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THE CONSULTANT'S VIEW ON SERVICE LIFE DESIGN

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Abstract

There is a rapidly growing international demand for long-term well-performing concrete structures without premature need for maintenance and repairs. Major structures like bridges and tunnels are expected to have a long service life in the order of 100, 120 or even more years to ensure that the investment is spent in a rational way.

Past decades have shown that the classical procedures for durability of reinforced concrete structures have often failed to provide reliable long-term performance in aggressive environments. Within Europe this awareness has led to the development of new service life design approaches to provide necessary and valuable tools to satisfy present day design needs. These new design tools allow the grossly over-simplistic deem-to-satisfy durability design methods of traditional codes and standards to be replaced with rational scientifically sound service life design methods using the same reliability based methods as used for decades for structural design. These new service life design tools have been implemented in ***fib*** bulletin No. 34 *Model Code for Service Life Design* and will be part of the new ***fib*** Model Code for Service Life. Furthermore, it will be transferred into an ISO standard in the near future.

COWI spearheading the international developments for such rational service life design methods during the last decades has adopted this new service life design approach for the several larger infrastructures worldwide.

The paper presents one of today´s most upfront durability design methodology exemplified by some case studies.

1. INTRODUCTION

During the past years, clients have asked for bridges, tunnels, prestigious engineering structures to be designed to satisfy a specified service life, typically 100 and 120 years, and in particular cases even 200 years. This substantially surpasses the assumed design life of most traditionally used codes and standards.

Most commonly, the durability is generally "ensured" simply by adopting deem-to-satisfy rules as given in the codes and standards such as Eurocode, AASHTO *LRDF*, BS, or DIN. Experience shows that these rules based on a combination of experience, research and intuition have many drawbacks and often they result in inadequate durability design. In short, present codes and standards are often inadequate and not quantifiable.

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 for the "number of years" during which the structure must perform satisfactorily without unforeseen high costs for maintenance. In this way, the time factor is introduced as a design parameter.

In Europe this awareness has led to the development of more rational service life design approaches to satisfy the above design needs. These approaches mainly developed within the European research project 'DuraCrete' (Probabilistic Performance based Durability Design of Concrete Structures, 1998), further developed in the subsequent 'DARTS' research project (Durable and Reliable Tunnel Structures, 2004) have nowadays been implemented in the ***fib*** Bulletin No. 34 *Model Code for Service Life Design*, 2006.

2. SERVICE LIFE DESIGN APPROACHES

2.1 Traditional durability design approaches

Most design codes and standards for concrete structures contain a prescriptive or deemed-to-satisfy approach to the design and specification of reinforced concrete in various exposure environments, including exposure to chlorides. This approach generally comprises the specification of limiting values for maximum water/cement ratio, minimum cement content and minimum cover for various cement types in a limited number of exposure environments. Somewhat surprising, despite the obvious time-dependent nature of the risk of concrete deterioration such as reinforcement corrosion, design life has not been included as a specific consideration. One serious drawback of this deemed-to-satisfy approach is that the design life is not quantifiable. Predicting the expected service life of concrete structures is not possible. This philosophy makes the life-cycle cost analysis impossible and hinders the decision-making process.

The development of the deemed-to-satisfy durability provisions in standards and codes has generally not been based on fundamental principles but on experience, field observations and limited research data with a significant element of compromise and engineering judgment within code and standard committees.

The traditional approach for durability design has other serious limitations. For instance, a method of testing the initial quality of the concrete in relation to the design life has not been stated. In addition, the codes and standards often do not differentiate sufficiently with regard to the actual exposure. For example, considering the concrete pier shown in Figure 1, each concrete pier shown could be divided in three exposure zones. The first zone remains submerged at all times. Another zone, which is located above the submerged zone, is subjected to dry and wet cycles as water elevations change with possible chloride accumulations due to evaporation effects (splash and tidal zone). Finally, there is a zone that always stays above the water level and is subjected to atmospheric conditions only. These three zones behave differently and require different approaches for detailing and design for service life, a requirement that current codes and standards are not able to answer.

Traditional durability design guidance is usually specific to the area in which the guidance has been developed and may not necessarily be applicable in other locations. A good example of this is the Middle East, which when large-scale development began in the 1960's and 1970's, had no local design codes or standards. Designers often used the design standards from their own countries with no allowance for the often much more aggressive conditions, resulting from the high temperatures, aggressive groundwater and high salinity sea water, and often poor construction quality. Much premature deterioration of concrete structure occurred, mainly due to chloride induced reinforcement corrosion.

