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Numerical model-based design of bolted shear connections – bearing resistance

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Abstract

Numerical model-based design of steel bolted connections is an emerging application field in the design of steel structures. The new EN 1993-1-14 provides background for the standardized application of the direct resistance check for bolted connections, which should be designed based on plastic design theory. However, there is a lack of detailed investigation and accurate design rules on the model input parameters regarding to steel material model and the allowed maximum plastic strains to be used during the non-linear design calculation. On the other side, the bearing resistance check has been significantly modified in the second generation EN 1993-1-8. The resistance is increased according to the latest design method, which increase should be also reproducible by the numerical model results. Therefore, the current investigation presented in this paper aims to propose accurate material model and design limit state criteria in terms of the maximum allowable plastic strain for the bearing resistance check of bolted connections.

Keywords

shear bolts, bearing resistance, plastic design, direct resistance check, numerical model-based design.

1 Introduction

The current paper investigates the bearing resistance of a shear bolted connection with one M30 double shear bolt. The motivation of the investigation is twofold: (i) by using three different analytical-based design models, the differences between the obtain bearing resistances for the specific joint was significant and its accuracy was questioned, (ii) the applicability of the plastic design methodology (e.g. allowed plastic strains) of the EN 1993-1-14:2025 [1] was also to be checked to accurately calculate the bearing resistance of the connection by using direct resistance check. The current study enables a direct comparison of analytical-based, numerical model-based, and test-based design approaches. The bearing resistance according to the first generation EN 1993-1-8:2005 [2] and the second generation EN 1993-1-8:2024 [3] reveals significant disparities, resulting in an increase in resistance of ~20% for the specific connection studied. Furthermore, both design methods yield considerably higher bearing resistances compared to the existing Hungarian design code, which is still in use for steel bridges in Hungary. This discrepancy necessitates a thorough evaluation of the accuracy of the Eurocode-based resistance models. Conversely, advanced numerical model-based design methodologies can also be employed to analyze the relevant load-carrying capacity, adhering to the design regulations outlined in EN 1993-1-14:2025 [1]. It is important to note that the bearing resistance check is a plastic resistance calculaton, wherein significant plastic deformations may occur, and this must be taken into account within the numerical design. Additionally, the application of the maximum allowed plastic strain is subject to scrutiny, with its design value currently under investigation. To address these issues, an experimental campaign involving six test specimens is conducted to compare analytical approaches and verify the numerical model-based design. During testing, the failure mode was bearing-type failure of the connection plate. From the six specimens, the characteristic and design resistances are calculated, serving as reference values for the assessment and evaluation of both analytical and numerical model-based design approaches. The test results lead to an evaluation of the bearing resistance from EN 1993-1-8:2024 [3], confirming its accuracy for the specific analysed geometrical conditions. Additionally, the paper presents findings from a numerical research program investigating various material models within the context of direct resistance checks demonstrating the proper application of advanced GMNI analysis to determine bearing resistance. The current paper is limited to one connection type and

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geometry and demonstrates the adeqacy of the analytical and numerical design methods. In the future, the research work can be extended and generalized for other geometries and connection types as well.

2 Literature review

2.1 Bearing resistance acc. to EN 1993-1-8

The shear ($F_{V,Rd}$) and bearing resistance of a bolted connection with one bolt can be calculated by using Eqs. (1)-(4) according to EN 1993-1-8:2005 [2].

$$F_{v,Rd} = \frac{\alpha_v \cdot f_{ub} \cdot A}{\gamma_{M2}} \tag{1}$$

where: α_v is equal to 0,6 if shear plane passes through the unthreaded portion of the bolt, f_{ub} is the ultimate strength and A is the gross cross-section of the bolt.

$$F_{b,Rd} = \frac{k_1 \cdot \alpha_b \cdot f_u \cdot d \cdot t}{\gamma_{M2}} \tag{2}$$

where for one outer bolt:

$$\alpha_b = \min\left(\frac{e_1}{3 \cdot d_0}, \frac{f_{ub}}{f_u}, 1.0\right) \tag{3}$$

$$k_1 = \min\left(2.8 \cdot \frac{e_2}{d_0} - 1.7, 2.5\right) \tag{4}$$

f_u is the ultimate strength of the steel plates, d is the bolt diameter, t is the plate thickness. Further input data are according to EN 1993-1-8:2005 [2].

