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A PROCEDURE TO DERIVE PARTIAL SAFETY FACTORS IN TEXTILE-REINFORCED CONCRETE MEMBERS

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Abstract. In the last decades, modern technological and research developments of textile-reinforced concrete have led to extensive applications in building and civil engineering structures all over the world. Examples of textile-reinforced concrete can be found in retrofitting of existing buildings, facade slabs or bridges. Despite its potential, the widespread use of textile-reinforced concrete remains still limited. This is partly explained by the lack of a consistent design framework since conventional design methods used for other materials (e.g., steel reinforced concrete) cannot be directly applicable to textile-reinforced concrete. Thus, procedures to derive partial safety factors for textile-reinforced concrete would be a major step forward towards a regular procedure for the design of structural members made of this material.This paper offers a general procedure to determine safety factors. The approach is illustrated with a bending design example of a textile-reinforced concrete facade slab. The example is calculated in a recently developed software package for structural reliability analysis built in the statistical programming language *R*. For the derivation of safety factors, initial data is required, which can be obtained from experimental or numerical tests or from literature. The paper includes the basics of data evaluation as well as the statistical characterisation of data extracted from literature.

Keywords: Partial safety factor, R-package, reliability-based methods, textile reinforced concrete.

1. Introduction

In the last decades, encouraged by modern technological and research developments, textile-reinforced concrete (TRC) has emerged as a promising alternative to conventional steel reinforced concrete (e.g., [1–5]). Examples of TRC can be found in multiple structural applications as in retrofitting and rehabilitation of existing reinforced concrete structures, facade slabs or bridges. In Albstadt-Ebingen (Germany), an innovative bridge with a span of 15 meters is a well-known example of a structure made of TRC [6].

Besides the well-defined material properties, high strength-to-weight and stiffness-to-weight ratios, non-metallic reinforcements, such as carbon or glass, are insensitive to corrosion [7]. Consequently, cover requirements of the reinforcement can be reduced to minimum static values, allowing to decrease the overall thickness of TRC elements to 10-30 mm [8]. In addition, since no passivation of the reinforcement is required, a low-clinker content cement can be also used allowing to reduce the environmental footprint of the material regarding its CO_2 emissions [8].

Despite the potential of TRC, its widespread use remains still limited. This is partly explained by the lack of a consistent design framework since conventional design methods used for other materials, such as steel reinforced concrete, cannot be directly applicable to TRC due to its distinct mechanical behavior. Normally practical applications of TRC require a proof of usability or a specific approval. To this, building authorities may request extensive load-bearing tests that tend to be complex, time-consuming, costly, and can even lack consistent specifications (e.g., [8–11]). To overcome such difficulties, structural designers have long needed a suitable safety format not only for the design of TRC, but also for the reliability assessment of structural systems and components, as previous research studies have showed (e.g., [4, 10, 12]).

This paper offers a general procedure to determine partial safety factors based on structural reliability methods for structural members made of TRC. The procedure is illustrated using a bending design example of a facade slab made of TRC. The example is calculated in a recently developed software package for structural reliability analysis built in the statistical programming language *R* [14]. This open-source package has been developed in the context of an ongoing research initiative promoted by the German Federal Ministry for Economic Affairs and Energy (BMWi) with the goal to develop a general standard for deriving partial safety factors based on probabilistic methods (i.e., Levels II and III) and to establish it in the form of a Guideline. Ultimately, this Guideline aims to facilitate and promote the use of reliability-based approaches among structural engineering practitioners and scientific communities [15, 16].

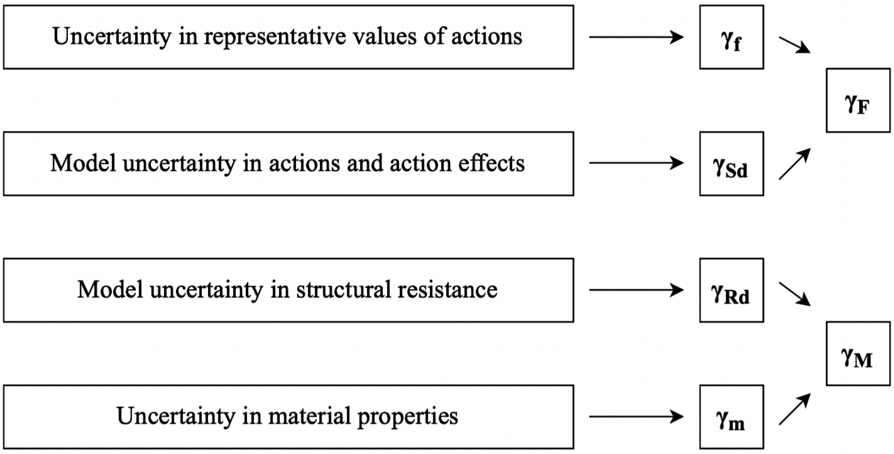

Figure 1. Relation between individual partial factors (adapted from EN1990 [13]).

