DURABILITY, RELIABILITY, SUSTAINABILITY AND CLIENT'S DECISION

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Summary

The performance-based approaches, sustainability and whole life costing have gained considerable attention in recent years. These approaches deal also with the durability and reliability of structures, both of these factors having pronounced economical and sustainability impacts. The level of reliability in the context of durability should be left to the client's decision as well as the appropriate serviceability criteria; unfortunately there is a lack of recognition from investors in this respect, in spite of the fact that the mutual impact of these values on the cost of the project may be crucial. So the durability implications in the context of reliability should be addressed during the design process and discussed with the client. Examples of user-friendly tools based on the probabilistic approach and models for degradation of concrete structures are briefly described, and some possibilities for applications are shown.

Keywords: Service life, reliability, life-cycle costs, limit states, concrete structures, degradation models, software

1 Introduction

Advanced techniques and know-how for urban design and buildings enhance the competitiveness of the construction industry. This sector is based on client- and user-driven complete life-cycle processes. Cost reduction for the overall value chain may result in increased competitiveness, new business opportunities, new investments and in economically viable services for the largest possible client base. An optimal allocation of available economic resources should be achieved. New research focuses on how technology can also address human sciences and socioeconomics and show the way to the knowledge of how the sector can profit from exploring the current design gaps [1].

In this context the durability issue has gained considerable attention recently – considering performance-based approaches, sustainability and whole life costing. This has been clearly demonstrated at numerous international conferences, in scientific publications, by international joint projects and it is also reflected in recent standardization activities and future documents [2, 3, 4].

Thus, probabilistic performance-based service life design is gaining considerable attention from researchers, and more recently, designers, and hopefully also other stakeholders. These approaches deal with **durability** and **reliability** issues, which rank amongst the most decisive structural performance characteristics, also having pronounced economical and sustainability impacts. Broad application is, unfortunately, prevented by the insufficient dissemination of basic ideas, relevant knowledge or experimental evidence, and by a lack of recognition from investors. Usually, relevant simple, user friendly and yet efficient design instruments (software and others) with appropriate capabilities are also lacking.

The **level of reliability** in the context of durability should be left to the client's decision as well as the appropriate serviceability criteria - as indicated in both documents [2, 3]. It should be noted that reliability level, limit state definition, target service life and economical results are mutually related - some elements of whole life costs are service-life dependant. The joint impact of these values, as well as their impact on the cost of the project, may be considerable.

The durability and its reliability implications need to be addressed during the design process; the agreement or decision of the client should be a basic agenda - which is not common yet. The client's role in driving innovation will facilitate the inherently safe, efficient and human-friendly production of buildings and infrastructure [1]. Tools for the assessment of the overall life-cycle costs of a construction are needed as well as for the development of standards that are performance-based and inherently open to innovation and suggestions for performance-based legislation, including performance indicators.

The present paper is aimed at underlining the role of mutual impacts and the dependency of the target service life and the relevant reliability level of structures on overall costs and on the environmental load.

2 Service life cycle costs

As it is relatively well recognized in recent years, the costs for a whole life cycle are composed from different parts, some of which appear with a certain probability and refer to a certain time periods:

$$N_{tot} = N_{in} + N_{op} + N_m + P_1 . N_1 + P_2 . N_2 + P_3 . N_3 \quad (1)$$

N_{in} initiation costs are composed of pre-construction costs and construction costs (design and building costs, project management, fixtures, fittings and furnishings)

N_{op} operational costs (like insurance, energy, water, sewage, facility management – all during the designed service life t_D)

N_m maintenance costs (actions planned during the designed service life t_D)

$P_1.N_1$ repair costs coming with probability P_1, during the designed service life

$P_2.N_2$ replacement (of elements) and reconstruction costs (which may come with the probability P_2, including possible loss due to the discontinuation of operation)

$P_3.N_3$ removal and disestablishment costs – termination of building operation due to the necessity of non-economical repairs, obsolescence or due to new requirements on performance (which may appear with probability P_3)

The percentage **discount rate** should be applied – whole life costing is simply the application of net present value analysis to a construction project [5].

What is not well recognized yet is the understanding of the above shown probabilities, their relevance to different limit states and approaches for assessing the relevant reliability level. A resolution regarding who is "responsible" for deciding about these values, or who can require them, is also needed.

In frequently-occurring situations the probabilities mentioned in Eq. (1) are associated with the probability of failure P_f (see par 3.1) and may have the following meaning: P_1 is a value of probability associated with either the Serviceability Limit State (SLS) or the Ultimate Limit State (ULS) – whichever one is relevant; P_2 or P_3 may be probabilities associated with ULS or the Obsolescence Limit State (OLS), or with new requirements on performance. *Note*: both ULS and SLS are common in the design of constructions – c.f. [5], [6]. What is "new" and not common yet are the OLS and the **limit states based on durability requirements** – for more details see 3.2.

