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THE INFLUENCE OF METHODS AND MATERIALS ON THE DURABILITY OF REPAIRS TO CONCRETE COASTAL AND OFFSHORE STRUCTURES

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THE RESEARCH AND INFORMATION GROUP FOR THE UNDERWATER AND OFFSHORE ENGINEERING INDUSTRIES
A PART OF CIRIA – THE CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION

FOREWORD

This report is the result of a UEG Project Definition Study to examine the arguments for and against durability testing of repairs to concrete in a marine environment and to make appropriate recommendations for further work.

The study was carried out under contract to UEG by M B Leeming of Arup Research and Development under the supervision of T P O'Brien. The UEG Research Manager for the study was R W Barrett.

The study was financed through UEG by a joint venture of 13 organisations, indicated by an asterisk in the list below. The resulting report was prepared under the guidance of a Steering Group which comprised invited specialists and representatives of participating organisations:

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Part I of this report is aimed at readers with a general interest in the subject and contains: the main arguments for and against doing further research into the durability of repairs to marine concrete; and the conclusions and recommendations. Part II is more specific and contains the background information on which the conclusions are based.

Cover pictures courtesy of Sir Robert McAlpine & Sons Ltd and the Building Research Establishment.

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SUMMARY

This report examines the arguments for and against durability testing of repairs to concrete in a marine environment. Current techniques and materials used for the repair of concrete are reviewed. The need for repair and the factors that will influence the subsequent durability are discussed. The choice of materials, type of testing and costs of research in relation to the repair market are examined. The report considers the durability of repairs to concrete in the marine environment both above and below water in the area of the North West European Continental Shelf. Possible research projects covering the main research strategies are defined and a minimum viable research programme is suggested.

PART I

1. INTRODUCTION

The excellent durability to date of existing concrete structures is mainly due to the high quality of design, materials and workmanship. Yet inevitably there will be areas which will need some repairs during the lifetime of the structures, if only because of mechanical damage. It is necessary that these repairs be of adequate quality so that the operational life of the parent structure is not affected. The problems of access and the difficulty of carrying out repairs to marine structures mean that it is necessary to take special care to avoid the need to repair the repairs.

1.1 Background

In 1982, when the contributors to the Concrete in the Oceans Programme started to consider some additional work to be undertaken in parallel with Phase II of the Programme, the highest priority topic was the question of the durability of repairs to concrete in a marine environment. For organisational reasons, it was considered inappropriate to undertake any such work within the Concrete in the Oceans Programme as this Programme was scheduled to end before any long-term durability testing of repaired concrete could have been completed.

1.2 The pros and cons of durability testing

Supporters of the proposal, that some durability testing of concrete in the marine environment be undertaken, felt a need for guidance on: the durability of materials; the effect of repair methods on durability; any other factors that might affect their decisions about how to repair damaged concrete in a marine environment.

Those doubting the usefulness of such an exercise felt that it would not be cost-effective to test several currently available repair materials, it would be almost impossible to select generic materials for test and, even if it were possible, the repair materials available at the end of any testing programme could be very different from those actually tested. They contended that only the relative merits of a few currently available materials would be obtained and this information would not actually help the selection of materials for repair when the durability testing programme came to an end.

A meeting was held to discuss both contentions and it was agreed that, as an initial approach, a Project Definition Study should be undertaken to examine the arguments in more detail, bring together in one volume a succinct summary of all the techniques and materials available, including published test data, and, if appropriate, make proposals for further work.

1.3 Objectives

The objectives of the study leading to this Report were:

a) to undertake a brief state of the art review of current techniques and materials used for repair of concrete in the marine environment

b) to identify any durability test data relating to repaired concrete which is openly available and to identify any conclusions that can be drawn from the work

c) to examine the arguments for and against a programme of durability testing of repaired marine concrete

d) to make recommendations on the need for and/or usefulness of any durability testing programme or any other appropriate further work

e) to prepare outline proposals for any recommended further work.

1.4 Scope

The study leading to this Report covered the repair of all types of concrete structures directly exposed to the marine environment e.g. offshore oil and gas platforms, offshore loading facilities, jetties, lighthouses, coastal and harbour works, and subsea pipelines. In this context marine is defined as 'in contact with seawater or in an environment dominated by seawater'. Structures can be defined as coastal where 'there is relatively easy access from the land' as opposed to offshore structures which 'require a substantial voyage by sea or air to gain access'.

In assessing the need for or value of undertaking any durability testing programme, the study has taken careful account of the rate of advance in repair materials technology and the difficulty of selecting generic materials for testing.

The study was to some extent limited by budget and timescale and it was felt that the objective of undertaking a brief state of the art review could most economically be achieved by using the Report by the Concrete Society Working Party on the Repair of concrete damaged by reinforcement corrosion [1] as the foundation and extending it particularly into the area of repairs to structures in the marine environment. Reference is made to that Report throughout this document.

This Report is aimed at those with some knowledge of repair methods and attempts to provide the reader with sufficient information to assess the relevance of any further research proposed.

The Report covers the durability of repairs to concrete in the marine environment both above and below water and is confined to the North West European Continental Shelf. Arctic and tropical considerations are outside the scope of the study.

The detailed scope of the study, as approved by the Steering Group, is set out in Appendix 1.

2. THE NEED FOR REPAIR

The need for repair and the factors that will influence the subsequent durability must be addressed before further research is formulated.

2.1 The need in relation to the location in the structure

There are four distinct zones to all concrete coastal and offshore structures. These are the underwater zone, the tidal zone, the splash zone and the atmospheric zone. The splash and tidal zones take on a different significance for coastal and offshore structures. Coastal structures are dominated by the tidal range while offshore structures are subject to constant wave action and a much smaller tidal range. In both types of structure there is an intermediate zone between the underwater and splash zones where the concrete is saturated but is exposed to air for part of the time. Here the concrete is subjected to the more aggressive corrosion conditions of the splash zone yet the difficulties of carrying out repairs are similiar to those encountered under water. For simplicity only the underwater and above water zones are differentiated for the purposes of this report.

There are two further aspects to the need for repair that require consideration: structural requirements; and the need to arrest deterioration as a result of corrosion of the reinforcement.

The need to repair a structure that has suffered accidental damage or overload can only be judged after a thorough design reappraisal. The need to repair to limit corrosion is best addressed in two main areas, the underwater and above water zones. It is the latter which is dominated by the splash zone requirements which are in most cases similar to, but more onerous than, the atmospheric zone. The repair of cracks presents different requirements to bulk repairs and is treated separately in this report.

The general topics of concrete durability and reinforcement corrosion are treated in the Concrete Society Technical Report No. 26, section 1: Introduction and section 2: Diagnosis [1].

2.1.1 <u>The underwater zone</u>

Recent research [2] into the corrosion process in marine concrete has shown that, under water, corrosion of the reinforcement does not occur in normal circumstances. However, where significant areas of reinforcement are directly exposed to seawater, for example in cracks over 0.6 mm wide or in areas where impact damage has occurred, corrosion can occur but this can be controlled by the application of cathodic protection. These areas may need repair if cathodic protection is not applied, or it may be desirable to repair to reduce the drain on a cathodic protection system. The main reason to repair an underwater concrete structure which has suffered accidental damage, foundation failure or structural inadequacy is to maintain structural integrity. Coastal structures sometimes suffer loss of concrete section at seabed level due to abrasion from water borne sediments and repair may be required to maintain serviceability.

2.1.2 Above water

The area of a concrete structure just above the water level, usually termed the splash zone, is the most vulnerable with regard to deterioration due to corrosion damage. This area is also vulnerable to physical damage due to shipping impact and to abrasion from fenders, mooring ropes and wave action. Conventional cathodic protection with impressed current or sacrificial anodes immersed in water is effective only for areas above water. However, techniques incorporating anodes formed from arrays of wires or conductive coatings have been developed for use on bridge decks, piers and abutments. Distributed sacrificial anodes are also being developed. These techniques are now being applied experimentally to coastal structures.

Spalled areas and areas of low cover require repair and maintenance as corrosion rates can be high and deterioration may proceed to a state where structural integrity may become suspect. The splash zone provides the most harsh environment with regard to durability for both reinforced concrete and any material used for its repair.

2.1.3 The repairing of cracks

The main reasons for repairing cracks are:

a) to stop leaks

b) to maintain the structural integrity across the crack

c) to prevent ingress of aggressive species causing corrosion of the reinforcement

d) for cosmetic reasons.

Unless the crack is wide (1.5 to 2 mm), pure resin is the most likely material to be used as it can be formulated to be less viscous than cement grout. In most cases the injected material acts as a filler and has few structural or physical requirements other than the ability to penetrate. The material is protected from the environment by the bulk of the concrete and therefore durability is not usually a problem. There may, however, be instances where some bond strength is required so that further cracking is distributed. There may then be a durability problem if loss of bond occurs with time; water penetration down the interface between the resin and steel has been experienced in the past. Whether the same phenomenon occurs between an epoxy resin/concrete interface is not known, nor whether it is a result or a cause of lack of bond. Segmental concrete bridges are an example where ingress of chloride bearing water through epoxy sealed joints could result in deterioration.

