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UNCERTAINTY IN SHEAR RESISTANCE OF REINFORCED CONCRETE BEAMS WITH STIRRUPS – COMPARISON OF EN 1992-1-1 AND *fib* MC 2010 APPROACHES

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Abstract

The submitted contribution is focused on the model uncertainty related to shear resistance of reinforced concrete beams with stirrups. Using available test results, effects of basic variables on the model uncertainty are analysed. Considering the section-oriented models provided in EN 1992-1-1 and in the new *fib* Model Code 2010 are critically compared. Proposed probabilistic description of the model uncertainty consists of the lognormal distribution having the mean and coefficient of variation dependent on the considered model. Strength of shear reinforcement seems to be the most important basic variable for most of the considered models.

Keywords

Model uncertainty, shear resistance, reinforced concrete, beam.

Abstrakt

Příspěvek je zaměřen na modelové nejistoty smykové odolnosti železobetonových prvků s třmínky. S využitím dostupných experimentálních dat se porovnávají nejistoty modelů v EN 1992-1-1 a *fib* Model Code 2010. Jsou identifikovány veličiny významně ovlivňující modelovou nejistotu. Teoretický popis nejistot se opírá o lognormální rozdělení s průměrem a variačním koeficientem závislým na použitém modelu. Pro většinu uvažovaných modelů je pevnost smykového vyztužení nejvýznamnější základní veličinou.

Klíčová slova

Modelová nejistota, smyková odolnost, železobeton, nosník.

1 INTRODUCTION

Previous studies [1-4] indicated that structural resistances can be predicted by appropriate modelling of material properties, geometry variables and uncertainties associated with an applied model. The effect of variability of materials and geometry has been extensively investigated and is

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relatively well understood. However, improvements in the description of model uncertainties are still needed [4].

The presented study is focused on the model uncertainties of the shear resistance of beams with stirrups. Model uncertainty in the shear resistance according to the new *fib* Model Code [5] (hereafter "MC 2010") is analysed. The results are then critically compared to those obtained in a previous study [6] for the model in EN 1992-1-1 [7] (hereafter "EN 1992-1-1"). Beams not affected by degradation are taken into account.

2 MODEL UNCERTAINTY

The model uncertainty should always be clearly associated with an assumed resistance model. In common cases actual resistance can be estimated as a product of the model uncertainty and resistance obtained by the model. In this study the model uncertainty θ is considered to be a random variable. The multiplicative relationship for θ is assumed in accordance with [8]:

$$R = \theta\, R_{\text{model}}(\boldsymbol{X}) \tag{1}$$

where:

R – denotes the response of a structure (actual resistance estimated from test results and structural conditions);

R_{model} – model resistance (estimate of the resistance based on a model); and

$\boldsymbol{X}^{\text{T}} = (X_1,\ldots, X_m)$ – vector of basic variables X_i.

Assuming lognormal distribution with the origin at zero (hereafter simply "lognormal distribution") for R and $R_{\text{model}}(\cdot)$, the model uncertainty given by relationship (1) is also lognormal.

The model uncertainty θ in general depends on basic variables $\boldsymbol{X}$. Influence of individual variables on θ can be assessed by a regression analysis [9]. It is also indicated that the model describes well the essential dependency of R on $\boldsymbol{X}$ only if the model uncertainty:

- Has either a suitably small coefficient of variation (how small is the question of the practical importance of the accuracy of the model) or
- Is statistically independent of the basic variables $(X_1,\ldots, X_m)$.

More information about the model uncertainties can be found in [6,10,11].

3 SHEAR RESISTANCE ACCORDING TO THE CONSIDERED MODELS

Three levels of approximation are distinguished in the models for shear resistance of reinforced concrete beams according to MC 2010:

- MC 2010 Level 1 (hereafter "Level 1") requires few input data and is simple to evaluate.
- For Level 2 more input data are needed and the evaluation is more complex than in Level 1.
- Level 3 requires the same input data like Level 2; however its evaluation is the most laborious.

Evaluation of the shear resistance for all the levels is based on analytical relationships that are essentially easy to compute (see relationship (2) below and Annex A). Input data for the three levels are summarised in Tab. 1. In MC 2010 it is expected that Level 1 leads the most conservative results, Level 2 is less conservative and Level 3 provides the most accurate results.

