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From experiments to design: A probabilistic definition of design formulations from empirical and semi-empirical resistance models

Desde experimentos hasta diseño: una definición probabilística de formulaciones de diseño a partir de modelos de resistencia empíricos y semiempíricos

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Abstract

The definition of design equations from empirical or semi-empirical resistance models is a matter of relevance for structural engineering. In common practice, the limit states design approach predicts the direct application of partial safety factors to the resistance of the materials in order to obtain design formulations coherent with a prescribed level of reliability. As empirical or semi-empirical models are calibrated, adjusting empirical coefficients to fit a set of experimental data, the application of partial safety factors to material properties alone is not able to provide a correct estimation of structural reliability.

In the present paper, a methodology based on the Monte Carlo method for probabilistic calibration of empirical and semi-empirical resistance models is proposed. Its application related to the probabilistic calibration of the semi-empirical model proposed by *fib* Model Code 2010 for the estimation of laps and anchorages tensile strength in reinforced concrete structures is reported and discussed.

Keywords: Structural reliability; Empirical and semi-empirical models; Model uncertainties; Probabilistic calibration; Laps and anchorages

Resumen

La definición de las ecuaciones de proyecto a partir de modelos resistencia empírica o semiempírica es una cuestión de importancia para la ingeniería estructural. En la práctica común, el proyecto segun los estados límites prevee la aplicación directa de factores de seguridad parciales a la resistencia de los materiales, con el fin de obtener formulaciones de diseño coherentes con un nivel de fiabilidad prescrito. Como los modelos empíricos o semiempíricos se calibran ajustando los coeficientes empíricos para adaptarse a un conjunto de datos experimentales, la aplicación de factores de seguridad parciales a las propiedades de los materiales por sí sola no permite una estimación correcta de la fiabilidad estructural.

En el presente trabajo se propone una metodología basada en el método de Monte Carlo para la calibración probabilística de modelos de resistencia empírica y semiempírica. Su aplicación relacionada con la calibración probabilística del modelo semiempírico para la estimación de la resistencia a tracción de superposiciones y anclajes en estructuras de hormigón armado es reportada y comentada.

Palabras clave: Fiabilidad estructural; Modelos empíricos y semiempíricos; Incertidumbres del modelo; Calibración probabilística; Vueltas y anclajes

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1. Introduction

Commonly, in structural engineering design formulations must always comply with a prescribed reliability level. To this end, physical or empirical and semi-empirical resisting models should be properly calibrated by the application of consistent safety formats.

The resisting models based both on physical laws (e.g. equilibrium of forces and kinematic compatibility) and on semi-empirical or empirical formulations (e.g. [1,2]) fitted on experimental results are really frequent in structural engineering.

In the limit states semi-probabilistic design approach [3], the safety requirements are fulfilled applying partial safety factors accounting for material properties and geometry statistical variability and model uncertainties. Concerning the resisting models based on physical assumptions, the direct application of partial factors to materials strength leads to design expressions consistent with a specific reliability level. This does not happen in the case of empirical or semi-empirical resisting models that are based on experimental test set. In such kind of models, all the empirical coefficients embedded in the formulation are calibrated as best fitting on the experimental results and assuming mean values of material properties (i.e. the actual values measured during the experiment execution). In this case, it implies that the direct application of partial safety factors to materials strength does not lead to a proper evaluation of reliability.

In the literature, several methodologies for probabilistic assessment of physical, empirical and semi-empirical models are proposed [4–6]. In order to apply these theoretical procedures consistently, an accurate assessment of model uncertainties is necessary as proposed in [7–11].

However, a general and ease-to-apply procedure able to calibrate empirical or semi-empirical formulation in relation to a specific level of reliability is still not available and defined.

In the present paper a methodology based on the Monte Carlo method [12] for calibration of empirical and semi-empirical resisting models is proposed. This procedure is able to account for both statistical variability of material and geometric properties and the influence of the resisting model uncertainties. After the detailed description of the methodology, its application to the calibration of the semi-empirical model for laps and anchorages tensile strength evaluation suggested by Model Code 2010 [13] is proposed and commented.

2. Methodology for the assessment of design expressions from empirical or semi-empirical resisting models

In this section the methodological approach for probabilistic calibration of empirical and semi-empirical models is described.

The proposed methodology grounds on four main points:

- the individuation of the empirical or semi-empirical resisting model;
- the definition of the probabilistic model;
- the definition and characterization of the resistance random variable;
- the estimation of the fractiles of the resistance random variable and determination of the design expressions.

2.1. Individuation of the empirical or semi-empirical resisting model

In general, an empirical or semi-empirical resting model is calibrated grounding on a set of experimental results and the estimated value of the resistance R_{model} can be expressed in the following form:

$$R_{\text{model}} = C \cdot f(X_{1,m}, X_{2,m}, \ldots, X_{i,m}, \ldots, X_{K,m}) \cdot A,$$
$$i = 1, 2, \ldots, K \quad (1)$$

where C is best fitting empirical coefficient calibrated on the experimental database; X_i is a set of K random variables which plays a significant role in the resisting model ($i = 1, 2, \ldots, K$); $f(X_{1,m}, X_{2,m}, \ldots, X_{i,m}, \ldots, X_{K,m})$ is a function of the abovementioned random variables assumed with their mean or experimental value; A is a function of all the parameters that can be assumed as deterministic (e.g. geometry).

The value of R_{model} estimated by means of Eq. (1) should be intended as a mean resistance as it is calculated assumed mean or experimental material properties and empirical coefficients fitted on experimental tests. Then, the direct application of Eq. (1) for design purposes it is not correct as it is deprives of any safety assumption.

2.2. Definition of the probabilistic model

Once all the parameters that can influence the resisting model with their statistical variability are selected, the following vector of random variables X can be defined:

$$X = (X_1, X_2, \ldots, X_i, \ldots, X_K, \vartheta), \quad i = 1, 2, \ldots, K \quad (2)$$

The vector of random variables X includes also the model uncertainty random variable ϑ that should be calibrated base on the statistical assessment of the ratio between experimental results and model predictions according to [14]. The vector of random variables X can group both statistically independent and statistically dependent random variables.

All the random variables grouped in X have to be represented by their probabilistic distribution (i.e. PDFs and/or CDFs) which must be able to describe their statistical variability accurately.

Suggestions for the definition of the probabilistic model can be acknowledged by [14].

2.3. Definition of the resistance random variable

The resistance random variable can be evaluated in function of the vector X descending from Eq. (1) as follow:

$$R(X) = \vartheta \cdot C \cdot f(X) \cdot A \quad (3)$$

The expression reported by Eq. (3) is able to represent the random variability of the resistance accounting for material sta-