2. Deriving partial safety factors (PSF) for TRC

2.1. Brief overview on the code safety format for structural components

It is widely acknowledged that the traditional engineering approach to deal with uncertainty and risk in structural engineering has been to apply safety factors in design calculations [17]. Modern structural design codes, such as Eurocodes [13, 18] and *fib* Model Code [19], incorporate probabilistic reasoning in the selection of safety elements (i.e., resistance, actions or partial material factors) with the goal to ensure that the reliability levels for representative structures in design do not exceed an acceptable target (or threshold) reliability level. To this, partial safety factors for different resistance and action variables, γ_M and γ_F respectively, need to be calibrated (e.g., [13, 20, 21]).

In addition, limit state verifications can be made with the design values of basic variables (see Figure 1). Current design and examination procedures for the ultimate limit state are based on the verification of the inequality given by Equation (1):

$$R_d \geq E_d \tag{1}$$

where R_d is the corresponding design value of the resistance and E_d is the design value of the internal force at the cross-section being analysed. Typically, the R_d value depends on partial factors applied to material strength variables γ_M which is influenced by the factor for model uncertainty in structural resistance γ_{R_d} and by the factor for uncertainty in material properties γ_m. The E_d value depends on partial factors applied to action variables γ_F which is influenced by the factor for model uncertainty in actions and action effects and the factor for uncertainty in representative values of actions γ_f (see Figure 1).

In principle, safety factors for resistance variables shall account for uncertainties in the modelling of material properties, geometric variables and uncertainties related to the model under consideration [22]. Recently, Yu et al. [8] highlighted that in addition to the basic uncertainties, these safety factors should also account for approximations and uncertainties in the safety format calibration. Safety factors for action variables should consider uncertainties in the values of actions and uncertainties related to the models of actions and action effects.

Like the considerations adopted for conventional steel reinforced concrete, also for TRC, the design values of basic variables shall be defined through partial safety factors for resistance variables (in the design of TRC these factors are commonly expressed as γ_T) and action variables γ_F.

As it is explained in [8], to define a safety format for TRC structures, only the partial safety factors related to the resistance need to be calibrated, while the partial safety factors for action variables γ_F from Eurocodes [13, 18] can theoretically be maintained.

2.2. Brief overview on code calibration procedures

Code calibration refers to that particular activity that is exercised when some superior method is applied to assign values to the variables of a code format such that a specific design code is formulated [23]. In the past, for example in Eurocodes [13, 18], calibration procedures were based on the so-called Level I methods (i.e., deterministic, historical and empirical methods) where the code calibration was also deterministic, historical and empirical [21]. Nowadays, due to several pioneering calibration efforts, there is broad agreement on the procedure to be followed for code calibration. For example, inspired by the work of Lind [24], Baker [25], Hawrenek & Rackwitz [26] and Ellingwood et al. [27] among others, Melchers [20] recently presented a general formulation for probabilistically-based code calibration (see Figure 2) where a set of essential steps are proposed. These are: (1) define scope, (2) select calibration points, (3) (analyse) existing design code, (4) define limit states, (5) determine statistical properties, (6) apply method of reliability analysis, (7) select target safety index (or reliability index), (8)

