Durable safety and serviceability: a performance based design format

Autor(en): **Siemes, Ton / Rostam, Steen**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **74 (1996)**

PDF erstellt am: **29.06.2024**

Persistenter Link: https://doi.org/10.5169/seals-56054

Durable safety and serviceability - a performance based design format

Ton SIEMES
Civil Engineer
TNO Building and Construction Research
Delft
Netherlands

Ton Siemes, born in 1947, got his civil engineering degree from Delft University in 1973. Shortly after that he joined TNO, where he is working on durability problems of building materials and structures.

Steen ROSTAM
Civil Engineer
COWI
Copenhagen
Denmark

Steen Rostam, born in 1943, got his civil engineering degree in 1969 and his PhD degree in 1977 from the Technical University of Denmark. In 1978 he became associate professor. Now he is head of the department on Assessment and Rehabilitation from COWI. Since 1978 he has chaired the CEB-activities on durability.

Summary

The paper gives a framework for a performance based procedure for the design of structures for durability. This procedure is in principle a modification of the structural limit state design. This implies that the performances are given as limit state functions and expressed in terms of reliability. At this moment several activities have been started for the further development of the performance based durability design. It is expected that within a few years the first results will be available for the building industry.

1. Present durability design approach

A lack of durability can cause serious safety and serviceability problems for structures. Despite this designers have at this moment, considerably more attention for load and resistance based structural design than for durability design. The recent history has however shown that due to a lack of durability serious collapses and other types of damages can occur with tremendous amounts of damages. Some examples of them are:

- The Ynys-y-Gwas bridge in Wales (UK) collapsed [1] on 4 December 1984. This concrete bridge was a single, 18 meters span segmental post-tensioned structure. The cause of the collapse was serious corrosion of the post-tensioned tendons.
- In Germany the outer roof of the Berlin Congress Hall collapsed on 21 May 1980 due to hydrogen-induced stress corrosion [2]. One person died. Another was badly injured.

- In 1990 a reinforced concrete gallery in Wormerveer (NL) collapsed. This was caused by chloride induced corrosion in a crack that was caused by poor construction.
- In Melle (B) a prestressed concrete bridge collapsed during the passage of a truck. The driver died. The cause was a crack that opened during the passage of high loads. Chloride could penetrate through this crack and reach the post tensioned tendons.
- In Uster (CH) the roof of a swimming pool collapsed in 1985 [3]. The roof was made of stainless steel that was supposed to be resistant to the present damp, chloride contaminated atmosphere and the high temperatures. Nevertheless the steel corroded and 12 people were killed.
- Further it can be mentioned that woodrot in foundation piles have caused serious damages in the buildings that they carry.

This list of accidents with structures makes clear that durability should have serious attention from structural engineers during design and construction. Both the ultimate and the serviceability limit state must be analyzed.

The design approach with respect to durability of structures is in the existing building codes to a large extent empirical. It is mainly based on deem-to-satisfy rules. For instance for concrete these rules relate to the minimum concrete cover, the water-cement ratio or the maximum crack width. For steel rules have been given for the maintenance. For timber the various wood species have been classified in durability classes. If these rules are met, it is assumed that an acceptably long but unspecified lifetime will be achieved.
A major part of testing the durability of metallic and organic coatings is based on standard tests that do not represent the environment in which the building components will be exposed [4]. It is obvious that the result is a bad correlation between test results and the durability in practice.
The design rules in the present codes are not related to the performance of the structure. They are not yet formulated as limit states as is usual for structural designs.

The problem is not exclusively related to large structures. Metal anchors for façade plates, metal ties for cavity walls, steel angles for supporting the outer leaves of masonry cavity walls are relatively small structural components for which the safety is directly coupled to their durability. Indeed these are examples of serious safety and durability problems.
These examples show a main safety and durability problem in the building industry. The problem arises from the combination of:

- a long intended service life (say more then 50 years)
- failure will lead to exceeding an ultimate limit state for which high reliability indexes apply (Eurocode 2 requires in these cases β-values of 3.8)
- safety is to a large amount dependent on the durability
- inspection or monitoring is not usual or even impossible
- hardly any pre-warning before collapse.

