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Durability design strategies for new cementitious materials

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ABSTRACT

In order to fully utilise the advantageous durability properties of new high-performance cementitious composites performance-based durability concepts are required. Following an introduction of available durability design philosophies, this paper introduces a framework for these durability concepts. At the heart of this framework is the choice of an appropriate combination of models for the relevant deterioration processes and the uncertainty associated with these models and their input variables. It is shown that a fuzzy-probabilistic uncertainty model combined with an empirical deterioration model provides the best balance between user-friendliness and accuracy. As an example, such a durability concept for strain-hardening cement-based composites (SHCCs) exposed to chlorides is briefly introduced. This concept is considered a first significant step towards a comprehensive durability design framework for SHCC and may serve as a template for other new cementitious materials.

1. Introduction

Durability is “the capability of a structure to maintain minimum performance under the influence of loads”, and service life design ensures that this performance is achieved over the intended period of time, i.e. the service life [1].

It has been recognised for some time that insufficient durability is a major cause for premature damages to reinforced concrete structures. To improve durability, a number of performance-based service life design concepts have been developed [2–4]. For structures made of crack-free ordinary concrete they allow a rigorous durability assessment and an economical service life design, which ensures that the desired service life is reached with the required reliability.

They do not, however, address the deterioration processes at the material level. To this end, ordinary concrete compositions are being optimised, for instance through the application of new admixtures [5,6], and new high-performance materials such as textile-reinforced concrete (TRC) and strain-hardening cement-based composites (SHCCs) are being developed [7–10].

The superior durability performance of these new composites can be demonstrated in laboratory experiments. Such experiments cannot, however, answer the question by how much and with what reliability a new material will increase the service life of real members and structures. This information, which is required to justify the application of a material economically as well as with regard to sustainability, can only be obtained from a performance-based durability and service life design concept.

Such a design concept must quantify member durability or service life either in real terms or relative to that of a member made from a reference composition. In doing so, it must strike the right balance between accuracy and user-friendliness in light of the design problem at hand, the knowledge about the deterioration process in question, and the available information about the material behaviour.

The lack of available information is a key constraint. Hence, transparency regarding the limitations of any deterioration model as well as input and output variables and their uncertainties is of utmost importance. To reduce uncertainty, the concept should also allow for the inclusion of additional information as it becomes available, both for the individual structure (e.g. through a “birth certificate” [11]) and generally for the material in question.

Based on an overview of existing durability design strategies for ordinary concrete, this treatise proposes a conceptual framework for the durability design of members made from new cementitious materials, which meets these requirements.

2. Durability design strategies for ordinary concrete

2.1. Design philosophies

A structure's durability and the consequences of the deterioration of one or more of its components or members may be assessed using a fault tree analysis [12]. At the core of such an analysis are design concepts on the member level such as the one developed in the DuraCrete project ([2], cf. Section 2.2). However, it must be stressed that service life design begins with sound architectural and structural design and detailing, including the choice of appropriate materials, to avoid failure- and more specifically corrosion-prone details.

As can be seen in Fig. 1, two fundamentally different design strategies can be distinguished on the member level. On the one hand, an environmental load may be avoided, for instance, by coating the member or component with an impervious barrier or by replacing

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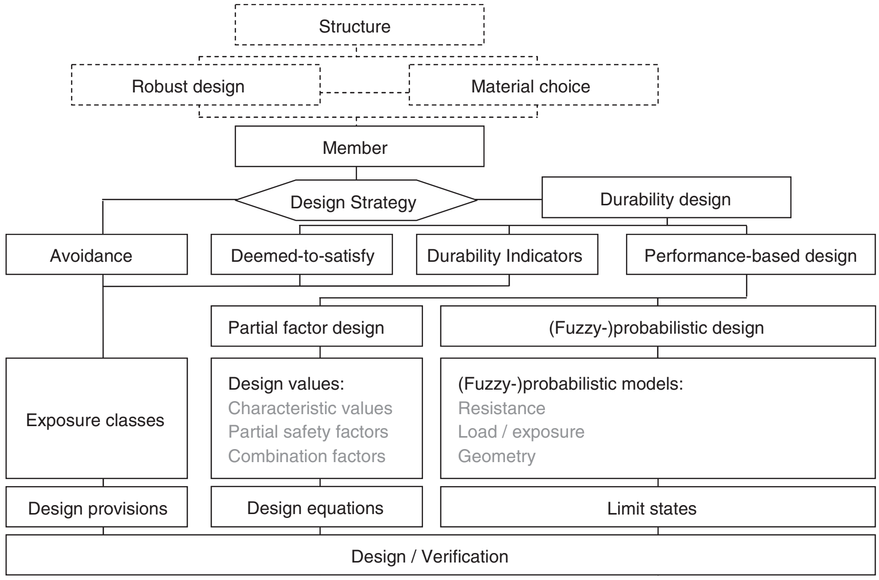

