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UNCERTAINTY IN RESISTANCE MODELS FOR STEEL MEMBERS

Abstract

Resistance of steel structures is primarily dependent on material properties, geometry and uncertainties related to an applied model. While materials and geometry can be relatively well described, the uncertainties in resistance models are not yet well understood. In many cases significant efforts are spent to improve resistance models and reduce uncertainty associated with outcomes of the model. However, these achievements are then inadequately reflected in the values of partial factors. That is why the present paper clarifies a model uncertainty and its quantification. Initially a general concept of the model uncertainty is proposed. Influences affecting results obtained by tests and models and influences of actual structural conditions are overviewed. Statistical characteristics of the uncertainties in resistance of steel members are then provided. Simple engineering formulas, mostly based on the EN 1993-1-1 models, are taken into account. To facilitate practical applications, the partial factors for the model uncertainties are derived using a semi-probabilistic approach.

Keywords

Model uncertainty, steel structures, partial factor, reliability, resistance.

1 INTRODUCTION

It is recognised that structural resistances can be predicted by appropriate modelling of material properties, geometric variables and uncertainties related to a model under consideration. The effects of variability of materials and geometry on reliability of steel structures are relatively well understood. However, better description of model uncertainties is desired as they significantly affect reliability of most steel structures. Improved information on the model uncertainties can be utilised in both structural design and assessment of existing structures. In the latter relative importance of the model uncertainties may increase since tests may reduce the uncertainties in basic variables.

The submitted study provides a general concept of the model uncertainty. Statistical data and available probabilistic models for the uncertainty in resistance of steel members are overviewed. Simple engineering formulas mostly based on the models provided in EN 1993-1-1 [1] (hereafter "Eurocode 3") are taken into account. Generally applicable models for the model uncertainties are then proposed. To facilitate practical applications the partial factors for the model uncertainties are derived using a semi-probabilistic approach. Outcomes of this study can be utilised not only in civil engineering, but also in mechanical engineering, power engineering and other industries where steel structures are used.

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2 GENERAL CONCEPT OF MODEL UNCERTAINTY

The model uncertainty can be represented by a random variable accounting for simplifications of considered models [2]. Model uncertainties can be associated with:

- Resistance models (based on simplified relationships or complex numerical models),

- Models for action effects (assessment of load effects and their combinations).

The model uncertainty can be obtained from comparisons of physical tests and model results. Obviously the model uncertainty should be always associated with a computational model under consideration. Moreover, actual structure-specific conditions need to be taken into account when they significantly deviate from test conditions. The significance of influences affecting tests, model results and actual structural conditions depends substantially on an analysed structural member or load effect. A general concept of the model uncertainty indicated in Fig. 1 is applicable to both resistance and load effect models.

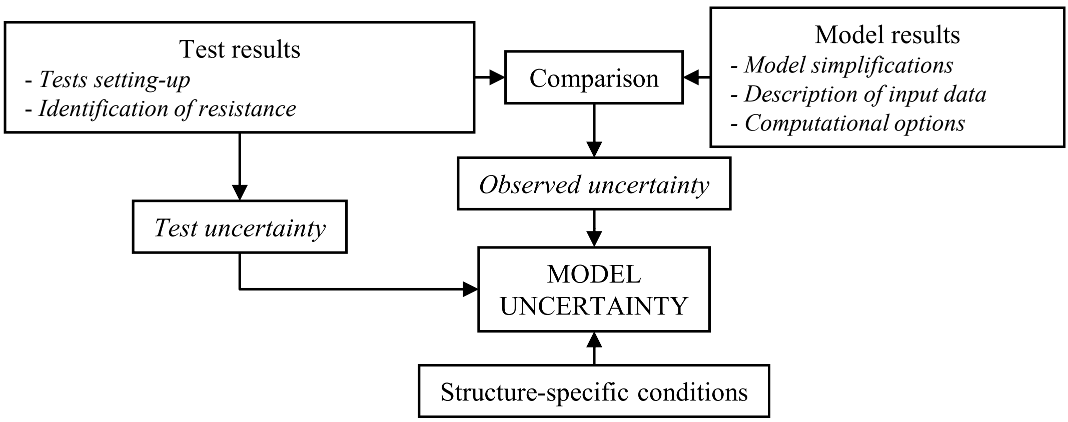

Fig. 1: General concept of the model uncertainty

The uncertainties in resistance models are hereafter discussed only. Examples of the influences affecting test and model results for resistance variables are given in Tab. 1. A similar list could be provided for load effect models.

In general the following aspects should be considered in the assessment of the model uncertainty:

- Test conditions should be correctly defined and test results properly evaluated.

