PREFACE

The basic objectives of the REHABCON project relate to the development of a practical management system and repair Manual for existing concrete structures such as buildings, bridges, multi-storey car park and dams which form an important part of the infrastructure. The concrete infrastructure is deteriorating due to the effects of aggressive actions (corrosion, frost, abrasion, chemical action, etc). Decisions are required on whether to repair, upgrade, or demolish and rebuild, and an established methodology for rational decision-making does not exist. The purpose of this project is to provide such a methodology, by building on previous partnership experience (and outputs) on structural assessment, and concentrating on repair options. Emphasis is put on performance criteria, based on whole life costing, and the principles of life cycle analysis and sustainability.

The Community is well served in terms of design guidance and standards for new construction. Comparable Standards do not exist for the assessment of existing structures, although guidance documents are becoming available. Indeed, the partners in this proposal have been involved in producing such guidance.

In working with the users of the technology it has become apparent that improved methods of assessment are not sufficient. Owners are concerned with the long-term management of their assets. This means that they need guidance on if and when to repair, and how to choose the best option, against defined performance criteria.

REHABCON is targeted at this important strategic area. The need is European-wide and is demand driven. Infrastructure underpins the social, industrial and economic well-being of the Community. Management of these vital infrastructure assets can only be managed effectively and in a sustainable way if the appropriate decision-making procedures and tools are developed and integrated into existing management systems.

Partners:

**Swedish Cement and Concrete Research Institute (CBI), Sweden** (coordinator) [www.cbi.se](http://www.cbi.se)
**Building Research Establishment (BRE), United Kingdom** [www.bre.co.uk](http://www.bre.co.uk)
**Geotecnia y Cimientos S.A. (Geocisa), Spain** [www.geocisa.es](http://www.geocisa.es)
**Instituto Eduardo Torroja (IETcc), Spain** [www.ietcc.csic.es](http://www.ietcc.csic.es)
**Lund Institute of Technology (LIT), Sweden** [www.byggmaterial.lth.se](http://www.byggmaterial.lth.se)
**National Car Park, NCP Limited, United Kingdom** [www.ncp.co.uk](http://www.ncp.co.uk)
**NCC AB, Sweden** [www.ncc.se](http://www.ncc.se)
**Sika Sweden** [www.sika.se](http://www.sika.se)
**Swedish National Rail Administration, Sweden** [www.banverket.se](http://www.banverket.se)
**Swedish National Road Administration, Sweden** [www.vv.se](http://www.vv.se)
**TRL Limited, United Kingdom** [www.trl.uk](http://www.trl.uk)
**Vattenfall Utveckling AB, VUAB, Sweden** [www.vattenfall.se](http://www.vattenfall.se)
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1 INTRODUCTION

Concrete structures constitute a great value in today’s society. They form a great part of the infrastructure, underpinning the social, industrial and economic well-being of the community. However, concrete structures are deteriorating due to aggressive actions such as corrosion, frost, abrasion, chemical action, etc. Decisions are required on whether to repair, upgrade, or demolish and rebuild. The process of making these decisions is very complex, involving many assessments considerations and comparisons, both from the technical and non-technical point of view. The process is further complicated by budget constraints and the uncertainty in predicting future developments in society, its needs, economic growth, scientific and technical progress, climate changes, etc. The majority of concrete structures have design service lives which extend over generations. It is important therefore that these structures be managed in an effective way.

The decision on whether to repair or replace a concrete structure has become of great concern to many owners and managers of structures. In the developed world more and more emphasis is being placed on the management of existing structures. While many documents and guidelines deal with the technical aspects of repair and rehabilitation methods, there is little guidance available on procedures to ensure that the most appropriate action is carried out in order to optimise the remaining service life of a structure.

1.1 The REHABCON project

This Manual was developed as part of an EU project entitled “Strategy for maintenance and rehabilitation of concrete structures” (REHABCON), funded through the EU Innovation Programme. REHABCON is a three-year project concerned with developing a management system for the maintenance and rehabilitation of the existing concrete infrastructure. The project continues on from the CONTECVET project (see Chapter 3 and references [3.1] [3.2] [3.3] [3.4]) in which a validated user’s Manual for the assessment of deteriorated concrete structures was developed. REHABCON is based on the principles outlined and developed through this previous project. The consortium partnership is a mix of end users, research institutes, and industrial organisations (contractors and material suppliers), the majority of which have collaborated successfully on previous projects. Three countries are represented in the consortium, Sweden, Spain and UK. The prime technical tasks relate to repair technology, including the establishment of performance criteria. The non-technical tasks relate to the development of a management system, incorporating both assessment and repair, and are closely linked to the market research conducted at the outset of the project.

The objective of REHABCON is to provide a strategy for the repair and rehabilitation of the concrete infrastructure. The two main components of the project are a review of available repair and upgrading systems against defined performance requirements and the integration of repair technology into inspection and assessment technology to produce methodologies and tools which can be incorporated into different management system. The end product will be a comprehensive and practical Manual which can be used to enable decisions to be made on the management of
deteriorated concrete structures. Strong emphasis is put on performance criteria, based on whole life costing, and the principles of life cycle analysis and sustainability.

1.2 Scope of the REHABCON Manual

The Manual is intended to be a practical tool to assist structure owners and managers in carrying out repair and rehabilitation works from the conception stage to execution. The purpose is to integrate this vital element of structural management into the overall asset management system in a consistent way. It covers identification of repair strategies, choice of optimum strategy, design, execution, and future maintenance requirements. Principles and methodologies for optimising the selected repair method are presented.

The Manual brings together the technical and non-technical aspects which are involved in the identification, optimisation and selection process. The Manual is targeted primarily at structure managers and their agents with adequate technical knowledge to understand the engineering principles involved. However, it is likely that different parts of the Manual will be used by non-specialist people to enable them to have a broad understanding of different repair methods and their requirement. It includes advice on how to ensure that not-technical issues are given due consideration at all stages of the process.

It is intended that the Manual should cover all concrete structures including those made from reinforced, unreinforced and prestressed concrete. The principles on which the Manual is based are directly relevant to the more common civil engineering structures such as bridges and buildings. Other specialist structures such as dams, car parks water retaining structures and nuclear reactor vessels are not specifically covered, although many of the principles presented here may still be relevant. The Manual has been devised bearing in mind the general principles contained in EN1504 (see Annex C), which specifies the requirements for the identification, performance and safety of the various techniques, systems and products used for the repair and rehabilitation of concrete structures.

The Manual relates to the main deterioration mechanisms that affect concrete structures. This includes reinforcement corrosion resulting from concrete carbonation and chloride contamination, alkali-silica reaction, frost attack and leaching. Other forms of impairment not covered specifically by the Manual, can be dealt with using the principles outlined. These include design defects, bad workmanship, structural damage arising from to overloading, impact, etc. However, the treatment of fire damaged structures is a specialist area and is beyond the scope of this Manual.

1.3 Contents and layout

The structure of the Manual allows the user to carry out the decision-making process for the repair and rehabilitation of structures within the framework of an overall asset management
strategy. Chapter 2 describes the general principles of asset management and indicates how the procedures presented in the Manual can be integrated into existing Asset Management Systems.

A prerequisite for any successful repair work is an accurate assessment of the structure and Chapter 3 describes how such an assessment should be carried out. The assessment should define not only the condition in terms of the cause and extent of the defects to be repaired, but also the strength of the structure in terms of the required loading. The conclusions of the assessment are the main parameters in determining what remedial action may be necessary and the urgency of intervention. Assessment methods such as those presented in the CONTECVET manual (developed through a previous EU project) are presented.

The purpose of Chapter 4 is to identify the performance requirements that need to be taken into account in determine the range of potential repair options. Then main requirements to be fulfilled are defined and reviewed. These include technical requirements (service life, durability, structural stability and safety, execution of work, maintenance requirements) as well non-technical issues (environmental, health, social, political and legal).

When the deteriorated structure has been evaluated and the decision to carry out repair, rehabilitation or strengthening has been taken, several options may be appropriate. In Chapter 5, the most common repair and rehabilitation options for each type of deterioration are presented. A brief description is given in Chapter 5, with more detailed information presented in the Annexes. The Annexes contain detailed information on commercially available repair, rehabilitation and strengthening techniques. They include details recommendations on design, execution, quality control and safety during and after execution, and useful information on future maintenance requirements for the repaired structure. References to existing standards and guidelines are given as appropriate.

Once the cause and type of damage are known and the requirements to be fulfilling by the rehabilitated structure have been established, a number of intervention options may be possible. The next step is to evaluate the different repair options with regard to these performance requirements so that an optimum intervention strategy can be identified. Chapter 6 presents the principles and tools to be used in this evaluation. This should takes into account all the technical and non-technical requirements identified in Chapter 4.

Finally, Chapter 7 described several methods that can be used for the selection and optimisation of the rehabilitation strategy. These include Life Cycle Cost Analysis (LCCA) and the Repair Index Method (RIM).
2 PROCESSES FOR MANAGEMENT

2.1 Introduction

The decision on whether to repair or replace a concrete structure has become of great concern to many owners of structures and authorities, and establishment of a Management System is a measure to rationalise and facilitate the process of making decisions. A properly designed and maintained management system facilitates application of Life Cycle Cost (LCC) analysis which promotes an efficient use of the available financial resources. Furthermore, a properly designed and maintained management system helps to sustain a certain level of safety and serviceability and helps to prevent unforeseen disruptions and failures.

The intentions of this chapter are to describe the process and elements of management, to highlight those elements which are considered in this Manual, and link them to the subsequent chapters of the Manual.

2.2 Asset management system for concrete structures

A management system is a set of procedures developed to organise a particular operational activity such as inspection, maintenance, repair and rehabilitation of structures, etc. An Asset Management System (AMS) will include several such operational activities. It might cover aspects of safety, user satisfaction, asset value, accessibility, as well as legal requirements and government objectives on, for example, health and safety, transportation, sustainability and social issues. Other terms used for an AMS are Integrated Management System (IMS) and Maintenance, Rehabilitation and Repair system (MR&R-system).

The complexity of an Asset Management System depends on the type, function, number, and condition of the assets but, inevitably, it requires consideration of both engineering and financial aspects. As a consequence, asset management systems have been developed in response to particular customer needs. Hence, the components of an Asset Management System might vary from owner to owner and from one asset type to another. Some very sophisticated systems are now being routinely used, particularly for bridges and road pavements.

There is a wealth of information on asset management systems in the literature, and numerous standards and other documents are available on the management of highway structures. A summary of some existing management systems is presented in Annex A and in [2.1]. It is unnecessary, therefore, to provide an overview of the various management systems or a critique of any particular system.

The aim of this chapter is to present the issues that might be addressed in assessing the effectiveness of the repair and remedial measures. It should be noted that asset management systems are not normally devised to cover just repair and remedial works. In fact many
management systems include the capability of recording structural modification, inspection and maintenance routines but they have tended not to incorporate any components assisting the decision making process for determining appropriate repair and remedial measures. Their decision making process differs from the process presented here.

The processes of recording, inspection, assessment, repair and remediation are the fundamental components of an asset management system. Such a system comprises cycles of inspection and assessment, with occasional interventions for repair and remedial works. The timescale of the cycles and the details of the various components vary according to the type, value, function and condition of the asset.

A complete Asset Management System may consist of several modules each designed for a specific operational activity. The modules may interact and exchange information, i.e. they may share the same database. The type and number of modules included in an Asset Management System, and the way and the degree of the interaction between the modules, depend on the type of assets and owners. Furthermore, any of modules may consist of several sub-modules, or may be a sub-module in another superior module within the AMS.

The framework of the AMS can be presented in many different ways depending on the type of assets, type of owner and foremost how the work is organised. Therefore, it is difficult to present a framework which is applicable for all types of assets and owners. In this chapter only the functions and contents of the different modules and the sequences of the events in the decision making process for the repair of concrete structures are presented. Some systems currently used by different types of owner are presented in Annex A.

---

Figure 2.1  Elements of an asset management system
2.3 Underlying approach for maintenance and repair of concrete structures

Figure 2.1 summarises several stages in the management of structures. As mentioned the particular modules and submodules may vary. The main aim of the figure is to emphasize the parts in an AMS in which REHABCON is contributing. In general:

- An economical investment is made when the structures are built. At that stage, requirements concerning safety, functionality and aesthetics are defined in the design phase. Non-technical-requirements are also considered in this initial phase of the structure life. Note that many concrete structures are designed to have long service life and the requirements, legislations, the way of exploitation, etc may change during the life time of the structure therefore the prevailing requirements may by somewhat different from those during the design phase.

- In order to maintain the value, safety and serviceability of the structure throughout its expected service life a maintenance policy has to be established and inspections must be carried out in order to assess the prevailing condition of the structure.

- If the inspection and the subsequent assessment reveal that the structure doesn’t fulfil the prevailing requirements, actions may have to be undertaken. There are four actions available:
  
  i. Do nothing at present, i.e. postpone repair for a certain time and decide on how to supervise and inspect the structure.
  ii. Issue restricted use.
  iii. Repair now.
  iv. Demolish and re-build.

Some or all of the actions may be selected for further considerations. The advantages and disadvantages of the selected actions will be weighed and the most appropriate action will be chosen. Actions i, ii and iv should be considered as a possible solution during the decision making process and information on these actions can be obtained when the structure is being assessed. The focus of this Manual is on repair action the remaining actions are note considered in the Manual.

- Once the repair action is decided the best repair option must be selected. For the selection, the repair alternatives are evaluated to determine whether their application enables the structure to fulfil the prevailing requirements. Among the different possible repair solution, the most convenient is selected through an exercise of benchmarking between them. Furthermore, the procurement for the execution of repair work is undertaken. This repair should upgrade the structure in order to fulfil the requirements put on it, and actualise the value of the investment made at the building of the structure.
In summary, the aim of the overall management is related to the maintenance or improvement of the investment, while the technical management is focussed on maintaining or upgrading the technical requirements defined at the design phase of the structure.

Figure 2.1 shows the components of the overall process dealt with in the REHABCON Project. The project deals with the Strategy of Intervention mainly and is therefore, more focussed to the technical management. It is based on the Technical Requirements and how they are used in the selection of the most appropriate solution of repair/strengthening of concrete structures.

The particular subjects which are dealt with by REHABCON are shown in Figure 2.2. The figure provides a brief description of the subjects, highlights the details which should be taken to the subsequent processes, and indicates the relevant chapters in the Manual. An accurate assessment is a prerequisite for any successful repair work. Therefore, Chapter 3 is devoted to the assessment of the condition and structural safety of the structure. Links to existing assessment procedures and manuals are provided.

Furthermore, the Manual provides the way dealing with requirements (Chapter 4), technical solutions (Chapter 5) and evaluation and optimisation of the best repair option (Chapter 6 and 7).
Assessment

Cause and type of damage are determined

The impact of the damage on the structure has been determined. It has been showed that the structure does not fulfil the requirements. Requirements may be associated with present use of the structure or with the future use which the owner is planning for it.

Levels of requirements:
- Statutory requirements
- Owner’s strategic goals, and owner’s performance requirements

Type of requirements:
- Service life
- Structural stability
- Execution of work
- Environmental and health
- Economy
- Aesthetics, social, political…..

Complete assessment data, calculations and tests.
Chapter 3

Requirements

Analysis of basic requirements on the structure.
Chapter 4

Levels of requirements:
- Repair principles
- Main repair methods
- Variants of the main repair methods, different materials, different applications, etc

Type of requirements:
- Service life
- Structural stability
- Execution of work
- Environmental and health
- Economy
- Aesthetics, social, political…..

Selection of a few repair principles, main repair methods and systems.
Chapter 5

Technical solutions

Actions:
- Do nothing, postpone the repair
- Issue restricted use
- Repair
- Demolish

Levels of technical solutions:
- Repair principles
- Main repair methods
- Variants of the main repair methods, different materials, different applications, etc

Evaluation of repair methods and preparation for the decision process.
Chapter 6 & 7

Optimisation

Elements of optimisation:
- Evaluate the repair methods with regard to service life, structural stability and safety, execution of work, environmental and health, economy, aesthetics, social, political, ….
- Determine the disturbance which the repair methods may cause
- Determine different types of risks associated with the repair method

Make decision

Final decision

Decision maker:
The final decision is taken by the owner or by the owner appointed consultant.

Actions:
- Do nothing, postpone the repair
- Issue restricted use
- Repair
- Demolish

Figure 2.2 Repair process
2.4 Modules of the asset management system

Details of the various modules of an asset management system might vary according to the type of the owner or company responsible for the assets, and according to the type, value, function and condition of the assets. In the subsequent sections details of the modules that an AMS should contain are presented.

2.4.1 Asset inventory

The AMS should include a computer-based system containing important technical information on structures. For each structure there should be a “register” containing basic information on the structure, from construction to inspection and repair. Information of importance in such a register is:

- Original design (drawings, calculations, etc).
- Construction data (test results during construction, weather conditions during construction, problems during construction, geometry of the finished structure, etc).
- Data from routine condition inspections or from continuous monitoring of the structure.
- Previous assessments of safety, serviceability, residual service life and other characteristics.
- Information on previous repair and rehabilitation (repair methods and materials, test results from repair etc).

2.4.2 Routine inspections

The AMS system should contain principles or rules for routine inspection. Examples of such principles are:

- Frequency of inspections should be defined for each type of structure and each type of structural component. The frequency might be every two years or less frequently depending on the type and importance of the structure, and on the previous condition of the structure.
- The contents of an inspection should be described. The inspection might be different for different structures and for different structural elements depending on the consequence of failure. Inspection might be purely visual or contain quantitative measurements of strength, degree of damage, rate of damage, etc. Different levels of inspection might be appropriate at different inspection intervals.
- Methods used in the inspection should be described in detail. References can be given to established test methods if such exist.

An important aim of routine inspections is to identify the structures that are in need of more detailed inspection and structural assessment.
2.4.3 Assessment

Where a routine inspection indicates that deterioration is going on or there are any indications that the strength or serviceability of the structure has been impaired, the structure should be subjected to an assessment of its present safety and serviceability. In addition, the future safety and serviceability should be evaluated. Thus, the future service life should be evaluated. Principles and practical methods for such condition assessment of structures shall be included in the AMS.

There are different levels of such an assessment varying from visual assessment, i.e. inspection, to detailed assessment which includes determination of the load bearing capacity, serviceability and remaining service life. Assessment is addressed in Chapter 3.

The assessment process will identify the need for future intervention, and the four options of do nothing, restrict use, repair now, or demolish and rebuild, will need to be considered. All available options should be examined and the most appropriate one should be selected. Even though this Manual focuses on the repair of concrete structures the possibility of using other options should be kept in mind and compared with the selected repair methods. The most appropriate option is selected on the basis of how well the options fulfil the requirements. The final decision is made by the owner.

2.4.4 Requirements

The requirements of the structure are fundamental for all decisions made and are strongly connected to the preceding assessment. These requirements may trigger further assessment and investigations.

Prior to this step the cause and type of the deterioration, and its future development have been determined from a thorough and accurate inspection (see 2.4.3). At this stage it should be determined whether the requirements are met or not. If intervention is required, the decision on which option should be taken is based on how well the requirements are met. If it is decided to repair the structure the selected repair system must also meet the owner’s requirements. Thus the requirements are the crucial elements in an AMS. Measures such as assessment and repair cannot be performed properly without well-defined, quantified and accurate requirements.

The AMS should identify and consider all the existing technical and non-technical requirements and restrictions associated with the assets. All sources of restrictions and standards should be taken into consideration. These include EN and national standards, policies and rules for each state, company policies and rules including restrictions such as budgeting, scheduling, health and safety, environment, etc.

A comprehensive survey of requirements is presented in Chapter 4. A few basic aspects about the requirements are presented here.

Requirements for the damaged and the repaired structure should be clearly stated in the ASM system. Such requirements are set on different levels:

- Statutory requirements,
Owner’s strategic goals and owner’s performance requirements.

All statutory (legal) requirements on structures, both on the European and national levels, must be fulfilled. On the European Union level, the Construction Products Directive (Council Directive 89/106/CE) [4.1] sets essential requirements for construction products to be used in construction works. On the National level, each country has its own sets of laws, regulations and policies. The owners may also have their own set of strategic goals, developed by the owner in order to identify the appropriate actions from a commercial point of view.

The requirements concerning deteriorated and repaired structures are as follows:

- Service life
- Structural stability and safety
- Execution of work
- Environmental and health
- Economy
- Aesthetics, social, political…..

It is very important to include requirements of a non-technical character related to the repair operation. Non-technical issues and their interaction in the decision making process are discussed in Chapter 6. All types of requirements are further discussed in Chapter 4.

In addition to the above requirements, certain restrictions might also apply during construction, e.g. limited accessibility or limited time for carrying out the work.

**2.4.5 Technical solutions**

Repair is just one of the options which may be considered. This Manual focuses only on the repair options and on the choice of the most suitable repair method. This depends on the type and cause of damage, which must be determined with confidence.

There are several damage causes. The following causes are dealt with in this Manual:

1. Reinforcement corrosion
2. Alkali-silica reactions, ASR
3. Salt frost and internal frost damage
4. Leaching

For a deteriorated structure there is often more than one damage type. For each combination of type and cause, there are normally only a few repair principles and a few main repair methods that are appropriate. For each repair method there are many variants, each of which has associated risks.

Different types of repair principles, main repair methods, and underlying sub-groups are presented in Chapter 5.
2.4.6 Optimisation

The aim of the optimisation process is to identify the optimal repair method. Normally, there is more than one repair method which is reasonable and appropriate for a particular situation (see Chapter 5). In order to find the best solution a refined analysis has to be made. It should contain the following elements:

1. On the basis of the overall performance requirements stated in official rules and codes, or defined by the owner’s strategic goals, one or more repair methods that best fulfils the requirements can be selected.

2. Analysis of structural safety, serviceability, service life, environmental impact, economy, and other major requirements, determines the functional requirements. This in turn defines the material properties that have to be satisfied. Methods by which these overall requirements on the repaired structure can be transformed to requirements on the repair material and repair system have to be described in the AMS, together with test methods by which material properties shall be verified.

3. Analysis of impact of the repair methods on conditions outside the structure such as noise and other disturbance.

4. Analysis of risks involved in the repair method. Risk can be linked to economy or to health hazards or other factors. Principles for how risks are to be handled should be included in the AMS.

5. Analysis to compare the different repair methods is carried out to determine the optimum method.

Tools for analysis are described in Chapter 6, and methods for selection and optimisation in Chapter 7.

The most difficult task is to weigh the different requirements against each other, such as environment versus economy, or service life versus economy, etc. Methods for how to find the optimal solution should be described in the AMS system: a few methods are discussed in Chapter 6 and 7.

Thorough and accurate optimisation is not possible without clear, straightforward and quantified requirements and restrictions. It is the owner’s responsibility to prescribe the requirements, and to identify the regulations, restrictions and the standards to be followed.

The optimisation process is simplified if the critical requirements are identified and the process is initiated by selecting the repair principles and methods on the basis of a few but most crucial requirements.

If, for instance, requirements for structural safety and service life are prescribed and are considered to be the critical factors (which is normally the case) the optimisation process can initially be based on these. The methods which do not meet the requirements for structural safety and service life can then be disregarded from further analysis. The
selected repair principles and methods can be subjected to further analysis. As discussed in Chapter 6 there are many variants within the same main repair method. For example, there are many repair materials (brands) available. Therefore, other main requirements, such as requirements with regard to environment, economy, simplicity of execution, etc, might be optimised by selecting the most suitable material type and brand.

An important input in the optimisation is the follow-up of repair made previously on similar structures. This information can be contained in the asset inventory.

### 2.4.7 Final decision

The final decision is taken by the owner (or the owner’s appointed consultant) who may not have been involved in the selection of the repair principle, repair method and repair system and associated analyses. Therefore, it is important that the information presented to the owner be as complete as possible and contain following details:

1. a structural assessment,
2. an analysis of basic requirements on the structure,
3. a priority ranking,
4. a thorough analysis of suitable repair principles,
5. a list of repair methods which meet most important requirements,
6. a final selection of repair method.

As far as possible, the decision should be based on quantitative analysis, methods for which should be described in the AMS (see Chapter 6).

It should be noted that the owner may still be considering other actions such as do nothing, postpone the repair, restricted use or demolish the structure. Therefore, the material should also contain a prognosis about the damage development and a consequence analysis.

### 2.4.8 Execution of repair. Site work

Strategies for how to organise control of the site work should be contained in the AMS. Test methods for quality control at different moments in the repair and when the repair is finished should be stated. How the site work should be organised is not considered in this Manual. However, in Chapter 6 the principles of evaluation of execution of a repair work are described.

### 2.4.9 Follow up

Methods and systems for monitoring the long-term behaviour of the repaired structure should be described in the AMS. Such methods might involve on-going measurements of deformations, cracking, corrosion rate, moisture level, chloride penetration, etc. Normally intermittent measurements are made at certain defined intervals, e.g. at the routine inspections.

Data obtained during the repair work, and from monitoring the structure, should be fed back to the asset inventory. Methods for this should be described in the AMS.
2.5 Existing management systems

There are many management systems available, and their structure and content vary from country to country and from owner to owner. Most management systems have been developed according to different standards, for different purposes and different structures. Although it is very instructive to study all these different systems, it is beyond the scope of this Manual: comprehensive descriptions of the systems are elsewhere in the literature. For example some bridge management systems are described in the EU project BRIME (Bridge Management in Europe [2.1]).

Examples of systems applied to bridges are the Danish DANBRO [2.2], the American PONTIS [2.3], the Swedish BaTMan [2.4] and the Spanish BMS developed by GEOCISA. Other systems have been developed and used by owners of installations for nuclear power and hydropower. Examples are systems used by the Swedish power producing company Vattenfall [2.5]. A summary of all these management systems can be found in Annex A.

Various management systems are used in the UK. The Highways Agency has developed their own in-house system (SMIS), which is used to manage the bridges and structures on motorway and trunk road network. Other bridge owners (Network Rail, Local Authorities) have their own systems developed in response to particular requirements. Some of these are commercially available systems. TRL has developed BridgeMan which has been adopted by some local authorities in the UK other bridge owners overseas. BridgeMan acts as a central location to keep all the information on the bridge stock, storing general inventory information and inspection reports, as well as providing a means to link to other data in the form of photos, drawings, reports, etc. BridgeMan is intended as a flexible application that can easily be tailored to meet a user’s specific requirements, including integration with existing management systems and GIS systems. See Annex A for more details.

2.6 Conclusion

The intention of this chapter is to describe the process of the management of repair and highlight the important topics that should be considered in the repair process. The process starts when damage is detected and the following structural assessment, as described in Chapter 3, implies that some action should be taken. This Manual focuses on the process required to identify the optimum repair method. Different repair methods are presented in Chapter 5. Tools for evaluation of the repair methods are provided in Chapter 6 and methods for selection and optimisation of the repair methods are given in Chapter 7.
3 ASSESSMENT METHODS FOR DETERIORATED STRUCTURES

3.1 Introduction

Concrete deterioration results in several types of damage such as cracking, delamination and spalling of concrete, loss of steel cross-section and loss of bond between constituents, all of which can decrease the load-bearing capacity of a structure.

The rigorous assessment of deteriorated structures is a very complex task due to the fact that there are no generally accepted models relating the degree of deterioration to the loss of structural performance [3.5].

A correct assessment of a deteriorating structure is a crucial basis for the success of a repair, rehabilitation or strengthening system. Experienced has shown that in many cases repairs fail much earlier than expected due to improper diagnosis of the actual situation of the structure, either because the actual cause of deterioration was not properly understood, or the extent of the damage was under-stated.

The presentation of detailed procedures for assessment is beyond the scope of the REHABCON project. However, an accurate assessment process is crucial to the selection and application of an effective repair strategy, as it defines the main performance requirements of safety, serviceability and durability of the structure. Any assessment procedure that fulfils the requirement described above can be used for this stage of the process. On such methodology was developed through CONTECVET, an EU-funded project completed in 2000 dealing with the residual life of deteriorated concrete structures. The remainder of this chapter presents the principles and procedures developed through this project.

3.2 Structural assessment

Figure 3.1 summarises the main aspects of the structural assessment of a deteriorating structure. These include [3.6-3.11]:

1. The need to establish the level of present performance by establishing the type, extent and cause of the damage
2. The establishment of the average rate of deterioration
3. The prediction of the loss of the structural capacity
4. The identification of the minimum acceptance level of performance
5. The urgency of intervention.
The main stages to accomplish this process are:

1. Inspection and testing on-site
2. Diagnosis of the cause of damage and its effect on structural performance
3. Prediction of the development of the damage and the structural consequences.

These steps are described in the CONTECVET Manuals [3.1] [3.2] [3.3] [3.4] for the main four mechanisms of deterioration:

1. Reinforcement corrosion
2. Alkali Silica reaction
3. Frost attack: salt scaling and internal damage
4. Leaching.

### 3.3 CONTECVET Manuals

CONTECVET was funded via the EU Innovation Programme and was concerned with assessing the residual service life of deteriorating concrete structures. The project was completed in 2000, with the principal outputs being three Manuals, covering deterioration due to corrosion, frost action and alkali silica reaction (ASR). Building on the scientific work undertaken in a previous BRITE-EURAM projects (BRITE 4062), the emphasis was on developing engineering models for structural assessment, while attempting to fit these into an embryo asset management system.

The Manuals are based on the principle of progressive screening, with the investigation proceeding only as far as is necessary to obtain a reliable estimate of capacity and to determine with confidence whether any intervention is required. The procedure is shown in Figure 3.2. As the investigation progresses, decisions to act may be taken at any of the four indicated levels, depending on what is found. However, the key levels in the process are:
**Simplified Assessment**

A qualitative approach, based on damage classification methods, leading to values for SISD ratings (Simplified Index of Structural Damage).

**Detailed Investigation**

A quantitative structural assessment is made of the impact of deterioration on individual action effects (bending, sheer, bond, etc).

