Tailor Made Concrete Structures – Walraven & Stoelhorst (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-47535-8

Tailor-made concrete structures – Case studies from projects worldwide

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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. 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 service life design tools have been implemented in ***fib*** bulletin 34 *Model Code for Service Life Design* and will be part of the new ***fib*** bulletin 34 Model Code for Service Life. The paper presents one of today's most modern durability design methodologies exemplified by some case studies.

1 INTRODUCTION

During the past years clients have asked for bridges, tunnels and other infractures 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.

Currently, the durability is generally "ensured" simply by adopting deem-to-satisfy rules as given in the codes and standards such as AASHTO *LRDF*, BS, or Eurocode. Experience shows that these rules based on a combination of experience, research and intuition have a lot of 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 with 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 /1/ have recently been implemented in the ***fib*** Bulletin No. 34 *Model Code for Service Life Design*, 2006 /2/.

2 SERVICE LIFE DESIGN APPROACHES

2.1 *Traditional approaches for designing bridges for service life*

The traditional approaches for service life used in various codes and standards such as AASHTO *LRFD* Specifications, Eurocodes, or British Standards are in an indirect form, specifying the use of certain details such as cover thickness, crack width, concrete compressive strength, etc. In short, they are not quantifiable. The approach is also called the 'Deemed-to-satisfy' approach. Eurocodes and British standards normally assume 50 years for service life, whereas AASHTO *LRFD* is based on 75 years of service life. The specified details in these codes are mainly based on experience, field observations and limited research data. The approach taken by the current codes does not allow predicting the expected service life of bridges. This philosophy makes the life-cycle cost analysis impossible and hinders the decision-making process.

This 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/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

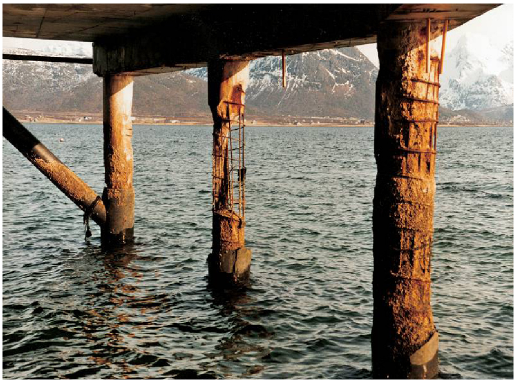

Figure 1. Importance of differentiation in exposure classes /3/.

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/standards are not able to answer.

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 modeling) 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 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:

1. A full probabilistic design, also called 'DuraCrete' approach
2. A partial factor (semi-probabilistic) with factors calibrated with level 1 above
3. A deem-to-satisfy design corresponding to methods in current codes and standards but requirements calibrated with level 1 above to the extent possible
4. 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