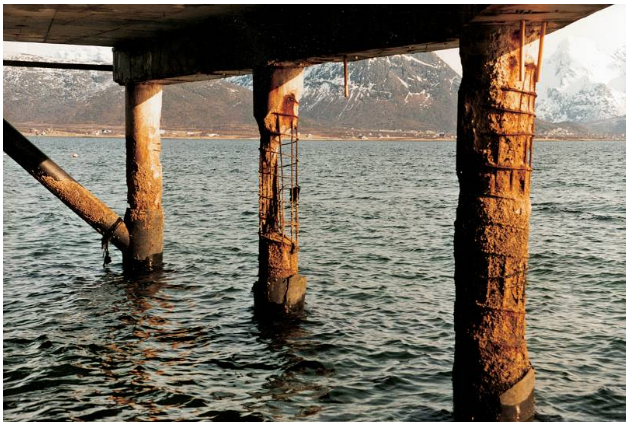

Figure 1: Importance of differentiation in exposure classes

First, the latest generation of Eurocodes and European Standards such as EN 2 and EN 206 do reflect the time-dependant deterioration behaviour and take the service life into consideration on some way.

2.2 European approach for design for service life - the *fib* bulletin 34 approach

Based on experience showing that the traditional procedures for durability of reinforced concrete structures have often failed to provide reliable long-term performance, European research focus has therefore shifted towards studying the mechanisms, which govern deterioration of concrete and corrosion of reinforcement and their interrelations. The type of cements used and the quality of concrete, particularly the influence of the denseness represented by the diffusivity of the concrete, have attracted more focus.

Between 1996 and 1999, with financial support of the European Commission, a series of studies were undertaken to develop scientifically verified methods to design and evaluate concrete structures for durability or service life. The project is referred to as the DuraCrete Project as an abbreviation for 'Probabilistic Performance-based Durability Design of Concrete Structures'. The project was led by COWI and included 12 partners, all from Europe.

Seven major tasks were undertaken under the DuraCrete project ending up with a new design tool (computer modelling) for service life of reinforced concrete structures. It is a probabilistically and performance-based service life design approach which considers the probabilistic nature of the environmental aggressiveness, the degradation processes, and the material properties involved. This 'full probabilistic' approach is basically based on the same design methodology as generally used for structural designs and, among others, represented by the *LRFD* methodology (Load and Resistance Factor Design). Similar to structural design codes for load, this means that safety requirements and limit states must be defined for the design service life.

The approach can be used for the design of new structures and in the verification of the service life of existing structures (re-design). It addresses mainly chloride and carbonation induced-reinforcement corrosion. These two types are often the decisive deterioration processes of concrete structures. Chloride- and carbonation-induced corrosion is addressed through deterioration and transport models capable of predicting the time that it takes to start the corrosion. Therefore, the approach is performance-based as the time factor of these effects is taken into consideration.

Other sources of deterioration in concrete such as sulfate attack, alkali-silica reaction (ASR) and freeze and thaw attacks are addressed by another approach, the 'Avoidance of Deterioration' approach. In this case, deterioration is prevented up-front by using appropriate quality concrete, i.e. non-reactive aggregates, sulfate resistant cements, low alkali cements and concrete with artificial air entrainment. The use of stainless steel reinforcement belongs to the 'Avoidance of deterioration' approach as well and may be an alternative to the probabilistic design approach in case of reinforcement corrosion.

This approach for durability design has been adopted by national authorities (e.g. the Dutch Ministry for Transport) and individual clients all over the world. It has been implemented in the ***fib*** Bulletin No. 34 *Model Code for Service Life Design*. The flow chart in Figure 2 illustrates the flow of decisions and the design activities needed in a rational service life design process with a chosen level of reliability. Currently, ***fib*** is working on a full revision of the CEB/FIB Model Code 1990, where the ***fib*** Bulletin 34 approach for durability design will be fully integrated. The ***fib*** Bulletin 34 identifies four levels of sophistication in the performance-based design of concrete structures:

- A full probabilistic design, also called 'DuraCrete' approach
- A partial factor (semi-probabilistic) with factors calibrated with level 1 above
- A deem-to-satisfy design corresponding to methods in current codes and standards but requirements calibrated with level 1 above to the extent possible
- Avoidance of deterioration.

The different levels can be combined within the same structure, but for different parts with different degrees of exposure.

The direct service life calculation following the full probabilistic design will mainly be used for larger infrastructures with a required particularly long service life such as bridges, tunnels, airports, marine structures etc., whereas the deemed-to-satisfy approach is meant for everyday buildings and normal structures.

It shall be noted that ***fib*** Bulletin 34 also has its limitation as it is mainly concerned with the service life of concrete structures as related to concrete durability. Other factors affecting the service life of structures such as expansion joints, bearings, coatings etc. are not addressed to the same level. Further, load effects are not considered. For instance, fatigue caused by dynamic loading leading to time-depending material degradation and corrosion fatigue developed by simultaneous action of corrosion and environmental factors are not addressed.