### 3.3.1 Grouping of structural elements

The assessment made in CONTECVET Manuals is based on the grouping of structural elements relating to:

![Flow diagram for progressive screening](image_url)

**Figure 3.2 Flow diagram for progressive screening**
• The structural type of element
• The environmental conditions
• The type, degree and extent of damage

In consequence, as is shown in Figure 3.2, the assessment is made in each of the groups established at the desk study phase. By grouping the structural elements, the zones needing intervention can be better identified and classified.

Following assessment, the functional capacity of the structure will be defined. If it fails to meet the defined minimum level of performance, various strategies of intervention can be indicated, as presented in Figure 3.3. These are:

1. Demolish
2. Do nothing
3. Repair (to maintain current capacity or recover initial design capacity)
4. Strengthen (to up-grade the capacity).

For each element, or each group of elements, the CONTECVET Manuals can be used to give an indication of the timing for any of these levels of intervention. This time is defined as the Urgency of Intervention when a Simplified Assessment is made and as Residual Life (when the structure reaches some minimum level of performance) when a Detailed Investigation has been performed.

### 3.4 Strategy of intervention

The assessment phase provides the information needed to define the strategy of intervention. The main data needed are:

• The type of damage and its extent
• The cause of damage
• The average rate of deterioration
• The time to intervention or Residual Life

All this information can be provided by CONTECVET Manuals for the four main deterioration mechanisms (other assessment procedures and methodologies can also be used). The REHABCON Manual can then be used to consider using this information to decide initially on the best intervention strategy and then to select by optimisation the most appropriate solution.

3.4.1 Reinforcement corrosion

Reinforcement corrosion is the rusting of the reinforcement producing oxides whose expansive character induces cracking of the concrete cover. It is the most frequent type of damage and the main consequences for the structure are (Figure 3.4) [3.6-3.11]:

• Loss of concrete and steel cross-sections
• Decrease in steel ductility
• Loss of bond between the steel and concrete

![Figure 3.4 Consequences of reinforcement corrosion](image)

Corrosion needs moisture to progress and therefore is dependent on the surrounding environment and the climatic changes. In order to make a prediction of the progress of the damage, an average corrosion rate in mm/year of attack penetration, $P_x$, has to be established by one of the following:

a) measuring the loss in cross-section in each group of elements and dividing by the number of years of the corrosion period,

b) measuring the instantaneous corrosion rate on site several times per year and averaging them or

c) measuring the instantaneous corrosion rate only once but averaging it with measurements in cores drilled from the representative element of the corresponding group.

The CONTECVET Manual for reinforcement corrosion (available at www.ietcc.csic.es) contains the procedures for the Preliminary or Simplified Assessment and the Detailed Assessment (Figure 3.5) and several Annexes where the most important principles and
fundamentals are compiled. The Simplified Assessment serves to establish priorities by ranking the urgency of intervention in four levels. The Detailed Assessment can be applied when particular important structures are affected and their load-bearing capacities compromised.

The Simplified Assessment is based on establishing the ranking of element performance through the definition of a Simplified Index of Structural Damage, (SISD) deduced from a Corrosion Index, (SCI) and a Structural Index, (SI); see Figure 3.5.

By the addition of numerical values calculated for the SCI and the SI it is possible to obtain an average value of a Simplified Index of Structural Damage, SISD. This SISD value serves to define the Intervention Urgency, IU which is ranked in four levels (Table 3.1).

### Table 3.1  Urgency of Intervention (years)

<table>
<thead>
<tr>
<th>SISD value</th>
<th>Urgency of intervention</th>
<th>Action needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>&gt; 10</td>
<td>Periodic inspections</td>
</tr>
<tr>
<td>Medium</td>
<td>5 – 10</td>
<td>Reassess structure during this time</td>
</tr>
<tr>
<td>Severe</td>
<td>2 – 5</td>
<td>Structural assessment within this time</td>
</tr>
<tr>
<td>Very Severe</td>
<td>0 – 2</td>
<td>Repair or detail structural assessment within this time</td>
</tr>
</tbody>
</table>
The *Detailed Method* was developed for the rigorous assessment and the quantification of the reduction in load-bearing section of concrete and steel (Figure 3.6). The procedure is based on identifying the corrosion depth, $P_x$, in the reinforcements and the measurement of the corrosion rate, $I_{corr}$. From $P_x$, the residual bond, steel cross-section, concrete section and the crack width are established through predetermined structural models given in Annex F of the CONTECVET Manual. Once these new properties are established, the determination of the load effect resistance is made through the verification of the structural behaviour by means of ULS and SLS theories. Finally, a Deterioration Curve (Figure 3.1) for each property is calculated by introducing the time evolution from the corrosion rate. After a Detailed Assessment it is necessary to establish the time to intervention (Residual Life) by defining a Minimum Technical Performance or Limit State. After a Detailed Assessment it is also necessary to establish the time to intervention.

Both Simplified and Detailed Assessment consider the need to carry out a minimum set of tests in each group of elements in order to identify the cause of damage. This, together with the quantification of the extent of damage and the degree of deterioration (by measuring the corrosion penetration depth and the corrosion rate), enable the REHABCON Manual (Chapters 5, 6 and 7) to be used for the selection of the most appropriate repair option.
With reference to the type of intervention the distinction between SLS and ULS can be made in the Detailed Assessment to help to determine whether, in addition to a geometric or aesthetic repair, strengthening is also needed, i.e., to determine whether intervention 3 or 4 is required. The REHABCON Manual presents guideline on how to choose the best repair technical solution.

3.4.2 ASR

ASR is not a unique type of deterioration due the very different sources of aggregates and their different reactivity. It is becoming more common as the structures age as usually is slow in development.

The damages affect mainly to the concrete due to the high related alkalinity result protective towards the steel. However in presence of chlorides, the cracking generated by the reaction opens paths to the quick penetration of this aggressive

Preliminary assessment

It is based in establishing a SISD rating as shown in Figure 3.2. The steps involved may include some combination of:

- visual inspection;
- desk top studies;
- testing and diagnosis;
- structural considerations, including sensitivity.

The procedure for deciding on the steps is shown in Table 3.2, in simplified form for ASR. If the index is classed as A (very severe) or B (severe), there is generally concern over structural capacity and a Detailed Investigation is usually undertaken.

Table 3.2 Deciding on the next step

<table>
<thead>
<tr>
<th>Initial structural severity rating</th>
<th>Condition in the context of ASR</th>
<th>Action</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>n D</td>
<td>Satisfactory</td>
<td>Nothing beyond standard inspection routine</td>
<td>Easy decision</td>
</tr>
</tbody>
</table>
| C B                               | Borderline                       | Conservative choice from:  
  • Detailed assessment  
  • Limited action  
  • Monitoring  
  • Load testing | Difficult areas to decide on action, may need more investigation |
| A                                 | Possibly inadequate              | Remedial works and load testing depending on Detailed Assessment results | Relatively easy decision |

Notes to Table 3.2:
i) Most structures may contain elements with a combination of SISD's. Elements with similar SISD's should be grouped together for management purposes.

ii) The time scale for actions will depend on the structure, its condition, future use and life requirements. These can be broadly related to the SISD.

iii) Any strategy should be aimed at ensuring structural adequacy, 'increasing life' and improving appearance. This is likely to be conservative at this stage.

iv) It may be necessary to proceed to a detailed assessment before proceeding to the stage of deciding on management options.

**Detailed investigation**

Following the principle of progressive screening (Figure 3.2), the decision to move to this level is based on the SISD rating, as shown in simplified form in Table 3.2. In addition, other factors may come into play, these include:

- Uncertainty: where the results from the preliminary assessment are based on limited data, or where the condition is classed as borderline or possibly inadequate
- Criticality: where here the structure is of such importance, or where the consequences of failure are so significant, that a preliminary assessment is insufficient
- Sensitivity: where here there is little redundancy in the structure as a whole, or where local detailing is poor

The quantitative approach in the three Manuals is based on modifying the corresponding design models and on the insertion of modified mechanical or geometrical properties, to allow for the observed/measured deterioration.

### 3.4.3 Internal frost damage

**Identification of frost as the cause of damage**

Internal frost damage only occurs when the structure has long-term access to free water. Typical structures exposed to frost attack are:

- structures sucking ground water
- structures in contact with moist back-fill, like support walls
- structures constantly exposed to water, like hydraulic structures, dams etc.
- railway bridge troughs filled with moist ballast
- structures more or less constantly exposed to drainage water

In order to estimate if frost can be the cause of damage, it is important to clarify the wetness of the environment surrounding the structure.

It is sometimes difficult to distinguish internal frost damage from alkali silica reaction. In both cases the concrete surface has a more or less dense crack pattern indicating internal disintegration due to expansion. Other destruction types causing similar cracking due to internal expansion are sulphate attack and delayed (secondary) ettringite formation. Often a petrographic analysis is needed to establish the cause of damage. It is
very important that the diagnosis is correct, since the evolution of damage is quite different in a frost-damaged structure than in a structure damaged by the other mechanisms.

In Figure 3.7, the crack pattern in a core from a frost-damaged concrete is shown. There is a random system of cracks in the heart of the concrete together with cracks parallel to the surface of the concrete. In many cases there are also long cracks parallel to joints and edges of the concrete, or emanating from corners.

The amount of damage can vary from place to place in the same structure. Therefore, in most cases, series of data from many different places are required. Only in special cases can data taken from one place be used for the entire structure.

![Figure 3.7 Typical internal crack pattern induced by internal frost action](image)

**Effects of frost damage on the structure**

Internal frost damage appears as loss in compressive and tensile strength, loss in E-modulus, and loss in bond strength. Reductions in tensile and bond strength as big as 70%, or more, can be obtained. The effect on compressive strength is often limited to about 30% for normal grade concrete. The effect on E-modulus can be extremely high; reduction can approach 100%.

Internal damage will affect the moment and shear capacity of slabs and beams, and the compression capacity of columns, by lowering the compressive and bond strength. It might seriously affect the structural capacity of pre-stressed concrete by significantly lowering the E-modulus of the concrete. It also changes the moment and force distribution in the structure by changing the stiffness in parts of the structure.

Destruction mechanisms and the effects of frost on mechanical properties of concrete are described in [3.2].

**Assessment - principles**

Assessment shall be used for judging which of these measures should be taken: (i) replacement, (ii) immediate repair, (iii) postponed repair.

Assessment shall be made with regard to:

1: *structural capacity and safety*
2: **serviceability** (deformation, permeability, effect of cracking on other destruction types, like reinforcement corrosion).

Assessment shall be made with regard to; see Figure 3.9:
1: **status at time of inspection**
2. **future status** if no repair is made

An assessment can be: 1) **preliminary** and 2) **detailed**. (Figure 3.8)

![Figure 3.8  Assessment of a structure with internal damage caused by frost](image)

**Preliminary assessment of the present status**

The preliminary assessment can be either **qualitative** or **(semi-)quantitative**.

*Qualitative* preliminary assessment is based primarily on:
(i) wetness of environment (divided in “Moist”, “Very moist”, “Extremely moist”).
(ii) consequences of failure (“Slight”, “Severe”)

*Quantitative* preliminary assessment is based on:
(iii) lower bound values for strength and stiffness of frost damaged concrete.

Definition of wetness of environment is given in Table 3.3. Definition of consequences of failure, and lower bound values are given in [3.2].

*Since it is almost impossible to judge the actual status of frost damaged concrete by visual inspection only, and since the description of environment is difficult, a preliminary assessment will be very unsafe and is normally not recommended.*
**Detailed assessment of the present status**

The effect of internal frost damage is analysed by a *re-design* of the structure using actual data for; (i) strength and stiffness of concrete, (ii) amount, and location of reinforcement, (iii) concrete cross-section, (iv) concrete cover, (v) load. A total re-design of the entire structure is often not required, only a control of critical sections in the structure; see Figure 3.9.

![Figure 3.9](image)

*Figure 3.9  Assessment of the present and future structural capacity of a frost damaged structure. Analysis of crucial sections*

The same design procedures as for new structures are used. Extra consideration must be taken to the fact that the E-modulus of damaged concrete might be different in different parts of the structure. Therefore, the moment and force distribution can be different in the frost damaged structure than what was anticipated when the structure was designed.

The characteristic values of the compressive, tensile, and bond strength to be used, are based on measurements on cores taken from critical parts of the structure considering variations in measured data, shape of specimens and moisture content in these. In the general case, material data varies from place to place within the same structure. Therefore, many sections of the structure must normally be analysed for structural capacity, using individual data for each section. The location of sections for measurements of strength, E-modulus, scaling, and other essential properties, are determined by an experienced investigator in collaboration with the structural engineer who is going to perform the assessment.

The characteristic material data are transformed to design values using partial coefficients for which consideration can be taken to the fact that much is known of the structure.
Pre-stressed concrete structures can be more affected by internal frost damage than normal structures. Both the E-modulus and the tensile strength can be very much affected. This reduces the pre-stressing force, and the possibility to anchor tendons.

**Detailed assessment of the future status**

Assessment of the future status can only be made as a detailed assessment. The assessment is made exactly as for a detailed assessment of the present status. The difference is that the material data used in the structural "re-design" are time-extrapolations of data determined at the time of inspection. The principles of an extrapolation are illustrated by Figure 3.9. The extrapolation might be different for different parts of the structure depending on different moisture conditions in different parts.

The extrapolation of material properties depends on the wetness of the environment. This is divided in three groups, Table 3.3.

**Table 3.3 Classification of environment with regard to internal frost damage**

<table>
<thead>
<tr>
<th>Environment 1)</th>
<th>Moisture characteristics</th>
<th>Example of structural parts</th>
</tr>
</thead>
</table>
| 1: Moist      | Outer: Periods of exposure to water followed by longer periods of drying.  
Inside concrete: No accumulation of water over time. | Vertical parts of façades. |
| 2: Very moist | Outer: Long periods of exposure to water followed by periods of drying.  
Inside concrete: A certain increase in water over time. | Horizontal surfaces exposed to rain and melting snow, like balcony slabs, hydraulic structures  
Some meters above the water line. |
| 3: Extremely moist | Outer: Constant exposure to water. No drying periods.  
Inside concrete: A gradual increase in water content over time. | Hydraulic structures close to the water line. Foundations in ground water above the lowest level of zero temperature.  
Bridge piers in fresh water. |

1) Environments causing low moisture levels in the concrete are not included, since they cannot cause internal frost damage in normal concrete.

Extrapolation curves for the 3 moisture classes are shown in Figure 3.10. The curve is horizontal (no future change) for moisture class 1. It is gradually increasing with the square-root of time for moisture class 2. It is linearly increasing with time for moisture class 3.
Salt-frost scaling

Identification of salt-frost as the cause of scaling

Surface scaling might appear when a concrete surface freezes while it is in contact with saline solutions (often of weak concentration); e.g. sea water or water polluted by de-icing salts. Also other water solutions, like solutions of alcohol might cause salt-frost scaling. If scaling on a concrete surface exposed to frost is observed, and if one knows that there is a saline environment caused by de-icing salts, or other salts, like sea water, one can be quite sure that salt-frost attack is the reason. Other causes might be leaching, acid attack, or mechanical erosion.

The surface is often rough, since the mortar phase is more eroded than the coarse aggregate. The scaling is not only limited to parts that are directly exposed to salt, but also to other parts of the structure. The reason is that there is often a “salt mist” around the structure.

The scaling depth can be quantified by measuring the depth from the non-eroded level. This can often be based on adjacent parts that are un-scaled.

Besides measuring the scaling depth, one should also measure the chloride profile and the carbonation depth in the remaining concrete in order to assess if there is risk of reinforcement corrosion; going on or starting in the near future.

Effects of salt-frost scaling

Scaling will only affect the surface. Un-scaled concrete normally maintains its
mechanical properties. Thus, the major effect of scaling is that it reduces the effective cover and the cross-section.

The initial scaling occurs in the cement paste phase while the aggregate grains are intact, provided aggregate is non-porous and sound. Due to the gradually deeper and deeper scaling of the cement paste, also coarser aggregate grains are eventually lost. In serious cases a big portion of the cover can be eroded. Therefore, scaling might have very big effect on the anchorage capacity of the reinforcement bars. It also affects the function of compression reinforcement and shear reinforcement.

Theories for the scaling destruction mechanism are presented in [3.2].

Scaling also affects the service life with regard to reinforcement corrosion, by gradually reducing the concrete cover. This effect, and the way to handle this, is described in [3.12].

**Assessment – principles**

1: The effect of scaling on the *structural capacity* should be assessed.
2: The *synergy between scaling and reinforcement corrosion* must normally be assessed.

Assessment shall be made with regard to:

1: *The present status at time of inspection*
2: *The future status*

![Diagram](image)

**Figure 3.11** Assessment of a structure with internal damage caused by salt-frost scaling
Preliminary assessment of the present status

A preliminary assessment is based on visual inspection and few measurements of scaling depth. The assessment is made according to method described in [3.2]. The assessment is only based on average values of scaling depth, a qualitative description of environment, and a judgement of the consequences of failure.

The method is very insecure. Therefore, it is recommended to always use a detailed assessment.

Detailed assessment of the present status

A detailed assessment is based on detailed mapping of the scaling depth in vital parts for structural stability or corrosion, combined with detailed mapping of the concrete cover, carbonation depth and chloride profile. New values are inserted in a structural re-design of the moment, shear, and compression capacity of scaled parts of the structure.

Scaling also affects the anchorage capacity by reducing the cover. Scaling, however, seldom affects the strength of the residual cover. Thus, bond strength is normally unaffected by scaling. The reduced anchorage capacity is therefore calculated by inserting the reduced cover, and the actual amount of reinforcement in formulas for anchorage capacity given in the design code used for the assessment.

When scaling is so deep that the whole cover is lost, there is a risk of buckling of compressed reinforcement. In this case, reinforcement corrosion will, however, be the most important factor determining the structural capacity.

In the normal case, scaling and residual cover will vary quite much within the same structure. Relevant values for the actual section must be used in the assessment.

Detailed assessment of the future status

Assessment of the future status with regard to structural stability can only be made as a detailed assessment.

The assessment is made exactly as for a detailed assessment of the present status. The only difference is that the scaling depth, used in the structural design, is a time-extrapolation of the scaling depth at the time of inspection. The scaling is more or less constant with time for concrete that has sustained at least a decennium of salt frost action. Certain jumps in the scaling curve appears as coarse aggregate are lost at irregular intervals, but the general trend is linear, unless the outer conditions are changed, see Figure 3.12. Therefore, also the residual cover is a linear process.

In a case in which the exposure to de-icing salt will change in the future (increased, decreased, or ceased), a linear extrapolation will be misleading. In such cases, the extrapolation can be based on a salt-frost test. The principles behind such an extrapolation are described in [3.2].

In a detailed assessment, analysis should also make of the possible future effect of scaling
on reinforcement corrosion. A technique for this analysis is presented in [3.12].

![Surface scaling diagram](image)

**Figure 3.12** Salt-frost scaling curve with jumps caused by loosening of coarser aggregate particles

### 3.4.5 Leaching

**Identification of leaching as the cause of damage**

Leaching will primarily occur in the following types of structures:

1. Concrete structures exposed to pure water for long time, such as water pipes, water reservoirs, storage tanks for de-ionised water, cooling towers, hydropower structures, etc. In these structures, leaching normally occurs as a gradual dissolution of surfaces that are in constant contact with water.
2. Concrete structures exposed to one-sided water pressure forcing water through the structure, such as dam walls, water reservoirs, retaining walls, etc. In these structures, leaching normally occurs as more or less homogeneous dissolution over the entire cross-section. Leaching also occurs in crack-walls parallel to water flow.

Homogeneous leaching by water flowing through the structure can be easily identified by water streaming on the downstream face, or by the existence of white, often thick, deposits of calcium carbonate on the downstream face. Leaching can hardly be mixed up with other destruction types. The amount of damage can be investigated by visual inspection and chemical analysis of surfaces, and by measuring the residual lime content in the interior of the structure, combined with measurements of water flow, and lime content in water flowing through the structure.

**Leaching mechanism**

Water is able to dissolve calcium-based components in the cement paste. The total amount of such components is about 65% of the cement weight in concrete and about 60% of the cement paste volume, [3.4]. Thus a concrete with 300 kg cement per m³ contains no less than 200 kg of potentially dissolvable lime. Different calcareous components in the cement paste have different solubility. The most soluble component is calcium hydroxide (portlandite), its solubility in pure water (pH 7) being 1.85 g/litre at
0°C and 1.65 g/litre at +20°C. The solubility increases with decreasing hardness and pH of the water. The total content of portlandite is about 25% of the cement weight. For a concrete with cement content 300 kg/m³ it is about 75 kg/m³.

A concrete surface in constant contact with water will be gradually dissolved increasing its porosity and reducing its strength. Surface dissolution is a gradually retarded process. Significant destructive effects might occur if water is able to flow through the structure. This might occur if there is a big water pressure gradient across the structure, and the concrete has high permeability (w/c-ratio above 0.60). In such concrete leaching will lead to a gradual loss of lime over the entire cross-section with a corresponding increase in porosity and permeability. Therefore, leaching caused by water percolating the structure can be expected to be an accelerating process. The total amount of water required for total solution of all portlandite is high. For concrete with cement content 300 kg/m³ the required water volume is about 40 m³/m³ of concrete. Thus, it is only in highly permeable concrete that important homogeneous leaching across the entire concrete volume can take place.

Leaching can also be a problem in cracks. Water flowing through a crack will dissolve lime in the crack walls thereby increasing the risk of other destructive processes, such as reinforcement corrosion. Often, however, water flowing in a crack has so high pH-value due to its contents of lime that corrosion cannot occur. Besides, thin cracks often seal by precipitation of lime downstream. It is only in rather coarse cracks with high rate of water flow, that such secondary effects of leaching could be a problem.

NOTE: Alkali hydroxides in the concrete will also be leached. These components are even more soluble than calcium components, and will therefore be lost before significant calcium leaching has taken place, reference [3.13]. Leaching of alkali hydroxides will not affect strength and stiffness, but might have negative effects on reinforcement corrosion.

**Effects of leaching on concrete**

Leaching will increase concrete porosity. Therefore, it will reduce the concrete strength and stiffness (E-modulus). These effects have been discussed in [3.4]. An example of the effects of leaching on tensile strength is shown in Figure 3.13. According to this, strength loss is directly proportional to amount of leaching.

Effects of leaching on E-modulus have not been investigated. As a first approximation it is reasonable to assume, however, that a certain relative loss in tensile strength gives the same relative loss in E. A method for theoretical calculation of the loss in E based on information of leaching is given in [3.4].
Effects of leaching on the structure

Strength loss will have a direct negative effect on the structural stability and safety of the structure. To what extent depends on the amount of leaching, and on the location of leaching. Loss in compressive strength will reduce the capacity for bending moments and the capacity for axial compressive load. Loss in tensile strength can be assumed to give the same relative loss in bond to reinforcement (this has been found to be valid for the effect of frost damage on concrete, [3.2]). By estimating the effects of leaching on these basic properties determining structural stability, this can be assessed. An example of an assessment of the effect of leaching on the future structural stability and residual service life of a lamellae dam is given in [3.13].

Loss in E-modulus will affect the serviceability of the structure. It will also affect the force distribution in statically undefined structures, thereby having a direct effect on structural stability.

Leaching might also have a more indirect effect on the structural stability by changing the internal water pressure profile (uplift profile) within structures exposed to water pressure gradients, like dams. Thus, the risk of overturning the structure might increase.

Leaching in cracks will normally not affect the structural stability unless corrosion of reinforcement occurs as a consequence of leaching. On the other hand, it might negatively affect the serviceability of the structure in cases where water tightness is essential, like in water reservoirs or when the concrete is used as a barrier between water upstream and a space downstream which has to stay dry.
Synergistic effects

Leaching will significantly influence other destructive actions, and must therefore be considered when the effect of these actions are assessed. Potential synergetic effects are discussed in reference [3.2] and [3.13].

Assessment – principles

Assessment shall be made with regard to:

1. Structural stability and safety of individual structural parts within the structure
2. Stability of the structure as a whole, such as the risk of overturning
3. Serviceability, including the effects of leaching in cracks

Assessment shall be made with regard to:

1: The present status at the time of inspection
2: The future status

Figure 3.14 Assessment of a structure with internal damage caused by leaching

Assessment of the present status

There is no real reason to distinguish between a preliminary assessment and a detailed assessment since both require the same type and amount of information. Only when potential synergetic effects between leaching and other destructive mechanisms shall be
evaluated is there need of more detailed information, such as carbonation depth, chloride profile, chloride diffusion coefficient, degree of corrosion etc. This type if assessment is more complex and it is not described here.

Required information:

1. Actual compressive strength in parts vital for safety.
2. Actual tensile strength in vital parts such as parts in which anchorage of reinforcement is important.
3. Actual bond strength between concrete and reinforcement in vital parts. This might be calculated from the tensile strength in the same parts.
4. The E-modulus in parts of importance for assessing structural stability; i.e. for assessing possible transfer of force from one part in the structure to another.
5. The hydraulic profile across the structure.

Strength measurements are based on cores drilled from the structure. The test data has to be transformed to characteristic values to be used in the structural analysis.

The hydraulic profile is determined by logging the water level in drilled vertical holes located in different parts over the cross-section of the structure. It can also be determined by pressure gauges.

The actual structural stability is assessed by a normal structural analysis using the field data for residual strength and E-modulus, and using real load data (e.g. real data for hydraulic head etc.).

The overall stability (safety against overturning) is based on the uplift pressure field inside the structure estimated from the hydraulic profile. Traditional calculation methods for dams are used.

Estimation of serviceability is mainly coupled to the water flow in cracks and bulk concrete. This flow is compared with the maximum flow that can be accepted.

Assessment of the future status

Required information is the same as for assessment of the present status. However, in order to be able to assess the future status, it is essential to be able to estimate the future reduction in strength and stiffness, and the future rate of leaching. Therefore, also the following additional information is required:

1. The actual degree of leaching. This is based on measurements of the residual calcium content in vital parts of the structure. This is made by chemical analysis of cores taken from the structure.
2. The rate of water flow at the downstream face in un-cracked “bulk” concrete and in cracks.
3. The concentration of calcium ions in leached water coming from vital parts of the structure.
Equations for extrapolation of future leaching and future increase in porosity based on actual leaching rate, actual calcium concentration in leaching water, initial porosity of cement paste, and actual degree of leaching (amount of leached calcium) are given in reference [4]. Extrapolation can be based on two different scenarios:

1. No future change in permeability. This will give future constant rate of leaching and therefore linear increase in porosity with time.

2. Gradual increase in permeability due to leaching. The increase is either (i) linear with leaching, (ii) progressively increasing with leaching, or (iii) linearly increasing with time. This will give progressive (accelerating) increase in leaching rate and porosity.

The future change in strength can be calculated from the extrapolated porosity-time curve, reference [3.4].

The estimated future strength curves, adjusted to design values as described above, are used as input in a structural design. Thereby, the future stability and safety can be estimated making it possible also to assess the residual service life.

On basis of the predicted increase in leaching rate the future uplift pressure curve across the structure can be estimated and used in a calculation of the risk of overturning the structure.

Future increased leaching in cracks can be estimated from the actual leaching rate and the rate of diffusion from crack walls to the water flow in the crack. Methods for this calculation are given in reference [3.13].

### 3.5 Other assessment methods

#### 3.5.1 Summary of documents and procedures in Sweden

**Introduction**

The Swedish National Road Administration is the primary producer of codes and guidance documents for the design, construction, assessment, maintenance, repair and strengthening of bridges and other related structures such as retaining walls and pile decks in Sweden. Other bridge owners such as the Swedish National Rail Administration and local authorities rely heavily on these documents.

**Maintenance inspection**

Both the road and rail administrations in Sweden use the same basic approach to maintenance inspection. The two main differences are that the inspection intervals are slightly different and that the rail administration does not carry out general inspections between the principal inspections. There are four main types of maintenance inspections that are normally carried out:
Superficial inspection: This is a cursory visual inspection to detect obvious defects at an early stage. The road administration divides these into inspections performed by the maintenance contractor and those which are carried out to verify that the stipulations in the maintenance contract are fulfilled. The rail administration carries out safety inspections one or two times per year depending on the type of bridge.

General inspection: This is a visual inspection with the aim following up the defects recorded in the preceding principal inspection. These are carried out within 3 years after the last principal inspection. The rail administration does not carry out this type of inspection.

Principal inspection: This is a close visual inspection of all parts of the structure, including those parts located under water that is carried out at intervals of less than 6 years. Some testing, such as for chlorides and carbonation in concrete or cracking in steel, may be performed.

Special inspection: This can be a visual inspection but is usually more thorough and is only carried out when there is a need to investigate in greater detail certain parts or aspects of the structure. Specialists and special equipment may be required.

The rail administration’s fundamental requirements for maintenance inspection are stated in a set of internal documents of which two pertain to bridges [3.14], [3.15]. These documents state the scope and aims of the inspection and the maximum intervals between inspections. However, the documentation used at a practical, detailed level is the digital handbook included in the bridge management system BaTMan [3.16]. This digital handbook is quite comprehensive and is based on four earlier publications including the road administration’s Bridge Inspection Manual [3.17].

**Structural assessment**

The rail and road administrations use similar assessment codes for the structural assessment of existing structures. The design codes for new bridges, Bro 2002 [3.18] and BV Bro [3.19], are not used for assessment. Instead special assessment codes have been written. The assessment code for road and foot bridges [3.20] has been used as a template for writing the assessment code for railway bridges [3.21]. The structure of the publications and all text that pertains to both road and railway bridges is thus the same. These publications are not self-contained in the sense that they refer to approximately 20 other documents, both internal and external. The main references are to the national building code BKR [3.22] and to the corresponding national handbooks for the design of steel and concrete structures, BSK [3.23] and BBK [3.24], respectively. Other references treat specific areas or aspects of the assessment such as drilled piles in non-cohesive soil. The assessment codes even treat outmoded forms of bridge construction such as masonry arch bridges and riveted steel bridges.

