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Probabilistic Assessment of Laps and Anchorages Strength in Reinforced Concrete Structures

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Abstract. In common practice and in design codes, the evaluation of laps and anchorages strength in reinforced concrete structures is performed by means of empirical or semi-empirical equations. These models couple the knowledge coming from both the experiments and the physical assumptions related to the actual resisting mechanism. In *fib* Model Code 2010 an efficient semi-empirical resisting model for the evaluation of laps and anchorages strength has been proposed. However, such kind of model should be calibrated referring to the levels of reliability required by the design codes in order to use it for design purposes and structural verifications. In the present paper, a consistent calibration procedure based on Monte Carlo method is used for the probabilistic assessment of the abovementioned semi-empirical model, accounting for both aleatory and epistemic uncertainties. Then, the design formulation is defined according to a specific level of reliability, and its application for the calculation of the required laps and anchorages length in reinforced concrete structures is commented. Finally, the comparison with the provisions of Eurocode 2 and *fib* Model Code 2010 is proposed and discussed.

1. Introduction

The resisting models can be based both on physical laws (e.g., equilibrium of forces and kinematic compatibility [1]) and on semi-empirical or empirical formulations (e.g. [2]-[4]) calibrated on experimental results.

In the limit state semi-probabilistic design approach [5], the safety requirements are fulfilled by means of partial safety factors accounting for material properties, geometrical 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 almost consistent with a specific level of reliability. For the empirical or semi-empirical resisting models, the direct application of partial safety factors within the formulation does not lead to an accurate assessment of the design expressions. In fact, empirical and semi-empirical resisting models are calibrated basing on the experimental tests [6], and by means of empirical coefficients embedded in the formulation. These coefficients are adjusted in order to achieve the best fitting between the model predictions and the experimental outcomes. Furthermore, empirical and semi-empirical coefficients are calibrated basing on the mean values (i.e., observed during the experiments) of material properties. Then, they have significance only when mean values of material properties are considered within the formulation. This implies that the direct application of partial safety factors to materials strength does not allow a proper evaluation of the level structural reliability without a proper probabilistic calibration of the model accounting for aleatory and epistemic uncertainties. Several approaches and methodologies for the consistent application of reliability analysis in the design practice are widely discussed by [7]-[11]. In the present work, the calibration of the semi-empirical model for laps and anchorages tensile strength evaluation suggested by *fib* Model Code 2010 [12] is described. A methodology based on the Monte Carlo method [14] for calibration of empirical and semi-empirical resisting models is proposed. The procedure is able to account for both statistical variability of material and geometric properties (i.e., aleatory uncertainties) and the influence of the resisting model uncertainties (i.e., epistemic uncertainties). Finally, the reliability-based expression evaluated for laps and anchorages strength with the proposed methodology is compared with the provisions of *fib* Model Code 2010 [12] and EN 1992-1-1 [13].

2. Laps and anchorage strength in fib Model Code 2010

Within *fib* Model Code 2010 [12], the evaluation of laps and anchorages tensile strength f_{st} is performed by means of the semi-empirical model proposed by [15] that is a modification of the approach suggested in [16], based on the literature studies [17]-[18]. The best-fitting semi-empirical expression for laps and anchorages strength estimation, which is calibrated on a large set experimental results [19], is represented by Eq.(1):

$$f_{st,Model} = 54 \cdot \left(\frac{f_{cm}}{25}\right)^{0.25} \left(\frac{l_b}{\Phi}\right)^{0.55} \left(\frac{25}{\Phi}\right)^{0.2} \left[\left(\frac{c_{\min}}{\Phi}\right)^{0.25} \left(\frac{c_{\max}}{c_{\min}}\right)^{0.1} + k_m K_{tr}\right] \quad (1)$$

where f_{cm} is the mean concrete compressive strength (or the actual compressive strength coming from experiments); l_b is the lap/anchorage length; Φ is the bar diameter; concrete covers c_{min}, c_{max} and effectiveness coefficient k_m are evaluated according to Figure 1(a-b). The coefficient K_{tr} accounts for the effect of confinement provided by shear links/stirrups situated along the lap or anchorage, and it can be calculated as follows:

$$K_{tr} = \frac{n_l n_g A_{sv}}{(l_b \Phi n_b)} \quad (2)$$

where n_l is the number of legs of a link/stirrup; n_g is the number of groups of links/stirrups; A_{sv} is the transverse area of each leg of a link/stirrup; n_b is the number of individual anchored bars or pairs of lapped bars.

