ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 6, NO. 5 (2005)
PAGES 423-445

SERVICE LIFE DESIGN OF CONCRETE STRUCTURES - A CHALLENGE TO DESIGNERS AS WELL AS TO OWNERS

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ABSTRACT

Future demands for performance of concrete structures pose multidisciplinary challenges on the designer. He must master the integration of structural design, durability and service life design, and the rapidly growing demands for sustainability. However, such designs required to fulfil the long-term performance of structures poses also challenges to the owners or clients. They will have to define their service life demands in a factual and verifiable manner, and to agree to the acceptance criteria to be fulfilled. This new integrated approach to service life design of concrete structures identifies a new design procedure - a change in design paradigm-which shall be followed, if real improvements shall be achieved. The changes in design paradigm are not at all dramatic, but the consequences of adopting such changes may well be dramatic regarding improved performance, service life and reliability - and will greatly increase the competitiveness of structural concrete. With this new perspective in mind such demands for service life designs will also reflect on revised engineering university curricular.

1. INTRODUCTION

Concrete is the most versatile and robust construction material available and has therefore obtained a dominating position in construction. Thus it becomes an economic disaster when urban dwellings, large bridges, or major marine structures deteriorate just after a few years in service. With increasing frequency such examples have been reported from the 70´ies and on. The reasons are very complex but fortunately the main causes have now been identified. It is essential to have these causes highlighted with the aim of adjusting - and in some cases rectifying-design methods, construction procedures, material compositions as well as maintenance and repair procedures, to ensure more reliable structures in the future.

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2. STRUCTURE - ENVIRONMENT INTERACTION

2.1 Performance characteristics of concrete structures

With respect to deterioration, concrete structures have some important characteristic properties, which differ fundamentally from structures made from other structural materials.

These properties are the following [1]:

- The quality of the concrete and the designed durability performance of the structure are only assumed properties at the design stage.
- The true quality and performance characteristics of the structural concrete are determined through the actual execution process during construction on site. Hence, the very short time period of construction (hours, days and weeks) constitutes the most important phase where the required durability performance of the finished structure is determined.

To manage these special properties of concrete structures, an integration is needed of a durability performance based design concept approved by the owner, a conscious execution process, and a planned inspection and maintenance programme.

2.2 Durability

A structure is considered durable when it performs satisfactorily and maintains acceptable appearance as long as the owner and the user need the structure. However, such a definition is not operational as basis for design, maintenance and repair.

The operational way of designing for durability is to define durability as a service life requirement. In this way the non-factual and rather subjective concept of "durability" is transformed into a factual requirement of the "number of years" during which the structure shall perform satisfactorily without unforeseen high costs for maintenance [2].

Designing for a specified service life requires knowledge of the parameters determining the ageing and deterioration of concrete structures. Hence, the precondition is to have scientifically sound data and mathematical modelling available of the:

- Environmental loadings
- Materials and structural resistances, including transport mechanisms for substance into and within concrete, and deterioration mechanisms of concrete and reinforcement.

Therefore, it is evident that the quality of the outer concrete layer - or the concrete cover - and the cover thickness becomes the one single most important quality determining parameter, Figure 1, Ref. [3].

This is the only rational way of performing a quantified service life design for new concrete structures - and a residual service life design for existing structures.

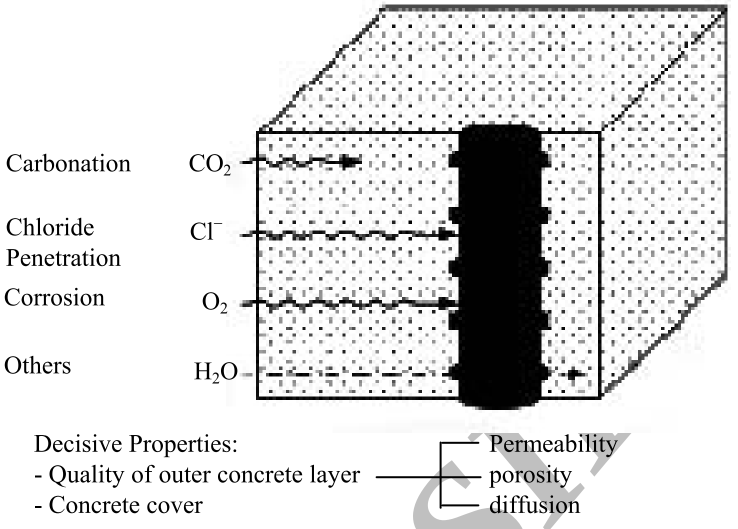

Figure 1. Importance of the penetrability of the outer concrete layer, and the thickness of the cover on the reinforcement to protect the structure against ingress of aggressive substance and deterioration of concrete and reinforcement

2.3 Service life design and life cycle costing

The owner shall recognise that all structures - regardless of building material - will age and deteriorate with time. Hence, he must clarify his needs up front regarding design service life. When doing so, his decision has not only impacts on the short term cost of creating the structure but just as much on the long term costs for maintaining and repairing the structure to comply with his long term performance requirements. The main issue when deciding upon a specific service life is to clarify the event, which will identify the end of the service life.