The aim in the assessment codes has been to eliminate unnecessary conservatism in the assessment. The level of safety that must be maintained is the same as in the design codes, but the design codes are much more conservative due to several reasons. One
reason is that many simplifications are used, which saves time in designing the bridge but results in higher construction costs. A margin for error is also useful in order to ensure that the bridge when built will meet or exceed the requirements for the desired load capacity. The risk of having to strengthen or rebuild a new structure is thus reduced. It is also desirable to allow for substantial future increases in traffic load. This approach of over-designing bridges is used because the marginal building costs of a structure with greater load-bearing capacity are relatively low when compared with the cost of replacing or strengthening the structure due to inadequate capacity at the time of erection or due to a future increase in traffic load.

The assessment codes require the structural engineer to ascertain all existing information about the structure and determine its condition through inspection and, if necessary, testing before the calculations are completed. Adequate guidance regarding deterioration is not given in the assessment codes. This is left to the expertise of the structural engineer. The structural assessment is carried out mainly in the ultimate limit state, but some criteria in the serviceability limit state such as for deformation and displacement must be met for rail bridges.

The assessment is a multi-level process. A standard codified assessment using a simplified analysis and partial safety factors is carried out first. If the highest calculated load class or line speed does not meet or exceed the required load and speed, then a more refined calculation may be performed using, for example, a non-linear finite element analysis. More material testing can be performed in order to better specify the material parameters. The use of this information can also be used to reduce partial safety factors, but this is not normally done and neither the road nor the rail administration provides guidance documents in this area. Reliability analyses using full or approximate probabilistic descriptions may also be used, but here again there are no guidance documents provided by the administrations.

The standard assessment is always performed in order to determine the critical areas of the structure. The extent of the more complicated and thus more expensive analysis can thereby be kept to a minimum. The decision to make a more refined analysis, although often based on the recommendations of a consulting engineer, is always made by the manager of the structure.

A structural assessment can be initiated by a change in use, construction defects, deterioration or as a preventive measure. Increased traffic load is currently the most common reason for initiating structural assessments on rail bridges in Sweden since many railway lines are being upgraded due to market demands. Assessment Procedures for Railway Bridges [3.25], an internal rail administration publication, gives the general requirements for how the assessment is carried out, who is responsible and what documents are to be used.

**Repair and Strengthening**

The technical requirements for repair that are used by both the road and rail administrations are contained in the road administration’s maintenance code for bridges [3.26]. This publication builds upon the design code and is thus not self-contained. For example, the basic requirements for construction materials are found in the design code.
and only amendments to these requirements are found in the maintenance code. The
design of repairs is most often done by a consulting engineer, but for certain types of
minor repair work the maintenance contractor has the responsibility to both plan and
carry out the work. Surface treatments, for example, are often carried out by the
maintenance contractor.

The technical requirements for strengthening, however, are contained in the design code
itself. The design code is made up of ten parts, one of which contains the requirements
specific to strengthening. Design calculations are normally only required when the load
bearing capacity of the structure is affected. This includes repairs that affect the section
and all forms of strengthening. The design including the calculations is almost
exclusively carried out by a consulting engineer. Decisions regarding these actions are
made by the manager, however.

3.5.2 UK highways agency documents relevant to bridge
inspection, assessment and strengthening

Procedures and guidelines currently used in the UK for the management of highway bridges
including design, inspection, assessment, repair and strengthening are specified in the
Design manual for roads and bridges (DMRB) [3.27] which is summarise in Annex B.

3.5.3 Assessment methods in Spain

Scenario

The assessment of structures has been developed in Spain, as it has been in many other
countries, during decades, although non specific standards were published.

It is sure that in the last years owners and contractors more and more have realized that
maintenance, assessment and repair are more than a need and a business target.

This communion has permitted the development of specific Assessment Manuals and
Standards, as well as several publications and Work Groups, as are mentioned in the
references from [3.28] to [3.36].

Methods

As it has been commented, assessment has been completely carried out in Spain for
years. For both, buildings and civil structures, a systematic has been develop based on
engineer criteria an outer experience.

Assessment has a basic cataloguing:
• Simple or preliminary assessment based, usually, on visual inspection (as Principal Inspection for bridges) and focused on the general state of the structure.
• Detailed assessment includes testing, structural evaluation or any kind of studies required (as Special Inspection for bridges). This assessment has its target on specific or general damage origin and its influence on the structural reliability.

For the reliability evaluation previous and current standards are used, adapting the safety factors depending on the measured works developed on the materials, loads, environment, etc.

Nowadays only the Spanish Technical Code for Buildings, that it is about to be approved, has developed and specific Chapter for Assessment of existing structures by semiprobabilistic methods.

**Conclusions**

Only existing structures conform the owner’s heritage, since new ones become existing as soon as they are finished. This assert justify the developed of specific assessment codes.

Specifically in Spain the assessment knowledge is already grow-up, but it is necessary to take the form on the paper.
4 PERFORMANCE REQUIREMENTS

The purpose of this chapter is to review and define performance requirements that can be taken into account in the repair process. Once the cause and type of damage are known and the requirements to be fulfilling by the repair structure have been established, some repair options exist. The next step, described in Chapter 6, will be to evaluate the different repair options with regard to these performance requirements.

4.1 Introduction

The Council Directive 89/106/EEC of 21 December 1988 [4.1] on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products define provisions, including requirements, relating not only to building safety, but also to health, durability, energy economy, protection of the environment, aspects of economy, and other aspects important in the public interest. The definition of Requirements is therefore an essential step in the process of management of an Asset of structures.

The essential Requirements defined in the CPD are based in that the products must be suitable for construction works which are fit for their intended use, account being taken of economy. The essential requirements are the following:

Mechanical resistance and stability

The construction works must be designed and built in such a way that the loadings that are liable to act on it during its constructions and use will not lead to any of the following [4.2]: (a) collapse of the whole or part of the work; (b) major deformations to an inadmissible degree; (c) damage to other Parts of the works or to fittings or installed equipment as are result of major deformation of the load-bearing construction and (d) damage by an event to an extent disproportionate to the original cause.

Safety in case of fire

The construction works must be designed and built in such a way that in the event of an outbreak of fire: (a) the load-bearing capacity of the construction can be assumed for a specific period of time, (b) the generation and spread of fire and smoke within the works are limited, (c) the spread of the fire to neighboring construction works is limited, (d) occupants can leave the works or be rescued by other means, (e) the safety of rescue teams is taken into consideration.

Hygiene, health and the environment

The construction work, must be designed and built in such a way that it will not be a threat to the hygiene or health of the occupants or neighbors, in particular as a result of any of the following: (a) the giving-off of toxic gas, (b) the presence of dangerous particles or gases in the air, (c) the emission of dangerous radiation, (d) pollution or...
poisoning of the water or soil, (e) faulty elimination of waste water, smoke, solid or liquid wastes, (f) the presence of damp in parts of the works or on surfaces within the works.

Safety in use

The construction work must be designed and built in such a way that it does not present unacceptable risks of accidents in service or in operation such as slipping, falling, collision, burns, electrocution, injury from explosion.

Protection against noise

The construction works must be designed and built in such a way that noise perceived by the occupants or people nearby is kept down to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions.

Energy economy and heat retention

The construction works and its heating, cooling and ventilation installations must be designed and built in such a way that the amount of energy required in use shall be low, having regard to the climatic conditions of the location and the occupants.

Taking the format of the essential requirements of CPD as an example, in REHABCON Manual, requirements to be fulfilled by the repaired structure will be identified and defined. The will be called in general as Performance Requirements as they deal with mainly the life remaining life of the structure.

4.2 General performance requirements

As stated in the CPD, requirements constitute both the general and specific criteria with which construction works must comply; whereas such requirements are to be understood as requiring that the said works conform with an appropriate degree of reliability.

In repair processes for existing structures, standards related to construction works as EN1992 [4.2] about design of concrete structures would have to be taken into account.

This chapter includes a general overview of performance requirements contained in EN1504 which specifies the requirements for the identification, performance and safety of the various techniques and products for the protection and repair of concrete structures. EN1504-9 includes principles and repair options related to defects in concrete (see Chapter 5). Test methods for the different properties related to the general requirements described along this chapter will be commented in chapter 6 and referred to the specific standards. All these EN1504 and other European standard are listed in Annex C.

A selection of the general performance requirements considered to be taken into account in this Manual is given in Table 4.1. The object of compiling this list is to define the possible range of technical and non-technical requirements that may need to be taken into account in identifying the optimum repair option.
Owners of structures will generally have to consider technical aspects and the physical condition of the structure in question and the way these factors influence the functional performance of the asset (often referred to as technical requirements) but in many cases they also need to embrace the wider environmental, economical, social or political issues as well. This latter group is sometimes referred to collectively as being the non-technical requirements.

Because of the large range of structure types and conditions being covered within the scope of this Manual, it is not possible to be prescriptive in which requirements and how they should be considered. The list of requirements should be drawn up for each specific structure, along with some measure of their importance in the particular context.

For some schemes, non-technical issues will have little influence on the decision-making process. For others, the process will be straight-forward, in that non-technical issues may act as constraints on the potential solutions and may, for example, result in the elimination of particular options. Others have costs associated with them that can be taken into account through an economic evaluation. In all cases engineering judgement will required. Chapter 6 will give tools for evaluation repair options with regard to these requirements and Chapter 7 methods to select the best repair option comparing different alternatives also with regard to these requirements.

The requirements influence each other and can even be contradictory. For example, durability influences aesthetics and safety and almost every requirement influences the economy.

One of the main requirements of the structure is that it shall maintain full function during the prescribed service life, defined by the owner. By function, it can be meant requirements for structural stability and safety or load-carrying capacity. And also it can be related to service life, durability and serviceability (operation and function), by which is meant the capability of the structure to fulfil requirements that are not directly coupled to structural stability like watertightness, appearance, deformation, cracking, serviceability, etc.

The rest of requirements are grouped for execution, environmental, economic and other non technical factors (social, political and legal).

From Table 4.1 some of the technical and non technical requirements will be selected in Chapter 7 and Indicators for each one will be defined in order to evaluate the different repair options and select the best one. In this Chapter 4, definitions of the general performance requirements are given next.
### Table 4.1 Check list of general performance requirements

<table>
<thead>
<tr>
<th>Category</th>
<th>General performance requirements</th>
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<tbody>
<tr>
<td><strong>Service life / Durability</strong></td>
<td>Durability</td>
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<td>Deformation / Displacement</td>
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<td>Cracking</td>
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<td>Watertightness</td>
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<td>Slip resistance / Roughness</td>
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<td>Visibility</td>
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<td>Flexibility</td>
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<td>Serviceability</td>
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<td><strong>Structural stability / Safety</strong></td>
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<td><strong>Execution</strong></td>
<td>Minimisation of downtime. Rapidity</td>
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<td>Impact on environment</td>
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<td>Disturbance</td>
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<td>Climatic conditions</td>
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<td>Need of additional equipments</td>
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<td><strong>Environmental factors (&amp; Sustainability)</strong></td>
<td>Service life of the repair</td>
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<td>Ecology (external environment)</td>
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<td>Indoor environment</td>
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<td>Energy consumption</td>
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<td><strong>Economy</strong></td>
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<td>Demolition and disposal costs</td>
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<td>Failure costs</td>
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<td><strong>Social</strong></td>
<td>Aesthetics / Appearance</td>
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<td>Social perception (public confidence)</td>
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<td>Insurance and future liabilities</td>
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<td>Strength of local economy</td>
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<td>Improvement of asset values</td>
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<td>Cultural Heritage</td>
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<td><strong>Political</strong></td>
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<td>Government policies and initiatives</td>
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<tr>
<td><strong>Legal</strong></td>
<td>Legal issues</td>
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</table>
4.3 Requirements related to service life and durability

What is expected for the repaired structure is in general the same as for new structures and also in particular to the Serviceability Limit States design.

The service life requirement might be broken down into a number of measurable quantitative many of which are related to transport properties of the repair material and to the durability of this. As many of these properties declines with time these have to be defined by the owner for a prescribed life time.

Requirements coupled to service life of the repaired concrete are the following.

4.3.1 Durability

Durability will have to be defined for the original structure and the rehabilitated parts of the structure. The durability of the treated structure will depend on the environment exposure, properties of repair material and substrate, substrate preparation and application methods.

Investigations, laboratory studies, real world applications and also manufacturer’s data about durability (life time expectancy) depending on the environment of different repair methods and materials can be used for predictions. Repair method has to be designed in order to achieve the expected life time. For example, for coatings by calculating the effective thickness of the repair material applied.

Durability of the repair material and also of the repair structure maybe affected by different exposure classes or aggressive agents as withstands de-icing salts, CO2, chlorides and moisture, to different levels depending on its sensitivity to the local microclimate environment.

This makes necessary to consider the following properties in order to achieve the expected or prescribed durability, and in some cases protection of the structure and a good maintenance maybe needed against environmental attacks.

- Transport properties: frost resistance (de-icing salts) and chemical attack (CO2 or chlorides) resistance (carbon dioxide diffusivity, chloride diffusivity) which depend on the moisture level in the repair materials.

  To prevent moisture transport, capillary absorption should be as small as possible and water vapour permeability as large as possible so that entrapped moisture can leave the concrete.

- Crack bridging capacity is another aspect to consider in order to protect the concrete against frost and chemical attack and to provide an effective moisture control. (See section 4.3.3)

- Mechanical properties: stiffness or elasticity, ductility, wear resistance, fire resistance, thermal response (water vapour thermal), shrinkage and creep, leaching resistance etc.
Durability of the bond (adhesion strength) between repair and old concrete which is the critical component must also be taken into account. For a good adhesion, an accurate preparation and correctly preformed application is needed.

Compatibility of repair and original material will also affect the durability when different materials are used due to differences in physical, chemical and electrochemical properties. For example cracking and debonding may be expected if they are not physically compatible.

The application of some repair materials with only limited experience available require specialized workers with experience, knowledge in products, application methods and quality control tests. Good execution control is obtained by the verification of the supplied materials, concrete substrate for bonding and application process.

Durability of the repair structure may be also affected by accidental attacks (impacts, fire, vandalism…) and abrasion, being suitable properties to prescribe for this field of application abrasion resistance and impact resistance. Protection of the repair structure maybe needed against accidental attacks.

4.3.2 Deformation / Displacement

Volumetric changes (shrinkage or expansion) and also extensibility or plasticity to avoid cracking under strain could be restrained.

The use of high tensile strength materials (higher than the concrete strength) induces section stiffening and therefore a reduction in the whole deflection of the structure and redistribution in the crack pattern of the element. The first may induce a non elastic distribution of efforts and therefore of cracks induced by these efforts.

The effect on deflection can be modelled using normal codes as for a “homogeneous” section for example in case of strengthening with reinforced concrete.

4.3.3 Cracking

Cracking due to restrained volume changes (shrinkage or differential movement between the new and parent concretes) can induce corrosion since it increases the permeability of the concrete allowing penetration of aggressive agents (frost and chemical attack) and water. As commented in section 4.3.1, crack bridging capacity may have to be considering in order protecting the concrete. Normally no cracks in the new cover shall be tolerated. Temperature cycling and shrinkage can contribute to shrinkage cracking.

As commented in sections 4.3.2, the use of high tensile strength materials induces section stiffening and therefore cracks and also redistribution in the crack pattern of the element. The irregular distribution of crack spacing and width does not correspond to those prescribed in mathematical models in codes.
The effect on cracking can be modelled using normal codes as for a “homogeneous” section for example in case of strengthening with reinforced concrete. And crack movement can be checked by mechanical or electrical gauges.

4.3.4 **Drainage**

In some structures and climatic conditions, good drainage may be important in the selection of the repair option. Bad or insufficient drainage may cause moisture problems, accelerating for example ingress of chlorides.

4.3.5 **Watertightness**

It may be a key factor for dams and it could be affected in different way by each repair option depending specially on the permeability of the repair material used.

4.3.6 **Slip resistance / Roughness**

It may be important depending on the location of the structure, environment and on its function (e.g. for floors and roads) and it could be tested by visual inspection, sand test or profile meter.

4.3.7 **Visibility**

It could be an important issue to be taken into account especially during inclement weather (e.g. water spray on motorways).

4.3.8 **Flexibility**

Ensure that it is possible to meet future requirements as for example the rehabilitation method should not preclude future modification such as strengthening or additional repair methods. This compatibility will depend on the chosen products or systems.

4.3.9 **Inspectability**

It must be possible to inspect the rehabilitated structure. This check can be a visual inspection if damages results in cracking, delamination, etc and more detailed inspection using tapping, ultrasonic techniques or thermography and also in combination with load test or long test monitoring for measuring strain or deflection.

The type of inspection depends also in the repair option, for example for patching a visual examination can be enough although using tapping is also useful for checking the bond. When the failure is ductile it is easier to detect before an ultimate failure.

4.3.10 **Maintainability**

A good maintenance shall be needed against environmental attacks and may increase the durability of the repair. High environmental aggressiveness increases the need of protecting measures and a good maintenance.
4.3.11 Serviceability

Availability, functionability, comfort and convenience to users (for example, limited vibrations, no dropping water on users under a structure, etc) have to be taken into account. If, for example, a bridge has less functionality or low quality of the rehabilitated structure it can have an impact on vehicle operating costs and additional factors such as traffic safety.

Good jointing and on the detailing of edges and boundaries could be prescribed for example in case of bridges avoiding to affect traffic. A continuous barrier largely unaffected by traffic load could also be prescribed.

Some repairs can modify the design of the structure (original section of the structure) and insufficient functionality can cause loss of income.

4.4 Requirements for related to structural stability and safety

What is expected for the repaired structure is in general the same as for new structures and also in particular to the design considering Ultimate Limit States. After repair, the structural performance would be the same that was before deterioration through restoring the strength and recovering of structural continuity.

Requirements related to bearing capacity and structural considerations have to be taken into account under the temporary conditions during the repair options and for the long term in-service performance of the repaired elements. And a prescribed life time have to be defined for structural stability and safety because properties which determine those declines with time.

4.4.1 Strength

The primary structural performance requirement is to restore or enhance the original strength, stiffness, stability (and serviceability).

The reduction of strength (and stability) in case of removal of deteriorated concrete should be taken into account in the design and application of the repair option, making necessary to provide additional support if dead and live loads are needed to be removed. Propping have to be well design and executed in order to avoid overstresses after depropping. Properly installation and pre-loading if necessary has to be taken into account.

The repair has to be designed to accommodate the redistribution of loads. In case of external prestressing to be effective, new loads have to be transmitted correctly to the parent structure, so that the structural integrity of the parent element is not affected. Specialised techniques generally are carried out by experienced companies.
Compatibility of repair and original material will also affect the structural behaviour when different materials are used due to they introduce changes in the stiffness of the structure and the distribution of cracking.

The adhesion and bond characteristics (also taken into account in section 4.3.1) between repair and substrate are a crucial aspect for a structural repair and sometimes adhesion strength must be checked by measurements. A good surface preparation is crucial to ensure the adhesion and bond characteristics perform as expected.

When repair materials with more tensile resistance than concrete are used this stiffness increment shall affect two details: the minimum reinforcement for avoiding brittle fracture shall be incremented and the elastic or redistributed diagram of bending moments shall dramatically affected.

Strength (and stability) could be ensuring by additional mesh reinforcement when significant thickness of repair material is used.

In the particular case of inhibitors, as it is not possible to guarantee their performance over long periods of time, safety factors are used when determining performance levels.

For some repair materials its brittle failure mode in case of bad design maybe considered.

4.4.2 Fatigue

The effectiveness under fatigue (or dynamic) loading may be a key factor for bridges and it could be affected in different way by each repair option.

4.4.3 Fire and earthquake resistance

Additional fire protection or repair materials with fire resistance could be prescribed specially in case of tunnels or buildings. Regulations for each country prescribe fire and earthquake requirements.

Fire and earthquake damage and its evaluation and repair methods are not covered by this Manual.

4.5 Requirements related to execution of work

4.5.1 Minimisation of downtime. Rapidity.

The time required to carry out the repair will depend on the circumstances of the structure (situation or extend of damages) and weather conditions (windy weathers might demand prolonged curing periods).

It is important to minimise inconvenience or impact to users during the rehabilitation and maintenance actions. This could be achieved by maintaining the functionality of the structure during and after repair and maintenance works and also conducting quick repair
works. Rapidity need to be considered as part of economical evaluation (traffic, delays costs, lane rental const, bonuses and penalties, etc).

4.5.2 Impact on environment

Questions related to environmental impact during repair as creation of dust with references to industrial welfare codes (see also section 4.6.2), harmful effects (see also section 4.6.3) and energy consumption (see also section 4.6.4) maybe taken into account and are regulated in local environmental legislation.

In some cases selection of repair material could depend on the viewpoint of working environment. For example water solvents are preferred to organic solvents.

4.5.3 Health and safety

Questions related to health and safety for the workers and also on users and public during handling of some repair materials could be regulated in local working environment legislation. Health and safety instructions provided by the supplier of repair materials always shall be followed.

Some repair products could be harmless during execution, allergenic or toxic to inhale requiring suitable protection (protecting glasses, leather gloves and half masks). They could be also electrically conductive or extremely flammable so smoking or fire should not be allowed next to them.

Barriers, railings and prevention of pieces of concrete falling from the structure due to spalling or other deterioration on workers and users have to be considered. Evacuation and emergency escape routes may be taken into account especially in emergency repair actions. Also risks of accidents related to access tools as elevating work platforms, mobile ladders, scaffolds, etc shall fulfil the requirements of the health and safety regulations of the country.

4.5.4 Disturbance

Disturbance to functionality of the structure or the surroundings on third parties during repair, as for example disturbance of traffic (see section 4.3.11) must be minimised. The disturbance to the users is low since the means involved are limited and the repair is carried out in a short time (see section 4.5.1).

The disruption to the users of the facility is currently a very decisive factor in some repair works. Special care has to be taken close to residential areas in which the least noisy (vibrations) removal methods must be chosen. In highway and bridge works, for example, traffic delay costs are generally incorporated in the economic evaluation and are often the dominating factor.

Space required for access tools and for storage of materials has to be considered. Scaffolds must be designed in order to reduce disturbance the most, and risks of falling materials must be completely avoided. Temporary props have to be properly installed and pre-loaded as necessary and also ensuring easy access.
Cleaning and removal methods should be chosen so they generate the least dust possible as it reduces visibility.

4.5.5 Climatic conditions
Weather and moisture conditions could be a critical point for some repair materials which require specific curing temperatures making some repair options to be rejected in specific weather conditions, stopped during execution or making necessary to use additional tools or special measures.

4.5.6 Need of additional equipments
Additional equipments like forms and scaffolding needed by each repair option and in general the difficulty or simplicity of applying a technique (place ability and workability) may be important factors for decision making.

4.6 Requirements related to environmental and health
Environment and sustainability impact basically depends on repair materials used and there exist different regulations for each country.

4.6.1 Life time of the repair
Environmental impact has to be considered during all life time of the repair and not only at application and recycling, specially the effect on ecology which it is usually overlooked during service life of the repair. The total effect of a method could be more favourable with less life time although environmental impact is bigger.

The effects of recycling the repair material after the demolition of the structure have also to be considered.

4.6.2 Ecology (external environment)
Consumption of non-renewable raw materials induces deposition of materials that can not be recycled or reused, at least not immediately and therefore creation of dust. Minimisation of wastes, recycling, reuse and disposal are needed. The waste of the repair materials can be highly toxic and need a special treatment. The waste of the removed slurry for some removal techniques as water jetting can be difficult to take care of and also need a special treatment. Usually the removed concrete and reinforcements can be considered as conventional rubble.

Related to emissions to air (CO$_2$, CO, SO$_2$, NO$_x$, dust), soil and water and effect on ground after repair different local regulations in each country classify different substances as ecological dangerous, depending for example on toxicity to water organisms. In many cases leakage of small amounts are not dangerous to the environment but it should be collected and handled as waste according to local instructions.
4.6.3 *Indoor environment*

Harmful effects such as spillage, leakage, dust or the emission of toxic fumes, either spontaneously or due to situations such as fire both afterwards rehabilitation works are taken into account. A material without emissions of any harmful or irritating substances into the indoor atmosphere should be used.

Also noise control and vibrations during all service life of rehabilitation are considered.

4.6.4 *Energy consumption*

Reduce the energy consumption for all service life of the rehabilitated structure (e.g. in case of cathodic protection) may be prescribed.

4.6.5 *Health and safety*

Health and safety regulations are becoming progressively more stringent. When planning safety measures, techniques for the recognition of possible hazards are very helpful and can fall within strategies for *Reducing* the cause of the risk, *Avoiding* the risk by changing the concept or the objectives, *Controlling* the risks by using suitable alarm systems, vigilance, inspections, etc or *Overcoming* the risks by providing an adequate capacity.

Repair materials should comply with all health and safety legislation for all service life of the repair. For considerations in health and safety during execution see section 4.5.3.

4.7 *Requirements related to economy*

Reduce or limit whole life costs related to owner cost and users cost for the rehabilitated structure

4.7.1 *Operational costs*

Reduction/increase of income of assets for example due to insufficient functionality, disruption costs (see also section 4.5.4).

Reduction/increase of market shares, good will, effects on the environment, costs returns to the users and third parties, changes on the increased insurance value are taken into account.

4.7.2 *Preparation, repair and maintenance costs*

The cost depends on the circumstances of the structure, means involved getting access to the damages (easiness to get access, distance between damages…), the repair material used and its amount and durability, time required to carry out the repair (curing periods may depend on the weather…) and the periodical maintenance needed after repairing. An accurate preparation of the substrate and correctly performed application is needed to achieve the expected durability of the repaired structure.
It has to be taken into account that although some repair materials or methods are more expensive, they can be easier to apply and need no curing decreasing time to carry out the repair.

Total cost will include material, labour work, access tools (scaffolding…), preparation of substrate and maintenance. Sometimes protecting the repairs are recommended and also renewing it every certain years.

Restrictions on the application of products due to weather conditions shall stop completely or special measures shall be taken in order to allow its use, therefore raising the cost of the repair.

Low initial costs coupled with frequent future intervention may be economically the better option in some circumstances, but may introduce risks to third parties, and hence potentially could impose additional liability on the owner or operator of the asset.

4.7.3 Demolition and deposition costs

Consumption of non-renewable raw materials induces deposition of materials that can not be recycled or reused, at least not immediately and creation of dust (see also section 4.6.2).

4.7.4 Failure costs

Costs of collapse or unsuccessful repair costs may be a key factor and it could be affected in different way by each repair option.

4.8 Requirements related to other non-technical issues (NTI)

4.8.1 Requirements related to social aspects

Aesthetics / Appearance

Today aesthetics often play a very important role not only in the choice of repair method but also on the decision as when to repair. The degree to which aesthetics may affect decision making depends to a great extent on the type of structure, the circumstances and the people involved.

For example, the upgrading of the appearance of a car park can be of great importance to the surrounding neighbourhood and to the attractiveness and prosperity of the businesses affected. Such actions have been used to act as a catalyst for improvements to the vitality of the whole surrounding area.

The aesthetic of the repair depends mainly on the execution and the materials that have been used. The rehabilitated part of the structure shall look the same and have the colour and texture as close as possible to the rest of the structure. It also must look safe to satisfy users. If the repair has been carried out carefully and the colour and texture of the repair materials are similar to the concrete, it will be difficult to detect the repaired areas,
especially as time goes by, even if the structure is not painted afterwards. If the entirely exposed surfaces are done at the same time a non-uniform appearance will be avoid.

The *durability* of the aesthetics of the rehabilitated part of the structure shall be as long as the durability of the rehabilitation action, or as long as the rest of the structure if this period is shorter. Aggressive agents as UV radiation, ozone or acid rain may affect durability of aesthetics.

If a protection method is applied after repair, it must be consider how it affects the appearance and its durability considering the environmental factors that will affect the protective system.

**Social perception (public confidence)**

The repair of structures carried out as part of a regional regeneration scheme can have great impact upon the social perceptions of the area. It can be in the owners’ interest to enhance positive social perceptions for example by undertaking cosmetic repair or upgrading within the area. Because society is investing in the neighbourhood, in the long run these actions can have a positive influence upon the level of inhabitation in dwellings blocks or other types of buildings or in the overall attractiveness of the neighbourhood.

Social alarm can detract from, or even negate, the potential benefits of rehabilitation schemes, particularly when they are carried out in conjunction with regional regeneration. Income from loss of usage will have a direct impact on the value of repair work.

The public can be alarmed by inappropriate or badly implemented repair work, or by their perception of the safety of a structure. Care needs to be exercised when proposing the use materials or new innovative methods with unknown (at the time of selection) long-term behaviour. Previous problems, for example with high alumina cement, have caused a certain degree of social alarm and blight of property when the difficulties and problems have become general knowledge. In such circumstances it is very important that appropriate investigations are made of the affected structures and that there is provision of relevant information to owners and the public.

Related to the reliability of the repair methods it is important to reduce the risk if an unsuccessful rehabilitation method.

**Insurance and future liabilities**

Insurance of assets during the progress of the repair or rehabilitation works can influence the contractor’s decision on how he plans to carry out the works. A potential quandary might arise from whether the contractor should use a robust and a reliable repair method proven through many years of years of experience or should he instead use a new cheaper alternative, but with which there is less experience.

When a repair option is well know its reliability is high if execution is correct.

**Strength of local economy**
The method of procurement and type of works undertaken can increase the skill base and technical capabilities of the company and therefore have an effect upon its competitiveness in the marketplace. Competitive advantage does have economic consequences, although precise quantification of these may not be possible. These factors may have an effect upon the strength of the local economy and the wealth of the local area.

**Improvement of asset values**

Maintaining or improving the value of the asset in question can be a key factor in a decision to intervene made on a commercial basis. Factors which affect this value will not solely be technical ones such as the presence of cracking, but also by the perceptions held by users of the asset and perhaps more widely by the general public. Such perceptions may be very powerful. Even if an asset retains its structural integrity and its functional ability, but looks shabby or dilapidated, it may well be considered to be in an unsatisfactory condition by users and the public.