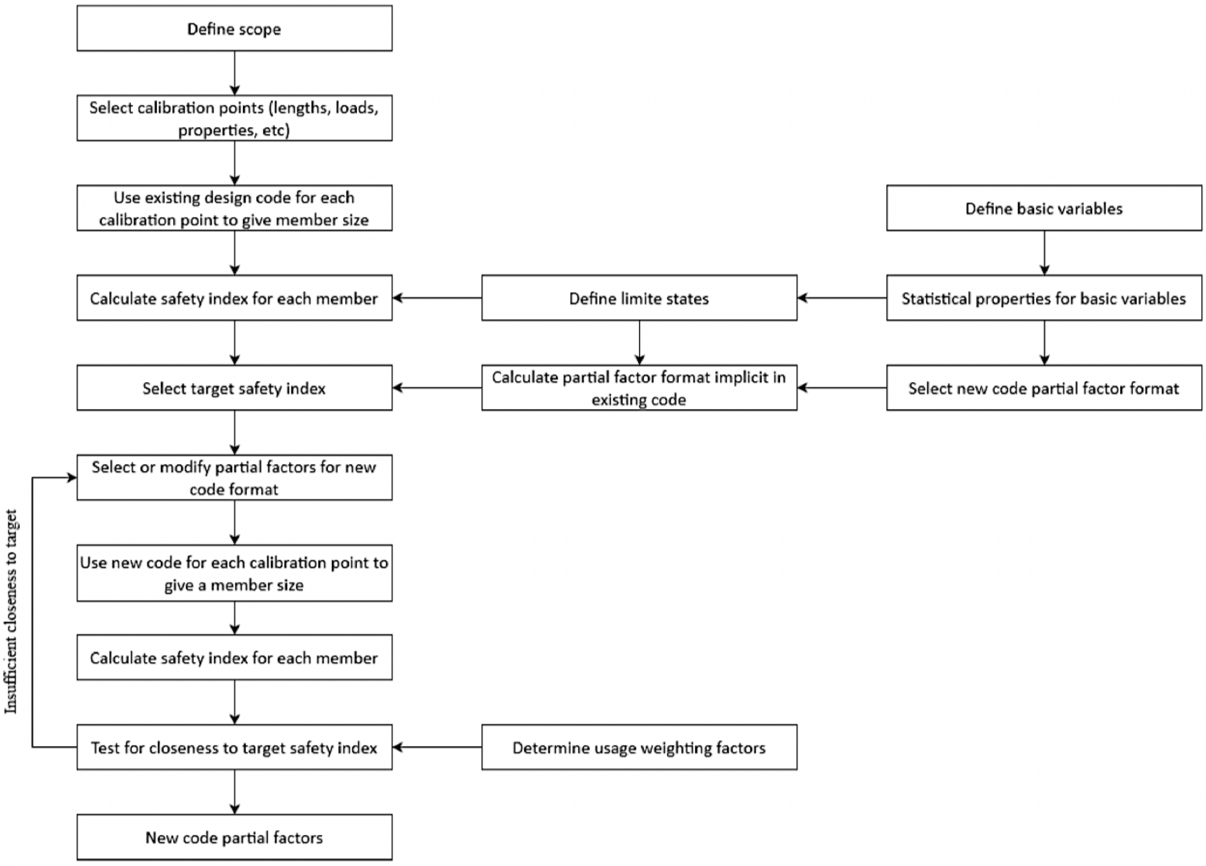

Figure 2. Flowchart for calibration of code safety-checking format [20].

observe partial factor format implicit in existing code, and (9) select partial factors.

The iterative nature of this general formulation seems to be in line with the principles adopted in modern structural codes. In current Eurocodes [13, 18], the proposed safety factors are based on the so-called Level II methods using First-Order Second Moment methods. As explained in [21], the primary assumption of these methods is the independent load combination where a load reduction occurs. This is implemented by sensitivity factors of actions and resistance (i.e., α_E and α_R, respectively), which decrease the target safety index β_T and cause a load reduction. It is highly unlikely that, in this load combination, the highest permanent load and the highest variable load occur simultaneously. Here, the partial safety factors are set by minimizing Equation 2 in all feasible design cases (i.e., in all materials and in permanent-variable load proportion). In other words, for a given range $1, \dots, m$ of calibration points, the safety factors that best approximate a uniform target safety level β_T can be obtained, in principle, by minimising the value of a measure of 'closeness to a target safety level. The approach aims to minimize the weighted least-squares error in β_T:

$$S = \sum_{i=1}^{m} \left(\beta_T - \beta_{Ci}\right)^2 w_i \tag{2}$$

where β_T is the target safety level (with nominal failure probability $p_{fT} = \Phi(-\beta_T)$) and β_{C_i} is the nominal reliability index for a given calibration point i (with target failure probability $p_{fCi} = (-\beta_{Ci})$). The term w_i denotes the weighting factor accounting for the importance of the calibration point relative to design practice, which should result in $\sum_{i=1}^{m} w_i$. As Melchers [20] emphasised, the safety factors are not constant for a given code safety-checking format and given value of β_T. For normal design, it is convenient for the safety factors in the code safety-checking format to be constant, at least over large groups of design-checking situations. To achieve this, some deviation from β_T is to be expected. Hence, the selection of appropriate partial factors involves a certain amount of subjective judgement.

It should be noted that to determine the partial factors for the new design code-checking format, trial values of the safety factors are used to calculate β_{Ci} for each calibration point i [20]. By repeated trial and error, and perhaps by (arbitrarily) assigning values to one or more partial factors, the set of partial factors minimizing Equation 2 can be obtained. These values will be then the safety factors in the new generation code safety-checking format.