The requirement for a specific service life performance of a structure is closely associated with the short and long-term costs of this requirement. The owner must therefore acknowledge that he has to take decisions on both the service life and on the associated performance requirements, and he must accept both the short and the long-term costs - and savings - associated with his decisions. Therefore, life cycle cost optimisation (e.g. formulated as an optimisation of the net present value) becomes an integral part of a service life design to be accepted by the owner.

For the everyday buildings and normal structures the national codes and regulations will have defined society's service life requirements - often not explicitly but implicitly through the standards and codified design requirements. However, it is often forgotten that complying strictly with the performance requirements stated in codes and standards will only provide the minimum quality and performance being acceptable to society, and the assumed service life is in general only of the order of 50 years.

For many special structures additional requirements would be required if truly long-term performance and service life of the structures are needed. This aspect is often completely overlooked by owners and clients.

2.4 Environmental loading

With respect to service life design one of the most important decisions to be taken by the designer is the determination of the exposure conditions for which each member of a structure shall be designed, as the structure itself has decisive influence on the future micro-climate to be expected. Different parts of a structure may be in different exposure conditions. Obvious examples are the submerged, the tidal, the splash and the atmospheric zones of a marine structure, but also different geographic orientations (north / south / east / west, or seaward / landward orientation) may be in different exposure classes. Even very local differences can be taken into account such as vertical faces, horizontal surfaces facing upward (risk of ponding) or facing downward (protected against wetting by rain).

2.5 Materials and structural resistance

Having identified the environmental aggressivity the next step of the durability design is to identify the relevant degradation mechanisms. Mathematical models describing the time dependant degradation processes and the material resistances are needed. The big step forward towards performance related durability design is that these models enable the designer to evaluate the time-related changes in performance depending on the specific material and the environmental conditions.

Among the deterioration mechanisms relevant for concrete structures chloride induced reinforcement corrosion is by far the most serious problem, particularly in the hot humid and saline environments around the world like in the Persian Gulf, Refs. [3-4].

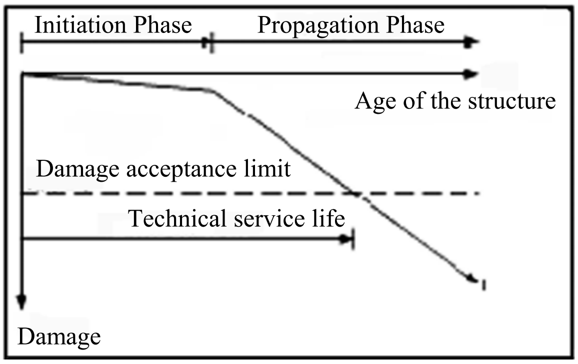

Figure 2. Service life of concrete structures. A two-phase modelling of deterioration. [Tuutti model (1982)]

2.6 Deterioration mechanisms

The two-phase diagram illustrated in Figure 2 may model the development in time of nearly all types of deterioration mechanisms of concrete structures.

The two phases of deterioration are the following:

- The initiation phase. During this phase no noticeable weakening of the material or the function of the structure occurs, but the aggressive media overcomes some inherent protective barrier. Carbonation, chloride penetration and soleplate accumulation - the latter two accelerated by cyclic wetting and drying - are examples of such mechanisms determining the duration of the initiation period.

- The propagation phase. During this phase an active deterioration develops and loss of function is observed. A number of deterioration mechanisms develop at an increasing rate with time. Reinforcement corrosion is one such important example of propagating deterioration. The propagation phase may be divided into several events.

Figure 3 shows in principle the performance of a concrete structure with respect to reinforcement corrosion and related events. In general points 1 and 2 represent events related to the serviceability of the structure, point 3 is related to both serviceability and ultimate limit states and point 4 represents collapse of the structure.

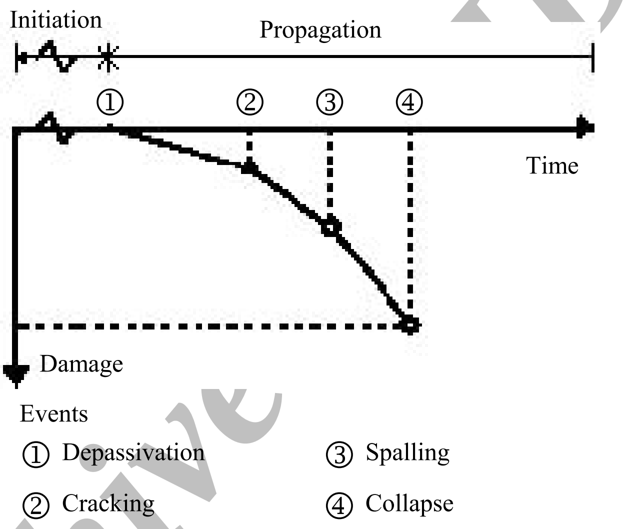

Figure 3. Events related to the service life, and detailing of the propagation phase

2.7 *Effect of Temperature*

The temperature level is decisive for the rate of transporting aggressive substance into and within concrete. Therefore, the temperature is a decisive factor regarding the rate of deterioration of concrete structures. Chemical and electro-chemical reactions are accelerated by increases in temperature.

