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Partial safety factor for resistance model uncertainties in 2D non-linear finite element analysis of reinforced concrete structures

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A B S T R A C T

This work evaluates the partial safety factor related to the resistance model uncertainties in non-linear finite element analyses (NLFEAs) for reinforced concrete structures. Various experimental tests concerning different typologies of structures with different behaviours and failure modes, i.e., walls, deep beams, panels, are simulated by means of appropriate two-dimensional finite elements (FE) structural models (i.e., plane stress configuration). Several FE structural models are defined for each experimental test to investigate the model uncertainty influence on the 2D NLFEAs of reinforced concrete structures in terms of global resistance, considering different modelling hypotheses to describe the mechanical behaviour of reinforced concrete members (i.e., epistemic uncertainties). Subsequently, the numerical results are compared to the experimental outcomes. Then, a consistent treatment of the resistance model uncertainties is proposed following a Bayesian approach. Specifically, the prior distributions of the resistance model uncertainties for the different modelling hypotheses are evaluated and then each one is updated on the basis of the data obtained from the other models to evaluate the posterior distributions. After that, the mean value and the coefficient of variation characterizing the resistance model uncertainties are identified. Finally, in agreement with the safety formats for NLFEAs of reinforced concrete structures, the partial safety factor related to the resistance model uncertainties is evaluated.

1. Introduction

In the last decades, non-linear finite element analyses (NLFEAs) have increasingly become the most common and practical instruments able to model the actual mechanical behaviour of structural systems, such as reinforced concrete elements, in any loading condition (i.e., service limit state (SLS) and ultimate limit state (ULS)). In this context, although several guidelines for NLFEAs have been recommended by [1–4] in order to assure an accurate calibration and definition of the structural FE model, the results from such complex modelling need to be properly processed in order to satisfy safety and reliability requirements for engineering purposes. To this aim, Bayesian finite elements have been proposed by [5] to take into account the model uncertainties for structural analysis. Contextually, different safety formats for NLFEAs have been proposed in literature by several authors [6–9] and international codes [10,11] as well as their applications have been discussed by [12–14]. In these safety formats, uncertainties regarding the material (i.e., aleatory uncertainties) and the definition of the structural model (i.e., epistemic uncertainties) should be properly addressed in order to derive reliability-consistent design values of the global structural resistances. With regard to the material uncertainty, the corresponding randomness is usually well known and assessed, whereas the model uncertainty (i.e., uncertainty mainly related to the definition of the resistance model) associated with NLFEAs is not typically simple to be evaluated due to the different modelling hypotheses for the definition of a non-linear FE structural model. In fact, the prediction of the actual structural response through NLFEAs is characterised by a certain level of uncertainty because any numerical model aims to describe the essential characteristics of the overall behaviour neglecting other aspects. As discussed by [7], structural elements which failed in compression or in bending (with under- and over-reinforced sections) or in shear, presented ratios between the resistances of experimental tests and of numerical simulations with a coefficient of variation ranging from 5% (flexural failure with under-reinforced cross-section) to 40% (shear failure due to crushing of concrete). Hence, the numerical model as well as the predicted response are just approximations of the real behaviour and of the actual response of a structural member. According to [15], for well validated models, the hypothesis of assuming mean value and coefficient of variation (COV) equal to 1 and to 0.1, respectively, may be considered realistic in order to take

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into account the model uncertainties. Nevertheless, it is also straightforward that, for reinforced concrete structures, the validation of a non-linear FE model with respect to the actual failure mode represents another important and difficult challenge. For this reason, JCSS Probabilistic Model Code [15] suggests coefficients of variation for model uncertainties of 0.15 and 0.25 for bending and shear models, respectively, associated to mean values equal to 1.2 for bending failure and to 1.4 for shear failure, respectively. However, bending and shear failures usually characterise the beam response and are not always distinguishable, particularly for complex geometries when 2D or 3D non-linear FE models are defined. In [16], a comprehensive procedure for the determination of model uncertainties of non-linear analyses is discussed highlighting the dependence on the failure mode with the proposal of a specific value of model uncertainties for punching of slabs. Therefore, all these research studies evidence the need to assess the model uncertainties by means of a comparison between simulations and experimental outcomes with the consequence that an in-depth characterization of the model uncertainties for NLFEAs of reinforced concrete structures is necessary to incorporate their effects on the global structural resistance assessment within the safety formats. In [17], it is proposed a method for NLFEA model uncertainty characterization distinguishing the possible failure modes, reproducing the experimental tests of 38 benchmark systems through numerical simulations. However, the assessment of the model uncertainties for calibration of a partial safety factor should also consider the different modelling hypotheses to run NLFEAs due to the different assumptions regarding the parameters that govern the equilibrium, kinematic compatibility and constitutive equations. In fact, different choices related to the described above parameters may lead to discordant results (i.e., epistemic uncertainty [18]).