Finally, it should be also mentioned that the use of full probabilistic methods − the so-called Level III methods − has not been implemented in modern structural codes yet; however, the use of these methods is being considered in the second generation of Eurocodes being under development since 2015 [28].

2.3. Proposed methodology to derive partial safety factors for TRC

Considering the existing approaches for code calibration (see Sections 2.1. and 2.2.), a general methodology to derive partial safety factor for TRC is proposed:

1. Define the basic random variables that are relevant for the investigated design case and identify all the parameters that are deterministic.
2. Define all the statistical properties for all the basic random variables and specify all the deterministic values.
3. Specify the limit state function for the investigated design case. It should be noted that normally the following verification is defined $M_{Ed} = M_{Rd}$.
4. Assign a set of possible values for the partial safety factor γ_T being investigated. Note that this factor shall be higher than 1.
5. Specify the target safety index β_T (e.g., $\beta_T \geq 3.8$).
6. Calculate the failure probabilities and the corresponding reliability indexes β_i for the set of values specified for the partial safety factor (Step 4). To this, different reliability assessment methods (i.e., Level II or Level III methods) can be used.
7. Evaluate the reliability indexes β_i obtained in Step 6. The goal is to attain a β_i-value close to the selected target safety level β_T (e.g., $\beta_T \geq 3.8$). If the reliability index β_i is smaller than the target level β_T, the partial safety factor γ_T being investigated shall be increased. Otherwise, if the reliability index β_i is higher than the target level β_T, the partial safety factor γ_T shall be decreased. Repeat step 6 until the β_i-value is close to the target level β_T.

Here it is important to evaluate if the partial safety factor γ_T being investigated for a specific design case (e.g., partial safety factor γ_T for bending) has an influence on the value of M_{Rd}. For example, in the case of bending, it should be evaluated if there is a (theoretical) failure mode in the reinforcement (tension zone) or in the concrete (compression zone). If there is a failure mode in the concrete, certain parameters can lead to values with no influence on the partial safety factor γ_T.

3. Practical example

3.1. Methodology

In this numerical example a facade slab under bending is chosen to demonstrate the derivation of a partial safety factor in a TRC member. As described in the previous section, Step 1 entails the selection of basic random and the identification of all the variables and parameters. The static system and the respective geometric parameters were selected from [10] and are illustrated in Figure 3:

Then, in Step 2 all the basic random variables as well as the deterministic parameters were specified. For reasons of simplicity and inspired by [10], the following basic variables were selected for the characterisation of the resistance side:

- Model uncertainty for flexural bending for TRC members θ_R
- Flexural depth d
- Concrete compression strength $f_{c,cyl}$
- Strain of concrete ε_C
- Textile reinforcement strength f_t
- Modulus of elasticity of textile reinforcement E_t

Follows the definition of the statistical properties for the investigated design case. As well as in Step 1 the chosen values are chosen in comparison to those which are used in [10]. The unknown partial safety factor is γ_T. To specify the design case (Step 3), the limit state function was also taken from [10] with the constant approach for stress-strain curve of the concrete regarding to Eurocode 2 [18].

$$M_{Ed} \leq M_{Rd} \tag{3}$$

In Step 4, the set of values for the partial safety factor γ_T was chosen between 1.15 (safety factor of steel rebars $\gamma_S = 1.15$.) and 1.5. Then, the target safety level β_T was chosen so that $\beta_T \geq 3.8$ (Step 5). Next, in Step 5, the failure probabilities p_f and the corresponding reliability indexes β_i for the specified design case were calculated with suitable probabilistic-based methods. For this numerical example, a Level II method was selected − the *First-Order Reliability Method* using the classic algorithm of Rackwitz and Fiessler [29, 30]. Finally, Step 6 entails the evaluation of the β_i-values. This evaluation is discussed in the following section.

3.2. Results of parameter study

As described above, the goal of this exercise is to find a suitable partial safety factor which satisfies the requirements for safety in codes. Normally, this requires a parameter study with variation of the unknown partial safety factor. The results of this parameter study give an indication of the value of the unknown partial safety factor (see Figure 4).

Figure 4 shows that the reinforcement ratio ρ_l has an influence on the reliability level. For reinforcement ratios of $\rho_l \geq 0.6\,\%$ there is no influence of the chosen value for γ_T. Furthermore, there is a difference if the (theoretical) failure mode is in compression (concrete) zone or in the tensile (textile reinforcement) zone. For a failure mode in reinforcement, a partial safety factor γ_T of 1.3 or higher, reach the defined target safety level ($\beta_T \geq 3.8$). For a failure mode in concrete, a smaller γ_T of 1.15, satisfies the defined target safety level ($\beta_T \geq 3.8$).

