since my 1960s childhood) addresses a change in perspective coupled with an ambiguous sense of surface, inside and outside, up and down. The speed of the pattern is the variable that leads to perspectival effects. In a regular articulation of a typical frame structure, the viewer is confronted with a one-point perspective with a constant rate of change. But by disrupting the pattern, the rate of change relative to the floor heights cannot be easily located, resulting in a perpetually shifting speed of scale and, consequently, multiple simultaneous perspectives. **| fig. 9**

Afterward, we questioned the program within that space; how would we accommodate common types of office layouts within a warped space with varying



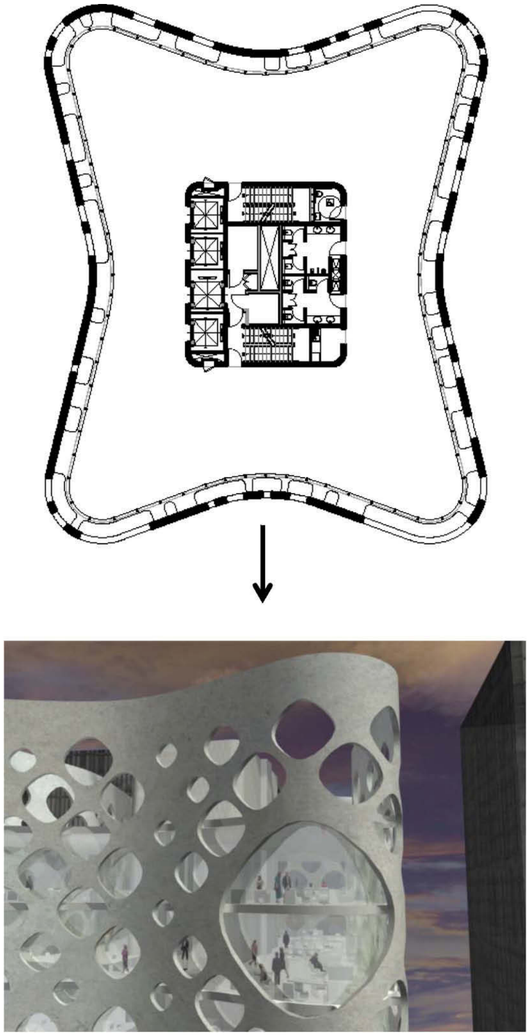


fig. 9 | Plan and interior, Inland Steel building, by Skidmore, Owings and Merrill, Chicago, Illinois, 1958; plan and exterior, 0-14, 2009 surface curvature? In answering, we realized that this was not simply a matter of consistency to a normative arrangement of office spaces but that the fenestration would affect these arrangements through gradations of light and dark zones and possible views that vary from floor to floor. | figs. 10, 11 We consider this a reasonable balance between the specific and the generic. Since we could not determine how O-14's column-free space would actually be occupied, we were at least able to attach enough architectural specificity to the effects of the shell to partially predict the outcome, feed this back into the design, and ultimately produce a design that would lead the program-determining process in a beneficial way.

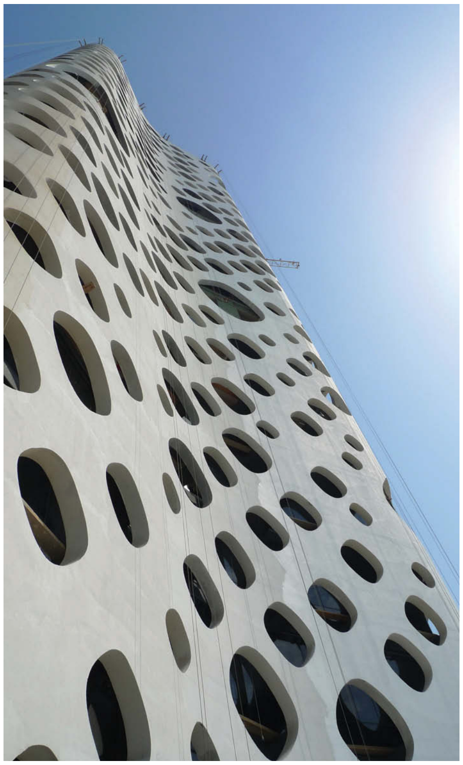


fig. 10 | Facade, O-14, 2009

For us, another important interior consideration was the breaking of the horizon line when viewing outside. The O-14 shell is separated from the slab edge by a one-meter (3.3-foot) gap, so when looking out the facade holes, one can also view up and down, past the level of the floor slabs. This creates an experience of staccato perception, where diagonally arranged frames actually pass beyond the slabs, breaking the senses of horizontality and verticality.

The basket-weave structure also relates directly to material specificity, as well as the steel frame itself. Once completed, the basket weave is not evident; it is an underlying component of the structure, buried beneath the form-giving concrete. The frame, in a way, is also embedded, realizing our ambition for the project.

Les Robertson's design for the World Trade Center used fourteen different alloys of steel to keep the facade uniform. | fig. 12 With O-14, we were approaching the inverse—an ambition for a much more heterogeneous fenestration pattern while keeping the material composition the same. To achieve this, we had to vary the density of the reinforcement and the ratio of solid to void. We performed an iterative process of adjustments, changing the components according to the overall pattern of stresses and managing the aesthetic consequences. At the end of this back-and-forth design process, we were less interested in the pattern becoming an index of the forces than in the specific visual effects that could be produced. And, of course, it could be argued that forces flow where the material is located, and not where it is absent.

Once the building received its final coat of paint, there was a return to the ideality of the rendering. After all, the contemporary interest in the material logics and performance of the pattern, what became its most expressive quality, was related to the graphic or ideal. This is not a new idea within our work, and it is evident in several other recent projects. Our Alishan Bridge project in Taiwan started as wood and was eventually changed to steel. | fig. 13 Test models were made in wood, and a series of formal variations were explored, but in the end, it was more

fig. 11 | Looking out from O-14, 2009

about preserving and enhancing a material geometry rather than a true interest in any material specificity.

Likewise, in our project for Shenzhen Bao'an International Airport, the concept evolved as a reaction against the prevailing airport style of high-tech, leading us to investigate concrete as a material choice. | **fig. 14** The shell pattern was an extension of O-14, which had a direct material resonance in concrete. Throughout the competition, we also explored a steel version of the scheme, which resulted in different consequences related to cost and time but preserved the precise formal relationships and visual effects of the initial design.

Ultimately, the exploration of expression is not the skin and bones of the Chicago frame, nor a kind of structural expressionism as seen in Santiago Calatrava's PATH Station project, but a well-toned expression, in which both structural logics and formal effects assert their dominance in nonuniform ways at the same time.

1 | Colin Rowe, *The Mathematics of the Ideal Villa and Other Essays* (Cambridge, MA: MIT Press, 1976), 89–118.

