Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 73/1/73/2 (1995)

Artikel: New approaches to monitoring and repair of concrete structures

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DOI: https://doi.org/10.5169/seals-55159

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New Approaches to Monitoring and Repair of Concrete Structures
Innovations dans la surveillance et la réparation des structures en béton
Neue Wege zur Ueberwachung und Instandsetzung von Betonbauwerken

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SUMMARY

Corrosion of reinforcement due to severe micro-environments and/or concrete quality has caused serious damages to concrete structures. To avoid damage and repeated damage after repair, new approaches to durability design, monitoring and repair of concrete structures, based on the mechanisms governing the deterioration processes, are presented. Like for load design, design for durability should be performance-based, taking into account the probabilistic nature of the processes and the material properties involved. Testing of the durability related quality parameters and monitoring the structures during use must be integral parts of the design and maintenance procedures for concrete structures.

RÉSUMÉ

La corrosion des armatures due à l'action d'environnements sévères et/ou à la pauvre qualité du béton sont à l'origine de détériorations graves des ouvrages en béton. Dans le but d'éviter ce type de dégradation et l'apparition de détériorations après remise en état, de nouvelles approches, en vue d'une bonne durabilité, sont présentées pour le projet, la surveillance et la réparation des ouvrages en béton. La définition de la durabilité peut, et doit, tout comme la définition de la charge, être exprimée en termes de performance et prendre en compte la nature probabiliste des processus et des propriétés des matériaux impliqués. Le contrôle des paramètres qualitatifs agissant sur la durabilité ainsi que le suivi des ouvrages en béton pendant leur exploitation, font partie intégrante des procédures d'étude et de surveillance de ces derniers.

ZUSAMMENFASSUNG

Korrosion an der Bewehrung infolge extremer Umwelteinwirkungen und/oder mangelhafter Betonqualität hat erhebliche Schäden an Betonbauwerken verursacht. Zur Vermeidung solcher Schäden und neuer Schäden nach Instandsetzungen werden neue Wege zur Dauerhaftigkeitsbemessung, Ueberwachung und Instandsetzung von Betonbauwerken vorgestellt. Dauerhaftigkeitsbemessung kann und muss, wie die Lastbemessung, auf Performance-Konzepten beruhen und auf probabilistischer Basis aufgebaut werden. Eine Ueberwachung der dauerhaftigkeitsrelevanten Qualitätsmerkmale und eine Ueberwachung der Bauwerke während der Nutzung sind integraler Bestandteil von Bemessungs- und Ueberwachungskonzepten.

1. INTRODUCTION

Corrosion of reinforcement caused by carbonation of concrete, chlorides and/or low quality of the concrete cover has caused serious damages to concrete structures in recent years. There are various reasons for durability failures, some of them being

- non-awareness of the problem by the people responsible for design, execution and use
- insufficient problem related education and knowledge of the same group of people
- poor codes of practice
- non-existing real design for durability
- insufficient durability related quality assurance and quality control procedures
- non-existing or insufficient maintenance during use.

All these aspects need to be covered by Design Concepts for Durability, both for the design of new structures and the design of repair of damaged structures.

One important basis for design and repair concepts and procedures must be a clear understanding of the mechanisms governing deterioration and the resistance of our materials and structures against deterioration. The understanding needs to start with the micro-environment, to continue with the interaction of the micro-environment with the structures, the transport and deterioration processes within the structure and to end with the consequences of repair measures. For one of the most important deterioration mechanisms, corrosion of the reinforcement, a new approach for durability design, monitoring and repair of concrete structures will be outlined in this paper.

2. CORROSION OF STEEL IN CONCRETE - MECHANISMS

2.1 Initiation Process

Carbonation

The mechanisms of carbonation of concrete and the consequences thereof are well understood nowadays. Due to carbonation the initially high pH-value of the concrete pore water - pH > 13 for OPC-concretes - falls below 9, thus causing depassivation of the reinforcement and the risk of corrosion. The main parameters influencing the rate of carbonation are

- permeability of concrete cover, mainly depending on w/c-ratio and curing
- alkaline buffer capacity of the matrix, mainly influenced by the type of binder
- moisture content of the concrete, depending on the micro-climatic conditons at the concrete surface.

Although no real durability design procedure exists, carbonation of concrete will normally not lead to corrosion problems as long as the requirements related to concrete composition, cover and curing given in the existing codes will be fulfilled.

Chlorides

Compared to carbonation problems in connection with chloride induced corrosion are by far more complex, complicated and unsolved:

- Transport and binding mechanisms of chlorides in the porous matrix, chloride treshold values as well as the corrosion process itself are far away to be fully understood in connection with the prevailing micro-environmental conditions.
- The severity of chloride environments varies within a wide range.

- Traditional protection measures (high quality of concrete cover) may be insufficient to ensure a sufficiently long service life (e.g. 50 years) in the case of severe attack (e.g. chloride containing splash water).
- Corrosion due to chlorides normally is much more severe compared to carbonation induced corrosion and may therefor affect the structural stability.
- A reliable repair of chloride induced corrosion is much more difficult and costly (if not impossible at a late corrosion stage in extreme cases) compared to carbonation induced carbonation.

Chlorides penetrate into the concrete within partly or completely water filled pores. They are partially bound chemically or physically within the cement matrix. Unlike carbonation, chloride penetration is not associated with a reaction front. On the contrary, a chloride profile with a chloride content decreasing from the concrete surface to the interior is usually found.

A detailed description of the major influencing factors on chloride penetration is given in [1]. They can be summarized as follows:

- Transport mechanisms: Two basic transport mechanisms are involved, chloride ion diffusion and chloride transport combined with water transport. Under practice conditions pure chloride ion diffusion is negligible. Practically all chlorides penetrating into the concrete are transported with water.
- Permeability: A decrease of the w/c-ratio from e.g. 0.6 to 0.4 increases the penetration resistance (expressed by the effective diffusion coefficient D_{eff}) by a factor of 2 to 4. Bad and good curing have influences in the same order of magnitude.
- Type of binder: By far more important is the type of binder. The penetration resistance ($1/D_{eff}$) is about a factor 10 higher for concretes made from slag- and fly-ash cements with high amounts fo blending agents compared to OPC concrete. By far the worst chloride penetration resistances show SRPC-concretes.

It is evident from current knowledge that the critical chloride content is not a fixed value but is dependent both on the quality of the concrete cover (type of cement, w/c-ratio, curing, thickness) and on environmental conditions. Fig. 1 presents this relationship in qualitative terms [2].

In various studies considerably varying results have been obtained with respect to the critical chloride content. Some of these contradicting test results can be explained by the influence of the test method and set up employed. However, as the interrelations are extremely complex, more precise conclusions as compared to Fig. 1 cannot be drawn at present. Critical chloride contents for existing structures can therefor be determined only for the specific situation of single structures on the basis of special investigations, taking all decisive influencing parameters and mechanisms (e.g. macrocell corrosion, see below) into account.

2.2 Propagation Process

Reinforcement corrosion visible with the naked eye is the outward manifestation of the effects of a number of small corrosion cells on the steel surface.

A corrosion cell is essentially a short-circuited battery consisting of a metallically and electrolytically connected anode and cathode. Unlike the process in a rechargeable battery, the corrosion process is not, however, reversible. The voltage of a corrosion cell is set up through differences in potential on the steel surface. The differences in potential needed for corrosion of the reinforcement may be caused by overlapping local differences in the chemical composition of the concrete, differing aeration conditions, inhomogeneities in the steel surface or uneven coating of the steel surface with corrosion products. In the case of concrete-covered steel, there are always differences in potential.