- The uncertainty of a resistance model is dependent on the failure definition (maximum load, strain, deflection etc.). Here it is assumed that the maximum load and corresponding resistance is to be estimated by a model. Greater variability of the model uncertainty is anticipated for the other failure criteria, however.

Tab. 1: Examples of the influences affecting test and model results (resistances)

Categories	Influences	Explanation	Examples
TEST RESULTS	Test setup	Uncertainties related to test procedure	- accuracy of test method (accuracy of gauges, friction, assembly stiffness) - deviations of individual tests (variability of particular conditions) - boundary conditions (supports of specimens) - loading conditions (transfer, speed)
	Identification of resistance	Vagueness in failure indicator	- ultimate strength, strain, deflection
MODEL RESULTS	Model simplification	Simplifications and approximations of model under consideration	- boundary conditions - idealized stress-strain diagram of steel - geometrical imperfections such as lack of verticality, straightness or flatness - steel hardening - lack of knowledge
	Description of input data	Assumptions concerning variables with unknown actual values	- internal dimensions, residual stresses, yield and ultimate strength, plastic strain
	Computational options	Choices (simplifications) to be made by analysts in setup of model	- discretisation, type of finite elements, boundary conditions

It should always be assured that a specimen fails in an investigated failure mode; e.g. when the model uncertainty in shear is analysed, beams failed in bending should not be considered.

The following circumstances often yield differences between structure and test specimens and should then be considered in the assessment of model uncertainty:

- Quality control of execution (particularly for in-situ assembled structures),
- Boundary conditions (supports, joints),
- Loading conditions (transfer, combination of shear and bending moments),
- Degradation aspects etc.

A care should be taken to avoid double considerations of some effects given above; for instance the quality control can be reflected separately from the model uncertainty. If needed, appropriate modifications of the model uncertainty, such as increasing variability and/or adjustments of the mean value, should be accepted. In most cases expert judgement is necessary to account for the effects of actual structural conditions. Their general quantification is hardly possible and thus these effects are not discussed hereafter.

3 ASSESSMENT

The uncertainties in resistance models should be estimated considering the following aspects [3]:

- The database of observations or test results, including all test parameters required for repeating of the tests and calculating the resistance by the model under investigation forms the basis of model uncertainty assessment.

- The range of parameters for the dataset (such as material strength classes or slenderness) defines the range of applicability of the model uncertainty derived for a given failure mode and resistance model.

- Statistical treatment of model uncertainty observations includes proof of unbiased sampling, goodness of fit tests and tests of outliers.

The multiplicative relationship is accepted here [2]:

$$R(\mathbf{X},\mathbf{Y}) \approx \theta\, \mathrm{R}_{\mathrm{model}}(\mathbf{X}) \tag{1}$$

where:

R – is response of a structure - actual resistance estimated from test results,

$\mathrm{R}_{\mathrm{model}}$ – is model resistance - estimate of the resistance based on the model results,

θ – model uncertainty due to factors affecting test and model results (Tab. 1),

$\mathbf{X}$ – vector of basic variables included in the resistance model and

$\mathbf{Y}$ – vector of variables neglected in the model, but possibly affecting the resistance.

In general the model uncertainty can be viewed as an auxiliary variable selected to provide the best estimates of test results on the basis of the considered model. The mean value of θ should be determined in such a way that, on average, the calculation model predicts correctly the test results.

For model uncertainties a lognormal distribution with the origin at zero (hereafter “lognormal distribution”) is commonly accepted [2]. For a given database of test and model outcomes, characteristics of θ can be assessed using the procedure for the statistical determination of a resistance parameter according to EN 1990 [4].

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

It may also be important to define ranges of the input parameters $\mathbf{X}$ for which the accepted model uncertainty is valid. Such intervals should be established on the basis of:

- Admissible ranges of $\mathbf{X}$ for the model (for instance limits on steel strength) and

- Simplifications in modelling of θ (for instance when θ can be considered independent of the basic variable in a specified interval).

Detailed discussion concerning model uncertainties is provided elsewhere [12, 13].