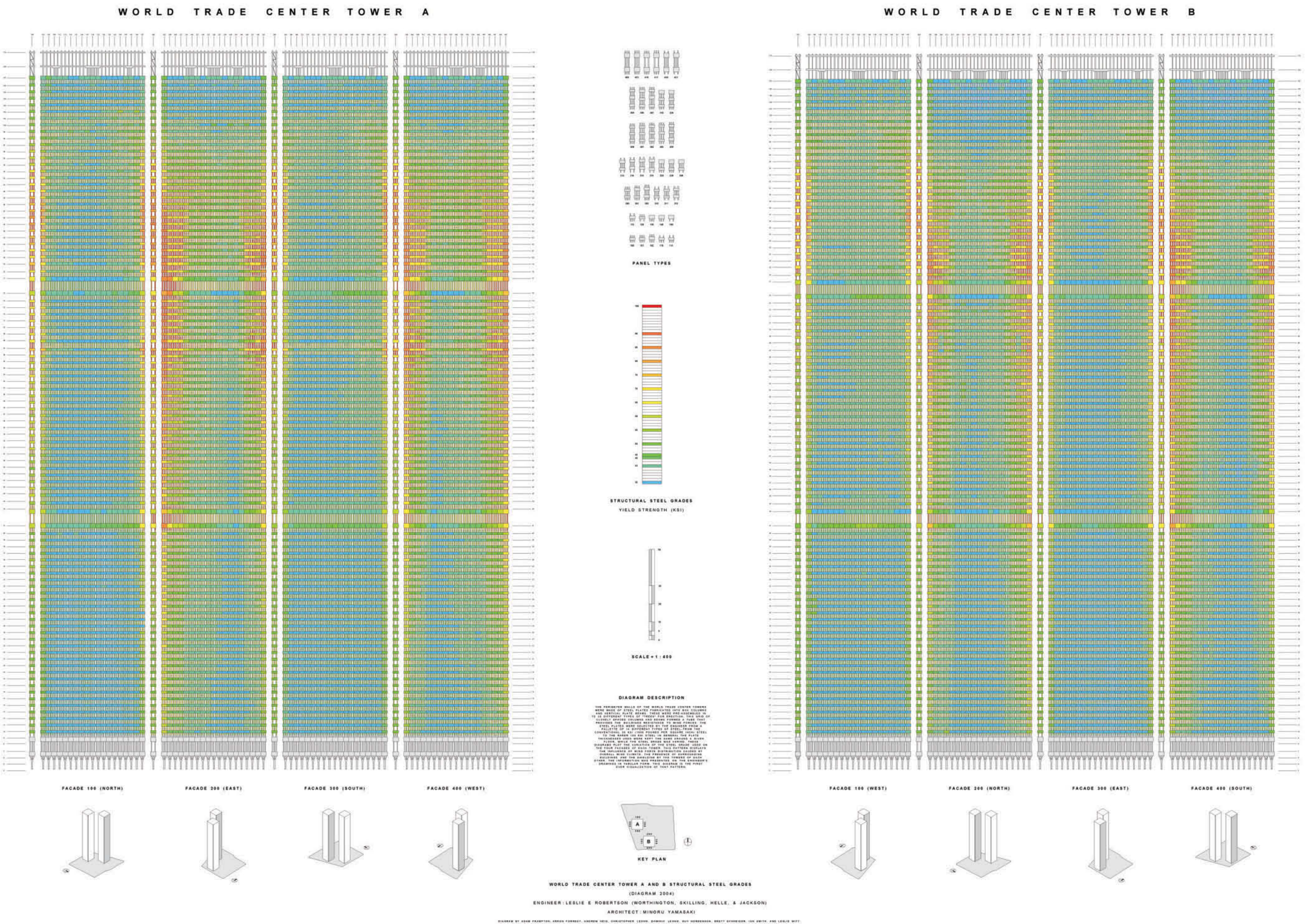
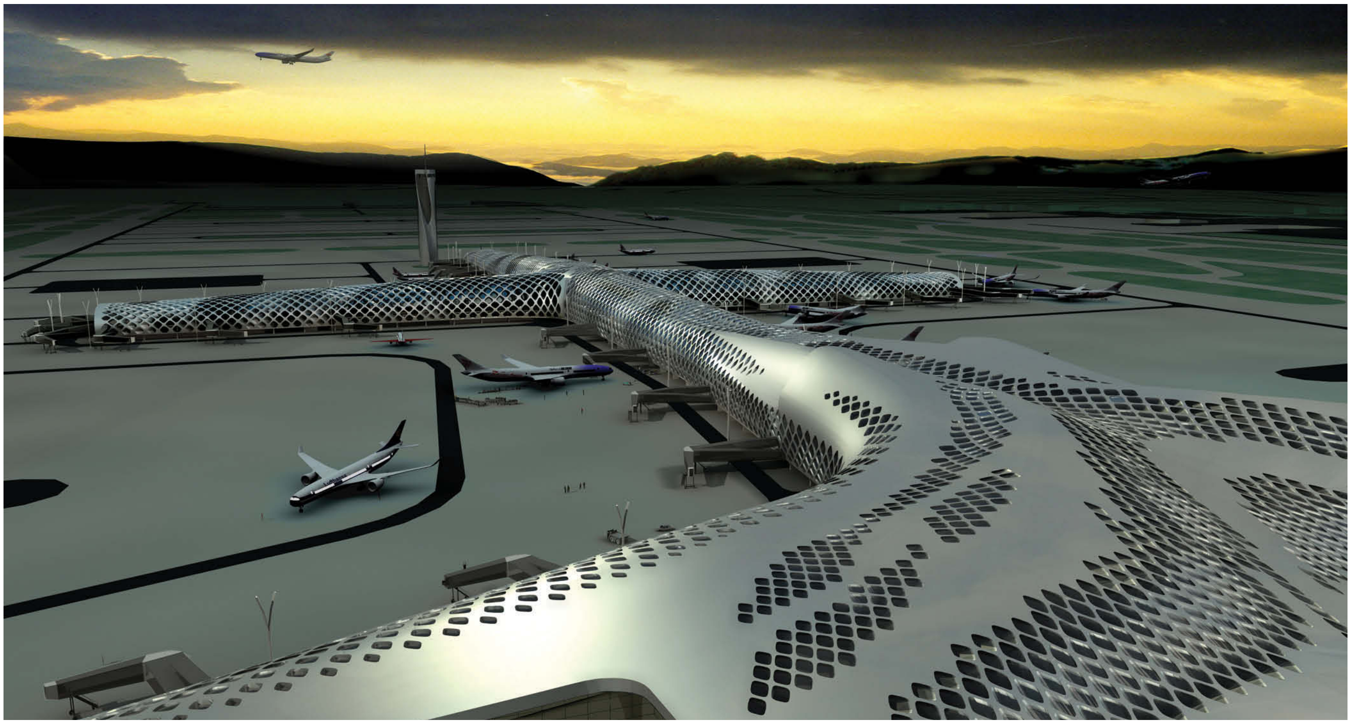


fig. 12 | Facade study, World Trade Center, by Minoru Yamasaki, New York, New York, 1966–77 (above)

fig. 13 | Alishan tourist routes, by Reiser + Umemoto, Taipei, Taiwan, 2003 (opposite top)

fig. 14 | Rendering, Shenzhen Bao'an International Airport, by Reiser + Umemoto, Shenzhen, China, 2007 (opposite bottom)



Testing Material Limits, Testing Material Territories

David Benjamin

Material Design

In the early years of World War II, as it became clear that England was holding out against Germany because of superior technology, the Royal Institute of British Architecture (RIBA) established a new committee called the Architectural Science Group. The committee's task was to consider the implications of technology for architecture, and its report concluded that unless architects devoted more time to science, they risked losing leadership of the building industry. The committee encouraged professors to prioritize building technologies and urged universities to create a new faculty position: Chair of Architectural Science. Architecture schools were not convinced.

But more than ten years later, even as wartime concerns and the urgency of technological progress faded in England, educators in Australia picked up on the idea. In 1953, the University of Sydney launched a new Department of Architectural Science and hired a forty-year-old lecturer from England named Henry Cowan as Chair. Cowan was perfect for the job. He was an energetic structural engineer with an international reputation for research on reinforced concrete, including the invention of a new kind of strain gauge to test the performance of concrete beams without boring into them.

During his early years in Sydney, Cowan broadened his approach. He established the journal *Architecture Science Review*, mentored hundreds of young students, and became an expert on topics ranging from acoustics to thermal performance to the use of computers in architectural design. Cowan also became addicted to completeness. Believing that knowledge of architectural science and design should be aggregated and categorized, he wrote two dictionaries, an encyclopedia, and several manuals on building technology.

Yet times continued to change, and knowledge continued to evolve. In the preface of his sobering 1971 book, *Architecture Structures*, Cowan observed that the study of structures was becoming more complex, calculations were increasingly done by computers, and engineers were assuming sole authorship of building structural systems. So Cowan posed the same question that the RIBA had asked thirty years earlier: in the context of these transformations, what should the architect do?

