

Overview of the model factor for shell-type FE-models of steel I-section girders

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ABSTRACT

Advanced design approaches based on finite element analysis (e.g. direct resistance check) are increasingly being applied in steel structural design practice. In the context of direct resistance check, where the resistance is derived directly from numerical analysis, further development is required to adequately address model uncertainties and to ensure compliance with the prescribed safety requirements of the Eurocode. Design procedures based on the finite element method must account for both the resistance model uncertainties traditionally considered in analytical design approaches (by having empirical design background) and those associated with numerical modelling, to achieve a level of safety consistent with the provisions of the Eurocode standards. This study summarises the methodology for assessing uncertainties on the resistance side and proposes model factors (γ_{FE}) for different failure modes (bending, shear and patch loading) adjusted to the failure probability criteria of EN 1990. The study focuses on models using shell elements and applies the results of previous laboratory experiments to determine the modelling uncertainties and the model factor for different failure modes separately. The methods used to define imperfections is also examined (application of equivalent geometric imperfections or initial geometric imperfections and residual stresses) from the model factor point of view and their application specialties are also highlighted.

1. Introduction

The use of advanced numerical models is becoming increasingly important in the design of steel structures. In engineering practice, it appears on two levels: (i) indirect and (ii) direct resistance checks. The former (perhaps currently more typical) method is if the numerical model is used to calculate the System Response Quantities (SRQs), which can then be used to calculate the resistance of the structure using analytical design expressions (this design method is called in the EN 1993–1–14 as “analysis requiring subsequent design check”). In direct resistance check (which use is expected to increase in the future), the numerical model is used to calculate the load-bearing capacity of the structure directly. In this case, geometric and material nonlinear analysis with imperfections (GMNIA) is used to calculate the characteristic resistance of the structure. The advantage is that it is more efficient than traditional analytical design calculations and allows for more accurate design, thus enabling material savings and CO₂ emission reduction. In addition to economic and sustainability considerations, it also allows for shorter and more transparent design. However, by using the direct resistance check, the uncertainty of the numerical model must also be

taken into account; for which there were no previous design considerations and recommendations in the international literature. For safe-side design, in addition to the partial factors on the resistance side specified in the Eurocodes, an additional (supplementary) partial factor should be taken into account, known as model factor. The model factor can be calculated within the model validation process on the basis of the comparison of the numerical results to laboratory experiments; following the FE-model development, validation, and statistical evaluation of the results, the value of the model factor corresponding to the given phenomenon, model type, etc., can be determined.

The practical implementation of FEM-based design in everyday engineering workflows would become significantly more straightforward if designers were not required to perform detailed statistical evaluations to determine the model factor at the outset of every project. Instead, a predefined value could be adopted, depending on the level of the numerical model and the governing failure mode. The broader application of the direct resistance check method would represent a substantial advancement in the structural design process. However, the case-by-case determination of the model factor for each individual design task would increase the required effort and time, thereby reducing the overall efficiency of the approach. It is therefore reasonable to

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Notations	
R_{exp}	resistance value measured in laboratory tests,
R_{act}	resistance value determined by deterministic calculations using numerical model applying GMNIA with measured geometry, material properties and imperfections,
R_{nom}	resistance value determined by deterministic calculations using a numerical model applying GMNIA with nominal values for geometry, material properties and standardized imperfections,
$R_{k, stoch}$	the lower 5% percentile value of resistance obtained from stochastic calculations (numerical model, GMNIA), referred as characteristic value,
$R_{d, stoch}$	the lower 0.1% percentile value of resistance obtained from stochastic calculation (numerical model, GMNIA), referred as design value,
$R_{d, 1}$	the design value of the resistance determined according to 'Method 1' (the method described in Section 2.)
$R_{d, 2}$	the design value of the resistance determined according to 'Method 2' (the method described in Section 2.)
<i>The notations associated with partial factors are the followings</i>	
γ_{FE}	model factor taking into account the modelling uncertainties,
γ_M	resistance side partial factor calculated from the ratio of characteristic to design value,
γ_{M^*}	modified resistance side partial factor calculated from γ_M using a correction factor Δk according to Eq. (6), in this case nominal values are taking into account,
γ_m	resistance side partial factor considering the material uncertainties [1],
γ_{Rd}	resistance side partial factor, the uncertainty of the calculation model, which is used in the paper when the discussion does not specifically relate to numerical model-based design,
$\gamma_{Rd, meth}$	resistance side partial factor for shell FE-models considering only the uncertainties of the calculation method (imperfection definition method for the numerical modelling),
$\gamma_{Rd, num}$	resistance side partial factor for shell FE-models considering the uncertainties of the resistance model (including the uncertainty of the numerical model and the calculation method).

if a specific software environment and finite element modelling strategy are applied. Since model uncertainty quantification has so far received limited attention in the literature, such an investigation may constitute one of the initial steps toward a more systematic understanding of the topic.

If using FEM-based design, various failure modes and structure types can be analysed with the numerical model; for each we need a model factor. There are only a few studies on this topic in the international literature, so the aim of the current study is (i) to summarise the possibilities for determining the model factor (γ_{FE}) to be used in direct resistance checks and (ii) to specify the model factor for basic failure modes allowing efficient design process. This study uses shell-type FEM models, so the current findings are limited to these, leaving open the question of how to determine and include the model factor in the case of other types of numerical models (beam or solid element models).

2. Literature review

The Eurocodes constitute the harmonized European structural design standards and provide a unified framework for the verification of safety, serviceability and durability of civil engineering structures. Within this system, EN 1990 [1] establishes the fundamental principles of structural reliability and defines the semi-probabilistic design format based on partial factors. This approach is of highest importance in civil engineering practice, as it ensures a consistent target level of safety across different structural materials and failure modes. In the Eurocode methodology, uncertainties affecting structural performance are addressed separately on the action side and on the resistance side through the application of partial factors. These factors are introduced in order to increase the design values of actions and to reduce the design values of resistances, thereby providing an appropriate margin of safety. The underlying principle is that safety factors should be applied directly to those quantities in which uncertainties arise.

On the action side, uncertainties are associated both with the modelling of actions and action effects, represented by the factor γ_{Sd} , and with the determination of representative action values, represented by γ_f . On the resistance side, the partial factor γ_{Rd} accounts for uncertainties in the structural resistance model, while γ_m reflects the variability of the basic variables governing resistance, such as material properties and geometric parameters. The products of these components result in the partial factors applied to the action effects (γ_F) and to the resistance (γ_M), respectively. In accordance with EN 1990 [1] and detailed with examples [2], the design verification is performed using these factors to ensure that the required reliability level is satisfied, as expressed in Eqs. (1)–(2).

$$\gamma_F = \gamma_{Sd} \bullet \gamma_f \quad (1)$$

Table 1

The characteristic factor k_n according to EN 1990 [1].

n	1	2	3	4	5	6	8	10	20	30	∞
known V_X	2.31	2.01	1.89	1.83	1.8	1.77	1.74	1.72	1.68	1.67	1.64
unknown V_X	-	-	3.37	2.63	2.33	2.18	2	1.92	1.76	1.73	1.64

Table 2

Model factors for model uncertainties [4].

Failure type	μ_Θ	V_Θ	γ_{Rd}
Punching	0.971	0.076	1.16
Shear	0.984	0.067	1.13
Bending	1.072	0.052	1.01
All failure modes	0.979	0.081	1.16

investigate how the model factor (γ_{FE}) varies for different failure modes

$$\gamma_M = \gamma_{Rd} \bullet \gamma_m \quad (2)$$

The EN 1993–1–14 [3] standard introduces the model factor, which can be used to achieve the safety level specified in the EN 1990 standard if numerical models are used for design and direct resistance check is applied for the structural resistance calculation. The model factor, which describes the uncertainty of the numerical model, is applied on the resistance side in addition to the required partial factor γ_M . The uncertainty and its effect may vary for different FE-models and different failure modes. Accordingly, the application and value of the model

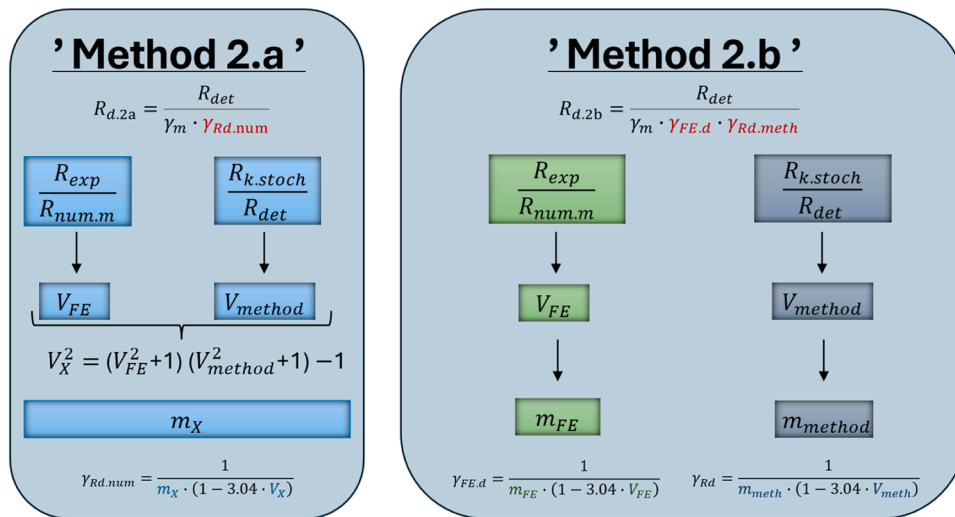


Fig. 1. Overview of 'Method 2a' and 'Method 2b'.