The bearing resistance check is changed within the second generation EN 1993-1-8:2022 [3] to Eqs. (5-8), which increases the resistance for many connection geometries:

$$F_{b,Rd} = \frac{k_m \cdot \alpha_b \cdot f_u \cdot d \cdot t}{\gamma_{M2}} \tag{5}$$

where for one end fastener:

$$\alpha_b = \min\left(\frac{e_1}{d_0}, 3 \cdot \frac{f_{ub}}{f_u}, 3.0\right) \tag{6}$$

$$k_m = 1 \quad \text{for steel grades up to S460} \tag{7}$$
$$k_m = 0.9 \text{ for steel grades equal to or higher than S460}$$

In addition, a new design equation is added to reduce the bearing resistance for connections, where the plastic deformations due to bearing of the fastener against the plate are to be limited. The reduction factor $\alpha_{b,red}$ should be obtained from Eqs. (8-9).

$$\alpha_{b,red} = \min(0.8 \cdot \alpha_b, 2.0) \text{ for steel grades up to S460} \tag{8}$$

$$\alpha_{b,red} = \min(\alpha_b, 2.0) \text{ for steel grades equal to or higher than S460} \tag{9}$$

2.2 Plastic resistance check acc. to EN 1993-1-14

EN 1993-1-14:2025 [1] specifies different modeling levels and analysis types for both daily design practice and research and development (R&D) engineering. The code organizes design rules into two primary tracks based on their purpose: (1) numerical design calculations and (2) numerical simulations. The first track, numerical design calculations, addresses practical design scenarios and is further divided into two sub-tracks: (a) analysis requiring a subsequent design check, and (b) direct resistance check. In the direct resistance sub-track, the ultimate structural resistance is determined directly from the numerical simulation, obviating the need for additional analytical or empirical calculations. This approach necessitates the use of a materially non-linear analysis (MNA), geometrically and materially non-linear analysis (GMNA), or geometrically and materially non-linear imperfect analysis (GMNIA) to determine structural resistance. The specific analysis chosen depends on whether second-order effects and imperfections significantly influence the non-linear behaviour and resistance. For instance, GMNA is appropriate when imperfections have negligible impact on structural resistance, such as for tension members, restrained structural members (beams/columns) without stability issues, or components designed using plastic design methods (e.g. certain joint components). For the numerical design calculations, nominal geometric and material properties should be employed to predict internal forces or the characteristic resistance of the structure.

The second track, numerical simulation, facilitates the supplementation of physical experiments and model validation. EN 1993-1-14 includes this option to enable product development and R&D engineers to expand experimental datasets using accurate geometrically and materially non-linear numerical models. Results from these simulations should be treated equivalently to experimental test results, with the same design rules applied for their evaluation. For numerical simulations, geometric and material properties should reflect measured or statistically predicted mean values. These calculations are intended to be equivalent or quasi-equivalent to laboratory test results, with their inherent uncertainties accounted for through statistical evaluation (of actual or virtual Finite Element tests) for partial safety factor determination or design resistance calculation. In this paper, the application of both tracks will be demonstrated for the analyzed shear bolted connection by using plastic design check. For plastic limit states, two analysis types are appropriate: (i) materially non-linear analysis (MNA) or (ii) geometrically and materially non-linear analysis (GMNA). Geometrically non-linear analysis is crucial for structures where changes in geometry significantly influence internal force and stress distribution. Materially non-linear analysis should be conducted by incrementally applying the design load level (or the load level of the specific load case combination) from zero until failure or 100% of the applied load is reached. The resulting load-displacement path is then evaluated according to the rules specified in EN 1993-1-14:2025 [1].

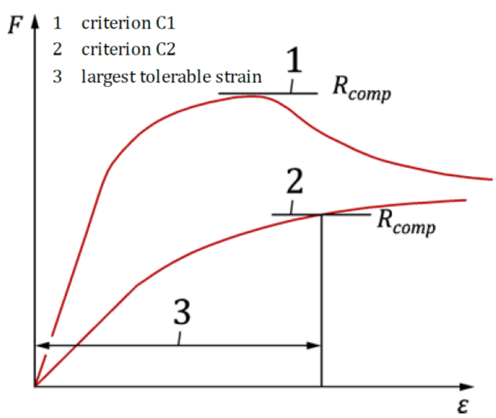

Figure 1 Evaluation strategy of load-displacement path according to EN 1993-1-14 [1].