Cells where the differences in potential result from the combination of different metals are referred to as "contact cells", cells with differing concentrations of certain components in the electrolyte, in this case the pore solution of the concrete, are termed "concentration cells" and cells with differing levels of oxygen admission to the steel surface are known as "aeration cells".

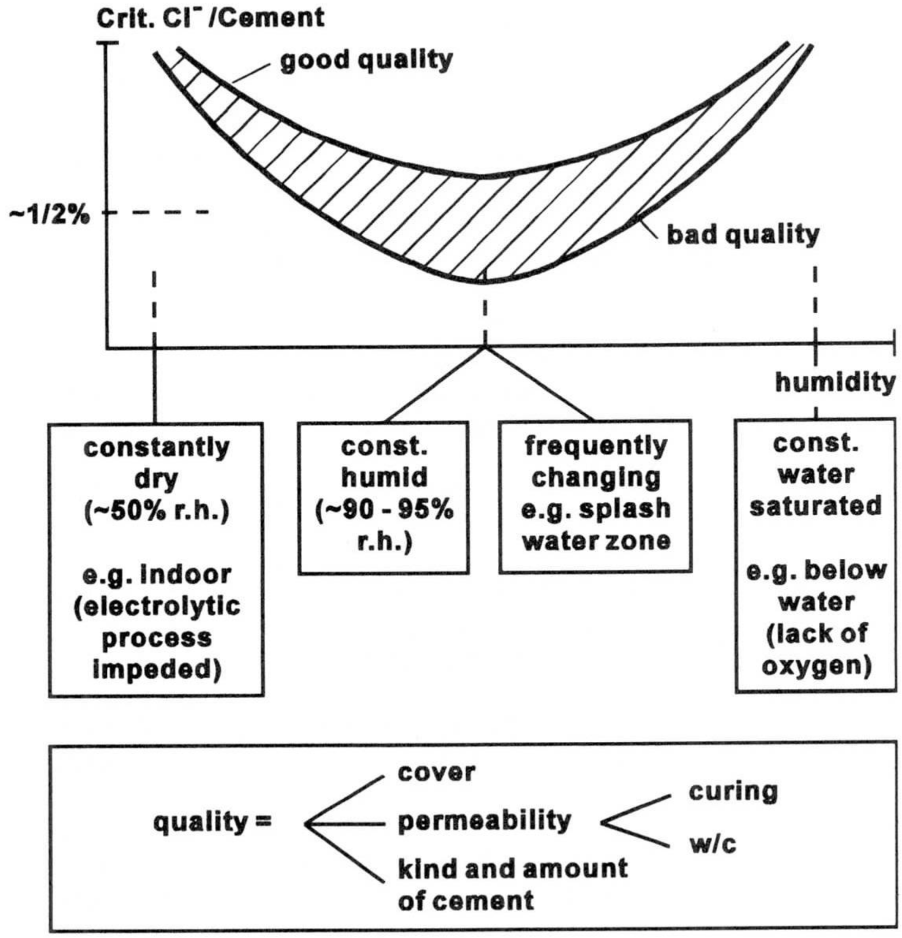


Fig. 1 Influence of concrete cover and environmental conditions on critical chloride content

The corrosion process takes place in two sub-processes, as outlined in Fig. 2:

- At the anode, iron ions pass into solution, separating from the electrons. They are converted into rust products in further reactions.
- At the cathode, electrons, water and oxygen are converted into hydroxyl ions. The cathodic process doesn't cause any deterioration of the steel.

These hydroxyl ions transport the negative charge in the electrolyte through the electrical field created between the anode and the cathode, towards the direction of the anode. Near the anode, they react with the steel ions in solution. Depending on moisture and aeration conditions, this intermediate product may continue to react, producing the final corrosion products.

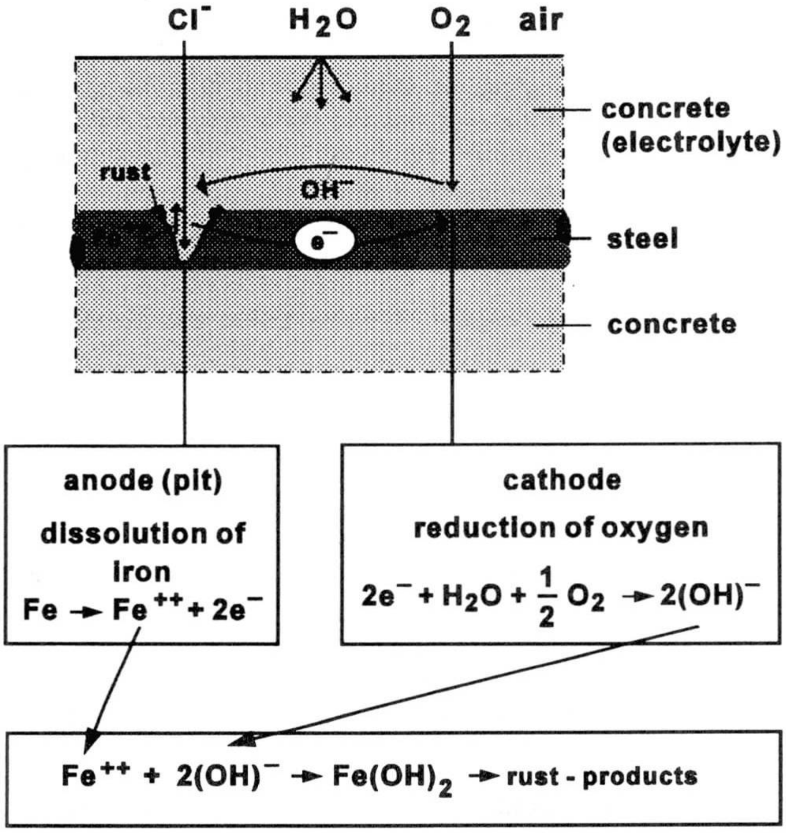


Fig. 2 Diagram showing chloride-induced corrosion of steel in concrete schematically

Individual processes are in fact much more complicated. The RILEM Report (60-CSC) [3] indicates the state of knowledge in this field.

In order for the corrosion process to take place, a number of preconditions for the anodic and cathodic process and for the electrolytic process must be satisfied simultaneously:

- As already noted, there must be differences in potential. The preconditions for sufficiently large differences in potential are, however, virtually alsways met, and in the case of chloride-induced corrosion these may be several 100 mV.
- Anodic and cathodic surface zones of the steel must be connected electrically and electrolytically, i.e. a flow of electrons and ions between them must be possible.
- The metallic connection necessary for an electron flow from the anode to the cathode is provided by the reinforcement system in the reinforced concrete. The electrolytic connection is represented by the concrete. This must, however, be sufficiently moist, since otherwise there can be virtually no migration of ions. In dry interior situations, for example, the electrolytic conductivity of the concrete is too low to permit corrosion of the reinforcement, even if the carbonation front reaches the reinforcement, leading to loss of alkalinic protection.
- Anodic solution of iron must be possible due to depassivation of the steel surface. The cathodic process can, however, take place even in zones with a passive steel surface.
- Sufficient oxygen must be available at the cathode. There must be continuous diffusion of oxygen from the surface of the concrete to the steel surface acting as the cathode. There is therefore practically no risk of corrosion to reinforced steel components which are permanently immersed in deep water.

If all conditions for corrosion are fulfilled simultaneously, the reinforcement will corrode. If only one of the conditions can be eliminated, corrosion can be prevented or brought to a stop. This knowledge is the basic key to fundamental repair principles (see chapter 4).