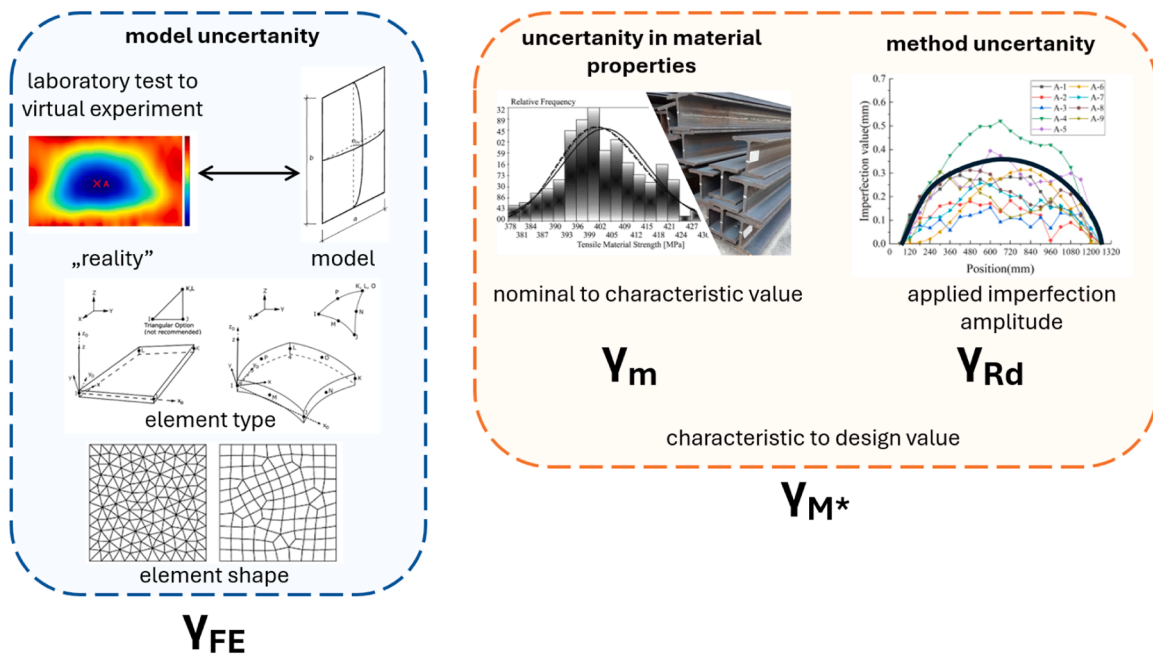


Fig. 2. Required partial factors on the resistance side in the case of direct resistance check.

factor are inherently linked to the selected analysis approach and the specific characteristics of the numerical model employed.

The model factor takes into account that different designers build different models for the same problem: different software, different finite element type, different mesh type, etc. There might be different models, therefore, its value should be determined for each model separately. The determination of the model factor is practically part of the validation process. By using a well-documented experimental campaign with known measured material properties, geometric dimensions, imperfections, it shows, how accurate the experimental load capacity can be obtained by the numerical model. The model factor (γ_{FE}) is determined by comparing the numerical calculation (R_{check}) with the known test results ($R_{test,known}$) or the resistances obtained using approved calculation methods ($R_{k,known}$). For each investigated case, the ratio ($R_{k,known}/R_{check}$ or $R_{test,known}/R_{check}$) between the reference resistance and the numerically predicted resistance (R_{check}) is determined. Based on these ratios, the mean value (m_X) and the coefficient of variation (V_X) are

calculated. The model factor is subsequently derived through statistical evaluation in accordance with Eq. (3). The characteristic resistance corresponding to the numerical model can then be obtained using Eq. (4), where R_{GMNIA} denotes the resistance determined by deterministic GMNIA.

According to the rules of EN 1993-1-14, k_n should be chosen to determine the 5% characteristic value of the resistance according to EN 1990 [1] Table D1. The calculated value is noted by $\gamma_{FE,k}$.

$$\gamma_{FE} = \frac{1}{m_X \cdot (1 - k_n \cdot V_X)} \geq 1.0 \quad (3)$$

$$R_k = \frac{R_{GMNIA}}{\gamma_{FE}} \quad (4)$$

where:

m_X is the mean of the ratio of the measured (or known) to the calculated results for sample n ,

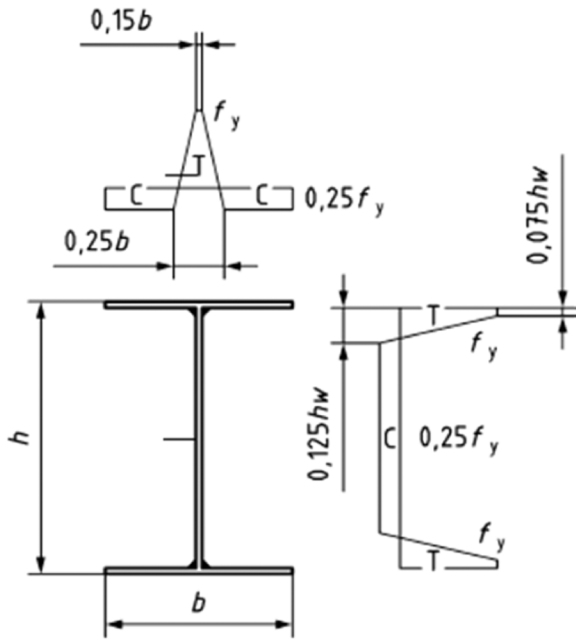


Fig. 3. Applied residual stress model based on EN 1993-1-14 [3].

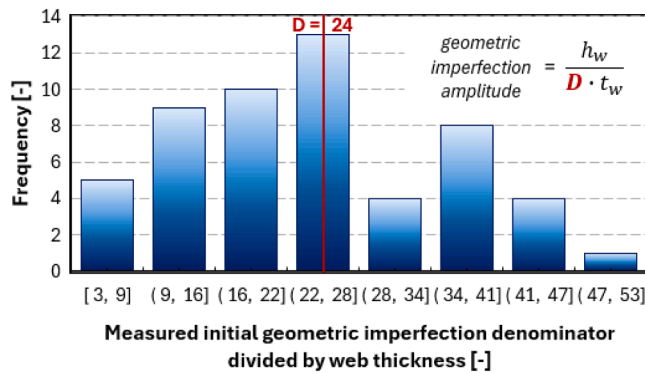


Fig. 4. Measured initial geometric imperfection based on literature experiments.

k_n the characteristic factor according to EN 1990 [1], Annex D, Table D.1 (the data series for the unknown V_X shall be used), see Table 1, V_X is the coefficient of variation of the ratio of the measured (or known) to the calculated results for n samples.

Model uncertainty in concrete structures has been extensively investigated over recent decades, with the most recent contributions summarised in [4–7]. In these studies, nonlinear finite element analyses were carried out using advanced constitutive models for concrete, reinforcement, and their interaction, implemented in the finite element software ATENA. Model uncertainty was quantified as the ratio between experimentally measured resistance and the corresponding resistance predicted by the numerical simulations. To isolate the intrinsic uncertainty of the numerical model, other sources of randomness were minimized. Specifically, experimentally measured material properties of concrete and reinforcing steel were directly incorporated into the numerical analyses, thereby excluding material variability from the evaluation. The resulting model uncertainty was treated as a random variable and characterized statistically by its mean value, standard deviation, and coefficient of variation (CoV). A log-normal probability distribution was assumed for the evaluation, and the corresponding model factor was determined according to Eq. (5).

$$\gamma_{Rd,num} = \frac{\exp(\alpha_R \cdot \beta \cdot V_X)}{m_X} \geq 1.0 \quad (5)$$

The safety level is expressed by a target reliability index of $\beta = 3.8$. The corresponding sensitivity factor for resistance is defined as $\alpha_R = 0.4 \times 0.8 = 0.32$, where 0.8 represents the sensitivity factor associated with resistance and 0.4 accounts for model uncertainty considered as a non-dominant variable. These safety parameters were adopted in accordance with the recommendations of Model Code 2010, Section 4: Principles of structural design [7]. Based on these assumptions, model factors were derived for solid finite element models implemented in the ATENA software, and the resulting values were proposed as failure-mode-dependent model factors. The values are summarised in Table 2 proposed as failure mode dependent model factors.

For steel structures, the authors [8] investigated the resistance-side model uncertainty for bending-type failure mode of welded steel box-section girders. A numerical parametric study was performed by deterministic and stochastic nonlinear analyses to determine the required partial factors. The paper distinguishes two principal approaches for incorporating resistance-side uncertainties, commonly denoted as ‘Method 1’ and ‘Method 2’, the latter including two alternative formulations. The approaches primarily differ in how partial factors on the resistance side are derived and applied. In the first approach, a single global partial factor is used, without explicitly separating material uncertainty from resistance model uncertainty, while an additional model factor is introduced to represent uncertainties associated with numerical modelling. In contrast, the second approach decomposes the resistance side partial factor into separate contributions accounting individually for uncertainty of material properties, structural resistance model, and numerical model. Based on these formulations, deterministic analyses are performed to evaluate characteristic resistances across a range of slenderness ratios, which are subsequently converted into design resistance values using the investigated approaches. Comparative evaluations reported in the study indicate that the resulting design resistances obtained from the different methods are of similar magnitude and consistently remain below the reference values derived from stochastic analyses. Consequently, all approaches provide conservative estimates and are considered suitable for practical design applications.