The structural resistance R_{comp} (e.g. R_{MNA}, R_{GMNA} or R_{GMNIA} according to the analysis type applied) should be obtained from the load-deformation response by taking the lowest resistance using the following two criteria C1, C2 (see Figure 1). Criterion C1 is the maximum load of the load-deformation response. Criterion C2 is the load corresponding to a limiting deformation or strain criterion, where this occurs before reaching the maximum load. If there are no other values given, a recommended value for the maximum equivalent plastic strain of the material may be assumed by 0.33 $\cdot\varepsilon u$ for uniaxial and 0.15 $\cdot\varepsilon u$ for biaxial stress-strain state. In case of triaxial stress-strain state or multiaxiality, strain limits should be based on advanced damage theory.

In the case of stability problems, C1 will usually govern. In the case of plastic failure modes which have large plastic deformations (e.g. Class 1-2 cross-sections under bending, welded and bolted joints), C2 can limit the value of the structural resistance. For plastic failure modes for steel structures, it can often happen that the solver increases the applied load or deformation with increasingly large plastic deformations and distortions without a decreasing of the applied load level. This is due to the effect of strain hardening and the large ductility of the steel material. If the material model does not contain a damage criterion (which is the usual situation), the C2 criterion is the only limitation of the excessive plastic deformations, therefore its consideration is highly important for plastic design. EN 1993-1-14:2025 [1] gives general (structure-type independent) proposals for the applicable limit values which refers to the current state-of-art knowledge. In this proposal, the maximum allowed plastic strain is linked to the plastic elongation capacity of the steel material (which depends on the manufacturing method and steel grade) and the stress state of the analysed structure. This topic is currently an intensive research field, where new results are expected soon. The current paper also support these investigations. This topic has also a wide international literature; due to lack of space in the conference paper, only standardized approaches are discribed.

3 Experimental research program

In the tested connection two L150.100.12 L-profile tension rods are connected to a 20 mm thick connection plate with an M30 bolt. The geometry of the test specimen (consisting of a connection plate and two L-profiles) is shown in Figure 2.

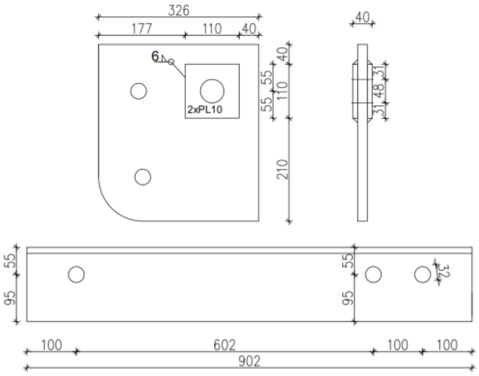

Figure 2 Geometry of the test specimens.

The hole diameter is 32 mm, the screw is placed in the root line of the L-profile. The two angle sections are connected through their longer (150 mm) sides. The distance between the axis of the screw and the edge of the L-profile is 100 mm. In the case of the connection plate the distance between the bolt centre point and the edge of the plate is 90 mm. At one end of the L-profiles, one M30 bolt (d=30 mm; d_0=33 mm) is used (this end is under investigation during the test). At the another end two bolts are applied to localize the failure. The test layout is shown in Figure 3.

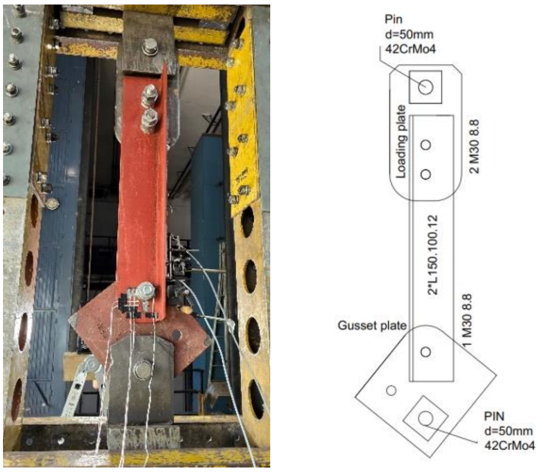

Figure 3 Test specimen and test arrangement.