3. MONITORING AS A PART OF A RATIONAL DURABILITY DESIGN PROCEDURE

3.1 Design-For-Durability Approach

A performance based design is well established for load design, however no rational design approach for durability exists. We still apply simple deemed-to-satisfy rules (w/c, cover etc.) related to poor environmental classifications. A framework for a rational approach to design for durability is sketched in Fig. 3. It needs to start with the definition of the desired performance during the anticipated life time, e.g.

⇒ depassivation front (carbonation or chlorides) shall not reach the reinforcement, corrosion excluded.

Depending on the definition on performacne criteria, the aggressivity of the environment and the maintenance strategy (e.g. no maintenance possible) the basic defense strategy needs to be chosen.

In principle there are two basic defense or protection strategies

A Avoid the degradation reaction considered.
B Select optimal material composition and detailing to resist the degradation reaction considered.

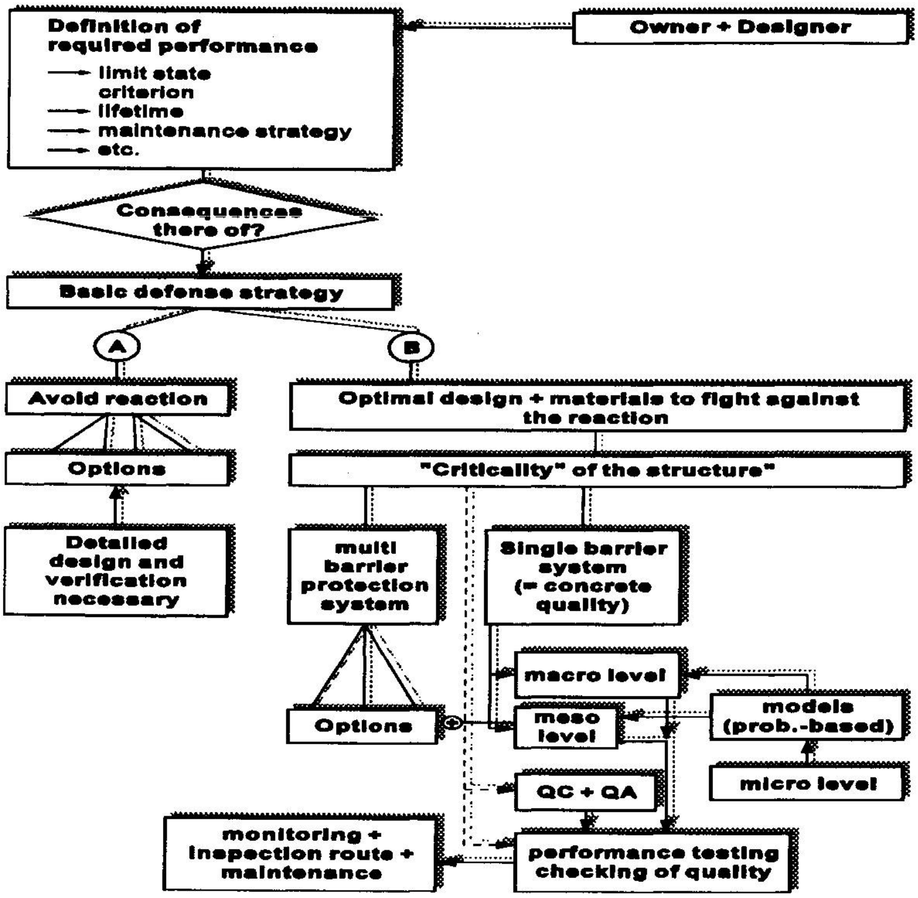


Fig. 3 Format for Durability Design

Strategy A can be subdivided into three possibilities:

A1 Change the environment, e.g. by tanking, membranes, coatings etc.
A2 Select non-reactive materials, e.g. stainless steel, coated steel.
A3 Inhibit the reaction, e.g. cathodic protection or cathodic prevention.

Strategy B is to fight against deterioration by optimal design and choice of materials. The choice of the protection strategy very much depends on the micro-environmental aggressivity. For structures or parts of a structure exposed to very aggressive environmental conditions or/and long target service lifes (100 years or more) multi barrier protection strategies are advisible. Such a strategy could be the provision of

- excellent concrete quality plus
- increased cover plus
- extra protection for the concrete or the reinforcement plus/or
- provisions for later extra protection should it become necessary.

In addition to these strategies monitoring of the structures e.g. by installing sensors into the most sensitive parts of the structure is indispensible (see chapter 3.2).

The design of concrete quality and concrete cover may be done on different levels. For the majority of structures the „macro-level“ is sufficient. Macro-level means to apply prescriptive rules like we use than nowadays (w/c-ratio, cover thickness etc.), however based on probabilistic models describing the deterioration mechanisms encountered and related to better defined micro-environmental conditions.

Identifying and classification (quantifying) the aggressivity of the environment, modelling the transportation of aggressive substance into and within the concrete, and modelling the possible deterioration mechanisms, becomes the first challenge to overcome if service life designs shall become realistic. The definitions and classifications of environments in existing standards are absolutely insufficient for a real durability design. This will be examplified in a simplified way for a partly immersed sea structure (see Fig. 4). If we, for example, consider the risk for reinforcement corrosion, the sketched micro environments (1 to 5) and transport mechanisms cause extremely varying aggressivity along these structures. The difference in the risk of reinforcement corrosion between the low aggressive areas (under water and air zone) and the highly aggressive areas (splash water zone) may be in the range of one order of magnitude.

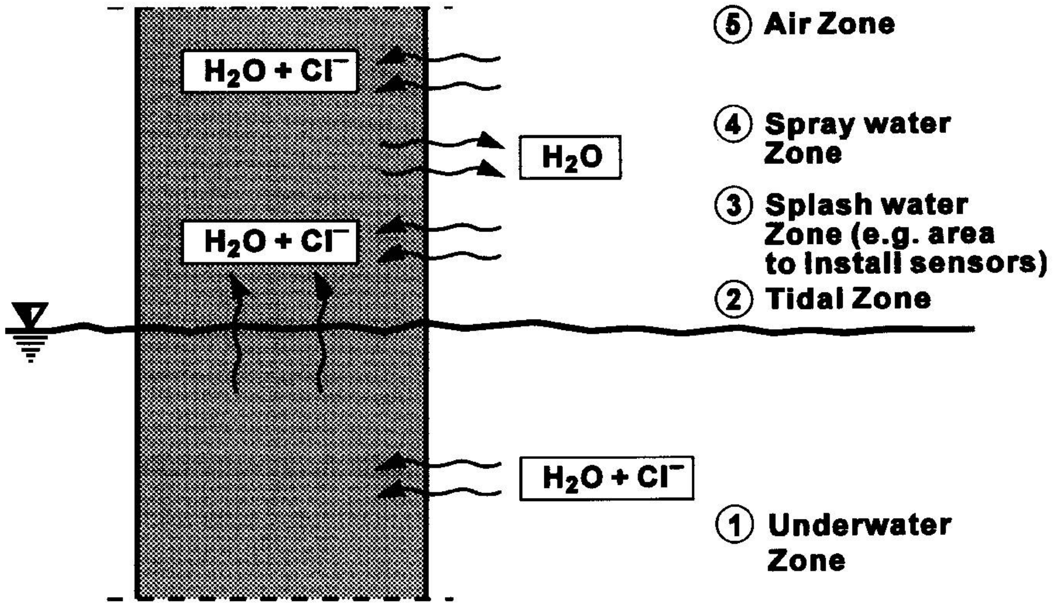


Fig. 4 Extremely varying micro-environmental conditions
Example: Marine Structure

For structures as sketeched in Fig. 4 the meso-level (see Fig. 3) approach is appropriate. The time dependant penetration of chlorides can be calculated using simplified penetration laws modelling the prevailing penetration mechanisms. Within such a model the effective diffusion coefficient could be the relevant material parameter, e.g. in a very simplified way

$$d_{Cl} = K \cdot \sqrt{D_{eff}} \cdot t^n$$

d_{Cl}: penetration depth of chlorides (critical chloride content)
K: factor describing the micro-environment
n: exponent describing the micro-environment
D_{eff}: effective diffusion coefficient

As the effective diffusion coefficient is the performance parameter of concrete governing the resistance of the structure it needs to be incorporated in the material characterisation, starting from the production of the binders to the execution of the structure. The overall system is sketched in Fig. 5. If we replace D_{eff} in Fig. 5 by strength we realise exactly the system we are using for load design since ever.