When a crack has to be filled under water, or when injection is attempted to stop leaks, the resin has to displace the water in the crack. The ability of a particular system to achieve this will influence the durability of the repair.

2.2 The objectives of carrying out repairs

When a structure is repaired for structural requirements, the main objective is to restore the original strength of the member that has been damaged. The main requirements are: to provide adequate strength; that the modulus of elasticity is compatible; that creep and shrinkage properties are acceptable; and that a good bond is made to the existing concrete. One aspect of 'durability' will concern the change of the above properties with time as result of being exposed to a marine environment.

The other objective, of restoring or maintaining the corrosion protection to the reinforcement, is a more complex problem. In a chloride-free environment, any cementitious or polymer-modified cementitious material will generally return the reinforcement to an alkaline environment so limiting further corrosion. The corrosion protection afforded by pure resin repair is a passive mechanism by exclusion of the environment - see Concrete Society Technical Report No. 26, section 3.1.3: Restoring Protection [1]. In a marine environment the parent concrete will be contaminated with chlorides. Therefore, if a repair is chloride-free, back diffusion of chlorides into the repair material, out of the chloride-contaminated parent concrete, may occur. A chloride-free repair may also provide a cathodic area, resulting in the possible activation of incipient anodes in the still chloride-contaminated parent concrete [3]. A highly impermeable repair could so restrict oxygen diffusion that conditions for 'negative active' corrosion and crevice corrosion [2] could occur.

2.3 Repair strategies

The extent to which a structure will need repair will be constrained by the extent to which continued serviceability is required and by the need for structural safety. There are several approaches to repairs which will depend on the requirements of the structure:

a) do nothing as eventual failure is beyond its intended useful life

b) do sufficient to slow deterioration so that the intended useful life is at least met

c) accept that repairs have only a finite life and that further repairs on a regular basis will be needed to extend the life of the structure

d) accept the present deteriorated state of the structure and stabilise the deterioration at that level for the remaining life of the structure

e) restore the structure as closely as possible to its original condition.

The choice of strategy may be different in the two broad categories of structures considered in this project, namely coastal and offshore. The offshore industry takes a more detailed interest in repair methods. Serviceability and safety requirements are relatively well defined and offshore structures are generally massive. Many coastal structures are of beam, slab and column type; their future requirements are less well defined and standards may be lower.

3. ARGUMENTS FOR AND AGAINST DOING FURTHER RESEARCH

3.1 The problems of doing research on the durability of repair systems

3.1.1 The choice of materials

The available materials are discussed in section 8. They range from pure cementitious to pure resin systems, with various composites in between. There is a problem in classifying these materials into generic types, as classification by principal ingredient is not sufficiently precise. Even within this broad classification there are a large number of parameters, and quite small changes to a formulation can result in significant changes in properties. In addition, the exact composition of repair systems are seldom declared and many of these materials may still be under development and therefore subject to change during the course of any experiment. However, in the present climate of the industry with a downturn in major construction projects particularly offshore, less development of specialist materials for use offshore is being carried out compared with five to ten years ago. Materials that appear to be adequate for their purpose are now available and there is little reason for further development until experience finds them to be lacking. The situation for coastal structures is, to some extent, the opposite; repair and renovation being preferred to replacement. Manufacturers of materials for the onshore market see this as an opportunity and are developing their range of materials for use in marine conditions.

3.1.2 Type of testing

Because the factors that influence the durability of repairs in service are not well understood, it is desirable to work as closely as possible to full scale to avoid scale effects that may influence such factors as curing rate, curing shrinkage and differential thermal expansion. It is also desirable to carry out the repairs to specimens by methods that are realistic in comparison with actual repairs in practice and, as a result, relatively large specimens are required so that the materials and defects can be modelled at full size. The natural environment is so complex that artificial simulations are often inadequate and exposure effects cannot easily be accelerated. Therefore specimens need to be exposed in real sea conditions for a long period of time. Repairs are most often carried out on old concretes with many years of exposure to a marine environment. True simulation would require an initial marine exposure to newly cast specimens which further extends the timescale. These effects reinforce the problems in section 3.1.1, that the formulation of the materials can change within the duration of the experiment. The problem of the long timescale, which stems from the inability to accelerate the environment effectively, could to some extent be overcome by carrying out research on materials that have already been exposed for some time. Significant information will only be gained from this strategy if the original repair operation was well documented.

A further problem with the manufacture of specimens in the laboratory is that laboratory prepared specimens tend to be of a higher quality than the obviously greater volume of concrete that is cast on site. Furthermore, repairs are usually required as a result of work carried out imperfectly on site and also as a result of accidental damage, and these effects are difficult to simulate in the laboratory. Similiar difficulties arise when attempting to simulate in the laboratory the conditions under which surface preparation has to be carried out in the field. These effects arise as a result of scale as well as that of a hostile environment and are probably more significant with regard to structures in the marine environment compared with land based structures.

3.1.3 The number of parameters

The range of material types, the variation within each material type, the effects of proportioning, mixing and workmanship, the range of properties required, variations in types of damage requiring repair, variations in the base material to be repaired, the numbers of combinations of tack coats, the different temperatures and environments within which repairs can be carried out, all lead to a large number of possible parameters. Only a few parameters can be investigated in any one project otherwise the experiments become unmanageable and the results difficult to interpret. Even if only a few parameters are selected it is sometimes difficult to control the remaining parameters at a constant level.

3.1.4 The knowledge gained

The exposure of large numbers of specimens of a reasonable scale in real sea environments over long periods is expensive. The likelihood of things going wrong means that replication of specimens is important otherwise valuable information can be lost. The high cost of these experiments must be equated to the knowledge gained which may be on a limited range of materials and applications and may be related to outdated technology.

3.1.5 The outcome of existing research and experience

There is a body of opinion that considers that enough research has been done already. However, much of what has been done to date is confidential. The majority of this experience is not published and resides within the firms that offer repair systems commercially. The ultimate test is whether the client believes he understands enough of the technology to know what he is getting and whether he is satisfied that the work that he had commissioned will last for the remainder of the life of the structure. He must be clear as to whether he expects a once-only extension to the life of the structure or whether he is prepared to accept continued maintenance.

3.1.6 Research should be done by the suppliers

Because there are no identifiable basic generic materials, each supplier offers a different product. There is a valid argument that the supplier should be able to satisfy the client that his material is fit for its purpose and therefore the burden of research lies with the suppliers. This argument relies on the client having sufficient knowledge to understand the problems, appreciating the claims made and being clear about what the results of the test mean.

3.1.7 Cost of research in relation to the market

The major market for repairs to marine structures probably lies in coastal works and jetties. Owners of these types of structures are numerous and varied and have little research funding available. Repairs to offshore structures are required less often although the cost of doing the work is very much higher. The offshore operators' requirements for methods and materials are, however, more exacting. Suppliers prefer to direct research funds to their own materials rather than to collaborate in joint industry research.

3.2 The benefits of doing research on the durability of repair systems

The daunting list of the problems of doing research on the durability of repair systems may be seen as a sufficient argument for not doing work in this field. There is however benefit alone in examining the arguments so that research projects may be defined with confidence of the objectives being achieved.

It is possible to categorise repair materials broadly and to pick relatively well known materials to typify these categories. Research on these will provide valuable basic information on the parameters controlling durability and will provide benchmarks against which the properties of more recently developed materials can be judged. A study of the durability of repairs to old structures would enable a wider range of materials and methods to be investigated, compared with laboratory studies, as well as providing information on relative performance. Surveys may well identify problems that are peculiar to a particular category of repair system and could indicate whether certain factors are influenced by materials or workmanship.

The major benefit in doing research into the durability of repair systems is to achieve cost effective repairs. Carrying out repairs is a labour intensive operation, with the major cost being in access and preparation for repair such as breaking back to sound concrete and fixing of formwork which are common to all systems. The final preparation and the choice of the right material can have a disproportionate effect on the durability, and therefore overall economy, of the complete operation.

At present, there is little information on the durability of repair systems either onshore or for marine applications. The choice of material is made largely on guesswork and on experience of what has been adequate in the past. This is inhibitive of improvement. Many structures are now being repaired less than 20 years since they were constructed. Few repair systems have demonstrated reliability for periods in excess of this. These facts suggest that continued maintenance must be accepted for structures that were designed for a 120 year life. Offshore structures have a much shorter planned useful life than onshore structures but conversely safety considerations and the level of investment at stake are much more important.

Research on the durability of repair systems will give confidence in the choice of materials and will result in repairs being carried out more effectively. It will allow improvement in repair materials and systems as knowledge is gained of the mechanisms involved. Confidence will be gained in carrying out repairs as the important parameters affecting durability will have been identified. As knowledge is gained, repair systems can be formulated that are less sensitive to ambient conditions so that the consequences of bad workmanship and inexperience can be minimised.

4. RESEARCH STRATEGIES

4.1 Overall strategies

There are three possible research strategies which could be adopted.