In ‘Method 1’, the γ_{M^*} factor should be determined from a correction of γ_M . The partial factor γ_M can be calculated based on the ratio of the characteristic and design values of the resistance using stochastic analysis or extensive parametric analysis according to the recommendations of Annex D of EN 1990 [1]. According to Schillo [9] and other researchers using the method similarly, the values of γ_{Mi} in EN 1993 are all derived from γ_{M^*} , which is derived from the ratio of the nominal values R_n (instead of the characteristic resistance R_k) to the design values. According to Johansson et al. [10][11] and by European background documents [12], the partial factor γ_{M^*} required for design can be calculated as the product of the theoretical partial factor γ_M and a correction factor (Δk) using Eqs. (6)–(7).

$$\gamma_{M^*} = \Delta k \cdot \gamma_M \quad (6)$$

where:

$$\Delta k = \frac{r_{nom}}{r_k} = \frac{\exp(-2Q_{fy} - 0.5Q_{fy}^2)}{b \cdot \exp(-k_{\infty}Q - 0.5Q^2)} \quad (7)$$

where Q_{fy} is equal to 0.035–0.07 depending on the material grade based on EN 1993-1-1 [13] or JCSS recommendations [14] and b is the mean value correction factor for the resistance function according to EN 1990 [1].

The correction factor takes into account that, in most cases, the parameters (e.g. material properties) are used at their nominal values to determine the characteristic values, rather than at the lower quantile of

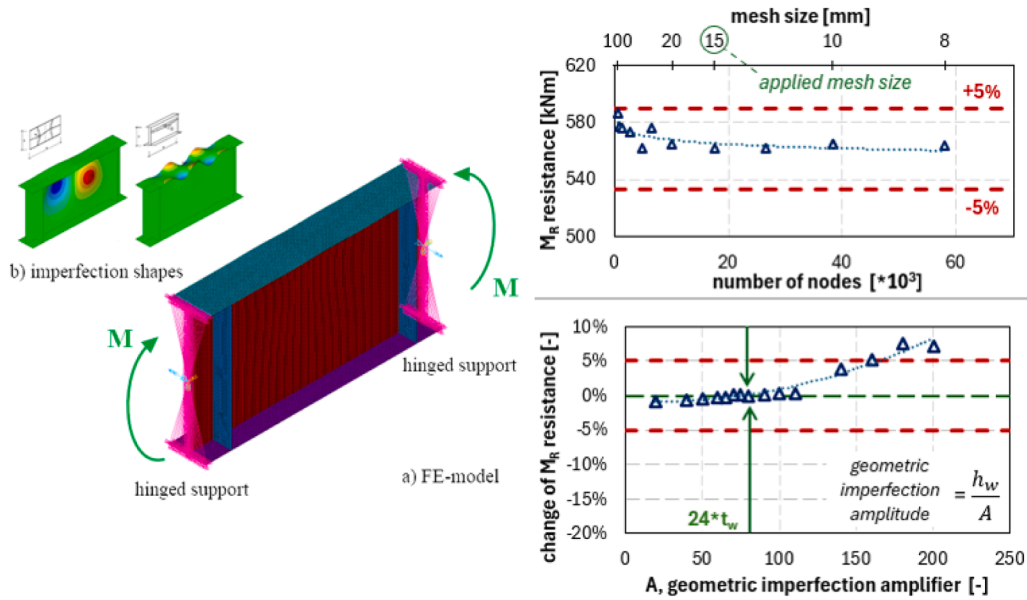


Fig. 5. The finite element model a) mesh, boundary, loading conditions and b) applied imperfection shapes c) mesh and imperfection sensitivity study.

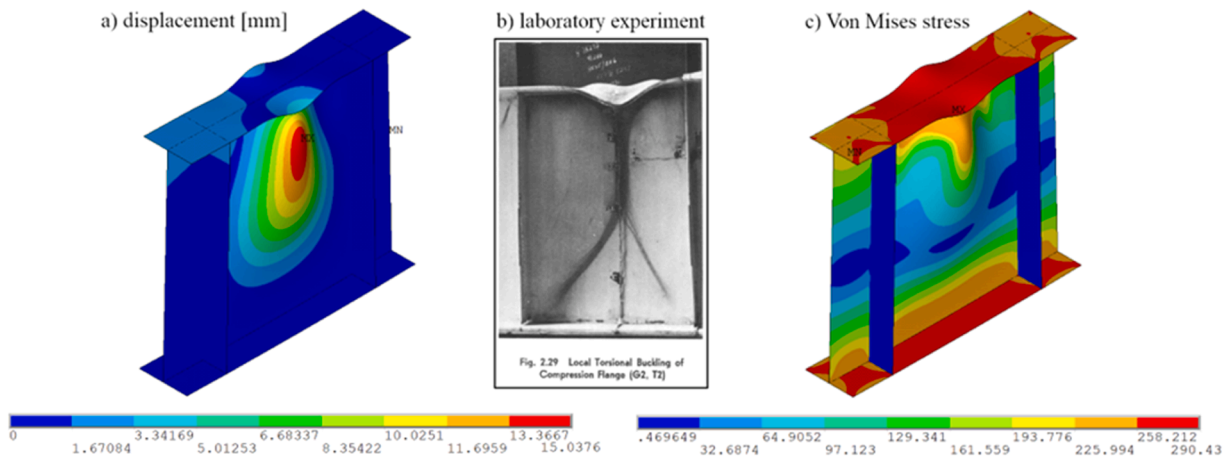


Fig. 6. Failure mode a) in the FE-model (displacement), b) in the laboratory and c) the stress distribution for one specimen.

5%.

In addition to the γ_{M^*} , the $\gamma_{FE,k}$ should be applied in the case of FE-based design in accordance with EN 1993–1–14 [3]. According to the authors, this method is easier to apply than 'Method 2'. Dividing the value of R_{nom} by $\gamma_{FE,k}$ and γ_{M^*} , the design value of the resistance is obtained according to 'Method 1': $R_{d,1}$. Hence, it can be calculated according to Eq. (8).

$$R_{d,1} = \frac{R_{nom}}{\gamma_{FE,k} \bullet \gamma_{M^*}} \quad (8)$$

In the case of 'Method 2', the γ_{M^*} should be separated: the γ_m factor associated with material uncertainty and the γ_{Rd} factor arising from the uncertainty of the method should be determined. The latter can also be divided into two parts: (i) model uncertainty (ii) uncertainty arising from the form and amplitude of imperfections. Section 3.1. deals with the concept of 'model uncertainty' in more detail. 'Method 2.a' and 'Method 2.b' versions are developed, their calculations are given by Eqs. (9)–(10).

$$R_{d,2a} = \frac{R_{nom}}{\gamma_m \bullet \gamma_{Rd,num}} \quad (9)$$

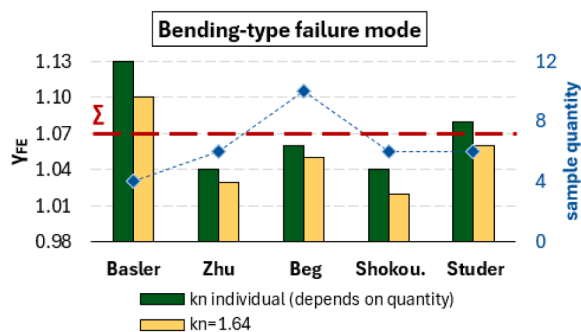
$$R_{d,2b} = \frac{R_{nom}}{\gamma_m \bullet \gamma_{FE,d} \bullet \gamma_{Rd,meth}} \quad (10)$$

Since in 'Method 2' γ_{Rd} does not 'reduce' the characteristic value of resistance to the design value, $\gamma_{FE,d}$ is required instead of $\gamma_{FE,k}$. The difference between the two methods is illustrated in Fig. 1.

Radwan [15] examined the suitability of previously proposed local and global imperfection patterns for the analysis of purely local, purely global, and interaction buckling modes in welded box-section columns subjected to axial compression. Deterministic numerical load-carrying capacities corresponding to the various imperfection models reported in the literature were compared with the 5% lower fractile resistance obtained from stochastic simulations, in which the probabilistic distributions of material properties, geometric parameters, and imperfections were considered. In accordance with the design provisions of EN 1993–1–14 [3], a model factor was subsequently determined for each case individually. The resulting values were generally found to lie in the range $\gamma_{FE} = 1.0$ – 1.1 .

Table 3Determination of γ_{FE} based on laboratory tests (RS means residual stresses).