In the following practical examples for the full probabilistic design and the avoidance of deterioration approach are presented for exemplification.

3. EXAMPLES FOR *FIB* BULLETIN 34 DESIGN APPROACHES FOR DURABILITY

3.1 Full probabilistic approach

3.1.1 General

The Busan-Geoje Fixed Link project comprises a 8.2 km motorway link from Busan, Korea's southernmost and second largest city, to the island of Geoje (Figure 3). The connection includes a 4 km immersed tunnel - the deepest in the world at a water depth of 50 metres - and two cable-stayed bridges, each 2 km long. The project is scheduled for completion at the end of 2010. COWI is the leading consultant for both the bridges and the tunnel; DAEWOO E&C is the leading contractor.

The bridges and the tunnel should be designed for a service life of 100 years. A project specific design basis was developed as an initial part of the design, and details were agreed with the client and owner. Chloride-induced reinforcement corrosion was identified as the governing deterioration mechanism in the design for service life, as all other potential deterioration mechanism (sulfate attack, alkali-silica reaction, frost) were solved through the 'Avoidance of deterioration' approach.

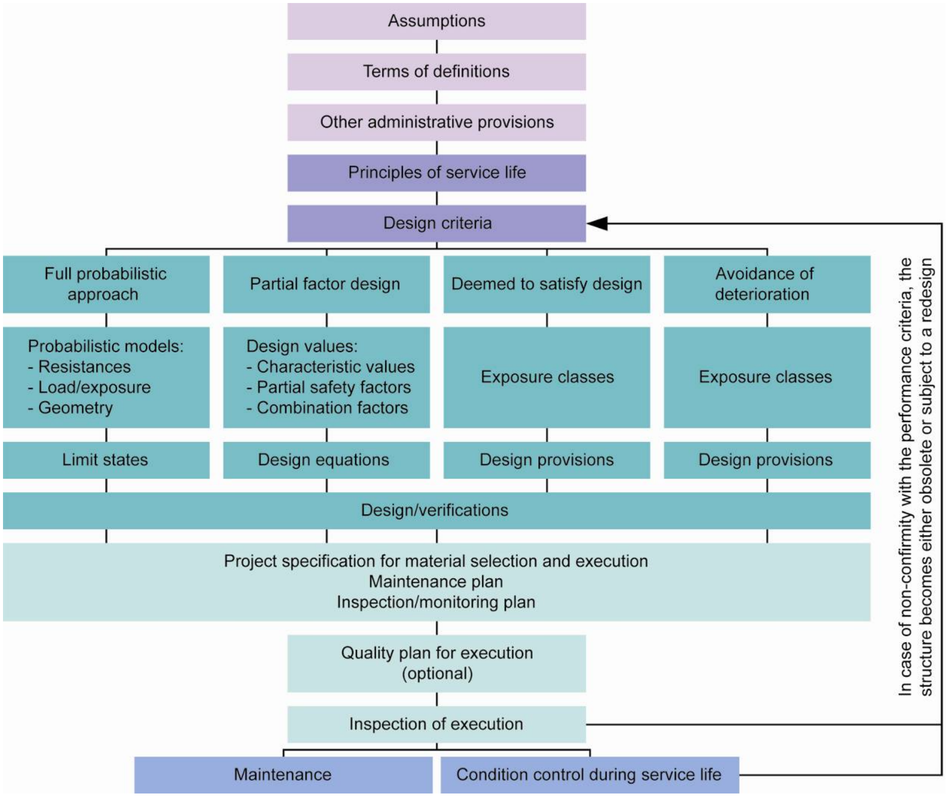

Figure 2: The ***fib*** Bulletin 34 approach for durability design showing four different levels of sophistication for service life design

Figure 3: Busan-Geoje Fixed link with bridges and immersed tunnel designed for 100 years' service life using the full probabilistic service life approach following the DuraCrete approach

The following operational basis for the service life design was adopted:

- The design life is 100 years
- The initiation phase of the deterioration by chloride ingress represents the design life. During the initiation phase chloride penetrates the concrete and reaches the reinforcement level. The initiation phase ends when the chloride content reaches the critical level at the reinforcement (threshold level). Thus, the chloride initiation is defined as the nominal end of service life, see Figure 4.
- A 90% probability of not having any corrosion initiated before the 100 years has passed, corresponding to 10% probability of premature corrosion initiation. Or, in other words, adopt the corresponding reliability index (β = 1.3) as design basis. The ***fib*** bulletin 34 indicates a value for β = 1.5-1.8 (6.7% - 3.6% probability of corrosion initiation).
- Design the minimum concrete cover using the DuraCrete tool. This will provide the minimum concrete cover and the maximum chloride diffusion coefficient of the concrete complying with the above-given design criteria.