4.1.1 Exposure tests

This strategy involves the repair of large scale specimens with several different proprietary or representative systems, and the exposure of these repairs to a real sea environment for several years. The strategy has most of the problems outlined in section 3.1 and favours existing materials. An alternative to the use of new specimens would be to monitor repairs to existing structures, although control of these types of experiments is more difficult.

This strategy is closest to actuality if it can be carried out economically and the results are not required in the short-term. A well controlled experiment in which conditions are as close as possible to the real environment has advantages in that there will be more confidence in the outcome. It is not known how great an effect the method of repair has on durability as opposed to the effect of the material alone. Testing of large scale specimens in a real environment will also allow a much closer simulation of repair methods thereby eliminating a number of variables.

4.1.2 Study the durability of existing repairs

The following studies could be pursued under this strategy:

a) In-service repairs to offshore structures. There are relatively few of these covering a very limited range of materials.

b) Repairs carried out to offshore structures during construction. There are a greater number of these which are known to the operators. They were, however, mostly made in the dry.

c) Repairs to jetties, harbour works, and concrete barges and boats. There are a large number of these covering a much greater timespan and range of materials. Unfortunately these tend to be much less well documented. Certain commercial firms have documented their own experience of existing repair systems during inspection of marine structures but their combined experience has not been compiled and published.

d) Repairs to bridges. This area has been well researched and in practice is generally well documented. There may be advantages in pursuing this aspect of repairs as the result of the application of de-icing salts on road bridges is similar to problems experienced in marine structures as a result of the ingress of chloride ions.

This strategy only examines old technology but results can be obtained relatively quickly. Surveys of this type can be of value provided that the original repair was well documented. However, they do not tend to be conclusive as the parameters cannot be controlled and because of the inherent difficulty of carrying out scientific work in the field. If the ultimate objective of the project is to convince the client that repairs as presently carried out are durable, then this strategy would probably provide sufficient evidence to allay his fears. It would, however, be very limited in its contribution to knowledge in this area as it gives information on whether a system works or not but does not necessarily indicate why. There could be benefit in acquiring background information on experience in carrying out repairs but this is difficult to communicate effectively.

4.1.3 Determine the parameters which influence durability, study their limits and perfect tests methods to measure them.

This strategy is not constrained by the need to test all the variations of each type of material. Provided all the limiting factors are covered in the full range of materials, the effects of the variations can be studied as required. A proper understanding of the factors affecting durability will stimulate improvements in materials, and the new materials can then be evaluated using standard test methods.

It is necessary to evaluate the test methods using well known materials so that experience can be gained on their accuracy and repeatability. The results from the test methods can then be related to the durability achieved in practice. It is necessary to determine levels of acceptance of the various parameters evaluated in the standard tests. It is also necessary to evaluate how the measured properties change with age, exposure to the environment and cyclic loading. A further aspect that requires evaluation is the effect that the conditions under which the repair is carried out have on both the results of test methods and the durability of repair systems.

4.1.4 Combined approach

It may well be advantageous not to concentrate exclusively on only one of the above approaches but to back up the major strategy with some work in other fields.

4.2 Detailed requirements

There are many aspects of durability that are common to both land based repairs and those in a marine environment. Research aimed specifically at the durability of repairs to marine structures should concentrate on those aspects of material degradation that are peculiar to the marine environment such as the action of sulphate reducing bacteria, the ingress of significant quantities of chlorides and high hydrostatic pressure due to deep immersion.

The interface bond has been the subject of considerable academic research but generally the test pieces have been made under ideal conditions. The specific conditions of a coastal environment may well require further research for the coastal and offshore interests. Particular aspects that need investigating are:

a) the influence of various methods of surface preparation in relation to surface contamination

b) the mechanical/physical requirements for the interface bond

c) the effect of time on the above parameter

d) whether an adequate bond can be achieved under water

e) the effect of cyclic loading on the interface bond.

The examination of cores taken from existing structures that have been repaired under well documented circumstances would provide valuable information on the actual properties of the interface bond under practical conditions which can then be compared with those achieved under laboratory conditions. The problems of obtaining historical data, of finding suitable structures and of carrying out the work in the field are dicussed in section 3. However, these problems are surmountable for old structures and an experiment could be set up to examine a structure immediately after repair.

The adequacy of interface bond is usually tested by the slant shear test, BS 6319 part 4 [4] and this test has been subject to considerable development [5-10], the work of Domone et al [5-6] being the more recent. In Germany this parameter is tested by the pull-off test which may be more adaptable to testing repair systems in situ.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

There is a need for documented repair techniques suitable for coastal and offshore concrete structures. Structural damage and deterioration as a result of corrosion of the reinforcement occurs particularly in the splash zones, and there are special problems in carrying out repairs to marine structures. These include the impossibility of keeping the repair area dry and avoiding the contamination from chlorides. Special methods and materials are therefore required to overcome these problems.

The durability requirements of a repair to a marine structure are different to and more severe than those to a building on land. The main factors affecting the durability concern the humidity of the environment combined with the action of chlorides which can affect the structural performance and the ability to control further corrosion damage.

There is at present very little published information on the durability of repairs in marine conditions so that there is no yard-stick by which to judge the choice of method or material for repairs.

The problems of access and the difficulty of getting the work done in marine conditions make the choice of the right method and material much more important from the economic point of view. For the above reasons there is a strong economic argument for carrying out research into the durability of repairs in the marine environment.

There are special difficulties in undertaking research in the marine environment. They lie mainly in the cost associated with long term exposure tests on a wide variety of materials still under development. Many of the problems are inherent in all research programmes and can be successfully overcome. A proper analysis of

d) whether an adequate bond can be achieved under water

e) the effect of cyclic loading on the interface bond.

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The main benefits in doing research are economic, allowing more confidence in the use of the right materials and a better understanding of the mechanisms involved so that improved methods and materials can be developed.

5.2 Recommendations

It is recommended that the most effective research strategy lies in determining the performance characteristics which affect the durability of repairs, the levels of acceptability of the relevant properties and the development of practical test methods to measure these properties. This would allow proper comparisons in the choice of materials and methods, and provide acceptance criteria for work carried out on site. This strategy avoids many of the problems of doing the research described in section 3.1 and will encourage the development of improved materials and repair methods. This approach would allow a programme to be split into several smaller projects which could be carried out in universities and polytechnics.

There would however be considerable advantage in backing up this study with some surveys on the durability of existing repairs to ensure that the correct mechanisms are being studied. Although there is difficulty in getting accurate scientific information from surveys, there are many benefits in learning from what actually happened.

Ingress of chlorides, high hydrostatic pressure, the action of sulphate reducing bacteria and sulphate attack have been identified as being the major possible causes of material degradation that are particular to the durability of repairs in a marine environment. The ingress of chlorides is the most important of these and should be investigated in any future research. High hydrostatic pressure could only be investigated satisfactorily by carrying out deep water testing in exposure tests (section 13.1) but this subject is not recommended due to the length of time needed to obtain results. The action of sulphate reducing bacteria is considered to be a special case and is being investigated as part of the COIN programme [50].

Sulphate attack has been identified as a possible deterioration mechanism for some materials [14] and all research projects defined in section 13 should be carefully monitored for signs of this type of deterioration.

If longer term testing is to be considered, it is recommended that the results of the BRE programme of work [14] be extended into a more practical situation by using selected materials from that programme to repair selected existing coastal structures and to subsequently monitor their performance in the field in a project similar to that defined in section 13.2.

5.3 The minimum viable programme

The projects described in section 13 have not been listed in priority order nor is it intended that they will all be carried out as this is well beyond any likely funding available. They have been defined individually to provide the basic information allowing them to be combined and adjusted to provide a minimum viable programme.

The **Exposure tests project** (section 13.1) provides the most straightforward approach to durability testing while the **Monitoring of new repairs to existing coastal structures** (section 13.2) represents a more practical and less costly approach but suffers from being a less well controlled and reproducible experiment. The **Study of repairs to existing offshore structures** (section 13.3) investigates the durability of repairs to a limited type of existing structures, namely those offshore, and for the desk study envisaged would provide useful information. The **Survey of past repairs to existing coastal structures** (section 13.4) investigates the much wider range of existing coastal structures but these may be less well documented. Adjustment of the number of structures surveyed will allow tailoring of the project to funds available. The **Development of test methods** (section 13.5) represents a more theoretical approach by assessing those factors which influence durability, and developing appropriate test methods to evaluate the relative merits of any repair system. This project can be divided into a number of sub-projects within the overall framework and has the advantage that it parallels and extends research on repairs for land based structures. The **Comparison of properties obtained in the laboratory with those achieved in practice** (section 13.6) takes existing test methods, which to date have been used mainly in laboratory investigations and which are directed at repair systems for use on land based structures, and relates them to what can be achieved in actual marine conditions.

A summary of the six projects proposed is given below in order of benefit:

		Estimated Costs	Duration
13.5	Development of test methods	£195K	3 years
13.4	Survey of past repairs to existing coastal structures	£185K	2 years
13.3	Study of repairs to existing offshore structures	£ 30K	18 months
13.2	Monitoring new repairs to existing coastal structures	£130K	7 years
13.6	Comparison of properties, site/practice	£ 85K	2.5 years
13.1	Exposure tests	£300K	7 years

The minimum viable programme is considered to be the **Development of test methods** (13.5) combined with at least part of the **Survey of past repairs to existing coastal structures** (13.4) at a total cost in the order of £300K over a period of three years. This programme can be split into a number of sub-projects and thereby enable it to be funded from wider sources.