Within the test specimens the steel grade of the L-profiles and the bolts are varied. In total six specimens are investigated, from which 3 specimens contained M30 8.8 bolts and L-profiles made from S355 steel grade. Another 3 specimens are manufactured by using M30 10.9 bolt and L-profiles having S275 steel grade. The steel grade of the connection plate is always S355. However, the bolt shear failure and the bearing-type failure of the L-profiles were not decisive for the connection, therefore all the six specimens could be treated statistically similar from the point of view of the connection plate bearing resistance. The bolts were not pretensioned within the test program. During the experiments, the relative displacement of the lower and upper connection plates are measured using inductive transducers, as well as the relative displacement of the connection plate in relation to the L-profile.

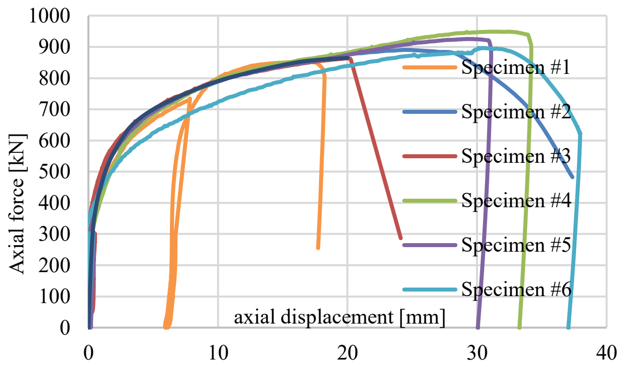

Figure 4 Test specimen and test arrangement.

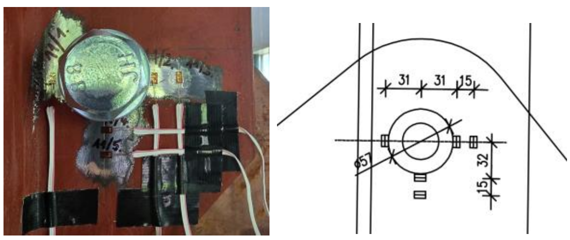

Figure 5 Location of strain gauges.

From the obtained values of force and displacements, the force-displacement diagrams are determined which are shown in Figure 4 for each specimen. In addition strain gauges and DIC measurements are also used to determine the stress distribution around the bolt hole and the surrounding region of the connection plate. The applied strain gauges and their locations are shown in Figure 5. Table 1 summarizes the material properties of the test specimens, the measured ultimate loads and the ultimate stress ($f_{u,exp}$) of the connection plate, which failure governed the structural behaviour and resistance. Column#6 presents the obtained ultimate resistances from the test results, while column #7 the corrected ultimate loads based on the correction of the measured ultimate stress of the connection plate compared to its nominal value (f_u=490 MPa). The statistical evaluation of the test results are made based on two different ways, both follows the rules of EN 1990 Annex D [4]. The first method does not convert the test results based on the material properties, but applied the partial factor equal to γ_{M2}=1.25. The second method makes the conversion based on the material properties, but determind the resistance design value directly.

Table 1 Parameters of the specimens and ultimate resistances.

id	Plate	L-profile	bolt	$f_{u,exp}$ [MPa]	F_{exp} [kN]	$F_{exp,cor}$ [kN]
1	S355	S355	8.8	505.8	851.3	824.7
2	S355	S355	8.8	520.8	890.3	837.7
3	S355	S355	8.8	519.7	863.4	814.1
4	S355	S275	10.9	516.7	949.0	899.9
5	S355	S275	10.9	520.0	925.4	872.0
6	S355	S275	10.9	521.3	896.8	843.0
Average resistance [kN]					896.0	848.6
Standard deviation [kN]					36.8	31.9
k_n for 6 specimens - V_x unknown acc. to EN1990 Annex D Table D1 [4]					2.18	
Characteristic value [kN] - Vx=2.18					815.9	
Design value [kN] - using γ_{M2}=1,25					**652.7**	
Design value [kN] -using V_x=6.36 acc. to EN 1990 Annex D Table D2. [4]						**645.5**

Figure 6 Failure mode obtained in the tests.

Based on the statistical evaluation, the obtained characteristic resistance is 815 kN, while the design value is 645 kN, or 652 kN, respectively. The obtained failure mode is shown in Figure 6, which is a ductile, bearing-type failure of the connection plate.