Name	R_{exp} [kN]	RS + geom. imp.		equiv. geom. imp		Ref.
		R_{act} [kN]	ratio [-]	R_{act} [kN]	ratio [-]	
Basler_G2_T1	600.5	651.0	0.9224	632.5	0.9495	[24]
Basler_G2_T2	640.5	661.8	0.9680	662.2	0.9674	
Basler_G4_T1	524.9	565.2	0.9286	556.6	0.9430	
Basler_G4_T2	556.0	566.3	0.9819	562.6	0.9883	[25]
UG_1_2	347.0	361.3	0.9604	363.8	0.9536	
UG_2_3	280.2	300.3	0.9335	315.3	0.8891	
Zhu_HSS_65_PB	69.48	69.5	0.9998	69.3	1.0020	[26]
Zhu_HSS_65_PBR	67.5	67.9	0.9943	67.8	0.9959	
Zhu_HSS_80_PB	100.96	101.7	0.9925	101.5	0.9943	
Zhu_HSS_80_PBR	100.91	102.2	0.9876	101.6	0.9928	[27]
Zhu_HYB_80_PB	91.36	87.6	1.0433	87.3	1.0459	
Zhu_HYB_80_PBR	90.78	87.3	1.0403	86.8	1.0458	
I-690-2	659	617.3	1.0675	620.5	1.0621	[17]
I-890-2	844	798.3	1.0572	801.5	1.0530	
Beg_A1	389	406.2	0.9577	425.3	0.9146	
Beg_A2	389	399.9	0.9726	408.9	0.9513	[21]
Beg_B1	391	372.8	1.0489	380.8	1.0268	
Beg_B2	386	366.3	1.0539	380.8	1.0137	
Beg_C1	359	354.4	1.0130	358.9	1.0003	[28]
Beg_C2	356	354.4	1.0045	360.0	0.9889	
Beg_D1	358	351.9	1.0174	358.9	0.9975	
Beg_D2	356	351.9	1.0117	358.9	0.9919	[21]
Beg_E1	311	315.2	0.9866	322.1	0.9655	
Beg_E2	308	318.5	0.9670	327.1	0.9415	
Shokouhian_C1	447.91	447.1	1.0018	436.6	1.0259	[28]
Shokouhian_C2	616.70	558.0	1.1052	577.4	1.0681	
Shokouhian_C3	784.86	772.5	1.0160	760.0	1.0327	
Shokouhian_H1	546.21	504.5	1.0828	504.1	1.0835	[28]
Shokouhian_H2	676.56	650.3	1.0405	650.3	1.0405	
Shokouhian_H3	879.90	859.6	1.0236	865.2	1.0170	
Studer_CSC1_1	522.06	520.8	1.0024	528.7	0.9874	[28]
Studer_CSC1_2	660.91	676.8	0.9766	675.9	0.9778	
Studer_CSC1_3	687.62	724.8	0.9487	727.9	0.9446	
Studer_CSC3_1	713.14	670.6	1.0634	670.6	1.0634	[28]
Studer_CSC3_2	902.81	874.7	1.0322	885.8	1.0192	
Studer_CSC3_3	939.29	922.3	1.0184	924.6	1.0159	

**Fig. 7.** Calculated γ_{FE} , evaluated separately and collectively from the experiments (using geom. imp + RS).

3. Study design and findings

3.1. Strategy and modelling fundamentals

Of the methods presented in the literature review, this paper deals only with ‘Method 1’. The calculation method of the γ_{FE} is of highly important and need careful considerations, to eliminate the duplication of the consideration of the modelling uncertainties. Fig. 2 illustrates the safety factors on the resistance side. Uncertainties on the resistance side include uncertainties in material properties and geometric dimensions – in all cases, whether calculations are performed using analytical or numerical models. These remain unchanged with the introduction of the

direct resistance check. The uncertainties of the calculation model should also be taken into account. For FE-models, this includes the method of imperfection modelling (selection of its shape), the magnitude of the imperfection, type of finite element used and analysis of the resistance check (solver settings, failure criteria, etc.). The uncertainties of the resistance calculation model – which is in the case of the direct resistance check is a numerical model – is partially included in the model factor (γ_{FE}) and in the calculation method uncertainty (γ_{RD}).

The γ_{M^*} factor has already been determined by several researchers for many failure modes, various girder types and applied imperfections. Theoretically, this includes the uncertainty of the calculation method γ_{RD} and the material uncertainty. The uncertainty of the calculation method in the case of direct resistance check includes the method of defining the amplitudes of the imperfections used (e.g., constant or dependent on the slenderness), while in the case of manual calculation methods, the buckling curves consider the effect of imperfections based on laboratory experiments. γ_{M^*} can be determined using stochastic analysis; in this case, the material and geometric properties and the amplitude of the imperfection are probability variables, and this partial factor can be calculated from the load-bearing capacity values corresponding to the 5% and 0.1% quantiles (and using Δk correction factor according to Eqs. (6)-(7)). However, it is important to emphasize that the calculation is performed using one specific numerical model; thus, this factor does not describe how accurately the given FE-model, finite element type, and imperfection shape can represent the real capacity and behaviour. The open question is how accurately the results of laboratory experiments can be reproduced with an FE-model (preferably with knowledge of measured material properties, geometric dimensions, and imperfection amplitudes) for different failure modes, given a specific method of defining imperfections (equivalent or geometric imperfection and residual stresses) – these uncertainties are part of the model factor. The current research aims to specify the γ_{FE} factors for three basic failure modes (I-section in bending, shear buckling and patch loading).

The γ_{FE} model factor accounts for deviations arising from the approximation of the finite element (mesh, shape, type) used. It also considers, how accurate the applied finite element model in terms of the applied element type is, solver technique, solver settings, failure criteria, convergence criteria, etc as well as the material model applied. The model factor accounts for the uncertainty arising from the fact that the modelled geometric imperfections and the characteristics/shape of the residual stress distribution do not fully correspond to those observed in actual test specimens. During modelling, the initial geometric imperfection is accounted for using a general shape (e.g., a half-sine wave) in the FE-model, with the measured maximum imperfection amplitude. The resulting deviations and uncertainties are also covered by the γ_{FE} factor.

In the authors’ opinion, for the sake of applicability, it is advisable to specify a model factor for the various failure modes in the case of different numerical model levels. To this aim in this study, a series of experimental results are collected from the international literature for steel plated structures. In order to validate the numerical model and to determine the γ_{FE} factor, finite element models are created for each failure mode examined, using the parameters from the laboratory tests. There is no difference in the software used (Ansys 19.2 finite element software [16]), the FE-model level (shell-type), the finite element type (four-node thin shell elements), or the material model. The models are verified by checking the mathematical and geometrical adequacy of the finite elements and are validated by comparing the results to the test results.

For the nonlinear calculations based on the international recommendations and given in EN 1993-1-4 [3], a linear elastic – hardening plastic material model (quad-linear material model with strain hardening) is used for normal strength steel (NSS). This material model is defined by three basic parameters – elastic modulus (E), yield strength (f_y) and tensile strength (f_u). For high strength steel (HSS), the two-stage Ramberg-Osgood type material model is used in the numerical

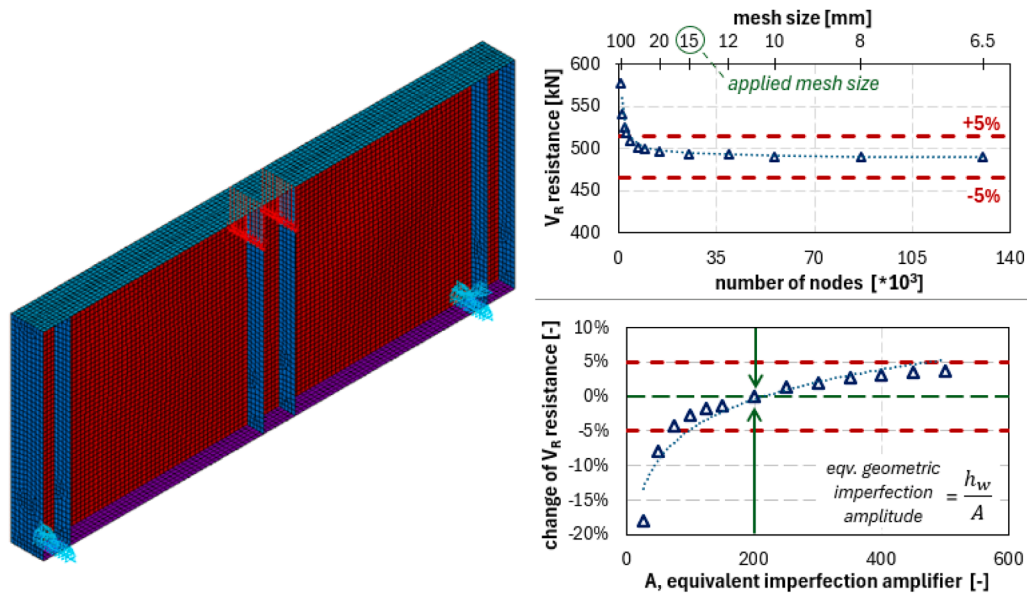


Fig. 8. The finite element model with mesh, boundary, loading conditions, mesh and imperfection sensitivity study.

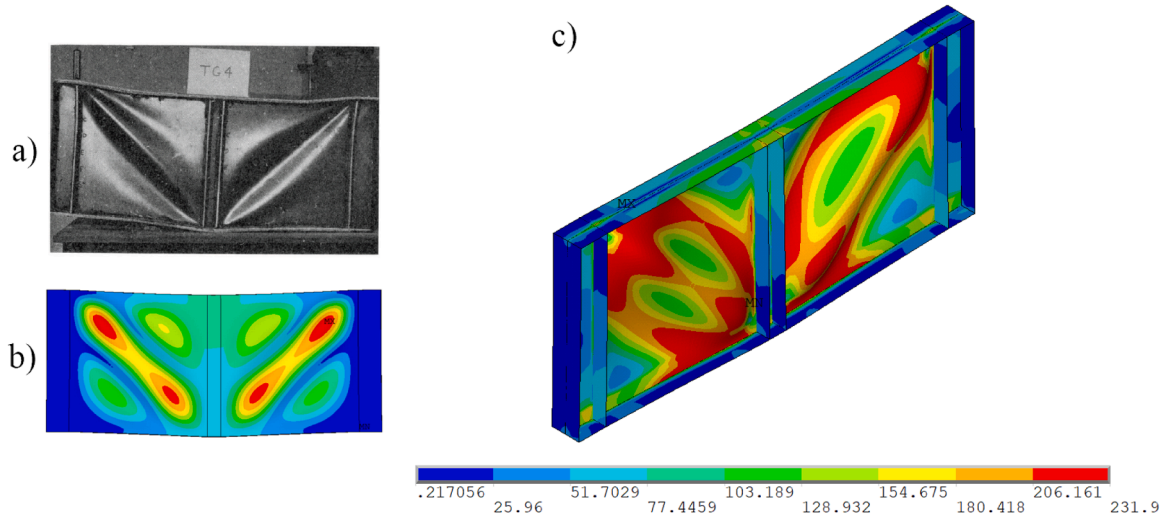


Fig. 9. Failure mode a) in the laboratory test, b) in the FE-model (displacement) and c) von Mises stress distribution for one specimen.

calculations [3], which is a nonlinear elastic-plastic material model that applies strain hardening. All calculations assume an elastic modulus of 210 GPa with a Poisson's ratio of 0.3. In each section, the laboratory investigations and the numerical model properties are shortly presented.