Fig. 1. Different levels of sophistication for service life design, adapted from [4,26].

a component such as mild steel with stainless steel. On the other hand, the member may be designed to withstand the environmental load. In this case, a reinforced concrete member's durability may be improved (i) by increasing the cover of the steel reinforcement, (ii) by managing crack width through structural design, and (iii) by planning for (later) additional barriers such as hydrophobic surface treatment to avoid further exposure. The latter actions blend into the avoidance strategy. On the material level (iv) properties such as concrete porosity may be improved, or (v) ordinary concrete may be replaced with new high performance composites such as SHCC. Depending on the criticality of the structure, one or more of the above strategies may be used simultaneously [13].

Most current concrete codes such as Eurocode 2 [14] prescribe a deterministic design approach: Environmental conditions are classified into a limited number of exposure classes, and for each class *deemed-to-satisfy rules* pertaining to, for instance, water-to-cement ratio, compressive strength, cement content, and concrete cover are prescribed. Structures designed according to these rules will have an acceptably long but not specified lifetime, even though a service life of 50 years is implicitly assumed within the Eurocode framework [15,16].

It has long been recognised that durability design using such empirical requirements derived from field experience combined with limited research data and expert judgement rather than scientific principles is unsatisfactory [17]. This gave rise to the development of more sophisticated approaches, culminating in (fuzzy-)probabilistic service life design concepts.

A first step was taken with the development of performance or *durability indicators* [18–20]. This design approach is also referred to as lab-performance design [21] and inconsistently classified sometimes as a deemed-to-satisfy [18], sometimes as a performance-based approach [22,23]. In contrast to classical deemed-to-satisfy rules, durability indicators are based on established relations between characteristic properties that can be measured in the lab and the deterioration process in question. Indicators include, for instance, the mass loss due to scaling after frost or freeze-thaw exposure as well as the chloride diffusion or migration coefficient. The aforementioned inconsistent classification may be resolved by differentiating between empirical indicators, which usually assume a service life of 50 years (deemed-to-satisfy design), and indicators quantified from probabilistic analyses (performance-based approach) [24].

Recent standards such as DIN EN 206-1 [22] specify, or are open to, the application of *performance-based design* concepts, especially for the design of structures with service lives of 100 years and longer [15,25].

Not shown in Fig. 1 are the steps following the design, including inspection of execution. As part of this inspection (some but usually not all) input parameters to the service life design model such as concrete cover depth might be tested in situ for compliance with the design assumptions. The resulting as-built-documentation is often referred to as the *birth certificate* [27].

The fib Model Code for Service Life Design [27] suggests ("*might be tested*") rather than prescribes ("*must be tested*") compliance testing. Nonetheless, it may be argued that these tests are an important element of any performance-based approach to durability. Otherwise a performance may have been achieved at the design stage, but without the confirmation of compliance of the built structure, it remains unclear if that performance will be achieved.

The validity of the argument in favour of compliance testing notwithstanding compliance testing will not be discussed in this paper beyond the observation that the principles as laid out e. g. in [27] are not material-dependent and hence apply not only to crack-free ordinary concrete but to all cementitious materials.

2.2. Performance-based design — the DuraCrete framework

2.2.1. Introduction

Using a limit-state approach, performance-based design concepts allow a systematic member design to ensure that the specified service life under the actual environmental loads is reached with the desired reliability. In addition to (*i*) *the definition of appropriate limit states* and the required reliability with which they must not be exceeded, these design concepts require (*ii*) *a sufficiently realistic deterioration model*. As discussed in Chapter 3, the deterioration model is a mathematical description of the deterioration process. The model itself and its (*iii*) *reliably quantified input variables* exhibit uncertainty, which must be modelled with (*iv*) *an appropriately sophisticated uncertainty model*. [3,26].

In recent years a number of probabilistic performance-based design concepts such as Life-365 [28] and the DuraCrete framework [2,29] have been developed for crack-free ordinary concrete. The latter was subsequently developed into the fib Model Code for Service Life Design [4] and integrated into the new fib Model Code 2010 [25,27].