Overview Of The Development Of Service Life Design For Concrete Structures

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Summary: After the introduction of reinforced concrete it was believed that the material was extremely durable. Soon it was found that reinforced concrete could have serious durability problems and that special care should be taken to avoid them. Durability became a design issue.

Based on experience from practice and research, construction rules have been formulated to ensure the durability of the reinforced concrete. Durability was twenty-five years ago however no real issue for design and practice. National organisations and international organisations like CEB and RILEM have become since than very active and widened the fundamental and practical knowledge on durability. This forms the basis of the present design manuals, standards and codes on durability of concrete.

The present durability method is based on a vague idea about the service life of the structure, being some decades. In a number of cases is however extensive maintenance and repair necessary. In a few cases lack of durability has even caused the collapse of concrete structures. This has initiated new research to the various degradation mechanisms. It changed also the approach to the problem: the service life has been taken into account explicitly. The design changed from a deem-to-satisfy approach to a performance-based approach with explicit attention for the design life, limit states and reliability. CEB has decided in 1996 to accept this approach as the basis for durability. In the mean time the research project DuraCrete (in the 4th framework programme Brite EuRam of the European Union) has been started to produce a first manual for design and assessment on this basis. This became available in the course of 1999. The knowledge of this project has been used recently to make the service life design of the whole Western Scheldt tunnel (bored tunnel in The Netherlands). This is the first time that a complete concrete structure has been designed on basis of service life, performance and reliability.

The history of service life design of concrete structures will not be ended by these achievements. Further knowledge, design methods, new materials, construction techniques, and so on need to be developed for the further improvement of concrete structures.

Keywords: concrete, durability, service life design, performance

1 INTRODUCTION

1.1 History of durability in concrete

When the gardener Monier combined concrete with a wire mesh he intended to improve the tensile properties of the concrete. Probably unintended he realised in that way a very durable structural material: reinforced concrete. In the course of time some durability problems occurred. The first durability requirements appeared in the concrete codes that were published after the Second World War. In the meantime we have reached a situation where the codes are based on deem-to-satisfy rules. These are based on a combination of experience, research, and intuition (good engineering judgement). For most of the environments and concrete structures this approach has the advantage of being simple, experienced, and reliable.
This conventional approach has however disadvantages:

- it cannot be used for structures with a service life that differs from the usual service life (about 50 years); this applies especially for structures with an intended long service life like infrastructures
- it cannot be used for new materials, such as the new cement types that are developed nowadays
- it cannot be used for new types of structures or new environments.

In general it can be stated that the conventional approach cannot be used under circumstances where we have a lack of experience. Through the years we have therefore seen a growing need to make designs for concrete structures based on a distinct, relatively long, service life. The development of durability requirements can be shown on basis of the design of real concrete structures in the past decade. This will be shown on the basis of some special concrete structures, like storm surge barriers and a bored tunnel that have been built in The Netherlands.

1.2 Noordersluis in IJmuiden
This is the biggest water lock in The Netherlands and has been built in the end of the twenties. The lock provides the connection between the North Sea and Amsterdam. In the twenties this water lock did not have the explicit function of a storm surge barrier. Nowadays it is considered as such. In that period durability was no issue. The construction of this lock has been used to improve the practical knowledge on concrete technology. For the construction of the lock many different types of cement (various types of Portland and blast furnace slag cement) and many concrete compositions have been used. The testing results of the concrete properties (both technology and strength) have been presented in small reports that were available to all interested people. Durability was in that period no explicit item for the design and construction of this water lock. At this moment reconstruction activities are carried out, mainly to repair damages that were the result of sabotage by the occupiers during the Second World War. Further shortcomings are the presence of alkali-silicate reaction in parts of the structure, leaching, and a low tensile strength.

1.3 Haringvlietsluizen south of Rotterdam
These sluices play an important role in the control of the water outlet of the rivers Rhine and Meuse in the Netherlands. The sluices were one of the first Delta works that have been built in The Netherlands after a storm surge in 1953 has caused the flooding of a south-western part of the country. Due to this flood about 1800 people were killed. During expected storm surges the sluices can be closed.

