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Safety factor calibration for a new model of shear strength of reinforced concrete building beams and slabs

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ABSTRACT

When assessing existing structures, the availability of adequate safety factors, calibrated with the most accurate models, and for established target reliability indexes, is of critical importance in order to take the right decision regarding the maintenance/repair/strengthening interventions. In the case of shear resistance in reinforced concrete (RC) structures, when using the current design codes provisions for new constructions in assessment results that, in many cases, existing structures may be considered unsafe, implying large economic costs in strengthening or even dismantling. In this research, a proposal of safety factor relative to a recently developed model for shear strength, for elements with and without transversal reinforcement, based on a reliability-based calibration is presented. A formulation is proposed to determine the adequate strength factor for a selected target reliability index of the existing structure and desired remaining service life by means of a safety factor format, considering the load factors present in the Eurocodes. The calibration is carried out considering typical geometry and load ratios of building floors, as well as normal and high strength concrete. The derived safety factor is almost independent of the chosen remaining service life.

1. Introduction

The design process of a new concrete structure, or assessment of an existing one, should verify a limit-state condition of the form:

$$R_d \geqslant S_d \tag{1}$$

Being R_d and S_d the design values of the resistance and action-effects, respectively. The semi-probabilistic approach is the most common methodology used in practical applications. In this case, the action design value is computed by means of partial factors for loads, as e.g. Eq. (2) for the case of persistent or transient load situations. Here, $S_{G,ki}$ and $S_{Q,kj}$ are the characteristic values of the permanent action "*i*" and variable action "*j*", γ_{Gi} and γ_{Qj} are the partial safety factors for the permanent and variable actions. Variable load $j = 1$ is the leading one, while the accompanying loads $(j > 1)$ are affected by a combination factor Ψ_j, which is less or equal to 1.0.

$$S_d = \sum_{i=1}^{n} \gamma_{Gi} S_{G,ki} + \gamma_{Q1} S_{Q,k1} + \sum_{j>1}^{n} \gamma_{Qj} \Psi_j S_{Q,kj} \tag{2}$$

The design value of the resistance may be computed by means of partial safety factors applied to materials characteristic values, usually concrete strength and steel yielding strength, as shown in Eq. (3), where f_{ck}, f_{yk}, γ_C, γ_S are the characteristic compressive strength, yielding strength and partial safety factors of concrete and steel. Alternatively, the design resistance can be obtained by a strength reduction factor, as shown in Eq. (4). In this case, γ_R is a strength safety factor which is applied in a global form to the resistance model, this is equivalent to the inverse of the strength reduction factor (ϕ).

In general, partial load factors account for the possibilities of unfavourable deviation of the load from its representative value, uncertainties in modelling of the load and of its effects. Materials partial factors and strength reduction factor account for the possibility of unfavourable deviation of the material property from the specified value, resisting model uncertainty, the geometrical deviations not considered explicitly and, in some cases, the consequences of failure.

Eqs. (3) and (4) represent, respectively, the two currently most used approaches in which safety factors are defined depending on the materials or the resisting mechanism involved, e.g. shear and bending require different strength reduction factors.

$$R_d = R\left(\frac{f_{ck}}{\gamma_C}; \frac{f_{yk}}{\gamma_S}\right) \tag{3}$$

$$R_d = \frac{1}{\gamma_R} R(f_{ck}; f_{yk}) = \frac{1}{\gamma_R} R_k = \phi R_k \tag{4}$$

If the partial safety factors have been appropriately calibrated, the

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Table 1
Load and strength safety factors in ACI-318 and Eurocodes.

	ACI-318-02 [1]		Eurocodes [3,4]
	Main body	Annex C (prior 2002)	
Dead load factor	1.2	1.4	1.35
Live load factor	1.6	1.7	1.5
Shear strength reduction factor ($\phi = 1/\gamma_R$)	0.75	0.85	–
Concrete strength partial safety factor (γ_C)	–	–	1.5
Steel strength partial safety factor (γ_S)	–	–	1.15

required level of safety is deemed satisfied through the verification of Eq. (1). Strength reduction factors shall be used together with the same set of load factors considered in their calibration, in order to approach the target reliability. For example, in the 2002 version of ACI-318 [1], the load factors were modified to adapt them to the ASCE/SEI-7 [2] general provisions for minimum design loads in order to simplify the design process of structures with components of different materials, that required a recalibration of the strength reduction factor for shear, see Table 1. However, the alternative set of load and strength factors in Annex C of ACI-318 is allowed, if they are used together.

In ACI-318 the strength reduction factor also considers the brittle or ductile nature of the failure mode. As in the former, the element is more sensitive to larger variation of concrete strength in tension and compression and consequences of failure may be higher, hence a more conservative value of the resistance, i.e. a lower fractile, is needed to achieve the needed reliability.