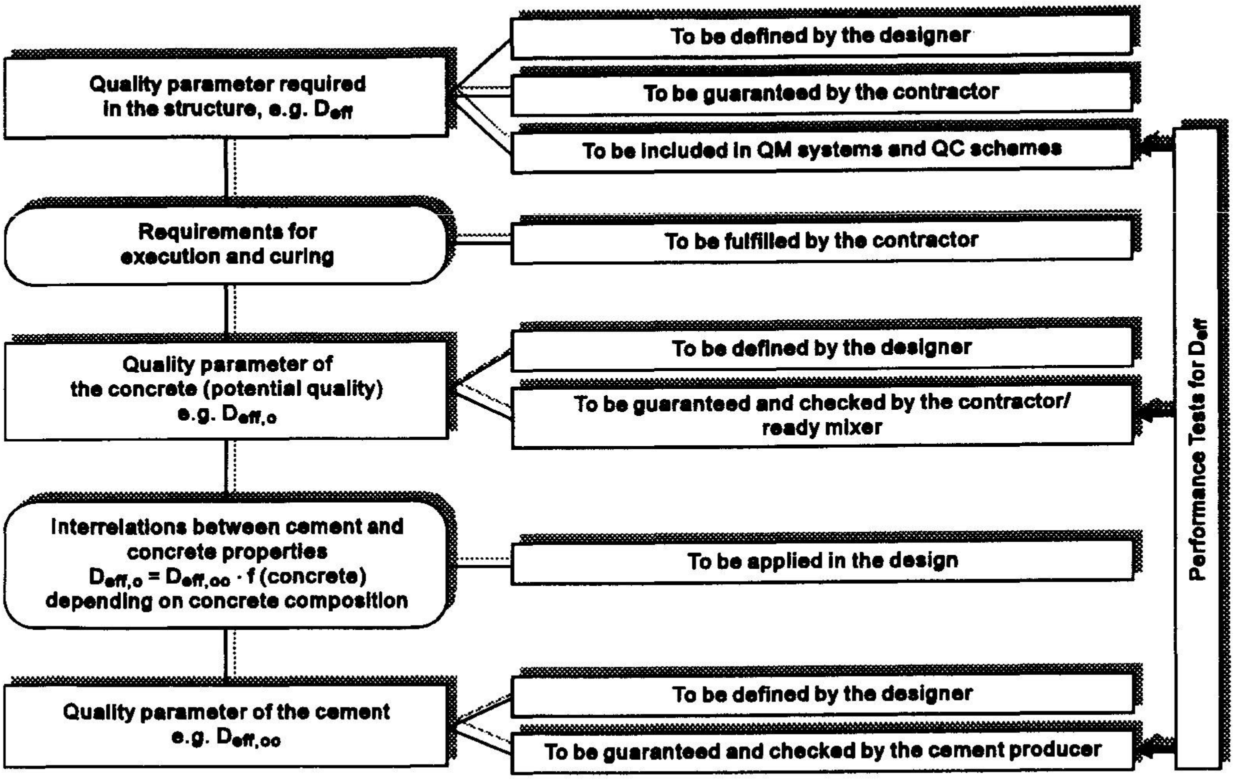


Fig. 5 Performance based durability design at the meso-level

Coming back to Fig. 3, the amount of quality control to check the real quality gained in the structure depends on the criticality of the structure, i.e. the consequences of durability failures and/or the possibilities to repair them.

3.2 Corrosion Monitoring Systems

3.2.1 Location of the Sensors

As mentioned above, monitoring of the structure, e.g. by installing sensors, is an integral part of an overall durability design approach, especically for structures exposed to very severe environments. Having analized the structure with respect to the severity of the micro-environments and sensitive areas (e.g. construction joints, areas of possible salt and water accumulations etc.) it is normally easy to define the most critical areas where sensors should be installed (see Fig. 4).

3.2.2 Corrosion Sensor

The development of the corrosion sensor was based on an extensive research program on the main factors influencing chloride induced macrocell corrosion of steel in concrete [4...8]. These investigations have been carried out using macrocell current measurements between anodically and cathodically acting steel surface areas. It was shown that the corrosion rate of the reinforcement can easily be monitored continuously by these electrical current measurements.

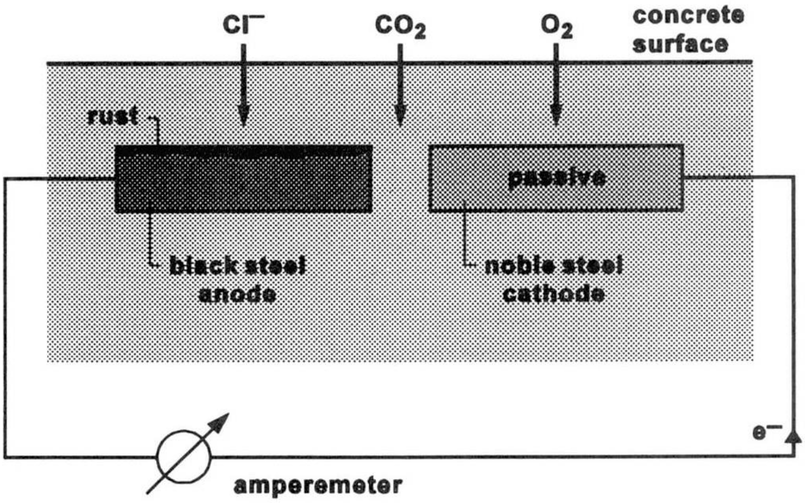


Fig. 6 Macrocell consisting of a black steel anode and noble metal cathode

The operation of a macrocell consisting of a piece of black steel (anode) and a noble metal (cathode) is shown in Fig. 6. In chloride free and non-carbonated concrete, both electrodes are protected against corrosion due to the alkalinity of the pore solution of the concrete (passive state). The electrical current between both electrodes is negligibly low under such conditions. If, however, a critical chloride content is reached, or if the pH-value of the concrete decreases due to carbonation, the steel surface of the anode is no longer protected against corrosion. Provided that the cathode material is corrosion resistant in chloride contaminated or carbonated concrete (e.g. stainless steel, platinum), and sufficient moisture and oxygen are available, oxygen reduction takes place at the surface of the cathode. The local separation of anodically and cathodically acting areas leads to an electron flow between the black steel and the cathode, which can easily be measured at the external cable connection.