Fig. 3 shows the residual stresses applied according to the EN 1993-1-14 [3], this is applied in all cases in the numerical models. At the web-flange junction are tension-type stresses equal to the yield strength and compressive residual stresses are applied at the middle of the plates, with a value of $0.25 \cdot f_y$ (the width of the tensioned and compressed parts is calculated by equilibrium conditions).

In many cases, measurements of initial geometric imperfections are missing from laboratory experiments. Based on research studies [17–23] in which these amplitudes were documented, we estimated their expected values as a function of the plate thickness. The probabilistic distribution of 54 measured imperfection results is shown in Fig. 4; the average of the denominators was $24 \cdot t_w$, which is used in cases where more precise data was not explicitly given in the background test reports.

3.2. Bending-type failure mode

3.2.1. Introduction of the experiment and numerical model

One of the most basic cases in the civil engineering problems is the beam subjected to pure bending; this task appears in almost every civil engineering design. The model factor value has already been determined for pure bending using several methods in [8]. The model factor is determined now using 'Method 1' supplemented for I-section beams, for a total of 36 laboratory experiments, [17][21][24–28]. The nominal values of the geometrical data (and used initial geometric imperfections) and the material properties of the tested specimens subjected to bending are summarised in Table 7 of the Appendix. The developed model is shown in Fig. 5 together with the finite element mesh, boundary and loading conditions as well as the imperfection shapes specified for the flange and the web plate. Fig. 5 shows both the mesh sensitivity analysis and the imperfection sensitivity analysis. A mesh size of 15 mm is used in the further analysis; thus, based on the mesh convergence study a smaller element size does not result in better accuracy, but it does increase computation time and capacity. Based on the calculation results, it can also be seen that the bending resistance is not particularly

Table 4

Resistances obtained during laboratory tests and virtual experiments (RS means residual stresses).

Name	R_{exp} [kN]	RS + geom imp.		equiv. geom. imp		Ref.
		R_{act} [kN]	ratio [-]	R_{act} [kN]	ratio [-]	
Rockey_TG_1a	112.5	126.0	0.8932	127.7	0.8813	[29]
Rockey_TG_1b	119.5	124.7	0.9580	131.5	0.9090	
Rockey_TG_2a	125.5	123.9	1.0132	134.1	0.9358	
Rockey_TG_2b	117	129.1	0.9065	130.4	0.8974	
Rockey_TG_3a	142	114.6	1.1740	138.6	0.9707	
Rockey_TG_3b	134.5	130.8	1.0853	155.1	0.9156	
Rockey_TG_4a	158.5	135.2	1.1166	156.8	0.9628	
Rockey_TG_4b	151	141.5	1.1203	173.4	0.9139	
Rockey_TG_13	207.5	184.3	1.1256	214.9	0.9655	
Rockey_TG_5a	116.5	119.8	1.0809	132.3	0.9788	
Rockey_TG_5b	129.5	109.7	1.0617	130.9	0.8898	[30]
Rockey_TG_6a	141.5	125.7	1.1258	154.9	0.9137	
Rockey_TG_6b	133	114.4	1.1629	136.9	0.9712	
Rockey_TG_9a	177	112.4	1.0675	128.1	0.9365	
Rockey_TG_9b	192.5	112.8	1.0856	135.0	0.9076	
Rockey_TG_10	201	112.6	1.1365	135.3	0.9462	
Kwon_S_120_120	206.5	641.7	1.1798	761.6	0.9941	
Kwon_S_120_180	122.5	522.3	1.0341	575.5	0.9385	
Kwon_S_120_240	120	443.7	1.0701	492.2	0.9646	
Kwon_S_120_300	128	400.0	1.0848	451.9	0.9601	
Kwon_S_100_120	177	545.3	1.1433	644.1	0.9680	
Kwon_S_100_180	757.1	455.0	1.0678	501.3	0.9691	
Kwon_S_100_240	540.1	403.0	1.0583	448.5	0.9509	
Kwon_S_100_300	474.8	370.7	1.0257	412.4	0.9219	
Kwon_S_80_120	433.9	473.9	1.1028	542.9	0.9625	
Kwon_S_80_180	623.5	396.4	1.0705	436.3	0.9725	
Kwon_S_80_240	485.8	356.1	1.0264	396.9	0.9209	
Kwon_S_80_300	426.5	342.6	0.9828	370.7	0.9084	
Kwon_S_60_120	380.2	384.3	1.1662	430.7	1.0407	
Kwon_S_60_180	522.6	325.8	1.0204	361.3	0.9201	
Kwon_S_60_240	424.3	311.7	1.0249	338.8	0.9431	
Kwon_S_60_300	365.5	301.2	0.9977	323.4	0.9293	

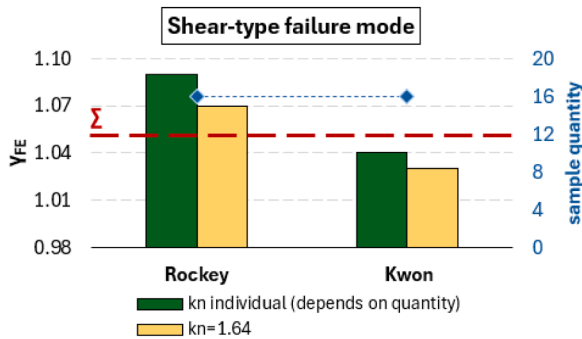


Fig. 10. Calculated γ_{FE} , evaluated separately and collectively from the experiments (using geom. imp + RS).

imperfection-sensitive (if the imperfection is too small, a significant increase in load-bearing capacity is observed), but the calculated ultimate resistance was within a 10% range depending on the imperfection magnitude.

Studer [28] measured the initial geometric imperfection of the flange for all cross-sections examined. The results are in good agreement with the $b_f/2/50$ value recommended by the EN 1993–1–14 [3], so this value is used in this study. The magnitude of the web imperfection is assumed as described in Section 3.1, thus no measured data were available. The numerical model shows good correlation with the failure mode obtained in the laboratory tests, as illustrated in Fig. 6.

3.2.2. Determination of the model factor (γ_{FE})

In the determination of the model factor γ_{FE} , the load carrying

capacity obtained from an accurate numerical model (constructed with the measured geometry, material properties and imperfection amplitudes if available) are compared to the load carrying capacities measured in the tests. The calculation is performed in two ways: (i) by using initial geometric imperfections and residual stresses, and (ii) by applying standard equivalent geometric imperfections. Based on the R_{exp}/R_{act} ratios, the γ_{FE} is determined using Eq. (3) according to the design specifications of EN 1993–1–14 [3]. The details of the calculation process and the ratio for all the 36 specimens from the literature are given in Table 3.

The mean value of the database is 1.01 (with equiv. geom. imp: 0.999) with CoV of 0.043 (with equiv. geom. imp: 0.045). The k_n parameter in the equation equals to 1.64 (>30 tests). The result of the calculation leads to the value of $\gamma_{FE} = 1.07$ (with equiv. geom. imp: 1.08).

The model factor values are further analysed in two ways: (i) separately for the different experimental series, and (ii) collectively for all the data, for the entire database. Fig. 7 shows the results obtained in cases where more than two test specimens were examined, the number of tests in the given study and the dashed line represents the γ_{FE} value determined based on all data.

This analysis examines the model factor values obtained if calculated based on only one study instead of 36 experiments altogether. In this case, the k_n values according to EN 1990 [1], Annex D, Table D.1 should be used in Eq. (3). The γ_{FE} values range from 1.02 to 1.13.

3.3. Shear-type failure mode

3.3.1. Introduction of the experiment and numerical model

In the case of plated structural elements, shear buckling is often the critical mode of failure, in bridge construction, where I-beams and other plate girders are frequently used. GMNIA can be an effective way to determine the shear buckling capacity as well, as has been proven and studied by several researchers in the past. The basic geometric characteristics of the tested specimens are summarised in Table 8 in the Appendix. The developed FE-model with the mesh, boundary conditions, load application is shown in Fig. 8, as well as the mesh sensitivity test and the imperfection sensitivity test. The shear force is applied to nodes along a line parallel to the lateral support at the girder's middle. A mesh size of 15 mm is used in the further analysis; thus, based on the mesh convergence study a smaller element size does not result in better accuracy, but it does increase computation time and capacity. It should be noted that shear failure is relatively imperfection-sensitive, much more than the bending-type failure mode was, therefore, the application of the imperfection shape and magnitude has a special importance within the calculation process.

Fig. 9 presents the comparison of the failure modes from the numerical analysis and the laboratory tests for one specimen, which is the shear buckling behaviour, presenting the out-of-plane displacements and the von Mises stress distribution at the ultimate load level.

3.3.2. Determination of the model factor (γ_{FE})

In the determination of the model factor (γ_{FE}), the load carrying capacity obtained from the accurate numerical model is compared to the load carrying capacities measured in the tests (summarised in Table 4). γ_{FE} is determined by Eq. (3), which takes into account the mean value and coefficient of variation of the resistance ratios determined through laboratory experiments and using a numerical model.

The mean value of the database is 1.07 (with equiv. geom. imp: 0.943) with CoV of 0.07 (with equiv. geom. imp: 0.04). The k_n parameter in the equation equals to 1.64 (>30 tests). The result of the calculation leads to the value of $\gamma_{FE} = 1.05$ (with equiv. geom. imp: 1.13).