In Figure 1 a sketch of a probability density function for the service life is given based on an intended service life of 50 years and a β-value of 3.8. The end of the service life is defined as the moment of collapse. The area under the curve between 0 and 50 years equals 10^{-4} whereas the whole area under the curve equals 1. Without further mathematical prove this implies that the structure must have a mean service life of some hundred years.

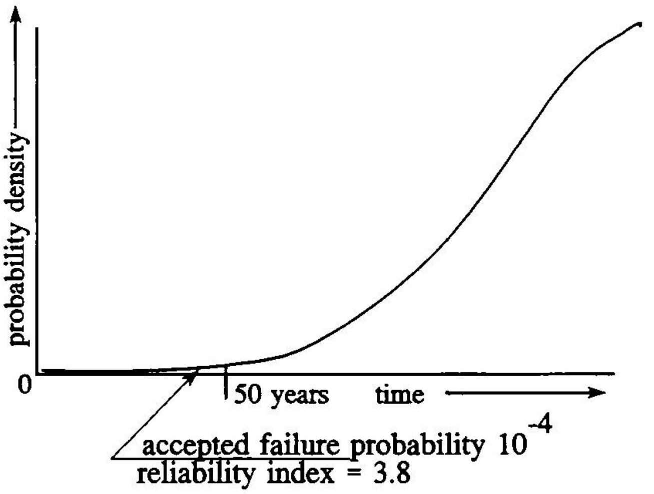

Fig. 1. Example of a probability density function of a service life for an intended service life of 50 years and a reliability index β-value = 3.8.

The performance based design that is illustrated in Figure 1, will provide the basis for an objective assessment of the durability. It must be based on realistic and quantified environmental and material models capable to predict the future behaviour of the structure. In this way it describes the performance in relation to time. This offers the following benefits:

- durability design can be based on the same principles as structural design (safety, serviceability, limit states and reliability)
- objective designs based on the total life cycle costs will be possible
- a reduction of the consumption of materials and energy by optimal use of the materials
- basis for design engineers, contractors and maintenance engineers to make tailor made designs, especially if the design is based on specific material properties
- realistic performance test procedures to establish the building material properties and the building component behaviour
- methodology can be extended to new materials and new applications; nowadays much attention is paid to a sustainable development and as a consequence waste materials or secondary materials will be used more and more.

2. Durability in Eurocode 1

In Eurocode 1: 'Basis of design and actions on structures' (ENV 1991-1, 1994) an attempt has been made to give fundamental requirements with respect to the durability of structures. It is stated that structures should be designed with appropriate levels of reliability for safety and serviceability, including durability. For this purpose a 'design working life' is defined, being the period for which the structure has to be used for its intended purpose with anticipated maintenance but without major repairs being necessary. For the design working life a classification is given varying from 1 to 5 years for temporary structures to 100 years for monumental buildings, bridges, and other civil engineering structures.

It is assumed in design that the durability of a structure or part of it in its environment is such that it remains fit for use during the design working life. The structure should be designed so that the deterioration does not impair the durability and performance of the structure. The environmental conditions have to be appraised at the design stage to assess their significance in relation to durability and to enable adequate provisions to be made for protection. The degree of deterioration may be estimated from calculations, experimental investigations, experience from earlier structures, or a combination of these considerations.

Although it is important that in Eurocode 1 attention is paid to durability the practical significance is still restricted. The main reason for that is the lack of a strict design format and of objective requirements. In some material related Eurocodes more elaborated requirements are given. These are however implicit and not related to performances or to the fundamental durability requirements in Eurocode 1.

All necessary ingredients for a performance based durability design procedure are nevertheless present in Eurocode 1. These ingredients are the performance based structural design method, levels of reliability, and reference periods (design working life).
In the performance based structural design [5] both the resistance R and the load S are considered to be time independent. In many loading situations this is not realistic. The limit state function should then be rewritten as a time dependent limit state function:

$$R(t) - S(t) \geq 0 \qquad (1)$$

A special case for this limit state function occurs if either R or S is not time dependent. Relationship (1) applies for all t in the time interval (0,T). T is the reference period(intended reference period or design working life). Even if the loading or the capacity of a structure is time dependent,the limit state functions for designing structures are rarely formulated in this way (with an exception for fatigue). They are often simplified to time independent quantities.