The assessment of Eq.(1) has been performed on an experimental database counting more than 800 tests on laps and anchorages coming from American (ACI) and European investigations [19]. In *fib* Bulletin N°72 [15] the following limits for Eqs.(1)-(2) are provided, as they represent also the limits of the mentioned above database:

- 15 MPa $\leq f_{cm} \leq$ 110 MPa;
- $K_{tr} \leq 0.05$;
- $0.5 \leq c_{min}/\Phi \leq 3.5$ and $c_{max}/c_{min} \leq 5$;
- $l_b \geq 10\cdot\Phi$;
- $25/\Phi \geq 2$;

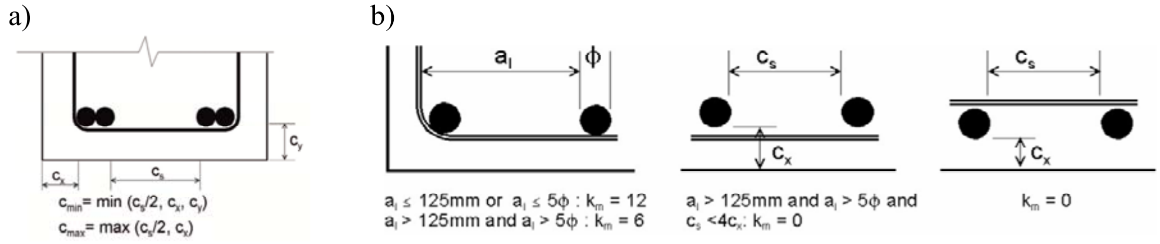

Figure 1. Assessment of concrete cover in Eq. (1) (a) and of the effectiveness of shear links (b).

3. Probabilistic calibration

In order to perform the probabilistic calibration of the semi-empirical model presented in Section 2, the main sources of uncertainties should be analysed.

In particular, the uncertainties affecting a resisting model can be grouped in two families: aleatory and epistemic. The aleatory uncertainties are related to the randomness of the variables that govern a specific resisting mechanism, whereas the epistemic uncertainties are mainly due to the "lack of knowledge" in the definition and calibration of the resisting model and the experimental tests [20]-[21]. The probabilistic calibration of a resisting model should explicitly account for both these families of uncertainty.

3.1. Definition of the probabilistic model

First of all, the main random variables affecting the resisting model should be identified. The concrete compressive strength is the random variable from which the laps and anchorages tensile strength strongly depends. The other parameters involved in Eq. (1) can be reasonably assumed as deterministic. Another important variable that should be accurately assessed is the model uncertainty random variable ϑ that, according to JCSS PMC [21], can be defined as:

$$\vartheta = \frac{R(X,Y)}{R_{Model}(X)} \tag{3}$$

where:

- $R(X,Y)$ is the actual resistance (e.g., estimated from laboratory tests);
- $R_{mod}(X)$ is the resistance predicted by the model;
- X is a vector of basic variables included into the resistance model;
- Y is a vector of variables that may affect the resisting mechanism, but are neglected within the model (e.g., variables whose influence is still not completely clear or widely assessed).

The model uncertainty random variable ϑ should be calibrated based on the statistical assessment of the ratio between experimental results and model predictions according to [22]:

$$\vartheta_h = \frac{R_{Experimental,h}}{R_{Model,h}} \tag{4}$$

where $R_{Experimental,h}$ and $R_{Model,h}$ are respectively the h-th experimental outcome and model prediction, and ϑ_h is the h-th realization of the random variable ϑ [23].

In the present investigation, the following probabilistic model is assumed:

- f_c is the cylinder compressive strength random variable. According to *fib* Model Code 2010 [12], the statistical variability of f_c can be described by means of a log-normal distribution with coefficient of variation V_c equal to 0.15 and mean value equal to f_{cm} depending on the concrete strength class (Table 1).
- ϑ is the resisting model uncertainty random variable. The assumed mean value μ_ϑ and the coefficient of variation V_ϑ are listed in Table 1 according to the statistical investigation proposed by [24]. Complying with [24], [12] and [22], ϑ can be described by means of a log-normal distribution.