If insufficient funding is available for the above, the **Study of repairs to existing offshore structures** (13.3) recommends itself as a relatively inexpensive and quick method of gaining knowledge for these particular structures.

PART II

6. METHOD OF CARRYING OUT THE STUDY

The study leading to this Report was carried out in three stages.

6.1 Data gathering

The existing experience within the Arup organisation was extended by a literature search to identify research and development done abroad. Specialists in the UK were visited with the objective of obtaining details of recent research and unpublished information at first hand. This work mainly covered the first two objectives stated in section 3 and looked particularly at the following factors:

a) the available materials and methods of repair. Classification of the materials into generic groups was studied in order to expose inherent problems in classification. This aspect is covered in section 8 of this report

b) the data gathered on repairs known to have been carried out. This is presented and discussed in section 12

c) the details of research to date. This included suitability of specimen sizes, test methods and relevance of the work. This information is contained in section 10

d) the design and certification requirements for an effective repair. This aspect is covered in section 11.

6.2 Assessment

The information gathered in the first stage was assessed in particular for the following aspects and the results are contained in the relevant sections:

a) the extent to which the subject has already been covered both by independent research organisations and by manufacturers in developing their proprietary products. This exercise determined whether there is a need for further research (section 10)

b) the likelihood of further projects achieving worthwhile results within the funding that is likely to be available in an appropriate timescale (section 5)

c) the judgement of the arguments for and against doing further work, presenting them so that potential contributors can judge whether they consider further work to be worthwhile (sections 3 & 5).

These aspects mainly cover the third and fourth objectives of the study.

6.3 Outline proposals

In the belief that data gathering and assessment show convincingly that further work is necessary, brief outline proposals for further work are presented in section 13).

7. THE LITERATURE SEARCH

A literature search was carried out on the Compendex database using the following descriptors: concrete, concrete construction, repairs, maintenance, port structures, bridges, offshore structures. Only those references judged useful are included in the list of references in this report.

Further references were obtained from various sources, noteably papers and books on cement and concrete received in the C&CA library, lists of which are published in the Magazine of Concrete Research.

The Steering Group's assistance was sought in identifying further useful references and these have been added to the reference list.

INFOIL 2, the joint UK/Norwegian on-line database of offshore related research and development projects, was interrogated and yielded a number of current projects in the repair field. These are listed in section 10.

The Metadex and the AERE Harwell databases were also interrogated.

The literature search yielded a limited amount of information on research carried out [13-18], on test methods [5-12] (discussed in section 10), on repairs carried out on offshore structures [19-30] and to coastal structures [31-44] (discussed in section 12). The literature search has not yielded any useful information on the durability of repairs in a marine environment.

8. REPAIR METHODS AND MATERIALS

Repair methods and repair systems are described in more detail in the Concrete Society Technical Report No. 26, chapters 3 & 4 [1]. The range of available materials are stated here in order to present clearly the range of parameters that might be considered in any research project.

There are generally four parts to any repair system:

a) after preparation of the surface of the parent concrete, it may be treated with a bond coat [1, sections 3.2.1, 3.2.4 & 4.3.4]

b) after cleaning the reinforcement a priming coat may possibly be applied [1, sections 3.2.2, 3.2.3 & 4.3.4]

c) the void is then filled with the bulk repair material [1, sections 4.1 to 4.4]

d) a coating may be applied to the whole concrete surface for cosmetic reasons and to provide additional protection to the unrepaired areas [1, section 4.6]. Coatings are difficult to apply and have a short useful life in marine conditions, and therefore are not often used.

All these steps have an influence on the integrity of the repair and its subsequent durability and as a result the complete system should

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All these steps have an influence on the integrity of the repair and its subsequent durability and as a result the complete system should be studied rather than its component parts. Bulk repair systems for cavities can be broadly categorised as follows:

a) Cementitious. These comprise mainly ordinary Portland cement, aggregate and water. The proportions of the mix can determine the properties but, additionally, various types of admixtures and blends of other cementitious materials such as pfa, blastfurnace slag and silica fume can provide variations within this group [1, section 4.2]

b) Polymer modified cementitious. Various organic polymers can be added to the basic cementitous mix to provide additional properties. These additions can vary not only in the polymer/cement ratio but also in the type of polymer [1, section 4.3.2]:

   i) SBR (styrene butadiene rubber)

   ii) acrylic

   iii) modified acrylic

c) Resin. These systems have resin binders and can vary in the proportion of resin to filler. Organic polymers are capable of formulation for a wide range of properties. The main resins are for example: [1, section 4.4 hand-applied resin-based mortars]

   i) epoxy

   ii) acrylic.

For the repair of cracks where some structural performance is required of the repair, epoxy resins are normally used. Cement grout can be used but is unable to penetrate fine cracks. Where non-structural crack sealing is required, an SBR or acrylic emulsion can be used [1, section 4.5, repair of cracks].

The literature search did not yield any useful references that discussed generally the choice of materials specifically for use in a marine environment. The Concrete Society Technical Report No. 26 [1] remains the best basic reference. However another useful reference is a paper by Hewlett [12] which discusses the properties of polymer based repair materials compared with Portland cement mortar and concrete. The references on repairs carried out give some details of actual materials and methods used, see section 12.

Appendix 5 gives details of all the repairs known to have been carried out to existing offshore structures. This indicates that cementitious repairs have been preferred for repairs of large volume, while resin had generally been used for crack injection and for repairing small gouges and areas where a thin additional coat is required to increase cover thickness. The references to repairs carried out to coastal structures cannot be considered to be comprehensive and indicate only the variety of materials and methods that have been used.

9. ASPECTS OF DURABILITY

There are four main aspects that can affect the durability of repair systems.

9.1 Material degradation

The majority of materials used for the repair of reinforced concrete have qualities, with regard to durability in a marine environment, which are as good, if not better, than the parent concrete. However, there have been instances where materials have deteriorated rapidly [13-14]. These problems are caused mainly by wrong formulation, inaccurate proportioning, inadequate mixing or poor application. These conditions generally result in a very porous material and the deterioration process is due to the action of the water. Quality assurance, proper supervision and site testing should avoid these problems. Past experience is the most reliable source of information on these problems and further programmes of testing are unlikely to be effective. There may be some benefit in gathering together the experience and disseminating it for the user so that future problems can be avoided.

There have also been reported cases of what were thought to be sulphate attack both to SBR modified cement mortar containing glass fibres and to a rapid setting repair system [14].

Other possible causes of material degradation are the action of sulphate reducing bacteria, the ingress of significant quantities of chlorides, and high hydrostatic pressure due to deep immersion.

It is believed that present polymer systems, when correctly formulated and applied, are at least as durable as well constructed concrete and have generally behaved well. It is thought therefore that material degradation even in the long term is not a major problem.

9.2 Interface bond

This aspect is considered to be of major importance. Inadequate bond of the repair material can lead to poor structural performance, detachment of the repair material and can provide a path for aggressive agents causing corrosion of embedded reinforcement. It is a problem that can occur with all repair materials under all conditions, but marine conditions can present special problems such as contamination of the surface of the concrete with chlorides and with algae and marine growth. These relate particularly to the greater difficulty in surface preparation and to the contamination of the surface with chlorides, particularly when the repair is carried out under water.

9.3 Corrosion protection of the reinforcement

Continued corrosion of embedded reinforcement will cause further deterioration of the repaired structure and will possibly disrupt the repair material. One major consideration in the need to repair will be to stabilize or minimise further corrosion whether or not the original damage was caused by impact or by spalling due to corrosion. Because of initial low cover, repair materials are sometimes required to perform better with regard to corrosion protection than the

original concrete. The mechanisms of the corrosion protection provided by concrete to the reinforcement in a marine environment are not fully understood although recent research [2] has considerably advanced present knowledge.

Other than the work by the Building Research Establishment [13], the mechanisms of corrosion protection to the reinforcement provided by various repair materials has not been studied in detail. There is a fundamental difference in the mechanisms of protection provided by mainly cementitious and purely resin repair systems. The former attempts to replace the contaminated or damaged concrete with a material similar to the original, hopefully returning the reinforcement to an alkaline environment thereby repassivating it. Resin repair systems provide a purely passive protection by attempting to encapsulate the reinforcement in an inert material impervious to corrosive influence.

The addition of various repair materials into the environment further complicates the problem. There is evidence to show that freshly repaired areas can accelerate the corrosion of adjacent areas of chloride contaminated concrete [3]. Back diffusion of chloride ions from the parent concrete into the repair material may be a factor that could influence the durability of repair systems.

9.4 Physical factors

Resistance to surface scour (abrasion), impact damage, fire and freeze/thaw cycles may be aspects that could influence the durability of repair materials but have not been considered further in this report. They are additional aspects which may happen in certain circumstances and therefore require separate investigation as appropriate rather than complicating the general case.