The overall economic benefits or disbenefits to society can also play an important role in the decision-making process. For example, the upgrading of rural infrastructure can be used to encourage investment and promote regional economic development. This can also have major political impact. If these processes are applied in areas of low economic activity, the beneficial effect can be dramatic.

**Cultural Heritage**

Structures having cultural or historic value require special treatment.

4.8.2 Requirements related to political aspects

**Media and press**

Media interest in a construction or repair project can have an important role, especially where decisions are being made principally on the basis of political influence. This can be used to raise public awareness, encourage participation and consultation, etc.

**Government policies and initiatives**

Considerable influence is exerted by local and national government targets for social or regional development, reduction of road casualties, sustainability, reduction in construction waste, etc. There may be political priorities which have great importance especially on the decision when and how to repair, potentially over-riding some of the technical requirements.

In some situations, such as work on a very major development or nationally important asset, for labour union aspects to be considered in the planning process and in the decision on the repair method and material to be used.
4.8.3 Requirements related to legal aspects

Legal implications and responsibilities can also influence the decisions to be made, especially on when to repair or to upgrade infrastructure assets such as bridges for example. The owner and others involved with the maintenance or repair of a structure typically have a duty of care to the users of the facility and possibly also more widely to the public. This is not only for what may be done, but also for what might not have been done. Consider the situation where cracked or spalled concrete has not been removed from a structure and there is a risk of falling debris causing injury or worse to the public or users. In these circumstances not removing the hazard, an act of omission, could be a failure to discharge the duty of care.

Legal implications to be considered, such as those arising from planning laws, consultation requirements, environmental impact legislation, access for utilities, health and safety regulations etc.
5 REPAIR TECHNIQUES

Once the assessment of a damaged structure has been completed and the decision of repair has been taken, the most appropriate repair technique or combination of techniques has to be selected between those options that can be used.

Chapter 5.1 summarise and discuss principles and methods for repair included in EN1504-9. Principals for repair are used in EN1504 as basic objectives (protection, restoration, strengthening, etc…) which repair methods have to fulfil. It is the way in which repair methods are classified in EN1504. Some examples of methods based on each principle are given. Different parts of EN1504 and other European Standards are listed in Annex C.

Chapter 5.2 gives the possible options between the existing repair techniques for the most frequent cause and type of damage. Table in Chapter 5.2 is described in more detail and used as a base for a qualitative evaluation of the repair options in chapter 6.1 (and Annex M). In chapter 6 repair methods as combinations of the different repair techniques included in this one will be described.

Finally Chapter 5.3 includes short descriptions of these repair techniques making references to a more detailed description in Annexes.

5.1 Repair principles and repair methods according to EN1504-9

In a European context, the principles for repair and repair methods are emerging from CEN Standards, especially the ten parts of EN1504 and its supporting Standards on product specifications and test methods. (A list of relevant standards in existence or are being developed is given in Annex C). Guidance in this Manual derives from these Standards, for practical reasons, since much work has already been done. One of the approaches via EN1504 is to identify repair options which are defined by cause and type of damage in Chapter 5.2. Another approach is to establish performance requirements for each repair technique (see Annexes from D to L) and to check that these are met, by use of recommended test methods.

Table 5.1 lists the eleven principles contained in EN1504-9. The principles are expressed in terms of basic objectives (protection, restoration, strengthening, etc). The methods for each objective can vary considerably, in terms of:-

(i) action/function in meeting the objective (eg compare 1.2 and 1.4; 4.1 with 4.3 or 4.4; etc)
(ii) method of application (eg compare 3.1, 3.2 and 3.3)
(iii) dependency on a product and workmanship, compared with a self-contained process (compare 7.1 or 7.2 with 7.3 or 7.4).
On the other hand, some of the methods appear against more than one principle (eg 1.2, 2.2 and 8.1, for surface coatings), possibly requiring different formulations to meet the different objectives.

For these reasons, it is necessary to re-order the various methodologies to reflect better the physical or chemical actions involved. Further, Table 5.1 has a strong emphasis on repair and remedial work where the principal deterioration mechanism is corrosion; other forms of deterioration (eg ASR, frost action, or others which directly attack the concrete) may require a more limited set of repair options, which can be fitted into a re-ordering of Table 5.1.

Table 5.2 presents the outcome of this re-ordering. In general, the five categories in the Table are presented in order of decreasing direct structural intervention, with category 1 being the most significant and category 5 the least.

The timing for introducing a chosen repair or remedial measure will depend on the owner’s strategy and on the criteria selected for decision-making. For example, with corrosion, the owner may wish to intervene at any of the following stages of deterioration:

(i) before carbonation or chloride fronts have reached the reinforcement;
(ii) when the fronts have just reached the reinforcement;
(iii) when corrosion has just started;
(iv) when corrosion has reached a certain maximum depth;
(v) when cracking or spalling of the concrete cover is about to occur;
(vi) when a maximum allowable loss of rebar section has occurred.

The selection of an option from Table 5.2 will plainly depend on the nature and extent of the observed damage. It will also depend on the extent of the inspection and investigation (associated with confidence levels) and on the sensitivity of the structure – as well as on the owner’s future plans for that structure. For corrosion, categories 3-5 in Table 5.2 are possibly most relevant for stages (i)-(iii) above, with categories 1 and 2 coming into play for stages (iv)-(vi). Whatever remedial technique is selected, the timing of the intervention will influence both the specification and the performance requirements for that technique.

In order to help the identification of repair options in the repair process, Table 5.3 has been developed defining the suitable repair options by cause and type of damage.
<table>
<thead>
<tr>
<th>Table 5.1 EN1504-9 Principles and methods for repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Protection against ingress of adverse agents (PI)</td>
</tr>
<tr>
<td>1.1 impregnation</td>
</tr>
<tr>
<td>1.2 surface coating with and without crack bridging ability</td>
</tr>
<tr>
<td>1.3 locally bandaged cracks</td>
</tr>
<tr>
<td>1.4 filling cracks</td>
</tr>
<tr>
<td>1.5 transferring cracks into joints</td>
</tr>
<tr>
<td>1.6 erecting external panels</td>
</tr>
<tr>
<td>1.7 applying membranes</td>
</tr>
<tr>
<td>2. Moisture control (MC)</td>
</tr>
<tr>
<td>2.1 hydrophobic impregnation</td>
</tr>
<tr>
<td>2.2 surface coatings</td>
</tr>
<tr>
<td>2.3 sheltering or overcladding</td>
</tr>
<tr>
<td>2.4 electrochemical treatment</td>
</tr>
<tr>
<td>3. Concrete restoration (CR)</td>
</tr>
<tr>
<td>3.1 applying mortar by hand</td>
</tr>
<tr>
<td>3.2 recasting with concrete</td>
</tr>
<tr>
<td>3.3 spraying concrete or mortar</td>
</tr>
<tr>
<td>3.4 replacing elements</td>
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<tr>
<td>4. Structural strengthening (SS)</td>
</tr>
<tr>
<td>4.1 adding or replacing embedded or external reinforcing steel bars</td>
</tr>
<tr>
<td>4.2 installing bonded rebars in preformed or drilled holes in the concrete</td>
</tr>
<tr>
<td>4.3 plate bonding</td>
</tr>
<tr>
<td>4.4 adding mortar or concrete</td>
</tr>
<tr>
<td>4.5 injecting cracks, voids or interstices</td>
</tr>
<tr>
<td>4.6 filling cracks, voids or interstices</td>
</tr>
<tr>
<td>4.7 prestressing - (post tensioning)</td>
</tr>
<tr>
<td>5. Physical resistance (PR)</td>
</tr>
<tr>
<td>5.1 overlays or coatings</td>
</tr>
<tr>
<td>5.2 impregnation</td>
</tr>
<tr>
<td>6. Resistance to chemicals (RC)</td>
</tr>
<tr>
<td>6.1 overlays or coatings</td>
</tr>
<tr>
<td>6.2 impregnation</td>
</tr>
<tr>
<td>7. Preserving or restoring passivity (RP)</td>
</tr>
<tr>
<td>7.1 increasing cover to reinforcement with additional cementitious mortar or concrete</td>
</tr>
<tr>
<td>7.2 replacing contaminated or carbonated concrete</td>
</tr>
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<td>7.3 electrochemical realkalisation of carbonated concrete</td>
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<tr>
<td>7.4 realkalisation of carbonated concrete by diffusion</td>
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<tr>
<td>7.5 electrochemical chloride extraction</td>
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<tr>
<td>8. Increasing resistivity (IR)</td>
</tr>
<tr>
<td>8.1 limiting moisture content by surface treatments, coatings or sheltering</td>
</tr>
<tr>
<td>9. Cathodic control (CC)</td>
</tr>
<tr>
<td>9.1 limiting oxygen content (at the cathode) by saturation or surface coating *</td>
</tr>
<tr>
<td>10. Cathodic protection (CP)</td>
</tr>
<tr>
<td>10.1 applying electrical potential</td>
</tr>
<tr>
<td>11. Control of anodic areas (CA)</td>
</tr>
<tr>
<td>11.1 painting reinforcement with coatings containing active pigments</td>
</tr>
<tr>
<td>11.2 painting reinforcement with barrier coatings</td>
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<tr>
<td>11.3 applying inhibitors to the concrete</td>
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</tbody>
</table>

(*) It is not covered within this Manual
### Table 5.2 Re-classification of repair and remedial methods, according to physical function or method of action

<table>
<thead>
<tr>
<th>Option</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. External strengthening or barriers</strong></td>
<td>(a) is used, when deterioration is extensive, and disruption to operations is minimal. (b) and (c) are used where additional strength is required. Calculations will be required. For (b), bond and adhesion are important, and it is necessary to demonstrate composite action, while ensuring compatibility of materials. (d) may also be used when additional strength is required, or to provide extra protection against the risk of corrosion. Method of installation is important in ensuring good bond and an effective dense concrete.</td>
</tr>
<tr>
<td>(a) replacing complete elements</td>
<td></td>
</tr>
<tr>
<td>(b) plate bonding</td>
<td></td>
</tr>
<tr>
<td>(c) external prestressing</td>
<td></td>
</tr>
<tr>
<td>(d) provision of additional concrete cover (with or without additional rebars)</td>
<td></td>
</tr>
<tr>
<td>(e) waterproof membranes or sheets *</td>
<td>(e) is common practice for bridge decks and specifications do exist. Enclosures have also been used for bridges, to control local micro-climates. Generally physical barriers may be either separate or bonded to the parent structure; examples are cladding to bridge sub-structures.</td>
</tr>
<tr>
<td>(f) enclosures or physical barriers</td>
<td></td>
</tr>
<tr>
<td><strong>2. Structural repairs</strong></td>
<td>Variations of these methods are aimed at restoring or increasing strength, within the perimeter of the existing structural elements. (a) may be used when the damage has been caused by chemical or physical actions, such as ASR, frost action or abrasion. (b) and (c) relate to corrosion damage. These are structural repairs, and the temporary conditions during repair operations require structural consideration, with adequate propping being provided where necessary. The materials used and their formulations, may depend on the size of the areas to be replaced. Many proprietary systems are on the market, and it is important to ensure compatibility with the parent concrete, as well as full composite action. Pre-preparation is crucial, to ensure bond both with the substrate and the rebars, and good workmanship is paramount, for all the application methods which may be used.</td>
</tr>
<tr>
<td>(a) cutting out contaminated, cracked or defective concrete and replacing it</td>
<td></td>
</tr>
<tr>
<td>(b) cutting out and replacing corroded reinforcement</td>
<td></td>
</tr>
<tr>
<td>(c) cutting out concrete, adding protection to the reinforcement and replacing the concrete</td>
<td></td>
</tr>
<tr>
<td><strong>3. Surface coatings and impregnations</strong></td>
<td>Essentially, the objective here is to prevent the ingress of adverse agents, or to control moisture (but see the different principles in Table 4.3). There are numerous proprietary systems on the market, with a range of formulations. It is important to understand the nature of each, exactly how it operates and what is necessary for effective installation. The likely life of each should be established within reasonable bounds, for the particular location and environment. Surface treatment may involve making good minor defects, followed by a coating. Surface coatings, to be effective, require a smooth surface and to have the ability to accommodate movement (including cracks) without fracture to the protective film or barrier. Impregnations, by definition, must be able to penetrate the concrete to a minimum specified depth, commensurate with their effectiveness.</td>
</tr>
<tr>
<td>Surface treatments</td>
<td></td>
</tr>
<tr>
<td>Coatings</td>
<td></td>
</tr>
<tr>
<td>Impregnations</td>
<td></td>
</tr>
</tbody>
</table>
4. **Filling cracks and voids**

The materials or techniques used depend on the size of the voids or the width of the cracks. Surface voids or defects can be treated as patch repairs. For the effective filling of cracks, injection is often used. Again, there are many systems on the market and choice is important, while ensuring that the materials used comply with relevant product standards. This technique is often complemented by a surface coating or treatment.

5. **Electro-chemical techniques**

(Principles 7, 9, 10 and 11 in Table 4.3)

(a) re-alkalisation
(b) chloride extraction
(c) cathodic protection
(d) cathode or anode control *

These techniques are all grouped together because they are effectively self-contained processes, which require Performance Standards - unlike categories 2-4 above, which relate more to product Standards, supported by acceptable test methods and backed by specifications for installation and workmanship. All have been used with some success, with cathodic protection perhaps the most common and already having its own specification/standard.

(*) It is not covered within this Manual
5.2 Repair options for different types of damages

The suitable repair option depends on the cause, type and location of damages. Table 5.3 summarizes the different repair techniques as possible options for every cause and type of damage. In the left-hand side of the table some damages causes and types are shown and in the right-hand side the possible repair options for each damage are included. Damages are divided in 10 damage classes.

I. Reinforcement corrosion
II. Erosive surface attack
III. Internal expansive attack
IV. Expansive surface attack
V. Loss of lime

VI. Damage caused by moisture movement and thermal movement
VII. Overload. Accidental load
VIII. Damage cause by structural load
IX. Damage in structures with aluminous cement
X. Aesthetic damage

An overview of all the possible cause and type of damages are shown in Table 5.3 but only reinforcement corrosion, ASR, frost and leaching are deeply covered within the scope of this Manual.

Some of the repair options in Table 5.3 can be applied alone while others need to be used in combination in order to provide an effective solution. They can be used to protect the structure from future damage by considering the prevailing system of deterioration.

Repair techniques included as options in Table 5.3 are shortly described in chapter 5.3 and in more detail in Annexes.

1. Concrete recasting
   (See chapter 5.3.6 and Annex I Strengthening with reinforced concrete)

2. Concrete polymer recasting
   (See chapter 5.3.6 and Annex I Strengthening with reinforced concrete)

3. Local patch repair
   (See chapter 5.3.5 and Annex H Patching)

4. Additional cement based cover
   (See chapter 5.3.5 Annex H Patching)

5. Surface treatment
   (See chapter 5.3.3 and Annex F Surface treatments)

6. Crack injection
   (See chapter 5.3.4 and Annex G Injection and sealing of cracks)

7. Strengthening using external post-tensioning

 Covered in the Manual

Not covered in the Manual
(See chapter 5.3.9 and Annex L)

8.- Strengthening with carbon fibre
(See chapter 5.3.7. and Annex J)

9.- Strengthening using externally bonded steel plates
(See chapter 5.3.8 and Annex K)

10.- Cathodic protection
(See chapter 5.3.1 and Annex D Electrochemical techniques)

11.- Chloride extraction
(See chapter 5.3.1 and Annex D Electrochemical techniques)

12.- Realkalisation
(See chapter 5.3.1 and Annex D Electrochemical techniques)

13.- Demolishing/replacement

Table 5.3 is described in more detail, introducing repair principals to achieve as in EN1504 for each cause and type of damage, in the qualitative evaluation of Chapter 6.1 and Annex M.
Table 5.3  Repair options for different types of damage (more detailed in Annex M)

<table>
<thead>
<tr>
<th>CAUSE OF DAMAGE</th>
<th>TYPE OF DAMAGE</th>
<th>REPAIR OPTIONS</th>
</tr>
</thead>
</table>
| Chloride induced corrosion             | Corroded reinforcement                              | 1: “Concrete recasting”  
2: “Polymer concrete recasting”  
3: “Local patch repair”  
4: “Additional cement based cover”  
5: “Surface treatment”  
6: “Crack injection”  
10: “Cathodic protection”  
11: “Chloride extraction”  
13: “Demolishing/replacement” |
|                                        | Corrosion not yet started. Threshold concentration almost reached the bar |                                                            |
|                                        | Spalling of cover with or without cracking           |                                                            |
| Carbonation induced corrosion          | Corroded reinforcement                              | 1: “Concrete recasting”  
2: “Polymer concrete recasting”  
3: “Local patch repair”  
4: “Additional cement based cover”  
5: “Surface treatment”  
6: “Crack injection”  
10: “Cathodic protection”  
11: “Chloride extraction” |
|                                        | Corrosion not yet started. Carbonation front almost reached the bar |                                                            |
|                                        | Spalling of cover with or without cracking           |                                                            |
| Salt frost attack                      | Surface scaling                                      | 1: “Concrete recasting”  
2: “Polymer concrete recasting”  
3: “Local patch repair”  
4: “Additional cement based cover”  
5: “Surface treatment”  |
| Mechanical wear by water, cavitation or other means | Evenly eroded surface  
Local erosion, cavitations  
Dissolved surface with or without mechanical erosion | 5: “Surface treatment”  |
| Acid attack                            | Internal expansion                                   | 5: “Surface treatment”  
8: “Strengthening with carbon fibre”  
9: “Strengthening with externally bonded steel plates”  
13: “Demolishing/replacement” |
| ASR                                   | Internal frost attack caused by freezing of cement paste | 8: “Strengthening with carbon fibre”  
9: “Strengthening with externally bonded steel plates”  
13: “Demolishing/replacement” |
| Internal frost attack caused by freezing of unsound aggregate | Internal expansion  
Loss of strength and cohesion  
Insufficient structural stability | 5: “Surface treatment”  
8: “Strengthening with carbon fibre”  
9: “Strengthening with externally bonded steel plates”  
13: “Demolishing/replacement” |
| Sulfate attack                         | Dissolution of surface                              | 1: “Concrete recasting”  
2: “Polymer concrete recasting”  
4: “Additional cement based cover”  
5: “Surface treatment”  
6: “Crack injection”  |
| Delayed ettringite formation           | Dissolution in cracks. Decreased watertightness      | 5: “Surface treatment”  
6: “Crack injection” |
| Alkali-dolomite reaction               | Moisture swelling of coarse aggregate                | 5: “Surface treatment”  |
| ASR                                   | “Pop-out” craters in surface                        | 1: “Concrete recasting”  
2: “Polymer concrete recasting”  
4: “Additional cement based cover”  
5: “Surface treatment”  
6: “Crack injection”  |
| Sea water attack                       | Cracking and weakening of surface                    | 2: “Polymer concrete recasting”  
4: “Additional cement based cover”  
5: “Surface treatment”  |
| Leaching                               | Dissolution of surface                              | 2: “Polymer concrete recasting”  
4: “Additional cement based cover”  
5: “Surface treatment”  
6: “Crack injection”  |
| Drying and autogeneous shrinkage       | Dissolution of interior. Strength loss               | 2: “Polymer concrete recasting”  
4: “Additional cement based cover”  
5: “Surface treatment”  
6: “Crack injection”  |
| Thermal shrinkage                      | Through cracking                                     | 2: “Polymer concrete recasting”  
4: “Additional cement based cover”  
5: “Surface treatment”  
6: “Crack injection”  |
| Surface cracking                       | Surface cracking                                     | 5: “Surface treatment”  
6: “Crack injection” |
| Surface impact                         | Loss of cover. Exposed reinforced                    | 1: “Concrete recasting”  
3: “Local patch repair”  
5: “Surface treatment”  
6: “Crack injection”  |
| Overload during building phase         | Loss of cross section                                | 5: “Surface treatment”  |
| Bending fracture                       | Crushing of concrete                                 | 1: “Concrete recasting”  
3: “Local patch repair”  
4: “Additional cement based cover”  
5: “Surface treatment”  
8: “Strengthening with carbon fibre”  
9: “Strengthening with externally bonded steel plates” |
| Anchorage fracture                     | Cracking                                             | 3: “Local patch repair”  
4: “Additional cement based cover”  
5: “Surface treatment”  
8: “Strengthening with carbon fibre”  
9: “Strengthening with externally bonded steel plates” |
| Shear fracture                         | Yield in reinforcement                               | 5: “Surface treatment”  
8: “Strengthening with carbon fibre”  
9: “Strengthening with externally bonded steel plates” |
| Fatigue fracture                       | Fracture in concrete, bond or reinforcement          | 5: “Surface treatment”  
8: “Strengthening with carbon fibre”  
9: “Strengthening with externally bonded steel plates” |
| Compressive fracture                   |                                                      | 5: “Surface treatment”  |
| Conversion of hydration products to products with low strength | Loss of cohesion, strength and stiffness | -- |
| Efflorescence                          | Discoloration                                        | 5: “Surface treatment”  |
| Aesthetic                              |                                                      | 5: “Surface treatment”  |
5.3 Short description of repair techniques

5.3.1 Electrochemical techniques

The electrochemical techniques (see also Annex D) used for stopping corrosion in concrete structures are:

- Cathodic Protection (CP)
- Chloride Extraction (CE)
- Realkalisation (RE)

All electrochemical maintenance methods have principles and practical details in common. The main differences are the amount of current flowing through the concrete and the duration of the treatment as given in Table 5.4. The general set-up that is valid for all electrochemical methods is that by means of an external conductor, called the anode $\Theta$, a direct current is flowing through the concrete to the reinforcement which thereby is made to act as the cathode $\Theta$ in an electrochemical cell. The final result of the current flow is to mitigate or stop the corrosion by repassivation of the rebars due to polarisation of the reinforcement to a more negative potential, or by removing the aggressive ions (chloride) from the pores of the concrete or by reinstating the alkalinity of the pore solution.

As far as the principles and the effects on the reinforcement and the concrete are common for the three electrochemical repair techniques, various details and aspects on which they differ are presented Annex C.

Table 5.4 Main differences between electrochemical maintenance methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Duration</th>
<th>Typical Current Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathodic Protection</td>
<td>Permanent</td>
<td>$10 \text{ mA/m}^2$</td>
</tr>
<tr>
<td>Realkalisation</td>
<td>Days to Weeks</td>
<td>$1 \text{ A/m}^2$</td>
</tr>
<tr>
<td>Chloride Removal</td>
<td>Weeks to Months</td>
<td>$1 \text{ A/m}^2$</td>
</tr>
</tbody>
</table>

Following some of the advantages of these three electrochemical techniques are listed:

**Cathodic protection:**

- Stops corrosion
- Increases the alkalinity on the reinforcement surface
- Increases in the $\text{OH}^-/\text{Cl}^-$ ratio favour passivation phenomena

**Chloride extraction:**

- Chloride content of the concrete is reduced
- Electrolytic production of hydroxyl ions at the reinforcing steel surface
- Treatment: 6 to 10 weeks. Therefore, when the process is terminated and the installation is removed
Realkalisation:

- Can be effective in stopping corrosion of reinforcement in carbonated concrete
- Carbonated concrete can be left in place; there is no need to break out and replace it
- 
- 

Following some of the disadvantages of these three electrochemical techniques are listed:

- Increases the alkalinity around the reinforcement can cause damage if the concrete contains alkali-reactive aggregates.
- Bond loss between concrete and reinforcements at very negative potentials.
- Embrittlement of steel by atomic hydrogen generated as cathodic reaction (in cathodic protection).

Cathodic protection and chloride extraction are particularly suited when corrosion is caused by the chloride contamination (by environmental contamination or because of the introduction of chloride during the casting. Otherwise, Realkalisation stops reinforcement corrosion induced by carbonation.

5.3.2 Corrosion inhibitors

Reinforcement corrosion inhibitors (see also Annex E) can be employed in reinforced concrete structures to prevent reinforcement corrosion. It falls within one of the five “Principles” which are the basis of “Methods” known to control reinforcement corrosion (Method 11.3) in EN 1504: Part 9 - “General principles for the use of products and systems” (see Table 5.1).

There are two generic types of inhibitors:

- cast-in (admixture) inhibitors used for new build structures as a preventative measure
- surface-applied (retro-applied) inhibitors used predominately for existing structures as a curative or preventative measure

Admixture (cast-in) inhibitors

Admixed inhibitors can be used to help retard the onset of corrosion. They are generally added to the concrete mix in sufficient, but preferably small, concentrations prior to casting. They have been shown not to significantly affect the physical properties of the concrete (e.g. compressive strength, setting time and microstructure). Admixed inhibitors have also been used in conjunction with concrete repair materials and applied to existing structures as part of a rehabilitation strategy. However, there is some uncertainty about how effective admixed inhibitors are in providing protection against the formation of incipient anodes.
**Surface Applied (retro-applied) Inhibitors**

Surface applied inhibitors are predominantly used as a rehabilitation or curative measure for reinforcement corrosion in existing structures. However, it is increasingly used also as a proactive corrosion intervention measure to delay the onset of corrosion.

These inhibitors are either applied directly to the surface of existing concrete structures or are placed in drilled holes within the parent concrete at discrete locations. They are designed to penetrate the concrete matrix and suppress or control the corrosion rate of the embedded steel reinforcement. The various mechanisms by which the inhibitors ingress the concrete matrix are still not entirely understood, and so is the exact concentration of inhibitor required at the steel/electrolyte interface in order to suppress corrosion.

**5.3.3 Surface treatments**

The reason to use protective surface treatment (see also Annex F) is to maintain old structures and protect them against different deterioration processes or reduce the deterioration rate. Surface treatments can increase the length of the initiation period preceding the degradation by limiting transport of water, chloride, sulphate, acids or some other aggressive compound. This preventive effect is of course more pronounced if the surface treatment is applied at the start of the initiation period. When the aggressive compound has nearly reached a “critical value” it might be too late to take action. On concrete structures where degradation has started the deterioration rate might be reduced, and then consequently the service life can be extended, by the use of surface treatments.

Surface protective treatments can be classified in several different ways. They can e.g. be classified according to the main generic component, function, cure requirement, or by specific properties such as degree of penetration and the thickness of the surface film. European standard prEN 1504-2 (see Annex C) uses a classification system that divides surface treatments in “Hydrophobic impregnation”, “Impregnation” and “Coating”. Hydrophobic impregnation produces a water-repellent surface; impregnation produces a discontinuous thin film (usually 10 – 100 µm) that partly fills the capillaries and coatings produce a continuous layer (typical thickness 0.1 – 5.0 mm) on the surface of the concrete.

**Service life**

Adhesion to substrate is essential. For coatings the crack bridging capacity must be considered on cracked substrate. The product must be durable in its environment and withstand UV-radiation, moisture, alkali, ozone, etc. Temperature cycling and shrinkage can give internal stresses in coatings that might cause cracks and blisters and contribute to degradation. Experience shows that dense thin coatings can cause frost damage.

**Corrosion:** Diffusion of carbon dioxide or chloride through the surface treatment shall be low enough (test required). Moisture control might be a possible way to reduce the corrosion rate. **ASR:** Moisture control might be a possible way to reduce ASR. Risk that the decrease of moisture content will be insufficient.

**Execution**
Requires a clean substrate without contaminations. For coatings the preparation should aim at obtaining an even surface. Errors in the preparation might lead to insufficient adhesion. Penetration of a hydrophobic agent is strongly effected by the exposure time and the moisture conditions in the concrete cover. For coatings the total thickness shall meet the specified maximum and minimum thickness since many properties depend on the thickness. Application procedure shall follow the recommendations given by the supplier. Surface treatments are sensitive to the quality of preparation and to variations in standards of workmanship during installation.

**Environment and health**

The effect on ecology, indoor environment and health and safety during the entire lifetime of the surface treatment should be considered. The effect depends on type of surface treatment used. *Ecology:* The effect on different ecology parameters (energy, emissions etc.) is evaluated for all life cycle phases of the repair. *Health and Safety:* Handling of products is regulated in the EC legislation. Relevant information is found in the Safety Data Sheet. *Indoor environment:* To be considered only at indoor repair activity. Parameters like self-emissions, sound etc. are evaluated.

### 5.3.4 Injection and sealing of cracks

Cracks are normal in reinforced concrete structures. However, they can have a negative influence on the durability and integrity of the structure and in many cases action has to be taken. Before taking any action however, it is important to determine whether injection/sealing is an appropriate remedial measure. The cause of the cracking must be identified, as treatment methods will vary depending on whether the cracks are dormant or live. The moisture conditions within the concrete must be known. In some cases, injection or sealing of cracks is not appropriate. Injection should not be used where the reinforcement is corroding or where the cracks are caused by corrosion. Injection is not an effective method for treating ASR affected structures. In such cases, other rehabilitation techniques are more appropriate, for example, removal and replacement of contaminated concrete.

Crack injection, although often used in conjunction with strengthening, is not a strengthening method in itself. It is used to repair cracks in reinforced concrete components to avoid progressive damage, maintain integrity of the concrete and improve durability. While crack injection improves the tensile capacity of the concrete locally, the overall stiffness of an injected beam is only marginally modified, as new cracks can develop in the unrepaired concrete.

There are two main methods to treat cracks:

- Injection: an internal treatment used to fill most of the cracks and voids and thus seal the cracks; and
- Surface sealing: an external used to protect the concrete or the reinforcement from ingress of aggressive materials. Sealing can be divided into two groups:
  - Membranes applied either as liquids or preformed (bonded or unbonded) sheets; and
  - A suitable sized groove is made and filled with an appropriate sealant.
Injection is usually made with hydraulic binders, polymer binders or gels injected through holes drilled into the cracks. It can be carried out through a half pipe attached to the concrete surface along cracks.

Surface sealing with grooves is usually used for live cracks. The width of the groove is dimensioned in such a way that the total movement will not exceed about 25% of the width. The depth of the groove is dependant on the sealant, which can be some type of mastics, thermoplastics or elastomers.

