Residual Service Life of Existing Concrete Structures – Is it Useful in Practice?

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Abstract. An increasing number of existing reinforced concrete structures are approaching their intended design service life. The common assumption is that these structures will thus soon require more maintenance cost and attention from their owners. In order to manage and plan maintenance activities in a predictable and transparent way asset owners desire quantitative information on their structures' actual condition. Periodically performed visual inspections don't provide unambiguous quantitative figures that support decisions for maintenance activities on the long-term. Consequently the residual service life was identified as an alternative to indicate the condition. The involvement of numerous experts has resulted in a scientific approach on service life prediction in which mathematical models to describe a time-dependent deterioration process dominate.

From an asset owners point of view such an approach introduces uncertainties and questions. As a result predictions of the residual service life based on a modelling approach generally don't significantly affect the conservation and maintenance strategy of Rijkswaterstaat for concrete structures. These questions are raised because of the high latent variability of the outcome of these predictions that makes decision making by asset owners, based on this result, more obscure instead of more transparent. In this paper the origin of the variability will be demonstrated to critically discuss the usefulness in practice of service life predictions based on a modelling approach from an asset owner's point of view. Simple examples of situations encountered in practice will be presented to elucidate the actual problems. It will be demonstrated that the modelling approach is not considered suitable to quantify the condition of an individual structure to make asset management more predictable and transparent. The authors would like to open a discussion on alternative and more practical methods to keep the stock of existing structures in a serviceable and structurally safe condition in a predictable and transparent way.

Keywords: Residual lifetime · Asset owner · Asset management · Situations in practice · Need for predictions · Spatial variability

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1 Historical Developments

Rijkswaterstaat is the operational department of the Dutch Ministry of Infrastructure and the Environment and as such acts as the asset manager of the national road and water networks. The major task of Rijkswaterstaat is to keep these networks in a serviceable and structurally safe condition during their full operational lifetime. In view of the vital importance of these infrastructural facilities for the national economy an efficient and effective asset management is required with the main objective to achieve a maximum availability for the users at the lowest long-term cost.

A major portion of the present stock of Dutch national infrastructure facilities dates from the 60's and 70's, or from much earlier times, e.g. the sluices and lock gates in the Afsluitdijk dating from 1930–1936. Figure 1 provides an overview of the year of construction of the current stock of infrastructure which demonstrates a clear peak in construction of bridges and viaducts between 1965 and 1980. Thus at present a large number of structures is between 35 and 50 years of age and consequently in only 30 years the first structures from this construction boom will have reached 80 years of age. The age of 80 years is most often implicitly considered to be the expected lifetime of most civil engineering structures, since from 1990 until the introduction of the Eurocodes this was used as the intended design service life of newly built structures. In this respect, it should be borne in mind that before 1990 it was uncommon that structures were designed and built for a clearly specified service life. The intended design service life is therefore actually not applicable to the considered structures from the construction boom. Despite this many asset managers anticipate that the workload on structural maintenance and replacements will significantly increase during the next decades when the structures reach the age of 80 years.

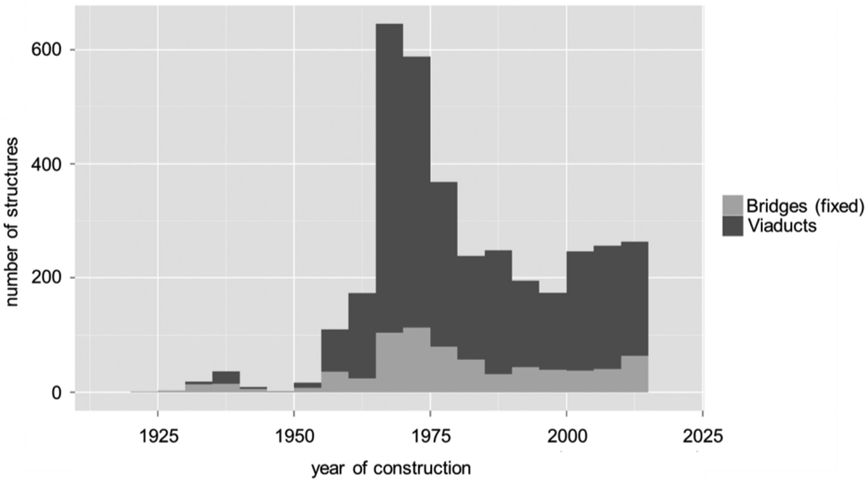

Fig. 1. Year of construction of fixed bridges and viaducts (Nicolai et al. 2016)