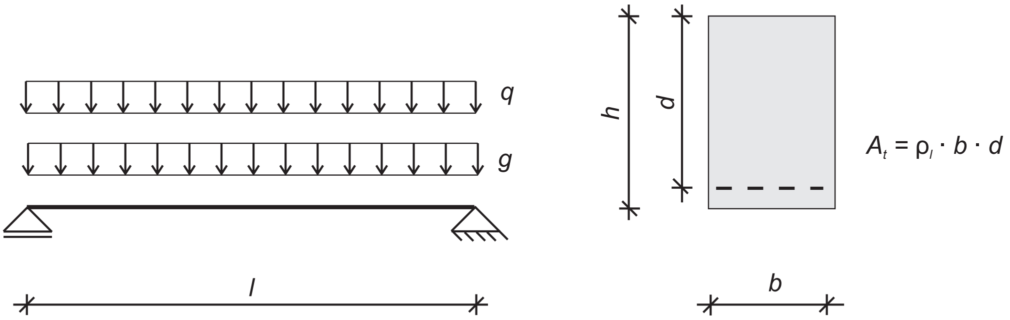

Figure 3. Chosen boundary conditions for [10] a) static system and b) geometric parameters. .

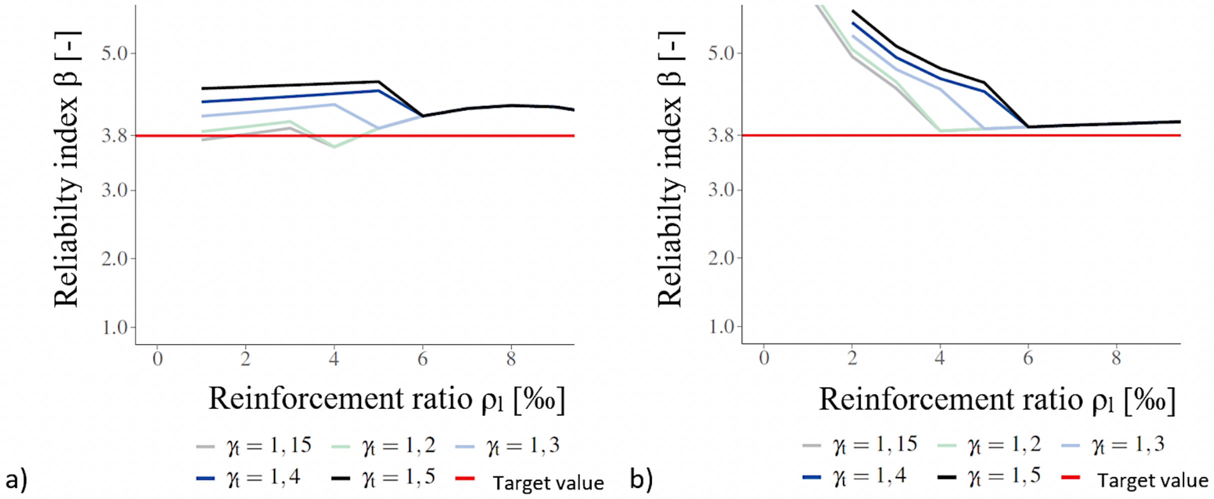

Figure 4. Parameter study for the bending design case for different reinforcement ratios and with target safety level β_T (red line): a) failure mode of reinforcement and b) failure mode of concrete.

Despite not being a generalised design case, the investigated example illustrates the procedures required to derive a partial safety factor for a structural member made of TRC. For general partial safety factor, broader parameter studies shall be conducted.

4. Conclusions

Despite the potential of TRC as an alternative to conventional steel reinforced concrete, its widespread use is still limited due to the lack of a consistent design framework for code calibration. To overcome such limitation, this study proposes a generic methodology to derive partial safety factors for structural members made of TRC. The feasibility of the methodology was demonstrated by means of a generic bending design example. Despite being applied to a specific failure mode, the generic methodology can be further extended to derive partial safety factors of TRC members for different failure modes. The proposed methodology will be further addressed and extended in a new guideline being currently under development in Germany. Finally, this study has highlighted that there is a need for more universal parameter studies to derive partial safety factors in European codes.

This study can give a high-level methodology consisting of six steps. Further research work shall be done towards a more detailed methodology for the calibration of code safety-checking. This is particularly relevant for the universal derivation of new partial safety factors in structural engineering. In addition, further parameter studies with a major range of parameters (e.g., different ranges of concrete strength, different ranges of flexural depth, among others) shall be conducted to derive such universal partial safety factor for codes.

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