The Haringvlietsluizen (Fig. 1) have been built in the sixties without any specific service life requirements. The design philosophy was simple: make a durable and robust structure. Based on the existing knowledge the following main measures have been taken:

- the use of blast furnace slag cement
- water/cement ratio lower than 0.45
- concrete cover of at least 70 mm
- prestressing where possible

The sluices are at present about 35 years old and show no serious durability problems. A small durability problem is present near the centring pins where a low quality mortar has been used to fill the holes.
1.4 Storm surge barrier in the Eastern Scheldt

This barrier (Fig. 2) has been built in the eighties. Like the Haringvlietsluizen it is an open barrier that only will be closed if a storm surge is expected. With a total budget of about 3.5 billion Euro this is the most expensive structure ever built in The Netherlands. Because of this high amount of money and the growing awareness of the safety aspects of such a storm surge barrier the durability requirements were extreme. The design service life was set on 200 year! To achieve this long service life similar measures have been taken as for the Haringvlietsluizen.

Figure 2. Storm surge barrier in the Eastern Scheldt

Design calculations that have been made, showed that the concrete cover would protect the reinforcement against corrosion for at least 80 year. In cracked areas the protection period was estimated as at least 30 year. These restricted periods have been excepted as it was found that improving the protection period would cost more money than the replacement of parts of the concrete cover after 30 year respectively 80 year.

1.5 Storm surge barrier in the Nieuwe Waterweg (north of Rotterdam)

This is the last structure that has been built in the framework of the Delta plan (Fig. 3). It has been built in the beginning of the nineties. The design service life has been set on 100 year. To achieve this service life the following consideration has been made. The requirement for the concrete cover in code of that moment was at least 35 mm in combination with a water/cement ratio not higher than 0.50. The general impression at that moment was that these requirements would lead to a concrete structure with a service life of at least 50 year. To extend this service life to 100 year the value of the concrete cover has been increased with a factor $\sqrt{100/50} = \sqrt{2}$, giving a round value of 50 mm. The square root function has been applied as the ingress of chloride into the concrete roughly follows this function.
1.6 Bored tunnel in the Western Scheldt

Building bored tunnels in soft clay and sand is a relatively new development in the Netherlands. First a pilot tunnel was built and now the construction of a 6.5 km long tunnel with two tubes under the Western Scheldt is in progress (Breitenbücher et al, 1999). The contractor had to prove that this tunnel has a service life of at least 100 year. No method has been prescribed to prove this service life. Further it has not been defined for which part and for what functions and performances of the tunnel this service life had to prove.

The investor and the contractor decided finally that the DuraCrete methodology, the knowledge, and data from this project should be used as a basis for the service life design. The requirements with respect to the reliability indexes for the ultimate limit states and the serviceability limit states have been copied from the Dutch Building Decree. The limit states with respect to prevention of corrosion have been considered as serviceability limit states. This is a simplified approach, as these are in principle economic limit states. For economic limit states the reliability index should be defined on basis of an economic optimisation.

The service life design of the Western Scheldt Tunnel, both the prefabricated bored tunnel (Fig. 4) and the entrances, is the first concrete structure that has been designed on basis of a probabilistic approach and on basis of performances. Even some special parts made of steel have been designed on this basis.

1.7 Cargo railway link between Rotterdam and Germany and the High Speed Railway Link between Amsterdam and Brussels

The cargo railway link and the High Speed Railway Link are intended to improve the infrastructure in the Netherlands. The construction costs for each of both projects are estimated on 4 billion Euro. All structures will be made of concrete. The durability requirement is that these structures should have a service life of at least 100 year.
1.8 Summary

The presented examples show clearly that owners and investors of important infrastructures want to have more durability for their structures than for more common structures. This was even true some decades ago. In practice the higher durability was achieved by paying more attention to the construction works and by making the durability requirements in codes and standards more strict. Although some attempts with service life calculations were made, this failed as no proper methods were available and a design framework was lacking.

2 REQUIREMENTS FROM THE OWNER

From these examples it can be concluded that owners of structures realised the need for a long service life for important and expensive structures. This is in line with the demands from the society. The methods used to prove the service life were crude and based on a deterministic view. The scatter in the service life has been totally neglected. Looking back it can also be stated that the service life design was mainly the job of structural engineers. Material scientists and engineers played no important role in the durability design. This situation was also present in many other countries in that period.

For structures like the Great Belt Link in Denmark and the Oresund Link between Denmark and Sweden material specialists have used improved degradation models for the service life design. These models were however still be used as mainly deterministic models.