The other parameters involved in Eqs.(1)-(2) are herein assumed as deterministic.

Table 1. Probabilistic distribution function and statistical parameters for the random variables affecting the resisting model for laps and anchorages tensile strength.

	Ref.	Mean value	Coefficient of variation	Distribution function
Concrete compressive strength (f_c) [MPa]	[12], [22]	f_{cm}	0.15	Log-normal
Model uncertainty (ϑ) [-]	[24]	0.98	0.13	Log-normal

3.2. Definition of the resistance random variable

In the following, the procedure for the probabilistic calibration of Eq.(1) is explained in details. First of all, Eq.(1) can be rewritten, in sake of simplicity, as follows:

$$f_{st,\mathrm{Model}} = R_{Model} = 54 \cdot f_{cm}^{0.25} \cdot g(\phi, \mathrm{l_b}, c_{\min}, c_{\max}, K_{tr}) \tag{5}$$

with:

$$g(\phi, \mathrm{l_b}, c_{\min}, c_{\max}, K_{tr}) = \left(\frac{1}{25}\right)^{0.25} \left(\frac{l_b}{\Phi}\right)^{0.55} \left(\frac{25}{\Phi}\right)^{0.2} \left[\left(\frac{c_{\min}}{\Phi}\right)^{0.25} \left(\frac{c_{\max}}{c_{\min}}\right)^{0.1} + k_m K_{tr}\right] \tag{6}$$

Eq.(5) can be written as a function of the concrete compressive strength random variable f_c and according to Eq.(3) as follows:

$$R(f_c, \vartheta) = \vartheta \cdot R_{Model}(f_c) = \vartheta \cdot 54 \cdot f_c^{0.25} \cdot g(\phi, \mathrm{l_b}, c_{\min}, c_{\max}, K_{tr}) \tag{7}$$

where $R(f_c,\vartheta)$ can be denoted as the resistance random variable, and it depends on the concrete compressive strength random variable f_c (which represents the influence on the resisting model of the aleatory uncertainty), and on the model uncertainty random variable ϑ (which represents the influence on the resisting model of epistemic uncertainty).

In order to perform the probabilistic calibration of Eq.(5), another auxiliary random variable Z should be introduced as follows:

$$\mathrm{Z}(f_c, \vartheta; f_{ck}) = \frac{R(f_c, \vartheta)}{R_{Model}(f_{ck})} = \frac{\vartheta \cdot 54 \cdot f_c^{0.25} \cdot g(\phi, \mathrm{l_b}, c_{\min}, c_{\max}, K_{tr})}{54 \cdot f_{ck}^{0.25} \cdot g(\phi, \mathrm{l_b}, c_{\min}, c_{\max}, K_{tr})} = \frac{\vartheta \cdot f_c^{0.25}}{f_{ck}^{0.25}} \tag{8}$$

where: $R(f_c,\vartheta)$ is the resistance random variable according to Eq.(7); $R_{Model}(f_{ck})$ is the semi-empirical model described by Eq.(5) expressed as a function of the 5% characteristic concrete compressive strength f_{ck}. Commonly, the resisting models proposed by the Codes [12]-[13] are based on the 5% characteristic compressive strength of concrete. Then, the definition of the auxiliary random variable Z allows, at the end of the probabilistic calibration, to define a reliability-based design equation expressed as a function of f_{ck} complying to the practice of the Codes.

3.3. Monte Carlo simulation

It is possible to generate a large sample of the population of the auxiliary random variable $Z(f_c,\vartheta;f_{ck})$ by means of Monte Carlo technique [14]. In the present paper, a number of samples equal to 10^6 has been generated adopting the direct Monte Carlo sampling [14] from the probabilistic distributions of the basic random variables listed in Table 1. The associated relative frequency function is reported in Figure 2.

The Chi-square test with 5% level of significance has been performed confirming that hypothesis of log-normality of the variable $Z(f_c,\vartheta;f_{ck})$. Hence, the auxiliary random variables $Z(f_c,\vartheta;f_{ck})$ can be described by means of log-normal distributions having mean values equal to 1.04 and coefficient of variation (*C.o.V.*) equal 0.14, respectively (Figure 3(a-b)).