4 Numerical model development

An advanced finite element model is developed in ANSYS finite element program [5]. The model represents the test specimens and their loading and support conditions in a reliable and accurate way by using solid elements. Figure 7 shows the numerical model, the applied FE mesh, boundary conditions and the applied loads.

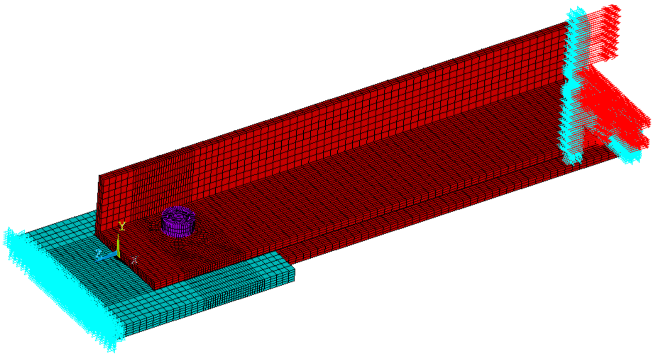

Figure 7 Finite element model.

First the numerical model is verified to determine the accurate mesh size to be used during the analysis. The numerical verification proved, that a maximum FE size equal to 8 mm is sufficient for the complex model with a mesh refinement around the hole having the maximum element size of 4 mm. The numerical paramtric study is executed by these settings. The ultimate load is determined by geometric and material non-linear analysis (GMNA), which is sufficient for the analysed problem. In the numerical model-based design one of the key parameter of the calculation is the applied material model and the maximum allowed plastic strains. To check the accuracy of the numerical calculations, material models by using the characteristic (nominal) material properties are applied which is accurate for the numerical design calculations, direct resistance check. Another track of the analysis is the application of measured material properties, which alignes the application process of the numerical simulation. Both are studied in the current research program.

For both track, the numerical model incorporates a quadlinear material model proposed by the EN 1993-1-14:2024 [1] as shown in Figure 8.

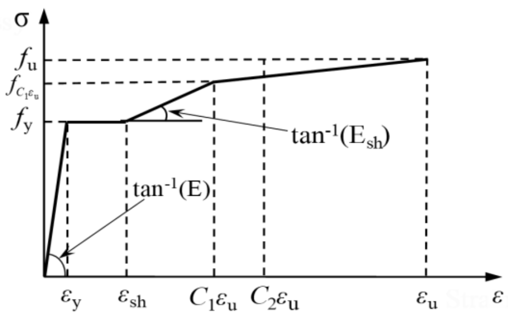

Figure 8 Material model for steel grades having a yield plateau according to EN 1993-1-14 [1].

This material model requires defining coefficients specific to the steel grade under investigation. These parameters are critical for representing the material's non-linear response and include the yield strain ($\varepsilon_y = f_y/E$), the strain hardening modulus (E_{sh}) and the elongation coefficient (A)

to reflect post-fracture behaviour. In the material model two coefficients are introduced (C_1) and (C_2), which governs the slope of the strain-hardening region. The material model is given by Eqs. (10)-(15).

$$\sigma(\varepsilon)=\begin{cases} E\varepsilon, & \varepsilon\le\varepsilon_y \\ f_y, & \varepsilon_y<\varepsilon\le\varepsilon_{sh} \\ f_y+E_{sh}(\varepsilon-\varepsilon_{sh}), & \varepsilon_{sh}<\varepsilon\le C_1\,\varepsilon_u \\ f_yC_1\varepsilon_u+\dfrac{f_u-f_yC_1\varepsilon_u}{(\varepsilon_u-C_1\varepsilon_u)}(\varepsilon-C_1\varepsilon_u), & C_1\,\varepsilon_u<\varepsilon\le\varepsilon_u \end{cases} \quad (10)$$

$$E_{sh}=\frac{f_u-f_y}{C_2\varepsilon_u-\varepsilon_{sh}} \quad (11)$$

$$\varepsilon_{sh}=0.1\frac{f_y}{f_u}-0.055\ but\ 0.015\le\varepsilon_{sh}\le 0.03 \quad (12)$$

$$\varepsilon_u=0.6\left(1-\frac{f_y}{f_u}\right), but\ 0.06\le\varepsilon_u<A \quad (13)$$

$$C_1=\frac{\varepsilon_{sh}+0.25(\varepsilon_u-\varepsilon_{sh})}{\varepsilon_u} \quad (14)$$

$$C_2=\frac{\varepsilon_{sh}+0.4(\varepsilon_u-\varepsilon_{sh})}{\varepsilon_u} \quad (15)$$

All applied material models are using these equations, but differ in the application of the engineering or true stress/strain relationship; measured or characteristic material properties and value of the maximum allowed plastic strain. The summary of the applied material models and their differences are shown in Table 2.