Cowan's answer to his own question was documented in the methodical chapters of his book, which were then neatly summarized in an appendix titled "Preliminary Structure Design Charts" by Philip Corkill, an architecture professor

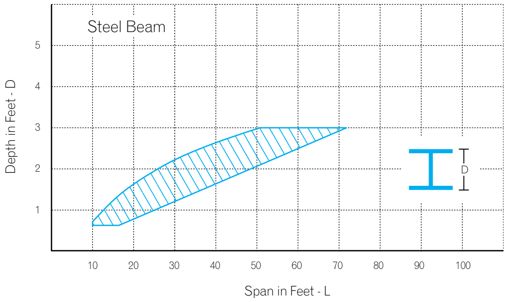


fig. 1 | Chart comparing depth to span for a steel wide-flange beam, from *Architectural Structures*, by Henry Cowan and Philip Corkill, 1971 (left)

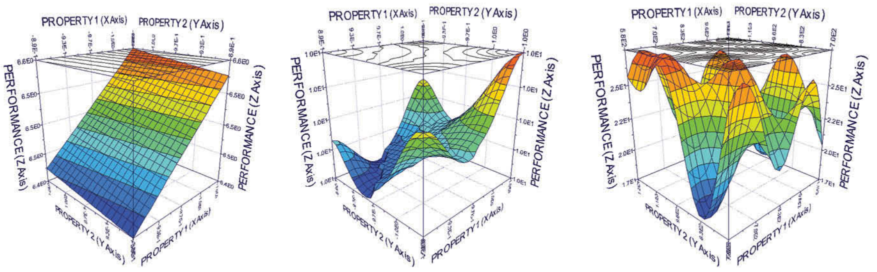


fig. 2 | Topological representations of design space range from simple to complex. (right)

from Nebraska. This section offered fifty-eight meticulous, gridded diagrams to cross-reference dimensions to spans for every known structural system. One chart declared that in order to span sixty feet with a steel beam it was necessary to make the beam three feet deep. | fig. 1 Other charts offered similar guidelines for aluminum geodesic domes or folded steel plates. The charts responded to changing conditions by amassing more and more design guidelines. When compiled, the charts provided a comprehensive study in material limits. They encapsulated knowledge. They gave the faltering architect solid rules of thumb for structural systems. The architect, in turn, was to use the charts to create intelligent preliminary sketches and have informed discussions with engineers. This, Cowan offered, was how to design structures.

Design Space

On an abstract level, every design problem has a potential design space—the territory of all possible design permutations. When a design space is represented in three dimensions, it becomes a topological surface, with the x-axis and the y-axis registering the properties of potential designs, and the z-axis measuring the performance. Depending on the specifics of the design problem, this topological surface might be a simple shape, such as a slanted plane, or a complex shape, such as a mountain range with multiple peaks. | fig. 2 In addition to visualizing a design problem, the topological surface can be approximated by a mathematical function, and then used to predict the performance of new design permutations.

The structure design charts in Cowan and Corkill's appendix are a focused, two-dimensional version of this abstraction. They are roadmaps of specific material territories. The charts—which are still photocopied and distributed in architecture schools and professional offices to this day—are useful because they are concise guides to direct relationships between properties and performance: deepen the beam and the spanning capacity increases. In other words, the charts are ideal for design problems that involve known design space and predictable relationships. They catalog all possible solutions, via all known rules of thumb. But in doing so, they shrink from the unknown.

Clearly, each design problem may be more or less known, and one way to think about different types of design space, corresponding to different design problems, is to locate them on a spectrum between exploration and exploitation. A designer interested in exploitation wants to find the single best-performing design according to her objectives. She wants to exploit small differences in inputs to achieve the best output. She requires high resolution and generally prefers a narrow, continuous design space. And she is pleased to see a simple distribution diagram like the charts that Cowan and Corkill produced. The simpler it is, the faster she can find the optimal design.

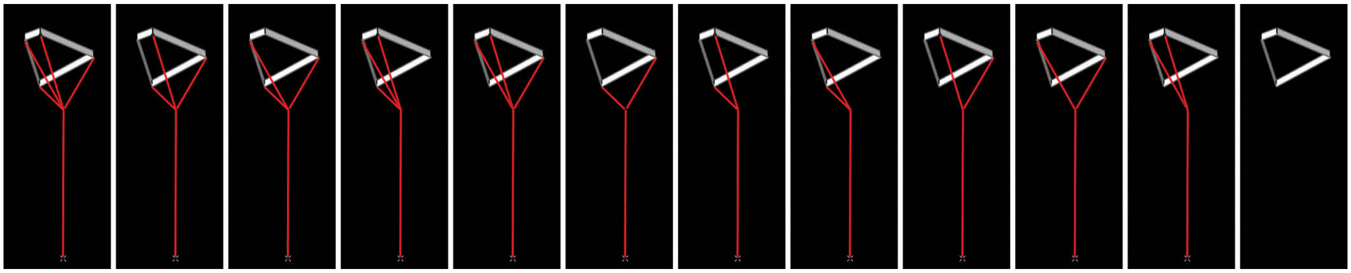
But a designer interested in exploration wants to find novel designs above a minimum threshold of performance. She wants to explore completely different sets of inputs that might result in similar outputs, and does not require high resolution or the single best-performing design. Instead, she is interested in a range of designs that are high performing and unexpected. For this reason, she generally prefers a wide, discontinuous design space. And she loves nothing more than a complex, multi-modal distribution diagram. The more complex it is, the more likely that she will make an interesting discovery.

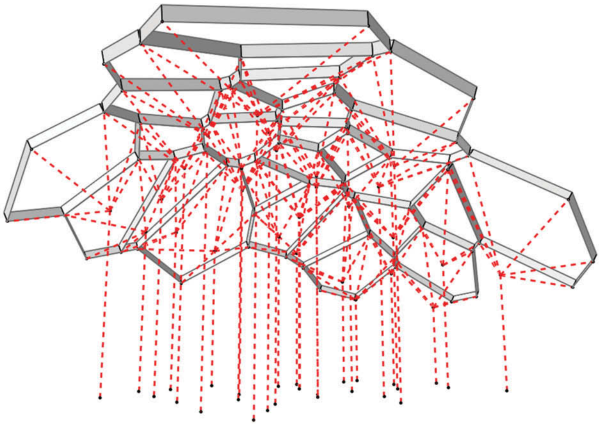
Living Light

Steel is the champion of metals. It is inert and immutable. Its strength, its stamina, and its material limits are proven. It is graphed in dozens of Cowan and Corkill's charts. Steel lies in well-documented and well-understood material territory.

Yet it is surprisingly easy to wander off the map, and this is exactly what we aimed to do when designing a pavilion for a public park in Seoul. Our pavilion involved a small steel structure: a steel-framed canopy supported by slender steel columns. But because of its asymmetrical profile and its irregularly shaped cells, there was no relevant structure design chart. When faced with this specific and unusual design space, Cowan and Corkill were mute. Though the performance of our building material was clear, the performance of our structural system lay in uncharted territory. So for the design of our metal structure, we proceeded not by rule of thumb, but by testing.