Tab. 1: Description and range of variables included in the database and entering to the assessment

Basic variables for which data are included in the database		**Min.**	**Max.**	**Applied in model**
a/d (-)	shear span-to-depth ratio	2.49	5.05	-
b_w (mm)	smallest width of a cross-section in the tensile area	76	457	all models
d (mm)	effective depth	95	1200	all models
f_c (MPa)	concrete compressive strength	12.8	125	all models
f_{yw} (MPa)	yield strength of stirrups	182	820	all models
s (mm)	stirrup spacing	48	600	-
V_{fail} (kN)	shear force at failure	15.6	1172	Levels 2, 3
$\rho_l = A_{sl} / (b_w d)$ (%) [(1)]	longitudinal reinforcement ratio	0.5	4.54	Levels 2, 3
$\rho_w = A_{sw} / b_{ws}$ (%) [(2)]	shear reinforcement ratio	0.07	1.19	all models
$\rho_w f_{yw}$ (MPa)	strength of shear reinforcement	0.21	2.62	all models
Auxiliary variables derived from the basic variables (in MC assessment)				
E_s (GPa)	modulus of elasticity of reinforcing steel	210		Levels 2, 3
k_v (-) [(3)]	strength reduction factor for concrete cracked in shear	[(7)]	[(7)]	Levels 1-3
k_ε (-) [(4)]	strength reduction factor for concrete cracked in compression	[(7)]	[(7)]	Levels 1-3
ε_x (-) [(5)]	strain in the core layer	[(7)]	[(7)]	Levels 2, 3
ξ (°) [(6)]	angle between concrete compression struts and the main tension chord	[(7)]	[(7)]	all models

[(1)] A_{sl} – denotes area of longitudinal reinforcement

[(2)] A_{sw} – area of shear reinforcement

[(3)] $k_v = 180 / (1000 + 1.25\, z)$

[(4)] for Level 1 $k_\varepsilon = 0.55$

for Level 2 $k_\varepsilon = \min[1 / (1.2 + 0.55(\varepsilon_x + (\varepsilon_x + 0.0025) \cot 2\xi)), 0.65]$

[(5)] $\varepsilon_x = (M_E / z + V_E) / (2\, E_s\, \rho_l\, b_w\, d)$, where $M_E = V_{fail}\, z$, $V_E = V_{fail}$ and $z = 0.9d$

[(6)] ξ may be chosen between limits $<30^\circ, 45^\circ>$ for Level 1 and

$<20^\circ + 10000\, \varepsilon_x, 45^\circ>$ for Level 2

[(7)] depends on an applied model

Considering no axial compressive force and f_c in MPa, the shear resistance according to Levels 1 and 2 is:

$$R_{\text{model}}(X) = \min\begin{bmatrix} \max(k_v \min(8, f_c^{1/2}) b_w z, \rho_w b_w z f_{yw} \cot\xi) \\ k_\varepsilon \min(1, (30/f_c)^{1/3}) f_c b_w z \sin\xi \cos\xi \end{bmatrix} \tag{2}$$

Evaluation according to Level 3 is more complex and is described separately in Annex A. Actual concrete strengths instead of characteristic values are applied in all the models. Notation of the basic variables affecting the shear resistance is provided in Tab. 1. The symbol ξ for the angle between concrete compression struts and the main tension chord is introduced here instead of θ (used in MC 2010) to avoid confusion with the symbol for model uncertainty.

The shear model provided in EN 1992-1-1 for beams with stirrups is:

$$R_{\text{model}}(X) = \max_{1 \le \cot\xi \le 2.5} \{\min[\rho_w b_w z f_{yw} \cot\xi; b_w z v_1 f_c / (\cot\xi + \tan\xi)]\} \tag{3}$$

where:

v_1 – denotes the strength reduction factor for concrete cracked in shear, $v_1 = 0.6$ for $f_c \ge 60$ MPa or $v_1 = \max[0.5; 0.9 - f_c / 200 \text{ MPa}]$ otherwise.

More information about the model and related uncertainties can be found in [6].

4 DATABASE OF EXPERIMENTAL RESULTS

Researchers at the University of Stellenbosch collected a database of 222 tests of beams with stirrups [12] that is used here to assess the uncertainty in the MC 2010 models. For 22 tests information on ρ_w and f_{yw} is missing and these test results are hereafter not considered. Ranges of material and geometrical characteristics of the tested beams are given in Tab. 1. The database covers a wide range of beams with low to high concrete strengths, shear reinforcement ratio, and effective depths. Beams with light, moderate and heavy shear reinforcement are included.

It should be noted that the design rules in EN 1992-1-1 are valid for reinforcement with the characteristic yield strength f_{yk} between 400 to 600 MPa and the database contains 97 specimens out of this range. However, these specimens have insignificant influence on the model uncertainty and are thus taken into account in the further analysis. No similar limits are included in MC 2010.

