Durability reliability analysis for corroding concrete structures under uncertainty

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ABSTRACT
This paper presents a durability reliability analysis of reinforced concrete structures subject to the action of marine chloride. The focus is to provide insight into the role of epistemic uncertainties on durability reliability. The corrosion model involves a number of variables whose probabilistic characteristics cannot be fully determined due to the limited availability of supporting data. All sources of uncertainty, both aleatory and epistemic, should be included in the reliability analysis. Two methods are available to formulate the epistemic uncertainty: the imprecise probability-based method and the purely probabilistic method in which the epistemic uncertainties are modeled as random variables. The paper illustrates how the epistemic uncertainties are modeled and propagated in the two methods, and shows how epistemic uncertainties govern the durability reliability.

1. Introduction

The assessment of safety, serviceability and durability of the built environment requires proper modeling of various sources of uncertainties in the capacity of the systems and the demands imposed on them. In traditional structural reliability analysis, uncertainties are handled by probabilistic modeling and statistical analysis. Structural safety is measured by a probability of failure, $P_f$. The probabilistic model of an uncertain quantity often needs to be estimated on the basis of limited data or incomplete information. For instance, the statistical parameters (e.g., mean and standard deviation) are usually estimated by statistical inference from sample observational data. If the supporting data are limited or nonexistent, the distribution estimated may differ from the actual one, introducing a source of uncertainty to the safety assessment. Such an uncertainty due to incomplete information is epistemic (knowledge-based) in nature, and is different from the inherent randomness of a physical quantity (often referred to as “aleatory” uncertainty).

Traditionally, the effect of epistemic uncertainty is either ignored, or at most, recognized by combining both epistemic and aleatory uncertainties into one overall uncertainty [1]. With the recent developments in structural engineering, many have noted the importance of differentiating aleatory and epistemic uncertainties [2–4]. There are circumstances where the epistemic uncertainty needs to be defined clearly and its impact to reliability assessment be formulated explicitly. One area is the risk-informed decision making for the maintenance of aging structures whose strengths deteriorate due to environmental aggressive factors. Large epistemic uncertainties exist in the current models for aging and degradation of construction materials, as well as in the past and future demands from service requirements and environmental stressors.

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Reliability analysis under epistemic uncertainty requires (1) a mathematical model to represent epistemic uncertainty, and (2) numerical techniques that can propagate the epistemic and aleatory uncertainties separately at a reasonable computing effort. From a pure probabilistic point of view, epistemic uncertainty is modeled as (Bayesian) random variables and combined with aleatory uncertainty through the total probability theorem [3–6]. Judgmental information is needed to estimate the prior distributions for the Bayesian update. The numerical techniques for propagating the two uncertainties separately are generally complex and computationally costly [4].

Alternatively, an imprecisely known probability function can be modeled by a family of all candidate probability distributions which are compatible with supporting data. This is the general idea of imprecise probabilities [7]. A practical way to represent a family of probability distributions is to specify its lower and upper bounds. As a consequence, the risk (probability) measure is not a point estimate, but varies in an interval. A number of imprecise probability models use this probability bounding strategy, including the probability box, random set, Dempster-Shafer evidence theory, interval probability theory, and fuzzy probabilities [8–10]. The approach of imprecise probability generally requires less subjective information than the purely probabilistic approach. It was argued that, from a frequentist point of view, the epistemic uncertainties can be more faithfully represented using the imprecise probability method [7,11].

Over the last decade many efforts have been directed towards structural reliability assessment using imprecise probability theory e.g. [12–18]. These work focused on new structures. Only limited studies have been conducted to apply the imprecise probability theory to reliability assessment for existing deteriorating structures. Sarveswaran et al. [19] examined the remaining capacity of corrosion-damaged steel beams. The thickness of corroded steel beams was represented by intervals to account for the large uncertainty in visual assessments of thickness loss. Interval probability theory was applied to calculate the approximate bounds for the probability of failure. In [20], the thickness of corroded steel elements was considered as imprecision that has upper and lower probabilities. Strength limit state was considered for the steel cables and girders of a cable-stayed bridge. Zhang et al. [21] considered marine corrosion of steel structures. The epistemic uncertainty of the bias function for the corrosion model was represented with different uncertainty models, including pure probabilistic method, interval modeling, fuzzy methods, and imprecise probability. The models were applied to find the bounds for the failure probabilities of a steel plate and a steel off-shore platform. Zhang et al. [22] modeled the atmospheric corrosion of steel structures with incomplete information. The analysis framework is based on the theory of imprecise probability. Copula is used to model the dependency between random variables. Ma et al. [23] considered the probabilistic prediction of corrosion damage in aging reinforced concrete bridges when the initial statistical parameters of random variables cannot be accurately obtained. A hybrid description of aleatory and epistemic uncertainties was proposed using the marginal integration. The methodology was demonstrated by a numerical example of corrosion damage prediction of an existing reinforced concrete bridge.

The purpose of this paper is to develop insight into the role of epistemic uncertainties on the durability reliability of corroding reinforced concrete (RC) structures. The study considers a sea bridge being constructed in the subtropical coastal region of China. With the advent of life-cycle engineering and sustainable decision-making, durability has become a major concern for large civil infrastructures. The model for predicting chloride penetration involves a number of variables that are strongly environmental and material dependent. These variables would need to be modeled as random variables in a probabilistic durability assessment. However, data collection for deterioration is very difficult. Only limited supporting data are available for estimating the statistical properties of these variables. The paper demonstrates how the epistemic uncertainties are modeled in the imprecise probability-based method and the purely probabilistic method. The impact of the epistemic uncertainties on the durability reliability of the structure is examined.

The concept of probability box and interval Monte Carlo simulation is described first. The corrosion model for chloride penetration is presented in Section 3, followed by the discussion of uncertainty modeling in durability analysis. Section 5 presents the reliability analyses using both the probability box method and the purely probabilistic method.

2. Probability box

Among the various mathematical models using the probability bounding strategy, we choose the probability box for formulating imprecise probability distributions [11]. The probability box is closely related with other imprecise probability methods, such as random set and Dempster-Shafer evidence theory [24,25]. For instance, a random set on the real line can be converted to a probability box (and vice versa) [11]. For our purpose, these two methods may be considered to be equivalent.

2.1. Basic notions

Let $F_X(x)$ denote the cumulative distribution function (CDF) for a random variable $X$. Suppose that the data is insufficient to define a unique probability measure. Instead, a closed interval $[F_X^{-1}(x), F_X(x)]$ can be found to bound the possible values of $F_X(x)$, i.e., $F_X(x) \leq F_X(x) \leq F_X(x)$. The two CDF’s $F_X(x)$ and $F_X(x)$ thus form the envelopes of the probability family
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