The project was commissioned by City Gallery and the Municipal Government of Seoul. Our proposal, called Living Light, was to combine issues of public space, environment, and interactivity into a floating domelike canopy in the shape of the city. We envisioned a building envelope that glows and blinks according to air quality data and public interest in the environment. To bring it to life, we first designed the size and shape of the canopy according to material dimensions and site conditions. Then we designed lighting panels and steel struts for the





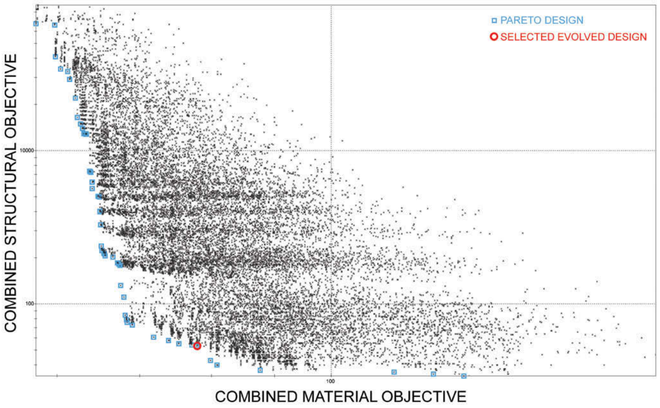


fig. 3 | A four-sided cell has twelve possible arrangements of branches. For each arrangement except the empty cell, there are six possible heights of the branching point. This cell has a total of sixty-seven (11 x 6 + 1) possible configurations. (top)

fig. 4 | For each design permutation, some of the potential supports (represented by dashed lines) become steel trunks and branches, while the rest disappear. (bottom left)

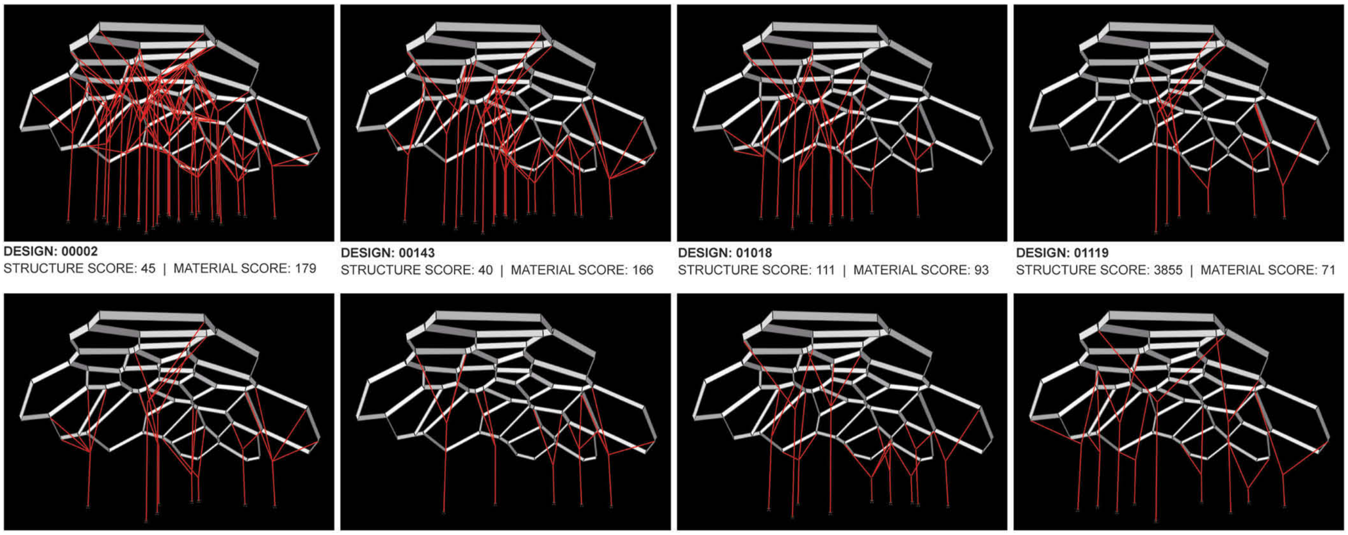
fig. 5 | The twenty-five thousand design permutations produced by the automated test are graphed according to the objectives of least structural weakness and least amount of material. From the Pareto Frontier (the set of best designs), we selected a single permutation that was high performing and unexpected, and its performance was verified through further structural analysis. (bottom right)

canopy.[1] With the panels and the steel struts fixed as a rigid frame, we turned to the supporting structure.

At this point, we set up an experiment to explore possible arrangements of slender steel columns and decided that for each cell of the canopy, there could be either a branching column or no column. If a column was present, it could have a variety of configurations, depending on several factors: the number of branches, the connection points of the branches, and the height of the branching point. For example, a four-sided cell in the center of the map could have sixty-seven configurations. | **fig. 3** Cells with more sides could have many more configurations. When considering all the cells together, the structure could have many billions of design permutations. | **fig. 4**

To explore these permutations, we set up an automated test with a search algorithm and a fitness function combining two objectives: best structural performance and least amount of material. We then used a workflow of multi-objective optimization to generate and evaluate twenty-five thousand possible designs.[2] The experiment involved looking for high-performing design permutations but also ones that were unexpected. We were interested in exploration more than exploitation. | **fig. 5**

Based on a quick intuitive analysis of the design problem, before running our automated test, we sketched a possible solution for the support structure



DESIGN: 00002
STRUCTURE SCORE: 45 | MATERIAL SCORE: 179

DESIGN: 00143
STRUCTURE SCORE: 40 | MATERIAL SCORE: 166

DESIGN: 01018
STRUCTURE SCORE: 111 | MATERIAL SCORE: 93

DESIGN: 01119
STRUCTURE SCORE: 3855 | MATERIAL SCORE: 71

DESIGN: 01219
STRUCTURE SCORE: 122 | MATERIAL SCORE: 83

DESIGN: 01318
STRUCTURE SCORE: 5415 | MATERIAL SCORE: 69

DESIGN: 15816 (SELECTED AS EVOLVED DESIGN)
STRUCTURE SCORE: 53 | MATERIAL SCORE: 78

INTUITIVE DESIGN
STRUCTURE SCORE: 378 | MATERIAL SCORE: 79

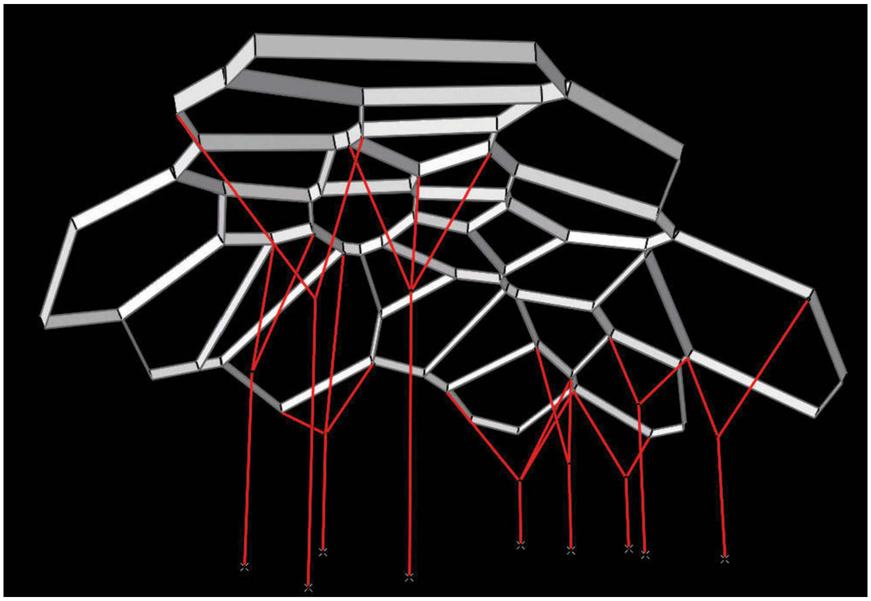


fig. 6 | A comparison of sample designs from the test, as well as the "intuitive" design, shows a trade-off between competing goals of structure and material use. (top)

fig. 7 | The evolved design is different than any simple rule of thumb would suggest. (bottom)

with columns evenly distributed around the perimeter of the canopy—about nine columns total, with one column for every other perimeter cell. In terms of structure and use of material, this design configuration performed relatively well and became a benchmark for the experiment. We predicted that many of the best designs from the test would evolve in this direction.

But after sorting through the results of the experiment, we observed an unexpected trend. In a significant number of designs, instead of an even distribution, the columns clustered under two distinct areas of the canopy. One cluster of four to five columns was located at the western perimeter, under the cells lowest from the ground. The other cluster of four to five columns was located near, though not at the edge of, the eastern perimeter, approximately under the cells highest from the ground. This configuration was clearly different than our prediction. | **figs. 6, 7** Both designs—our new evolved design and our original intuitive design—had nine columns. Both used around the same amount of material. But to our surprise, the evolved design performed better structurally than our intuitive design.