Grubb's test of outliers is performed considering a significance level of 0.05 [13]. One sample is removed for all the levels of MC 2010 (for EN 1992-1-1 none of the 200 samples was excluded [6]).

5 STATISTICAL EVALUATION AND COMPARISON OF THE MODEL UNCERTAINTY

For each experiment the model resistance is assessed from equation (2) and Annex A and the model uncertainty is evaluated from equation (1). Sample characteristics of θ (mean μ_θ and coefficient of variation V_θ) for the whole database are given in Tab. 2a for MC 2010 and in Tab. 2b for EN 1992-1-1 (adopted from [6]). A lognormal distribution is assumed in accordance with [8].

Fig. 1 shows probability density functions of θ associated with EN 1992-1-1 and MC 2010, based on the sample characteristics derived from the whole databases. It appears that Level 3 is the most appropriate model – the mean of the uncertainty is close to unity and coefficient of variation is relatively small.

To verify influence of basic variables (Tab. 3) on the model uncertainty, a simple sensitivity analysis proposed in [12] is conducted for the present database. Trends in θ with a basic variable X_i are assessed using the correlation coefficient ρ (correlation between θ and X_i). Note that information on stirrup spacing s is missing for 67 tests. These tests were removed from the database only for a particular assessment of influence of s on θ as this variable is not an input parameter for any of the considered shear models.

Tab. 2a: Sample characteristics of the model uncertainty according to MC 2010

Level of approximation	**Level 1**		**Level 2**		**Level 3**	
Description of the sample	μ_θ	V_θ	μ_θ	V_θ	μ_θ	V_θ
Whole database, n = 199	2.23	0.27	1.88	0.28	1.11	0.22
Lightly reinforced beams ($\rho_w f_{yw} \leq 1$ MPa), n = 147	2.43	0.21	2.05	0.23	1.13	0.23
Moderately reinforced beams (1 MPa < $\rho_w f_{yw} \leq 2$ MPa), n = 44	1.80	0.23	1.50	0.26	1.11	0.20
Heavily reinforced beams (2 MPa < $\rho_w f_{yw}$), n = 8	1.08	0.21	0.92	0.20	0.82	0.19

Tab. 2b: Sample characteristics of the model uncertainty according to EN 1992-1-1 adopted from [6]

Description of the sample	μ_θ	V_θ
Whole database, n = 200	1.63	0.32
Lightly reinforced beams n = 147	1.80	0.26
Moderately reinforced beams, n = 45	1.24	0.23
Heavily reinforced beams, n = 8	0.76	0.19

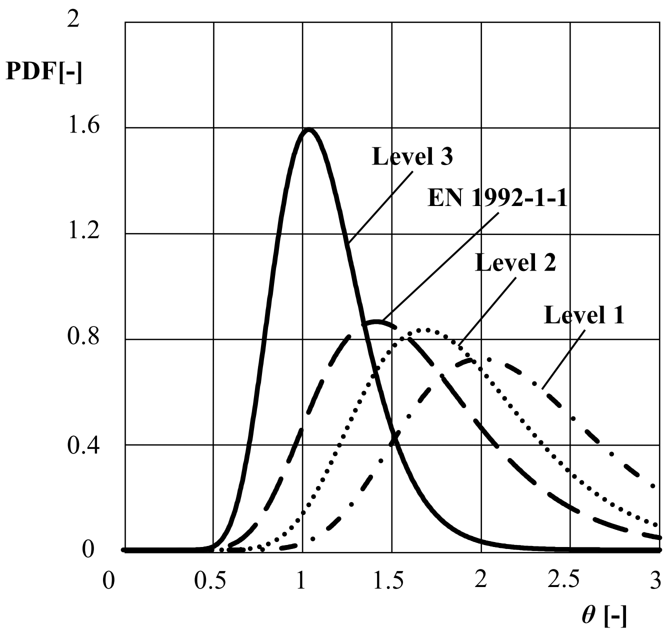

Fig. 1: Probability density functions of θ associated with the EN 1992-1-1 and MC 2010 models for the whole databases

Tab. 3: Coefficient of correlation describing the influence of variables included in the database on θ