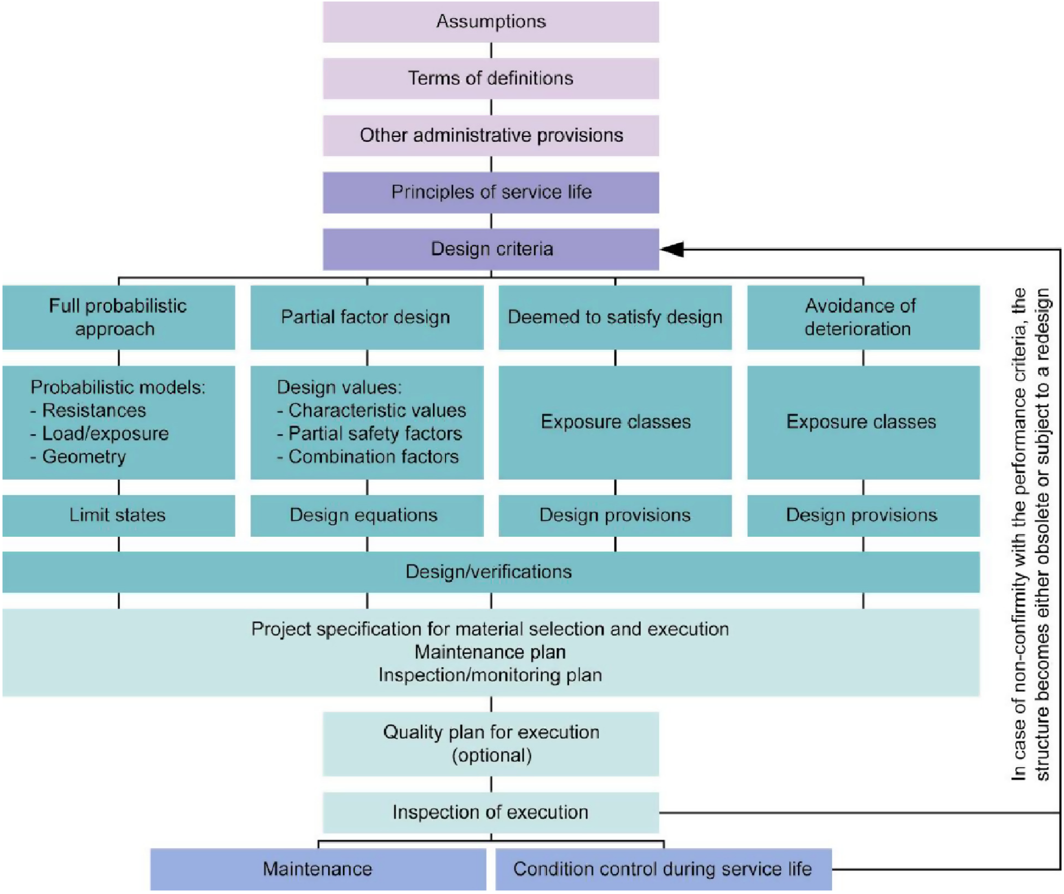

Figure 2. The **fib** Bulletin 34 approach for durability design showing four different levels of sophistication for service life design /2.

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.

In the following practical examples for level 1 and 4 of the performance-based design approaches of the ***fib*** Bulletin 34 are presented.

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

3.1 *Full probabilistic approach*

3.1.1 *Busan-Geoje Fixed Link, Korea*

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. 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 in 2009. 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.

Input to the service life design

In the following the different design steps (1–4) and the important DuraCrete input parameters (mean values)

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 **fib** Bulletin 34.

are listed used for the tunnel design:

1. *Identification and quantification of the environmental exposure of the different structural members and their location.*
   With regard to chloride-induced corrosion as the decisive deterioration the following different exposure classes have been investigated:
   - Atmospheric environment (internal tunnel faces of external walls, roof and bottom slab)
   - Submerged zone (external tunnel faces of external walls, roof and bottom slab).
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: Cl_s^- between 2–4 % by weight of binder depending on the exposure class.
   - 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 *critical chloride concentration* (Cl_{cr}^-) is decisive for the chloride concentration at the level of reinforcement, as it triggers corrosion on the reinforcement: Cl_{cr}^- between 0.6 and 1.8% by weight of binder representing the different exposure classes.
   - The *ageing factor* (α) represents the ability of the concrete to develop an increased denseness. It is represented by decreasing diffusion coefficient with increasing age: α between 0.4 and 0.6 depending on the type of binder and the environmental conditions.

Table 1. Interrelation chloride diffusion coefficient D_{Cl-} age factor α- reliability β. Immersed tunnel, internal tunnel faces (atmospheric zone).

Nominal cover (mm)	Max. D_{Cl-} at 28 days of maturity (m^2/s)	$\alpha = 0.40$ (β)	$\alpha = 0.50$ (β)
75	3×10^{-12}	2.4	3.1
	4×10^{-12}	1.9	2.7
	5×10^{-12}	1.5	2.3
	6×10^{-12}	1.3	2.1

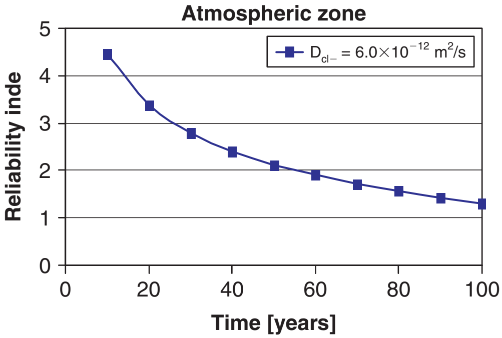

Figure 4. Reliability index versus service life – atmospheric zone – internal tunnel faces (max. $D_{Cl-} = 6.0 \times 10^{-12}\ m^2/s$, cover: 75 mm, age factor $\alpha = 0.40$).