The present design approach with respect to durability of concrete structures is based on a reasonable understanding of the main degradation processes for concrete, reinforcement and prestressing steel. The performance of the design is however not explicitly formulated as a service life. It is based on deem-to-satisfy rules (for example minimum cover, maximum water/binder ratio, and crack width limitation) and the assumption that if these rules are met, the structure will achieve an acceptably long but unspecified life. The information about the service life to be achieved is to a large extent empirical. Improving the durability increases building costs without any quantification of the reduction of maintenance costs or failure costs. Current design methods only permit to calculate the whole life cycle costs from assumptions with respect to maintenance and failure rates. There are thus no objective means for demonstrating that future maintenance and repair costs will be acceptably low.

This common design approach to durability has other disadvantages. The rules are inadequate in some aggressive environments, while they are too rigorous in other environments. In some cases, this results in a ‘belts and braces’ approach (many different types of measures on top of each other), which may contain unnecessary and even counteractive measures. Lack of durability can cause serious safety and serviceability problems for structures. Despite this, designers have usually considerably more attention for load and resistance based structural design than for durability design. Recent history has however shown that due to a lack of durability, serious collapses and other types of damages may occur with large amounts of damage, maintenance and repair.

To improve this situation a new concept for durability design needs to be established. Similar to the current procedures for structural design, a design for durability should be performance based taking into account the probabilistic nature of the environmental aggressiveness, the degradation processes and the material properties involved.

In order to quantify the durability the concept of a service life design has been introduced. In this respect the performance requirements for a service life design as stated in the CEB-FIP Model Code 1990 has been adopted: ‘Concrete structures shall be designed, constructed and operated in such a way that, under the expected environmental influences, they maintain their safety, serviceability and acceptable appearance during an explicit or implicit period of time without requiring unforeseen high costs for maintenance and repair.’

Such a rational design for durability, however, requires both an overall methodology and calculation models for the actual degradation processes of concrete structures. Similar to the structural design code for loads, safety requirements and limit states must be defined for the design service life.

3 DEVELOPMENT OF SERVICE LIFE DESIGN KNOWLEDGE

3.1 Rilem

Within the international organization Rilem (International Union of Testing and Research Laboratories for Materials and Structures) many technical committees have contributed to the understanding of degradation mechanisms for concrete, reinforcement and prestressing steel. The accompanying tests were developed and evaluated in round robin tests. Despite this effort it was not possible yet to understand all relevant degradation mechanisms. With respect to, for example, frost attack, the influence of frost and de-icing salts, alkali-silica reaction, or alkali-carbonate reaction, the essential knowledge to fundamentally understand the mechanisms is still lacking.

The main strategy in the durability work of Rilem was to avoid these adverse reactions. Figure 5 presents a scheme with all adverse effects that can occur due to corrosion. The following two main stages can be distinguished:

- initiation of the corrosion process due to carbonation of the concrete or ingress of chloride
- propagation of corrosion of the reinforcement
Figure 5. Various adverse events during corrosion of the reinforcement

In the propagation phase several adverse events can happen:

- cracking of the concrete cover
- spalling of the concrete cover (parts of the cover come loose)
- loss of bond of the reinforcing bars
- loss of cross section of the reinforcing bars
- loss of bearing capacity of the structure, resulting in collapse.

For corrosion of steel in concrete this means that much attention has been paid to initiation processes like carbonation and ingress of chlorides. These processes consume much time before a situation is achieved where corrosion can start. Little is however known about the corrosion process itself. There we must think about the dependency on fluctuating temperature and humidity, cracking and scaling of the concrete cover, loss of bond and finally collapse.

The strategy ‘avoiding reaction’ instead of ‘defending against reaction’ was also followed for other types of degradation reactions. For example for frost, frost in combination with the presence of de-icing salts, acid attack, and sulphate attack. To prevent the both frost mechanisms deem-to-satisfy rules had to be followed with respect to the maximum value of the water/cement ratio, or to the amount of entraining of small air bubbles in the concrete. For acid or sulphate attack rules with respect the composition of the cement had to be followed.

In the building industry the interest has grown during the last years towards a more performance based approach. The same applies to the work on durability of concrete from Rilem. Examples are the report on performance criteria for durability of concrete from Kropp & Hilsdorf, 1995 and the report on probabilistic service life modelling for concrete structures edited by Sarja and Vesikari 1996. Publications like these opened the way to service life design on the same basis as other design items like structural integrity.