The surface chloride concentration being generated by the local marine environment is the force driving the chlorides into the concrete and towards the reinforcement. This value was determined based on extensive data from similar types of exposure.

The determination of the design quality of the concrete with respect to its chloride penetrability is the basic protective parameter against premature corrosion initiation and shall be determined at the initial stage together with the testing of the design compressive and tensile strength needed for structural design.

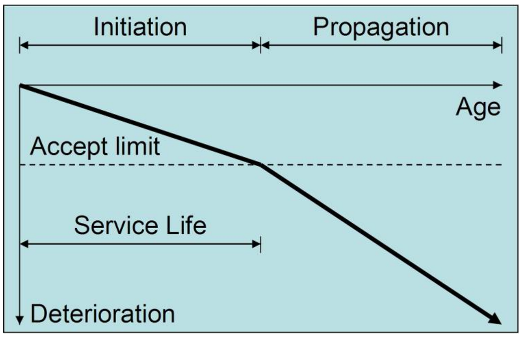

Figure 4: Service life of concrete structures. A two phased time-related modelling of deterioration - initiation and propagation phase

3.1.2 Different design steps and input parameters

Regarding the general concept of the full probabilistic approach and the reliability- and performance-based principles reference is made to e.g. DuraCrete report, Rostam, Gehlen & Schiessl, Siemes. One important issue of the approach is that the probabilistic nature of the environmental aggressivity, the degradation processes and the materials' properties involved will be taken into account by stochastic variables, i.e. all input parameters will be defined by mean values and distribution functions. In the following, the different design steps (1-4) and the important input parameters (mean values) are listed for the bridge design:

1. **Identification and quantification of the environmental exposure of the different structural members and their location:**

It is assumed that the main potential deterioration risk for the bridges is chloride induced reinforcement corrosion due to marine exposure. With regard to chloride-induced corrosion the following different exposure classes have been investigated:

- Splash zone (piers, pylons, caissons)
- Submerged zone (caissons)
- Atmospheric environment (piers, pylons, abutments, bridge decks).

2. **Determination of the design quality of the concrete with respect to its design penetrability for the aggressive substances and their concentrations, as identified from the environmental exposure:**

The following input parameters are decisive: The design surface chloride concentration (Cl^-s) as expected for the quality of concrete and foreseen when exposed to the different environments:

- Splash zone: Cl^-s = 4 % by weight of binder
- Submerged zone: Cl^-s = 3 % by weight of binder
- Atmospheric environment: Cl^-s = 2 % by weight of binder

The *background chloride concentration* foreseen in the concrete mix: Cl^-_0 =0.1% by weight of binder.

The *chloride diffusivity* (D_{Cl^-}), typically the decisive design transport parameter measured by standard NT Build 492. The test method determines the chloride migration coefficient, which in the scope of this paper is comparable with the chloride diffusion coefficient. The diffusion coefficient is a functional requirement within the concrete specification with which the contractor has to comply: D_{Cl^-} between 2-7x10^{-12} m^2/s represents the possible spectrum of different types of cement and binder combinations based on European experience.

The critical chloride concentration (Cl^-_{cr}) is decisive for the chloride concentration at the level of reinforcement, as it triggers corrosion of the reinforcement:

- Splash zone: Cl^-_{cr} = 0.6 by weight of binder
- Submerged zone: Cl^-_{cr} = 1.8 by weight of binder
- Atmospheric environment: Cl^-_{cr} = 0.8 by weight of binder

The *ageing factor* (α) represents the ability of the concrete to develop an increased denseness. It is represented by a decreasing diffusion coefficient with increasing age: It depends on the type of binder and the environmental conditions:

- Splash zone: α = 0.4, 0.5 and 0.6
- Submerged zone: α = 0.3, 0.4 and 0.5
- Atmospheric environment: α = 0.4 and 0.5

3. **Adoption of design life and acceptance criteria:**

See above: P_f = 10% corresponding to a reliability index β = 1.3.

4. **Determine the nominal concrete cover using the DuraCrete methodology.**

3.1.3 Service life calculations - DuraCrete results

In the following, the service life verification for the Busan-Geoje Fixed Link is exemplified for the bridge and the different exposure zones.

Tables 1-3 show the spectrum of the obtainable reliabilities β depending on the maximum chloride diffusion coefficient and the age factor α for the concrete structures for the selected final nominal concrete cover of 75 mm.