With this aim, this work compares 25 experimental tests known from the literature, concerning different typologies of structures having different behaviours and failure modes (i.e., walls, deep beams, panels) in terms of global structural resistance with the numerical outcomes achieved by means of appropriate two-dimensional non-linear FE structural models (i.e., plane stress configuration). Several non-linear FE structural models are defined for each experimental test in order to investigate the influence of the model uncertainties on 2D NLFEAs of reinforced concrete members. Precisely, the assessment of the resistance modelling uncertainties in 2D NLFEAs, that belong to the group of the epistemic uncertainties, is herein based on the definition of nine (9) plausible structural models using different types of software and different mechanical behaviours for the reinforced concrete elements (i.e., modelling hypotheses [18]). Then, a consistent treatment of the resistance model uncertainties is proposed following a Bayesian approach. Specifically, the prior distributions of the resistance model uncertainties for the different structural models are evaluated and then each distribution is updated on the basis of the data obtained from the other models to evaluate the posterior distributions. Then, averaging the statistical parameters of the posterior distributions related to the different structural models, the mean value and the coefficient of variation characterizing the resistance model uncertainties are identified. Finally, in agreement with the safety formats for NLFEAs of reinforced concrete structures [10,11], the partial safety factor related to the resistance model uncertainties is evaluated and proposed as a function of the pre-assigned reliability level for new or existing structures, of the failure consequences and of the hypothesis of dominant or non-dominant resistance variable.

2. Uncertainties related to resistance models within the safety formats for NLFEAs

In general, the uncertainties in structural engineering can be classified in two families: aleatory and epistemic [18]. The aleatory uncertainties concern the intrinsic randomness of the variables that governs a specific structural problem, whereas the epistemic uncertainties are mainly related to the lack of knowledge in the definition of the structural model [18–21] and sometimes represented also by auxiliary non-physical variables/choices [18]. The safety assessment of a structural system by means of NLFEAs should account for explicitly both these sources of uncertainty.

Within the semi-probabilistic limit state method [22–24], the safety assessment of a structural system requires a reliable definition and characterization of the structural resistances, which increasingly often derive from NLFEAs. For this purpose, different safety formats have been proposed in the literature [6–11]. In particular, EN 1992 [10] defines a safety format based on the definition of the partial safety factors descending from representative values and design values of the material strengths (i.e., concrete compressive strength and reinforcement steel yielding strength). While, *fib* Model Code 2010 [11] provides three different methodologies for the assessment of the structural reliability: the probabilistic method, the global resistance method and the partial factor method. These different safety formats (with the exception for the partial factor method) allow the estimation of the design structural resistance R_d, that represents the global structural resistance of a structure with its behaviour and failure mode, as expressed by Eq. (1):

$$R_d = \frac{R_{rep}}{\gamma_R \gamma_{Rd}} \tag{1}$$

where R_{rep} denotes the value representative of the global structural resistance estimated by means of NLFEAs and in compliance with the selected safety format, γ_R is the partial safety factor accounting for the randomness of material properties (i.e., aleatory uncertainties) and γ_{Rd} represents the partial safety factor related to the modelling uncertainties (i.e., epistemic uncertainties). Therefore, the aleatory uncertainties are separated from the epistemic uncertainties within *fib* Model Code 2010 safety formats for NLFEAs [6,11,15]. The procedure for the estimation of the partial factor γ_R is suggested by the corresponding safety format. Conversely, the value of the partial safety factor for the resistance model uncertainties γ_{Rd} remains an object of investigation. In this context, EN 1992 [10] proposes to assume a value equal to 1.06 for γ_{Rd}. This value has been defined concerning the framework of non-linear analyses of concrete bridge decks and beams and not for other structural members (e.g., massive structures, walls, beams with variable geometry, panels etc.). More recently, *fib* Model Code 2010 [11] has suggested to assume different values of γ_{Rd} depending on the level of validation of the structural model. The γ_{Rd} factor equal to 1 may be adopted for models with no epistemic uncertainties (i.e., presence of evidences of model validation in the actual design conditions [11]). When structural models present, respectively, a low or a high level of uncertainties (i.e., difficulties in the definition of actual structural conditions due to unknown design situations) the values, set equal to 1.06 and 1.1, are proposed.

However, when NLFEAs have to be performed on structures having more complex geometry (that may differ from the simple case of the beam in the failure mode), the epistemic uncertainties related to the definition of the resistance model may be larger than expected. Therefore, an in-depth characterization of the partial safety factor γ_{Rd} needs to be addressed.

3. Methodology to assess the resistance model uncertainties and to estimate the partial safety factor

This section describes the methodology adopted in the present work for the assessment of the partial safety factor related to the resistance model uncertainties in the definition of 2D NLFEAs. As discussed by [25,26], the following aspects have to be considered in order to identify the resistance model uncertainties for NLFEAs:

– the database of the experimental data should contain, if possible, all