Well-known simplifications are:

- assuming that the material strength during the service life period is either equal to the short term strength or to the long term strength
- for (semi) static loads one characteristic maximum value, related to the reference period, is defined
- for fluctuating loads (like wind, traffic or waves) one characteristic maximum fluctuation in the reference period is defined.

The durability design can be presented in two different, but theoretically equivalent, formats. These are the 'intended service period design' and the 'lifetime design'. In the intended service period design the condition is that the limit state may, with a certain reliability, not be reached within the intended service period. The format for the intended service life design is largely comparable with the format for the conventional structural design. In the lifetime design the reliability of the structure is related to the probability that the design lifetime will be exceeded. The lifetime ends at the moment that the limit state is exceeded.

The concept of the intended service period can be expressed in a design formula:

$$P_{f,T} = P\{R(t) - S(t) < 0\}_T \leq P_{target} = \Phi(-\beta) \qquad (2)$$

in which:

$P_{f,T}$ - the probability of failure of the structure within T
T - intended service period.
P_{target} - the accepted maximum value of the probability of failure
Φ - standard normal distribution function
β - reliability index (this value is normally given in codes instead of the failure probability)

Probably it will be possible to simplify this relationship in a later stage to a design format equivalent to the conventional design formulas.

Example 1:
A steel rod with a diameter of $ø$ = 20 mm and a tensile strength f_a = 500 N/mm² is loaded with an axial tensile force F =105 kN. Due to corrosion the diameter reduces with a speed s = 0.1 mm/year. In this case the design formula for the period t = 0 to T years is:

$$P_{f,T} = P\{R(t) - S(t) \leq O\}_T = P\{\tfrac{1}{4}\ \pi\ (ø - s\ t)^2 f_a\ - F \leq 0\}_T$$

$$= P\{\ [\tfrac{1}{4}\ \pi\ (20 - 0.1\ t)^2 - 150.10^3 \leq 0]\ \}_T \leq P_{target} = \Phi(-\beta)$$

In some structural codes indications have been given for values of T and P_{target}. For example in Eurocode 1 for the ultimate limit state (collapse): T = 50 years and $\beta = 3.8$ corresponding with $P_{target} = 7.10^{-5} \approx 10^{-4}$.

For the lifetime design relationship (1) must be transformed to a lifetime function. This can be done by writing it as an explicit function of the time:

$$L = t\{R,S\} \tag{3}$$

In which:
L - the lifetime of the structure.

The reliability of the structure can be introduced by limiting the probability of exceeding a target value:

$$P_f = P\{L \leq T\} \leq P_{target} = \Phi\ (-\beta) \tag{4}$$

A possible, more practical form for a design formula is:

$$t_d \geq t_{target} \tag{5}$$

In which:
t_d - design value of the lifetime
t_{target} - target lifetime.

Example 2:
For the same steel rod that was presented in example 1 the life time function is:

$$P_f = P\{\ L \leq T\ \} = P\{ø - \sqrt{\{[\ F / ¼\ \pi f_a] / s\}} \leq T\}$$

$$= P\{\ [20 - \sqrt{\{[105000 / ¼\ \pi\ 500\ ] / 0.1\ \}} < P_{target} = \Phi\ (-\beta)$$

In Figure 2 the durability design procedure is illustrated. It shows the similarities and differences between the service period design and the lifetime design. The illustration makes clear that for both approaches the same information is used. Consequently they will lead to exactly the same result. Moreover the lifetime distribution in Figure 2 shows that the margin between the mean service life $\mu(L)$ and the target value T can be very large. This margin depends on the type of the distribution, the scatter and the target failure probability (As the target failure probability is very small; it is almost impossible to draw the figure in the right scale!).