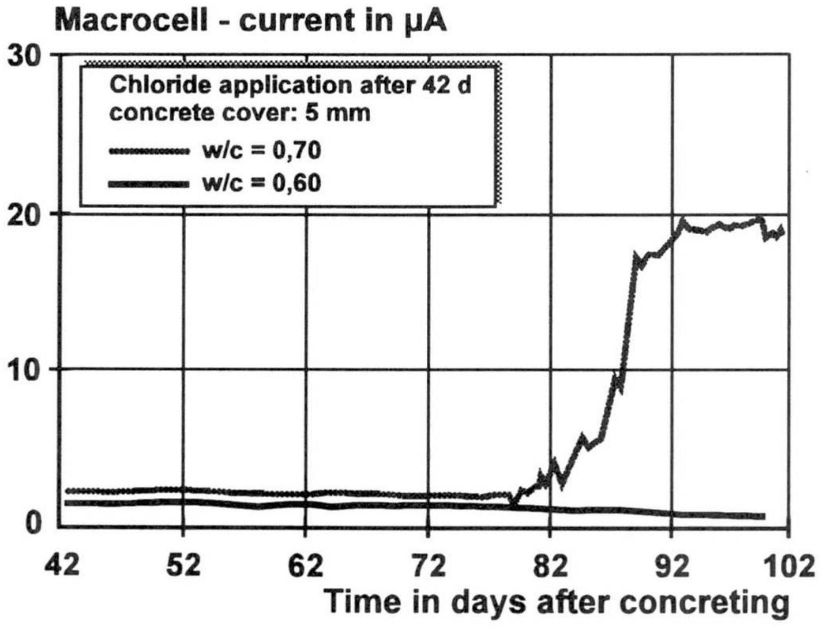


Fig. 7 Time-dependent behaviour of the electrical currents between anode and cathode

Fig. 7 shows the result of electrical current measurements (demonstration test in the laboratory) between a black steel anode and a stainless steel cathode in two concretes with different water-cement ratios. The macrocells were embedded with a concrete cover of only 5 mm (0.20 in.) to initiate corrosion by applying a chloride solution on the concrete surface within a short period of time. The results of the macrocell current measurements showed that the critical chloride content reached a depth of 5 mm (0.20 in.) at the specimen with w/c = 0.7 about 80 days after concrete placement. This caused a significant increase of the macrocell current while the specimen with a lower w/c and a higher resistance against chloride diffusion remained passive.

To monitor the corrosion risk for the reinforcement depending on its distance from the concrete surface, several anodes can be placed in the actual concrete structure at defined cover depths. The cathodes should be positioned at locations that are near the anodes and that are not water saturated because oxygen is needed at the cathodically acting metal surface.

Fig. 8 shows exemplarily a possible arrangement of anodes and a locally separated cathode.

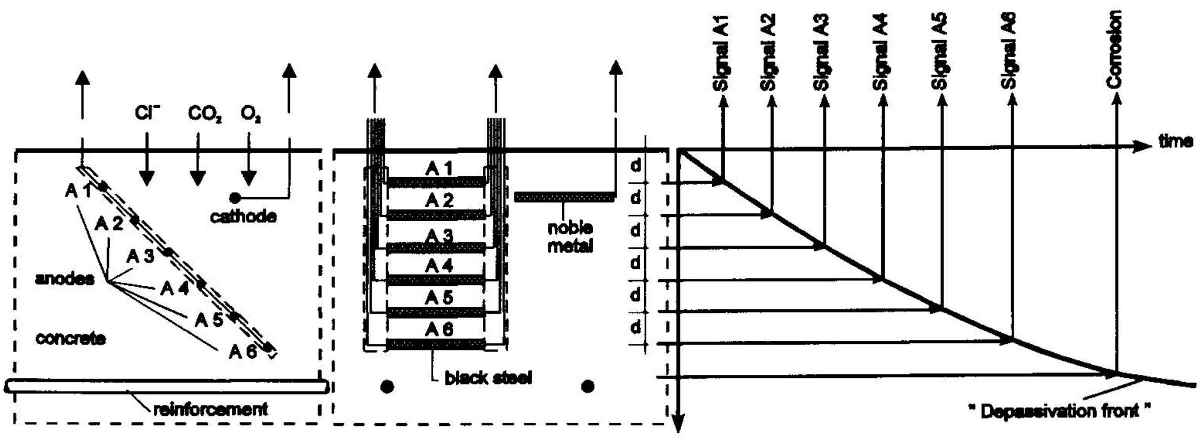


Fig. 8 Arrangement of the anodes and cathodes to monitor the corrosion risk for the reinforcement

Normally all the electrodes are disconnected from each other to prevent electrochemical interactions between them. Only during the electrical current measurements the anodes are coupled with the cathode one after the other.

As long as the critical chloride content and the carbonation front have not reached the surface of the first anode A_1, all the electrical currents are negligibly small. As soon as the steel surface of the first anode A_1 is depassivated due to the action of chlorides or carbonation the electrical current between A_1 and the cathode increases significantly whereas the currents of the other electrodes remain zero.

In the course of time the other anodes will also be depassivated one after the other. By measuring the electrical currents continuously or in regular intervals the relationship between the depth of the critical chloride content or carbonation and time can be determined. Having this information, the time to corrosion of the reinforcement can be estimated by extrapolation using appropriate calculation models.

A typical layout and arrangement of a corrosion sensor consisting of 6 single anodes is shown in Fig. 9. Each of the 6 black steel anodes is positioned 50 mm (2 in) from the next one to prevent interactions between the anodes.