A simple rule-of-thumb says that an increase in temperature of 10 °C causes a doubling of the rate of reaction.

This factor alone makes hot humid tropical environments considerably more aggressive than temperate climates. The effect of temperature can be clearly demonstrated by comparing the damages in the picture in Figure 4 with the damage in the picture in Figure 5. In the former case the average yearly temperature is approximately 30 °C higher than in the latter case, which would lead to a 2 x 2 x 2 = 8 times faster deterioration in the Gulf compared to the rate of deterioration in the Nordic Countries. The pictures are clear documentation of this dependency on the temperature.

Figure 4. Reinforced concrete jetty in the Gulf exhibiting extensive chloride induced corrosion damage with delamination already after 2-3 years, and having reached a stage of failure and collapse after 7.5 years when this picture was taken

Figure 5. Bridge piers exposed to a temperate Nordic marine environment. Extensive damage in the splash zone after 18 years due to chloride induced reinforcement corrosion

2.8 Concrete resistance to chloride ingress

To focus on the main principles of modern service life design the calculations have been simplified by defining the nominal service life of new structures to be equal to the initiation period. This means that the time for the chlorides to reach the reinforcement and induce depassivation and initiate corrosion is equal to the nominal design service life.

The initiation phase ends when the chloride concentration at the reinforcement reaches a critical threshold value initiating corrosion. Carbonation of concrete can be treated in a similar manner.

Depassivation does not necessarily represent an undesirable state, as illustrated in Figure 2. However, this event must have occurred before corrosion will begin.

3. DESIGN

3.1 Structural design versus durability design

When designing a structure today the designer first defines the loads to be resisted. As these loads usually vary, he applies some safety factors to be on the safe side. These factored loads must then be resisted by the structure through selecting a combination of structural systems, element geometry, material types and materials' strengths.

When it comes to durability design to verify that the intended life can be achieved with an acceptable level of reliability, the situation is entirely different. It seems to be acceptable without question to use a grossly over-simplistic approach. The codes provide only qualitative definitions of exposure and they fail to define the design life in relation to durability. In particular, they fail to define and quantify the durability limit states that must be exceeded for the design life to be ended.

Previous approaches fail to recognise that, in relation to durability, it is not the properties of the materials or components alone that define performance, but the condition of the structure in its environment as a whole, and its individual need for intervention. This performance can be defined by functional requirements such as fitness-for-purpose, which includes issues such as deflections, cracks and spalling, vibrations, aesthetics and structural integrity.

3.2 Design strategy

In principle two basically different design strategies for durability can be followed [6]:

A. Avoid the degradation threatening the structure due to the type and aggressivity of the environment.

B. Select an optimal material composition and structural detailing to resist, for a specified period of use, the degradation threatening the structure.

Modelling of deterioration processes is only relevant for Strategy B. An outline of a procedure for Design Strategy B could be the following:

- Start with the definition of the performance and service life criteria related to the environmental conditions to be expected.
- The next important element is the realistic modelling of the actions (environment) and the material resistance against these actions.
- Based upon the performance criteria, performance tests are indispensable for quality control purposes. The performance tests must be suitable both to check the potential quality of the material under laboratory conditions and, even more important, the in situ quality.
- From this approach the design procedure can be established.

Strategy A and Strategy B can of course be combined within the same structure but for different part with different degrees of exposure (foundations, outdoor exposed parts, indoor protected parts, etc).

3.3 Multi-Stage Protection Strategy

The approach of the service life design following strategy B is to select intelligently an appropriate number and types of co-operating measures to ensure the required service life.

This is considered a multi-stage protection design strategy, or a multi-barrier approach, [3-4]:

1. Identify the type and aggressivity of the environment in which the structure shall operate.
2. Forecast the possible movement and accumulation of the aggressive substance
3. Determine which transport mechanism govern (permeation, diffusion, capillary action) and which parameters control the mechanisms
4. Select barriers that can co-operate in slowing down or prevent the transport and

accumulation processes.

This was a so-called 1st - Generation service life design approach introduced first time for the 100 year service life design for the Great Belt Link in Denmark, [4], see Figures 6 and 7. Later this design has been evaluated using the reliability-based service life design - the so-called 2nd - Generation service life design methodology, see Section 3.5 below and currently it seems as if 150 years service life could be expected.