Variable	coefficient of correlation ρ for exponential (linear) regression			
	EN 1992-1-1	**Level 1**	**Level 2**	**Level 3**
a/d	0.12 (0.11)	0.09 (0.05)	0 (-0.04)	-0.08 (-0.12)
b_w	0.14 (0.11)	0.17 (0.17)	0.20 (0.19)	-0.15 (-0.13)
d	-0.01 (-0.04)	0 (-0.02)	0.04 (0.02)	-0.36 (-0.33)
f_c	0.16 (0.14)	0.18 (0.17)	0.19 (0.18)	0.06 (0.08)
f_{yw}	0.09 (0.05)	0.22 (0.22)	0.21 (0.20)	0.21 (0.24)
s	0.03 (0.01)	0.01 (-0.02)	0.05 (0.03)	-0.37 (-0.33)
V_{fail}	-0.02 (-0.04)	0.04 (0.04)	0.07 (0.07)	-0.07 (-0.06)
ρ_l	0.07 (0.08)	0.09 (0.11)	-0.08 (-0.06)	0.15 (0.13)
ρ_w	-0.69 (-0.60)	-0.7 (-0.61)	-0.72 (-0.62)	-0.2 (-0.23)
$\rho_w f_{yw}$	-0.75 (-0.68)	-0.69 (-0.62)	-0.7 (-0.63)	-0.13 (-0.12)

Regression analysis is based on a linear or exponential model described by the following relationships:

$$\text{linear: } \theta(\rho_w f_{yw}) = b_0 + b_1\, \rho_w f_{yw} \tag{4}$$

$$\text{exponential: } \theta(\rho_w f_{yw}) = \exp(b_0 + b_1\, \rho_w f_{yw}) \tag{5}$$

where:

b_0 and b_1 – denote regression parameters determined by the Least square method.

The results provided in Tab. 3 reveal strong correlations between θ and ρ_w or $\rho_w f_{yw}$ while weak correlations appear for the other shear parameters for EN 1992-1-1, Levels 1 and 2. Influence of ρ_w or $\rho_w f_{yw}$ on θ for Level 3 is considerably reduced which is the key improvement of this model. Medium correlations between θ–d and θ–s are observed for Level 3. For most of the shear parameters the exponential regression is more appropriate than linear regression.

Figs. 2 and 3 show variation of the model uncertainty with the strength of shear reinforcement and its exponential trend for the Level 3 and EN 1992-1-1 models, respectively. The model uncertainty for EN 1992-1-1 (and also for Levels 1 and 2) clearly decreases with an increasing $\rho_w f_{yw}$ and its differentiation with respect to this parameter is thus proposed. The uncertainty related to Level 3 seems to be independent of $\rho_w f_{yw}$ and the differentiation is not necessary.

Sample characteristics of θ for light to heavy reinforced beams are provided in Tabs. 2a and 2b; limits for lightly, moderately and heavily reinforced beams are accepted from [14]. It follows that the mean of the uncertainty μ_θ depends on the strength of shear reinforcement while the effect on the coefficient of variation is less significant.

Based on the results given in Tab. 2a mean $\mu_\theta \approx 1.1$ and coefficient of variation $V_\theta \approx 0.2$ may be accepted for the shear resistance of the members with stirrups for Level 3. For the other models both the characteristics μ_θ and V_θ are mostly greater. For heavily reinforced beams an unambiguous recommendation cannot be now provided due to the lack of experimental data.

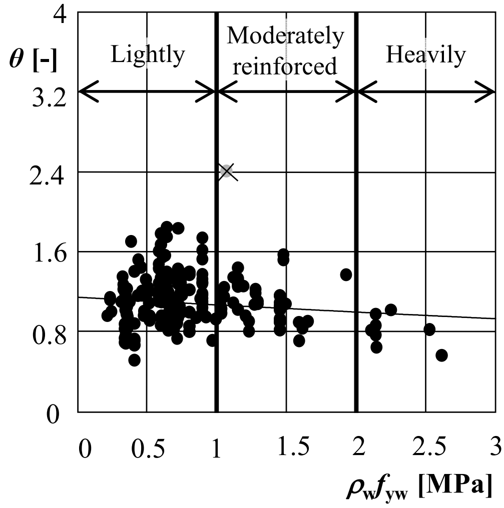

Fig. 2: Variation of θ with $\rho_w f_{yw}$ for Level 3 (whole database)

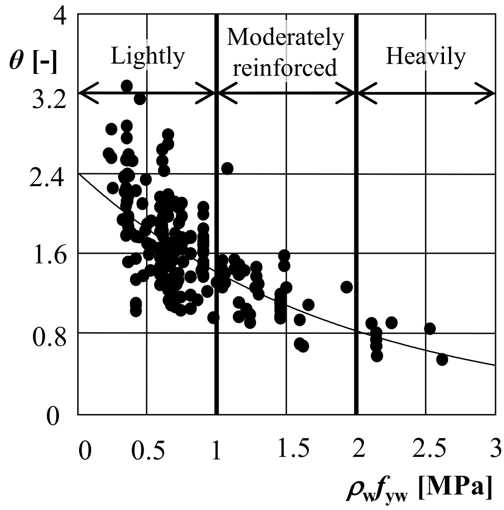

Fig. 3: Variation of θ with ρwfyw for EN 1992 1 1 (whole database)

Note that the residual scatter R^2 [15] could be determined as an additional parameter describing relationship between θ and the basic variables. However, R^2-values improve information deduced from the ρ-coefficient insignificantly in the presented case.