10. RESEARCH TO DATE

Research to date has been carried out in six main areas.

a) An independent research project in two parts is being conducted by the Building Research Establishment [13-14] to test "the durability of concrete repair systems with special reference to their ability to provide continued protection to the reinforcing steel". Details of this project are given in Appendix 2.

   This project is ongoing but the conclusions [14] after 6.5 years exposure are that:

   - rapid setting systems suffer from long term dimensional instability

   - for protection for more than five years, OPC or OPC-SBR modified mortars have been shown to be the most effective as they provide inhibitive protection which enhances the likelihood for passivity to develop and resist chloride ion migration to the reinforcing steel

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beneath resin repairs systems, steel priming coats need to be inhibitive to avoid crevice corrosion under chloride conditions.

b) Three commercially based studies, partly funded by the Department of Energy, to develop suitable repair systems for use offshore, were carried out by Wimpey Laboratories Ltd [15], McAlpine Offshore Ltd [16-44] and Taylor Woodrow Research Laboratories [17-18]. The last of these concentrated mainly on the structural aspects of repairs. Details of the extent of the first two projects are given in Appendix 2. The only information available on these projects is contained in the above references which mainly refer to details of specimens and test methods but give no results with respect to durability.

c) Test methods for evaluating resin repair materials.
Research has been carried out on the slant shear test at University College [5-6]. Tabor has published several papers on this subject [7-10]. Further research is being carried out at Queen's University, Belfast, by Cleland and Long under the COIN programme of research. (See Appendix 3a).

Brighton Polytechnic is about to start a research project (funded by SERC, DoE, FERFA) to determine the relationship between the fundamental parameters influencing the failure of polymer mortars and concretes to enable well-formed engineering judgements to be made. It is in four main parts, a study of case histories, characterising the fundamental engineering properties of the materials, establishing experiments simulating full scale repairs, and monitoring live case studies. This project is aimed more at engineering properties than long term durability and to general repairs rather than marine applications.

There is a British Standards Institution working party considering test methods on resin compositions [11]. A number of test methods have been published in various parts of BS 6319 [4] and further tests are published as drafts for comment or are under consideration. The British Standard tests are further discussed by Hewlett [12] who goes on to suggest further tests to determine the extent of cure of polymer materials.

d) Research is also being carried out under the COIN programme at Imperial College by Perry who is investigating the structural implications of repairs to concrete slabs previously damaged by impact of dropped objects. (See Appendix 3b).

The Royal Military College of Science is carrying out research (funded by SERC) into the structural effectiveness of resin and polymer modified mortars as used in the repair of concrete. Particular aspects in the investigations are curing shrinkage, differential thermal expansion, creep and fatigue performance.

e) CIRIA is engaged in a research project relating to the repair and maintenance of reinforced concrete in the UK and the Arabian Gulf region. (See Appendix 4).

f) A programme on 'Durability of concrete offshore structures' being carried out in Holland (MaTS/IRO) has also recently been completed. This programme included a project on repairs to concrete marine structures, some results of which were presented in a paper to the BOSS conference in 1985 [51].

The project provided important information on the influence of placing methods and factors such as workability, extent of bleeding and cohesion on the subsequent watertightness, compressive strength and bond strength of a repair. While the results obtained to date provide short-term data, they ultimately affect the long term durability of the repair system.

The basic repair material used was concrete containing blast furnace slag cement. Various cement contents were used together with three types of superplasticiser and a mix containing a cellulose based additive.

The results of tests carried out in the Scheldt estuary and in the laboratory indicate that the cellulose-based additive produced a much more cohesive mix which considerably reduced wash-out of the cement paste as the repair material made contact with the bottom surface of the repair cavity. Marine growth was found to have a considerable influence on the bond strength between the repair material and parent concrete depending on the length of time between the surface preparation and the casting of the repair. The type and rate of growth of marine organisms was investigated. A severe reduction in interface bond strength was experienced after only a four day delay in casting the repair. An easily removable anti-fouling paint was developed to combat this problem.

The Dutch work indicates the important influence of environmental conditions, placing methods and physical properties of the mix on the soundness of a repair. It reinforces conclusions elsewhere in this report that durability testing and the development of test methods for marine repairs must reflect the environmental difficulties of carrying out the repair.

11. RELEVANT CODES AND STANDARDS

Apart from the Concrete Society Report No. 26 [1] little information exists in the form of codes, standards and guidance for carrying out concrete repairs in general, and even less information exists about repairs in marine conditions.

Repairs to onshore structures are considered in BS 6270, British Standard Code of Practice for cleaning and surface repair of buildings, Part 2, Concrete and precast concrete masonry [45] but the section is very limited.

The only other relevant British Standard refers to test methods for resin materials, BS 6319, Testing of resin compositions for use in construction, Parts 1 to 8 [4].

The Recommendations for the design and construction of concrete sea structures, FIP, third edition [46] gives brief guidance on carrying out repairs to marine structures. These recommendations are brief completed. This programme included a project on repairs to concrete marine structures, some results of which were presented in a paper to the BOSS conference in 1985 [51].

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The ACI Guide for the design and construction of fixed offshore concrete structures [47] contains one page of guidance on repairs and, like the FIP recommendation above, adds little further information. The ACI have produced a number of publications relevant to the carrying out of repairs. Some of these are specifications and guides but none relate specifically to marine applications.

The Department of Energy has commissioned a study for the preparation of Draft Guidance Notes on repair requirements and suitable techniques for offshore steel and concrete structures [48].

The following standards and guidance notes are relevant to concrete construction, particularly in a marine environment, but do not cover repairs:

British Standard Code of Practice for Maritime Structures, BS 6349

British Standard Code of Practice for Fixed Offshore Structures, BS 6235

British Standard for the Structural use of Concrete, BS 8110: 1985

Department of Energy: Offshore installations: Guidance on design and construction, 1984

Det norske Veritas: Rules for the design, construction and inspection of offshore structures, 1977.

12. REPAIRS CARRIED OUT AND REVIEW OF PUBLISHED INFORMATION

The repairs that are known to have been carried out to offshore structures in the North Sea are summarised in a table in Appendix 5. There have been two major repairs due to ship and dropped object impact where the repair has been carried out using cementitious materials. There have been two instances of major cracking which have been repaired by epoxy injection. There have been five instances of superficial damage due to various causes where steps have been taken to restore the cover to the reinforcement by use of epoxy systems. References [19-30] cover these repairs and further details are given in Appendix 5.

These references mainly cover the reasons for the repair and how each was carried out. None of them give any information on the durability of the subsequent repair.

There are many instances of the repair of minor defects during construction of offshore platforms [26] but details have not been published. These repairs are usually known to the operators so that they can be checked during inspections. Although these repairs have mostly been carried out in the dry on freshly cast concrete, they could provide valuable information on the durability of repairs. However, some work would be required in gathering together the and add little that is not already contained in the Concrete Society Report No. 26 [1].

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There have been a large number of repairs carried out in a marine environment to jetties, docks, bridge piers and concrete ships but the details of only a small number have been published.

Dyton's paper [31] presents six case studies of the deterioration and the solution adopted in the repair of coastal structures in the UK such as jetties, piers and quays and discusses the reasons for failure and deterioration such as physical damage, fire damage, durability of materials, frost, chemical attack and corrosion of reinforcement. The paper concludes that chloride induced corrosion of the reinforcement is the major cause of deterioration and mainly occurs between the upper limit of marine growth and the top of the splash zone, deck support beams being the worst affected. Impact and abrasion are also significant contributory factors.

Heneghens paper [32] describes the shotcrete (Gunite) repair to a concrete pier in the USA. It reviews the principle causes of damage and makes recommendations on methods and materials for use in carrying out shotcrete repairs.

Geymar's paper [33] describes in detail the methods used to repair a concrete jetty in Venezuela. Cementitious or epoxy mortars were used above water and the use of epoxy mortar for the repair of piles under water is described.

Schrader et al [34] describes a trial repair of a navigation lock wall in the USA which had deteriorated after 10 years due to freeze/thaw cycles. As opposed to conventional breaking out and repair, six types of coating by shotcrete are evaluated for cost, 'constructability' and performance after a year in service. As a result of the trials, the complete lock was to be treated with a thin sprayed-on fibreglass reinforced latex modified cement coating.

Glassgold [35] reviews repair methods for typical coastal structures. Deterioration characteristics are briefly described. Three basic zones are analysed for repair procedures (submerged, tidal and exposed) although there are essentially only two basic approaches for repairing structures in seawater: 'dry' or 'wet'. 'Wet' applies to repairs where the water is displaced by the repair material while 'dry' assumes some sort of cofferdam and dewatering. Workmanship and quality of materials needs to be higher for the 'wet' process while working in the 'dry' allows evaluation of the problem, greater flexibility in the choice of material and method and better inspection, supervision and control. 'Dry' repairs are the desirable choice except when physically impractical or uneconomic. These remarks apply mainly to submerged repairs but also to those in the tidal range except those repairs are easier to carry out. The use of shotcrete and other repair methods is discussed.