Tab. 2: Statistical characteristics of the model uncertainty accepted in various studies for the calibration of partial factors in Eurocode 3

Type of model	Mean μ_θ	Coefficient of variation V_θ	Reference
Resistance model for generic steel member	1.15	0.05	[5, 6]
	1.00	0.05	[7]
	1.10	0.07	[8]
Bending resistance	1.0	0.05	[2]
	1.10	0.07	[9, 10]
Shear resistance	1.0	0.05	[2]
Deflection of beams	1.10	0.07	[9]
	1.00	0.05	[11]
Resistance of a column	1.30	0.10	[9]
Welded joints	1.15	0.15	[2]
	1.20	0.2	[9]
Bolted joints	1.25	0.15	[2]
Bolted joints - failure of flange	1.07	0.11	[9]
Bolted joints – bolt failure	1.11	0.05	[9]
Bolted joints – bolt failure/ yielding of flange	1.05	0.06	[9]

4 AVAILABLE PROBABILISTIC MODELS

4.1 Models accepted in calibrations of codified models

Available publications concerning calibrations of partial factors indicate that approximations for the uncertainties in resistance models of steel members are often adopted. This is illustrated in Tab. 2 that shows statistical characteristics of the model uncertainty accepted for the calibration of partial factors in Eurocodes.

Except for effects of the loss of local stability, the resistance models for verifications of cross-sections of steel members (bending moment, axial force and shear) are nearly identical in various normative documents. Therefore, it seems that the same characteristics of θ can be accepted for these models in a first approximation.

The comparison [14] of the provisions adopted in AISC-360 [15] and Eurocode 3 revealed a minor difference in the calculation of buckling resistance of members in compression or bending. The study [16], focused on the models provided in SNIP II-23 [17] and Eurocode 3, indicated that the models for buckling resistances are slightly different. An important difference is that buckling curves in Eurocode 3 correspond to a 5% fractile while the curves accepted in the Canadian and American standards were obtained as mean values (50% fractiles).

Tab. 3: Statistical parameters of θ for bending resistance (cross-section)

Description	μ_θ	V_θ	Ref.
Partly restrained - $\lambda_{LT} < 0.4$ (Class 1 or 2 cross-sections)	1.14	0.032	[19]
Fully restrained - $\lambda_{LT} \approx 0$ (Class 1 or 2 cross-sections)	1.19	0.023	[19]
Development of plastic deformation (Class 1 or 2 cross-sections)	1.10	0.11	[20]
Yielding (Class 3 cross-sections)	1.07	0.06	[20]
Statically determinate beams with uniform moment (Class 1 or 2 cross-sections)	1.02	0.06	[21]
Statically determinate beams with gradient moment (Class 1 or 2 cross-sections)	1.24	0.10	[21]
Statically indeterminate beams (for Class 1 or 2 cross-sections)	1.06	0.07	[21]

In some cases the resistance models significantly differ; this is particularly the case of models taking into account the loss of local stability [16, 18]. Therefore, a crude approximation may be gained when the uncertainty in a particular model for buckling or lateral torsional buckling is inferred on the basis of results obtained for another model.

4.2 Available statistical data

In the following statistical data for the uncertainty in resistance of steel members are overviewed.

Bending resistance of the cross-section

Statistical information concerning the bending resistance model according to Eurocode 3 (rolled I-sections of Class 1 and 2) provided in [19] (Tab. 3) is based on test outcomes of:

- 20 specimens that were partly restrained from the loss of stability (non-dimensional slenderness $\lambda_{LT} < 0.4$) and

- 12 specimens fully restrained from the loss of stability (continuous restraints of member, $\lambda_{LT} = 0$).

The test resistance was obtained as a minimum of the ultimate resistance and the resistance for which the angle of rotation at the support was 6°. It should be noted that one of the main objectives of the study [19] was to minimise the factors affecting test results (Tab. 1). This likely reduced variability of the test results and a very small coefficient of variation V_θ was achieved.

Statistical data for bending resistances obtained during 80 years in Canada [20] are given Tab. 3. Rolled and welded sections were not distinguished which, in general, is incorrect particularly in the case of stability verifications (due to different effects of residual stresses on imperfections). In addition Tab. 3 shows the statistical parameters of θ for the bending resistance with the development of plastic deformations provided in [21] for

- Statically determinate beams exposed to a uniform bending moment (33 tests),
- Statically determinate beams with a gradient bending moments (43 tests) and
- Statically indeterminate beams (41 tests).