Figure 6. Great Belt Link, East Bridge. Denmark. L=1416m. Design Life: 100 years

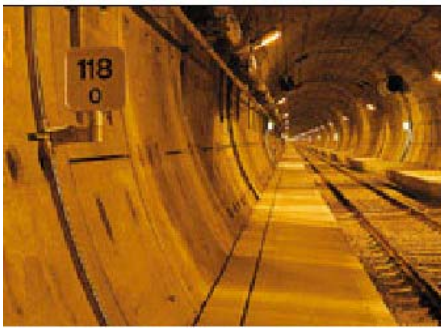

Figure 7. Great Belt Link, East Tunnel. Denmark. Design Life: 100 years

3.4 Durability enhancing methods

For the majority of ordinary structures to be placed in aggressive environments the design approach for durability described in this paper will ensure a satisfactory service life.

In this connection, it must also be recognised up front that in many cases, with structures in highly corrosive environments, the usual choice of design parameters for durability will not provide adequate service life - as has been painfully experienced in the past. Often the damage is only developing on a very small or local part of the structure, which is particularly prone to premature deterioration. This may be due to a particularly corrosive micro-environment (e.g. ponding of seawater) or due to local construction defects (e.g. unintentionally small covers or local honeycombing).

3.5 Reliability-based service life design

The theories of probability and reliability in structural design have been developed and matured remarkably during the past five years. These theories have been transformed from the level of research and development to now being directly applicable and operational in practical engineering design. The methodology has been internationally recognised and used for many decades as basis for the structural safety design through the well-known semi-probabilistic load-and-resistance-factor-design (LRFD).

However, the factors and mechanisms governing the durability and performance of structures throughout their service life have only recently been developed in similar ways. This has among others been achieved through a European research project 1996-1999 "DuraCrete", "Probabilistic performance based durability design of concrete structures" [5].

This has allowed the treatment of transport and deterioration mechanisms to be modelled on a probabilistic level and introduced in the general service life design of concrete structures. Thus, design for safety and for durability can be performed using similar procedures. This opens the eyes of the owners now being able - or forced - to take decisions regarding his required long-term performance of their structures and then to accept the consequences regarding maintenance and costs.

This new durability design methodology is based on the reliability theory as traditionally used in structural design. The purpose of a reliability analysis is to determine the probability of a given event, e.g. the event, which marks the end of the service life - the so-called 2nd Generation service life design methodology.

This formal - or design - end of service life may not necessarily be the real end of the useful life of the structure as illustrated in Figures 2 and 3. Depassivation of the reinforcement is such an example, and this stage is often used as the formal end of the design life for the design of a new structure, a service life limit state, as stated in Section 2.8. In Figure 8 a schematic representation of the problem is shown [7]. The problem can be solved by well-known reliability methods.

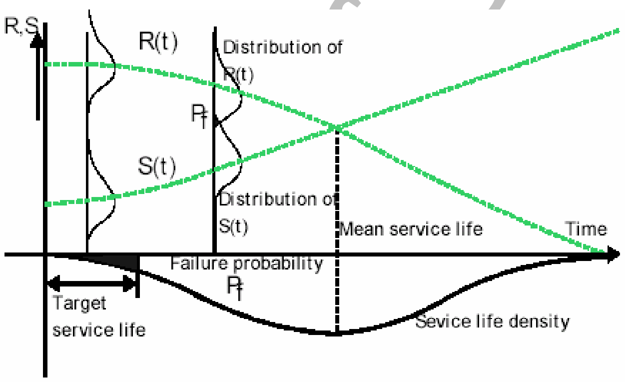

Figure 8. Probability of corrosion initiation and target service life [7]

The DuraCrete Design Guide, [5], aims at obtaining a sufficient level of safety of the design service life with respect to the considered events.

3.6 Deterministic versus probabilistic service life design

The merits of the probabilistic approach to durability design are illustrated by the following example of a marine structure [1,8]. Two different environments are considered, representing yearly average temperatures of 10 °C (exemplified by Northern Europe) and 30 °C (exemplified by the Gulf Countries) respectively. The design requirement is 50 years service life. For simplicity the service life is also in this example defined as the length of the initiation period, i.e. the time until corrosion initiation due to chloride ingress.

Figure 9 depicts the required concrete covers in each of the two environments, based on a traditional deterministic approach.

Figure 10 highlights the fact that the deterministic approach only provides a 50% probability of achieving the required 50 years corrosion free service life. This fact is often overlooked in usual design for durability. If, say only a 10% risk of having corrosion initiated before 50 years is considered acceptable, then much larger covers are required, as seen from Figure 10.

The deterministic approach used here is based on mean values of the governing parameters. In the probabilistic approach the relevant distribution functions with the mean values of these parameters, and their known or assumed uncertainties (coefficients of variation), are used.

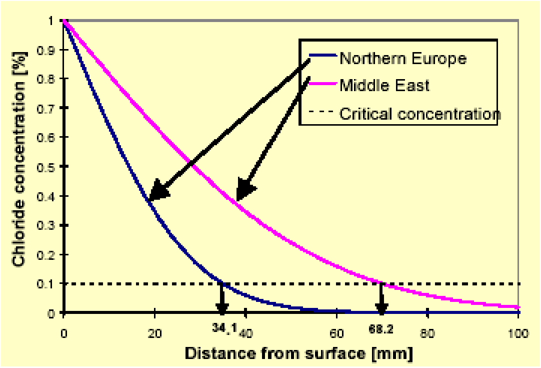

Figure 9. Deterministic approach. Required concrete cover to ensure 50 years service life and assuming a chloride threshold value of 0.1% by weight of concrete.