For many decades visual inspections are being used to detect premature signs of structural distress. These visible signs usually act as an early warning to take well-timed appropriate actions. In practice this approach is commonly adopted in order to keep existing structures in a serviceable and structurally safe condition and it is therefore generally considered a satisfactory and economically acceptable method to do so. However, periodically performed visual inspections to detect premature damage reflect a more or less reactive approach. Considering the assumed workload some believe a more pro-active and predictable transparent approach could be beneficial and more cost-effective for asset management, in particular on the long term.

Within this pro-active approach frequently performed condition assessments and residual service life predictions based on time-dependent deterioration modelling prevail. However practice has demonstrated that the modelling approach raises many questions and results in a high variability of the outcome, making decision making by the asset owner even more complicated and obscure. Therefore at Rijkswaterstaat this approach did not result in maintenance alterations, cost reductions or more predictable and transparent asset management yet.

2 Predicting Replacements

At Rijkswaterstaat the expected lifetime of the entire stock of concrete bridges and viaducts is frequently computed. Based on the ages and numbers of the present overview of demolished and remaining structures a Weibull distribution of the predicted lifetime is plotted (Nicolai et al. 2016). Figure 2 shows the distribution as for the year of 2015. The calculated average lifetime for individual structures until replacement amounts to approximately 80 years. Perhaps fortuitously equal to the intended design service life used since the 90's. However, the lifetime distribution demonstrates a rather high variability. Approximately 90% of the structures is expected to reach a lifetime between 45 and 115 years of age.

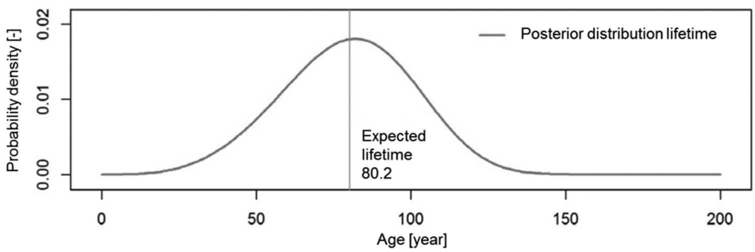

Fig. 2. Distribution of lifetime fixed bridges and viaducts (based on Nicolai et al. 2016)

From these data one may conclude that replacement of the structures from the construction boom – currently at 35 to 50 years of age with a 90% chance of reaching a lifetime between 45 and 115 years of age – is about to happen at this very moment already.

A recent study on the nature of demolitions of Rijkswaterstaat bridges and viaducts sheds more light on this conclusion. It was concluded that at present 89% of the demolished bridges and viaducts of Rijkswaterstaat have been demolished and replaced for functional reasons (IV-Infra 2016). In most situations the capacity of the road was considered insufficient and too many congestions occurred. To facilitate more traffic lanes the structure had to be extended either in the longitudinal or latitudinal direction and complete replacement was considered to be the most viable solution. This approach is typical for large projects as to upgrade long tracks of the motorways on the short term. Thus, merely 11% of the demolished structures had been replaced for a variety of technical reasons, encompassing an expected insufficient level of structural safety in the near future, the structure wasn't able to meet the demands on reliability and availability anymore, or the expected maintenance costs were higher than agreed upon with the Ministry. This means that out of an entire stock of approximately 3800 concrete fixed bridges and viaducts up to now less than 25 structures are known to have been replaced or demolished for technical reasons, only a very small share. Hence structures are being replaced already, but generally for functional reasons now and their replacement has mostly been concealed since it was included in large upgrading projects.