Table 1: Splash zone (piers, pylons and caissons (external). Interrelation chloride diffusion coefficient, D_{Cl^-}; age factor, α; reliability, β

Nominal cover	**Max. D_{Cl^-} at 28 days of maturity**	**α = 0.40**	**α = 0.50**	**α = 0.60**
(mm)	**(m^2/s)**	**β**		
75	2 x10^{-12}	2.2	3.0	3.3
	3 x10^{-12}	1.5	2.3	2.7
	4 x10^{-12}	1.1	1.9	2.3
	5 x10^{-12}	-	1.6	1.9
	6 x10^{-12}	-	1.3	1.7
	7 x10^{-12}	-	-	1.5

- Not determined (β << 1.3)

Table 2: Submerged zone (piers, pylons and caissons (external).
Interrelation chloride diffusion coefficient, D_{Cl^-}; age factor, α; reliability, β

Nominal cover	**Max. D_{Cl} at 28 days of maturity**	**α = 0.30**	**α = 0.40**	**α = 0.50**
(mm)	**(m^2/s)**	**β**		
75	2 x10^{-12}	3.2	>>2.0	>>2.8
	3 x10^{-12}	2.5		
	4 x10^{-12}	2.0		
	5 x10^{-12}	1.7		
	6 x10^{-12}	1.4		
	7 x10^{-12}	1.2	2.0	2.8

Table 3: Atmospheric zone (piers, pylons, abutments and bridge decks).
Interrelation chloride diffusion coefficient, D_{Cl^-}; age factor, α; reliability, β

Max. D_{Cl^-} at 28 days of maturity	**α = 0.40**	**α = 0.50**	**α = 0.40**	**α = 0.50**
(m^2/s)	**nominal cover = 40 mm**		**nominal cover = 50 mm**	
	β			
2 x10^{-12}	1.3	2.1	2.1	2.5
3 x10^{-12}	0.9	1.6	1.5	1.9
4 x10^{-12}	-	1.2	1.2	1.4

- Not determined (β << 1.3)

3.1.4 Final selection of the durability related design parameters

The maximum chloride diffusion coefficients D_{Cl-} and external concrete covers (nominal covers) shown in Table 4 have been selected as design basis. Since the composition of the actual concrete mix(es) and thus the properties of the selected mix(es), particularly the age factor, have been unknown at the design stage, the age factor was chosen at the low end of achievable values. Thus, the design parameters recommended below are considered to be on the safe side.

Table 4: Selected durability design parameters

Exposure zone	Level	Max. D_{Cl-}(m^2/s)	Cover (mm)
Atmospheric	above level -3.5	$3.5x10^{-12}$	50
Splash			75
Submerged	below level -3.5	$6.5x10^{-12}$	75

3.1.5 Concrete durability testing

The durability strategy has been implemented by the elaboration of project specific concrete specifications. The chloride diffusion coefficient is one of the functional requirements with which the contractor has to comply. During pre-testing and production testing the contractor has to verify that the actual diffusion coefficient to be achieved for the actual concrete fulfils the requirement stated in the concrete specifications on the specific location, with the available concrete constituents (type of cement, cement replacements, etc.) and with the competence of the available workforce and with respect to local traditions.

A comprehensive pre-testing of different concrete mixes has been undertaken by DAEWOO E&C Institute of Construction Technology (DICT) to find concrete mixes, which comply with the design requirement for the chloride diffusion coefficient, see Figures 5 and 6. As shown in the figures several concrete mixes have the potential to be as durable as required as the chloride migration coefficients are lower than the required limits of 3.5 $x10^{-12}$ m^2/s (splash zone) and 6.5 $x10^{-12}$ m^2/s (submerged zone).

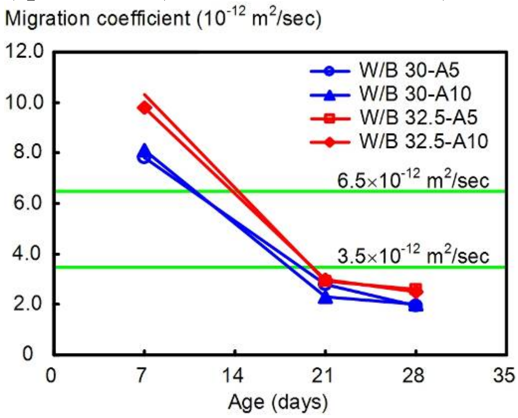

Figure 5: Chloride migration coefficient determined during pre-testing for the Busan-Geoje Fixed Link. Different potential concrete mixes with Portland Cement (A5 = 5% air content and A10 = 10% air content)