Repair methods and materials used on beams supporting the decks of piers are described by Schwarz [36], McCurrich et al [37], West et al [38-39] and by Ingram et al [40]. Repairs to concrete piles by use of a fibre reinforced jacket filled with either epoxy or cement, are described by Scheffel [41], by West et al [38-39] who describes a trial with rigid shutters compared with a fabric jacket with the gap grouted and by Ingram et al [40] where a fabric jacket filled with micro concrete was used. Morgan [42] discusses the durability, damage and repair of concrete ships.

The above references [31-40] provide a valuable series of case histories of repairs carried out to coastal structures throughout the world and describe methods and materials used and causes of deterioration. Several of these references describe the results of short term evaluation trials but none of them give any information on the long term durability of repair systems. Shotcrete is extensively used in the USA as a repair method but experience from periodic in-service inspection of concrete offshore structures has shown that shotcrete used to compensate for minor deficiencies in the cover thickness in the construction phase of these structures has shown a tendency to spall off in service [25]. In freeze/thaw testing of prestressed beams in the tidal zone, Schupack [43] gives conclusions regarding different types of end anchorage protection which in effect are similar repairs. He concludes that an impermeable repair made to concrete can lead to concrete deterioration with time if the concrete becomes saturated and is subject to cycles of freezing and thawing. If delamination occurs at the epoxy-concrete interface, any reinforcing steel passing through the joint can be subject to more intensive corrosion. Attempting to encapsulate with epoxy the ends of protruding reinforcing bars of various specimens in the Concrete in the Oceans Programme [2] has yielded similar experience.

The repair of bridge decks subject to de-icing salt deterioration may be a fruitful source of information and experience, although no search for suitable references has been made as part of this study.

13. DEFINITION OF RESEARCH PROPOSALS

The arguments for and against doing further research are set out in section 3. These show that while there are problems in doing research into the durability of repairs in a marine environment, these problems can be largely overcome by careful project definition and that there are considerable benefits that will accrue from doing research. However it is clear that this research can only be done if sufficient funding is forthcoming. It is therefore considered appropriate to define possible research projects covering all the main research strategies so that the financial implications can be evaluated.

13.1 Exposure tests

Objective — To study the durability of repair systems in an environment closely modelling actual marine conditions so that conclusions can be drawn regarding the requirements for more durable systems

Parameters — Exposure: deep submergence & tidal/splash
Duration: five years minimum
Size of specimen: not less than 1200x300x300 mm
Cover: 25 mm
Condition of reinforcement: bright and pre-rusted
Type of repairs: bulk repair of not less than 0.01 m^3 and repairs to cracks

with micro concrete was used. Morgan [42] discusses the durability, damage and repair of concrete ships.

The above references [31-40] provide a valuable series of case histories of repairs carried out to coastal structures throughout the world and describe methods and materials used and causes of deterioration. Several of these references describe the results of short term evaluation trials but none of them give any information on the long term durability of repair systems. Shotcrete is extensively used in the USA as a repair method but experience from periodic in-service inspection of concrete offshore structures has shown that shotcrete used to compensate for minor deficiencies in the cover thickness in the construction phase of these structures has shown a tendency to spall off in service [25]. In freeze/thaw testing of prestressed beams in the tidal zone, Schupack [43] gives conclusions regarding different types of end anchorage protection which in effect are similar repairs. He concludes that an impermeable repair made to concrete can lead to concrete deterioration with time if the concrete becomes saturated and is subject to cycles of freezing and thawing. If delamination occurs at the epoxy-concrete interface, any reinforcing steel passing through the joint can be subject to more intensive corrosion. Attempting to encapsulate with epoxy the ends of protruding reinforcing bars of various specimens in the Concrete in the Oceans Programme [2] has yielded similar experience.

The repair of bridge decks subject to de-icing salt deterioration may be a fruitful source of information and experience, although no search for suitable references has been made as part of this study.

13. DEFINITION OF RESEARCH PROPOSALS

The arguments for and against doing further research are set out in section 3. These show that while there are problems in doing research into the durability of repairs in a marine environment, these problems can be largely overcome by careful project definition and that there are considerable benefits that will accrue from doing research. However it is clear that this research can only be done if sufficient funding is forthcoming. It is therefore considered appropriate to define possible research projects covering all the main research strategies so that the financial implications can be evaluated.

13.1 Exposure tests

Objective	To study the durability of repair systems in an environment closely modelling actual marine conditions so that conclusions can be drawn regarding the requirements for more durable systems
Parameters	Exposure: deep submergence & tidal/splash Duration: five years minimum Size of specimen: not less than 1200x300x300 mm Cover: 25 mm Condition of reinforcement: bright and pre-rusted Type of repairs: bulk repair of not less than 0.01 m^3 and repairs to cracks

Repair materials: about five types

Conditions during repair: to be carried out under conditions of actual exposure using recommended repair procedures

Examination : visual; potentials, resistivity etc; chloride ingress and permeability; cores for interface bond; and finally destructive.

No of Specimens : 2x2x2x2x5 = 80 with no replicates or controls

Method	The specimens could be exposed at Portland and Loch Linnhe. The project should build on the results of the BRE series of tests and more specifically look at the dimensional stability in larger specimens and the complete repair/parent concrete situation, in particular the formation of incipient anodes and back diffusion of chlorides.
Benefits	A straightforward approach to durability testing which is as close as possible to actual conditions and the result can easily be applied to practice by maintenance engineers.
Estimated cost	Approximately £300K. The project is similar in size and complexity to the Concrete in the Oceans exposure tests which cost £222K in the two phases.
Duration	Seven years (assumes one year startup, five years exposure and one year testing and reporting)

13.2 Monitoring of new repairs to existing coastal structures

Objective	To monitor closely the durability of repairs carried out on existing coastal structures so that conclusions can be drawn as to which materials and methods are more appropriate to provide adequate durability under practical conditions.
Method	Identify one or several sites to monitor, which either have structures that need repair or which have recently been repaired. For five different materials, it is important to identify one structure in need of extensive repairs so that the five materials can be used on that one structure. An alternative is to undertake repairs on five different but comparable structures. Assume that the major cost of the repair is borne by the owner of the structures, but that the extra costs of the different materials and monitoring are charged to the project. It is necessary to build in instrumentation, and monitor, on a yearly basis for at least five years, such factors as electrode potentials, chloride ingress, resistivity changes as well as visual signs of deterioration. Additionally, cores could be taken and ultrasonic measurements assessed for usefulness.
Benefits	In a reasonably well controlled experiment such factors as the formation of incipient anodes, back

	diffusion of chlorides and interface bond can be investigated on an aged substrate.	
Estimated cost	Identify structures and determine repair methods	£ 20K
	Carry out repairs, extra cost	£ 40K
	Monitor on yearly basis, 4 x £10K	£ 40K
	Final, more detailed, examination	£ 30K
	Reporting	£ 10K
		£ 130K
Duration	Seven years (assumes one year startup, five years exposure and one year testing and reporting).	

13.3 Study of repairs to existing offshore structures

Objective To study repairs to existing offshore structures in order to determine whether the original specification was adequate and whether existing repair systems are durable.

Method Gather together details of all repairs carried out on existing offshore structures during construction and in service by discussion with operators and constructors. Select a number of typical repairs for examination and obtain detailed information from operators. During regular inspections these specific areas are already examined closely but additional information may be necessary from the next annual inspection. Coordinate reporting of results and draw overall conclusions. Confidentiality problems need to be overcome and the cooperation of the operators is essential for this project to be successful.

Benefits Provides historical information of actual repairs which is expected to be reasonably well documented and provides durability information after a reasonably long period of exposure to a harsh environment.

Estimated cost Assuming that the costs of any additional inspections are borne by the operator, setting up, coordinating and reporting are likely to cost about £30K.

Duration Eighteen months (the duration will be dependent on the timing of the project in relation to the annual inspections).

13.4 Survey of past repairs to existing coastal structures

Objective To survey a number of existing coastal structures which have been repaired at various times using various methods so that conclusions can be drawn with regard to the durability of existing methods and materials.

Method	Identify suitable structures for survey, obtain details of existing repairs, carry out visual examination together with potential surveys, non-destructive testing, drillings and cores for laboratory examination, coordinate results and report. Initial cursory look at 30 structures, more detailed look at 10 selected structures.
Benefits	Broad conclusions on the actual durability of repairs to marine structures can be obtained in a reasonable timescale covering a range of ages (oldest 15-25 years) and a range of materials and methods which have been carried out under practical conditions and exposed to a natural environment.

Estimated cost		
	Set up project	£ 10K
	Initial survey of 30 structures at £1.5K each	£ 45K
	Detailed survey of 10 structures at £12K each	£ 120K
	Reporting	£ 10K
		£ 185K

Duration: Two years

13.5 Development of test methods

Objective

To assess which parameters appear to have the most significance with regard to the durability of repair systems. To develop tests that measure these parameters with respect to age and exposure to a simulated environment so that repair systems can be evaluated relative to one another.

Method

Assess from existing research and literature which parameters appear to have the most significance with regard to durability. Assess present test methods with regard to these parameters and where appropriate develop additional tests. Carry out trials to prove the test methods. Undertake repeatability and reproducability trials. Report results.