This statistical information is being used to make the number of replacements and consequent cost predictable for the long-term. However, the data doesn't tell which structures have to be replaced, at what time and what maintenance is required. It is often argued that the scientific approach based on the modelling of deterioration processes helps to answer these remaining questions in a transparent way. Based on the experience of the authors however, the high variability of the outcome of such an approach only adds more questions and obscurity. In the following the origin of the variability based on the computation of two examples will be demonstrated.

3 Investigating the Condition of an Individual Structure

For reinforced and prestressed concrete structures with respect to durability it is commonly assumed that most of the premature damage encountered in practice is due to corrosion of the embedded reinforcement steel resulting in unforeseen major repair. Therefore methods to quantify the condition of a structure focus on this failure mechanism to a large extent. Only on the longer term corrosion of the reinforcement steel is expected to seriously impair serviceability and structural safety. Based on the experience of asset owners, such a situation is unlikely to occur provided that frequent inspections are executed and timely maintenance are undertaken.

For new structures, initiation of reinforcement corrosion is often considered to signify the end of service life. In practice for existing structures this event of corrosion initiation does not necessarily invoke replacement. Corrosion initiation remains largely unnoticed until after several years of corrosion propagation visible evidence through cracking and spalling occurs. Most often such a state of clearly visible distress will result in the execution of destructive investigations to complement or support results from periodically performed visual examinations. Regarding chloride-induced corrosion drilling cores is the common method to quantitatively assess the distribution of chloride over the concrete cover zone resulting from the frequent use of de-icing salt, combined with measurements of the concrete cover depth over the reinforcing steel.

In order to allow for a prediction of the corrosion initiation time, the thus obtained so-called chloride profiles are analyzed by using a diffusion equation to provide best-values for the relevant model parameters, i.e. the surface chloride content and the chloride diffusion coefficient. In addition to all other model parameters also the chloride content at which corrosion will initiate (known as the critical chloride content) is of a stochastic nature. Moreover, there is much uncertainty on its statistical characterization and this situation is reflected in a high variability for this parameter.

Figure 3a shows a fictitious example for an ideal case study in which the chloride penetration in one of the components of a concrete structure is determined at an age of 37.6 years and the measured chloride profile completely corresponds to the diffusion model. The input parameters to the model for the chloride content at the surface (C_s), the initial chloride content in the concrete (C_i), the concrete cover (c) and the chloride diffusion coefficient (D_a) are therefore deterministically known. In order to predict the time to initiation of reinforcement corrosion also the critical chloride content (C_{crit}) and the time-dependent effect on the chloride transport properties of the concrete cover zone by the maturing of concrete, the so-called ageing factor (n), are required. For C_{crit} the distribution according to *fib*-bulletin 34 is used. For the ageing factor n typically an estimation is made based on an expert opinion. For blast furnace slag cement CEM III/B, commonly used in the Netherlands, values varying from 0.4 to 0.5 are used. This estimated value appears to be of huge influence on the residual time to corrosion as Fig. 3b demonstrates. It shows the likelihood that the critical chloride content is reached at the depth of the reinforcement bars at a certain age as a probability density for four deterministic values of the ageing factor n. For n = 0.0, indicating that the chloride transport properties will remain essentially constant over time, the time to corrosion initiation roughly ranges from 50 years (probability of 5%) to 200 years (probability of 95%) for this example. For the more common value of n = 0.4 for blast furnace slag cement it ranges from approximately 60 to 350 years, indicating a huge variability of the outcome.

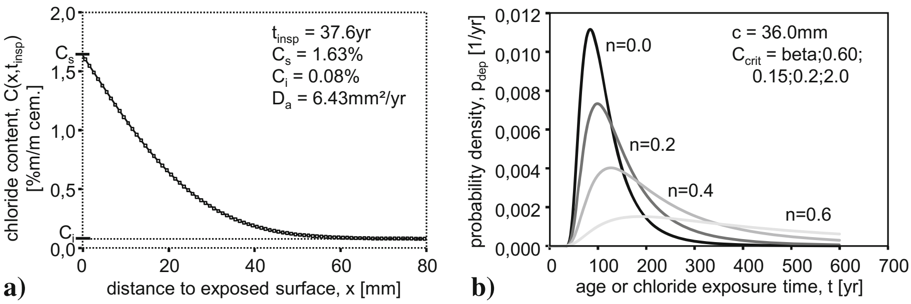

Fig. 3. Chloride profile (a) and resulting probability density for age at corrosion (b) for an ideal case (Gulikers 2017)