3.2 Comité Euro-International du Béton (CEB)

The ‘Comité Euro-International du Béton’ (CEB) has played an important role in providing a platform for discussion on design of concrete structures. The results of this discussion were published in reports that were named ‘bulletins’. These bulletins were often used as a basis of design or as a basis for national or international codes. CEB published her first bulletin in 1957, followed by a long row of reports on mainly structural aspects of concrete. Twenty-five years later in CEB Bulletin 148, 1982, a state-of-the-art report on durability was published. This was followed in 1984 with a report of an international workshop. In 1987 the first CEB guide on durable concrete structures followed. The present concrete codes in Europe are mainly based on these bulletins.

A new approach to durability design was published in 1997 in CEB Bulletin 238. By means of an example for carbonation induced corrosion, a performance and probability based service life design was introduced. The new approach combined the existing probabilistic framework for structural design with service life models that described the degradation processes in concrete. On this basis it was in principle possible to choose between different design options, for example increasing the concrete cover or decreasing the water/cement ratio. According to the conventional codes there is a minimum requirement for the cover and a maximum for the water/cement ratio. These requirements must both be fulfilled.

3.3 DuraCrete

The CEB Bulletin 238 presented only the principle of the new approach and gave one example. It will be clear that this is insufficient for a design guide. That should contain at least the following items:
The framework for the design process
- definition for the design service life (reference period)
- definition of the required performances
- definition of the required reliability, related to the performances and the design service life
- models for the loads, the aggressiveness of the environment, the structural response, and the degradation of the materials.

The amount of work to be done was too huge to perform within CEB. Twelve organizations in Europe initiated therefore the research project DuraCrete. That project was co-financed by the European Union. It took 3 years to perform the project, that was organised in separate tasks (Fig. 6).

![Flow chart of the DuraCrete project](image)

**Figure 6. Flow chart of the DuraCrete project**

The project was mainly based on existing data and knowledge on durability. The work focussed on
- collecting degradation models and environmental models, and find consensus about them; with respect to structural models and loads the Eurocode and the CEB Model Code were used
- developing compliance tests to define the durability characteristics with respect to concrete
- statistical quantification of the parameters in the models
- designing a number of structures according to the various national concrete codes in Europe
- making probabilistic calculations of the previous designs to find the reliability levels that are present in these codes; this result is used as a basis in the new design manual
- preparing a manual for probabilistic and performance based service life (re)design.

The DuraCrete project ended with a guide for the design of new concrete structures and the redesign of existing structures (DuraCrete, 1999). The background of the method and the knowledge and data that was gathered was published in some fifteen reports (DuraCrete, 1999-2001). Besides these results it was important that the work of material scientists, concrete technologists, structural engineers and designers, and reliability engineers was integrated. Further it was important that we are now able to replace the passive durability approach in the present codes by an active service life design. The project demonstrated that it is even possible to make a simplified service life design on basis of safety margins and characteristic values instead of the probabilistic design.

It is obvious that DuraCrete has not resulted in a final design manual. Many new things have to be developed. Missing degradations like alkali-silica reaction, and frost attack have to be added. The design models must further be calibrated to the
behaviour of existing structures. Finally it is necessary to make the modelling more unambiguous. In the present form only experts can use it safely, because they can identify ‘bugs’ and they are able to choose the proper models in case of non-standard situations. These are also conditions for standardisation of the method.

**Darts**

In the DuraCrete project a perfect match was made between structural design and durability design. This makes it possible to optimise with respect to both aspects. For many designs this is however not enough. There are more aspects to consider. In a new research project ‘DARTS’ (Durable And Reliable Tunnel Structures), that is co-funded by the European Union an integrated design method will be developed in the period from 2001-2003. The method will be restricted to the design of tunnels. The restriction was made to reduce the amount of work. Tunnels were chosen because of their high costs and social importance. The method can be extended with other types of structures in a later stage. The design aspects that will be considered are structural behaviour, durability, hazards, sustainability, and socio-economic aspects. A flow diagram is given in Fig. 6.

![Figure 6. Flow chart of the Darts project](image)

The project Darts is connected to various research related networks that are active in the field of tunnel fires and safety.