On the other hand, Eurocodes 2 [3] and 1 [4] provide a set of partial safety factors for steel (γ_S) and concrete (γ_C) properties, together with a set of partial load factors. The code was calibrated for a yearly target reliability index of $\beta_1 = 4.7$, which is equivalent to a nominal probability of failure in 1 year of approximately 10^{-6} [5].

When dealing with the assessment and/or strengthening of an existing building, a question about the suitability of using the same partial safety factors of the design of new elements arises. In general, there is less uncertainty in the geometrical and material parameters and an increment of the safety level may require a much larger economic effort than to achieve the same increment in a new design. Additionally, the required remaining service life may be shorter than in new constructions.

Therefore, the definition of the target reliability level for assessing existing structures should be based on risk of failure and cost optimization; including repair interventions, losses due to malfunction, environmental and psychological effects. A framework for establishing the target reliability corresponding to a remaining service life is available in some codes, as ISO 13822 [6], ISO 2394 [7], and recommendations, such as fib [8]. Hence, economic optimization can be used to derive target reliability values. However, human safety levels based on individual and societal risk for ethical issues should also be considered in the process, as stated in Sýkora et al. [9], Tanner and Hingorani [10], Steenbergen et al. [11]. As concluded in Steenbergen et al. [11], the minimum levels related to human safety are often critical target reliabilities for existing structures.

After the target reliability index is defined, suitable and properly calibrated resistance models are needed, including the statistical definition of the model error. The particular case of assessing shear resistance in existing concrete elements has gained much attention recently, as the current design provisions have raised doubts regarding the safety of constructed facilities, implying that many structures are to be strengthened or dismantled. Furthermore, contrary to bending strength, whose resisting theory is well consolidated, there are currently several shear strength theories, based on different hypotheses and with different accuracy and complexity levels. In recent investigations, experimental tests have been conducted in existing structures or elements that were deemed unsafe according to current design provisions, e.g. Zwicky and Vögel [12], Bergström et al. [13]. In some cases, shear performance observed by experimentation was much better than the expected according to the provisions for new structures. The use of adequate non-linear computational models accounting for non-linear shear behavior have also shown similar results, Ferreira et al. [14,15]. Hence, it can be expected certain cost reduction in strengthening of structures or even no need of posting or substitution, after an advanced assessment of the existing safety level.

However, adequate nonlinear models for shear assessment are not always available, or it is not possible to systematically build a computational model for a large number of different structures in a network and perform the probabilistic analyses. Therefore, simpler models that are adequate for hand or spreadsheet calculations are useful in these cases. In addition, for practical and fast assessment application in a semi-probabilistic format, the strength reduction factors should be calibrated.

The objective of the present study is to propose adequate reliability-based design/assessment equations with properly calibrated safety factors for reinforced concrete beams and slabs of buildings, failing in shear, for a various target reliability indexes. The current method is restricted to shear failure taking place in sections that have not yielded previously in bending or axial force.

The paper is organized in the following way. Section 2 presents a statistical analysis of selected existing models for shear resistance in concrete members to define the most accurate and statistically define the corresponding model error. By the use of this model and after the definition of the sample set, Section 3 carries out the calibration process to define the safety factor, and the analysis of the results and discussion is presented in Section 4. Finally, the main conclusions are drawn in Section 5.

2. Shear resistance model

For an appropriate calibration of safety factors, the first step is to derive accurate design equations for the shear strength capacity of reinforced concrete beams, based on the available theoretical models, jointly with the statistical characterization of the random variable of the "model error". This random variable represents the ratio of the actual response to the model prediction and is characterized by a statistical distribution, its mean value (or bias ratio) and standard deviation (or coefficient of variation, CoV).

In this paper, a recently mechanical-based formulation for shear-flexure strength of reinforced concrete beams, proposed in Mari et al. [16], is used. This model assumes a combination of the four classical shear resisting mechanisms; namely, capacity of the uncracked compression chord (V_c), capacity of the diagonally cracked web (V_w) and the contribution of the transverse (V_s) and longitudinal reinforcements (V_l). The model provides a set of mechanistic derived closed-form equations for each action, here summarized in Table 2.

Table 2
Summary of simplified equations derived for the different shear contributing actions.

Compression chord	$v_c = \frac{V_c}{f_{ct}bd} = \zeta\left[(0.88 + 0.70v_s)\frac{x}{d} + 0.02\right]$	(7)
Cracked concrete web	$v_w = \frac{V_w}{f_{ct}bd} = 167\frac{f_{ct}}{E_c}\left(1 + \frac{2E_cG_f}{f_{ct}^2 d}\right)$	(8)
Longitudinal reinforcement	$v_s > 0 \rightarrow v_l = \frac{V_l}{f_{ct}bd} = 0.25\frac{x}{d} - 0.05$	(9a)
	$v_s = 0 \rightarrow v_l = 0$	(9b)
Transversal reinforcement	$v_s = \frac{V_s}{f_{ct}bd} = 0.85\rho_w\frac{f_{yw}}{f_{ct}}$	(10)