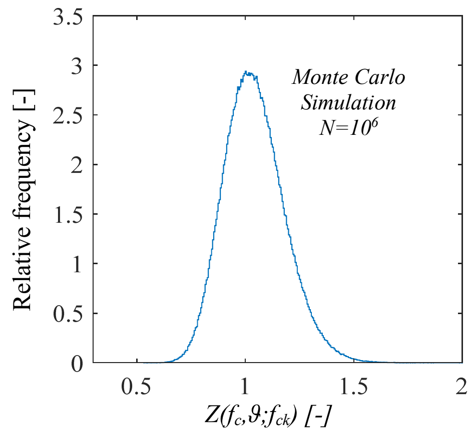

Figure 2. Relative frequency for the Monte Carlo simulation of the auxiliary random variable $Z(f_c,\vartheta;f_{ck})$ in the hypothesis of 10^6 samples.

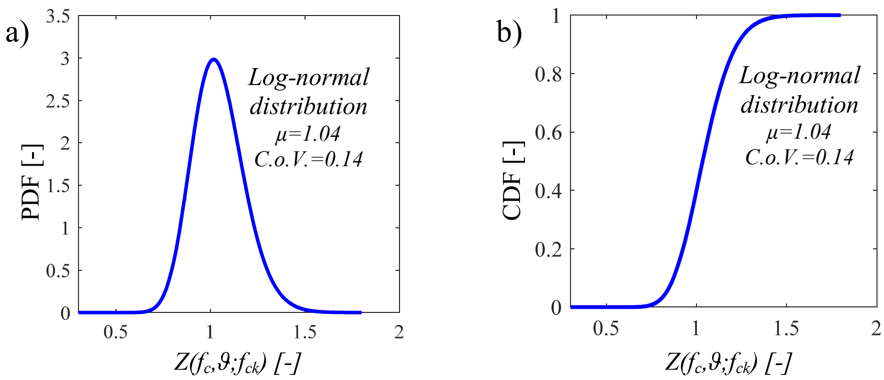

Figure 3. Log-normal distribution (PDF (a) and CDF (b)) representing the auxiliary random variable $Z(f_c,\vartheta;f_{ck})$.

3.4. *Definition of the design equation for laps and anchorages tensile strength*

In order to define relationships useful for design purposes, it is necessary to assess particular quantiles from the auxiliary random variable. This can be performed defining the following probability:

$$P[Z(f_c,\vartheta;f_{ck}) \leq \zeta_p] = p \tag{9}$$

where ζ_p is the quantile related to a certain probability not to be exceeded by the random variable $Z(f_c,\vartheta;f_{ck})$; p represents the probability of not exceedance for the value ζ_p. In reliability analysis and according to international codes [12]-[13], [25], the following quantiles of $Z(f_c,\vartheta;f_{ck})$ are commonly estimated:

- 50% quantile ζ_m, setting $p = 0.5$;
- 5% characteristic value ζ_k, setting $p = 0.05$;
- design value ζ_d, setting $p = \Phi(-\alpha_R \cdot \beta)$;

where β denotes reliability index [26], α_R represents the first order reliability method (FORM) correction factor (assumed equal to 0.8 for dominant resistance variables) [26] and Φ is the cumulative standard normal distribution. The quantiles ζ_m, ζ_k and ζ_d of the random variable $Z(f_c,\vartheta;f_{ck})$, with $p=0.5, 0.05, \Phi(-\alpha_R \cdot \beta)$ not to be exceeded are reported in Table 2. The design value ζ_d is estimated assuming the reliability index $\beta = 3.8$, for ordinary structures with 50 years' service life [12], [25], [27].

Table 2. Probabilistic coefficients (i.e., quantiles of auxiliary random variable Z) for $Z(f_c,\vartheta;f_{ck})$ and associated probabilities of not exceedance.