Though more testing is still necessary to explore this design space, our hypothesis is that three factors contributed to the trend we discovered: The irregular cell shapes and sizes meant that good solutions might not necessarily have evenly distributed columns. The asymmetrical tilt of the canopy meant that one good solution was to support many of the lowest cells and a few of the highest cells (supporting low cells led to a good score because it required less material). And the location of the largest cells at the perimeter of the canopy meant that another good solution was to support the cells inside of and adjacent to the perimeter, which were generally smaller than the perimeter cells (supporting small cells led to a good score because it required short branches and therefore less material).

So in the design of our steel support system, we deliberately created a complex design space. We moved beyond structure design charts, but we grounded our designs in measurable performance. We explored unknown possibilities, but we used precise constraints and objectives. The outcome of our experiment in material design was a high-performing structure with unusual geometry.

Yet our material and structural concerns were carefully balanced with our nonstructural, nonquantitative goals for the project. Performance in terms of metals and material limits quickly overlapped with performance in terms of atmospheric effect, civic engagement, and communication through architectural envelopes. The result was not merely an unlikely solution to a technical design problem. The more essential result was a canopy that seemed to float on a sparse scattering of trees. It was a building that talks with citizens. It was a tactile enclosure that suggested a building envelope can become a new kind of public space. It was a pavilion, mysterious yet meaningful, transforming to reveal the patterns of its broader ecosystem and glowing and blinking in new environmental rhythms, as if to remind you that architecture is so much more than the sum of its materials and efficiencies and plotted rules of thumb. | **figs. 8–10**

1 | For the canopy frame, we used a modified version of the Trusset system developed by Phillip Anzalone and the Avery Digital Fabrication Lab at Columbia University.

2 | The engine of our multi-objective optimization process was the software application modeFRONTIER by Esteco.

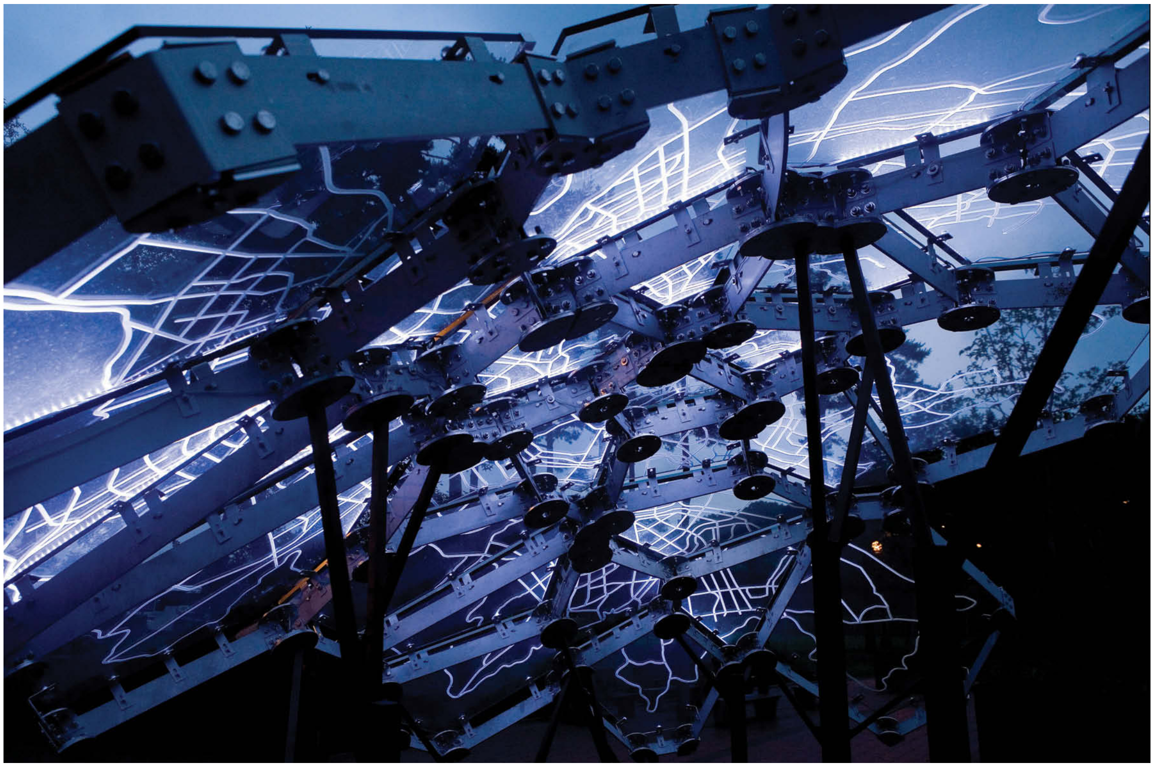


fig. 8 | The evolved design was constructed in Peace Park, next to the World Cup stadium in Seoul, Korea. Each night, neighborhoods light up if their air quality is better than last year. (above)

fig. 9 | Every fifteen minutes, the map goes dark and the neighborhoods light up in order of best to worst current air quality. (opposite top)

fig. 10 | Citizens can send a text message with a zip code to the Living Light hotline, receive a reply with the neighborhood's real-time air quality, and trigger one of the panels to blink. The building envelope registers collective interest in the environment and creates a new type of public space. (opposite bottom)