Please note that the illustrated prediction pertains to an ideal case study which will never be found in practice. In real concrete structures the spatial variability of both external chloride load and chloride transport properties is considerable. To demonstrate this in Fig. 4a six actual chloride profiles taken from the box girder bridge crossing the Eastern Scheldt at an age of 18 years are presented. The profiles were derived from six cores drilled at a very small area of only 1 m in length and 0.5 m in height. One might consider the exposure to chlorides from spraying salty sea water to be uniform. Since the box girder is made of precast concrete the concrete quality and concrete cover demonstrate very little variation as well. However, the figure clearly shows significant differences in chloride profiles. This consequently results in major differences in the age at which corrosion is predicted to initiate, as Fig. 4b shows. For profile C02 the age at corrosion initiation ranges from 20 to 60 years, for profile C06 from 70 to 200 years and beyond. The variability of the predicted time therefore only will increase significantly when realistic chloride profiles are being used, even if the exposure to chloride is considered uniform and the concrete is of a very homogeneous and high qualitative nature.

4 Acceptable Probability of Corrosion?

But which chloride profile in Fig. 4b should be used to make a prediction? Which one represents the whole of the investigated 0.5 m^2 of concrete? More importantly, which one represents the entire box girder bridge? In addition, in how many cores is corrosion initiation allowed? What probability for corrosion is acceptable? A major complicating factor is that a clear definition of 'end of service life' is lacking. For new structures EN 1990 has defined design working life as "the assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance without major repair being necessary". This definition indicates that, provided that during the operational service life timely maintenance actions are executed, the structure will remain in a serviceable condition. It does not distinguish between the type of structure or part of it, neither does it consider its importance for structural safety. In addition, it is

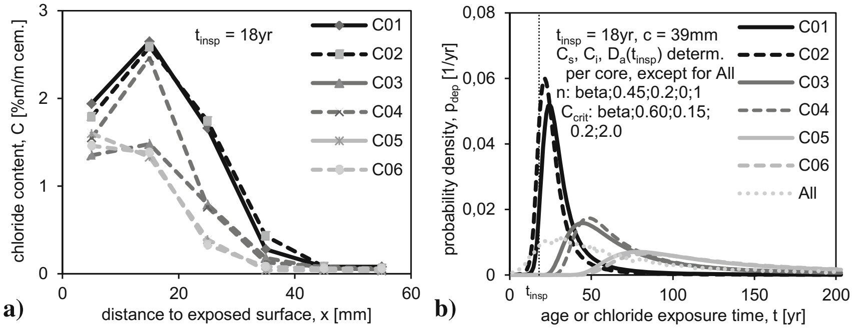

Fig. 4. Chloride profiles (a) and resulting probability density for age at corrosion (b) for box girder bridge (Gulikers 2017)

a vague qualitative rather than a unambiguous quantitative definition. The reference to major repair also suggests that economic instead of technical safety issues are considered relevant.

In literature several attempts have been made to agree on a fixed boundary condition for the acceptable probability. For new structures in *fib*-bulletin 34 a reliability index $\beta = 1.3$ (probability of 9.7%) is used (*fib* 2006). However, in the new European standards an index of 1.5 (probability of 6.7%) is proposed (Leivestad 2014). But what does this probability physically represent? Does it imply the likelihood is 9.7% that corrosion starts somewhere in the structure at the corresponding age in case of $\beta = 1.3$? Or does it imply that 9.7% of the reinforcement has already started corroding somewhere in time before this age?