3. *Adoption of design life and acceptance criteria.*
   The design life is 100 years. The initiation period represents the design life. Thus corrosion initiation is defined as the nominal end of service life. At the design stage the corrosion propagation period is not taken into account. There is 90% probability that corrosion has not initiated before 100 years have passed. In other words, adopt the corresponding reliability index ($\beta = 1.3$) as design basis.
4. *Determine the nominal concrete cover using the DuraCrete methodology.*
   In the following the service life verification for the Busan-Geoje Fixed Link is exemplified for the internal concrete faces inside the immersed tunnel. Table 1 shows the spectrum of the obtainable reliabilities β depending on the maximum chloride diffusion coefficient and the age factor α in case of the finally selected nominal concrete cover of 75 mm. Figure 4 shows the relation between the reliability index β and the service life for a chloride diffusion coefficient of $D_{Cl-} = 6 \times 10^{-12}\ m^2/s$. At 100 years the reliability index $\beta = 1.3$.

Results of the calculations

Due to purely practical reasons a general cover of 75 mm was chosen on all surfaces in this case. The

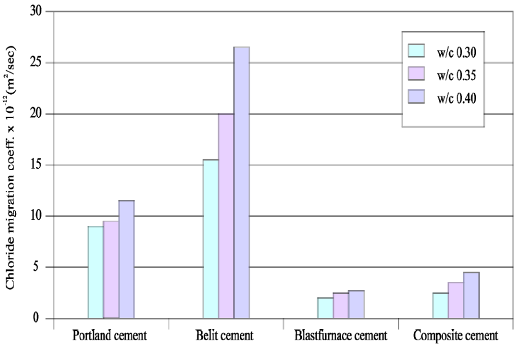

Figure 5. Obtainable chloride migration coefficient for different concrete mixes during pre-testing in the laboratory /7/.

maximum chloride diffusion coefficient was selected on the safe side lying to $5 \times 10^{-12} m^2/s$.

Concrete durability testing (compliance 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- 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 Figure 5. As shown in the figure several concrete mixes have the potential to be as durable as required as the chloride migration coefficients and are lower than $6 \times 10^{-12} m^2/s$. The Contractor selected a binder consisting of slag cement, fly ash and micro silica. An obivius choice as this binder combines a low chloride diffusivity with a low hydration heat temperature which is of upmost importance in case of an immersed tunnel (without membrane) to reduce the risk of early age through-going cracks.

3.1.2 *Qatar National Library, Qatar*

Investigations were undertaken to reassess the service life of as-built substructures (≈1500 piles and foundation) of the Qatar National Library with regard to initiation of chloride induced reinforcement corrosion. Based on the factual data received on the environmental aggressivity, the material properties of the concrete – as given by the measured chloride diffusion (migration) coefficient of extracted cores – and the actual cover to the reinforcement, the probability of initiation of corrosion depending on the service life of the piles has been calculated using the DuraCrete approach.

Figure 6. Qatar Nation Library, piles and foundation elements. Reassessment of service life.

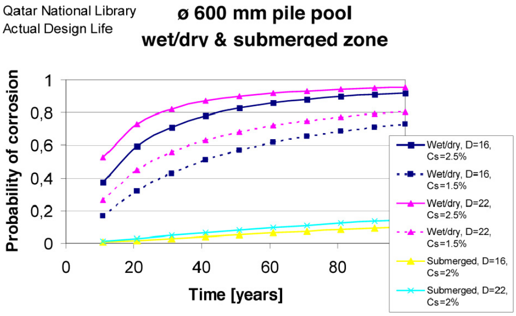

Figure 7. Probability of having corrosion initiated as function of the service life (D = diffusion coefficient, Cs = Cl^- at surface).