Fabricating the Pentagon Memorial

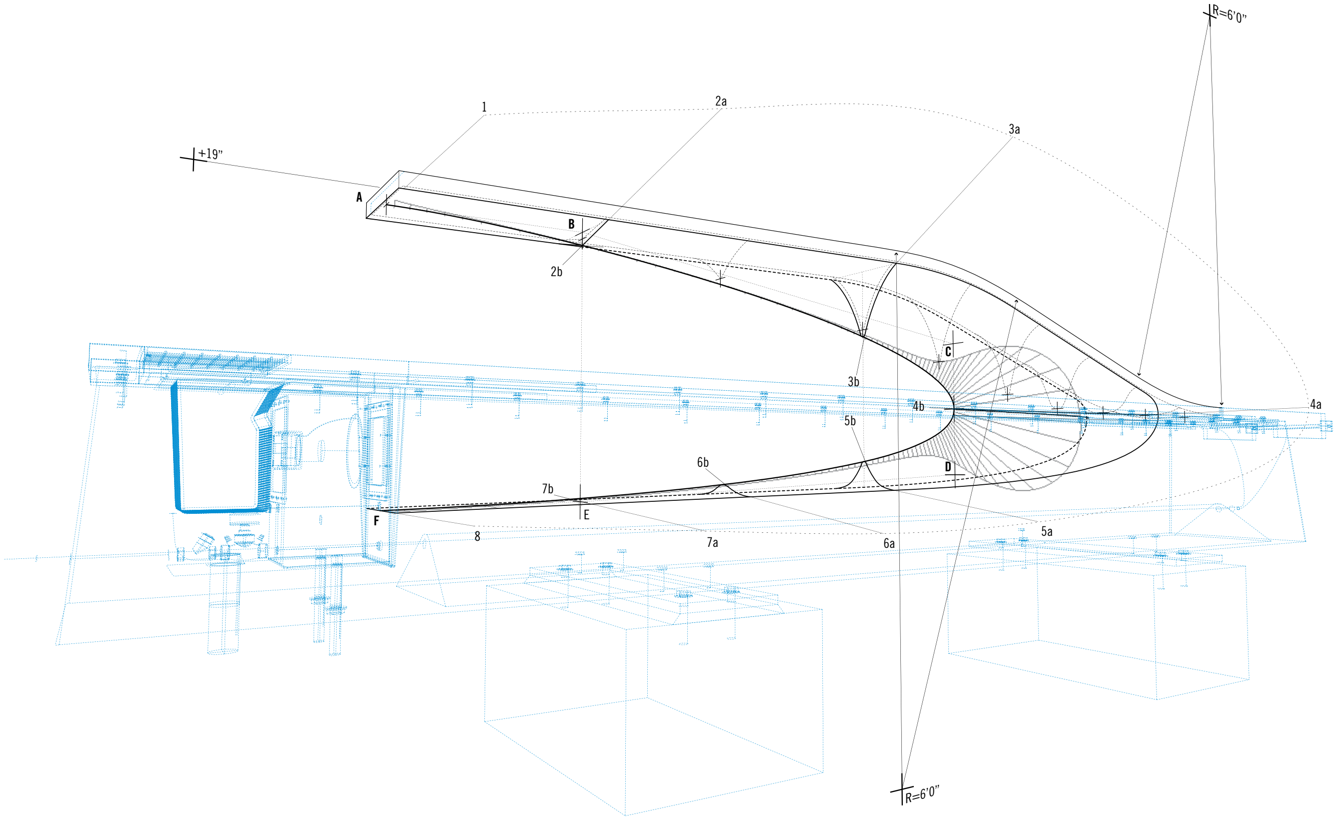
Keith Kaseman

An extraordinary team worked tirelessly over the course of six years to realize the Pentagon Memorial. Thousands of people poured their time, thoughts, and resources into this endeavor, and several hundred of those individuals made up our uniquely expansive design-build team. Discovering and tackling a host of fundamentally perplexing challenges created an exhaustive quest through a vast array of research, development, expertise, and exploration. Given the intensity and scope of the commemoration at hand, key academic, industrial, professional, and scientific advisors provided invaluable guidance with great magnanimity through every twist and turn of the intricately woven collaborative web that emerged. Navigating that web with agility and precision was paramount to achieving the high states of refinement required by our design intentions. Process limits were reached or surpassed through inventive strategies created by an incredible brain-trust of those involved with the production of highly customized components of the park. The deployment of these components on site demonstrated a rarely achieved level of sophistication in construction. All of this effort was to build a place with the utmost respect for those whose lives were taken and for all affected, while inviting contemplative thought into the distant future.

Fabricating the Pentagon Memorial

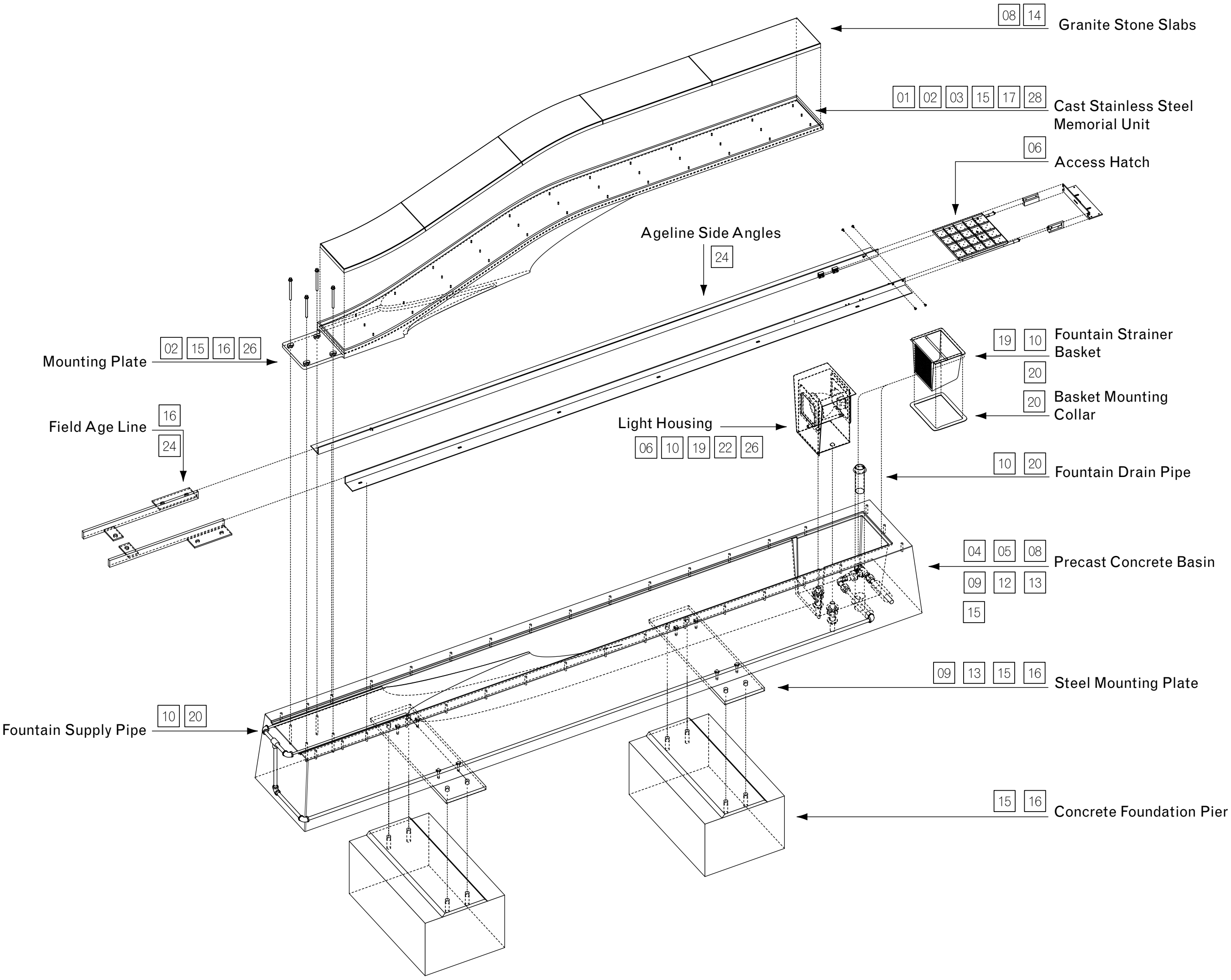
Keith Kaseman

Plan, Pentagon Memorial, by KBAS, Arlington, Virginia, 2008



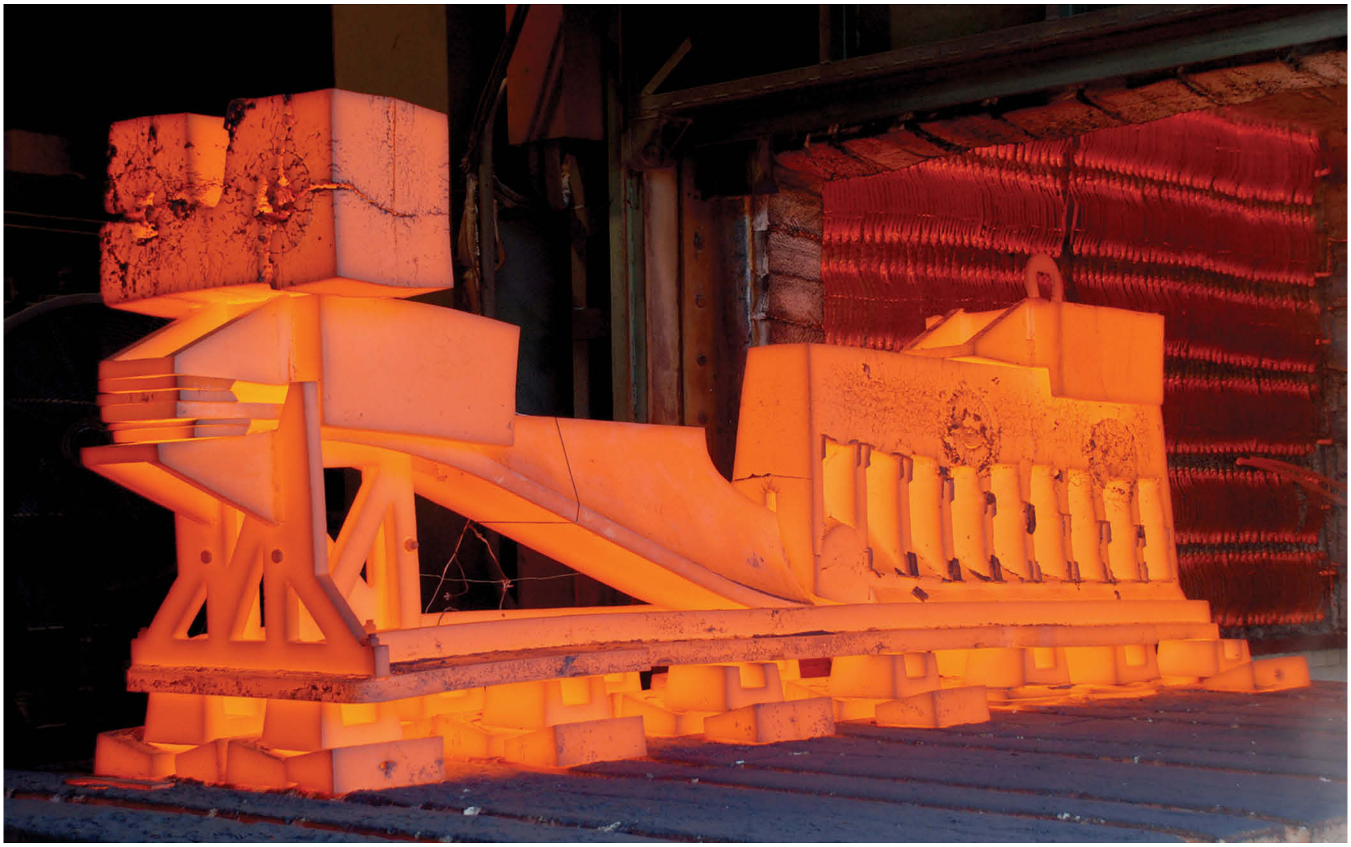
above: Drawing of the geometry of the Memorial units