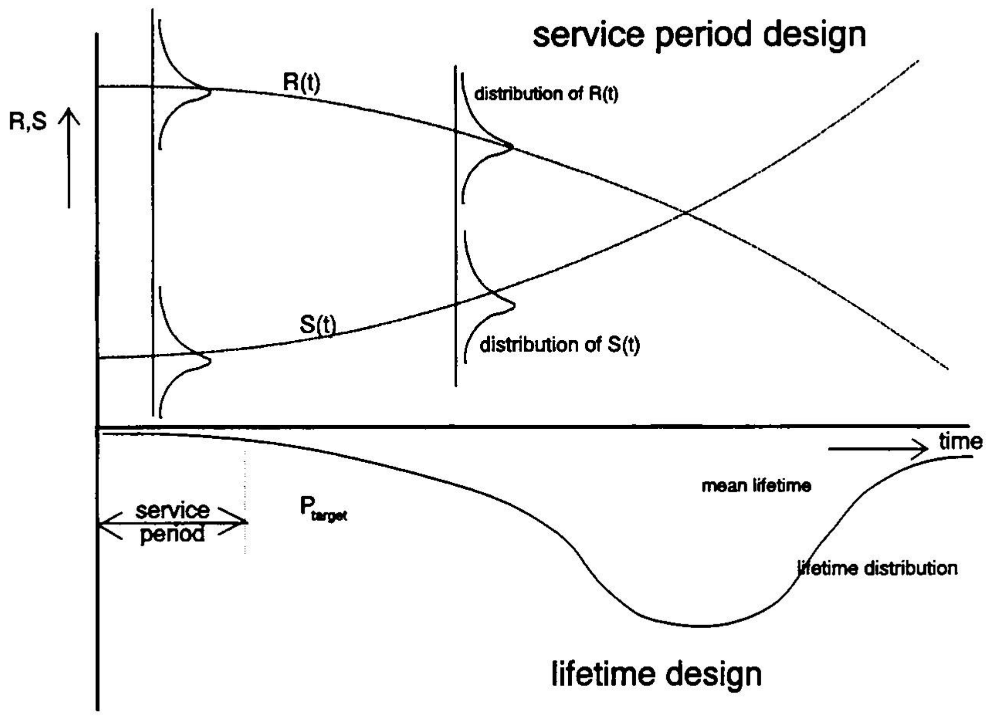

Fig. 2. Similarity between the service period design and the lifetime design

It is important to realise that both the intended service period design and the lifetime design are not necessarily restricted to the conventional ultimate and serviceability limit states. The processes (or mechanisms) involved can be of mechanical, physical, chemical, elector-chemical or biological nature. The limit states can refer to aspects such as structural safety, serviceability, functionality, comfort, aesthetics and so on. The accessory target reliability index depends on the type and the amount of damage.

In the limit state approach, as presented so far, the first exceedence of the limit state determines failure. Other types of criteria are however possible. Examples are: the number of exceedences of a limit state is restricted. Or: the duration of the exceedence of a limit state is restricted. The latter two examples may apply in reversible limit states. The two examples may be true for vibrations that cause discomfort. This paper deals for simplicity only with the conventional limit state approach. It may be expected that the extension in a later stage to other types of criteria will not meet fundamental problems.

The number of limit states (and their types of criteria) that have to be considered for one building is very large. That means there is a need for priorities and simplifications. In this paper no attention will be paid to that.

Some worked out examples of both concepts were presented some years ago in [6, 7, and 8]. These examples made it clear that the concepts can be used for various building materials, showing the generic character of these concepts. Rilem committee 130 CSL 'Calculation of the Service Life of Concrete' has prepared a report [8] that shows calculation examples for this approach for various degradations of concrete structures.

The conventional structural design is in practice restricted to performances with respect to safety and serviceability. This restriction is not necessary for the durability design (in fact there is neither a formal restriction in the conventional procedure). As long as it is possible to formulate a limit state, it will be possible to apply either the service period design or the lifetime design. It is obvious that the aimed reliability is related to the nature and the amount of damage that can be expected if the structure fails. If human lives are threatened or the economic losses are very high the acceptable failure probability must be very low. Higher values are acceptable for smaller damages. This principle is completely in line with the conventional approach for structural design. Possible performances for structures relate to:

- load bearing capacity (bending, axial, torsion, shear)
- stiffness (deflection, vibration)
- protection by coatings
- flat surface for walking, riding, driving or running
- fire protection
- heat storage
- sound insulation
- aesthetics.