To summarize the present paragraph: the interdependence of time (service life), reliability level (expressed by reliability index), costs and environmental stress should be recognized and well balanced/optimized – i.e. aiming for the inclusion of long-term financial implications in the evaluation of design, construction and real estate decisions.

3 Reliability and service life

3.1 Reliability measure

The safety level may be conventionally expressed with regard to the appropriate Limit State (LS) by the probability of failure P_f or by the reliability index β, which are interconnected simply by the formula

$$P_\mathrm{f} = \Phi(-\beta) \tag{2}$$

where Φ is the cumulative distribution function of the standardized Normal distribution. The use of β is the more convenient option in the design process. Target values for the reliability index, i.e. β_d (design or prescribed values) for various design situations, and for reference time periods are indicated in or [7] for certain types of LS (ULS mostly); for the particular position for SLS and Durability LS see the next paragraph.

3.2 Durability limit states

Reliability requirements for service life might be different from the requirements for structural safety in mechanical limit states due to economic, social and sustainability considerations, and, due to the level of knowledge about the technical history of the structure in question (in the cases of existing structures).

Selection of the target reliability for the durability of the structure and for each component shall be chosen based on the design service life of the structure or on the component service life related to the design service life of the structure, the difficulty and expense of maintenance, and the consequences of failure.

The serviceability criteria and the appropriate level of reliability should be agreed with the client and/or the appropriate authority [2].

As mentioned in 1.2, limit states are the basic approach currently utilized for structural design all over the world. The ULS and the SLS are traditionally distinguished. The general condition for the probability of failure P_f reads:

$$P_\mathrm{f} = P(A \geq B) \leq P_\mathrm{d} \tag{3}$$

where A = action effect, B = barrier and P_d = the target (design, acceptable) probability value. Generally, both A and B (and hence the P_f) are time dependent, which has not been considered for common cases of ULS or SLS very frequently in practice. Two exceptions have to be mentioned: (i) fatigue limit states (presumably ULS) – in this case the time domain is usually transformed into a number of load cycles; (ii) creep and shrinkage effects – special time dependent issues that mainly concern concrete structures and do not usually affect ULS.

Let us note that the reliability approach should generally cover safety (ULS), serviceability (SLS) and durability – see [6]. Durability is related to the design working life, and then time is the decisive variable. The service life assessment based on material degradation is pronounced.

For material deterioration resulting in failure due to loss of resistance, the ULS is defined when the resistance of the component or structure becomes equal to or less than the internal force, which represents a severe threat even to human lives.

The SLS is defined by:

- local damage (including cracking) or a change in appearance which affects the function of components;
- relative displacements which affect the function or appearance of components.

In the context of time (durability) a new type of time dependant LS has been defined – see [2, 3]: Durability (or Initiation) Limit States (DLS). This limit states are defined by the initiation of significant deterioration of a component that might precede the occurrence of the serviceability or ultimate limit state.

Let us explain it using the example of the durability of **reinforced concrete structures**, where the corrosion of reinforcement is the dominating effect.

The following LS can be recognized:

(i) depassivation of reinforcement due to carbonation or chloride ion penetration, and hence a possible starting point for reinforcement corrosion;
(ii) cracking in the concrete cover ;
(iii) delamination of the concrete cover;
(iv) a decrease in the effective reinforcement area - leading to excessive deformation, loss of bearing capacity and finally to collapse.

State (i) is typically a DLS, (ii) may belong to the DLS or SLS category depending on the definition of the limiting crack width, (iii) might fall in both the ULS and SLS categories depending on the location and grade of degradation, and, (iv) may belong to the SLS (deformation capacity) category ULS or (load bearing capacity).

As stated in the basic design code [6], the recommended value of the design reliability index β_d for the SLS (irreversible state) is $\beta_\mathrm{d} = 1.5$, which is relevant to a 50-year reference period. The values of $0.0 < \beta_\mathrm{d} \leq 1.5$ for the DLS are still under discussion. The level of reliability in the context of durability should be left to the client's decision together with the target service life, as indicated in both future documents [2, 3].

3.3 Client's Decision

As mentioned above the agreement or decision of the client about the demanded/optimal service life and associated level of reliability (i.e. maximum failure probability or corresponding reliability index) are needed. Regarding this point, he/she has to choose the appropriate serviceability criteria in the context of deterioration process modeling and to assess the relevant limit state. This will all be inevitably done in close cooperation with the designer. The economic consequence might be expressed as a shift from "**lowest price**" to "**gaining higher performance**". The crucial role of N_{in} (1) should be stressed; according to some European studies the range of N_{in} is 4 – 25 % of N_{tot}, i.e. it makes up an insignificant part of the total costs; on the other hand, the technological, material and constructional features gained by N_{in} costs might be decisive for service life, and will considerably influence N_{op}, N_m, N_1 and P_{1-3} , and, in this way, the total costs. This is illustrated in **Fig. 1**, showing that slightly increased initial costs may lead to pronounced service life improvements with total costs remaining unchanged.