Tab. 4: Statistical parameters of θ for bending resistance with the loss of stability (Eurocode 3 model) [22]

Description		μ_θ	V_θ
rolled profiles			
general case	$\alpha_{LT} = 0.21$	1.18	0.085
	$\alpha_{LT} = 0.34$	1.29	0.103
"special" case	$\alpha_{LT} = 0.34$	1.11	0.070
	$\alpha_{LT} = 0.49$	1.19	0.093
welded profiles			
general case	$\alpha_{LT} = 0.49$	1.19	0.168
	$\alpha_{LT} = 0.76$	1.31	0.213
"special" case	$\alpha_{LT} = 0.49$	1.06	0.119
	$\alpha_{LT} = 0.76$	1.14	0.159

Tab. 5: Statistical parameters of θ for bending resistance with the loss of stability (AISC-360 model) [23]

Description	μ_θ	V_θ
Uniform moment, welded section , $n = 117$	1.00	0.08
Uniform moment, rolled section, $n = 112$	0.99	0.06
Gradient moment, welded section, $n = 28$	1.13	0.11
Gradient moment, rolled section, $n = 27$	1.16	0.12

For a non-uniform (gradient) bending moment, the bias of resistance models μ_θ is greater (above unity) than for a uniform bending moment that could be attributed to underestimating the development of plastic deformation along a structural member.

Bending resistance of the member with the loss of stability (lateral-torsional buckling)

The model for bending resistance adopted in Eurocode 3, accounting for the loss of stability during bending of rolled and welded I-sections (lateral-torsional buckling), was verified in [22]. Statistical evaluation was made for 144 rolled profiles and 71 welded profiles. The two methods presented in Eurocode 3 were considered: general case (Section 6.3.2.2) and "special" case used for rolled sections or welded sections of similar dimensions (Section 6.3.2.3). The specimens complied mostly with assumptions made for the latter method. A non-dimensional slenderness, computed in accordance with Eurocode 3, varied within 0.4-1.5 for most of the specimens. The statistical parameters of θ are presented in Tab. 4 (α_{LT} = imperfection factor). It is observed that both the bias of the models (μ_θ) and coefficient of variation V_θ increase with the imperfection factor. Statistical parameters of the model uncertainty are significantly affected by the slenderness of a member. The largest variation of results was observed in the area of elastic-plastic buckling [22].

A recent study by Galambos [23] analysed the accuracy of the resistance models accepted in AISC-360 [15]. The statistical characteristics of θ provided in Tab. 5 considerably differ from those given in Tab. 4 for the Eurocode 3 model. The main reason is attributed to the different definitions of the buckling curves.

Tab. 6: Recommended statistical parameters of the uncertainties in the resistance models provided in Eurocode 3

Description	μ_θ	V_θ
Plastic resistance, uniform bending moment	1.00	0.05
Plastic resistance, gradient bending moment	1.15	0.10
Yielding resistance for bending	1.10	0.05
Bending resistance with the loss of stability (rolled or equivalent welded profiles)	1.10	0.08
Bending resistance with the loss of stability (general case)	1.15	0.10
Axial compression with the loss of stability	1.15	0.10

Axial compression with the loss of stability (buckling)

For this failure mode the greatest number of experimental results seems to be available. It is estimated that at least 1700 experiments were reported in literature, covering a variety of cross-sectional shapes, manufacturing processes, steel grades and other aspects affecting structural resistance [24]. Statistical parameters of θ for members exposed to axial compression with the loss of stability are provided in [24, 25]. It appears that the bias of the model uncertainty varies between $\mu_\theta \approx 1.1\text{-}1.2$ and the coefficient of variation between $V_\theta \approx 0.1\text{-}0.2$.

Shear resistance

An important study of uncertainties in the model of shear resistance adopted in Eurocode 3 was performed by Höglund [26]. That study provided estimates $\mu_\theta \approx 1.17$ and $V_\theta \approx 0.11$ ***on the basis of a large number of test results under different conditions (presence of ribs and their orientation, etc.). Another study by Galambos [23] was focused on the shear resistance according to AISC-360 [15];*** $\mu_\theta \approx 1.05$ and $V_\theta \approx 0.12$ were derived.

Based on the provided overview, recommended statistical parameters of the uncertainties in the resistance models provided in Eurocode 3 are given Tab. 6. Likewise in Section 4.2 the effect of test uncertainty is not taken into account. It is assumed to be small for tests of steel members.

5 MODEL UNCERTAINTY FACTOR FOR DETERMINISTIC VERIFICATIONS

In many cases significant efforts are spent to improve resistance models and reduce the uncertainty in a model outcome. However, these achievements are barely reflected in partial factors. That is why this study provides model uncertainty factors for deterministic verifications utilising the probabilistic models proposed in the previous section.

The design value of structural resistance R_d, irrespective of construction material, is commonly defined as (EN 1990 [4]):

$$R_d = R_k / \gamma_M \tag{2}$$

where:

R_k – is characteristic value of the resistance determined using characteristic or nominal values of material properties and dimensions and

γ_M – global partial factor for resistance.