3. Conclusions and further developments

The present deem-to-satisfy approach with respect to the design for durability, as is also present in the various parts of the Eurocode, gives no insight in the service life of a structure. In that sense existing methods are not objective and not generic for all building materials. A performance based durability design does not have these disadvantages. The Eurocodes strive in principle after such a type of design.

The format for a performance based durability design can be copied, to a certain extent, from the modern format for structural design as is also present in Eurocode 1. Characteristic for that format are limit states, reference periods and degrees of reliability. This structural format has to be extended to the time domain. It is obvious that this approach will offer a seamless connection between the structural and the durability design.

The performance based durability design can be extended from ultimate and serviceability limit states to non structural performances. This means it can also be applied for functional and aesthetical aspects of building materials and components.

At various occasions proposals have been made to extend the design procedure to durability aspects [e.g. 6, 7, and 8]. In the present work of CEB (Comité Euro-International du Béton) commission V 'Operation and Use' this approach has also been adopted with the aim to develop a reliability based Model Code for the durability design of concrete structures.

The amount of work that has to be done to achieve such a Model Code is tremendous. Therefore a consortium of companies that are convinced of the benefits of such an approach, has recently received a research grant from the Brite/Euram programme of the European Community. It is intended to develop the method to a practical design handbook for concrete structures including new performance tests for materials and components. Their research project is named DuraCrete. The actual research has been started in February 1996 and will end three years later.

During a workshop in December 1994 in Copenhagen an international group of about 25 experts in the field of durability of concrete has expressed that they would support the performance based design procedure. New initiatives for further research will also be taken by them.

The new developments will not be restricted to concrete structures. The intention is to extend the work to all structural materials, such as steel, aluminum, timber, masonry and plastics.

Both the service period and the lifetime concept correspond to the service life prediction method for building materials and building components of CIB/RILEM (9). This method gives a protocol for accelerated service life testing. One of the first steps in that protocol is establishing the functions R(t) and S(t). By extending the present protocol with the aspect that the lifetime is a stochastic quantity a full correspondence between the service period or the lifetime concept and the CIB/RILEM method can be achieved. In the CIB/RILEM method for predicting the service life of building materials and building components the reliability aspect must be introduced. In that case the method will correspond directly to the performance based durability design that has been presented in this paper.

4. References

1. Woodward R.J. and F.W. Williams, *Collapse of Ynys-y-Gwas bridge West Glamorgan,* 1988, Proceedings of the Institution of Civil Engineers, Part 1, Volume 84, August, pp. 635-669
2. Schaich J. and K. Kordina, H.J. Engell, *Partial collapse of the Congress Hall in Berlin - Causes of damage - report summary,* Beton und Stahlbetonbau, Vol. 75, No. 12, December 1980, pp. 281 - 294
3. Note in Krupp-VDM Berichte, Metal Times No. 8, 1992
4. Martin J.W. and S.C. Saunders, F.L. Floyd, J.P. Wineburg, NIST Building Series 172: *Methodologies for Predicting the Service Lives of Coating Systems,* 1994, pp. 68
5. Vrouwenvelder, A.C.W.M., Eurocode 1, *Basis of Design, Background Information,* Proceedings IABSE Colloquium Basis of Design and Actions on Structures- Background and Application of Eurocode 1, March 27-29 1996, Delft, The Netherlands.
6. Sentler L., Report TVBK-3018: *Service life predictions of concrete structures,* 1981, Department of Structural Engineering - Lund University of Technology, Lund, Sweden
7. Siemes A.J.M. and A.C.W.M. Vrouwenvelder, *Durability of buildings: a reliability analysis,* 1985, Heron, Volume 30, Number 3, Delft The Netherlands, 1985
8. Hergenröder M., *Zur statistischen Instandhaltungsplanung für bestehende Betonbauwerke bei Karbonatisierung des Betons und möglicher Korrosion der Bewehrung,* 1992, Technische Universität München, Germany
9. Sarja A. and E. Vesikari, Rilem report 14, *Durability Design of Concrete Structures - Calculation methods for service life design of concrete structures,* 1996, Chapman & Hall London, England (in print)
10. Masters L.W. and E. Brandt, *CIB W80/Rilem 71-PSL Recommendation: Prediction of service life of building materials and components,* 1983, Materials and Structures, Vol. 20, No. 115