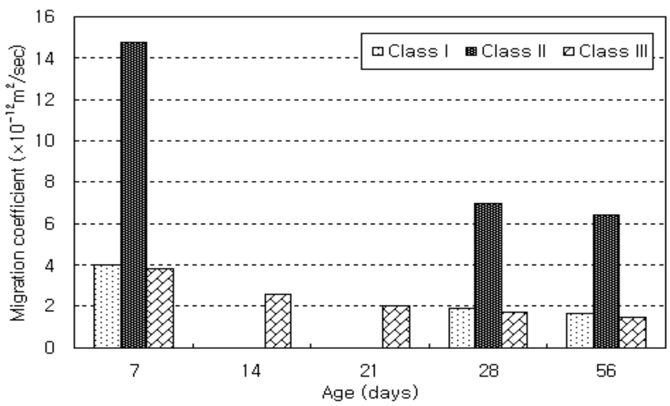

Figure 6: Chloride migration coefficient determined during pre-testing for the Busan-Geoje Fixed Link. Different potential concrete mixes with slag cement (Class I = mix design for Cut & Cover, Vent. B/D, Class II = mix design for Ballast, Class III = mix design for immersed Tunnel)

3.1.6 Other projects

A number of other projects have been designed and assessed along the outlined durability design approach. Reference is made to e.g. the following recent and current COWI projects:

- *Bahrain-Qatar-Causeway*, Qatar, 2009. Durability design of the bridges for service life of 120 years (Figure 7)
- *Cityring*, Denmark, 2009. Tender durability design for service life of 100 years
- *Salahal and Seeb Airport Project*, Oman, 2008. Durability design for service life of 50 years
- *Lusail Development Project*, Qatar, 2007. Durability design for service life of 50 years
- *Chong Ming Bridge*, Shanghai, China, 2005. Durability design for service life of 100 years
- *SuTong Bridge*, China, 2003. Durability design for service life of 100 years

The 40 km long Qatar-Bahrain Causeway was one of the first bridge projects in the Middle East where the client required a durability modelling following a recognized methodology. One specific task was to document the anticipated range of input parameters or confidence levels of the various assumptions. The durability modelling was based on the ***fib*** Bulletin 34 approach. The use of the approach required specific knowledge of the surface chloride concentration, the chloride diffusion and related ageing coefficient and how these change with time and temperature and how the extreme aggressive environment in the Middle East 'loads' the structure.

Figure 7: Qatar-Bahrain Causeway at night (rendering by Thomas Lavigne and Christophe Cheron Architects)

3.2 Avoidance of deterioration approach

3.2.1 Stainless steel reinforcement

The use of stainless steel reinforcement (SSR) in zones exposed to high chloride concentrations is considered a highly reliable solution following the 'Avoidance of deterioration' approach. This can ensure a very long problem-free service life in the part of the structure exposed to these high chloride concentrations provided the concrete itself is made sufficiently resistant to avoid other types of deterioration such as alkali-aggregate reactions, sulfate attack, or salt scaling.

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, which is a very attractive fact to the traditionally very conservative construction industry. Of particular importance is the often overlooked fact that SSR can be coupled with normal black steel reinforcement (carbon steel) without causing galvanic corrosion. 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 black steel reinforcement. Such highly exposed parts of bridges could be e.g. edge beams, parapets and crash barriers exposed to de-icing salts, splash zones of bridges in marine environment, lower parts of bridge columns and abutments exposed to salty groundwater etc. Another benefit is 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.

The Stonecutter Bridge in Hong Kong is one example where stainless steel (grade 1.4301) has been used successfully. The pylons are heavily reinforced with a multi-layer of ø 50 mm bars. To achieve a service life of 100 years SSR is used for the outer layer of reinforcement, the remaining reinforcement is ordinary black steel. In total approximately 3000 tons of reinforcement were supplied to the project.

Figure 8: Stonecuttter Bridge, Hong Kong. Design: COWI A/S in Joint Venture with Arup

Figure 9: The outer layer of reinforcement of the Stonecuttter Bridge is stainless steel. The remaining is ordinary black steel.

Similarly, the Shenzhen Corridor Bridge (between Hong Kong and mainland China), the Sheikh Zayed Bridge (Abu Dhabi) and the Sitra Bridge (Bahrain) have adopted the same approach. About 5400 tons of SST have been used at the Sitra Bridge. Also for piles the selective use of SSR has been attracted focus at some recent projects located in the Middle East. The coupling of SSR and carbon steel can easily be done.

Figure 10: Sheikh Zayed Bridge, Abu Dhabi, selective use of stainless steel reinforcement

Figure 11: Mix of stainless steel and ordinary black steel at piles, AL Khail Road Interchange, Dubai

Figure 12: Danish Motorway. Selective use of stainless steel reinforcement for edge beams

In addition, an additional benefit of SSR is the fact that SSR is a poorer cathode than carbon steel. Therefore, SSR can be beneficial in connection with repairs where ordinary carbon steel has corroded to such an extent that local replacement or added reinforcement is needed as part of the repair. A current example of such replacement is the repair of corrosion-damaged bridge edge beams on Danish motor- and highway bridges using SSR. As a consequence of this deterioration, the Danish Road Directorate now requires the use of SST for all edge beams of new bridges.