The global partial factor γ_M is the product of the following factors [30, 31]:

$$\gamma_M = \gamma_m \, \gamma_{Rd1} \gamma_{Rd2} \tag{3}$$

where:

γ_{m} – is partial factor accounting uncertainty in material properties,

$\gamma_{R\mathrm{d}1}$ – is partial factor accounting for model uncertainty and

$\gamma_{R\mathrm{d}2}$ – partial factor accounting for geometrical uncertainties.

Alternatively, the partial factor γ_{M} can be obtained from a probabilistic distribution of resistance (assuming a lognormal distribution [19, 27]):

$$\gamma_{\mathrm{M}} = R_{\mathrm{k}} / R_{\mathrm{d}} = 1 / [\mu_R \exp(-\alpha_R \beta V_R)] \tag{4}$$

where:

μ_R – is the mean value of the ratio of actual (experimental, measured) resistance to the characteristic resistance,

V_R – is coefficient of variation of the resistance,

α_R – FORM sensitivity factor ($\alpha_R = 0.8$ recommended for resistance in EN 1990 [4]) and

β – target reliability index that can be selected e.g. according to EN 1990 [4].

The mean value μ_R is estimated as follows:

$$\mu_R = \mu_\theta (\mu_{fy} / f_{\mathrm{yk}}) (\mu_z / Z) \tag{5}$$

where:

μ_{fy} – is mean value of material properties (yield stress),

f_{yk} – is characteristic value of material properties (yield stress),

μ_z – mean value of geometrical properties (area, moment of inertia) and

Z – characteristic value of geometrical properties.

For statistically independent variables, the coefficient of variation of the resistance is obtained as:

$$V_R = \sqrt{(V_\theta^2 + V_{fy}^2 + V_Z^2)} \tag{6}$$

where:

V_z – is coefficient of variation of material strength and

V_{fy} – coefficient of variation of geometrical properties.

Tab. 7: Statistical parameters of the resistance models

Description	γ_{M}	Recommended value
Plastic resistance, uniform bending moment	0.97-1.21	1.1
Plastic resistance, gradient bending moment	0.95-1.17	1.05
Yielding resistance for bending	0.88-1.10	1.0
Bending resistance with the loss of stability (rolled or equivalent welded profiles)	0.94-1.17	1.05
Bending resistance with the loss of stability (general case)	0.95-1.17	1.05
Axial compression with the loss of stability	0.95-1.17	1.05

The statistical parameters of material and geometrical characteristics considerably vary for different steel grades, profiles and production processes accepted by different producers [28, 29]. For common cases $\mu_{fy} / f_{yk} = 1.10\text{-}1.25$, $V_{fy} = 0.05\text{-}0.07$ and $\mu_z / Z = 0.99\text{-}1.03$ and $V_z = 0.01\text{-}0.03$ may be accepted. For these ranges and the statistical characteristics of the model uncertainty given in Tab. 6, variation of the partial factor γ_M obtained from Eq. (4) is indicated in Tab. 7 (considering $\alpha_R = 0.8$ and $\beta = 3.8$).

It is emphasised that improved estimates of the partial factors could be derived from the fully probabilistic approach. Note that partial factors for the ultimate limit states are discussed in this section only. The same procedure could be essentially accepted for the serviceability limit states with appropriate modifications of the target reliability level.

6 CONCLUSIONS

Description of model uncertainties can be a crucial problem in reliability verifications of steel structures. That is why the present study is focused on the model uncertainties in resistance of steel members. The following concluding remarks are drawn:

- Model uncertainties should be always related to test uncertainties, actual structural conditions and computational model under consideration.
- In common cases actual resistance can be expressed as a product of the model uncertainty and resistance obtained by the model.
- Uncertainties related to the EN 1993-1-1 models can be described by the following statistical characteristics and partial factors:
  - Uniform bending moment (plastic resistance): mean $\mu_\theta \approx 1.00$; coefficient of variation $V_\theta \approx 0.05$; model uncertainty factor $\gamma_M \approx 1.1$,
  - Gradient bending moment (plastic resistance), bending resistance with the loss of stability (general case), axial compression with the loss of stability: $\mu_\theta \approx 1.15$; $V_\theta \approx 0.10$ and $\gamma_M \approx 1.05$,
  - Yielding resistance for bending: $\mu_\theta \approx 1.10$; $V_\theta \approx 0.05$ and $\gamma_M \approx 1.0$,
  - Bending resistance with the loss of stability (rolled or equivalent welded profiles): $\mu_\theta \approx 1.10$; $V_\theta \approx 0.08$ and $\gamma_M \approx 1.05$.

Further research should be focused on uncertainties in resistance of structural systems (e.g. frames) and uncertainties in resistances based on advanced numerical models (such as those using the Finite Element Methods).

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