opposite: Axonometric drawing of unit components



KBAS / BBC+IPA Memorial Unit Collaborative Team

01	Robert Kelly, University of Virginia	Metallurgy Consultant
02	MetalTek International, Pevely, MO	Stainless Steel Foundry
03	Advanced Pattern Works, Collinsville, IL	Pattern & Mold Engineering and Production
04	US Army Research Lab, Aberdeen, MD	Polymers & Coatings Consultants
05	Bayer Material Science, Pittsburgh, PA	Specialty Coatings Manufacturer
06	Maloya Laser, Comack, NY	Advanced Steel Fabrication
07	Crown Polymers, Huntley, IL	Epoxy Polymer Concrete R&D
08	Tremco, Cleveland, OH	Sealant Manufacturer
09	Concreteworks, Oakland, CA	Specialized Formwork / Concrete R&D
10	CMS Collaborative, Santa Cruz, CA	Fountain Systems Designers
11	Syska Hennessy Group, Fairfax, VA	M/E/P Engineers
12	Swerv Co., Berkeley, CA	Pattern & Mold Engineering and Production
13	Arban & Carosi, Woodbridge, VA	Architectural Precast Concrete
14	Lorton Contracting Company, Springfield, VA	Stone Fabrication & Installation
15	Buro Happold, New York, NY	Memorial Unit Structural Engineering & Analysis
16	Alpha Corporation, Dulles, VA	Executive Structural Engineering
17	Buchtel Metal Finishing, Elk Grove Village, IL	Stainless Steel Polish & Finishing
18	OEC Engineering, Chantilly, VA	Sandblast Coordination
19	Starfire Lighting, Wood-Ridge, NJ	Light Fixture Manufacturers
20	Specialty Pool & Fountain, Silver Spring, MD	Fountain Contractors
21	Lighting Research Center, RPI, Troy, NY	Lighting Specification / R&D
22	Lightolier	Lighting Consultant
23	CTL Group, Skokie, IL	Memorial Unit Load-Testing
24	Alliance Steel & Fabrications	Stainless Steel Fabrication
25	Vandeventer Machine Works, St. Louis, MO	Precision Milling
26	MC Dean, Dulles, VA	Electrical Contractors
27	Atlas Tool & Die Works, Lyons, IL	Acid Etching
28	RTMoore Design	Graphic Design / Font Consultant



top left: The mold used to form each Memorial unit out of stainless steel
top right: The casting of a unit
bottom: The heat treatment process during fabrication of the units

Fabricating the Pentagon Memorial

Keith Kaseman

above: View of the Pentagon Memorial, facing east toward the Pentagon, showing the illumination of the units

The Pentagon Memorial is located on the west lawn of the Pentagon Reservation, directly adjacent to where American Airlines flight 77 crashed into the building.

Fabricating the Pentagon Memorial

Keith Kaseman

Acknowledgments

Post-Ductility: Metals in Architecture and Engineering is the third book in a series that has emerged from the Columbia Conferences on Architecture, Engineering, and Materials. Each volume is edited from an academic conference sponsored by the Graduate School of Architecture, Planning, and Preservation (GSAPP) in collaboration with the Fu Foundation School of Engineering and Applied Science at Columbia University. The idea—for architecture and engineering schools to collaborate on a conference and publication series—was initiated by Mark Wigley, dean of the GSAPP, with Christian Meyer, chair of the department of civil engineering, and Michael Bell, professor at GSAPP and chair of the conference. Partnerships between the schools and a scientific committee were formed with an interdisciplinary focus linking engineering, architecture, and materials science. Each year, the material focus migrates, but the essential structure of inquiry remains the same. As with the previous books on glass and concrete (*Engineered Transparency: The Technical, Visual, and Spatial Effects of Glass* and *Solid States: Concrete in Transition*, respectively), in considering metals, we examined the degree to which we could still, in fact, isolate a single material within the broad context of contemporary design and building practice.

Post-Ductility exhibits the breadth and diversity of metal applications throughout history. This history, in correlation with the ongoing experimental practices in the material research of metals, exemplifies significant interdisciplinary collaboration. Metals continuously cross the borders of architecture and engineering, a condition that these conferences have tried to capture through the assembly of practitioners and academics alike. Intent on expanding the definition of material processes, our colleagues show how metals continue to endure innovative developments and question the future state of these materials. These questions are not asked in isolation; they are embedded deep within the research of colleagues, and they are situated within historic and contemporary projects and preexisting collaborations. *Post-Ductility* explores these collaborations and places this work in an academic context, capturing a moment when the professions of architecture and engineering, and the scholarship that surrounds and often propels them, are far more reflexive and intertwined than they have been since the early twentieth century. It is the right time to examine this shared work, in part because the work is revealing new directions.

José Rafael Moneo was generous to not only serve as keynote speaker during the conference but also in hosting a tour of his then-in-construction Northwest Corner Building at Columbia. Bélen Moneo and Jeffrey Brock, his partners in this work, were also central to the conference. Werner Sobek and Heiko Trumpf have been consistent partners, sharing their research as members of the scientific committee and providing outreach to new colleagues in Europe and the United States. Theodore Prudon, Sylvia Lavin, Steven Holl, Jorge Otero-Pailos, and George Wheeler all supplied support during the formation of the conference. Prudon, Otero-Pailos, and Wheeler opened the work to historic preservation and in particular to the life span and material stability of metals in architecture.

If we were to identify each person that gave shape to the conference, the list would resemble this book's table of contents. Almost everyone who participated stepped outside of their comfort zone, especially those that took lead roles in structuring panels and exposing their long-standing work to new directions were integral to the development of the conference. Others generously allowed their work to be placed in relation to new colleagues and engaged in conversations reframed by issues of environmental engineering and energy concerns. All the participants witnessed their work being examined at the levels of art history and political and cultural history, forging a new kind of communication between scholars, engineers, and architects.