3.2.2 Steel-fibre reinforced concrete

The use of steel-fibre reinforced concrete is another design option following the 'Avoidance of Deterioration' approach.

Fibre reinforced concrete (FRC) is a concrete material modified, typically by adding steel or synthetic fibre reinforcement. The fibre reinforcement reduces the inherent brittleness of concrete and results in an improved and potentially high performance material suitable for civil infrastructure applications. FRC can be utilised together with or without conventional reinforcing bars (rebars).

For many applications, FRC is a very suitable solution for structural members. Besides advantages in terms of construction and cost, FRC provides structural benefits and superior durability properties compared to steel bar reinforced, conventional concrete (RC). The capacity of the fibres to reduce crack width and deflection is often more important than the increase in tensile strength of the concrete. Furthermore, the addition of fibres enables significant load carrying capacities after cracking and allows for stress redistribution, which makes the otherwise quasi-brittle behaviour of the concrete more ductile and the whole structure more robust.

For bored tunnels, the use of steel-fibres instead of the conventional steel bar reinforcement of the segments is already a common picture nowadays.

Several research investigations have shown that the durability of steel fibre reinforced concrete (SFRC) under chloride exposure is superior to the one of steel bar reinforced concrete (RC). Among others, it has been demonstrated that the chloride threshold of fibres in SFRC is 5-10 times higher than the one of rebars in RC. Under practical conditions, corrosion in SFRC is generally limited to fibres protruding from the surface or to the surface layer that may be affected by leaching or carbonation; rust stains on the surface may occur, but chloride-induced corrosion within a SFRC member is highly unlikely. Furthermore, even in the highly unlikely event of corrosion of internal fibres, spalling and cracking due to the formation of voluminous corrosion products (a common durability issue for RC) cannot take place for SFRC, because the individual cross-sections of the fibres are limited.

The superior durability properties of steel fibres have motivated the designer to build a 16.5 km long sewage tunnel in Abu Dhabi as SFRC bored tunnel lining. The tunnel is up to 50 m deep and has an internal diameter of 5 m. The project is located in an environment with extreme high concentrations of chlorides and sulfates in the soil and groundwater. Corrosion of steel fibres can be safely excluded for the entire cross section of SFRC lining, even if exposed to the worst chloride concentration of 9%. Hence, the durability design of the sewage tunnel is determined by the risk of sulfate attack of the concrete itself and the corrosion risk of additional splitting rebar reinforcement. This carbon steel reinforcement might be necessary along the longitudinal joints due to the combination of high hoop forces in this deep tunnel and the ovalisation due to the relatively soft surrounding rock. It should be noted that all internal concrete surfaces are protected by an HDPE membrane to prevent microbiologically induced corrosion due to the aerobic bacterial activity (sulfuric acid).

In conclusion, this means that corrosion of fibres is foremost an aesthetic problem, but it neither interferes with the durability nor with the structural performance of an uncracked SFRC member. The potential of adopting stainless steel fibre reinforcement will definitely gain more momentum in the future, not only for tunnels, but also for bridges or structural parts of bridges.

For bridges the use of SFRC looks promising in case of SFRC reinforced bridge deck overlays and edge beams. In other Nordic countries such as Sweden and Norway there is a long tradition for using steel fibres for overlays on bridges. SFRC overlays can potentially replace the traditionally used bridge insulation completely, see Figure 17. SFRC overlays are expected to be more durable and tough with respect to both reinforcement corrosion and wear from traffic. Thus, SFRC overlays are expected to be more cost effective than the traditional bridge insulation which needs replacement after 20-30 years depending on the amount of traffic. Similar enhanced durability is expected for edge beams of bridges or other bridge barrier systems which are often prone to heavy reinforcement corrosion if the traditional steel reinforcement can be partly or fully replaced by steel fibre reinforcement.

An ongoing Scandinavian research project financed by the Road Authorities from Denmark, Sweden and Norway aims to document the long-term performance of SFRC used as bridge overlays in the Nordic countries. The purpose of the research project, which includes the application of this layer on several new bridges in Denmark and Sweden, is to document the service life of bridges without traditional insulation with focus on the concrete durability and resistance against chloride ingress. The first bridges built in Sweden for about 20 years with this steel-fibre overlay show very promising results.

Another possible area where steel fibres may be used are bridge columns and pre-stressed elements where the conventional steel reinforcement is replaced by steel fibres. In Denmark the first pedestrian bridge (designed for tractor loads) will be built as steel-fibre reinforced pre-stressed concrete.