To summarise the above results it is recommended to prefer a model with the highest accuracy if data required for the assessment are available. It is expected that for most practical cases additional data for Levels 2 and 3 – V_{fail} (from a test or design assumptions), E_s and ρ_l (see Tab. 1) – are known. Computational demands for all the considered models are similar – all the models are based on analytical relationships which are easy to evaluate. Therefore, it is recommended to use the Level 3 model while assessing the shear resistance of lightly to moderately reinforced beams with stirrups.

6 DISCUSSION

Uncertainties related to the MC 2010 models are briefly discussed in [16] where a different database containing beams with a variable cross-section and with normal force is considered. Consequently the results by Sigrist et al. [16] slightly differ from those presented in this contribution. For Levels 1 and 2 they obtained less conservative mean values ($\mu_\theta \approx$ 1.35–1.5) and a smaller coefficient of variation ($V_\theta \approx 0.2$); for Level 3 higher mean ($\mu_\theta \approx 1.2$) and a smaller coefficient of variation ($V_\theta \approx 0.13$) was reported.

Uncertainties associated with two shear models (EN 1992-1-1 and the model proposed in [17]) were analysed in [18]. A test database used for the analysis is not described in detail. It can only be judged from provided figures that, regarding ρ_w, the database is somewhat similar to that accepted here – most of samples with a low shear reinforcement ratio ($\rho_w < 0.5$ %), some with moderate 0.5 % $< \rho_w <$ 1 % and very few with a high ratio $\rho_w > 1$ %. Busse et al. [18] considered ρ_w as the most important parameter instead of $\rho_w f_{yw}$. This makes a small difference as both these variables affect the uncertainty of EN 1992-1-1 model in a similar way [6]. For EN 1992-1-1 they obtained $\mu_\theta \approx 1.35$ and $V_\theta \approx 0.3$; for the model in [17] $\mu_\theta \approx 1.12$ and unrealistically low $V_\theta \approx 0.07$ were reported.

In further studies the differences amongst the reported results should be investigated and clarified.

7 CONCLUDING REMARKS

Description of uncertainties related to resistance and load effect models can be a crucial problem of reliability analyses. The presented comparison of uncertainties in the shear resistance of beams with stirrups according to the models in EN 1992-1-1 and *fib* MC 2010, leads to the following conclusions:

- In common cases actual shear resistance can be expressed as a product of the model uncertainty and resistance obtained by the model.
- Uncertainty related to MC 2010 Level 3 can be described by the lognormal distribution with a mean $\mu_\theta \approx 1.1$ and coefficient of variation $V_\theta \approx 0.2$; both these characteristics are more favourable than for the other considered models (EN 1992-1-1 and MC 2010 Levels 1 and 2).
- It is recommended to use the MC 2010 Level 3 model for assessing lightly to moderately reinforced beams since all the required input data are commonly available and computational demands are acceptable.
- No recommendation is provided for heavily reinforced beams due to the lack of experimental data.

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ANNEX A – SHEAR RESISTANCE ACCORDING TO MC 2010 LEVEL 3

In the Level 3 approach, the design shear resistance in the range $V_R < V_{R,\max}(\xi_{\min})$ is given by:

$$V_R = V_{R,s} + V_{R,c} \tag{6}$$

where:

$$V_{R,\max} = k_\varepsilon \min(1, (30/f_c)^{1/3})\, f_c\, b_w\, z \sin\xi_{\min} \cos\xi_{\min} \tag{7}$$

$$V_{R,s} = \rho_w\, b_w\, z\, f_{yw} \cot\xi \tag{8}$$

$$V_{R,c} = k_v \min(8; f_c^{1/2})\, b_w\, z \tag{9}$$

where f_c is in MPa. Variables k_ε and ξ are same as in the Level 2 approximation. $\xi_{\min}$ is a lower limit for ξ. Strength reduction factor for concrete cracked in shear is given by:

$$k_v = \max[0.4(1 - V_{fail} / V_{R,\max}) / (1 + 1500\varepsilon_x),0] \tag{10}$$

In the range $V_R \geq V_{R,\max}(\xi_{\min})$ the resistance is determined using the Level 2 model.

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