Table 2 Applied material models.

Material model #	values of f_y, f_u	stress / strain rel.	strain limit value
1	measured	engineering	20%
2			-
3		true	20%
4			-
5	nominal	engineering	-
6		true	-
7			15%
8			10%
9			5%
10			3%

Material models #1-4 use measured values for the material properties (f_y and f_u) and follow the material characteristic according to Figure 8. Material models #1 and #2 use engineering, while material models #3 and #4 are using true stress-strain relationship. Material model #1 and #3 include a limitation of the maximum allowed plastic strain at ε_u=20% elongation by using cumulative damage model; while material models #2 and #4 do not limit the plastic strain within the entire calculation process. These material model are used for numerical simulations.

Material models #5-10 are using the characteristic (nominal) value of the material properties (f_y and f_u) and also follow the characteristic curve according to Figure 8. Material model #5 uses the engineering stress-strain relationship, while material models #6 to #10 use the true stress-strain relationship by applying different values for maximum allowed plastic strains. These material models are used for the direct resistance check.

The obtained failure model within the numerical model is shown in Figure 9, which is the bearing-type failure of the connection plate with large plastic deformations. The obtained load-deformation curves in the numerical model are presented in Figures 10 and 11 by using the measured, or the characteristic material properties, respectively.

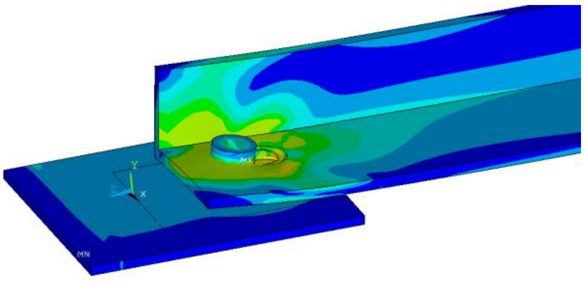

Figure 9 Failure mode in the numerical model.

The evaluation of the load-displacement pathes show, that by using the measured material properties the application of the material model #4 (using the true stress-strain relationship and not including any limitation for the plastic elongations) can accurately follow the average load-displacement curves obtained in the experiments. The computed ultimate resistance equals to 829 kN which shows only 2% difference compared to the 848 kN average resistance coming from the laboratory tests. By applying strain limits at 20% max. elongation (material model #3) leads to an 18% resistance reduction (the computed ultimate resistance is 684 kN). By using the engineering stress-strain relationship, the resistance values decreases to 725 kN and 652 kN, respectively. Both values are smaller than the characteristic resistance based on the statistical evaluation of the test results (779 kN).

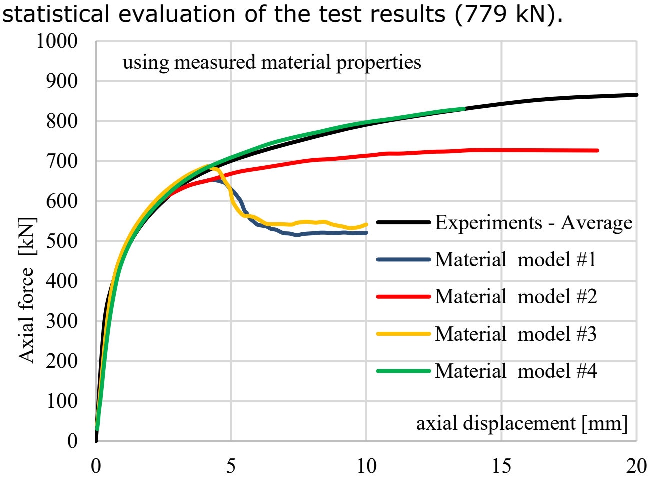

Figure 10 Computed load-displacement diagram using measured material properties compared to the average test result.