Figure 13: Heating Tunnel Copenhagen with steel-fibre reinforced concrete for the segmental lining

Figure 14: Steel-fibre reinforced concrete of tunnel segment

Figure 15: Surface alignment of the new STEP sewers in Abu Dhabi

Figure 16: SFRC tunnels and access shaft, STEP project, Abu Dhabi

4. WHOLE-LIFE COSTING TECHNIQUE FOR DESIGN EVALUATION

It has been acknowledged that the use of an initial costs basis, i.e. the lowest possible tender, for selecting a design and construction process is not the most cost-effective in the longer run. Some clients are thus requiring whole-life cost comparison during the design. The use of whole-life-cycle costing to evaluate the relationship between initial and in-service costs, and hence to determine the most cost-beneficial solution, has underlined the need to select materials and systems that will enhance durability and avoid costly maintenance and repair costs. Such a whole-life-cycle costing requires reliable prediction of deterioration rates and should include disruption costs to take account of any maintenance and repair work that requires closure of the structure.

Calculations show that whole-life costing evaluations are greatly influenced by the discount rate that is used. Because of the uncertainties about the future value of money it is very difficult to select an exact value for discount rates, so it is very difficult to calculate the absolute value for the whole-life cost of a structure. However, within the decision-making process, using the best available estimate of discount rate, whole life-cycle costing will give a good indication of the relative merits of alternative design options.

Figure 17: Steel-fibre reinforced concrete overlay instead of traditional bridge insulation

Figure 18: Steel-fibre reinforced concrete overlay

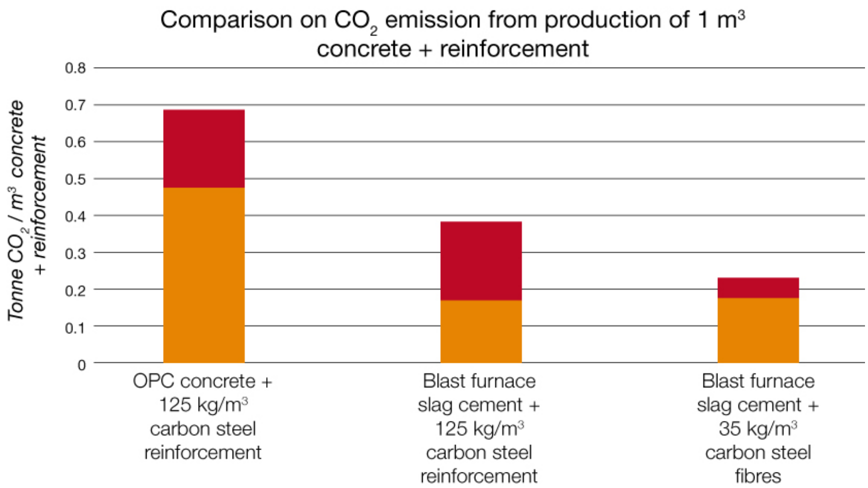

Figure 19: Comparison of CO_2 emission for different types of cement and steel reinforcement

5. SERVICE LIFE AND SUSTAINABILITY

Material selection and construction methods for civil structures are today mainly based on technical performance criteria such as durability and service life. A change in this might come in the coming years, because the society will demand that public authorities make sustainable choices. Owners and contractors will be able to meet this demand if they deliberately consider carefully a range of technical and environmental factors in different combinations.

One main factor is the use of cement. When building a structure the production of cement is usually the main source of CO_2 emissions. CO_2 emissions can be reduced significantly by replacing a proportion of the cement with fly ash, see Figure 19. Another approach is to choose an environmentally friendly type of cement, one which causes minimum CO_2 emission to produce.

For the first time a large project has been tendered in Denmark, the Cityring, where the client sets out strict environmental requirements. The Cityring is a 17 km long new subway line in the centre of Copenhagen. Among the requirements to the contractor is a minimum 30 per cent reduction of CO_2 emissions compared to the existing Metro line.

6. CONCLUSION

Today, valuable tools are available to perform performance-based service life designs for concrete structures including optimal life-cycle costing. The merits of a good concrete quality and alternative durability enhancing measures can be quantified. Furthermore, the consequences for the service life of the actually achieved concrete qualities as measured after completion of the structures can be used to update the service life.

Several international large infrastructure projects have proven that the probabilistically based durability approaches are viable and of benefit to the owner, the society and the construction engineering profession as a whole. In addition, design options such as the use of stainless steel and steel-fibre reinforced concrete with the aim to avoid the deteriorations are getting more focus.

However, some educational work is still necessary. First of all, a durability-related quality needs to be enforced by the owner. The owner must have help to clearly formulate requirements identifying the service life he wants. As the owner is very often not an expert in these matters, he has to be advised or educated in order to open up for these new design approaches and to overcome the still existing traditional way of durability thinking.

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