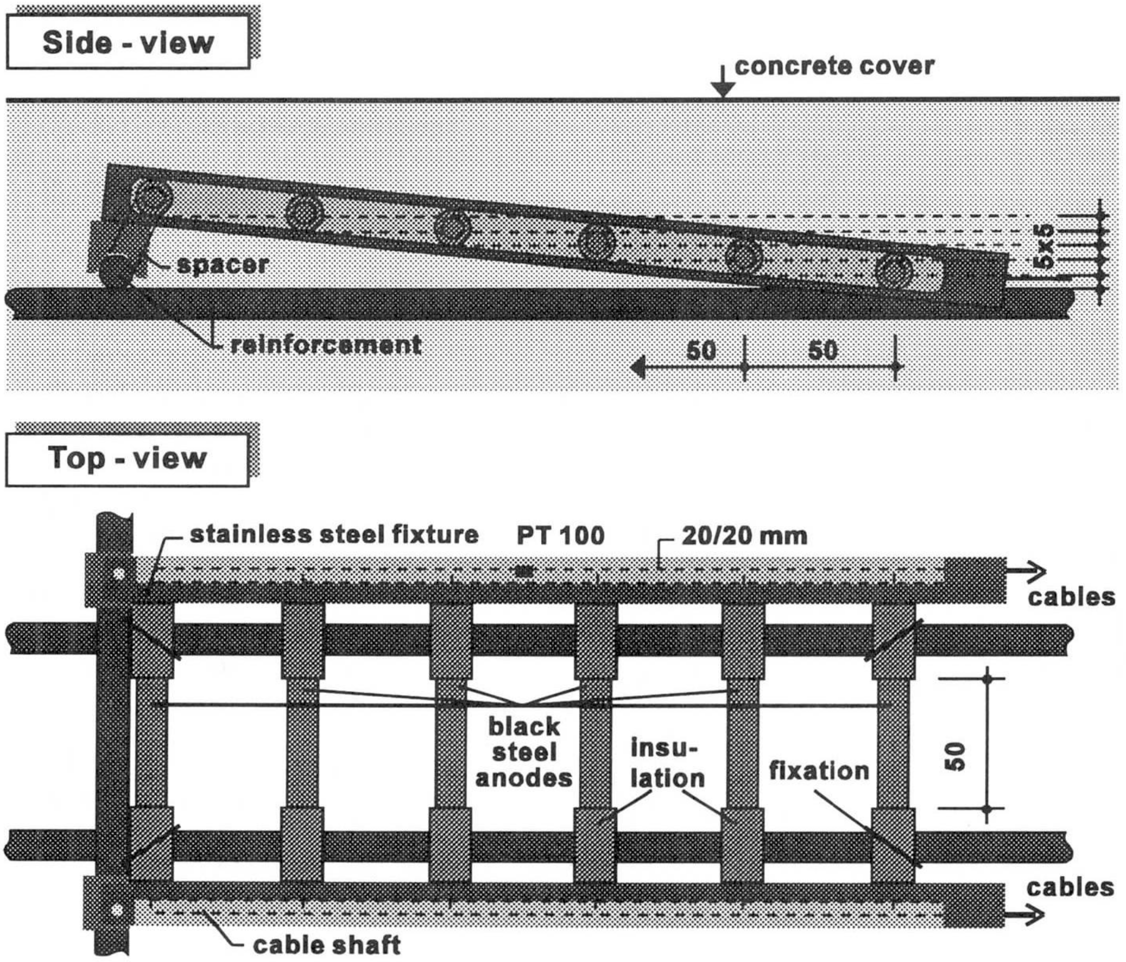


Fig. 9 Design of a set of 6 anodes

Fig. 9 also shows that the cables are lead through a stainless steel fixture to the measuring device. The cable shaft is filled with epoxy resin that acts as mechanical protection for the wires and a PT 100 temperature sensor that can be additionally installed. Two wires are connected with each single anode to get a redundant system. This allows the cables and cable connections to be checked after installation by resistance measurements.

The fixture is separated from the anodes by an insulation. This geometrical design of the sensor ensures that the concrete cover above every single anode is not affected by parts of the sensor, and that the penetration of chlorides into the concrete and the carbonation process are also not influenced.

The layout of the sensor system allows, besides the current readings other measurements improving the information on the overall corrosion risk within the monitored structure:

- The measurement of the potential between the anodes or the reinforcement and the noble cathode gives a further information on the onset of corrosion.
- The simultaneous measurement of the temperature by means of an incorporated temperature sensor allows a more detailed interpretation of the current readings.
- The anodes can be used as measuring electrodes for AC resistance measurements at different distances from the concrete cover. This type of readings for example can be used to monitor the efficiency of coatings, preventing water ingress into the concrete.

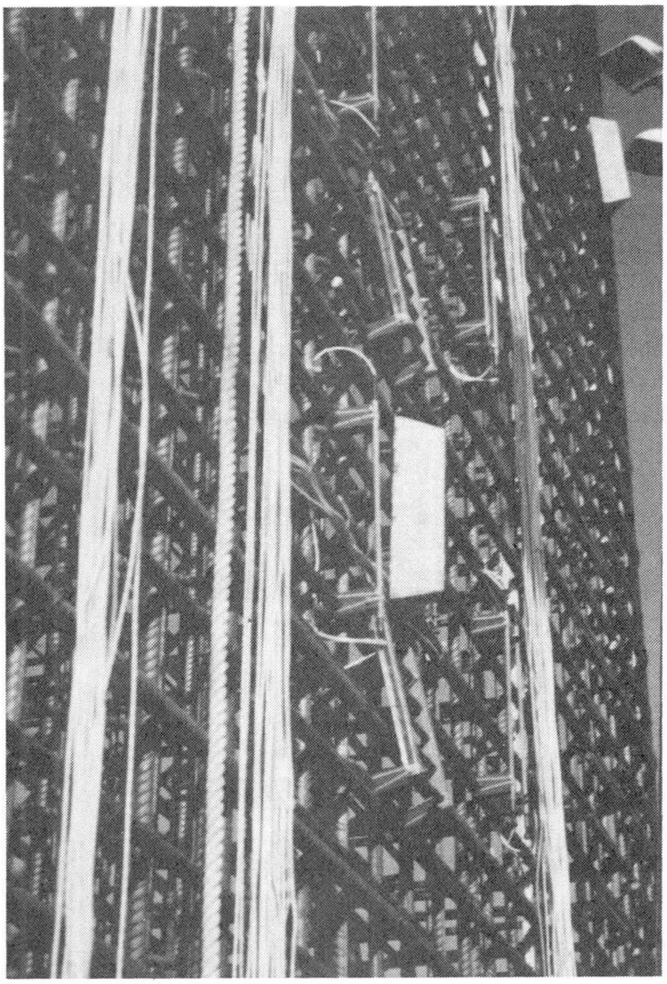


Fig. 10 Installed sensors (6 sets of anodes and 1 cathode - Pier shaft of the Western Bridge, Great Belt Link

Altogether about 500 sets of sensors have been installed so far into reinforced and prestressed concrete structures

- 8 sets of sensors for Bridge Schießbergstraße near Cologne,
- 204 sets of sensors for the tunnel of the Great Belt Link,
- 180 sets of sensors for the pier shafts and prestressed girders of the Western Bridges of the Great Belt Link,
- 42 sensors for the anchor blocks of the Eastern Bridge of the Great Belt Link,
- 6 sensors for the Nötsch Bridge in Austria,
- 20 sensors for a bridge in Egypt.

All installations have been done successfully without complications. No depassivation of sensors has happened so far.

3.2.3 Multi-Ring-Electrodes

Apart from other measures, one possible means of repairing damage at the concrete surface due to reinforcement corrosion is to apply a coating to the concrete surface to reduce the water content of the concrete. If the coating has a sufficient high penetration resistance against water and if no water enters the concrete from other sources, the water content of the concrete will remain low after the application of the coating, or the concrete will dry out slowly, provided that water can evaporate through the coating or through the opposite concrete surface.

In this way the corrosion rate of the reinforcement can be decreased significantly because the electrolytic conductivity of the concrete is reduced considerably. If the water content of the concrete is below a limit value, the corrosion rate of the reinforcement will be negligibly low. This limit value for the water content is not a fixed value but depending on different parameters, e.g. the concrete composition, chloride content and carbonation depth.

A multi-ring-electrode method for determining the water distribution within the concrete cover (between the reinforcement and the steel surface) has been developed at the Institute for Building Materials Research in Aachen, Germany. The electrode is used to determine AC resistance between nine noble metal rings, allowing the water content to be estimated at eight different distances from the concrete surface (see Fig. 11).

To estimate the effect of different types of coatings, time-dependent changes in resistance following wetting and drying of coated and uncoated surfaces were monitored. Fundamental laboratory investigations on the influence of concrete compositions, carbonation and chloride application have been carried out.

In addition to the above mentioned investigations multi-ring-electrodes have been successfully installed into existing structures. For this purpose the multi-ring-electrode will be fitted in a drilled hole and subsequently coupled to the old concrete. In laboratory tests coupling of the multi-ring-electrodes to hardened concrete has been performed on existing test specimens, allowing to compare directly the results of sensors installed into new structures with the results of sensors installed into existing structures. The tests show that the installation into existing structures provides reliable data on the moisture distribution within the concrete cover.

More informations about test results with this equipment can be found in [9].