Fig. 10 shows the model factor results obtained in two different ways: (i) separately for the different experimental series, and (ii) collectively for all the data. The dashed line represents the γ_{FE} value determined based on all the data set.

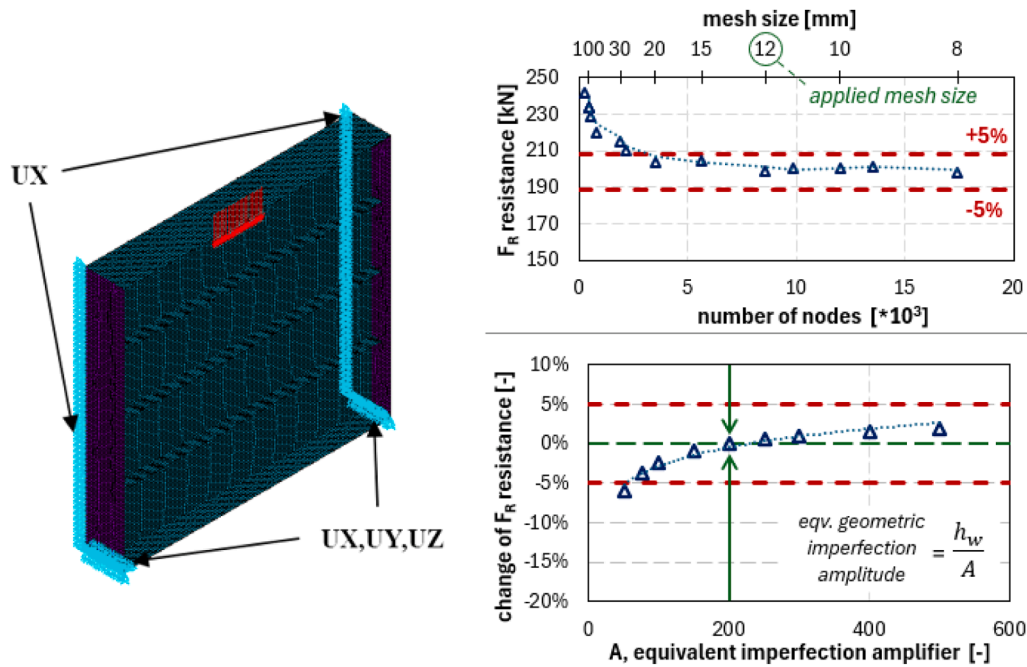


Fig. 11. The meshed finite element model with mesh, boundary- and loading conditions, and the mesh and imperfection sensitivity study.

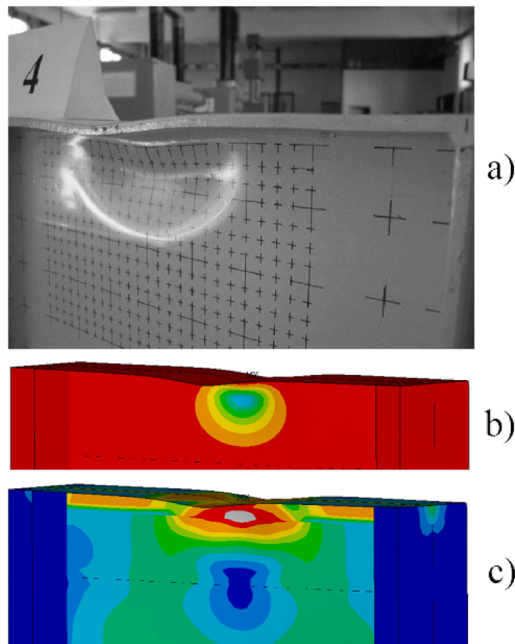


Fig. 12. Failure mode a) in the laboratory test, b) in the FE-model (displacement) and c) von Mises stress distribution for one specimen.

This analysis examines the model factor values obtained if calculated based on only one study instead of 32 experiments altogether. In this case, the k_n values according to EN 1990 [1], Annex D, Table D.1 should be used in Eq. (3). The γ_{FE} values range from 1.03 to 1.09.

3.4. Patch-loading type failure mode

3.4.1. Introduction of the experiment and numerical model

Slender plated structures can be sensitive to direct loading; therefore, the patch loading-type failure mode is often critical for bridges (especially under launching process). In recent decades, numerous studies

have addressed this failure mode. Both laboratory experiments and numerical analyses have been conducted; one of the most important issues addressed by this research is the effect of imperfections and their appropriate consideration. The shape of the imperfection included in the FE-model is an important point, as it has a significant effect on the load bearing capacity. The shape of the measured initial geometric imperfections determined by Kovacevic and Markovic [22] is typically the global buckling shape. Therefore, this imperfection shape is used in this study to determine the model factor. The current paper utilizes a total of 40 laboratory experiments. Where no measurement data was available for the amplitude of the initial geometric imperfection, an imperfection magnitude of $h_w/(24 \cdot t_w)$ depending on the plate thickness, is applied based on the average of the 54 existing data points, as described in Section 3.1. The nominal values of the geometric data and material properties of the tested specimens subjected to patch loading are summarised in Table 9 of the Appendix. The developed numerical model is presented in Fig. 11 with the finite element mesh, boundary conditions, and loading conditions. The length of an applied patch load varies between 1 and 250 mm depending on the actual conditions applied in the laboratory test program. Fig. 11 also includes diagrams of the mesh sensitivity test and the imperfection sensitivity test. For patch loading, an element size of 12 mm is used in the further analysis thus, based on the mesh convergence study a smaller element size does not result in better accuracy, but it does increase computation time and capacity. In terms of imperfection sensitivity, this can be considered that this type of failure mode is more sensitive to the bending-type was but less sensitive than the shear failure.

Fig. 12 presents the comparison of the failure modes from the numerical analysis and the laboratory tests for one specimen. The comparison shows good agreement, the obtained failure mode in the numerical model is the web crippling-type failure mode, which was also observed during the tests; the figure presents the out-of-plane displacements and the von Mises stress distribution at the ultimate load level.

3.4.2. Determination of the model factor (γ_{FE})

Table 5 summarises the results of the laboratory experiments and the load-bearing capacities obtained using the numerical model.

The mean value of the database is 1.1 (with equiv. geom. imp: 1.08)

Table 5

Resistances obtained during laboratory tests and virtual experiments (RS means residual stresses).

Name	R_{exp} [kN]	RS + geom. imp.		equiv. geom. imp		Ref.
		R_{act} [kN]	ratio [-]	R_{act} [kN]	ratio [-]	
Kövesdi_1	206.4	192.6	1.0719	201.3	1.0254	[31]
Kövesdi_2	258.4	249.4	1.0361	272.7	0.9474	
Kövesdi_3	271.0	280.5	0.9661	291.2	0.9303	
Kövesdi_4	320.4	283.0	1.1321	294.3	1.0886	[22]
Kövesdi_5	180.2	173.7	1.0373	178.6	1.0092	
Kövesdi_6	214.3	193.1	1.1100	201.5	1.0633	
Kövesdi_7	218.4	182.4	1.1971	189.4	1.1533	[23]
Kövesdi_8	223.8	187.5	1.1937	194.6	1.1499	
Kovacevic_B16	129.9	116.9	1.1112	121.0	1.0739	
Kovacevic_B13	148.6	136.8	1.0866	139.5	1.0655	[32]
Kovacevic_B14	147.9	137.4	1.0764	141.8	1.0430	
Kovacevic_B1	140.3	123.4	1.1368	127.7	1.0984	
Kovacevic_B3	164.9	150.5	1.0956	153.0	1.0778	[23]
Kovacevic_B15	176.9	160.2	1.1041	164.4	1.0762	
Kovacevic_B5	200.3	176.9	1.1323	180.9	1.1074	
Kovacevic_B2	174.6	141.2	1.2367	146.4	1.1929	[32]
Kovacevic_B7	240.3	226.4	1.0615	226.8	1.0595	
Kovacevic_B17	233.9	226.4	1.0333	226.8	1.0312	
Kovacevic_B12	190.9	154.3	1.2373	160.4	1.1905	[32]
Kovacevic_B4	275.3	274.6	1.0026	272.7	1.0095	
Kovacevic_B11	199.9	179.9	1.1114	186.9	1.0698	
Kovacevic_B6	290.3	272.5	1.0654	272.3	1.0662	[32]
Walbridge_1_C1	425.8	395.3	1.0771	405.3	1.0506	
Walbridge_5_C3	559.9	536.4	1.0438	537.6	1.0416	
Walbridge_6_C3	582.1	510.2	1.1408	511.6	1.1379	[23]
Walbridge_4_C2	520.6	499.1	1.0431	500.8	1.0396	
Kovacevic_A15	143.3	141.0	1.0164	144.8	0.9895	
Kovacevic_A14	165.9	144.8	1.1460	150.1	1.1056	[32]
Kovacevic_A12	154.6	145.8	1.0605	149.7	1.0330	
Kovacevic_A4	180.0	151.8	1.1858	155.4	1.1586	
Kovacevic_A1	165.0	146.7	1.1250	152.3	1.0835	[32]
Kovacevic_A3	183.0	168.8	1.0843	166.1	1.1017	
Kovacevic_A17	194.3	178.8	1.0867	186.2	1.0435	
Kovacevic_A11	199.0	163.5	1.2173	170.0	1.1704	[32]
Kovacevic_A5	225.0	193.9	1.1606	195.5	1.1506	
Kovacevic_A6	259.0	223.2	1.1604	221.7	1.1684	
Kovacevic_A2	215.0	198.1	1.0851	207.5	1.0363	[32]
Kovacevic_A7	255.0	233.0	1.0944	232.1	1.0987	
Kovacevic_A13	230.0	198.4	1.1593	207.7	1.1075	
Kovacevic_A16	244.6	241.9	1.0113	241.1	1.0147	[32]

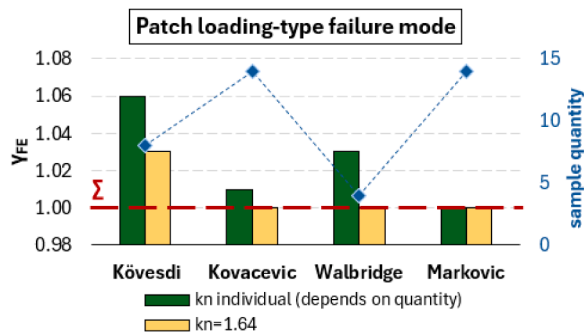


Fig. 13. Calculated γ_{FE} , evaluated separately and collectively from the experiments (using geom. imp + RS).

with CoV of 0.06 (with equiv. geom. imp: 0.06). The k_n parameter in the equation equals to 1.64 (>30 tests). The result of the calculation leads to the value of $\gamma_{FE} = 1.00$ (with equiv. geom imp: 1.02).