No unambiguous practical answer is given to these questions. Therefore typically this interpretation is subject to expert opinion as well. Consequently the asset owner isn't aware of what the age resulting from the calculations actually means and what effective maintenance has to be executed. For the case of the box girder bridge the calculated age at which the required probability will be attained is 21 years for $\beta = 1.3$ (calculated probability for all profiles as combined in Fig. 4b) and 18 years for $\beta = 1.5$. Hence the calculated residual lifetime at the moment of inspection was between 0 and 3 years. One might assume this only represents the lower boundary lifetime, since the probability that the residual lifetime exceeds the calculated one is over 90% at these reliability indices. Considering the aforementioned economic relevance of the design working life instead of the safety relevance, the practicality of such lower boundary value for decision making on maintenance and replacement is questionable. At least one can conclude that the obscurity around the physical meaning of the boundary condition introduces additional uncertainties and unquantifiable variability to the predicted age. In 2016, i.e. 15 years after the first investigation of the box girder bridge, no additional maintenance based on the lifetime calculation had been executed and despite that no damage was visible at the structure.

5 Decision Making

By nature, the variability of the residual lifetime predictions based on the modelling of deterioration processes for individual structures is high. This is the result of highly variable input parameters, such as largely varying ingress of chlorides in the concrete itself, even at a very constant exposure to chlorides and a very uniform concrete quality, and finally by an indistinct and unfamiliar physical meaning of the calculated result. Using this highly variable outcome as an indication for a structure's condition makes decision making about maintenance or replacement very hard and obscure for the asset owner. For illustrative reasons: for the advantageous case of the box girder bridge the modelling approach results in a distribution with a chance of 90% that the structure reaches a lifetime between 16 (probability of 5% for "all" combined in Fig. 4b) and somewhere around a 1000 years of age (probability of 95%). Implying a residual lifetime of −2 to a 1000 years of age when it was investigated at the age of 18 years. Whereas in Fig. 2 the entire stock of bridges and viaducts was expected to reach a lifetime between 45 and 115 years at the same probabilities. Although the latter neglects all possible additional information to better specify the condition of an individual structure, it does indicate the distribution of the lifetime of the entire stock and therefore of this individual box girder bridge, being part of that stock. On the one hand using the entire stock to indicate the condition of an individual structure is obscure as well, on the other hand it results in a much lower and therefore more practical variability for the same parameter, namely the expected residual service life of that particular structure.

For illustrative reasons imagine an asset owner with a structure at 43 years of age and a residual lifetime of 11 years based on deterioration modelling, who has to decide on appropriate maintenance or replacement. There is no visible damage yet and the owner knows there is a probability of at least 90% that the actual residual life-time is longer, perhaps much longer. The owner has several options to choose from: to replace the structure; to plan for a preventive repair, knowing that repairs tend to fail repeatedly and therefore require much attention and investments in the future; to drill more cores to get a more substantiated though still inaccurate result and thereby inflict permanent damage to the structure; or to wait for visual signs. Most likely he has confidence in the structure's durability and judgement based on comparable structures in his organization. The asset owner will wait until visual signs of decay appear in inspections and then take the appropriate maintenance and repair measures.

6 Conclusion and Recommendations

The residual service life based on the modelling of deterioration processes does not result in alterations of asset management of structures. The very high variability of the outcome of this approach is to blame. The origin of the variability has been demonstrated in this paper by means of two examples. It encompasses: high variabilities in model parameters, as demonstrated by a fictitious example; the spatial variability of both chloride load and chloride transport properties in concrete, as demonstrated by a real box girder bridge with uniform chloride loading; and the obscurity of the physical meaning of the calculated probability for corrosion. The high variability for the box girder bridge example results in a 90% change of having a residual lifetime between −2 and a 1000 years. For the Rijkswaterstaat stock of bridges and viaducts, however, based on historic data, it is now expected that 90% of the structures will be demolished between 45 and 115 years of age for either technical or functional reasons. The modelling approach for the residual service life does not contribute to lowering the variability of this parameter, on the contrary, and therefore does not contribute to a better understanding of an individual structure's condition as a basis for more predictable and transparent asset management by the asset owner.

Investigating chloride ingress can be a good help to detect the magnitude and origin of damage, but to quantify a structure's condition we need alternative and more pragmatic approaches. The desire to detect damage in a more early stage, in order to plan maintenance and replacements further ahead, remains. However, methods based on non-destructive measuring techniques are preferred. Improvements to better and earlier understand visual signs of damage in inspections and their effect on the long term may help as well as to keep existing structures in a serviceable and structurally safe condition in a predictable and transparent way.

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