This project could be carried out in several stages with the first stage being a state of the art review to assess durability parameters and to evaluate existing test methods. The results of this stage will detemine what tests and parameters are studied in the next stages.

The two main parameters are expected to be:

- interface bond
- permeability.

Other effects of importance are likely to be:

- leaching of repair constituents

- the effect of repairs on reinforcement corrosion
- leakage of water down the repair/concrete and repair/steel interface
- the effect of sulphate reducing bacteria
- ingress of chlorides
- the effect of sulphates
- the effect of high hydrostatic pressure.

A number of detailed aspects of interface bond are considered in section 9.2. The first three of these aspects are to some extent being covered by the work of Cleland and Long at Queens University, Belfast (see Appendix 3a) but the effect of achieving bond under water and of cyclic loading are not covered. A considerable amount of work is presently being done on the permeability of concrete [49], much of which will be applicable to repair systems. None of the other effects listed above are known to be covered by current research. The gas pressure tension test, developed at BRE, should be evaluated for testing interface bond on cores cut from existing structures. In all test methods the effect of ageing on the parameters should be considered with appropriate artificial ageing cycles.

The remaining stages of the project involve investigation of the individual parameters. Some of these sub-projects could be tackled by Universities. These projects should contain some element of exposure to a marine environment, simulated or otherwise.

Benefits

To allow the engineer to evaluate different methods of repair, to write performance specifications for carrying out the work and to supervise the workmanship more closely. Development of new and improved methods and materials are stimulated. Can be split into a number of sub-projects.

Estimated cost and duration

	Cost	Duration
Stage one. Evaluate parameters and test methods	£ 15K	1 year
Subsequent stages. The investigation of individual parameters at £60K each Estimate three parameters	£180K	2 years
Total	£195K	3 years

13.6 Comparison of properties obtained in the laboratory with those achieved in practice

Objective	Investigate appropriate properties achieved by repair systems actually carried out on site under real conditions for comparison with those obtained under laboratory conditions so that the relevance of test methods can be evaluated.
Method	Locate suitable marine structures that are being repaired. Following the repairs, carry out in situ testing and take cores for subsequent laboratory testing. Obtain samples of the repair materials and carry out standard laboratory tests. Compare the results of the tests on real repairs with those obtained on samples of laboratory specimens and report. This project represents a halfway house between exposure tests and the development of test methods and should be undertaken after stage one of project 13.5 has been carried out.
Benefits	It will promote a better understanding of the relevance of test methods to specifications and will lead to more appropriate research in the future.

Estimated cost		
	(Stage one of project 13.5	£15K)
	Inspection, coring and testing of approximately five existing repairs at £15K each	£75K
	Comparisons and reporting	£10K
	Additional cost to stage one of project 13.5	£85K

Duration	A further 18 months after completion of stage one of project 13.5 giving a total of 2.5 years.

13.7 Summary

		Estimated Costs	Duration
13.1	Exposure tests	£300K	7 years
13.2	Monitoring of new repairs to existing coastal structures	£130K	7 years
13.3	Study of repairs to existing offshore structures	£ 30K	18 months
13.4	Survey of past repairs to existing coastal structures	£185K	2 years
13.5	Development of test methods	£195K	3 years
13.6	Comparison of properties obtained in the laboratory with those achieved in practice	£ 85K	2.5 years

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SUMMARY

This report examines the arguments for and against durability testing of repairs to concrete in a marine environment. Current techniques and materials used for the repair of concrete are reviewed. The need for repair and the factors that will influence the subsequent durability are discussed. The choice of materials, type of testing and costs of research in relation to the repair market are examined. The report considers the durability of repairs to concrete in the marine environment both above and below water in the area of the North West European Continental Shelf. Possible research projects covering the main research strategies are defined and a minimum viable research programme is suggested.

APPENDIX 1 : DETAILED STUDY DEFINITION

Appendix 1a : Aspects of repair included in / excluded from the study

INCLUDED

3. Establish when repair is necessary

5. Testing methods:
   a) to monitor durability
   b) to measure characteristics

6. Mode of access - only in so far as it may put constraints on choice of materials
7. Type of defect to be repaired
   a) cavities
   b) holes
   c) replacement of cover
   d) cracks
8. Repair techniques
   a) hand placing
   b) concreting
   c) guniting
   d) impregnation
   e) grouting

9. Repair materials
   a) grouts
   b) mortars
   c) concretes
   d) cementitious
   e) polymer concretes
   f) resins
   g) fibre reinforcement
   h) admixtures
   i) pfa/slag/silica fume
10. Properties to be investigated
    All given in Appendix 1a to varying degrees
11. Durability to environment/ influence of:
    a) seawater/marine/offshore
    b) ageing
    c) cathodic protection
    d) fire
    e) physical damage
12. Design considerations
    a) required properties
    b) stress transfer
    c) fatigue

EXCLUDED

1. Inspection methods
2. Causes of damage
3. Mechanisms of deterioration causing repair
4. Marine growth
5. Testing methods:
   a) inspection
   b) quality assurance of materials
   c) acceptance of workmanship
6. Mode of access - methods of gaining access in order to carry out repairs
7. Type of defect to be repaired
   a) prestressing ducts

8. Repair techniques
   a) replacement of reinforcement or prestressing
   b) surface treatments
   c) cathodic protection
   d) steel bonding/plating

APPENDIX 1b :Factors to be considered in the choice of material for repairs to a marine structure.

1) Ability to be placed

   a) method - proven techniques
   b) temperature sensitivity
   c) sensitivity to seawater
   d) pot life/time to cure
   e) pumpability/workability/viscosity
   f) exotherm
   g) rate of gain of mechanical properties

2) Non-hazardous or non-toxic to users e.g. diver

3) Ability to form good bond to parent material

   a) to concrete
   b) to reinforcement
   c) to prestressing ducts

4) Thermal compatability with parent material

5) Durability in marine environment; effect of ageing on properties

6) Adequate mechanical properties with regard to:

   a) tensile strength
   b) flexural strength
   c) compressive strength
   d) modulus of elasticity/flexibility/ductility
   e) creep properties
   f) shrinkage
   g) fatigue properties

7) Protection of reinforcement against corrosion

   a) alkalinity
   b) permeability to water
   c) permeability to chloride ions
   d) permeability to carbon dioxide
   e) resistivity
   f) moisture content

8) Cosmetic considerations

APPENDIX 2 : DETAILS OF EXPOSURE TESTS ON REPAIR SYSTEMS

	BRE [14] Larger Specimens	BRE [13] Small Specimens	WIMPEY [15]	McALPINE
No. of Specimens	110	110	40	299
Specimen Size	400x125x125	250x105x105	1200x300x300	100 cubes 250x100x100 beams 500x100x100 beams
Concrete Mix	1:5,0.5 W/c	1:8,1:10 & 1:8+$CaCl_2$	1:4,0.45 W/c (CiO)	Grade 50
Reinforcement	2x6mmØ	4x6mmØ	4x30mmØ	1x5mm Ø } 500 beams only
Cover	12 & 25mm	12.5 & 25mm	75mm	47.5mm } 500 beams only
Condition of reinforcement	Prerusted and wire brushed, half chemically cleaned	Shot-blasted & pre-rusted	As received	As received } 500 beams only
Size of Repair	Corner 200 long, 12mm and no gap behind reinforcement	Corner 200 long, 10mm behind reinforcement	Slot 1000x20x75 deep & gouge 600x130x90 deep	Half of specimen with slant angles of 30°, 60° and 90°. 500 beams fully cast in repair material
Repair Materials	Various primer coat combinations with 1. Cement/sand mortar (2:3 & 1:3) 2. Rapid-setting mortar (2) 3. Partial epoxy repair 4. Fibre-reinforced mortar (2) 5. High build epoxy mortar 6. OPC/SBR mortar 7. OPC/SBR/fibre mortar	1. Commercial system 2. Rapid setting cementitious 3. Fibre reinforced cementitious 4. Epoxy resin mortar 5. OPC Sand mortar 6. (Polyester Putty)	Aggregate filled 2 types of resin, 1 commercial, and 1 Wimpey formulated	1. Cementitious with admixtures 2. Polymer modified cementitious
Exposure	Marine tidal	CO_2 & Marine tidal	Marine tidal & impressed current	Marine tidal & underwater with laboratory controls
Duration	6½ & 8½ years ongoing	Various up to 5 yrs 4 mths, ongoing	Various up to 10 years ongoing (1988)	4 years with testing every 6 mths
Temperature at time of repair	Ambient (Summer)	Ambient	5°C	7°C (20°C lab controls)
Surface preparation	Chiseled	Chiseled & wire brush	Cast surface	Saw cut
Application of repair	Hand applied	Hand applied	Resin pump	Cast
Place of Application	Insitu at low tide	Air	Underwater	Underwater
Examination	Visual & photographic Destructive	Visual & photographic Destructive Potentials AC impedance	Visual examination before and after destructive compressive load test	Bending test or cube test Inspection

APPENDIX 3 : DETAILS OF QUEENS UNIVERSITY, BELFAST, AND IMPERIAL COLLEGE, LONDON, RESEARCH PROJECTS

These projects are part of the managed programme of research 'Concrete Offshore in the Nineties - COIN', initiated by the Marine Technology Directorate of the SERC and sponsored by the Directorate, the Offshore Industry and the Department of Energy.