Probabilistic coefficients	Random variable $Z(f_c,\vartheta;f_{ck})$ [-]	Probability of not exceedance [-]
ζ_m	1.034	0.5
ζ_k	0.831	0.05
ζ_d (α_R=0.8; β=3.8)	0.691	$\Phi(-\alpha_R \cdot \beta)=1.18 \cdot 10^{-3}$

The reliability-based design $f_{st,d}$ expression for the semi-empirical model proposed by [12] and [15] for laps and anchorages tensile strength estimation can be evaluated, according to Eq.(7), as follows:

$$R_d(f_c,\vartheta) = \zeta_d \cdot R_{Model}(f_{ck}) = \zeta_d \cdot 54 \cdot f_{ck}^{0.25} \cdot g(\phi, \mathrm{l_b}, c_{\min}, c_{\max}, K_{tr}) \tag{10}$$

Finally, back to the original notation and setting $\zeta_d=0.691$ (Table 2), the reliability-based design expression for laps and anchorages laps strength can be represented as reported in Eq.(11):

$$f_{st,d} = 37.3 \cdot \left(\frac{f_{ck}}{25}\right)^{0.25} \left(\frac{l_b}{\Phi}\right)^{0.55} \left(\frac{25}{\Phi}\right)^{0.2} \left[\left(\frac{c_{\min}}{\Phi}\right)^{0.25} \left(\frac{c_{\max}}{c_{\min}}\right)^{0.1} + k_m K_{tr}\right] \qquad \alpha_R = 0.8;\ \beta = 3.8 \tag{11}$$

4. Comparison of the proposed model with Codes prescriptions for design of laps and anchorages

In the present section, the comparison between the provisions of EN 1992-1-1 [13], *fib* Model Code 2010 [12] and the proposed model for calculation of the required anchorage length $l_{b,req}$ is reported. The comparison is proposed according to the hypotheses of minimum requirement in terms of concrete cover (i.e., $c_{min}=c_{max}$, $c_{min}=\Phi$) and absence of shear reinforcements (i.e., $K_{tr}=0$). First of all, according to the latter hypotheses, Eq.(11) can be rewritten as follows:

$$\frac{l_{b,req}}{\Phi} = \left(\frac{\sigma_{sd}}{37}\right)^{1.82} \left(\frac{25}{f_{ck}}\right)^{0.45} \left(\frac{\Phi}{25}\right)^{0.36} \qquad \alpha_R = 0.8;\ \beta = 3.8 \tag{12}$$

where the ratio $l_{b,req}/\Phi$ represents the reliability-based minimum required anchorage length (in compliance with a reliability index $\beta=3.8$) expressed in terms of the diameter, and σ_{sd} is the design stress within the lapped or anchored reinforcement bar at ULS. According to the EN 1992-1-1 [13] and *fib* Model Code 2010 [12], $l_{b,req}/\Phi$ can be calculated as follows:

$$\frac{l_{b,req}}{\Phi} = \frac{\sigma_{sd}}{4 \cdot f_{bd}} \tag{13}$$

where the value of f_{bd} is the design bond strength calculated according to Table 3.

Table 3. Evaluation of bond strength according to EN 1992-1-1 [13] and *fib* Model Code 2010 [12].

Code	Bond strength f_{bd} [MPa]	Other parameters
EN 1992-1-1 [13]	$f_{bd} = 2.25 \cdot \eta_1 \cdot \eta_2 \cdot f_{ctd}$	$f_{ctd} = \dfrac{0.7 \cdot 0.3 \cdot (f_{ck})^{2/3}}{\gamma_C = 1.5} \leq C50/60$ $\eta_1 = 1 \quad (good\ bond)$ $\eta_2 = 1 \quad (\Phi \leq 32mm)$
fib Model Code 2010 [12]	$f_{bd} = \dfrac{\eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \cdot \left(\dfrac{f_{ck}}{25}\right)^{0.5}}{\gamma_C = 1.5}$	$\eta_1 = 1.75 \quad (ribbed\ bars)$ $\eta_2 = 1 \quad (good\ bond)$ $\eta_3 = 1 \quad (\Phi \leq 25mm)$ $\eta_4 = 1 \quad (steel\ grade\ 500)$

The comparison mentioned above is proposed in Figure 4 in function of the stress σ_{sd} according to the expressions reported in Table 3, assuming $\Phi=16\ mm$, $f_{ck}=25\ MPa$ and steel *Grade 500*.