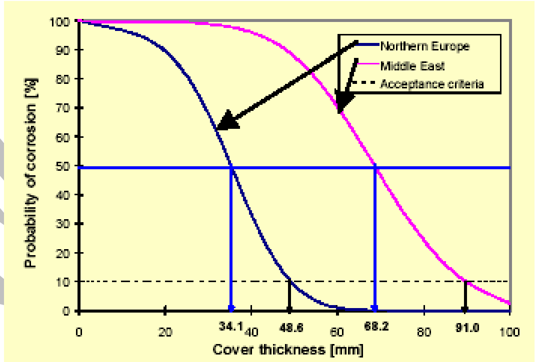

Figure 10. Probabilistic approach. The deterministic approach provides only 50% probability of avoiding corrosion at the age of 50 years. Accepting 10% probability of having corrosion initiated after 50 years results in considerably larger covers

4. CONSTRUCTION

4.1 Interaction between durability design and execution

Already at the design stage possible means of construction shall be considered and fixed, as this will influence the durability design.

It is important that this interaction between the foreseen execution and the provision to provide durable structures is identified at an early stage of the design in order to optimise the design and prepare the structure for easy inspection and maintenance.

4.2 Robustness in design and construction

One of the main obligations of the conscious designer is to adapt the design to the conditions under which the structure is to be constructed, operated and maintained. To avoid structures being sensitive to variations in the assumed qualities a degree of robustness in the design can be very advantageous with respect to the future performance and durability of the structure.

The following sub-sections indicate possible means of increasing the robustness of concrete structures.

4.3 Compaction and curing

Adequate compaction of the concrete in the cover may be difficult to achieve due to the limited space and the need for the cover concrete to be moved through the outer layer of reinforcement. This movement of the concrete may cause "sieving" of the concrete if the spacing of the reinforcing bars is small or the concrete is stiff. When designing the reinforcement layout the realistic ability to compact the concrete on site shall be respected.

Figure 11 illustrates a situation where this has not been achieved.

Figure 11. Example of reinforcement detailing which does not respect the need for reliable casting and compaction of concrete. Particularly the quality of the concrete “skin” (the cover) is in danger

Curing of the concrete is part of the hardening process, which ensures an optimal development of the fresh, newly cast concrete into a strong, impermeable and durable hardened concrete in the cover zone free from plastic shrinkage and thermal cracks.

Concretes with very low water/cement ratio, such as high performance concrete, may be particularly sensitive to correct heat, temperature and moisture control during the hardening process, see Section 5.1.

In short, good curing is needed to profit from a good concrete mix. Bad curing destroys an otherwise good concrete mix. And good curing cannot compensate for a bad concrete mix.

4.4 Controlled permeability form liners (CPFL)

The most important part of the structure protecting it against ingress of aggressive substance is the concrete cover, also considered the "skin" of the structure.

CPFL has proven effective in enhancing the denseness of the outer mm and cm of the cover by reducing the water-cement ratio and improving the curing of this outer concrete layer.

4.5 Self-compacting concrete (SCC)

The development of a concrete mix where the placing and compaction has minimal dependence on the available workmanship on site would improve the quality of the concrete in the final structure. This has been a main driving force in recent years development of SCC. With the aid of a range of chemical admixtures and optimal grading of the aggregates concrete with low water/cement ratio can be made to flow without segregation through complicated form geometry and around complex reinforcement layout.

The form can be filled and a uniform compaction without honeycombs can be achieved, also in the cover zone of the concrete, with no or only minimal additional contribution to the compaction and levelling of the concrete from the workforce on site. The flowing concrete will usually increase the pressure on the form, which shall be taken carefully into account when designing the formwork.

The use of SCC is also an environmentally friendly technology as the noise level from vibrators is nearly eliminated and the concrete workers need only minimal work with the vibrators, with all the adverse effects vibrating concrete has on the body ("white fingers").

4.6 Spacers

The minimum concrete cover specified in a design is usually the value used to calculate the expected service life based on assumptions regarding the penetration of de-passivating and corrosive substance to the reinforcement. Therefore this minimum value shall be ensured in the final structure by taking the relevant tolerances into account in the selection of type, dimension and spacing of spacers. The spacer material shall have good bond to the concrete and shall have similar hygro-thermal deformation characteristics as concrete. In this respect plastic spacers, see Figure 12, are not compatible with the surrounding concrete, in the sense that they have no direct adhesion to concrete and that they have different temperature coefficients than concrete (a factor of about ten), and furthermore they age and shrink under exposure to air, sun and marine environment. In aggressive environments high quality concrete spacers shall be the preferred option and it is important to ensure that the spacers are of the same high quality as required for the structural concrete itself.