Appendix 3a : Assessing the durability and strength of repaired concrete - Dr D J Cleland and Professor A.E Long, The Queens University of Belfast

The research programme, as proposed, falls into three main parts.

1. Validation of the test methods.

A number of test methods will be examined using a small number of repair material/surface combinations. This is aimed at determining their accuracy and repeatability and to examine any correlation between the various methods. The test methods will include:

Tension strength	Shear strength
Pull-off method	Direct shear
	Slant shear
	Torsion shear

2. Comparison of surface and materials

Using the most pertinent test methods (from Part 1) a number of variables will be examined for their short-term bond strength. The variables in the present concrete surface will be (a) sawn surface (b) irregular broken with angular aggregate (c) irregular broken with rounded aggregate. The variables in the material will include:

sand/cement mortar
sand/cement mortar with a bonding coat
polymer modified cementitious mortars
epoxy and polyester resin mortars.

Because of the volume of work involved not all permutations of material and surface will be tested but the earlier results (using the sawn surface) will be used to decide which of the others will be most significant.

3. Longer term characteristics of repairs

Selected combinations from Part 2 will be subjected to accelerated tests to determine if there is any break-down of bond strength. The tests will be carried out by subjecting the specimens to repeated cycles of (a) temperature change (b) freeze and thaw (c) shear, and then measuring the residual bond strength. A smaller number of permuations of material and surface will be considered.

Further tests will be carried out to determine the permeability of the repair materials using apparatus currently being tested at QUB.

Appendix 3b : Repair and test of concrete slabs and domes damaged by hard impact from dropped objects - Dr S H Perry and Mr J Holmyard, Imperial College, London

In the last few years, major repairs have been necessary to offshore marine structures where damage has resulted to base caisson roofs from accidentally dropped objects, such as drilling collars weighing as much as 20 tonnes. Repair methods have been, necessarily, ad hoc, undertaken, as they are, at great depths below the North Sea. There is a real need to learn more about the best materials for effecting repairs to cracked and damaged concrete, when in a marine environment, and the most efficient techniques for placing such materials. They must be able to bond successfully at temperatures of about 7°C, quickly achieve a sufficiently high strength and, at the same time, effect an impermeable repair.

This project is concerned with using both cementitious and epoxy resin formulations for the repair of a number of damaged concrete slabs and domes designed to model the roof members of offshore sea-bed oil storage tanks. The repairs themselves, and the curing of the repaired concrete, will take place in a tank filled with artificial seawater, chilled to a temperature of 7-8°C. After suitable storage time in the seawater tank, each concrete element will be tested to destruction by static loading of the repaired area.

APPENDIX 4 : CIRIA RESEARCH PROPOSAL ON THE PROTECTION, MAINTENANCE AND REPAIR OF REINFORCED CONCRETE STRUCTURES IN THE UK AND THE ARABIAN GULF

Introduction and statement of the objectives

With the advent of the construction pressures that developed in the late 1960s and early 1970s, changes in materials, the use of accelerators usually based on calcium chlorides, etc, there have been some problems with the performance of relatively new reinforced concrete structures in the UK, Northern Europe, USA and many other parts of the world. In the UK these problems have developed at a time when some of the country's early reinforced concrete structures are approaching the end of their 'design' life and this has added to the urgent need for information on repair and maintenance for reinforced concrete.

In maritime areas of the Gulf States, reinforced concrete construction deteriorates quickly. The rate of deterioration can be reduced very significantly by making proper use of the knowledge of concrete technology which has already been evaluated and published as part of CIRIA's Gulf Concrete programme in the CIRIA Guide to concrete construction in the Gulf region.

As the next phase of this programme, CIRIA's newest project as outlined in this description, is being concentrated on providing information and guidance to ensure that maintenance and repair operations to existing structures are suitable for the Gulf's environment and can effectively provide required performance standards.

Method of working

CIRIA produced its original Guide by evaluating existing information for its relevance to the Gulf situation and by bringing together the knowledge and experience of a Project Development Group drawn from its members.

If the recommendations for good practice given in the Guide are followed, the life and performance of new construction in the region will be greatly improved. In the meantime, it must be accepted that the present disappointing performance of many existing concrete structures in the Gulf States as well as in the UK has given rise to the problems of maintaining and repairing many buildings and structures to ensure that they are able to give a satisfactory service life.

Objectives

The objectives of the project are:

(a) to identify means of assessing structural condition, monitoring performance and estimating the future deterioration of reinforced concrete so that the needs for, and economics of, protection, maintenance and repair can be determined

(b) to provide guidance on the choice and likely performance of protective and repair methods and materials for reinforced concrete both in typical UK conditions and in the conditions which accelerate deterioration in the Arabian Gulf region.

Programme of work

This will include:

(a) collection and analysis of published information on reinforced concrete deterioration and repair from worldwide sources. This will continue throughout the period of the project, but has mainly been concentrated in the period of late 1985 to midsummer 1986. The information will be used to develop a database of information on the topic of reinforced concrete repair and maintenance. This database will concentrate on those areas of repair and maintenance of importance to the development of the CIRIA durability programme.

(b) visits are proposed to North America, Europe and the Gulf region to collect information on current research on concrete deterioration and methods of repair.

(c) a group of experienced practising engineers and researchers has been formed to consider the material that is obtained and to advise on the preparation of the report. This group is meeting regularly throughout the entire period of the project and will receive interim and progress reports at each meeting.

(d) funds to complete the financing for this project will be sought from relevant organisations in the construction industry and its suppliers of materials and equipment. The sponsoring organisations will be kept informed of progress and have access to the material and information collected and developed during the project

(e) between late 1986 and mid-1987 a report will be completed, drawing together the information found in items (a) and (b) of this programme and giving guidance and recommendations on materials and methods for the protection, maintenance and repair of reinforced concrete. Recommendations for a further programme of research relevant to the UK and Arabian Gulf region will also be made which will be submitted to the sponsoring organisations for funding.

Funding

Phase One of the project involves the development of information for both the UK and Gulf region. The UK Department of the Environment has approved the project and will provide 60% financial support, and CIRIA is now looking for the balance of 40% support from other sources.

In funding the first phase of the project, the Department of the Environment's financial support covers the development of information suitable for both the UK and the Gulf regions, since it is accepted that in this phase there is a considerable amount of common ground for both areas.

APPENDIX 5 : EXISTING OFFSHORE STRUCTURES AND REPAIRS CARRIED OUT

CONCRETE PLATFORM	YEAR OF INSTALL-ATION	OPERATOR	CAUSE OF DAMAGE	DAMAGED CAUSED	EXTENT	REASON FOR REPAIR	DEPTH OF REPAIR BELOW SEA LEVEL. m.	MATERIAL USED	METHOD	BY WHOM CARRIED OUT	REFERENCES	COST £M
EKOFISK	1973	Phillips		No information								
BERYL A	1975	Mobil	Construction	Cracking during construction	-	-	-	Cement grout	Injection	-	-	
BRENT B	1975	Shell	Riser pipe	Gouged shallow grove in leg	Superficial	Restore cover	35	Epoxy	Fill shutter	McAlpine Sea Services	20,23,24	0.4
			Fire damage	Spalled cover	Superficial	Restore cover	air	-	-	Yet to be carried out.	23	
			36" Riser	Hole in caisson roof	Major	Reinstate	90	Concrete	Shutter, place agg, grout	McAlpine Sea Services	19*,20,22 23,28*, 29,16	1.4
FRIGG CDP1	1975	Elf	Foundation failure	Cracking to diaphram walls	Major	Reinstate	80-90	Epoxy	Injection	Elf	21*,23	
FRIGG TP1	1976	Elf	Built-in steelwork	Leak	Minor	Stem leak	-	Cement grout	Injection	Elf	-	
FRIGG MCP01	1976	Total		No major repairs								
BRENT D	1976	Shell		No repairs								
STATFJORD A	1977	Mobil	Fire damage	-	Superficial	Restore cover	-	-	-	-	23	
			Submergence	Cracks leaking into cells	Major	Stem leak	110	Epoxy	Injection	Norwegian Contractors	26,27*	
DUNLIN A	1977	Shell	Drain caisson	Chipped groove	Superficial	Restore cover	120	Epoxy	Fill shutter	McAlpine Sea Services	20,22,23 24,16	1.5
FRIGG TCP2	1977	Elf		No information								
NINIAN CENTRAL	1978	Chevron		No repairs								
CORMORANT A	1978	Shell		No repairs								
BRENT C	1978	Shell	Ship impact	Through cracking to shaft	Major	Reinstate	0-2	Concrete	Form in dry	McAlpine Sea Services	20,22,23, 24,28*,29 16	1.0
STATFJORD B	1981	Mobil	Construction	Lack of cover	Superficial	Restore cover	-	Epoxy	Coating	Norwegian Contractors	26	
STATFJORD C	1984	Mobil		No information								