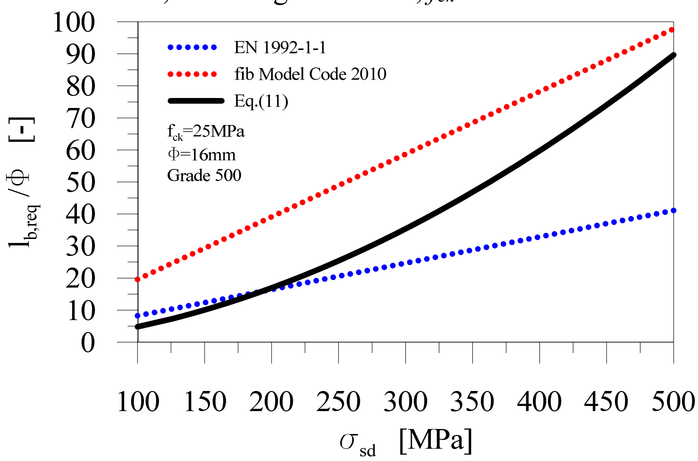

Figure 4. Required anchorage length $l_{b,req}/\Phi$ evaluated according to EN1992-1-1 [13], *fib* Model Code 2010 [12] and Eq.(12). $\Phi=16\ mm$, $f_{ck}=25\ MPa$ and steel *Grade 500.*

Firstly, it can be noted that according to Eq.(12) the required anchorage length $l_{b,req}/\Phi$ increases more than proportionally in function of the design stress σ_{sd} to be transferred at ULS. In fact, as discussed by [24], the experimental evidence deriving from laboratory tests on laps and anchorages shows that the increment of the lap or anchorage length gives origin to an increment of the lap/anchorage strength that is less than proportional. This non-linear behaviour is not accounted for by the models proposed by EN 1992-1-1 [13] and *fib* Model Code 2010 [12]. In fact, the latter proposes a constant value of bond strength f_{bd} which, according to Eq.(13), originates a linear variation as a function of σ_{sd}. Secondly, EN1992-1-1 [13] seems to be unsafe when high level of stresses should be transferred at ULS (i.e., $\sigma_{sd} \geq 250$-300 MPa). This result is in agreement with the observations performed by [28]. Conversely, *fib* Model Code 2010 tends to be too conservative, especially when low level of stress should be carried at ULS. Finally, concerning the required laps and anchorages length calculated in compliance with EN1992-1-1 [13] and *fib* Model Code 2010 [12], the level of reliability and the associated probability of structural failure are unknown, differently from what happens using Eq.(12).

5. Conclusions

A calibration procedure based on the Monte Carlo method has been applied to the semi-empirical model for the evaluation of laps and anchorages strength reported in *fib* Model Code 2010.

The reliability based-expressions for laps and anchorages strength have been derived, and the results of the probabilistic calibration have been compared to the provisions of EN1992-1-1 and *fib* Model Code 2010 for the required anchorage length calculation.

The reliability-based calibration of the semi-empirical model can be performed through the definition of a probabilistic coefficient ζ_d. This coefficient accounts for aleatory uncertainties (i.e., concrete compressive strength f_c), model uncertainties (i.e., ϑ), and the information related to the choice of the representative values of the random variables to be used within the final design expression (i.e., design expression in the function of the 5% characteristic compressive strength f_{ck} rather than the mean concrete compressive strength f_{cm}).

Both EN1992-1-1 and *fib* Model Code 2010 propose models for the calculation of the required anchorage length for which the ensured level of reliability is unknown. At ULS, EN1992-1-1 tends to be unsafe when high level of stress should be transferred, whereas *fib* Model Code 2010 is too conservative when low level of stress should be carried. Furthermore, both the codes show a linear increment of the required anchorage length with growing design stress σ_{sd} to be transferred, which is in contrast with the experimental evidence.

The proposed reliability-based model, which is consistent with a specific level of reliability, is also in agreement with the evidence from laps and anchorages laboratory experiments, where the lap or anchorage strength grows less than proportionally with the lap or anchorage length.

Acknowledgments

This work is part of the collaborative activity developed by the authors within the framework of the Committee 3 – Task Group 3.1: "Reliability and safety evaluation: full-probabilistic and semi-probabilistic methods for existing structures" of the International Federation for Structural Concrete (*fib*).

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