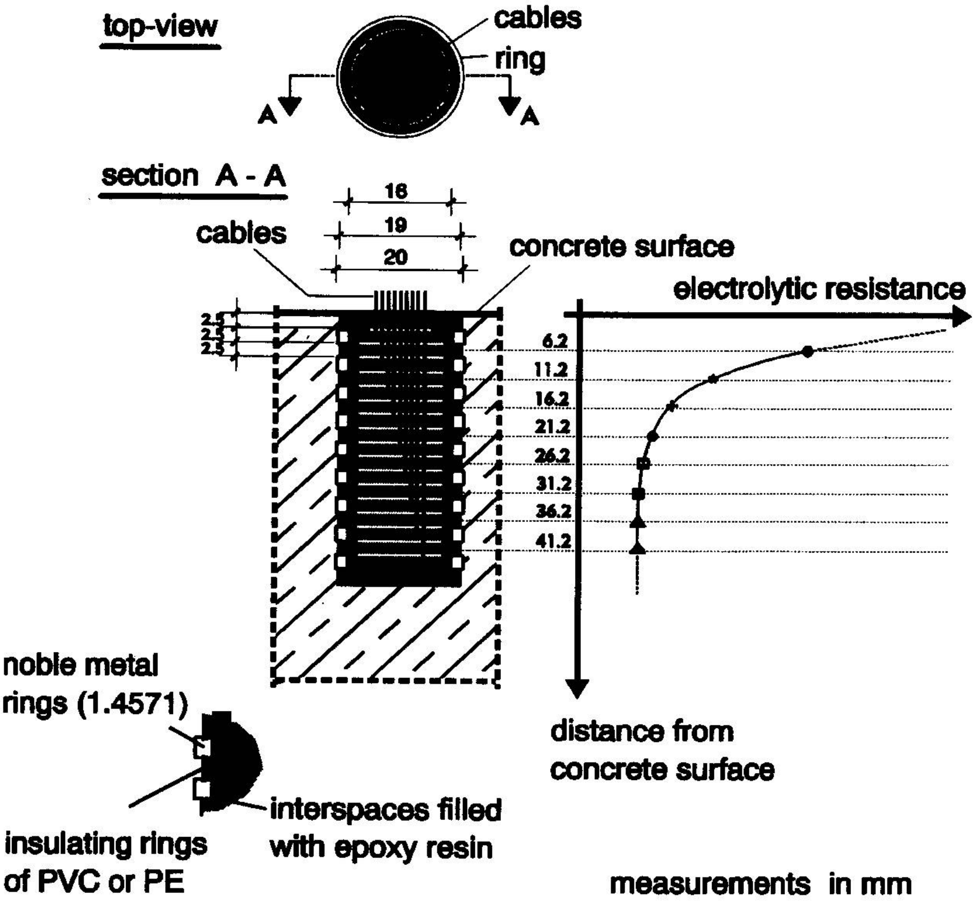


Fig. 11 Schematic representation of the multi-ring-electrode and a qualitative diagram of measured values

4 REPAIR STRATEGIES TO REPAIR CONCRETE STRUCTURES DAMAGED BY STEEL CORROSION - THE NEW RILEM APPROACH

The RILEM Technical Committee 124-SRC has prepared a RILEM Technical Recommendation on „Repair Strategies for Concrete Structures Damaged by Reinforcement Corrosion", published in [10].

The repair strategies and principles presented in this RILEM Recommendation are related to the design of corrosion protection of ordinary reinforcement.

The Recommendation describes the basic possibilities, strategies and methods for improving or restoring the corrosion protection of ordinary reinforcement. It is written for design engineers and consultants and describes basic strategies and requirements. As it is intended to give a basis for decision making, it does not contain detailed requirements for the materials to be used or guidelines for the execution of the repair work.

The strategies described apply to the majority of normal repair situations.

The format of this RILEM Technical Recommendation is sketched in Fig. 12. Strategy Level 1 deals with various possibilities of interventions, one of them being an intervention into the corrosion process. This strategy is treated in detail within Strategy Level 2 (chapter 4 of [10]). Based on the aim to avoid further corrosion after repair, different Principles of Repair are defined. Based on these principles possible Methods of Corrosion Protection are elaborated including the basic requirements needing to be fulfilled to ensure a successful repair. The presented options for repair are based on the existing knowledge at the time of drafting the document and are related to the possible deterioration processes prior to and after repair works.

The principles of repair are based on the electrochemical processes causing corrosion (see chapter 2.2).

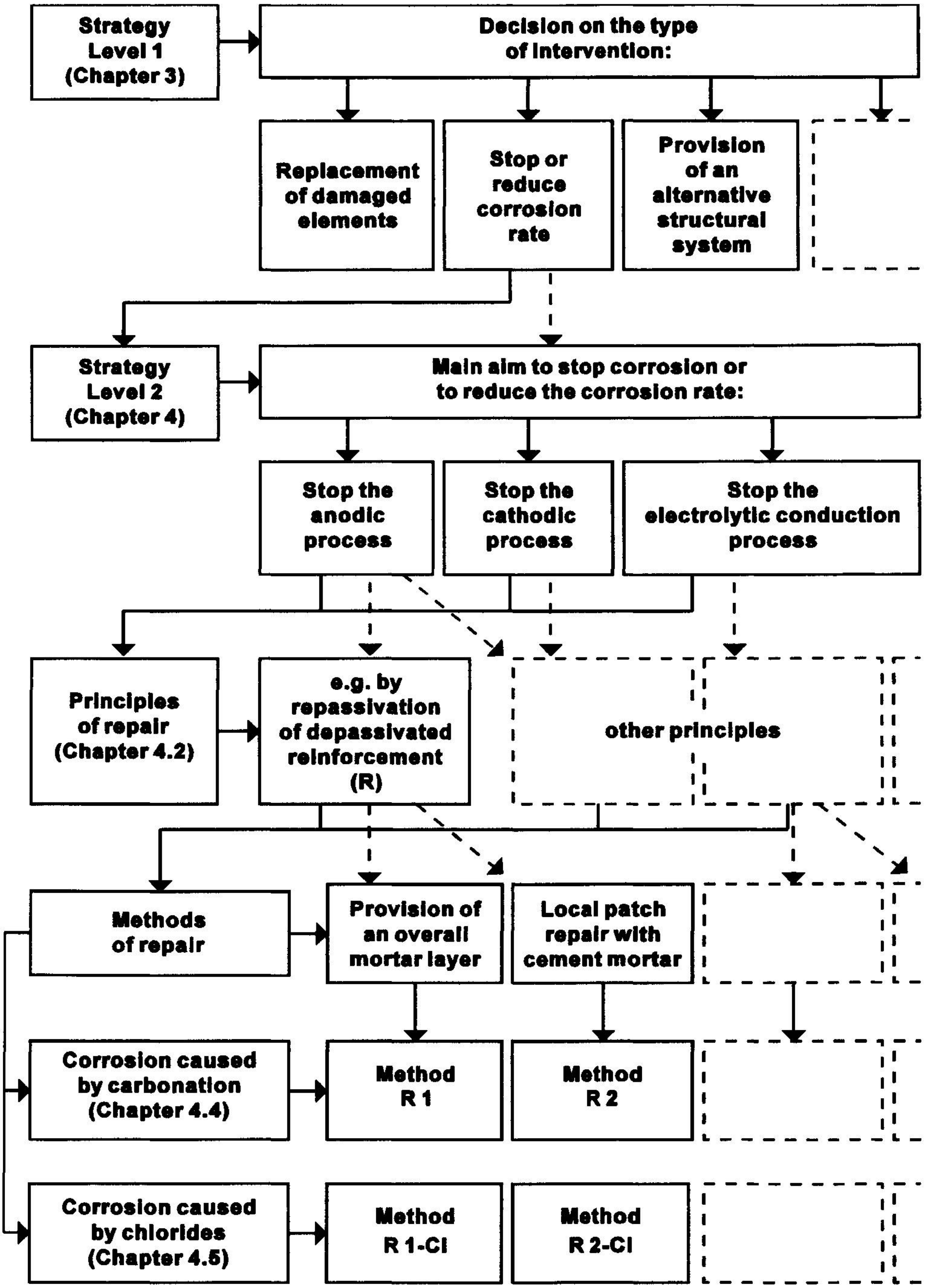


Fig. 12 Format of the Technical Recommendation

The basic aim for repair should be

- to stop the anodic process,
- to stop the cathodic process, or
- to stop the electrolytic conduction process.