Fig. 13 shows the model factor results obtained in two ways: (i) separately for the different experimental series, and (ii) collectively for all the data. The dashed line represents the γ_{FE} value determined based on all the data.

This analysis examines the model factor values obtained if calculated

Table 6

The calculated γ_{FE} factors for the failure modes examined, the name refers to the amplitude of the imperfection; + RS means the residual stress.

failure	sample quantity	imperfection	m_x	V_x	γ_{FE}
bending	36	$h_w/(24 t_w) + RS$	1.006	0.043	1.07
		equivalent geom. imp.	0.999	0.045	1.08
shear	32	$h_w/(24 t_w) + RS$	1.068	0.066	1.05
		equivalent geom. imp.	0.943	0.035	1.13
patch loading	40	$h_w/(24 t_w) + RS$	1.103	0.058	1.00
		equivalent geom. imp.	1.077	0.057	1.02

based on only one study instead of 40 experiments altogether. In this case, the k_n values according to EN 1990 [1], Annex D, Table D.1 should be used in Eq. (3). The γ_{FE} values range from 1.00 to 1.06.

4. Result discussions

The numerical models developed for the laboratory experiments are run for more than 30 cases for each of the three failure modes under investigation. Two variants are examined in terms of how imperfections are defined. Although, in theory, the model factor should be calculated using precise measured geometric and material properties—and thus the model should account for initial geometric imperfections and residual stress—the case of applying an equivalent geometric imperfection is also examined. Table 6 summarises the model factor values obtained for the analysed failure modes indicating the type of imperfection applied.

It can be seen that the case of equivalent geometric imperfection always gives the higher model factor value. Therefore, even though it is not entirely correct in theory, if the designer uses equivalent geometric imperfection for validation and determines the model factor based on this assumptions, the calculation will be on the safe side.

The resulting γ_{FE} values, using initial geometric imperfections and residual stresses, range from 1.00 to 1.07. These values appear to be safe for use with shell-type FE-models for the analysed failure modes. Furthermore, it should be emphasized that the model factor can also be determined independently through the validation of individually developed numerical models; however, it is important to ensure that the value of k_n is selected based on the number of laboratory experiments used. Obviously, the effect of the incorrect k_n factor is more significant the fewer test samples are included in the calculation.

5. Summary and conclusions

In this study, an FE-model is developed for three typical failure modes (I-section in bending, shear buckling and patch loading) of slender steel plated structures, and the model factors are determined based on previous laboratory experiments found in the international literature. The numerical models use the same finite element type, material model, and imperfection definition method; so the current results are limited to the here applied modelling assumptions, which are common modelling assumptions for the design of steel structures. It is also important to note that the conclusions of the study are based on a series of experiments conducted using a single software package. The study presented (i) provides an example of how users applying shell-type, nonlinear FE-models in a design context determine their own γ_{FE} values, (ii) offers guidance on how to determine these values for specific frameworks (e.g. shell model, imperfection in accordance with EN 1993-1-14 + bilinear material law involving strain-hardening + a given failure mode) and, following further comprehensive investigation, to recommend default values for use in practice. To determine reliable γ_{FE} values, a large number of well-documented laboratory experiments and their analysis would be required, and it should be investigated whether

the γ_{FE} factor depends on slenderness or other parameter. Further research on the model factor should be made to extend the current database to include further failure modes, experiments and finite element analysis software.

For each failure mode, more than 30 test specimens are examined, and the load-bearing capacities obtained in the physical and virtual experiments are compared. A statistical evaluation is performed, and the model factor is determined separately for each experimental program and for the entire dataset together. Two methods for defining imperfections are also examined. The following conclusions are drawn from the studies:

- To determine the model factor, measured material properties, geometric dimensions, and imperfection amplitudes (and, if possible, residual stress measurements) are required within the test program. The load-bearing capacity values obtained from the advanced numerical model developed based on the measurement data should be compared with those measured during laboratory testing in accordance with EN 1993–1–14 [3].
- The current investigations showed that using an equivalent geometric imperfection yields higher model factor values than by using geometric imperfections and residual stresses, making the application of the equivalent geometric imperfections with the currently proposed model factors a conservative approach.
- All the obtained model factor values within this study are between 1.0 – 1.13 by using different imperfection definition methods,

statistical evaluation processes and studied failure modes. The obtained model factor values are 1.07 for bending, 1.06 for shear, and 1.01 for patch loading by using the here applied numerical modelling settings, analysis-type, failure criteria and result evaluation method.

The obtained values could be refined in the future by extending the database with further numerical investigations and experimental results.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

In the appendix, the notations used in the columns of the tables are the following:

a – panel length; t_w – web thickness; h_w – web height; b_{f1} – lower flange width; t_{f1} – lower flange thickness; b_{f2} – width of upper flange; t_{f2} – flange thickness; f_{yw} – yield strength of web plate; f_{tw} – tensile strength of web plate; f_{yf} – yield strength of flange plates; f_{tf} – tensile strength of flange plates; r – distance between intermediate diaphragms; d_1 – distance between outer diaphragms; b_s – width of the stiffening rib; t_s – thickness of the stiffening rib; *meas. geom. imp.* – measured initial geometric imperfection amplitude; *N/A* indicates that no data is available; and *applied geom. imp.* denotes the amplitude of the applied geometric imperfection.

Table 7

Basic dimensions and material properties of the bending-type test specimens

Name	Geometry [mm]							Material [MPa]				Imperfection	
	a	t_w	h_w	b_{f1}	t_{f1}	b_{f2}	t_{f2}	f_{yw}	f_{tw}	f_{yf}	f_{tf}	meas. geom. imp. [mm]	applied geom. imp.
Basler_G2_T1	1905	7	1270	310	20	310	20	244	414	266	440	N/A	$h_w/(24 t_w)$
Basler_G2_T2	952.5	7	1270	310	20	310	20	244	414	266	440	N/A	$h_w/(24 t_w)$
Basler_G4_T1	1905	3	1270	309	20	310	19	299	419	259	440	N/A	$h_w/(24 t_w)$
Basler_G4_T2	952.5	3	1270	309	20	310	19	299	419	259	440	N/A	$h_w/(24 t_w)$
UG_1_2	1000	3	914.4	203	16	203	16	306	430	236	360	10.5	$h_w/87$
UG_2_3	1000	3	914.4	203	16	203	16	298	420	249	360	N/A	$h_w/(24 t_w)$
Zhu_HSS_65_PB	200	8	99.51	64	8	64	8	783	828	783	828	N/A	$h_w/(24 t_w)$
Zhu_HSS_65_PBR	200	8	99.7	62	8	62	8	783	828	783	828	N/A	$h_w/(24 t_w)$
Zhu_HSS_80_PB	200	8	119.85	80	8	80	8	783	828	783	828	N/A	$h_w/(24 t_w)$
Zhu_HSS_80_PBR	200	8	119.87	79	8	79	8	783	828	783	828	N/A	$h_w/(24 t_w)$
Zhu_HYB_80_PB	200	8	119.92	80	8	80	8	404	554	783	828	N/A	$h_w/(24 t_w)$
Zhu_HYB_80_PBR	200	8	119.91	80	8	80	8	404	554	783	828	N/A	$h_w/(24 t_w)$
I-690-2	440	8	341.06	160	12	160	12	690	745	690	745	2.0	$h_w/171$
I-890-2	440	8	341.12	160	12	160	12	890	945	890	945	2.0	$h_w/171$
Beg_A1	1200	10	221.7	300	13	300	13	775	814	843	883	N/A	$h_w/(24 t_w)$
Beg_A2	1200	10	220.9	299	12	299	12	775	814	843	883	N/A	$h_w/(24 t_w)$
Beg_B1	1200	10	222.7	271	12	271	12	775	814	797	808	N/A	$h_w/(24 t_w)$
Beg_B2	1200	10	221	269	13	269	13	775	814	797	808	N/A	$h_w/(24 t_w)$
Beg_C1	1200	10	221.3	251	13	251	13	775	814	776	808	N/A	$h_w/(24 t_w)$
Beg_C2	1200	10	222.3	251	13	251	13	775	814	776	808	N/A	$h_w/(24 t_w)$
Beg_D1	1200	10	220.9	221	12	221	12	830	864	873	883	N/A	$h_w/(24 t_w)$
Beg_D2	1200	10	221.4	220	12	220	12	830	864	873	883	N/A	$h_w/(24 t_w)$
Beg_E1	1200	10	220.7	199	13	199	13	830	864	797	808	N/A	$h_w/(24 t_w)$
Beg_E2	1200	10	222.6	199	13	199	13	830	864	797	808	N/A	$h_w/(24 t_w)$
Shokouhian_C1	1000	8	357.4	169	12	170	12	408	550	443	580	0.97	$h_w/368$
Shokouhian_C2	1000	8	358.48	264	12	264	12	408	550	443	580	3.96	$h_w/91$
Shokouhian_C3	1000	8	598.58	168	12	169	12	408	550	443	580	3.04	$h_w/197$