The conference and book benefited from the tremendous energy and work of Benjamin Prosky. The book was shaped with insight by our partners at Princeton Architectural Press, particularly Megan Carey and Jan Haux. Thanks are also due to Momo Araki, Meredith Baber, and Atreyee Ghosh for their assistance with images and permissions. The original graphic identity for the event was formed by Luke Bulman and his design firm, Thumb. Diana Darling and William Menking of the *Architect's Newspaper* were our media sponsors and helped situate the project's ambitions early on. The conference was accompanied by the exhibition *METALSMYTHS*, curated by Rosana Rubio-Hernandez with Alejandro de Castro Mazarro, who also provided advice and insight on the conference structure. Special thanks also to Lou Fernandez, John Ramahlo, Mark Taylor, and the GSAPP audiovisual crew. We would also like to extend a special thanks to Devon Ercolano Provan, director of the GSAPP Development Office, and Melissa Cowley Wolf of our Alumni Office. Associate Dean David Hinkle is at the center of any project at the GSAPP, and he helped guide this work.

The conference, book, and the accompanying documentary film have been generously supported by the Steel Institute of New York, the Ornamental Metal Institute of New York, as well as the American Institute of Steel Construction (AISC). In particular, we thank Gary Higbee, director of industry development for the Steel and Ornamental Metal Institutes, for his committed collaboration. We also thank Louis Geschwinder, vice president of the AISC. Through these collaborations, we were able to reach a far wider professional audience and broaden the scope of the school's engagement with industry. Their partnership creates a new engagement with industry that our professions and schools will increasingly rely on.

As a long-term project, the GSAPP continues to develop the Columbia Conference on Architecture, Engineering, and Materials, with the forthcoming book *Permanent Change: Plastics in Architecture and Engineering*, as well as the fifth conference in the series, focusing on the materiality of light. Dean Wigley has been tremendously inventive in opening the school to new opportunities for thinking and exchange. The conference and this book would not have been possible without his drive and momentum.

—Michael Bell and Craig Buckley

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Craig Buckley is an adjunct professor and the director of print publications at Columbia University's GSAPP.

Lise Anne Couture is a principal of Asymptote Architecture, a New York–based practice that she cofounded with Hani Rashid, and a visiting professor at Yale School of Architecture.

Anna Dyson teaches design, technology, and theory at the School of Architecture at Rensselaer Polytechnic Institute, and is director of the Center for Architecture Science and Ecology.

John E. Fernández is faculty in the department of architecture at the Massachusetts Institute of Technology (MIT) and director of the building technology program.

Laurie Hawkinson is a professor at Columbia University's GSAPP and a partner at the New York–based firm Smith-Miller + Hawkinson Architects.

Juan Herreros is a professor at the Superior Technical School of Architecture in Madrid and the founder of Herreros Arquitectos.

Steven Holl is a professor at Columbia University's GSAPP and the founder of Steven Holl Architects.

Keith Kaseman is cofounder of Kaseman Beckman Advanced Strategies (KBAS), based in Philadelphia, and an adjunct associate professor of architecture at Columbia University's GSAPP.

Sylvia Lavin is the director of critical studies in the architecture department at the University of California, Los Angeles (UCLA), and the director of the design/research group Hi-C.

Mark Malekshahi is an associate principal at Buro Happold Consulting Engineers in New York.

Rory McGowan is a director at Arup Dublin. He lectures frequently and has served as technical tutor at several architectural schools.

Christian Meyer is professor of chair of the Department of Civil Engineering and Engineering Mechanics at Columbia University's Fu Foundation School of Engineering and Applied Science.

Ana Miljacki is an assistant professor of architecture at MIT.

José Rafael Moneo is the Josep Lluís Sert Professor in Architecture at Harvard University's Graduate School of Design (GSD). In 1996, he was awarded the Pritzker Architecture Prize.

Marwan Nader is a vice president and project director at the civil and structural engineering firm T.Y. Lin International in San Francisco.

Jorge Otero-Pailos is an architect, artist, and theorist specialized in experimental forms of preservation. He is an associate professor of historic preservation at Columbia University's GSAPP.

Theodore Prudon is an architect and principal of Prudon & Partners, a firm specializing in restoration. He is an adjunct associate professor of historic preservation at Columbia University's GSAPP.

Jesse Reiser is cofounder of Reiser + Umemoto in New York. He is a professor in the School of Architecture at Princeton University.

Hilary Sample is a principal of MOS in New York, and an associate professor at Columbia University's GSAPP.

Hans Schober is a partner at Schlaich Bergermann and Partner, consulting engineers based in Stuttgart, Germany, and president of the firm's New York office.

Matthias Schuler is the founder and managing director of Transsolar Energietechnik GMBH based in Stuttgart, Germany, and an adjunct professor of environmental technology at Harvard University's GSD.

Craig Schwitter is a partner at Buro Happold Consulting Engineers.

Werner Sobek is the director of the Institute for Lightweight Structures and Conceptual Design (ILEK) at the University of Stuttgart, and the founder of the international firm Werner Sobek Engineering and Design. He is also a professor at the University of Hanover.

Galia Solomonoff teaches graduate design studios and seminars at Columbia University's GSAPP. She is a licensed architect in the state of New York and principal of Solomonoff Architecture Studio in New York.

Heiko Trumpf is a principal of Werner Sobek Engineering and Design.

Mark Wigley is an architectural critic and theorist and the dean (2004–present) of Columbia University's GSAPP.

Mabel Wilson is an associate professor of architecture at Columbia University's GSAPP, where she directs the program in Advanced Architectural Research.

Credits

Project Credits

Northwest Corner Building, Columbia University, New York, New York

Architect: José Rafael Moneo
Design project architects: Moneo Brock Studio
Architect of record: Davis Brody Bond Aedas, New York
Building area: 188,000 sq. ft. (54,860 sq. m)
Collaborators: Andrés Barrón, David Haft, Spencer Leaf, Clover Linne, Benjamin Llana, Mario Samara, Gene Sparling, Mayine Yu
Completion: 2010
General contractor: Turner Construction Company
Laboratory planning consultants: GPR Planners Collaborative, Inc.
Lighting consultants: Fisher Marantz Stone
MEP engineers: Arup
Project managers: Capital Project Management, Columbia University Facilities
Structural engineers: Arup

Yas Hotel, Abu Dhabi, United Arab Emirates

Architects: Asymptote Architecture
Design architects: Hani Rashid and Lise Anne Couture
Digital modeling consultants: Gehry Technologies
Grid shell engineers: Schlaich Bergermann and Partner
Lighting consultants: Arup Lighting
Local architects: Dewan Architects & Engineers and Tilke & Partners W.L.L.
MEP engineers: Red Engineering Middle East
Project team: Chris Delusky, Andrew Drummond, Theo Sarantoglou Lalis, Mick McConnell, Matthew Utley
Structural engineers: Dewan Architects & Engineers, Arup, and Waagner-Biro

Bioclimatic Towers, Vitoria, Spain

Architects: Iñaki Ábalos and Juan Herreros
Building area: Completed plot 39,500 sq. ft. (12,065 sq. m)
Client: Ensanche 21 / Jaureguizahar
Collaborators: David Sobrino, Juanjo González, Renata Sentkiewicz, Elena Cuerda, Christian Leibenger
Completion: 2006
Model: HCH Model
Structure: Obiol y Moya

Nanjing Museum of Art & Architecture, Nanjing, China
Architects: Steven Holl Architects
Associate architects: Architectural Design Institute, Nanjing University
Completion: 2011
Client: Nanjing Foshou Lake Architecture and Art Developments Ltd
Design architect: Li Hu
Lighting design: L'Observatoire International
Structural consultant: Guy Nordenson and Associates

Champlain Port of Entry, Champlain, New York
Architects: Smith-Miller + Hawkinson Architects
Civil engineers: HNTB
Client: U.S. General Service Administration
Construction managers: Pike Hill Joint Venture
Environmental graphic design consultants: Pentagram
General contractor: Northland Associates, Inc.
Glass engineering consultants: R.A. Heintges Architects
Landscape architects: Quennell Rothschild and Partners
Lighting consultants: Claude R. Engle Design
Specification consultants: Construction Specifications, Inc.
Structural, MEP, and security engineers: Arup

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History and Theory

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Projects

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Structural Engineering

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