Sustainability verification of deteriorating concrete infrastructure

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Abstract. Sustainable asset management is becoming increasingly important, both due to aging population of buildings and infrastructure and due to more restrict policies. Management optimization requires sustainability quantification and verification. The development in *fib* guidelines is summarized and supplemented with further suggestions for sustainability quantification. Methods for including depreciation rates in sustainability quantification need be established.

1 Introduction

A necessity for sustainability verification is combined quantification of the time dependent performance of the considered structure (or stock of structures) and the various impacts of relevance. Further, sustainability verification requires establishment of limit states (relative or absolute at local or global level). Limit states for sustainable reinforced concrete structures were discussed by Geiker et al. [1] stressing the need for considering the whole life cycle of a structure, and both engineering and sustainability limit states.

2 Guidelines

The European-funded DuraCrete project provided a durability design framework resembling the established structural design approaches [2]. This framework was further developed and formalized in the *fib* Model Code for service life design [3] and the ISO standard 16204 [4].

The *fib* Model Code for concrete structures 2010 [5] also provides design principles for sustainability (environmental impacts, social impacts, and aesthetics) (see [5] Section 3.4), and suggests life cycle assessment methods adhering to ISO 14040 [6] be used for verification (see [5] Section 7.10). However, [5] provides no specific design guidelines.

Addressing the intention of [5], a design and management framework considering environmental impacts was, based on Lepech [7], proposed by Lepech et al. [8, 9].

The *fib* TG 6.3 "Sustainability of precast structures" presents in [10] the Sustainable Structural Design (SSD) method, which considers both environmental and structural performance in a life cycle perspective. The SSD method combines in economic terms input from life cycle assessment with structural performance assessment. Emphasis is placed on the SSD method being modular, portable, and scalable to facilitate general applicability. The *fib* TG 6.3 further advocate for the use of the "MIVES" method, a multi-criteria decision-making method "capable of defining specialized and holistic sustainability models to obtain sustainability indexes". Reference is in [10] made to the Spanish Structural Concrete Code, where MIVES is proposed used for assessing the sustainability of concrete structures. Adopting MIVES, the *fib* TG 6.3 proposes a set of criteria be considered: economic: total costs, quality, dismantling, service life; environmental: consumption, emission, energy; and social: third parties; health and safety. Despite "health and safety" could include structural performance, this appears not explicitly mentioned neither in the general description nor in the cases.

The draft of the *fib* Model Code 2020 (MC2020) [11] fully integrates structural performance verification in "sustainable and through-life management & care". Structural performance is treated as the basic aspect of social performance of any concrete structure. In addition to stating requirements and criteria, the draft of MC2020 provides guidelines for evaluation/verification. To account for difference in performance of alternative concretes Müller and Boumaaza [12] introduced the "Concrete Sustainability Potential", CSP= $(f_{ck}{\cdot}t_{SL})/GWP$, where the characteristic concrete strength is multiplied by the service life divided by the global warming potential.

3 Further sustainability quantification

3.1 Sustainability development space

For sustainability assessment Holden et al. [13] introduced the "sustainability development space" limited by threshold values (acceptance criteria) illustrated in a radar chart/spider web diagram. Linnerud et al. [14] recently applied the concept and used the distance between "headline indicator" values and

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corresponding thresholds to quantify the sustainable development gap at different times and locations.

3.2 Age and use classes

Kohler and Hassler [15] introduced age classes and use classes to provide an integrated system analysis approach for assessment of larger building stocks. The approach was applied by Brattebø et al. [16] for sustainability assessment of building and infrastructure stocks. The authors claimed that (i) when using use-age matrices, the stock can be examined and documented over time considering changes in use characteristics and aging of the stock and (ii) when applying lifetime probability functions together with materials density and energy intensity coefficients of the system, life cycle environmental impact patterns can be quantified.

Considering infrastructure stocks, it is the present author's expectation that the division into age classes with benefit could be based on changes in the requirements to durability related properties (e.g., cover thickness and w/b ratio, alkali reactivity of aggregates, air entrainment for frost resistance) and construction practices (e.g., duration of curing and mitigation of early age cracking). Furthermore, it is suggested that for similar structures (e.g., highway bridges) the use class could be subdivided into type classes reflecting the condition of the structures. An example of such a subdivision is given in Figure 1. Using the concept according to Kohler and Hassler [15] and data from Osmolska et al. [17] the stock of Norwegian standard I-beam girders are subdivided into age and type classes based on regulations and observed corrosion damage.

Use/type class		Age class				
		≤ 1972	1973-80	1981-87	1988-93	≥ 1994
1: Inner coastal	1.1 Non-conformancies					
	1.2 Environmental attack					
	1.3 Non-conf. & env. attack					
	1.4 Other damage					
	1.5 No registred corr. damage					
2: Coastal	2.1 Non-conformancies					
	2.2 Environmental attack					
	2.3 Non-conf. & env. attack					
	2.4 Other damage					
	1.5 No registred corr. damage					
3: Harsh coastal	3.1 Non-conformancies					
	3.2 Environmental attack					
	3.3 Non-conf. & env. attack					
	3.4 Other damage					
	1.5 No registred corr. damage					

Figure 1: Division of stock into age and type classes to support sustainable asset management: Suggestion for subdivision of Norwegian standard I-beam girders based on regulations and observed corrosion damage. Concept according to Kohler and Hassler [15], data from Osmolska et al. [17].

3.3 Modelling approach

When uncertainty is characterized in life cycle assessment (LCA), Monte Carlo Simulation is the standard approach [18].

In a recent thesis, Wu [19] developed a method that uses neural network to generate simulations statistically equivalent to simulations based on multi-physics models, with much less computational time and resource. Such surrogate models enable optimization of design and maintenance for real world application. Furthermore, it enables generating probabilistic profiles of deterioration performance of real structures and thus supports probabilistic sustainability analysis.

3.4 Depreciation of impacts

Using climate gas emission as the only measure, the Norwegian Public Roads Administration recently compared alternatives for maintaining a marine crossing and demonstrated that cathodic protection resulted in only 10% of the emissions of a new marine bridge [20]. The gain would be less if extending the CSP-concept [12] and taking account for differences in expected service life. However, it is of high importance also to consider the urgent need for up-front emission lowering. Methods for such sustainability quantification, including depreciation rates, need be discussed and established.

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