(continued on next page)

Table 7 (continued)

Name	Geometry [mm]							Material [MPa]				Imperfection	
	a	t _w	h _w	b _{f1}	t _{f1}	b _{f2}	t _{f2}	f _{yw}	f _{uw}	f _{yf}	f _{uf}	meas. geom. imp. [mm]	applied geom. imp.
Shokouhian_H1	1000	8	358.54	168	13	168	13	545	630	443	580	1.35	h _w /266
Shokouhian_H2	1000	8	358.95	265	13	264	13	545	630	443	580	1.03	h _w /348
Shokouhian_H3	1000	8	598.14	167	13	168	13	545	630	443	580	3.78	h _w /158
Studer_CSC1_1	1000	16	268	210	16	210	16	393	537	393	537	N/A	h _w /(24 t _w)
Studer_CSC1_2	1000	16	268	210	16	210	16	507	563	507	563	N/A	h _w /(24 t _w)
Studer_CSC1_3	1000	16	268	210	16	210	16	543	593	543	593	N/A	h _w /(24 t _w)
Studer_CSC3_1	1000	16	268	310	16	310	16	393	537	393	537	N/A	h _w /(24 t _w)
Studer_CSC3_2	1000	16	268	310	16	310	16	507	563	507	563	N/A	h _w /(24 t _w)
Studer_CSC3_3	1000	16	268	310	16	310	16	543	593	543	593	N/A	h _w /(24 t _w)

Table 8

Basic dimensions and material properties of the shear-type test specimens

Name	Geometry [mm]							Material [MPa]				Imperfection	
	a	t _w	h _w	b _{f1}	t _{f1}	r	d ₁	f _{yw}	f _{uw}	f _{yf}	f _{uf}	meas. geom. imp. [mm]	applied geom. imp.
Rockey_TG_1a	610	3	610	102	5	12	250	253	360	253	360	N/A	h _w /(24 t _w)
Rockey_TG_1b	610	3	610	102	5	12	250	242	360	242	360	N/A	h _w /(24 t _w)
Rockey_TG_2a	610	3	610	102	7	12	250	238	360	238	360	N/A	h _w /(24 t _w)
Rockey_TG_2b	610	3	610	102	6	12	250	251	360	251	360	N/A	h _w /(24 t _w)
Rockey_TG_3a	610	3	610	102	13	12	250	204	360	204	360	N/A	h _w /(24 t _w)
Rockey_TG_3b	610	3	610	102	13	12	250	233	360	233	360	N/A	h _w /(24 t _w)
Rockey_TG_4a	610	3	610	102	16	12	250	231	360	231	360	N/A	h _w /(24 t _w)
Rockey_TG_4b	610	3	610	102	16	12	250	261	360	261	360	N/A	h _w /(24 t _w)
Rockey_TG_13	610	3	610	102	25	12	250	296	400	296	400	N/A	h _w /(24 t _w)
Rockey_TG_5a	914	3	610	203	10	30	85	296	360	296	360	N/A	h _w /(24 t _w)
Rockey_TG_5b	914	3	610	203	10	30	85	266	370	266	370	N/A	h _w /(24 t _w)
Rockey_TG_6a	914	3	610	203	16	30	85	301	360	301	360	N/A	h _w /(24 t _w)
Rockey_TG_6b	914	3	610	203	16	30	85	252	370	252	370	N/A	h _w /(24 t _w)
Rockey_TG_9a	1219	3	610	203	10	30	85	269	380	269	380	N/A	h _w /(24 t _w)
Rockey_TG_9b	1219	3	610	203	10	30	85	289	400	289	400	N/A	h _w /(24 t _w)
Rockey_TG_10	1219	3	610	203	16	30	85	273	390	273	390	N/A	h _w /(24 t _w)
Kwon_S_120_120	440	5	1176	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_120_180	740	5	1176	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_120_240	1040	5	1176	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_120_300	1340	5	1176	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_100_120	440	5	976	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_100_180	740	5	976	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_100_240	1040	5	976	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_100_300	1340	5	976	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_80_120	440	5	776	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_80_180	740	5	776	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_80_240	1040	5	776	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_80_300	1340	5	776	250	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_60_120	440	5	576	150	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_60_180	740	5	576	150	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_60_240	1040	5	576	150	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)
Kwon_S_60_300	1340	5	576	150	12	150	85	339	440	375	530	N/A	h _w /(24 t _w)

Table 9

Basic dimensions and material properties of the patch loading type test specimens

Name	Geometry [mm]							Material [MPa]				Imperfection	
	a	h _w	t _w	b _f	t _f	b _s	t _s	f _{yw}	f _{uw}	f _{yf}	f _{uf}	meas. geom. imp. [mm]	applied geom. imp.
Kövesdi_1	990	500	4	150	10	40	4	286	392	288	385	N/A	h _w /(24 t _w)
Kövesdi_2	990	500	4	150	10	40	4	318	405	268	377	N/A	h _w /(24 t _w)
Kövesdi_3	990	500	4	150	10	40	4	311	400	266	373	N/A	h _w /(24 t _w)
Kövesdi_4	990	500	4	150	10	60	4	314	405	283	386	N/A	h _w /(24 t _w)
Kövesdi_5	990	500	4	150	10	60	4	308	392	272	368	N/A	h _w /(24 t _w)
Kövesdi_6	990	500	4	150	10	40	4	343	444	262	370	N/A	h _w /(24 t _w)
Kövesdi_7	990	500	4	150	10	40	4	299	394	285	384	N/A	h _w /(24 t _w)
Kövesdi_8	990	500	4	150	10	60	4	311	393	288	384	N/A	h _w /(24 t _w)
Kovacevic_B16	1000	500	4	120	8	-	-	262	348	314	466	7.7	h _w /65
Kovacevic_B13	1000	500	4	120	8	30	8	315	434	313	463	5.7	h _w /87
Kovacevic_B14	1000	500	4	120	8	-	-	318	434	323	470	12.5	h _w /40
Kovacevic_B1	1000	500	4	120	8	-	-	257	348	316	462	10.4	h _w /48
Kovacevic_B3	1000	500	4	120	8	30	8	315	434	313	463	5.7	h _w /87

(continued on next page)

Table 9 (continued)

Name	Geometry [mm]							Material [MPa]				Imperfection	
	a	h _w	t _w	b _f	t _f	b _s	t _s	f _{yw}	f _{uw}	f _{yf}	f _{uf}	meas. geom. imp. [mm]	applied geom. imp.
Kovacevic_B15	1000	500	4	120	8	-	-	318	436	312	460	3.6	h _w /140
Kovacevic_B5	1000	500	4	120	8	30	8	318	436	312	460	3.6	h _w /140
Kovacevic_B2	1000	500	4	120	8	-	-	226	337	313	464	5.0	h _w /100
Kovacevic_B7	1000	500	4	120	8	30	8	327	439	339	486	9.6	h _w /52
Kovacevic_B17	1000	500	4	120	8	30	8	327	439	339	486	9.6	h _w /52
Kovacevic_B12	1000	500	4	120	8	-	-	226	337	313	464	5.0	h _w /100
Kovacevic_B4	1000	500	4	120	8	30	8	318	434	323	470	12.5	h _w /40
Kovacevic_B11	1000	500	4	120	8	-	-	257	348	316	462	10.4	h _w /48
Kovacevic_B6	1000	500	4	120	8	30	8	262	348	314	466	7.7	h _w /65
Walbridge_1_C1	1000	700	5	225	20	-	-	392	530	355	500	N/A	h _w /(24 t _w)
Walbridge_5_C3	1000	700	5	225	20	80	10	392	530	355	500	N/A	h _w /(24 t _w)
Walbridge_6_C3	1000	700	5	225	20	80	10	392	530	355	500	N/A	h _w /(24 t _w)
Walbridge_4_C2	1000	700	5	225	20	80	10	392	530	355	500	N/A	h _w /(24 t _w)
Kovacevic_A15	500	500	4	120	8	-	-	328	443	321	468	5.9	h _w /85
Kovacevic_A14	500	500	4	120	8	30	8	321	442	315	476	5.9	h _w /85
Kovacevic_A12	500	500	4	120	8	-	-	324	445	321	466	13.2	h _w /38
Kovacevic_A4	500	500	4	120	8	30	8	321	442	315	476	4.0	h _w /125
Kovacevic_A1	500	500	4	120	8	-	-	305	434	315	476	5.6	h _w /89
Kovacevic_A3	500	500	4	120	8	30	8	324	438	325	474	3.0	h _w /167
Kovacevic_A17	500	500	4	120	8	30	8	318	434	317	475	5.1	h _w /98
Kovacevic_A11	500	500	4	120	8	-	-	305	434	317	475	7.8	h _w /64
Kovacevic_A5	500	500	4	120	8	30	8	328	443	321	468	5.2	h _w /96
Kovacevic_A6	500	500	4	120	8	30	8	332	444	320	475	5.6	h _w /89
Kovacevic_A2	500	500	4	120	8	-	-	324	445	321	466	7.3	h _w /68
Kovacevic_A7	500	500	4	120	8	30	8	318	434	317	475	4.0	h _w /125
Kovacevic_A13	500	500	4	120	8	-	-	324	438	325	474	3.0	h _w /167
Kovacevic_A16	500	500	4	120	8	30	8	332	444	320	475	6.6	h _w /76

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