Obviously, the "type" of client and his/her plans and intentions have to be mentioned: a client who is in the position of **user** and/or **property owner** bears the costs N_{op}, N_m, N_{1-3} and would therefore try to efficiently balance N_{in} with the intention of **minimizing N_{tot}**. Such quantified evaluation techniques are seldom applied presently; a client (e.g. a **developer**), whose intention is to sell the building immediately or rather soon would prefer to **minimize N_{in}** without giving consideration to N_{tot}. So the "cheapest-is-best" method is utilized, which leads to **inefficient long-term investment**, the option unfortunately often currently encountered in practice.

The "cheapest-is-best" option is, of course, against the rules regarding sustainability, and should be avoided via legal means.

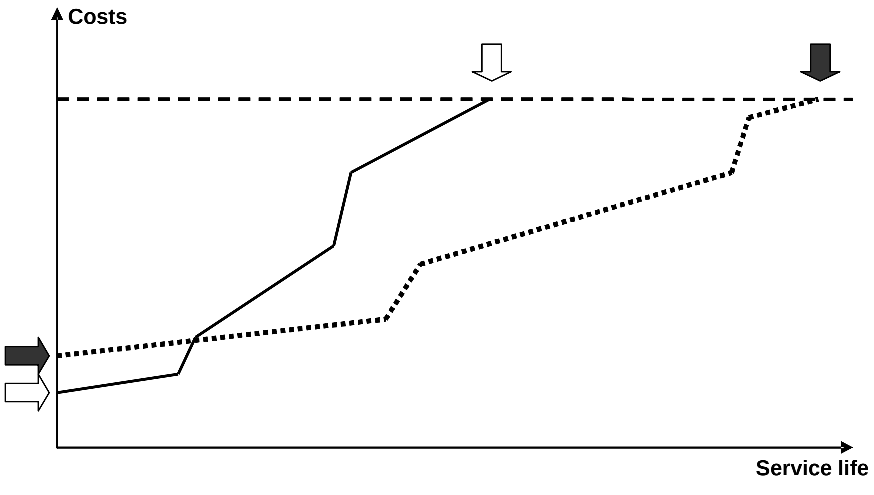

Fig. 1 Cumulative costs graph

4 Designer's role; software tools

4.1 Designer vs. client

The goal of society should be the optimization of total costs together with the relevant minimization of energy consumption and environmental loading during the whole life cycle of the building. As mentioned above this might (and should) be done in close cooperation with the designer – who, in turn, has to be well aware about such consequences and be skilled in durability design and probabilistic methods. This is not a common situation at present; the dissemination of such knowledge is needed. It should be stressed that current design codes use a 'deemed-to-satisfy' approach and so in many cases fail to define either service life or serviceability limit states relating to durability.

It cannot be ruled out that some design offices may specialize in the provision of such services in the near future.

4.2 Tools for Durability Design of Concrete Structures

Within the framework of the new probabilistic and performance based approach to durability design, some software tools for concrete structures have recently been developed at the Faculty of Civil Engineering, BUT Brno. They comply with the future codes [2, 3] and are briefly introduced below – for more details see [8]:

(i) **RC-LifeTime** utilizes the model of the carbonation process for concretes made from Portland or blended cements, considers the input data as random variables and performs a stochastic simulation technique. An assessment of service life is provided which considers the concrete cover quality and exposition type, and this together with reliability index assessment. It enables the user to make some assessment of CO_2 emissions and cost consequences among variants of concrete mix see [10]. **RC-LifeTime** is a rather simple and user friendly tool, freely accessible on http://rc-lifetime.stm.fce.vutbr.cz/;

(ii) **FReET-D:** A complex software tool for degradation assessment. Presently, it is available (http://www.freet.cz/) in a configuration encompassing several models for carbonation, for chloride ingress and reinforcement corrosion. The tool is based on the probabilistic multipurpose software package FREET (Novák et al., 2003). It will enable the incorporation of any degradation closed-form numerical model in the form of a limit state/response function.

These software packages are applicable for the assessment of service life (for newly designed concrete structures) or residual service life (for existing concrete structures) and relevant reliability levels. The consideration of input parameters as random variables is essential for results duality and decision making based on the probabilistic approach, and in this way might be also helpful with issues like "Meeting the clients requirements" and "Sustainability optimization".

5 Conclusions

With the goal of emphasizing aspects like quality, reliability, identification of the best value solution and avoiding inefficient investment:

- a sensible and foresightful client should well balance the whole life costs of a structure giving consideration to its service life, sustainability and related reliability level. So the target service life and the related reliability level based on suitable durability limit states have to be chosen/approved by the client;
- the designer should be equipped with the appropriate know-how concerning durability and reliability issues, thus being able to provide the client with relevant services - to help managers make better decisions;
- legal instruments should reinforce the concepts of the WLC and similar issues.

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