3.1.3 *Other projects*

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

- *Seeb International Airport*, Oman, 2007. Durability design for service life of 50 years
- *Al Reem Island Development Project*, Abu Dhabi, 2007. Durability design of foundations for service life of 50 years
- *Al Reem Island Development Project*, Abu Dhabi, 2007. Durability design of foundations for service life of 50 years
- *Lusail Development Project*, Qatar, 2007. Durability design for service life of 50 years

- *Bahrain Financial Harbour Development Project*, Bahrain, 2006. Durability assessment including "Birth Certificate"
- *Shannon Link Tunnel*, Hong Kong, 2005. Service life of 100 years
- *Chong Ming Bridge*, Shanghai, China, 2005. Durability design for service life of 100 years
- *Messina Strait Bridge*, Italy, 2005. Tender durability design for service life of 200 years
- *Offshore Wind Turbines*, Sweden, 2005. Durability design of foundations for service life of 25 years
- *SuTong Bridge*, China, 2003. Durability design for service life of 100 years

3.2 *Avoidance of deterioration approach*

3.2.1 *Stainless steel*

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 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.

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.

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

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

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

Figure 11. Steel-fibre reinforced concrete segments of the Copenhagen Heating Tunnel.

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 *Heating tunnel in Copenhagen, Denmark*

A convincing Strategy A design for a long service life (100 years) is the design for a 4 km long bored tunnel in Copenhagen where steel fibres are used for the segments instead of the conventional steel bar reinforcement. The tunnel will carry 2 steam pipes, 2 hot water pipes and 2 condensation pipes. Under operation the tunnel will heat up to a temperature of approx. 50 degrees. The elevated temperature in combination with the aggressiveness of the environmental exposure requires special attention. The tunnel is located in salty water, close to the harbour with chloride contents of 1–1.5%. Due to this, the most critical deterioration process in case of traditionally reinforced segments would be chloride induced reinforcement corrosion which, for structures in marine environment, would require special measures to guarantee a service life of 100 years.

In the present case, the situation is even more serious due to the increased temperature, as the temperature level is decisive for the rate of transporting aggressive substances such as chlorides into and within concrete. All chemical and electro-chemical reactions are accelerated by increase in temperature. According to a simple rule-of-the thumb an increase in temperature of 10°C causes a doubling of the rate of reaction. In the present case the temperature is approx. 40°C higher than in usual, bored tunnels with approx. 10°C, which will lead to a $2^4 = 16$ times faster ingress of chlorides in the heating tunnel compared to the ingress rate in normal, bored tunnels. In addition, the corrosion process may be accelerated due the risk of accumulation of chlorides in the internal tunnel surfaces due to evaporative effects. These factors would make is very difficult to design the heating tunnel for a 100 years corrosion free service life when trusting alone on the traditional durability measures such as sufficiently large and sufficiently dense concrete layers. In the present case, the traditional design would require covers of at least 70–80 mm. Covers which are far too large for bored tunnels as they induce a high risk of spalling of the very thick, unreinforced cover during handling and installation of the segments (thrust jacking forces etc.)

Therefore, a new durability design approach has been selected for the Copenhagen Heating Tunnel. As segment reinforcement is only necessary for load capacity during handling and transportation, the following questions were the catalyst for the alternative design:

- Why putting traditional steel reinforcement in if it is structurally not necessary during operation, however causing serious problems in case of ongoing reinforcement corrosion? The problem is often serious spalling of the cover concrete due to expansion forces of the corroding steel.
- Why not use steel fibres as reinforcement which on one side provide the structural capacity needed during handling and operation and, on the other side do not involve severe corrosion problems during operation?

Several research investigations have shown a favourable behaviour of steel fibre reinforced concrete with respect to durability. This is due to the fact that the critical chloride content of steel fibres in concrete is much higher than that of normal steel reinforcement, although identical steel compositions are used. Further, the corrosion activity of steel fibre reinforced concrete is very limited and limited to a surface rusting of some protruding single fibres. Although rust spots near the surface may occur, corrosion will not penetrate deeply. This means the steel fibre corrosion of uncracked concrete is first of all an aesthetic problem, (however often not relevant for tunnels) and has no influence on the structural behaviour.

The potentials of adopting stainless steel fibre reinforcement will definitely gain more momentum in the future, both on the contractors' side due to the obvious advantages regarding handling and transport, and hopefully also on the designers' side due to the advantage regarding durability resulting in reduced maintenance costs compared to conventionally reinforced segments.

4 CONCLUSION

Today, valuable tools are available to perform performance-based service life designs for bridge 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 as an update the service life.

Several international 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. 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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