### 3.4 Comité International du Bâtiment (CIB)

The activities of the Comité International de Bâtiment (CIB) are not specific directed to concrete applications. Some of the activities with respect to service life design are however material generic and are therefore also relevant to concrete. One of the scientific committees working on service life design is a joint committee between CIB and Rilem: CIB W80 / RILEM 175 PSL ‘Prediction of Service Life’. The present work of this committee relates to service life models. Recently a task group has been established to develop performance-base methods of service life design based on models of degradation and environmental actions in three different, but coherent levels:

- a fundamental and scientific approach and provide framework for different levels of design
- a simplification of scientific models to engineering design
- a development of simplified and practical design approach (factorial method).

The line of approach of this joint committee is parallel to the recent developments of service life design for concrete structures. This could mean that in the near future the concrete approach can be embedded in a generic performance and probability based framework for service life design.

### 4 RECENT APPLICATIONS IN THE NETHERLANDS

The construction activities in the Netherlands have increased in the past period with the objective to improve the infrastructure. These activities will prolonged for at least the next decade. Some of the special projects are:

- Second Heineenood Tunnel; this project has been finished; it is the first bored tunnel that was built in the Netherlands; the dimensions of the tunnel are relatively small (two tubes with a length of 950 m and outer diameter 8.30 m), because the construction served mainly to study the special items related to boring tunnels in soft soil
- Western Scheldt Tunnel; this is a two-tube bored road tunnel, with length of 6500 m and an outer diameter of 11 m; this is the first concrete structure that has been designed for 100 year service life on basis of the method developed by DuraCrete; the budget of this project is about halve billion Euro
- High Speed Railway Link Between Amsterdam and Brussels In Belgium; in this link various structures like bridges and tunnels are involved; one important tunnel is the Green Heart Tunnel; this is a single-tube bored tunnel with in the
middle a separation wall and a length of 7 km and a diameter of 14.9 m (world largest diameter for a bored tunnel); the budget is for the civil structures in the link is about 4 billion Euro.

- Cargo Railway Link Between Rotterdam and the Ruhr Region in Germany; the length of the link will be 160 km; it includes about 160 civil engineering structures including a seven kilometre long bored tunnel; the budget is about 4 billion Euro.

Giving the great importance of these project they have in common that the owners required a design service life of at least 100 year. Despite of this requirement no special performance based service life design was made for the Second Heinenoord Tunnel. After construction it could however be demonstrated on bases of the DuraCrete models that the expected service life will be substantially lower (Siemes & De Vries, 1999). The low service life was the consequence of a series of weaknesses in the design such as a low concrete cover, ignoring the presence of de-icing salt, and a wrong cement type.

The other mentioned structures are all designed for at least 100 year. For the design and construct contract of the Western Scheldt Tunnel (Breitenbüchner et al, 1999) the contractors made probabilistic, performance based designs. For the Green Heart Tunnel these probabilistic calculation were required in the design and construct contract. For the other structures the design calculations were made by the owner. The results of the design calculations were translated to requirements with respect to a combination of the concrete cover, the cement (binder) type and the diffusion coefficients for chloride and carbonation.

5 CONCLUSIONS

Reinforced concrete structures are used in practice for more than a century. Only after the Second World War special attention was paid to the durability of the structure. In the course of time this resulted in concrete codes with deem-to-satisfy rules (recipe’s) to guarantee the durability. These rules were based on a mix of experience and research. International research organizations like Rilem and CEB provided the necessary consensus, encouraged further research, and developed guidelines and model codes.

Owners who intended to build special structures, such as big infrastructures, were not always satisfied with the durability level in the existing concrete codes. Therefore they wished to have structures with an extra long service life. In general they required at least 100 year and sometimes even 200 year. It was unclear what they really wanted to achieve, as they did not define the related performances and the design method to be used. Nevertheless special provisions were taken, that in general improved the durability.

In the recent period the attention in the construction industry changed to performance and probability based design. This was developed for structural design to a high degree and implemented in the codes. On this bases new service life design methods were developed. They combined the concrete structural design methodology with environmental loads and degradation models. This finally resulted in the design methodology DuraCrete.

Various practical projects that recently were designed according to the DuraCrete method proved that it can be used for the service life design of concrete structures. The method is however only reliable if applied by experienced material scientists, with good capabilities to overview the consequences of the chosen models. To get a broad use it will be necessary to give more guidance to this aspect. Further some bugs should be repaired, and more relevant degradation mechanisms should be added.

It is expected that this service life design method for concrete structures will be further developed in the near future and will be made suitable for standardisation. A similar development can be expected for other structural materials. For example the progress of service life design of timber structures is in this respect promising (Foliente et al 1999).

6 REFERENCES

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