Membranes can be used to seal just the cracks or the whole surface. At live cracks an area along the crack is usually unbonded.

If surface sealing is not made on the most humid side of the structure there is a risk for increased humidity behind the sealing, which can lead to frost damage.

5.3.5 Patching

Patching (see also Annex H) is a repair technique for concrete structures which consists of replacing the lost, unsound or contaminated concrete with a material that can be new concrete, a repair mortar, a grout, etc. The objective of patching is to restore the esthetical and geometric properties of the structure in order to maintain its structural safety and increase its durability.

If it is a reinforced concrete structure and the reinforcement is corroded, or it is likely that they will be as a result of a thin, non-existing or contaminated cover, the procedure of patching also includes cleaning the rust from the reinforcement and protecting it from further corrosion before the concrete cover is restored.

Patching consists in the following stages:

- Identification of unsound/contaminated concrete
- Removal of unsound concrete
- Cleaning of concrete substrate and reinforcements
- Application of the repair material
- Surface treatment of the concrete substrate in order to increase bond strength

Patching is a very cost effective repair method, fast and very effective if it is well executed. On the other side, if execution is not right, patch repairs will be of no use for the structure. It is essential for the sake of the repair that the surface of the concrete substrate is completely cleaned, it is treated to improve bond strength, and the repair material is compatible with the old concrete.

Patching is an effective method for repair of local areas where there is no necessity to increase the strength of the structure. Patching is usually carried out to repair damage which does not compromise the structural strength. If the deterioration has affected strength, there are other methods which may be more suitable for the repair. Patching is also used to repair damages that may affect the appearance of the structure.
5.3.6 **Strengthening with reinforced concrete**

Strengthening with reinforced concrete (see also Annex I) can be used on structures affected by corrosion, salt-frost attack, mechanical wear by water or cavitation or other means, acid attack, alkali silica reaction (surface attack), sea water attack, leaching by pure or natural water, accidental load, overload and structural load.

Strengthening with reinforced concrete can be divided into two different types:

- Bonding of hardened concrete to hardened concrete, typically associated with the use of precast units in repair and strengthening.
- Casting of fresh concrete to hardened concrete using an adhesive bonded joint forming a part of the structure requiring composite action

The structural repair with reinforced concrete consists normally of the following actions:

- removing contaminated, cracked or defective concrete
- removing and replacing corroded reinforcement
- adding protection to the reinforcement
- casting and/or adding new reinforced concrete section for strengthening of the structure

It is important to ensure compatibility with the parent concrete, as well as full composite action. Pre-preparation is crucial, to ensure bond with the substrate and the rebars. Good workmanship is paramount for all application methods, which may be used.

Recasting with concrete has been used for a very long time and the experience is thus comprehensive. A correct performed repair gives a very good function. Some considerations and risks are listed below:

**Service life**

Adhesion is fundamental. Quality of new concrete must be high to secure long service life. **Corrosion:** A new concrete with low permeability (e.g. concrete with low $w_0/c$-ratio) reduces future chloride ingress and carbonation. The binder influences the threshold value and chloride binding capacity. **Salt-frost attack:** New salt-frost resistant concrete shall be used. The risk of internal frost damage in the old concrete due to dense concrete cover shall be considered. **Mechanical wear:** Concrete should have very high strength and contain wear-resistant aggregate. **Pop-out:** If lower moisture content cannot be achieved the new concrete layer must be able to withstand further ASR in the substrate without cracking or delaminating. Steel fibre concrete might be necessary. **Sea water attack:** Possible synergy with chloride induced corrosion and frost attack must be considered. **Leaching:** Concrete with low solubility (containing pozzolans, low $w_0/c$-ratio) should be used.

**Structural stability**

Adhesion and shear bond is fundamental. Dowels might be needed but waterjetted substrates normally give sufficient adhesion and shear bond strength. Compatibility is normally good when concrete is used. Removal of load and propping may be essential during execution.
Execution

All steps, i.e. concrete removal, preparation of substrate, material selection, casting and curing, must be performed correctly. To ensure bond with the substrate pre-preparation is crucial. Excellent workmanship is essential.

5.3.7 **Strengthening with carbon fibre**

Strengthening of concrete structures with externally bonded FRP (see also Annex J) can be used to improve service conditions, durability as well as to increase bearing capacity of the structure. It provides an alternative solution to traditional methods of strengthening such as externally bonded plates.

This type of strengthening is achieved by bonding the fibre material to the substrate of concrete with an epoxy adhesive. There are two different systems that can be used. The first consists of preformed laminates fabricated provided as strips, shells, jackets or angles which are bonded to the substrate and the second in the form of sheets or fabrics which are bonded and cured on site using a wet lay-up or hand lay-up systems. Laminates are provided with their final shape, strength and stiffness and sheets are impregnated with adhesive prior to application and cured in situ to achieve their final mechanical properties. In both cases adhesive is provided as a two part cold cured epoxy resin.

Externally bonded FRP has been used mainly to increase flexural capacity although it can also be used to increase shear capacity and axial load capacity. Bridge supports have been strengthened with FRP to provide increased resistance to impact loads where columns are wrapped with FRP a large component of the increased axial load derives from the restraint to the concrete provided by the FRP.

FRP materials are currently being used because of their high strength and resistance to corrosion. They make handling and installation easier than steel and their low weight reduces access requirements. A good execution process and preparation of the surface are essential for the durability of the strengthening system.

One of the main disadvantages of this technique (except in bridges) is the need to consider possible fire damage in the design of the strengthening as it can produce debonding of the FRP material affecting in the long term integrity of the strengthened structure. In general FRP strengthening can also be damage by accidental damage or vandalism unless the strengthening is protected.

5.3.8 **Strengthening using externally bonded steel plates**

Where reinforcement concrete elements are found to be under-strength due to deficiencies in the amount of steel reinforcement present, additional steel can be added in the form of external reinforcement by bonding steel plates to the concrete surface. This can increase flexural, shear and axial load capacity. Plate bonding can also be used to correct serviceability problems such as excessive deflections, excessive crack widths, prevention of progressive failure due to vibrations, etc. Design guidelines are presented in Appendix K.

This method of strengthening has been used for many years and there are many examples around the world (see Appendix K for some case studies). There are various national standards devoted
to this method of strengthening. In the UK, BA 30/94 presents guidelines for the use of plate bonding on concrete bridges. The guidelines presented in Appendix K are based on those contained in BA 30/94. It presents specifications for the application of plate bonding, design of bonded plate systems, appropriate materials, surface preparation, quality control and in-service inspection and maintenance.

For the plates to be effective, the bond must be sufficient to ensure full composite action. The critical parameters therefore are the structural properties of the adhesive and the preparation of the surfaces to be bonded. It is recommended that trials be carried out on any proposed methodology, taking account of the adhesive to be used, the proposed surface preparation of the steel plates and the condition of the concrete surface. The trials should also take account of any practical handling problems due to site conditions.

Plate bonding has been used generally to increase the flexural capacity of concrete beams and slabs. The plates are normally bonded to beam soffits which have easy access and are easily inspected. Plates can be bonded to the upper concrete surface to strengthen hogging regions or to supplement compression steel. However, in the latter case, additional problems are encountered, such as the possible buckling of the plates in compression and the difficulties associated with the inability to carry out inspection. Plates should not normally extend into compression zones. Where this cannot be avoided, supplementary bolts should be used, using a cover-meter to ensure that the bolts do not clash with reinforcement.

The main advantages of this method of strengthening are that it represents an inexpensive and easily installed solution, the increase in dead load is small and disruption to users is minimal. It is important that the installation be carried out with care and close site inspection by experienced engineers is necessary to prevent problems in the long term, particularly where unskilled labour is used. For bridge applications, the decrease in headroom is small, which may be an important consideration in certain situations, eg, bridges over railway lines. In addition, the plates are easily inspected, either visually or using simple techniques such as tapping with a hammer to determine the presence of voids, separation and corrosion.

Unless the structure is jacked to relieve the dead load from the component being strengthened, the modified composite section carries only the live load. The permanent loads continue to be carried by the original section only. This has the advantage that the adhesive is stressed only when live load is applied, so that creep is not a major problem. Care must be taken to ensure that the modified section is not over-reinforced: in some circumstances this may be permitted, provided excess capacity is provided to reduce the likelihood of sudden failure due to concrete crushing rather than yielding of the reinforcement.

The main structural problem associated with bonded plates is due to the shear and peeling stresses which occur at the ends of the plates. These are normally resisted by the provision of anchor bolts. The plates are also susceptible to corrosion which can have a serious detrimental effect on the adhesive bond. Effective corrosion protection after installation is necessary in order that plate bonding provide a safe and durable solution. An effective paint coating, of the same specification as used in new design, should be applied to all metal components. This should take into account all aspects of the environment of the structure. Special consideration should be given to any specific conditions which might affect the durability of a particular structure. The paint used should be compatible with the adhesive. The edges of the plates should be sealed to protect against moisture ingress under the plate.
Before deciding on plate bonding as the preferred method of strengthening, the suitability of the bridge must first be established. This should include site investigations to determine that the risk of corrosion in the existing structure is low and that the concrete is in good condition. Damp surfaces or surfaces subject to leakage through the deck can only be plated after remedial measures are taken to ensure that no further leakage will occur. Crack injection should be used to repair any cracks greater than 0.2 mm. Various pull-off tests can be carried out on the surface of the concrete to determine suitability for plate bonding. Where there is doubt, it is recommended that site trials be carried out.

5.3.9 Strengthening using external post-tensioning

The use of external prestressing as a means of strengthening concrete members is described in Annex L. The technique has been used in many countries and has been found to provide an efficient and economic solution for a wide range of structure types and conditions, and bridges in particular. It is growing in popularity because of the speed of construction and the minimal disruption to the structure which can in many cases be the critical factor in decisions regarding strengthening.

External post-tensioning can be used to improve the serviceability behaviour of existing structures. As in prestressed construction, the method can be used to delay or prevent the onset of cracking. It can also be used to reduce or close pre-existing cracks. This improvement in cracking behaviour also increases resistance to reinforcement corrosion. The increased stiffness provided by external post-tensioning can reduce in-service deflections and vibrations. The stress range can also be reduced and the fatigue performance can be improved. The presence of a deformation or sag in a concrete beam can be reduced or removed.

The basic principle of external post-tensioning is the same as that of prestressing, ie, the application of an axial load combined with a hogging bending moment to increase the flexural capacity of a beam and improve the cracking performance. It can also have a beneficial effect on shear capacity. Precise evaluation of flexural and shear capacity of beams with unbonded tendons, either internal or external to the section, is difficult. This is because the load in the tendons is a function of the overall behaviour of the beam, rather than just depending on the strain distribution at a particular critical section. Secondary effects, such as changes in the cable eccentricity as the beam deflects, are difficult to quantify. Many national and international codes present methods of determining capacity but these are based primarily on laboratory results obtained from tests on beams with internal tendons.

The anchorage systems used for bridge strengthening are similar to those used in conventional prestressed concrete design. The anchorages can be fixed at different parts of the deck, eg, in end blocks, diaphragms, on webs, flanges, etc. For reinforced or prestressed concrete beams, tendons can be installed either beneath the bottom flange or on opposite sides of the webs, depending on the design requirements. In box girders, the tendons are usually placed within the box to keep them out of sight and to provide some degree of protection against corrosion. Tendons can either have straight or draped profiles, depending on the design requirements. A draped tendon is made of straight segments stretched between specially fabricated deviators, usually made of steel. Shorter straight lengths of cable placed at different eccentricities can also be used.

As with all strengthening methods, there are various advantages and disadvantages associated with the use of external post-tensioning. The main advantages are as follows:
The method is economic in that it is cheaper to install than methods which require major reconstruction. The equipment required, while specialist in nature, is light and easy to use, particularly when single strand jacks are employed.

Both flexural and shear strength can be increased without the penalty of increased dead load. This can be a considerable advantage in some situations.

The ease of inspection increases the reliability of the structure as any stress loss or damage due to impact or corrosion can be determined by simple inspection procedures.

The tendons can be re-stressable and replaceable.

External post-tensioning can be applied without major disruption to the function of the structure.

For box girder beams, the tendons can be installed inside the box, so that they are not visibly intrusive.

As with other methods of strengthening, there are disadvantages and it is important that these be understood in order to make an enlightened evaluation of this method for particular situations. The main potential disadvantages are listed here:

- Application of the method is very dependent on the existing condition of the bridge. Concrete of poor quality should not be over-stressed and a full condition survey should be carried out to ensure that the bridge deck can take the increased stress.
- Installation of deviators and anchorages can be difficult in certain situations, and careful detailing is required to account for stress concentrations in the existing deck components.
- The tendons are more susceptible to corrosion, and often need to be placed in areas of run-off, e.g., near joints in bridges.
- The shear capacity of beams with external tendons is difficult to determine.
- For shear, strengthening near supports, the critical area for shear, is difficult because of access difficulties. For these reasons, the method has been generally confined to flexural strengthening.
- Installation of the tendons can mean working in difficult conditions and confined spaces, e.g., on abutment shelves, inside boxes, on scaffolding, etc.
- Where tendons need to be installed below the bottom flange, the decreased headroom is a distinct disadvantage.
- The appearance of the external cabling system might discourage their use.
- External tendons are more susceptible to accidental damage from fire, impact and acts of vandalism.
- For proper installation of external tendons, accurate fabrication and installation and careful site supervision and inspection are required.
6 PRINCIPLES AND TOOLS FOR EVALUATION

6.1 General procedures for evaluation of repair

6.1.1 Required information for evaluation

Evaluation of a repair system is based on the following background information and knowledge:

1: Type of damage, cause of damage, location of damage

It is assumed that type, cause and extent of damage have been established. Principles and practical methods for analysis of the present and residual status of a damaged structure are described in documents worked out within the European project “CONTECVET”. The damage types considered in these documents are:

- Reinforcement corrosion [3.1]
- Alkali silica reaction (ASR) [3.2]
- Frost attack (internal and external) [3.3]
- Leaching [3.4]

There are also other possible damage types; some are described in Annexes M and N. On basis of this analysis it can be decided whether immediate repair shall be made, or if it can be postponed.

Also the location of damage must be known, since it affects the selection of proper repair method. Location can be; (i) under water, (ii) on vertical surfaces, (iii) on top surfaces, (iv) on bottom surfaces, (v) at high altitude.

2: Requirements on the repaired structure and the repair procedure

Requirements to be considered are described in Chapter 4.

It is important that as many as possible of the requirements can be expressed in quantitative and measurable terms. It is also important to consider that the requirements have to be defined by the owner for a prescribed life time.

3: Data related to old structure, repair method, and repair material

An important basis for evaluation is data of various kinds; primarily material data on mechanical properties, permeability, durability, composition, etc. of repair materials, and data for the old structure required for analysing the short-term and long-term interaction between old concrete and repair. Evaluation of repair, therefore, relies upon the existence of good test methods for obtaining data.
Furthermore, data are required for the cost of different activities involved in the repair. Data are also required concerning environmental effects of execution of repair, and on chemicals used in repair materials.

**4: Existence of theories for analysing the interaction between repair and structure**

Evaluation also relies upon the existence of good theories for analysing interaction (short-term and long-term) between existing concrete and repair material. Thus, an evaluation cannot only be based on an analysis of the repair material itself, but must be based on an understanding of the interaction. This is particularly important for analysing service life and structural stability.

### 6.1.2 Steps in the evaluation

Evaluation of repair is made in three consecutive steps:

- **Step 1**: Selecting a suitable repair principle relevant for the actual structure, the actual damage, and the actual requirements.
- **Step 2**: Selecting a suitable repair method/system within the repair principle chosen.
- **Step 3**: Selecting a suitable repair material (material composition, or brand) to be used in the repair method chosen, or selecting a suitable type and brand of the process chosen for stopping continuing destruction.

In most cases, steps 1 and 2 in the evaluation are fairly simple and can be based on “common sense” and previous experience.

Step 3 is much more complex since different repair materials with different composition used in the same repair method can lead to quite different function of the repaired structure. Step 3 requires extensive data concerning the status of the old structure, and concerning mechanical and physical properties of the repair material. Data of this type are needed also for a qualitative evaluation, based on previous experience of interactions between old damaged structures and repair materials of different type. Data are absolutely necessary for quantitative evaluations of structural stability, serviceability and durability of the repaired structure.

Thus a vital element in the evaluation of repair is to select not only a suitable repair principle and method but also a suitable repair material that makes it possible to fulfil all requirements on the repaired structure.

### 6.1.3 Selection of alternative repair methods/systems

The most difficult task at selection of a repair method is to weigh different requirements against each other in order to find the “optimum” solution. Normally, however, requirements for structural safety and service life dominate. Thus, the most natural repair principle and repair methods are often fairly easy to find. Thereby, also the most natural repair method can be selected.

The suitable repair method depends on the cause, type and location of damage. For every damage type and cause, there are normally only a few repair principles, and a few main repair...
methods available. These repair principles, and main methods, are described in the tables in Annex M.

### 6.1.4 Evaluation parameters

Once, the most suitable repair method or system has been identified, it is important to consider that there are many variants within the same repair method. Therefore, main requirements other than those related to safety and service life, such as requirements with regard to environment, economy, simplicity of execution etc., might often be decisive for the final selection of materials and methods. The best material to be used in the actual case is decided on the basis of an evaluation of the alternatives. Information enabling such an evaluation for different objectives is described below in paragraphs 6.2 to 6.7.

Primarily, a repair method is evaluated with regard to the following 5 basic parameters:

1. service life/durability
2. structural stability/safety
3. execution of work
4. environmental effects
5. economy/cost

Additionally, factors of a non-technical nature, such as disturbances of different kind during repair work, have to be considered in the evaluation.

### 6.1.5 Different levels of evaluation

The evaluation of a repair method or repair material can be made on three different levels:

- Level 1: Approved solutions
- Level 2: Qualitative evaluation
- Level 3: Quantitative evaluation

#### Level 1: Approved solutions

The most simple procedure is to rely upon experience from previously executed repair and, therefore, select repair methods and materials that have proved to work sufficiently well in the past, for example by yielding long service life of the repaired structure, by being simple to execute, by being cost effective, and by having a low impact on environment.

The method is defensive, since it will conserve old techniques. New repair materials and principles cannot be evaluated this way, and might therefore be effectively prevented from being used.

#### Level 2: Qualitative evaluation

Based on experience from previous repairs, and on “semi-quantitative”, and/or qualitative reasoning, the experienced engineer might in many cases make a good evaluation of a repair system and a repair material in a given situation.
Annex M gives examples of such qualitative evaluations. The most frequent repair principles and methods for different types of repair are listed, together with a short description of advantages and problems.

Based on test results of materials to be used, combined with some elementary calculations, the effect on structural stability directly after repair can be evaluated. Using simplified analysis, some account can also be taken of future changes in the repaired structure, i.e. to the service life. The calculations used are fairly rough, however. No consideration to changes in moisture state of the structure after repair and its effect on durability is made. Synergistic effects of two or more destructive processes going on at the same time are also neglected.

Information furnished by the manufacturer on potential health hazard and environmental impact should be used for comparison of materials. Using such procedures, different materials can be rated as regards their capability to fulfil the requirements.

The drawback of a level 2 evaluation is similar to a level 1 evaluation; new repair methods might be stopped due to lack of reliable information.

**Level 3: Quantitative evaluation**

Evaluation on levels 1 and 2 are well suited for evaluations of execution of work, economy, environmental impact, and other requirements of non-technical character. These types of evaluation, however, give no real quantitative information on future changes in fundamental properties of the repaired structure; viz. structural stability and serviceability. Thus, they cannot be used for a more precise evaluation of service life of the repaired structure. During the last decades, methods for service life calculations, “service life design”, have been developed for new structures. The same principles can also be used for the calculation of service life of repaired structures.

Inputs in these types of calculation are:

- Material data valid at time of repair for repair materials, original structural concrete, and interfaces between these materials. Test methods are required for obtaining these data.

- Theories for calculating structural interaction between repair and the original structural concrete. Different theories might be valid for different types of repair system and different types of structural member; beam, column, slab, pre-stressed component, etc.

- Theories for calculating future changes in material properties determining structural capacity and serviceability of the repaired structure; primarily, strength and stiffness of concrete, erosion of concrete cross-section, and corrosion rate of reinforcement. Such theories are based on knowledge of the destructive processes. Test methods are required for determining properties of importance for deterioration of the repaired structure.

Quantitative evaluation with regard to service life is further described in paragraph 6.2, and Annex N. Quantitative evaluation with regard to structural stability and safety is treated in paragraph 6.3 and Annex O.
6.1.6 Example of evaluation principles

Principles

The evaluation principles are exemplified in Figure 6.1. When the cause of damage and type of damage are known, and the functional requirements of the repaired structure have been established, some alternative repair methods exist. For each method there are normally many repair materials (or processes) available. The method and the material (process) selected are evaluated with regard to the 5 characteristics shown in paragraph 6.1.4, and also for other characteristics, of non-technical nature. Basic principles for evaluation are given in paragraphs 6.2 to 6.7 below. More detailed methods for evaluation are shown in Annexes N to R.

![Evaluation of Repair Method Diagram]

Figure 6.1 Evaluation of a repair method. Principles.

Example

A more detailed example is shown in Figure 6.2. The damage cause is chloride-induced corrosion. The damage type is spalling of cover. Functional requirements of importance for evaluation of the five criteria are indicated in the figure. The selected repair method is replacement of the cover with new concrete cast in-situ. The quality (composition) and thickness of the new concrete must be such that the requirements for service life and structural stability are fulfilled. That this is the case must be verified at the evaluation.
Only evaluation factors for the criteria “service life” and “strength” are indicated in the figure. Evaluation factors for the criteria “execution”, “environment”, “economy”, and “non-technical issues” are omitted.

**Cause of damage/type of damage (1:1.4)**
Chloride induced corrosion/spalling of cover
(edge beam of a bridge)

**Fundamental requirements**
- **Service life**: Full structural safety shall be maintained during x years after repair (i.e., corrosion is not allowed to start, and there shall be full integrity of concrete for x years)
- **Strength**: The safety level shall fulfill requirements in the valid structural codes
- **Execution**: Society’s requirements for work environment and risks during repair work shall be fulfilled
- **Environment**: Society’s requirements for effects on environment shall be fulfilled at selection of repair method
- **Economy**: Lowest possible repair cost considering quality of finished work (“no competition on quality”)

**Repair method**
- Removal of chloride-infected cover using water-jet. Maximum acceptable chloride content in the remaining concrete 0.1 weight-% of cement
- Cleaning of uncovered reinforcement bars by steel brushing
- Adding new reinforcement for compensation of lost
- Casting new high quality concrete cover maintaining the outer dimensions of the structure

**Service life**
- Analysis of future moisture level in the old concrete (risk of concrete destruction)
- Analysis of time to onset of corrosion in repaired concrete
- Analysis of compatibility (risk of bond fracture)
- Analysis of the risk of cracking of the repair concrete
(These analyses give requirements to material properties, and to test methods used for verification of material properties and execution of work)

**Strength/load carrying capacity**
- Structural analysis of static/dynamic interaction between old structure and repair concrete.
- Gives requirements to:
  - Bond
  - Additional reinforcement
  - Strength of repair concrete
  - Stiffness and ductility of repair concrete

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**Figure 6.2 Example of the contents in an evaluation of a method and a material**

### 6.2 Evaluation with regard to service life

Additional and more detailed information is given in Annex N.

#### 6.2.1 Definition of service life

A fundamental requirement of a repair is that the structure maintains its full function during a minimum period, defined by the owner. This is illustrated in Figure 6.3. At time $t_1$, the structure has reached the lowest acceptable function $F_{\text{min}}$. After repair, function is raised to the initial value, or to any other value defined by the owners requirements. In most cases, the repaired structure will gradually reduce its function, due to the influence of aggressive agents in the external environment. Depending on the repair method used, this new degradation can be more or less rapid. At time $t_2$ the structure once again no longer fulfils the requirements. Therefore, it needs further improvement. The extension of service life due to repair is $\Delta t$, which should be in conformity with the value defined by the owner in his requirements.
“Function”, or “quality”, can be defined in different ways. It might be related to **structural safety**, or **load-carrying capacity**. Or it can be related to **“serviceability”**, by which is meant the capability of the structure to fulfil requirements that are not directly coupled to structural stability, like water tightness, appearance, deformation, cracking, etc. The actual minimum acceptable function, or quality, has to be defined by the owner, preferably in **quantitative and measurable terms**.

Selection of repair systems should be based on an evaluation of their capability to fulfil the owner’s requirements for service life. Such an evaluation is often very complicated, since it means that the complex interaction between the repair material and the old damaged structure often has to be evaluated with regard to service life, in addition to evaluating the repair material by itself.

Different combinations of repair and damaged concrete structure will give different values of the service life. This is illustrated by Figure 6.3. Repair Alt 2 gives shorter service life than Alt 1, because for example:

1. the **repair material** used in Alt 2 has in itself lower durability than the repair material used in Alt 1. Thus, the protecting capability of the material used in Alt 2 is more rapidly reduced with time. One example is when further chemical surface attack is to be stopped by a protective surface coating. Alt 2 is a coating with lower chemical resistance than Alt 1.

2. the **repair system** Alt 2 does not protect the old concrete from further deterioration as effectively as the repair system Alt 1. Thus, when Alt 2 is used, the previous deterioration process in the old structure continues, although at a retarded rate. When Alt 1 is used the future deterioration is effectively hindered. One example is when further reinforcement corrosion is to be stopped by a new cover. Then, Alt 2 is a cover which in itself allows more rapid penetration of carbonation or chloride than Alt 1.
In severe cases, the repair might even accelerate destruction of the old concrete by initiating new types of destruction; see Alt 3 in Figure 6.3. One example is when a structure with moderate frost resistance is repaired by a dense polymer surface coating, or by a layer of polymer-based concrete. Then, moisture might accumulate beneath the dense coating leading to rapid and severe frost damage of the old concrete. This type of damage stimulated by repair has frequently been observed in practice [6.1]. The risks have also been demonstrated in the laboratory, [6.2].

6.2.2 Basic service life requirements

The basic requirement is that the repaired structure shall maintain full function during the prescribed service life. By “function” is primarily meant requirements for structural stability and serviceability.

The repaired structure will in most cases be exposed to the same aggressive agents as it was before repair. It might even be, that exposure is aggravated after repair. The service life of the repaired structure, therefore, depends on the ability of the repair system to stop, or sufficiently retard, future deterioration of the concrete structure. When assessing the ability of a certain repair system to fulfil this requirement it is assumed that the concrete quality in the existing structure is normally of low, or fairly low quality compared with the repair concrete, unless otherwise is proven by testing.

6.2.3 Operative requirements constituting service life

For a good evaluation it is required that the basic service life requirement is broken down into a number of measurable quantities, many of which are related to durability and transport properties of the repair material. The manner in which such a transformation to measurable properties can be made is exemplified by the repaired slab in Figure 6.4. The slab has been damaged by internal frost and by reinforcement corrosion induced by carbonation, and/or chloride penetration. Repair is made by two alternatives: (i) removing old damaged chloride contaminated, and/or carbonated, cover and replacing with new cover, (ii) application of a coating without removing old concrete.

Requirements coupled to service life of the repaired concrete are:

1. A maximum allowable diffusion rate of carbon dioxide in the new cover (or in the coating). The diffusion rate depends on the moisture level in the repair materials. The lower the amount of lime able to carbonate, and the lower the moisture level, the more rapid is the penetration rate.

2. A maximum allowable penetration rate of chloride in the new cover (or in the coating.) The higher the moisture level, the more rapid the penetration rate (provided chloride enters by pure diffusion. If it enters by convection caused by capillary suction, high moisture content might be positive). Also the chemical composition of the cover plays a big role.

3. The old concrete must not be susceptible to frost damage due to moisture accumulation caused by the new cover (or coating).

4. Cracking in the new cover, or coating, causing unacceptable moisture and chloride
ingress to the old concrete, shall not be tolerated. Normally, this means that no through cracks bigger than 0.1 to 0.2 mm shall be tolerated. This requirement, in turn, can be translated to requirements for ductility, elasticity, thermal movements, moisture variations, and moisture movements, of the repair material, including the effect of natural ageing on these properties. The mechanical properties of the old concrete also play a role for the risk of cracking.

5. Total loss of bond between repair and old concrete shall not be tolerated, since cracks formed at the interface can accelerate moisture, chloride and carbon dioxide penetration into the old concrete. As for point 4., this requirement is related to mechanical properties of repair material and old concrete.

6. The new cover (and coating) shall be able to fulfil its protective function during the required service life. This means that it shall in itself have sufficiently high durability against all aggressive agents;

- it shall be frost resistant in the actual environment.
- it shall stand all potential chemical attack
- it shall be sufficiently wear resistant
- it shall not “age” in an unfavourable way (rapidly lose its protective ability)

![Diagram](image)

**Figure 6.4 Requirements on a repair system; example. (For explanation, see text.)**

6.2.4 Evaluation procedure - levels

Selection of a repair method is intimately coupled to the cause, type, and extent of damage. Thus, it is important to clarify these factors. After this has been done, it is possible to select relevant repair methods. Normally, there are only a few repair principles that are relevant. For each repair principle there are, however, often numerous variants in material composition and
properties. There are also variations in how the work is executed when applying the repair system. The service life may also vary for different repair systems and materials of the same kind.

Once a repair method and material has been selected, they have to be evaluated with regard to service life in order to confirm that the repaired structure fulfils the service life requirement.

The evaluation of service life of a repair method/material applied to a given structure can be made on three different levels as illustrated in Figure 6.5.

Figure 6.5 Different levels in evaluation of service life

Evaluations on level 1 and 2 are almost always used today in connection with selection of repair materials, although they do not give quantified information on service life. Quantitative evaluation on level 3 is seldom used although fairly good possibilities exist today, at least for some frequent repair types, like repair of concrete damaged by reinforcement corrosion. A detailed example of a quantitative evaluation of repair of a structure damaged by corrosion is presented in Annex N.