Figure 12. Plastic spacers allow direct access of chlorides to the reinforcement

4.7 Adapt requirements to local conditions

The conditions under which structures shall be constructed and used differ from case to case. It is therefore essential to adapt the requirements for the concrete mix, casting, compaction and curing to what can realistically be achieved at the individual location. The available concrete components, the local workmanship and the prevailing climatic conditions shall be considered.

This is particularly important for remotely located structures and in geographic regions with little or no alternatives to the local cement, aggregates and water, and only local, maybe unskilled, labour.

4.8 The handing-over situation: The "Birth Certificate"

In order to document the fulfilment of the design specifications, and verify the subsequent performance, the Quality Assurance documentation for design and execution should be enlarged to include information gathered during the operation and use of the structure.

Developing an Operation and Maintenance Manual specific for each structure can do this. This Manual should be prepared by the Designer and shall include all information from the structural design and the construction being relevant for the future inspections and maintenance. This Operation and Maintenance Manual shall also include recommendations regarding type and frequency of future inspections and should highlight possible sensitive or critical parts of the structure which are assumed beforehand to need particular attention during use.

When the structure is handed over to the Owner, the initial Operation and Maintenance Manual will constitute a “Birth Certificate” of the structure [1]. Information from future inspections and all other relevant events such as accidental impacts are then filled in as they occur. Depending on the nature and contents of such future information the type, frequency and selected special areas of concern shall be revised or updated by the Owner following his needs at that time.

5. MATERIALS

5.1 High performance concrete (HPC)

The continuous demand for increased strength and improved durability of concrete structures has led to the development of HPC. This development has had three main objectives in mind:

1. Protect the reinforcement against corrosion; in particular provide protection against ingress of chlorides by creating dense impermeable concrete in the cover zone with very low penetrability of aggressive ions such as chlorides, sulphates and of CO_2.
2. Resist deterioration of the concrete itself when exposed to the aggressiveness of the environment such as sulphates, seawater and other chemical attacks, as well as resist freeze/thaw attack.
3. Provide adequately high strength to fulfil the structural requirements.

This development has been very successful in many respects. The advanced HPC products available have met very complex and demanding structural challenges today, where the strength requirements usually remain within the range of say 50 - 80 MPa or higher. One drawback has been that these more refined concrete mixes become more sensitive towards the actual handling during execution. They set high demands on the competence, experience and workmanship of the workforce. To varying degrees these concretes differ from the long term known types of structural concrete.

The main driving force in introducing HPC has been objective no. 1 above. However, the availability of stainless steel reinforcement and used selectively, as described in Section 5.3, will in nearly all cases solve the problem thus reducing the need for HPC with its execution related drawbacks.

Solving the objective no. 1 above will require a highly alkaline concrete mix and a dense impermeable concrete in the cover protecting the reinforcement. From this it follows that:

- The more pure Ordinary Portland Cement in the mix, the more calcium hydroxide will be available in the hardened concrete to provide and sustain the high alkalinity.
- As obtaining the required strength generally is not a problem, then the so-called durability enhancing measures of adding large quantities of pozzolanic admixtures, using very low water/binder ratios and adding a mixture of chemical additives to ensure workability etc. - and having to add these costly additives and admixtures to the whole bulk of the concrete - is to a large part wasted, as they would only be needed in the cover zone.

These issues seem greatly overlooked by the design and construction industry - but they have adverse effects on environmental preservation and are counterproductive to a sustainable construction environment.

The nature of deterioration of concrete structures also highlights the fact that high performance concrete does not necessarily provide high performance concrete structures, as detailed in [9].

This conflict - and its practical consequences - is not easily understood by the classical research communities, but painfully experienced by many contractors and structures´ owners/operators.

5.2 Corrosion resistant reinforcement

Normal reinforcement - also termed mild steel, black steel or carbon steel reinforcement - is very efficiently protected against corrosion when cast into a good quality alkaline and chloride free concrete. This is the well-known unique benefit of using reinforced concrete structures in building and construction. Only when carbonation reaches the level of the reinforcement, or more seriously, when chlorides in sufficient quantity reach the surface of the reinforcement will the passivating effect be eliminated and corrosion may start. Particularly serious are the situations where the initial concrete mix has been polluted with chlorides from the aggregates, the mixing water or chloride-based accelerators. Recent year's developments within the area of non-corrodible or corrosion protected reinforcement for concrete structures are opening promising new doors in the fight against reinforcement corrosion. The following products with different degrees of resistance against corrosion are available:

- Stainless steel reinforcement (SSR). Merits described in detail in [10].
- Epoxy coated reinforcement.
- Hot dip galvanised reinforcement (zinc coating). This application is very limited, but may be a fully viable protection in concrete exposed to carbonation. In general zinc coating is not considered adequate - or cost-effective - for structures exposed to chlorides. Zinc coating is not discussed further in this paper.
- Non-metallic reinforcing bars such as reinforcing bars from glass fibres, aramid fibres or carbon fibres. The non-metallic reinforcing bars will probably for many more years only have limited applicability due to the major differences needed when constructing on site. They may have a potential within the pre-casting industry, and not discussed further in this paper.