By using the characteristic material properties, the obtained resistances are significantly lower depending on the maximum allowed plastic strain limit. The ultimate load by using the engineering stress-strain relationship equals to 683 kN. By using the true stress-strain relationship, this value goes up to 761 kN without using strain limitations

(C1 criteria is the governing). By applied damage material models (considering C2 criteria) the ultimate resistance goes down to 602 kN by using 15% allowed plastic strain, 557 kN by using 10% allowed plastic strain, 454 kN by using 5% allowed plastic strain and 408 kN by using 3% allowed plastic strain.

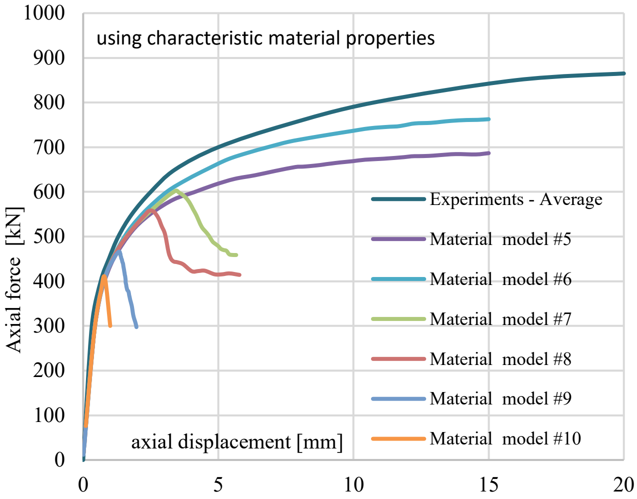

Figure 11 Computed load-displacement diagram using characteristic (nominal) material properties compared to the average test result.

Comparing these results to the analytically calculated bearing resistances and to the result of the test-based approach, the following conclusions can be drawn.

The characteristic and design value of the bearing resistance based on Eqs. (2)-(4) are 668 kN and 534 kN, respectively. These resistances are increased by the second generation EN1993-1-8:2024 (acc. to Eqs. (5)-(7) to 801 kN and 641 kN, respectively. However, the old Hungarian bridge design code allowed only 369 kN as design value for the bearing resistance, which is a very conservative value comparing to the Eurocode-based resistances.

The second generation EN 1993-1-8:2024 contains a design equation for such connections, where the plastic deformations are to be limited to ensure remontability of the joint. For these type of joint the design bearing resistance can be determined by Eqs. (8)-(9), which gives a design resistance of 470 kN for the specific connection.

It can be seen, that the second generation EN 1993-1-8:2024 provides ~20% resistance increase compared to the first generation EN 1993-1-8:2006 and provides a close value to the average test results. The design value based on the second generation EN 1993-1-8:2024 (641 kN) is also close to the statistical evaluation-based design resistance coming from the laboratory tests (645 kN). However the numerical model-based design approaches give only close result to the tests or to the standardized resistances if true stress-strain relationships are used in the material model. If no plastic limit values are used (C1 criteria is the governing), the characteristic resistance is 761 kN leading to a design resistance of 608.8 kN, which is ~5% smaller than the analytical-based or test-based bearing resistance. The load deformation curves also show that at the load level of 470 kN, the non-linear behaviour already started, but the plastic deformations are limited.

5 Conclusion

This paper investigates the bearing resistance of bolted shear connections, comparing three analytical, one numerical, and one experimental design approach. The study highlights a significant increase of approximately 20% in bearing resistance in the second generation EN 1993-1-8:2024 compared to its 2005 predecessor. A detailed numerical model is developed, exploring various material models and plastic strain limitations for one specific geometrical condition of the single bolted shear connection. The numerical model, utilizing measured material properties and a true stress-strain relationship without plastic elongation limits, accurately replicated experimental load-displacement behaviour, showing only a 2% difference in ultimate resistance. Conversely, incorporating plastic strain limits in the numerical model significantly reduced the computed bearing resistance, underscoring the importance of these parameters.

The characteristic and design bearing resistance values from EN 1993-1-8:2005 were 668 kN and 534 kN, respectively. The updated EN 1993-1-8:2024 significantly increased these to 801 kN for characteristic and 641 kN for design resistance. These second-generation Eurocode values align closely with the experimentally derived design resistance of 645 kN. The research concludes that numerical model-based design can accurately predict bearing resistance, particularly when using true stress-strain material models, but emphasizes the critical need for careful consideration of plastic strain limits, which needs further invstigations. The presented research results are validated for the analysed specific case, which can be later generalized for other connection types, geometries and numerical models.

Acknowledgements

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