6.2.5 Evaluation on Level 1: Approved solutions

Approved solutions will often satisfy the service life requirement although the approach is very defensive, since it will conserve old technique. New repair materials and principles cannot be evaluated this way, and might therefore be effectively prevented from being used. Examples are new untried innovative processes for stopping reinforcement corrosion.

Besides, it might very well be that many traditional methods are not as good as anticipated, since their real function has not been followed-up. For example, it might be that a repair, that
is supposed to stop further reinforcement corrosion for a long time, has not been effective, but this was not discovered, because no investigation of corrosion rate after repair was made. Another case is where a thick and highly impermeable polymer-based surface repair seemingly functions well, but in reality there has been substantial moisture accumulation in the old concrete, causing severe frost damage, that was not observed due to inadequate post repair investigations.

6.2.6 Evaluation on Level 2: Qualitative evaluation

Based on experience from previous repair, and on qualitative reasoning, the experienced engineer might in many cases estimate the durability of a given repair system. The engineer will not obtain a value of the service life in years, but might be able to distinguish one repair system and material from another, as regards their ability to fulfil the required service life.

Qualitative methods must be used for destruction types for which no quantified service life design models exist, such as different types of internal chemical attack and physical attack. They must also be used for evaluation of non-traditional repair methods for which the necessary data are missing.

Important input information in a qualitative evaluation is results from tests of the repair material itself, such as tests of frost resistance, chloride diffusivity and other transport properties, mechanical properties, chemical composition, etc. Reliable information from manufacturers and experts in durability can also be used in the evaluation.

Examples of qualitative evaluation

Example 1

An example of a qualitative evaluation is when different types of cement-based repair concrete, used as replacement for a frost damaged concrete cover over corroding reinforcement in a chloride environment, shall be evaluated. Then, without any calculations it is quite clear that the concrete with the highest salt-frost scaling resistance, demonstrated by a test, is superior to concrete with more inferior frost resistance. Furthermore, in cases where frost attack might be a problem, the concrete with the lowest water cement ratio ought to provide the best protection for the reinforcement. No quantitative calculations are needed to select the best material. On the other hand, this approach will not give a precise value for the service life, expressed in years, of the repaired structure.

Example 2

Another example is when one has decided that a polymer-based coating shall be applied as protection on a concrete surface. Then, the durability of the repair material in itself is fundamental. It is quite clear that the polymer with the highest anticipated (from experience) or measured alkali-resistance and UV-resistance, based either on experience or on test results, is most suitable, provided all relevant mechanical properties (strength, elasticity, ductility, wear resistance, etc.) seem acceptable.

Example 3

Also when a polymer coating shall be compared with a cement mortar as surface protection, a qualitative evaluation will normally show that the cement-based material is the best choice. The choice, however, will also depend on what mode of deterioration the surface layer will have to protect against; e.g. further frost or erosion attack, or further reinforcement corrosion.
In the first case the polymer might be the best choice, in the second the cement-based material might be the best. It will also be necessary to take account of other requirements associated with the execution of work in order to select the most appropriate repair method.

Example 4
Another case where cement has to be compared with polymers concerns the injection of cracks and holes. Principally, from a chemical point of view, cement is preferable, although this statement cannot be based on a service life calculation, but merely on qualitative reasoning. On the other hand, the feasibility of executing the work must also be considered, and, therefore, it is often necessary to select a polymer. The polymer with the highest alkali resistance, as demonstrated by testing or experience, should then be selected, provided its ability to penetrate the cracks is sufficiently high.

Example 5
Innovative procedures for reinforcement protection, or treatment of chloride infected concrete cover, such as different types of cathodic protection, chloride extraction, and re-alkalisation, cannot be based on practical experience, since there is almost no reliable long-term experience for most of these procedures. Further, there are no quantitative methods for calculating the effect of these new methods on service life. Therefore, the engineer has to rely upon his own common sense, and to the information provided by respected producers and contractors.

The same is the case with other new repair procedures like use of stainless steel reinforcement. According to manufacturers, and many researchers, cast-in stainless steel cannot corrode at normal chloride concentrations found in normal environment. Therefore, it might be a good material for repair, since it permits the use of low cover depths. This opinion has, however, been contradicted by other researchers, e.g. [6.3], who state that the positive effect of stainless steel depends on the composition of the steel, since some steels do not provide the increase in threshold chloride concentration needed for long service life at low concrete cover. In this case the engineer has to rely upon information from experts and his own judgement. There is, however, a good possibility of making a quantitative evaluation, provided reliable data for threshold chloride concentration can be obtained, either from the manufacturer, or from research.

Further examples of qualitative evaluation of different types of damage in Annex M, a qualitative evaluation repair principles and methods for concrete, damaged by different destruction mechanisms and types of damage are presented.

6.2.7 Evaluation on Level 3: Quantitative evaluation – service life design

General principles of service life design

Evaluation on levels 1 and 2 give no quantitative information, expressed in years, on the service life of the repaired structure. During the last decade useful methods for service life calculations, “service life design”, have been developed for new structures. Examples of such service life design procedures are furnished in reports from the EU-project DURACRETE, [6.4]. Service life is normally treated as a deterministic property, having one single value determined by single values of all material properties and environmental properties used in the analysis. However, in DURACRETE service life might also be treated as a stochastic
property having a certain mean value and a certain spread. Input in the calculations is quantitative data (mean values and spread) in material properties (like effective diffusivity of gases water and ions, threshold concentrations for onset of destruction), and environmental properties (like moisture, temperature, salt concentration). All these data are used in theoretical destruction models.

The principles for a stochastic service life evaluation are shown in Figure 6.6. Calculation is made with regard to a type of destruction governed by a diffusion process and a threshold concentration needed for start of destruction (e.g. Reinforcement corrosion). The diagrams indicate frequency functions of different properties and service life.

![Figure 6.6 Principles (simplified) of a stochastic service life calculation](image)

Service life calculation methods based on the same theoretical basis have also been developed for assessment of the residual service life of existing structures. Examples of such methods are given in the EU-project CONTECVET, [3.1] [3.2] [3.3] [3.4]. These methods can be modified also to consider variations in material and environmental properties.

The most advanced service life design methods have been developed for reinforcement corrosion, since this is a destruction mechanism largely governed by diffusion processes, for which the “time axis” can be quantified, at least in theory. For other destruction types, more embryonic methods exist. Examples are alkali-silica reaction, different types of frost attack (internal and external), and leaching of lime by percolating water, for which methods are described in [3.2], [3.3] and [3.4].

The rate of many destruction types is increased if another destruction mechanism is operating simultaneously. Such “synergistic effects” must be considered. Examples of how to consider synergy are discussed in [6.5].

**Application of quantitative evaluation of service life to repaired structures**

For the repaired structure, the assessment of service life is more complex than for a new, or existing, structure, since the interaction between the old concrete and the repair must be considered. Such interaction might be of a mechanical nature and result in cracking and loss of bond. Other interactions are of chemical nature, where the moist alkaline sub-base concrete might adversely affect the repair material, e.g. a coating, or crack injection, based on polymers.
A fundamental interaction for service life is the moisture interaction between repair and old concrete. This interaction can be extremely negative, especially if the moisture content in the old concrete is increased as a result of repair. Frost damage might then appear, and chloride ingress might be increased. If, on the other hand, the moisture content is reduced as a consequence of repair, the carbonation rate might be increased.

The service life assessment of a repaired structure is facilitated by the fact that much information on important material properties can be obtained by testing the old, damaged structure. Examples of such information are: amount of reinforcement corrosion, corrosion rate, carbonation depth (giving information on the carbonation rate), chloride profile, strength, erosion depth, etc.

A quantitative evaluation of the service life of a repaired structure requires the following information:

1. Knowledge of how to describe the time process of deterioration (the deterioration model) for all destruction processes involved
   - continued destruction of the old repaired structure
   - destruction of the repair material
   - destruction of the interface between old structure and repair material
   - possible synergistic effects

2. Quantified information on material properties of the repair material and also on properties of the concrete to be repaired. Important properties are:
   - transport coefficients of moisture (liquid and as vapour), gases and ions
   - binding isotherms of water, gases and ions
   - threshold concentrations of ions (primarily Cl–)
   - aging properties (“durability“) of the repair material itself when exposed to the actual environment (like high alkalinity, UV-radiation, frost, chemical aggressors, etc.)
   - mechanical properties needed for calculating risks of loss of bond and cracking.

A quantitative evaluation, therefore, relies upon test methods that measure relevant properties in a relevant manner. Thus, all transport coefficients shall be determined as a function of the moisture content inside the material, and not be measured only at some arbitrarily chosen RH-level. Likewise, the threshold chloride concentration shall not be some average value supposed to be valid for all concrete, but be the value that is valid for the actual concrete type.

**References to applications of quantitative evaluation of service life**

Applications of quantitative service life evaluations of repaired structures are given in the following documents:

*Annex N. Main text*: Gives principles for assessing service life with regard to some frequent damage types. Furthermore, information needed for a service life assessment, and test methods for obtaining this information is given in tables.

*Annex N. Appendix 1, 2, 3*: Describes how the moisture level, the carbonation depth, and the chloride profile in the repaired structure are affected by repair.
Annex N. Appendix 4: Gives a detailed practical example of a quantitative service life assessment.

6.3 Evaluation with regard to structural stability and safety

Additional information is given in Annex O.

6.3.1 Structural stability before repair

A vital part in the assessment of an existing, damaged structure is the analysis of its present structural stability and safety. Methods for this have been described in the EU-project CONTECVET, for the three damage mechanisms, reinforcement corrosion [3.1], alkali silica reaction (ASR) [3.2], and frost attack [3.3]. Information is also given on how to assess the status of concrete damaged by leaching, [3.4].

Basic input information in this assessment is residual strength of concrete, residual bond strength between concrete and reinforcement (estimated from measurements of tensile strength), E-modulus of concrete, depth of surface scaling, loss of cross-section of reinforcement, information on geometry of the structure (dimensions, cover). Other information might also be needed.

On the basis of the structural analysis it is decided whether the structure should be left without repair for some additional years, or if shall be repaired, or if it shall be removed or replaced.

Note: The decision whether repair shall be made or not will also depend on other things than the result of a structural analysis, although this is often of critical importance. For a structure that is acceptable from a structural point of view repair may be justified in order to reduce the ongoing rate of destruction, increase life, reduce future maintenance cost, or improve appearance.

If the decision is to repair one has to decide which technique to use. Often some strengthening has to be done in order to secure the required structural stability. Then, all data determined in the assessment of the damaged structure are also required in the analysis of the stability of the repaired structure.

6.3.2 Design of the repaired structure with regard to structural stability

The required structural stability and safety of structures are regulated by valid official codes. In many cases, society also prescribes the load the structure shall be able to carry with prescribed safety. All these official rules have to be followed in the analysis of the repaired structure.

The owner might have additional requirements on safety and load to be obeyed. So for instance, it might be that the structure shall be upgraded to higher load capacity after repair.

Once a repair procedure has been decided, a structural analysis of the selected procedure should be made in order to verify that the structure fulfils the requirements after repair. This analysis is equivalent to an ordinary structural design of a structure to be built. In the repair
case more information on material properties and dimensions are at hand. Therefore, it might be possible to reduce partial safety coefficients on material. This possibility should be considered since it might have significant positive economical consequence.

Input in the structural analysis is:

1. Data from the previous assessment of the damaged structure; see paragraph 6.3.1. *It is very important that the designer decides which data from the old structure are needed, and from what places in the structure these data shall be obtained.* Many times, there are only a few parts in the structure for which structural stability is crucial. Most data should be taken from these parts, and not from parts that do not significantly influence structural stability.

2. Data for the repair material; mainly, strength and deformation properties. *The required values of these have to be decided by the designer.* The real properties have to be verified by testing, or be guaranteed by the producer of the repair material.


The structural analysis can often be made using the same procedures as for the design of new structures. There are differences, however. One possibility, mentioned above, is a reduction of partial safety coefficients. Other important differences are:

1. Mechanical properties of the old concrete and the repair material are not the same. This will influence the stress distribution between the materials at loading. The repaired structure is a sort of *composite structure* and should be treated as such in the analysis.

2. The old structure is already exposed to stresses when repair is made, while the repair is unstressed. This will affect the effectiveness of the repair. This effect is especially marked for pre-stressed structures repaired by unstressed concrete. The design of the repair should be made in such a way that these differential stresses are taken into account.

3. The old concrete has almost no creep deformation left, and small moisture movements. The new repair material might have substantial creep and high early shrinkage. Therefore, stresses might arise at the interface that might lead to bond failure. This risk has to be considered. The risk will be diminished if a repair material is selected that has small long-term deformations. The maximum values of these, used in the calculations, should be stated by the designer, and used for the design of the repair material.

4. When a new concrete “encasement” is cast around an old structure that is relatively cold, big tensile stresses due to early temperature rise in the encasement can easily occur. The effect might be thermal cracking in the encasement and loss of bond. The risk of thermal cracking should always be analyzed by the designer. Maximum values of temperature rise in the repair concrete should be stated. The repair procedure has to be made in such a way that this fixed maximum temperature is not transgressed (e.g. by pre-cooling the repair material).
It is important that the designer of the repair prescribes what tests should be made on the repair material, and on the repaired structure; tests of bond strength, tests of mechanical strength of repair, etc.

If it turns out by the structural analysis described above, that the requirements for load-carrying capacity and safety cannot be met with the repair system selected, new repair systems have to be selected and evaluated in the same way until an acceptable system is found.

The structural evaluation does not have to consider execution of work (besides the risk of thermal cracking described above). Nevertheless, it has to be understood in the structural evaluation that it is possible to perform the repair that is evaluated. Therefore, repair systems that are difficult to execute in a safe way need not be evaluated.

Evaluation of execution of work of different types of repair is described in paragraph 6.4.

6.3.3 Long-term structural stability – service life

Design of the repaired structure as described in paragraph 6.3.2 gives the structural stability directly after repair. If no destructive action occurs in the future, the design is also valid for a long time after repair. Such “steady state” behavior is normally assumed at design of new structures, since then, no “time axis” after 28 days is considered. Required durability is instead secured by selecting material properties that are known to yield long service life.

In the repair situation, one might always assume that continued deterioration in the old structure will occur after repair, although at a reduced rate. However, in the structural design of the repaired structure the structural engineer need not consider future changes in structural stability, but base the analysis on the assumption that repair systems and materials with long service life have been selected. As previously stated, this is also the assumption made for the design of a new structure.

In order to facilitate the analysis of service life of the selected repair system and material, the designer shall, however, furnish information on minimum acceptable data for material strength, material stiffness and bond strength. Such data are also important in conjunction with supervision of the structure, since it gives the basis for decisions concerning whether renewed repair is required.

6.3.4 Repair methods of interest for structural analysis - Examples

Repair methods of interest for analysis of structural stability are such that require a mechanical/structural interaction between old concrete and repair material. Such methods are:

1. Removal of old concrete and replacement by new concrete with adhesion to the old rinsed concrete surface; with or without addition of new reinforcement, with or without fibres in the new concrete. The repair might be a surface repair, or a repair of more extensive damage reaching below the reinforcement level. Damage when this method is used has often been caused by reinforcement corrosion, or by some type of erosive surface attack (frost or acids).
2. Additional concrete cover (reinforced or non-reinforced, with or without fibre) on old concrete without taking any of this away. The damage when this method is used might be caused by reinforcement corrosion that has not yet led to spalling or cracking of the cover.

3. Same as point 1., or 2., but polymer concrete is used instead of cement based concrete.

4. Strengthening by application of fibre composites, steel plates or other strong materials glued to the surface. This method might be used when damage has weakened the strength of concrete, or when the structure is intended to take more load than before repair.

5. Repair of deep damage in the interior part of the old structure. Damage when this method is used has often been caused by some sort of expansive internal attack (ASR, frost, sulphate). Normally deep injection is used. In other cases the structure is strengthened by outer means (like concrete “corset”, or steel “corset”).

Also the Swedish “Öland Bridge” type of repair might be considered, i.e. when a new structure is cast outside the old, without significant mechanical interaction between the two structures directly after repair, but with gradually growing interaction as the inner structure gradually decays.

There are several examples in [6.6] of repair options that can be used for structural repair.

### 6.3.5 Example: Repair of beams

The principles of performing a structural analysis of the repaired structure are the same irrespective of the type of element. The principles are exemplified by the simple case, repair of beams, Figure 6.7.

As can be observed in the figure, beams to be repaired can be divided in three groups. Group 1 includes ordinary beams without pre-stressed or post-stressed reinforcement. Input in the structural analysis is an overall and generic description of how these types of beams can be repaired. The factors that should be taken into account in the structural analysis must be defined. As an example, consider a beam which is going to be repaired on the tension side due to damage caused by corrosion, or some type of erosion. A suitable, and much used, repair technique is to remove the cover to a depth where there is no damage and a low chloride level. Additional reinforcement bars will be placed, and a new cover will be cast.

As shown by Figure 6.7, there are four main options with regard to requirement on strength, and final geometry of the member. These options are the same for all beam types.

**Example; beam repair, option 1**

In this case the goal of the repair is; (i) to achieve the same load capacity and serviceability as was initially required when the structure was built, (ii) to maintain the same geometrical form as it had initially.

**Example; beam repair, option 4**
In this case the goal of the repair is, (i) to increase the load-carrying capacity and/or increase the safety of the structure, (ii) to allow changes in the initial geometry of the beam.

The quality of the repair material to be used (strength, stiffness) and the thickness of this depends on the load situation (location of damage, required strength of repaired structure), but also on properties of the old structure to be repaired (strength, amount of non-corroded reinforcement, dimensions, cover thickness, etc.). The aim of the structural analysis is, (i) to evaluate the most rational repair technique from a structural point of view, (ii) to define quality requirements on the materials and systems to be used for repair, (iii) to define the minimum acceptable levels of bond and other properties of importance for structural stability directly after repair and during the service life of the repaired structure.

The location of damage must be considered in the design, e.g. anchorage zone, tension zone, compression zone, shear zone. Different repair techniques are often needed for different location.

As stated in paragraph 6.3.2, the design is made according to traditional methods used for design of new structures. The main difference is that it might also be necessary to consider stress distribution between the old and new concrete, and its effect on deformation and strength. Another difference is that partial safety factors on concrete in the old structure might be reduced, because more reliable information than for a structure yet to be built, can be obtained by testing the old structure.

Practical evaluation methods for beams, but also for other structural members (slabs, columns, panels), are described in Annex O.
6.4 Evaluation with regard to execution of work

Additional information is given in Annex P.

6.4.1 Introduction

Different frequently used general procedures used in repair are described and analyzed in this document. Frequent procedures and effects of these are:

(i) Methods of removing the damaged concrete from the old structure, and their effect on the surface quality and bond to the repair material.
(ii) Methods of injecting cracks and porous concrete, and their effect on the permeability and strength of the “old concrete”.
(iii) Methods of placing the repair material on the old structure, and their effect on bond and other properties of importance for the behavior of the repaired concrete.
(iv) Methods of characterization of the surface quality after removal of the damaged concrete.
(v) Need of different types of formwork.

Other factors to consider in an evaluation are:

(i) Safety of workers and public.
(ii) Rapidity of different repair options.
(iii) Impact on environment.
(iv) Disturbance to function of the structure or to the surroundings during repair.

Many of the procedures used in repair will be the same regardless of the type and the cause of damage. For instance the methods for removal of a damaged reinforcement cover are the same for all damage causes that have led to deterioration of the outer part of the concrete. The decisive factors concerning removal of damaged concrete are the depth, location of damage on the structure, environmental conditions, requirements regarding physical and mechanical properties of remaining concrete, etc.

Therefore, the evaluation of execution can normally be carried out regardless of the type and cause of damage. Only the type of repair depends on the type and cause of damage, but normally not procedures used in execution of repair. There are exceptions, however, where the execution is directly related to one single damage cause, like cleaning of corroded reinforcement or application of corrosion inhibitors.

Certainly, all decisive factors needed for choice of repair method have to be determined and established before the execution. For instance, the thickness of the concrete layer, which has to be removed, has to be determined before the start of the execution of repair work.
6.4.2 Topics of repair action

Figure 6.8 shows 12 topics, or “elements”, involved in repair work. The topics are not given in any particular order. Some can be part of a repair method, while some may also serve as complete repair methods. The execution of any topic given in Figure 6.8 is independent of the type and the cause of damage. This will be shown by two examples.

Example 1 (Figure 6.8)

Consider the case were the reinforcement cover is damaged by chloride initiated corrosion. It has been decided that the following 4 or 6 topics shall be involved:

1. The concrete should be removed to a certain depth below the surface of remaining concrete.
2. The new concrete surface shall be cleaned from dust and other pollution.
3. The reinforcement should be cleaned from chloride and other pollution.
4. A new concrete cover should be cast (and cured properly) in order to protect the reinforcement, and to restore structural stability.
5. The repair method may also include application of “corrosion inhibitors”.
6. For aesthetical reasons a protective non-reinforcing surface layer on the cover, like polymer-based paint, will be used.

Another case is when the concrete cover has been damaged by some type of physical attack, for instance salt-frost attack. Even in this case, the depth of the concrete, that has to be removed, must be determined before repair work starts. Exactly the same topics in repair as were involved in Example 1 (except the use of inhibitors) can be used in order to repair the structure.

Example 2 (Figure 6.8)

Consider the same case as Example 1. In places where active corrosion is going on the chloride contaminated concrete has to be removed, and the same procedure as in Example 1 has to be used and be evaluated. In other parts, corrosion has not yet started, because the threshold concentration has not reached the bars. Surface cracks exist, however, in these parts. In order to stop (retard) ingress of chloride it is decided to remove chloride infected concrete from these parts, and besides to use crack injection of some type (cement-based or polymer-based). Therefore, also execution of injection has to be evaluated. This additional step is shown in Example 2 in Figure 6.8.

6.4.3 Evaluation of topics of repair action - principles

Each topic/element in a repair can be performed in different ways, and by different methods and materials. Examples are shown in Figure 6.9 and Figure 6.10. All these options should be evaluated.
Topics of repair actions

Example 1: Chloride initiated corrosion

Example 2: Chloride initiated corrosion. Cracking

Figure 6.8  Topics of repair actions and examples of repair methods including some of the actions
Topics of repair actions

Removal of damaged concrete
Application of material replacing the old concrete
Injection
Replacement and additional reinforcement
Chloride extraction and realkalisation
Cathodic protection

Optional techniques
1-Blasting
2-Milling
3-Mechanical hammering
4-Water-jetting
5-Grinding
6-Sawing
7-Drilling

Methods of application
1-Casting
2-Shotcreting
3-Grouting
4-Patching

Type of injection
1-Surface injection
2-Internal injection

Type of reinforcement
1-Non-tensioned reinforcement
2-Prestressed reinforcement

Material
1-Concrete with hydraulic binders
2-Fibre-reinforced concrete
3-Polymer modified concrete

Type of injection
1-Surface injection
2-Internal injection

Type of reinforcement
1-Non-tensioned reinforcement
2-Prestressed reinforcement

Material
1-Polymer based
2-Cement based

Material
1-Carbon steel
2-Stainless steel
3-Reinforced polymer rod

Optional materials

Figure 6.9 Methods to perform the repair actions, part 1

Topics of repair actions

Cleaning of concrete surface
Drying of the concrete surface
Application of non-reinforcing surface layer on the cover
Application of reinforcing surface layer on the cover
Cleaning of reinforcement
Inhibitors

Optional techniques
1-Water washing
2-Vaccum cleaning
2-Steam cleaning
3-Water blasting
4-Abessive blasting
5-Flame cleaning
6-Mechanical cleaning
7-Chemical cleaning

Methods of application
1-Hydrophobic surface treatment
2-Impregnation of polymers
3-Cement-based coating
4-Polymer-based coating
5-Painting

Material
1-Steel plate
2-Reinforced polymer plate
3-Fibre fabrics

Optional techniques
1-Blasting
2-Wire-brush

Figure 6.10 Methods to perform the repair actions, part 2
6.4.4 Evaluation parameters

Each topic of repair action, and each optional technique within the action (Figure 6.8, Figure 6.9 and Figure 6.10), should be evaluated with regard to the following aspects, called evaluation parameters:

i. Working environment, i.e. creation of dust, noise, vibration, hazardous substances affecting the workers, and any other impact on workers caused by execution of repair work.

ii. Effects of non-technical nature, such as disturbance of traffic, noise and other types of annoyance.

iii. Effects of climatic conditions during repair work; effect of cold, hot, moist weather.

iv. Simplicity or difficulties of applying the technique.

v. Degree of applicability with regard to the type of structure and location on the structure.

vi. Need of additional equipments, like forms and scaffolding

vii. Speed of the operation and factors influencing that.

viii. Influence of the action/method on the physical and mechanical properties of the remaining and new parts of the structure.

6.4.5 Evaluation of execution of work - example

In Table 6.1 an example of evaluation of techniques used in the topic “removal of damaged concrete” is presented. The table (somewhat revised) is taken from a Swedish book on concrete repair, [6.7].
Table 6.1  Example of evaluation of the repair action removal of damaged concrete, [6.8]

<table>
<thead>
<tr>
<th>METHOD</th>
<th>WORKING ENVIRONMENT</th>
<th>NON-TECHNICAL ISSUES</th>
<th>CLIMATIC CONDITIONS</th>
<th>APPLICATION SIMPLICITIES/DIFFICULTIES</th>
<th>APPLICABILITY WITH REGARD TO TYPE OF STRUCTURE</th>
<th>NEED OF ADDITIONAL EQUIPMENT</th>
<th>SPEED OF OPERATION</th>
<th>INFLUENCE ON PROPERTIES OF THE STRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blasting</td>
<td>Creates dust and noise. If the surface is contaminated additional protection is required.</td>
<td>Applied to infrastructure construction the method may cause disturbance of traffic and create dust and noise.</td>
<td>No restrictions.</td>
<td>Suitable for removing thin concrete layers.</td>
<td>Applicable to all types of structures.</td>
<td>Scaffolding may be needed for vertical structures. Equipment for suction of dust and particles often needed.</td>
<td>See blasting.</td>
<td>Micro-crack free surface. Good bond properties. Takes away stain from reinforcement.</td>
</tr>
<tr>
<td>Milling</td>
<td>See blasting.</td>
<td>See blasting</td>
<td>No restrictions.</td>
<td>Suitable for making grooves for additional reinforcement. Suitable for removing limited and thin concrete layers</td>
<td>See blasting Suitable for making grooves for additional reinforcement.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>See blasting.</td>
</tr>
<tr>
<td>Mechanical Hammering</td>
<td>See blasting. Also vibrations and noise</td>
<td>See above. Also heavy noise.</td>
<td>No restrictions.</td>
<td>Suitable for removing thick concrete layers. Applicable for making grooves for additional reinforcement.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>Partly damages the remaining concrete. May damage the reinforcement.</td>
<td></td>
</tr>
<tr>
<td>Water-jetting</td>
<td>No dust, low noise and no vibration.</td>
<td>Minor disturbance. If the surface is contaminated the water should be taken care of.</td>
<td>Freezing risk at low temperature</td>
<td>See mechanical hammering.</td>
<td>See blasting. Should be used with care for indoor structures.</td>
<td>Scaffolding may be needed for vertical structures. Water must be taken care of in indoor work</td>
<td>Rapid method.</td>
<td>See blasting.</td>
</tr>
<tr>
<td>Grinding</td>
<td>See mechanical hammering.</td>
<td>See blasting.</td>
<td>No restrictions.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>See blasting.</td>
</tr>
<tr>
<td>Sawing</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>No restrictions.</td>
<td>Suitable for removing parts of the structure/structural members. Suitable for making grooves for reinforcement.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td></td>
</tr>
<tr>
<td>---------</td>
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<td>------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>Drilling</td>
<td>See mechanical hammering.</td>
<td>See mechanical hammering.</td>
<td>No restrictions.</td>
<td>Suitable for making openings and grooves for reinforcement.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td>See blasting.</td>
<td></td>
</tr>
</tbody>
</table>
6.5 Evaluation with regard to environment and health

Additional information is given in Annex Q.

6.5.1 Introduction

In the evaluation process it is important that environment and health factors are considered in the whole concrete repair life cycle – from the production of repair material to demolition and waste disposal. In this paragraph it is described how such an evaluation can be done.

We have to face the fact that the experience of this type of evaluation is relatively limited and the technique is still under development within many types of industry and processes. It can also be stated that a lot of facts and figures are still missing, meaning that today it is not possible to make a complete evaluation resulting in figures for different environmental impact, like emissions into air and water, energy consumption etc. However, it can serve as a useful tool for comparing different repair methods from an environmental aspect. The evaluation process can also serve as a type of environment and health checklist for concrete repair methods.

Instead of starting with complicated and extended evaluation processes, with high risk of giving misleading results, it is therefore recommended to start with checklists and relatively simple comparisons of different repair methods.

Another important point in evaluation of environmental impact is the lifetime of the repair. The impact on environment and health has a very strong relation to the lifetime of the repair. When comparing different repair methods it has to be done on basis of the expected lifetime of the repair. In a comparison, “Method 1” could be evaluated as more environmentally friendly than “Method 2”, but if the lifetime for “Method 2” is expected to be double that of “Method 1”, the total effect could be more favourable than using “Method 1”.

The methods described here should, therefore, be used with “common sense”. It is recommended that initially a survey is carried out, to find the most important questions and risks connected to the evaluated repair process. Subsequently, these points could be further investigated and evaluated before a final decision can be made.

The methodology described in this chapter is a summary. For more details see Annex Q.