In order to achieve one of these effects, different repair principles, presented schematically in Fig. 13, are possible. The repair principles to restore corrosion protection need to be designed on the basis of the electrochemical corrosion processes at the steel surface and the chemical and physical processes within the surrounding concrete.

Fig. 13 presents basic principles and examples of techniques based on these principles. There are no generally proven repair procedures to stop the cathodic process, e.g., by the total block of oxygen access to the surface of the reinforcement. Although theoretically possible, the concept of stopping the cathodic process therefore is not included in Fig. 13.

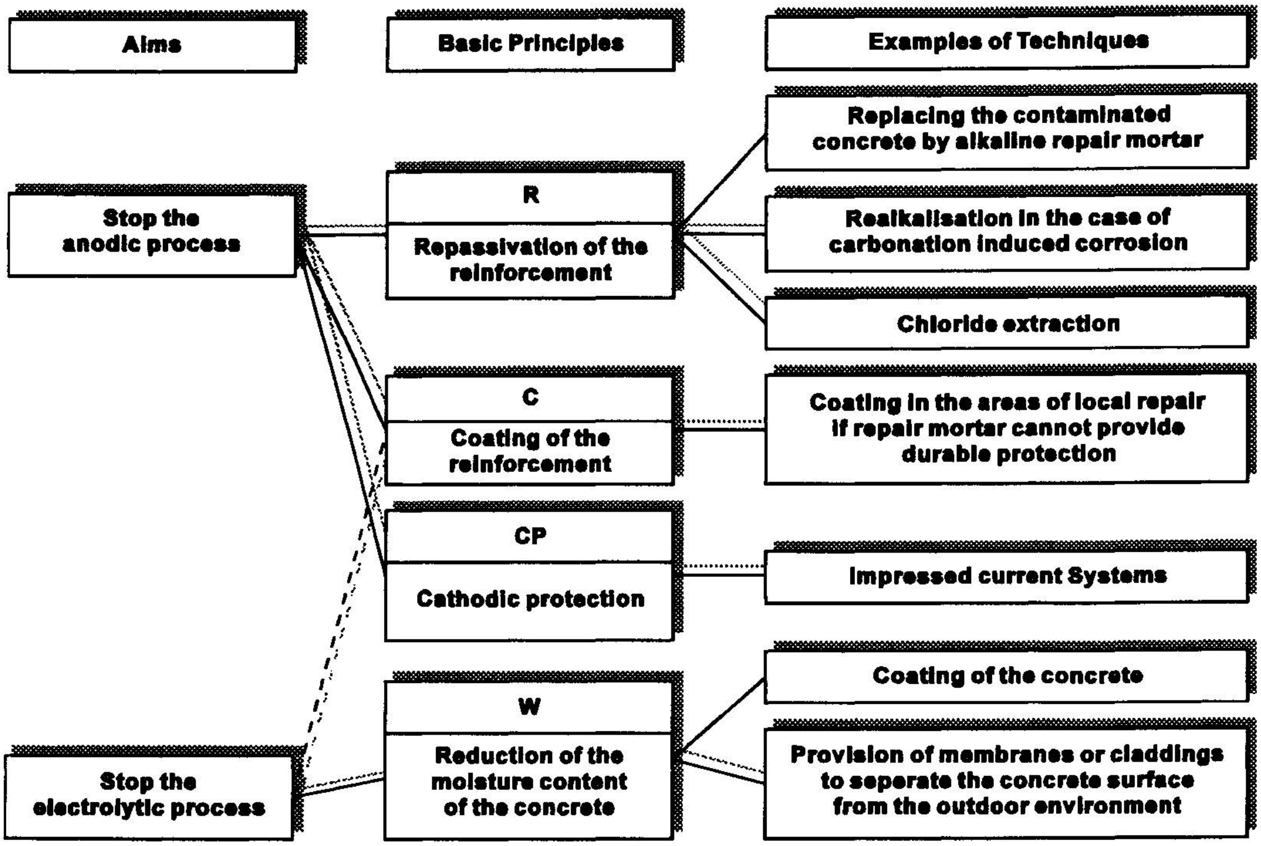
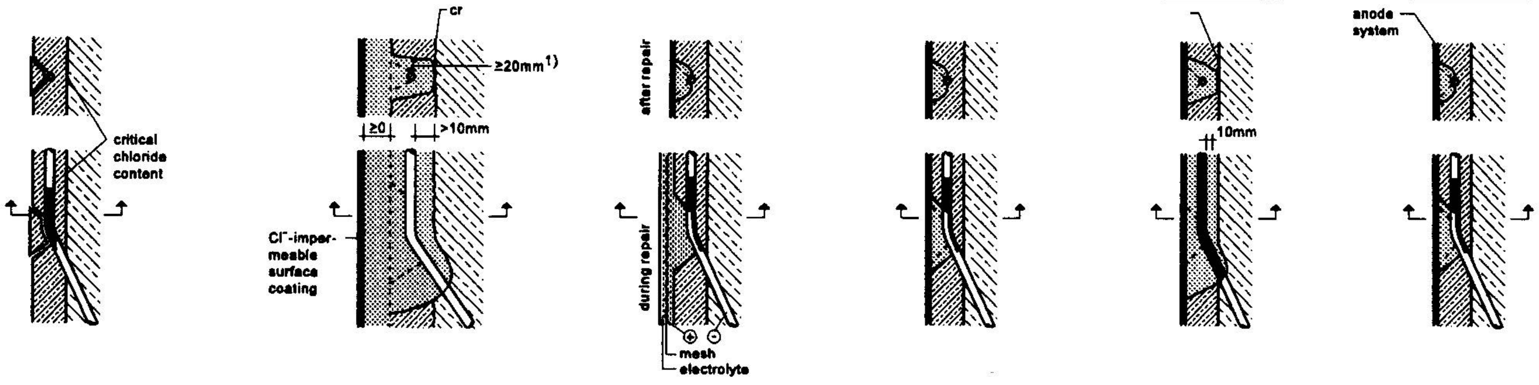


Fig. 13 Principles of repair to stop corrosion

For the different basic principles sketched in Fig. 13 different methods for repair must be elaborated, depending on the cause of depassivation (i.e., carbonation or chlorides).

As an example the basic methods for the repair of chloride induced corrosion, as presented in [10] are shown in Fig. 14.



on

Type of damage		R1 Repassivation Alkalinic repair mortar/concrete	R2 Repassivation Electrochemical Cl⁻-removal (see section 4.7.3)	W Limitation of moisture content surface coating	C Coating of the reinforcement	CP Cathodic Protection
concrete removal			X	X		X
		X			X	
surface treatment of steel	SA 2 1/2 + coating	coating not allowed	coating not allowed	not necessary	X	coating not allowed
	removal of rust	X including rust in pits	X including rust in pits	X including rust in pits		X
repair mortar/ concrete	alkaline, with buffer	X	X			conductive X
	no alkalinity, required			X	X	
surface treatment of concrete	not required					X
	required (Cl⁻-impermeable)	X	X	X	X	

Fig. 14 Basic methods for the repair of chloride induced corrosion

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