5.3 Stainless steel reinforcement (SSR)

The use of SSR in zones being exposed to high chloride concentrations is considered a highly reliable solution following design Strategy A, see Section 3.2. This can ensure a very long problem-free service life in that part of the structure, provided the concrete itself is made sufficiently resistant to avoid other types of deterioration such as alkali-aggregate reactions, sulphate attack or salt scaling.

In addition, there are regions where the chloride contamination is so widespread that all aggregates and mixing water is more or less chloride contaminated. Sometimes a 10 - 20 year service life has become the accepted norm in such regions, or continued repair works have been the accepted solution. Using SSR may often solve this problem completely.

Used selectively in the most exposed zones of the structure the increased costs per kg SSR compared to the costs of normal steel will most often have only marginal or negligible effect on the overall initial construction costs. In addition the service life costs will be reduced considerably due to savings in future repair and maintenance, [11-12].

From a practical point of view this technology is particularly interesting because it "only" solves the corrosion problem. All other techniques and technologies within design, production and execution of reinforced concrete structures remain practically unchanged, a fact that is very attractive to the traditionally very conservative construction industry.

Of particular importance is the often-overlooked fact, that SSR can be coupled with normal mild steel reinforcement (carbon steel) without causing galvanic corrosion, [11-14]. The reason is that the two types of steels reach nearly the same electro-chemical potentials when cast into concrete. This leads to the possibility to use SSR only in those parts of the structure where this is considered necessary, and then reinforce the remaining parts with ordinary mild steel reinforcement. Such highly exposed zones needing SSR could be splash zones of marine structures, foundations in contaminated soils, lower parts of columns above ground, balconies, etc.

A very convincing documentation of the performance of stainless steel reinforcement in highly chloride contaminated concrete is presented by the 65 year old 2.2 km long concrete pier out into the Mexican Gulf at Progreso in Mexico reinforced with stainless steel, see Figure 13. No corrosion has taken place within the structure, despite the harsh environment and poor quality materials used in the construction. The chloride levels, at the surface of the reinforcement were more than 20 times the traditionally assumed corrosion threshold level. A newer, only 35 years old parallel pier has already perished due to reinforcement corrosion of the ordinary carbon steel reinforcement used in this structure, as seen in the foreground of Figure 13 and the remaining parts on land is shown in Figure 14.

Figure 13. 65 year old stainless steel reinforced pier at Progreso in Mexico still fully intact without maintenance whereas the remains in the foreground is what is left of an only about 30 year old pier reinforced with ordinary black steel reinforcement, see Figure 14.

Figure 14. Close-up of the land based remaining parts of the "new" pier of which part of the remaining piles are shown in Figure 13. This pier was reinforced with ordinary black steel reinforcement and lasted only about 10 years.

A further documentation of a more recent adoption of stainless steel reinforcement is a large new Building Complex currently under construction in the Gulf region. SSR was introduced from somewhat below groundwater level-to-level +5m in the outermost structures directly exposed to the salty ground water and seawater spray of the Gulf waters. All remaining parts are reinforced with normal carbon steel as shown in Figures 15 and 16.

Figure 15. Overview of the construction site of a seaside Building Complex. Stainless steel reinforcement is used in the outer exposed structures from below ground water level up to level +5m. See Figure 16.

Figure 16. Detail from Figure 15. The remaining reinforcement is ordinary carbon steel. The design service life without corrosion damage is 50 years.

At the same time the reinforced concrete seawall protecting both the existing important buildings and the adjacent new Building Complex is being replaced using SSR throughout, see Figure 17.

Finally, an additional benefit of using SSR is the fact that stainless steel is a poorer cathode than carbon steel, [13]. Therefore, SSR can be beneficial in those repair cases where ordinary carbon steel has corroded to such an extent that local replacement or added reinforcement is needed as part of a repair. In this way the traditional problem of new corrosion developing on the reinforcement adjacent to the repaired area - and initiated in part by the repair - can be reduced or fully avoided. A current example of such replacements can be seen in the replacement of corrosion damaged bridge edge beams on Danish motor- and highway bridges and on crash barriers, using stainless steel in the edge beam and parapet replacements see Figure 18.

Figure 17. Stainless steel reinforcement used in the precast structural members to replace a corrosion damaged seawall protecting the existing important buildings and the new Building Complex (Figure 15) from the Gulf.

Figure 18. Replacing edge beams and parapets on Danish bridges and crash barriers on the motorways exposed to de-icing salt. SSR is introduced to avoid future repairs as well as avoiding the serious delays and inconveniences to the users, an issue becoming more and more in focus with the growing awareness of the costly societal consequences of such delays.

As it is recognised that the most serious durability problem for concrete structures is reinforcement corrosion it becomes evident that, Ref. [1]:

The reliable and readily availability of stainless steel reinforcement at reasonable and foreseeable prices may change - or revolutionise - major parts of the building *sector in aggressive environments, simply by solving the corrosion problem.*

The main reason is also the added value which follows from the possibility of accepting the use of locally available materials, even with chloride contamination, and also accepting the qualifications of the local workforce as it is, and still produce highly durable, robust and long lasting reinforced concrete structures with need for only minimal maintenance - when designed intelligently.