6.5.2 Methodology for evaluation - principles

The most thorough method for evaluating the environmental effect would be an Environmental Impact Assessment (EIA), or a Life Cycle Analysis (LCA). Since EIA is site specific, and more of a process than a method, it cannot be applied in the evaluation of a repair method. However, some of the methods used when performing an EIA may be suitable. To carry out an entire LCA on concrete repair might be too data demanding, but the “cradle to grave” thinking should be applied, and parts of such evaluation methods could be suitable.
In an evaluation the main focus is often on the effect of the repair on ecology, but other factors, such as impact on workers during application (see paragraph 6.4), and effects on a third party should also be considered. The reason for this is that some repair methods can produce pollutants and noise, making them unsuitable for use in some environments, like residential areas. Indoor environment should also be considered. Even if most concrete repair is executed in outdoor environment, there may be some cases where the indoor environment should be considered, e.g. at repair of floors. Thus the evaluation is made in three steps:

- Evaluation of ecology (external environment)
- Evaluation of indoor environment
- Evaluation of health and safety

In the literature, methods and models have been suggested for environmental evaluation of new structures; examples are references [6.8] and [6.9], using the life cycle perspective.

These methods are used as a base, and with some adaptation, they can be applicable to the concrete repair process. In the repair process the choice is not as extensive as it is for a new structure. For example the materials, design and heating system are already chosen, meaning that many parameters influencing the total ecology of the structure are already fixed and cannot be changed. Thus, some parts of the evaluating systems for new structures can be excluded or at least simplified in the repair case. Thus, the evaluation described here includes the steps in Figure 6.11.

**Figure 6.11  Life cycle steps in the ecology and health evaluation**
Each step in the process is then evaluated with regard to a number of indicators referring to ecology, indoor environment and health and safety.

6.5.3 Evaluation of concrete repair with regard to ecology

A number of indicators are chosen for evaluation, or calculation, of the environmental effect during the concrete repair life cycle. For the ecological evaluation the effects to be considered are:

- Consumption of non-renewable raw materials
- Consumption of non-renewable energy
- Emissions to air including CO₂, CO, SO₂, NOₓ, dust
- Emissions to soil and water
- Effect on ground

Table 6.2 Summary table for External Environment Parameters considered in the ecological evaluation of a repair method or activity

<table>
<thead>
<tr>
<th>No.</th>
<th>LIFE CYCLE PHASE</th>
<th>Type of energy</th>
<th>Raw materials</th>
<th>Emission to water</th>
<th>Emission to air</th>
<th>Effect on ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>CONSTITUENT MATERIALS</td>
<td>A</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>- Raw materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>- Recovered material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>- Origin of raw material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>PRODUCTION OF RAW MATERIAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>- Production process</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>DISTRIBUTION OF FINISHED PRODUCT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>- Production area / country</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>- Transport method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>- Distribution type</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>- Packaging</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>EXECUTION PHASE</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4.1</td>
<td>- Repair execution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>- Product adaption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>USAGE PHASE</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>5.1</td>
<td>- Operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>- Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>- Service life</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>DEMOLITION</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>6.1</td>
<td>- Dismantling</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>7.</td>
<td>WASTE PRODUCTS</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>- Reuse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>- Recycling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>- Energy production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td>- Tipping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>- Dangerous waste material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

More detailed information on life cycle phases and environmental parameters is given in Annex Q.

It can be stated again that a lot of information needed is still missing. Therefore, one has to accept that some part of the table will remain empty. However it’s often useful to make an approximate assumption making it possible to compare two or more repair methods with each other.
In the Swedish Building Products Declarations [6.10], the manufacturer/supplier should declare substances in a building material with certain limits. These limits can of course vary between countries.

A specific repair material in the repair process is declared in one declaration. Thus, the total impact on ecology of materials in a repair process is the combination of several declarations. The target is that the input data should be expressed in quantitative terms, although until more data are available qualitative data has to be accepted.

There are today several ongoing projects dealing with collecting and processing of available data so that it can be used as input to life cycle assessments, and other ecology evaluation processes.

As an example a LCI/LCA project run by the Cement Industry could be mentioned. One outcome from this project has been an environmental computer programme called “EcoConcrete” for providing LCA information on concrete structures. Access to the EcoConcrete program is limited to people who have passed a special training course.

Another project called “Eco-Service is sponsored by EC under Framework program 5 and covers research on the construction industry in relation to environmental sustainability. Within the project is an objective to create a baseline for the environmental impact from the production and use of concrete products in a life cycle. It is noted that information is needed in the areas of “Assessment of the impact from chemical additives” and “Possible leaching of harmful substances from concrete with residual products”.

Repair products to be placed in contact with drinking water need to meet specific requirements. There is a project running within the organization of European Commission (CEN/TC 104) with the goal to outline these requirements. A draft positive list of approved constituents of products for contact with drinking water is at the moment discussed but not yet agreed.

When it comes to concrete admixtures, EFCA (European Federation of Concrete Admixtures Association), have published an Eco-profile for plasticizers and superplasticizers, [6.10], [6.11]. The Eco-profiles include quantitative data for raw materials, emissions to air, emissions to water, solid waste and total energy per kg admixture. These eco-profiles are derived from primary data supplied by EFCA and its member organizations and verified by an independent consultancy from The Netherlands.

Information for data and the assessment procedure on dangerous chemicals are published by the European Chemicals Bureau (ECB), [6.12].

6.5.4 Evaluation of concrete repair with regard to indoor environment

Many people are reporting health problems related to the indoor environment. The symptoms are often asthma and allergies. There is great uncertainty today about what is causing the symptoms, and research is going on to try to find the relationship between
ill health and the choice of building material, design and construction method. These relations seem to be very complex. The information we have today indicate that the determining factor for the quality of the structure is how the materials have been built in to the structure rather than the individual properties of a specific material.

When choosing material for repair, a material without emissions of any harmful or irritating substances into the indoor atmosphere should be used. The material must also have good resistance to the various stresses to which they are exposed – not least moisture. This is of course valid for materials in new as well as in repaired structures.

As the processes leading to health problems caused by indoor environment are still not fully understood, this paragraph should be considered as a summary of factors to be taken into consideration by the various members involved in the concrete repair process.

Even in the case of indoor environment there is a shortage of facts and data meaning that the evaluation process should be seen more as a checklist than a complete evaluation tool. It can also be used as a tool for comparing the impact of different repair methods or repair materials on the indoor environment. This evaluation of indoor environment is only relevant when the repair activity takes place in an indoor structure. In the case of an outdoor structure this part of an evaluation can be left out.

Table 6.3  Summary table for indoor environment

<table>
<thead>
<tr>
<th>8.1</th>
<th>Harmful substances</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>Self emissions</td>
</tr>
<tr>
<td>8.3</td>
<td>The repair process</td>
</tr>
<tr>
<td>8.4</td>
<td>Surrounding materials</td>
</tr>
<tr>
<td>8.5</td>
<td>Basic data for recommended conditions for surrounding material</td>
</tr>
<tr>
<td>8.6</td>
<td>Operation and maintenance</td>
</tr>
<tr>
<td>8.7</td>
<td>Sound level</td>
</tr>
<tr>
<td>8.8</td>
<td>Electric and magnetic fields</td>
</tr>
</tbody>
</table>

More information on indoor environmental parameters is given in Annex Q.

6.5.5 Evaluation of concrete repair – health and safety during execution of work

Questions related to health and safety for the workers during handling of the repair materials are regulated in the legislation. The work on classification and labelling of chemical products is done on an international basis. This work has a high priority in Europe and the legislation within EC became common since about two years ago.

Manufacturers, importers and others, who place a product on the market for professional use, shall provide information on the properties of the product from the viewpoints of risk and safety.

Safety data sheets need not be provided when products are marketed, sold or supplied in consumer packaging in retail trade to the general public. Safety data sheets for such products shall on the other hand be made available if requested by a professional user.
All marketed substances and preparations placed on the European market must be classified and labelled in accordance with Directive 67/548/EEC (substances) and 1999/45/EC (preparations). The evaluation results in classification of the chemical product concerning physical-chemical properties, health and environmental effects. The information is communicated on the label and in the 16-point Safety Data Sheet (91/155/EC). Therefore Classification and Labelling is a useful tool for risk management of chemical products.

For evaluating the health and safety parts, data given in the 16-point Safety Data Sheet (point 1, 2, 3, 10, 11 and 15) can be used.

1. Identification of the substance/preparation and company
2. Composition/information on ingredients
3. Hazards identification
4. Stability and reactivity
5. Toxicological information
6. Regulatory information

The above-mentioned points contain the most important information for the evaluation of health and safety risks during the execution phase. This is essential information in the evaluation process at a state where two or more concrete repair methods are compared before the final choice is made. Other information in the Safety Data Sheet deals with protective measures and recommendations for handling. Of course this information is very important later in the process, for all people involved in the handling of the product.

In point 12 in the Safety Data Sheet ecological information is given. As this information is treated in a separate evaluation it is not treated here.

The above-mentioned paragraphs are taken from the EC Directive 91/155/EC valid December 2003. It’s always necessary to check the latest published Directive for the evaluation process.

More detailed information on the above mentioned paragraphs is given in Annex Q.

6.5.6 Example of an evaluation

The repair to be studied and exemplified is: Patch Repair (Annex H).

**Damage:** Deteriorated outer part of concrete.

**Method:** Removing of damaged concrete and application of new repair mortar using cement based mortar mixed at jobsite. In this case the indoor environment of the structure will not be effected meaning that only external environment and health and safety are evaluated.

**Evaluation of the concrete repair mortar with regard to ecology:**
**Name of product:** “Polymer modified cement based repair mortar”  
**Name of Manufacturer/Supplier:** “Supplier”  
**Environmental policy/Certification/Registration:** Yes/ISO 14000/No….

**Product information:**
- Product: Cement based one component repair mortar in powder
- Constituent material in structure: 100% concrete
- Safety data sheet: Yes
- Classification: Xi (irritating)

<table>
<thead>
<tr>
<th>No.</th>
<th>LIFE CYCLE PHASE</th>
<th>Type of energy</th>
<th>Raw materials</th>
<th>Emission to water</th>
<th>Emission to air</th>
<th>Effect on ground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>CONSTITUENT MATERIALS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>- Raw materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Standard Portland cement</td>
<td>Fossil and electricity</td>
<td>Limestone and sand</td>
<td>CO₂, NOₓ, SO₂</td>
<td>Limestone open-cast mine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aggregate, “crossed” and natural</td>
<td>Electricity and fuel for transport</td>
<td>Rock, nature</td>
<td></td>
<td>Open-cast mining*, gravel pit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Admixtures</td>
<td>Acrylic polymer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>- Recovered material</td>
<td>Energy in cement production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>- Origin of raw material</td>
<td>Europe</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>PRODUCTION OF RAW MATERIAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>- Production process</td>
<td>Electricity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>DISTRIBUTION OF FINISHED PRODUCT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>- Production area / country</td>
<td>Sweden</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>- Transport method</td>
<td>Truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>- Distribution type</td>
<td>Truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>- Packaging</td>
<td>Paper bag</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>EXECUTION PHASE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>- Repair execution</td>
<td>The mortar is usually mixed with electrical hand mixer and handapplicated at jobsite.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>- Product adaption</td>
<td>Small quantities are mixed during proceeding of work. No mixed mortar left.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>USAGE PHASE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>- Operation</td>
<td>Does not effect operation of structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>- Maintenance</td>
<td>No need</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>- Service life</td>
<td>Depends on environment, specific structure etc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>DEMOLITION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>- Dismantling</td>
<td>Normally no specific need.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>WASTE PRODUCTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>- Reuse</td>
<td>n.a.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>- Recycling</td>
<td>Yes, both material and packaging</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>- Energy production</td>
<td>Packaging: yes, material: no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td>- Tipping</td>
<td>Inert material: no restrictions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>- Dangerous waste material</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Evaluation of the concrete repair mortar with regard to health and safety:**

1. **Identification of the product and of the company:**
   - Product name: “Polymer modified cement based repair mortar”
   - Manufacturer/Supplier: “Supplier”
2. Composition/information on ingredients/classification of substances
Cement: 25-50%, Xi (irritating), R-phrase 41, 37/38. Contains chromium (VI). May produce an allergic reaction.

3. Hazards identification
Xi  Irritant
Information on hazards to man and to the environment:
37/38 Irritating to respiratory system and skin
41 Risk of serious damage to eyes
Contains chromium (VI). May produce an allergic reaction

10 Stability and reactivity
Materials to avoid/dangerous reactions.
Hazardous reactions possible with: Acids
Thermal decomposition and hazardous decomposition products: No decomposition if used as prescribed

11 Toxicological information
Sensitization: sensitive persons can observe allergic reactions.
Experience on humans:
When skin contact: May cause irritation.
When eyes contact: Irritation
When inhalation: Irritation
When swallowed: Small amounts may cause considerable health disorders.

15 Regulatory information
Labeling according to EEC Directive:
The product is classified and labeled in accordance with EC directives/the relevant national laws.
Danger symbols: Xi Irritant
R phrases:
37/38 Irritating to respiratory system and skin
41 Risk of serious damage to eyes
Contains chromium (VI). May produce an allergic reaction.
S phrases:
26 In case of contact with eyes, rinse immediately with plenty of water and seek medical advice
39 Wear eye/face protections

6.6 Evaluation with regard to economy
An application example is given in Annex R.

6.6.1 Introduction
Economical evaluation is an important part of an asset management system, and is used for different purposes. Two essentially different purposes are, (i) to fit the annual repair
and maintenance costs within a certain budget, (ii) to predict the cost of a certain repair and remedial action to be applied on a certain structure or structural member.

**Annual repair and maintenance cost**

This type of evaluation is normally conducted for a large number of functionally similar objects within an asset portfolio. The object can be a structure, for instance a bridge, or a certain part of a structure, for instance deck or side beam of a bridge.

A very important input for such an evaluation is the degradation function which relates the age of the structure, or the structural member, to a certain degradation level or class. Another important input is the cost to upgrade a structure from a level/class of degradation to a required level/class of “functionality” or “quality”. The required level/class of functionality may be defined as a condition which, besides the usual maintenance measures, does not require any repair or remedial measures during a prescribed period of time. The functionality and quality can be described in different ways. They may be related to the structural safety or load bearing capacity, etc, see paragraph 6.3.

For stocks consisting of a large number of structures the functions can be determined by means of experience and statistics. The functions are not directly based on a certain damage mechanism or damage type, but they only express the general condition of the stock. However, in some cases an underlying damage mechanism may be pointed out. For instance, the causes of deterioration for many edge beams subjected to de-icing salts are chloride initiated corrosion and salt-frost damage. Hence in this case the degradation function is related to the cause of damage.

**Prediction of the cost of a certain repair and remedial action**

This type of evaluation concerns with the cost of a certain repair or remedial action applied to a structure, or a structural member. The purpose of this evaluation is to compare the costs of different repair principles, main repair methods, or repair systems. The evaluation may be performed in different manners, and with different aims. The evaluation may only concern the partial or total costs of a repair and remedial action at the present time, i.e. at the time of execution, or it may also consider the total life-time costs of the action, i.e. “Life-Cycle-Cost (LCC)”.

This chapter deals only with the second type of the economical evaluation, i.e. “Prediction of the cost of a certain repair and remedial action”. A comprehensive description of both types of evaluation can be found in [6.18] and [6.7].

Repair and remedial actions prolong the service life of the structure, and can be considered as an investment. When a decision about an investment is made, many factors have to be considered. The investment analysis is one important part of the facts and figures to be considered in the decision, yet it is only one of many aspects. Other aspects are risks, environment, market shares, good-will etc. It is a hard task to provide an all-embracing tool for an investment analysis, which at the same time can meet different owner’s needs, and be applicable for different types of assets. This chapter provides only a method to compare different repair and remedial actions. This chapter
does not provide a straightforward calculation routine, which can lead to selection of the most profitable repair system. The method presented here should rather be regarded as a way to highlight the issues of importance.

The method of investment analysis will be presented within a LCC context because in this way it is possible to account for costs caused by failure, environment tolls, demolition, risks, etc. However, it should be noted that some of the decisive events/factors in an economical evaluation happen in a remote future, and the future is not easy to predict at least when the economical development is concerned.

6.6.2 LCC and its components

In the life cycle calculations (LCC), the investment is looked at from cradle to grave. When using this method it is important to look at the investment from an economical and a technical point of view, so all costs will be found and evaluated. The calculation is much more detailed than an ordinary investment calculation.

A LCC is often showed as an iceberg. The part that is visible, above the surface, is the direct investment cost, but underneath the surface are other sometimes even more important costs, which are called the operational costs. The operational costs must be part of the investment otherwise the investment will be incorrect. The costs depend certainly on the type of asset, how management is organized, which regulations exist, etc. In [6.18] and [6.7] different cost entries for bridges are presented. Below, some cost entries are generically presented.

The net total life cycle cost of a structure, $C_{NT}$, includes several costs and return entries, and can be expressed as follows:

$$C_{NT} = C_C + C_I + C_M + C_R + C_F + C_U + C_D + C_E + C_O - R_{RE} - R_{VI} - R_{RS} - R_U - R_O$$  \hspace{1cm} (6.1)

Where $C_C$ is the construction cost, $C_I$ the inspection cost, $C_M$ the maintenance cost, $C_R$ the repair cost, $C_F$ the failure cost, $C_U$ the user cost, $C_D$ the demolition cost, $C_E$ the environmental toll cost and $C_O$ the other costs, $R_{RE}$ is the rental return, $R_{VI}$ the value increase, $R_{RS}$ the residual value, $R_U$ the user return and $R_O$ the other returns.

The equation may be extended to include other types of the cost and return entries, or be shortened to include fewer entries. Furthermore, all cost entries in the equation may consist of several subentries.

The content of such an equation depends on the purpose of the analysis, type of asset, and will certainly vary from owner to owner. Several entries in the equations are interrelated, which, if carelessly used, can lead to erroneous conclusions. Some examples are given below:

- High construction standards; if these can be equated to a high construction cost, it may decrease the need for maintenance, and may postpone the time of repair. These may reduce the stop time and the costs of user or, due to the higher rents and tolls, increase the cost of the user.
A newly renovated building means increased value for the owner and a higher rent for the user.

The LCC analyses should be conducted cautiously, and the purpose of the analyses should be clear.

When two repair methods are compared, it is not necessary to include all type of costs, i.e. similar cost entries in the repair methods can be disregarded. Equation 6.1 can be reshaped in order to be used for estimation of repair costs. The elements included in the equation vary from case to case. Some elements are presented in paragraph 6.6.4 and 6.6.5, and in the application example presented in the Annex 6. Further elements can be found in [6.18] and [6.7].

### 6.6.3 Methodology

#### Mathematical tools

All entries in the equation 6.1 should be discounted to a reference time. Normally the present time is chosen as the reference time. The present time is normally the time that the investment is made.

The present value of the cost or the return entry \( i \) which will incur after \( j \) years, \( x_{i,j} \), can be converted to the discounted value \( X_i \), i.e. the value at the present time, by means of following equation:

\[
X_i = \frac{x_{i,j}}{(1 + r)^j}
\]

\[
r = \frac{1 + r_{\text{int}} - 1}{1 + r_{\text{inf}}} \quad \text{(6.3)}
\]

where \( r \) is the discount rate, \( r_{\text{int}} \) interest rate, \( r_{\text{inf}} \) inflation rate.

Equation 6.3 is one way of calculating the discount rate, [6.7] and [6.8]. The discount rate can also be expressed as the difference between the interest rate and inflation rate. However, the equation 6.3 is the theoretically correct way of expressing discount rate as a function of interest rate an inflation rate.

In practice the discount rate depends on many generally unspecified factors and there is no formula for its calculation. In general discount rates are significantly higher than the interest rate after inflation has been taken into account. This is primarily because the discount rate has to incorporate the risk of premature redundancy of the structure. The discount rate varies from country/company to country/company.

#### Application example 1

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The cost of a repair action \((i = 1)\), which will be conducted 8 years \((j = 8)\) from now, is estimated €100000 \((x_{i,8} = 100000)\), the interest rate is 5\% \((r_{int} = 0.05)\) and the inflation rate is 3\% \((r_{inf} = 0.03)\). The present value of the repair action \((X_i)\) should be estimated. The discount rate \((r)\) is calculated by means equation 6.3, which gives \(r = 0.02\). Then \(X_i\) is calculated by means of equation 6.2, which gives \(X_i = 85349\). Now this cost is comparable with, and can be added to, the other costs occurring at the present time, or will occur in the future but are converted to the present time.

Any individual cost entries, \(C_X\), in equation 6.1 consist of a number of sub-entries. For instance the repair cost \(C_X\) is sum of a number of sub-cost entries. The total cost is given by the following equation:

\[
C_X = \sum_{i=1}^{n} C_{Xi} = \sum_{i=1}^{n} \frac{c_{mi,j}}{(1 + r)^j}
\]

(6.4)

Where \(C_{Xi}\) is the discounted value of the sub-cost entry number \(i\), \(n\) is number of the sub-cost entries. It should be noted that for the sake of simplicity, all costs are presented as discounted values. A cost which occurs at the present time can be accounted for by using \(j = 0\).

The costs, and the returns, are sometimes recurrent. If the events have constant period and payments, their discounted total value can be calculated by means of the following equation [6.9]:

\[
Y_i = y_i \cdot \frac{1 - (1 + r)^{-km}}{[(1 + r)^m - 1]}
\]

(6.5)

\[k = \text{trunc} \left( \frac{N - 1}{m} \right)\]

where \(y_i\) is the amount of the periodical entry, for instance annual payments, \(Y_i\) is the discounted summation of all payments during the service life \(N\). \(m\) is the length of the period, number of years between the payments, and \(k\) is the number of the periods during the service life \(N\). Truncation (trunc) means that the lower integer of the calculated value is used.

Equation 6.5 is further illuminated in the Addendum at the end of this chapter.

**Application example 2**

Assume that the cost of the maintenance is €5000 every third years, service life of the structure is 30 years, and the discount rate is 2\%. The total discount cost of the maintenance should be calculated.
An application example for different repair scenarios is provided in Annex R.

Uncertain factors

Certainly most of the costs, which occur now or in the near future, can be estimated fairly well. However, factors the value of which must be estimated over a long period of time, are very uncertain, and may be decisive for the results of the economical evaluation. Three factors are very important, namely, the length of calculation period, the discount rate and the actual cost of the action in the future.

Assume that a newly developed repair system contains a component that cannot be dumped without paying a dumping toll. Some day the repair system will be removed and the toll should be paid. The total present cost of the component is the sum of the purchase cost, the cost of application, the discounted value of the removal cost, and the discounted dumping cost. The purchase and application costs occur at the present time, and are not difficult to determine. However, the two last costs can be rather uncertain to estimate. If the calculation period is long, and the discount rate is high, the present value of the component will be lower than the case where the calculation period is short and the discount rate is low. Furthermore, the longer the period, the more uncertain is estimation of the labour cost, dumping cost etc.

Example

Three repair options are being compared with each other. Assume that the structure, which will be repaired, should have 50 years service life after the repair. The first repair option \((RO_1)\) includes a repair system which can protect the structure during 25 years, and should be repeated every 25 years. The second repair option \((RO_2)\) includes a repair system which can protect the structure during the remaining 50 years of the service life of the structure. The third repair option \((RO_3)\) is that the repair will be postponed for 5 years, and after 5 years repair will be made. During the 5 years, special inspection and maintenance measures will be taken, which increase the inspection and maintenance costs. These options are studied in the application example in Annex R. Nevertheless, the results demonstrate that the discount rate has great influence on the outcome of the analysis. The difference between the total discounted costs is highly dependent on the discount rate.

6.6.4 Basic calculation factors

The information about basic calculation routines must come from the owner.

Service life and the economical life time
The calculation period is needed for determination of the total repair cost. The length of calculation period can be equated to the service life of the structure required by the owner. Such repair systems which have longer service life than required, and are able to extend the service life of the structure beyond the required service life, may induce a surplus value, which depends on the type and usage of the structure. The surplus value is only relevant if; (1) the structure continue in use after the end of the calculation period, and (2) the value of the rest materials exceeds the cost of dumping. However, it is the owner’s decision whether to take into account the surplus value or not.

The calculation period for the repair systems which shorter service life than that required for the structure can be equated to the expected service life of the repair system. This may lead to several applications of the same repair system during the remaining service life of the structure.

The service life of a repair system may be determined by means of theoretical models, or by means of experiences from previous repairs. There is not much information about the service life of the repaired structures. However, some owners may have information about how repairs performed in their asset inventory.

**Interest, discount and inflation rates**

The discount rate or rate of return (often used in private sector) are not constant, and fluctuate. The rate varies between countries and between companies. The rates are normally decided by the owner.

**Others**

Other important factors are taxes and their effects on the results. Furthermore, it should be pointed out whether the repair is considered to be an investment or a traditional maintenance (depreciation).

### 6.6.5 Examples of repair costs

**Initial costs**

The information about the initial costs of repair, which should not be mixed by the initial investment when the structure was being built, comes from the contractor and the owner. The initial costs correspond to the investment costs, which include the planning of the repair by the owner, and a tender from the contractor. The initial cost may include the establishment of work site, scaffold, extra ordinary works in the periphery such as roads, fence, acoustic barriers and other environmental protecting measures, etc. Factors to be considered are as follow:

- Repair planning
- Location of the structure, type of environment, communications, etc
- Type of structure and structural element
- Type and extent of the damage
Stop costs

The information about stop costs comes from the owner.

The stop costs may include costs to the owner, to the user, or both. Traffic delays caused by bridge repairs may include costs to the user, for instance transportation companies, and to the owner, for instance decreased way tolls. Another example is the lost of income from the car parks and apartment houses.

The stops may also involve lost of market share and good-will.

Models to determinate stop costs can be more or less complicated depending on the type of structure and type of repair. It is easier to establish a model which estimates the stop costs of the buildings, with almost constant and known incomes and expenses, than to establish a model which estimates the stop costs of roads, bridges and building complexes such as malls.

Models for estimation of traffic stop costs can be found in [6.18] and [6.7].

Operational costs and returns

The information regarding operational costs/returns can come from the owner and the contractor. The information may be based on their own experiences. The operational costs/returns can be originated from; reduction/increase of income from the assets, reduction/increase of market shares, and good-will, etc. Other sources of the operational costs/returns are those related to the effects on the environment, and costs/returns imposed to the third party and changes on the increased insurance value.

Maintenance costs

The data regarding maintenance costs can come from the owner and the contractor. The data can be based on the experience, i.e. data from the similar repairs, or results of the empirical and semi-empirical models. The data may include the service life of a repair system and their impact on the service life of the structure. The data may also be used to estimate the failure costs. The probability of the failure is a decisive factor in determining the costs of failure. Factors influencing the maintenance costs are as followed:

- The start time, duration, recurrence, and type of maintenance
- Type and contents of the maintenance work
- Costs of the maintenance work and its future development
- Consequences of the postponed maintenance
- Need of education for the workmanship

Residual value
The information about residual value comes from the owner and the contractor. Issues to be considered are:

- Future costs related to the removal of the repair system
- Costs and environmental tolls related to the dumping of the repair system
- Residual value of the repair system

Failure costs

The cost of failure can be divided into several parts. A possible subdivision is shown below:

1. Costs of collapse involving: cost of lives and injuries; cost of replacement of the structure and equipments; cost of loss of architectural, cultural and historical values; stop costs.

2. Costs of unsuccessful repair caused either by defective execution, choosing non-appropriate repair system or both involving: cost of repeating the repair and complementary works; cost of reduction of expected service life; cost of increased inspection and maintenance; cost of causing or accelerating another type of damage.

The first group should not be considered when comparing repair options or repair systems, because no repair option/systems should undergo economical evaluation unless they fulfil basic structural safety requirements. Furthermore, the future degradation of the repair system must be understood, and unknown repair systems should not be applied on the sensitive parts of the structure. Nonetheless, the insurance value of the structure can be used if it is found necessary to account for this type of costs. However, it is complicated to involve such costs in the calculations. The relationship between the failure of the repair, the failure of the structure and the consequences must be clearly described.

The second group, however, should be accounted for in the economical evaluation, although it might be complicated. When a repair system fails three measures, which involve costs, may be taken:

1. extra maintenance in addition to the ordinary maintenance,
2. minor repair and partial repair with the same type of system and
3. removal of the repair and re-repair of the structure with the same or another type of system.

The induced failure cost is then the cost, caused by the abovementioned measures, multiplied by the failure probability of the initial repair system. Major owners with a large asset portfolio may have information about some repair system in their asset inventory. It is possible to determine the degradation function for those repair systems. In this way it is possible to estimate the failure probability of the repair system. It is difficult to determine the failure probability of the newly developed repair systems.
**Addendum: Illumination of equation 6.5**

Let the repair/maintenance action be required every $m$ years. Let the service life be $N$ years. Then the number of actions during the service life can be shown by the following time lines:

![Diagram (a)](image)

5 maintenance actions will be needed to achieve a service life of $N$ years.

![Diagram (b)](image)

In this example 4 maintenance actions will be needed.

**Number of actions during the service life.**

The equation $k = \text{trunk}((N-1)/m)$ is obvious from the figure above. In this case $k$ is equal to 4, assuming that the service life is 43 years and the maintenance actions will be needed every 10 years.

The discounted summation of these recurrent costs during the service life is $Y_i$ which is given by:

$$Y_i = \sum_{k=1}^{k=k} y_j (1 + r)^{-mk} \quad (6.5b)$$

where $y_i$ is the non discounted recurrent cost, $r$ is discount rate, $k$ is the number of maintenance in the service life. Equation 6.5 can be obtained from equation 6.5b if the summation is conducted.
6.7 Considerations to non-technical issues (NTI)

Additional information is given in Annex S.

Decisions on repair of structures must consider the technical aspects and the physical condition of the structure in question and the way these factors influence the functional performance of the asset, but in many cases they also need to embrace the wider political, environmental and socio-economic issues as well.

Figure 6.12 illustrates the primary headings under which matters are often broadly grouped. These apply to both the construction phase and to the processes for through-life management of an asset. The Functional factors are often referred to as being technical issues, whereas the other topics concerned with Economic, Socio-cultural and Environmental factors are sometimes referred to collectively as being non-technical issues.

![Figure 6.12 Components of sustainable construction for provision of new assets and facilities, as well as for the management of their through-life performance](image)

Table 6.4 addresses selected non-technical issues and provides some insight as to where their influence might be in the decision making process, with the relevant points being identified in Figure 6.13 via the markers A to G.
Table 6.4 Some aspects of non-technical issues and their interaction in the decision model illustrated in Figure 6.13

<table>
<thead>
<tr>
<th>Primary Classification of Requirement</th>
<th>Non-Technical Issue (NTI)</th>
<th>Stage in Decision Making Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Economic and Financial</td>
<td>Procurement and type of contract</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strength of local economy</td>
<td></td>
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<tr>
<td></td>
<td>Improvement of asset values</td>
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<tr>
<td></td>
<td>Effect on third parties</td>
<td></td>
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<tr>
<td></td>
<td>Whole-life cost</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Cost versus benefit to society</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>User cost</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Public confidence</td>
<td>X</td>
</tr>
<tr>
<td>Social and Cultural</td>
<td>Target groups</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Education and training</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Aesthetics</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Social perception</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consultation</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Social alarm</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Reputation</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Media and press</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Government policies and initiatives</td>
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<tr>
<td></td>
<td>Labour union aspects</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Legal issues</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Health and safety requirements</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Insurance and future liabilities</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Working environment</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Repair time</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Risk and safety</td>
<td>X</td>
</tr>
<tr>
<td>Environment</td>
<td>Global environment</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Neighbourhood issues</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Internal environment</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 6.13, taken in conjunction with Table 6.4, illustrates where various non-technical issues might impact on different stages and aspects of the decision making process.

Non-technical issues and the manner to handle these are further discussed in Annex S.
**Figure 6.13** Potential interaction of non-technical issues and the overall decision making model described in [6.26]
7 METHODS FOR OPTIMIZATION OF THE REPAIR TECHNIQUE

In this Chapter some methods for optimization and selection of the best repair option are described in which the tools for evaluation from Chapter 6 have to be used.

First method proposed by the Manual and described in section 7.1 and Annex T is the Life Cycle-Cost Analysis (LCCA) by means of a detailed evaluation of the service life of the structure and of the economical consequences of each different alternative to reach the target. This method analyses costs for all service life of the structure defining construction, disruptions, maintenance and collapse costs. They will be considered at the moment in which they are produced obtaining finally a total cost of the alternative of repair.

Nevertheless, due its complexity and level of detail and when there is a lack of data and resources it is necessary to use a more simplified method as proposed in section 7.2 comparing Repair Indexes for the most important requirements and the different alternatives. The RIM [7.1] is a useful help to make decision process easier ordering the result of the evaluation of the different alternatives. This semi-empirical methodology is a way of thinking and it has to be used by experts due to it is only a theoretical tool for decision making in which the main requirements and its weight in the final decision have to be defined for each particular case using a lot of common sense.

7.1 Life Cycle-Cost Analysis (LCCA)

When damage is detected in a real structure, a strategy of intervention must be defined identifying the repair method or combination to be applied. The appropriate methodology would be a rigorous life cycle cost analysis, LCCA, to evaluate and benchmark the duration of service life and of the economical consequences of each of the alternative possibilities. This analysis requires the availability of a detailed and rigorous technical economical and status of the structure.

LCCA (see also Annex T) is based on the optimisation of the whole cash-flow of the structure. The concept of Life-Cycle Cost is not new in Civil Engineering processes such as power or nuclear plants, where a clear benefit is obtained from the construction of the infrastructure. One of the more complex terms in LCCA is the effect of time-variant degrading resistance and stochastic extreme load effects that can induce various failures related with strength, serviceability, durability, deterioration and damage though the service life of the structure.

7.1.1 The LCC of a structure

The general expression of the LCC of a structure can be quantified by means of expression (1):
\[ C_T = C_B + \sum_{i=1}^{T_1} M_i + \sum_{i=1}^{T_1} F_i \]  

(1)

where:
- \( C_T \) is the LCC
- \( C_B \) is the initial building cost
- \( M_i \) is the maintenance costs in the year \( i \) adequately converted to actual money
- \( F_i \) is the failure cost in the year \( i \) converted to actual money too

If expression (1) is expanded taking into account the actualisation rate and the year of each cost, it can be rewritten as (8), where \( r \) is the actualisation rate used in the analysis.

\[ C_T = C_B + \sum_{i=1}^{T_1} \frac{M_i}{(1+r)^i} + \sum_{i=1}^{T_1} \frac{F_i}{(1+r)^i} \]

(2)

Failure costs can be analysed by combining the failure probability \( P_F \) with the cost of damage, \( D \) giving:

\[ C_T = C_B + \sum_{i=1}^{T_1} \frac{M_i}{(1+r)^i} + \sum_{i=1}^{T_1} \frac{P_F}{(1+r)^i} D \]

(3)

It is commonly accepted that expression (1) should have a minimum value as is shown in Figure 7.1 because:

- the increase in durability will induce an increment in the cost of the structure.
- the increase in durability will induce a decrement in the failure probability and therefore a lower damage cost.

![Figure 7.1 Source of damage in structural concrete (REHABCON – 2001)](image)

Obtaining the minimum of expression (1) is not an easy task as durability of concrete is a time-dependent problem. The durability is itself a problem of aging where the time
effect is included. Thus, the failure probability is time-dependent and will increase with time. Not only the probability profiles with time are needed but also the effect of discount rate will play a significant role in the whole process.

Durability of concrete in terms of cost may be increasing due to an increase of concrete quality which usually means increments in all terms of concrete cost (concrete producing costs, concreting costs, etc.) but durability can be improved by means of an increase of cover, which usually provokes an increment in reinforcement ratio or an increment in elements weight. As summary it is considerably difficult to achieve a curve (or a curve family) like it is shown in Figure 7.1 for $C_i$.

Usually failure probability is considerably low and therefore it is preferred to express it in terms of reliability index ($\beta$). There is not a simplified expression which could link the reliability index with failure probability in order to compute the derivative. This aspect is the less important because of the existence of approximate expressions of $P_F$ in terms of $\beta$, depending of the range of values to be approximated.

The damage costs are close related to the Limit State to be considered. If limit estate is a simple depasivation, the cost of restoration could include some type of coating or paint, but if the Limit State considered is the spalling of the cover, the repair should include actions as patching. Apart from the cost related to the repair itself, it is necessary to take into account another type of costs such as user’s costs or indirect costs like (traffic delay, restriction, losses of rents, etc.)

### 7.1.2 Types of Life-Cycle Cost Analysis

A rational classification of LCCA can be established taking into account the uncertainty of the input data, thus it can be possible to speak about:

- Deterministic Life Cycle Cost Analysis (DLCCA).
- Probabilistic Life Cycle Cost Analysis (PLCCA).

Within the PLCCA, the costs can be accounted by deterministic quantities or by probabilistic quantities. Of course, the amount and quality of information is higher as higher is the level of the LCCA however the amount of input data should be increased in an equivalent manner.

**Deterministic life cycle cost analysis**

It is the simplest form of LCCA. It only considers deterministic costs and expected service life and durability. It can be considered as a first step in the selection procedure for repair strategies. Although their simplicity, usually practical approaches of economical optimization of a DLCCA.

The expression that can accounts for the total expected cost of the structure, taking into account the maintenance and repair interventions is collected in expression (1), where each expected cost should be translated into actual currency by means the discount rate $r$. 

The distribution of cost should be considered as localized – in – time costs, because the service life in DLCCA is deterministic. An example is shown in Figure 7.2.

![Figure 7.2  Example of distribution of costs in DLCCA](image)

**Probabilistic life cycle analysis**

It can be considered an evolution of DLCCA where all variables (except costs) are considered as stochastic, therefore the costs of maintenance, repair and strengthening are related to their probability of occurrence and their PDF. Thus, another type of costs should be considered. It is the cost of structure collapse, whose probabilities are certainly low to be taken into account in the DLCCA.

A more general expression that takes into account the probabilistic approach in the evaluation of LCC, can be rewritten in Equation 4, where it should be noticed that in the case of costs due to Maintenance ($C_M$), Repair / Strengthening ($C_{R,S}$) or Collapse ($C_f$) the sum is extended from the time $t=1$ because the probability of repair/maintenance or structural failure is higher than 0.

$$ C_T = C_I + \sum_{i=1}^{n} P_{F,M}(t_i) \frac{C_{M,i}}{(1+r)^i} + \sum_{i=T1}^{n} P_{F,R,S}(t_i) \frac{C_{R,S,i}}{(1+r)^i} + \sum_{i=1}^{n} P_{F}(t_i) \frac{C_{f,i}}{(1+r)^i} $$

(4)

Thus, the distribution costs throughout time are not localized as in DLCCA but continuous because the cost is multiplied by the probability which usually has a continuous distribution with time. In this sense, the product of probability by costs is usually known as damage.

**Models for repair / maintenance costs**
One of the most difficult points of using this type of approach (either Deterministic or Probabilistic) is the determination of realistic models for taking into account the costs due to repair / maintenance. The word *model* describes a mathematical expression that relates expected costs due to Repair / Maintenance and the geometrical, disposition or localization characteristics of the structure. Thus, a relatively short expression that can describe the costs due to a Repair / Maintenance operation in a structure can be written as shown in expression (5).

\[ C_{M/R} = C_D + C_H + C_U + C_E \]  

In expression (5) the costs included are: Direct cost of repair \((C_D)\), Cost of loss of contents or fatality and injury loses \((C_H)\), Cost of users \((C_U)\) and Socio – Economic loses \((C_E)\). In each case the cost can be multiplied by their appropriate Probability Density Function (PDF) and use PLCCA.

It can be considered that to assess a realistic (more or less) appropriate value of direct cost can be carried out. Typical prices list and standardization cost can be directly used. However the evaluation of indirect costs is quite difficult and depends on many factors. Some notes and examples will be shown in advance.

**Indirect costs models for buildings**

Indirect cost models are quite different for building and for bridges. Typical models for buildings include costs as shown in Eq. 6 where are included cost of contents \((C_C)\), economic loss due to business interruption \((C_B)\), cost of injury in repair processes \((C_{In})\) and costs of possible fatality in the repair process \((C_{Fa})\):

\[ C_{M/R} = C_D + C_C + C_B + C_{In} + C_{Fa} \]  

Cost of contents can be easily obtained from common price lists and cost of business interruption can be computed by accounting past economical reports of the factory or the cost of new rent if the building is dedicated to services, offices or residential. It is usually presented in terms of initial construction cost of the structure.

Cost of \(C_{In}\) and \(C_{Fa}\) are considerably difficult to analyze, because the special influence of human life. Although in old reports and documents it was said that trying to evaluate the economical value of a human life is rather immoral, new approaches suggest that the Life Quality Index may be assessed using LCCA.

**Indirect costs models for bridges and roads**

In general roads and bridges costs consist of five major cost items: vehicle operating costs, time delay costs, safety and accident costs, comfort and convenience costs and environmental costs. It is usually considered that two first are the most relevant although in order to evaluate those factors such as traffic network, location of the infrastructure and information of rehabilitations must be considered. A expression for accounting time delay costs can be written in expression (7).
\[ C_{TD} = \sum_{j=1}^{J} n_{pj} T_j u_{ij} \left( 1 - \sum_{i=1}^{N} r_i \right) \Delta t + \sum_{i=1}^{N} \sum_{j=1}^{J} r_i n_{pj} T_j u_{ij} + r_j n_{pj} T_j u_{ij} \Delta t_{ij} \]

where: \( j \) is an index representing the type of vehicle (business and non-business, etc). \( n_{pj} \) is the average number of passengers in vehicles type \( j \), \( T_j \) is the Average Daily Traffic Vehicle of type \( j \), \( u_{ij} \) is the unitary cost of unit of time for operator \( j \), \( r_j \) is the rate of occurrence of route \( i \) and \( \Delta t \) is the increment in time of route \( i \).

Costs of vehicle operation can be computed using expression (8) where it is considered the wages for each type of vehicle and the cost of fuel.

\[
C_{TD} = \sum_{j=1}^{J} \left( T_{0,j} u_{2,j} \right) \left( 1 - \sum_{i=1}^{N} r_i \right) \Delta t + \sum_{i=1}^{N} r_i \sum_{j=1}^{J} \left( T_{0,j} u_{2,j} \Delta t_i \right) + \sum_{i=1}^{N} r_i \sum_{j=1}^{J} T_{0,j} \left( u_{3,j} l_{di} - u_{4,j} l_{do} \right) + T_j u_{2,j} \Delta t_i
\]

Where \( u_{2ij} \) is the average operator wages for each type of vehicle, \( u_{3ij} \) is the average unit fuel cost pert unit of length on each detour route, \( u_{4ij} \) is the average unit fuel cost per unit of length in the original route, \( l_i \) and \( l_0 \) are the length of the detour and original route, respectively.

For other costs such as socio-economic costs, it is necessary to evaluate the Input-output table for the productivity of the country.

**Time – variant probabilistic LCCA**

From a direct examination of expression (1), it can be seen that each cost must be actualized in time. This actualization, as was explained above should be done continuously because the implication of probabilities in the computation. To compute directly expressions such as expression 1 is considerably difficult due to the calculation of probabilities with time. One of the simplifications proposed by authors is to compute that equation at the end of the expected service life of the repair. One possibility for simplification is to compute costs at a deterministic point in time and actualize currency values in the same manner.

\[
\sum_{j=1}^{n} P_{F,M}(t_i) \frac{C_{M,j}}{(1+r)^{t_i}} = \sum_{i=0}^{L} P_{F,M}(t_i) \frac{C_{M,j}}{(1+r)^{t_i}} = \frac{C_{M,j}}{(1+r)^{L}} P_{F,M}(t_L)
\]

The time-factor \( t_{act} \) takes into account the effect of increasing evolution of degradation with time. Of course \( t_{act} \) depends essentially of two factors: PDF of service life and discount rate.
It can be easily seen that the results are quite different depending of the discount rate \( (r) \) we chose for analysis. This aspect is one of the principal inconveniences of LCCA. Of course it is known by politicians as a way to force or delay future inversions in infrastructure or whatever type of business. Thus, it is commonly accepted that national administrations force the technicians to use specific \( r \) values depending on the type of inversion, these values are varying from 12\% to 6\%. An economical definition of \( r \) can be obtained as the difference between rate of interest and inflation, as shown in expression (10). Application of expression (10) to statistical economical data of several countries has shown that it is unrealistic to adopt values of discount rate above 2 – 5\%. Figure 7.3 shows the values obtained for several countries, taking into account time life windows of 50 and 10 years.

\[
r = \left( \frac{1 + i}{1 + a} \right) - 1
\]  

(10)

![Figure 7.3 Realistic Discount Rate in Europe](image)

7.1.3 Application

The application of these principles to the evaluation of the different repair technical solution, although feasible, needs assumptions that are empirical and not still well fundament. Examples can be made which give different solutions depending upon the costs of the repair in the different countries and geographical regions.

On the other hand the relative importance of the discount rate is calling for new approaches to introduce in a LCCA some elements in the equations able to take accounting of intangible values as, for instance, the value of the existence of the structure itself, or related to historical reasons or social benefits.

In consequence, LCCA is recommended to be performed only if the manager of the structure:
has confidence in the source of the costs
is able to account for types of costs not considered yet in the present formulation of LCCA
the effect of the discount rate is empirically balanced with the fact that the own existence of a facility or structure avoids investment of time to design a new one.

7.2 Repair index method (RIM)

When the previous process of selection and optimisation (LCCA) cannot be applied to a structure, due to the lack of data and resources, an alternative method may be used. This method is based on the evaluation of the fulfilment of the requirements (Table 4.1) by each available repair option (Table 5.3) through the use of some indicators.

As it is commented in the introduction of this chapter, RIM [7.1] is a theoretical tool or a way of thinking which have to be applied for experts and with care and a lot of common sense due to the result depends mainly in the definition of the main requirements and its weights that have to be taken into account. Tools for evaluation defined in chapter 6 have to be considered so that RIM is a philosophy for helping to order the results of this evaluation.

A set of requirements from Table 4.1 have been selected as an example to be taken into account in the process of evaluation/optimisation of RIM and some indicators are defined for each one in order to evaluate the repair alternatives with regard to them. These requirements together with the indicators are presented in chapter 7.2.1.

The ranking of the different repairs options for a specific structure to be repaired is obtained through the methodology described in sections 7.2.2 and 7.2.3.

7.2.1 Selected requirements and definition of the indicators

Technical and non technical requirements have been selected from table 4.1 and indicators for each one have been defined in order to evaluate the different repair options and select the best one as it is explained in sections 7.2.2 and 7.2.3.

A proposal for indicators summarised in Table 7.1 are explained bellow:

Service life and durability

- **Normal service life of the repair** evaluates the service life of the different alternatives. For example hydrophobic has less life than waterproofing with even more than 20 years. Another example could be the different types of expansion joints with different life (thormajoint or bituminous with 5 years).
- **Accidental attacks**: obviously the risk of suffering future attacks (impacts, fire…) will be the same for the different alternatives that are being evaluated in a particular case, but this indicator evaluates the degree in which this risk to suffer future attacks affects the durability of each repair alternative. For example, the
different fire performance of a CFR repair and an enlarging of the cross section in a column.

- **Exposure class**: obviously exposure class will be the same for the different alternatives that are being evaluated in a particular case, but this indicator evaluates the degree in which this exposure class affects the durability of each repair alternative. For example, CFR repair against steel plates strengthening in a marine environment.

- **Feasibility of post-repair monitoring** evaluates how easy it is to detect a faulty execution. It could be related to an execution failure for example the difficulty to detect failures in an epoxy resin once it has been applied. It could also be related to the easiness to detect that the structure is failing before it actually collapses.

- **Disturbance (after repair)** evaluates the disturbance or degree in which the repair affects the functionality of the different alternatives. For example, enlarging cross section of columns in a parking will have more disturbance than a CFR repair.

- **Compatibility with additional repair methods** evaluates the compatibility after the repair with additional repair methods of the different alternatives. For example, patching is highly compatible with additional repair methods while the ventilated façade is not because of the difficulty of access to the old façade of the building after repair.

**Structural stability and safety**

- **Structural consequences of failure** evaluate the risk of fatalities related to the place where the structure is sited. Obviously structural consequences of failure will be the same for the different alternatives that are being evaluated in a particular case, but this indicator evaluates the degree in which the safety of each repair alternative affect the consequences of failure.

- **Failure type** evaluates the different mode of failure (ductile or brittle) after repair. For example, FRC implies brittle failure and prestressing implies ductile failure.

- **Experience** evaluates the experience in the application of the different alternatives from all of points of view. It depends on number of years of application. For example, patching and steel plates strengthening are larger experienced alternatives than FRC.

**Execution**

- **Execution control** evaluates the quality control. For example cathodic protection quality control is high since the contractors are usually highly specialised. For electrochemical techniques quality control is much more difficult because of the treatment is less defined and therefore the control less clear.

- **Execution difficulty** evaluates the execution or application difficulty of the different alternatives. For example prestressing is more difficult than enlarging the cross section.
**Disturbance (during repair)** evaluates the disturbance or trouble during the repair of the different alternatives. For example, if a strengthening in a building is made in an office in the first floor or in the parking.

**Safety of workers and users (during repair)** evaluates the safety of workers and users of the different alternatives. For example, there is a certain risk of accident in cathodic protection when removing concrete and filling cracks or due to the possibility of an electric discharge than patching.

**Environment, health and sustainability**

- **Environmental effects** evaluate the environmental impact of the different alternatives (noise, atmospheric emissions, wastes, etc…) and the repair time from the environmental point of view. For example, waterproofing with lead or another material or sand blasting against laser techniques in a façade cleaning.

- **Resources consumption** evaluates the resources consumption (energy, materials…) of the different alternatives. For example, the most demanding are the electrochemical treatments considering energy consumed and materials due to they apply high voltage and need materials that are removed at the end of treatment.

- **Safety of users (after repair)** evaluates the safety of users of the different alternatives. For example, cathodic protection will be more dangerous due to the possibility of an electric discharge than patching.

**Economy**

All the aspects that can affect the repair cost are included as indicators. All other aspects that affect the economy of the society or the property as for example indirect costs related to traffic cuts, etc., are not included.

- **Direct cost**: direct cost per m² of the repair coming from a commonly used database for standard conditions. It will not include maintenance, indirect costs… This indicator is evaluated from 1 to 4 taking into account the relation between the direct cost of the repair with regard to the cost of the new structure. Reference values are shown in the Table 7.1.

The following indicators are modifications for this direct cost:

- **Maintenance cost** evaluates the relative maintenance cost of the different alternatives from all points of view. For example, cathodic protection has more maintenance cost than extraction of chlorides. Reference values are shown in Table 7.1.

- **Preparation of substrate** evaluates the preparation of substrate of the different alternatives. For example, CFR repair requires more preparation than strengthening with steel plates because the former permits less unevenness of the substrate surface than the latter.

- **Repair period** evaluates the time required for the different alternatives to be completed. Repair period will affect the indirect costs of the repair, not including the indirect cost to the society or the property that will be included in the **disturbance**.
- **Access tools (auxiliary equipment)** evaluate the access means needed by the different alternatives. For example in a cooling tower of a thermal plant for cathodic protection will only need access to some points against the extraction of chlorides that will need access to the whole of the surface.

- **Distribution of damages**: obviously the distribution of damages will be the same for the different alternatives that are being evaluated in a particular case, but this indicator evaluates the degree in which the particular distribution of damages economically affects each repair alternative. For example in a bridge with chloride problems in the columns, for a cathodic protection an extensive area has to be protected in order not to create areas with different performance but extraction of chlorides should only be needed in the affected areas.

- **Extent of damage**: obviously the extent of damage will be the same for the different alternatives that are being evaluated in a particular case, but this indicator evaluates the degree in which the extension of damage affects each repair alternative. Reference values shown in the Table 7.1 are related to the percentage of application in the structure. For example, enlarging the cross section is applied on the whole surface of the structure and patching is applied locally.

**Aesthetics**

- **Aesthetic contribution** evaluates the new look of the structure after repair. For example, in a building façade it will be interesting to repair it with a ventilated façade because it offers many options to improve the aesthetic of the building against other repair alternatives. Also, it will be necessary to repair the façade with patching if it must be done without changing the original look of the façade. If the original look of the façade is modified and there is not an aesthetic improvement, it will not be a useful repair option from the aesthetic point of view.

- **Variability of aesthetics** evaluates the variability from the aesthetic point of view related to possible alterations on the structure. For example, when resin mortars applied to FCR are exposed to sunlight for some weeks, they would turn into strange and unforeseen colours.

### 7.2.2 Repair performance index per indicator (RPI)

For the indicators defined for each requirement in section 7.2.1, Table 7.1 establishes the values that each repair option may obtain. First column corresponds to the selected requirements; second column to the proposed indicators and columns 3 to 6 establishes the criteria to adopt values from 1 to 4 (from negative to positive) for the Repair Performance Index (RPI) by indicator when applying to a structure to be repaired. Indicators presented in Table 7.1 are not the unique ones to take into account and different ones can be selected.

\[
RPI = \text{values from 1 to 4} \quad \text{“Repair performance index per indicator”}
\]
Table 7.1 Process of evaluation/optimisation to obtain the Repair Index

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Indicators</th>
<th>Indicator value meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>SERVICE LIFE &amp; DURABILITY</td>
<td>Normal service life of the repair</td>
<td>&lt;15 years</td>
</tr>
<tr>
<td>Accidental attacks</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Exposure class</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Feasibility of post-repair monitoring</td>
<td>Sensors</td>
<td>Periodic with NDT</td>
</tr>
<tr>
<td>Disturbance (after repair)</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Compatibility with additional repair methods</td>
<td>Very low</td>
<td>Low</td>
</tr>
<tr>
<td>STRUCTURAL STABILITY &amp; SAFETY</td>
<td>Structural consequences of failure</td>
<td>Very severe</td>
</tr>
<tr>
<td>Failure type</td>
<td>Very brittle</td>
<td>Brittle</td>
</tr>
<tr>
<td>Experience</td>
<td>&lt;10 years</td>
<td>10-20 years</td>
</tr>
<tr>
<td>EXECUTION OF WORK</td>
<td>Execution control</td>
<td>Not guaranty new method experience applicator</td>
</tr>
<tr>
<td>Execution difficulty</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Disturbance (during repair)</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Safety of workers and users</td>
<td>Very low</td>
<td>Low</td>
</tr>
<tr>
<td>ENVIRONMENT, HEALTH &amp; SUSTAINABILITY</td>
<td>Environmental effects</td>
<td>High</td>
</tr>
<tr>
<td>Resources consumption</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Safety of users</td>
<td>Very low</td>
<td>Low</td>
</tr>
<tr>
<td>ECONOMY</td>
<td>Direct costs</td>
<td>High</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Preparation of substrate</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Repair period</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Access tools (auxiliary equipment)</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Distribution of damages</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Extension of damages</td>
<td>&gt;80% of the structure</td>
<td>50-80</td>
</tr>
<tr>
<td>AESTHETICS</td>
<td>Aesthetic contribution</td>
<td>Not interesting</td>
</tr>
<tr>
<td>Variability of aesthetics</td>
<td>High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

1) This indicator does not show any difference between different repair options considered, but it is important to take it into account due to the importance of the structural failure.
7.2.3 Repair indexes

RIM is based on the calculation of repair performance indexes per indicator (RPI), ranked in four levels of importance, and averaging them to calculate a repair index per requirement \((R_i)\) and finally a repair index for the structure per alternative \((RI)\).

The value of the repair performance index \((RPI)\) per indicator varies from 1 to 4 (see a proposal of indicators and a way of quantification in section 7.2.2), being the value 1 the more negative effect and 4 the more positive one.

\[ RPI = \text{values from 1 to 4} \quad \text{“Repair performance index per indicator”} \]

The value of the repair index \((R_i)\) per requirement (service life, structural stability, etc) can be calculated by averaging its repair performance indexes \((RPI)\) of the indicators using expression (11) or different weights to each indicator may be used.

\[ R_i = \frac{\sum \text{RPI}}{\text{number of RPI}} \quad \text{“Repair index per requirement”} \quad (11) \]

The repair index \((RI)\) of the structure is obtained by means of the following expression:

\[ RI = \sum_{m=0}^{n} (I_m)(R_i) \quad \text{“Repair index of the structure”} \quad (12) \]

where \(n\)= number of requirements and \(I_m\) is the weight of each requirement.

Expression (12) may be applied through expression (13) in which an example for priority values is shown.

\[ RI = (0.2R_{ser}) + (0.1R_{str}) + (0.1R_{exe}) + (0.1R_{env}) + (0.4R_{eco}) + (0.1R_{aest}) \quad (13) \]

where:

- \(R_{ser}\) = RPI of the service life and durability requirement
- \(R_{str}\) = RPI of the structural stability and safety requirement
- \(R_{exe}\) = RPI of the execution of work requirement
- \(R_{env}\) = RPI of the environment, health and sustainability requirement
- \(R_{eco}\) = RPI of the economy requirement
- \(R_{aest}\) = RPI of the aesthetics requirement

Number of requirements and its weights \((I_m\) values) may vary depending on the specific conditions of each structure. These are subjective and they may vary depending on a variety of factors.

Table 7.2 is a suggested format to apply the previous procedure to select the best repair option and an example of application is shown in Annex S. This table can be applied to complete repair method or to partial aspects in each system (materials, preparation of substrate, finishing, etc) or to each technique (protection technique and strengthening technique).
### Table 7.2 Table to apply the RIM method

<table>
<thead>
<tr>
<th>REQUIREMENT</th>
<th>INDICATORS</th>
<th>INDEXES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SERVICE LIFE &amp; DURABILITY</strong></td>
<td>Normal service life of the repair</td>
<td>$R_{ser} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Accidental attacks</td>
<td>$R_{ser} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Exposure class</td>
<td>$R_{ser} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Feasibility of post-repair monitoring</td>
<td>$R_{ser} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Disturbance (after repair)</td>
<td>$R_{ser} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Compatibility with additional repair methods</td>
<td>$R_{ser} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td><strong>STRUCTURAL STABILITY &amp; SAFETY</strong></td>
<td>Structural consequences of failure</td>
<td>$R_{str} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Failure type</td>
<td>$R_{str} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Experience</td>
<td>$R_{str} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td><strong>EXECUTION OF WORK</strong></td>
<td>Execution control</td>
<td>$R_{exe} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Execution difficulty</td>
<td>$R_{exe} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Disturbance (during repair)</td>
<td>$R_{exe} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Safety of workers and users</td>
<td>$R_{exe} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td><strong>ENVIRONMENT, HEALTH &amp; SUSTAINABILITY</strong></td>
<td>Environmental effects</td>
<td>$R_{env} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Resources consumption</td>
<td>$R_{env} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Safety of users</td>
<td>$R_{env} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td><strong>ECONOMY</strong></td>
<td>Direct costs</td>
<td>$R_{eco} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Maintenance cost</td>
<td>$R_{eco} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Preparation of substrate</td>
<td>$R_{eco} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Repair period</td>
<td>$R_{eco} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Access tools (auxiliary equipment)</td>
<td>$R_{eco} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Distribution of damages</td>
<td>$R_{eco} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Extension of damages</td>
<td>$R_{eco} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td><strong>AESTHETICS</strong></td>
<td>Aesthetic contribution</td>
<td>$R_{aes} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td></td>
<td>Variability of aesthetics</td>
<td>$R_{aes} = \frac{\sum RPI}{\text{number of } RPI}$</td>
</tr>
<tr>
<td><strong>REPAIR INDEX (RI)</strong></td>
<td>$RI = \sum_{i=0}^{n-6}(I_{m})(R_{i})$</td>
<td>$RI = \sum_{i=0}^{n-6}(I_{m})(R_{i})$</td>
</tr>
</tbody>
</table>
REFERENCES


[2.2] DANBRO. Danish Bridge Management System, Danish Road Administration. (www.vd.dk)


[2.4] BaTMan (Bridge and Tunnel Management). Management system for bridges and tunnels. Swedish National Road Administration. (www.vv.se)


[3.28] Principal Inspections on Road Bridges (MOPT 1988, Ministerio de Obras Públicas y Transportes)