5.4 Epoxy coating of reinforcement

Epoxy coating of reinforcement has been used in North America since the mid 70'ies. This technology has now for many years been critically discussed.

The nearly unavoidable fine cracking occurring during bending, the pinholes occurring in the coating, and the inferior protective ability of the patch repaired zones and cut ends have led epoxy coated reinforcement to be a less attractive solution - mildly speaking. It also has the side effect that this technology will prevent the possible future use of cathodic protection, leaving no alternative but replacement of damaged members if corrosion develops. Currently, the coating industry is working on enhancing the technology, but still without the possibility to enhance the key source of uncertainty, namely the individual execution phases. Hence, the most acceptable application of epoxy coated reinforcement would probably be in the precasting industry - if used at all.

North American experience has thrown serious doubts on this approach, when following the traditional procedure of coating straight bars individually, then cutting them to length and bending them to the required shape, see Figure 19 and 20 from the Florida Keys. In several states epoxy coating is not allowed by the local Departments of Transport and in Ontario, Canada, SSR is taking over within bridge construction and bridge repairs.

The first public report on failing performance of epoxy coated bars was from January 10th 1992, [15], which concluded that the *"Epoxy coated rebar technology is flawed"*.

Figure 19. Bridge on the Florida Keys. Critical corrosion of epoxy coated reinforcement

This caused a major disturbance within the North American Continent due to pure commercial and biased reactions from the producers of epoxy coated reinforcement and their organisations. At that time the technology was in the process of spreading rapidly to Europe, the Middle East, mainly the Gulf Countries, and to some parts of the Far East.

Figure 20. Bridge on the Florida Keys. Critical corrosion of epoxy coated reinforcement leading to splitting of the V formed supports now strengthened by prestressed bolts

Using epoxy coated single bars would be to "put all the eggs in one basket" as it was termed. The North American experience with the traditional technology of epoxy coating together with additional testing and site investigations, among others in Ontario, Canada, [16], has lead to this technology not gaining foothold in Europe, and the technology is now slowly being phased out, also in the Middle East and Gulf Countries, see Figures 21-23.

Figure 21. Seawall reinforced with epoxy coated reinforcement-heavily damaged by reinforcement corrosion after about 12 years

Figure 22. Close-up of the corroded epoxy coated reinforcement shown on Figure 21

Figure 23. Details of the corroded epoxy coated reinforcement shown on Figure 21. The loose layer of epoxy on the corroding bar is clearly visible

6. CONCLUSIONS

The complexity of designing well performing, low maintenance and long-lived concrete structures has been presented in this paper. It highlights the multidisciplinary set of problems to be solved by the designer in order to ensure truly long service life with minimal maintenance of concrete structures.

However, the descriptions of the individual measures needed to achieve this goal have also been shown to be relatively simple - in most cases surprisingly simple, and using well-known methods, materials and technology. The real challenge is in fact twofold:

1. The owner shall formulate his performance requirements to the structure in a format that can be translated into a quantified design basis, taking the long term effects or consequences, including acceptable needs for maintenance, into account technically as well as in the economic evaluations.
2. The designer and the contractor need to combine readily available knowledge from design, construction, materials technology and deterioration mechanisms into an integral solution adapted to the individual structure in its foreseen environment.

Our daily terminology using "durable concrete" and discussing "High Performance Concrete" is misleading. In fact, no one cares very much about high performance concrete (except maybe the cement, concrete and admixture producers) but what we all need is *High Performance Concrete Structures*, and that is a completely different challenge, as highlighted in this paper.

It could seem as if the producers and suppliers have monopolised durability research for concrete structures throughout the past several decades by focusing only on the concrete and its refinements to ensure all aspects of corrosion protection of reinforcement, leading to more expensive types of concrete resulting also in more execution sensitive concretes causing distress at the construction site, and at times providing less durable concrete structures.

The fact that the more costly and execution sensitive HPC in general is only needed in the outer concrete cover, but unavoidably has to be used throughout the sections, has been overlooked by the design industry. The consequences has been a real global waste of expensive mineral and chemical additives and admixtures, often causing at the same time execution and curing difficulties,- and often also leading to inferior quality and insufficient durability of the finished structure.

This one-sided approach of looking only on the concrete mix and coatings to ensure the service life of reinforcement corrosion threatened structures does not enhance environmental protection due to often increased need for future maintenance and repairs, and does not contribute to a sustainable society.

Finally, the competence to fully understand the durability related problem-complex and to achieve optimised integrated performance based designs of concrete structures will have to start with adapting this into the engineering educational curricular. A new design paradigm is needed for the design and execution of concrete structures. This is a precondition for concrete structures to increase competitiveness and thus remain the solid and reliable foundation for future societal prosperity.

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