



Brno University of Technology



NSD Lab

Laboratory for Numerical Structural Design

Bolted End-Plate Connections Verification

Connections made of conventional S355 steel

Responsible investigators:

doc. Ing. Martin Vild, Ph.D.

Milana Bolotnikova

Institute of Metal and Timber Structures

Faculty of Civil Engineering

Brno University of Technology

Brno, Czech Republic, October 2026

Bolted End-Plate Connections Verification

Connections made of conventional S355 steel

In this verification study, a bolted beam-to-column connection using an end plate was investigated. The connection was subjected to a bending moment and comprised a large number of bolt rows. The connections considered in this study were made of S355 structural steel.

An example of the connection under study is shown in Figure 1.

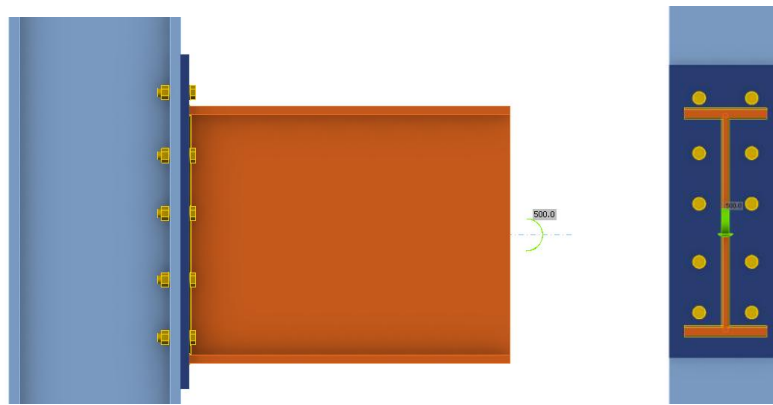


Figure 1: Joint example

Hand calculation according to EN 1993-1-8:2005:

According to *EN 1993-1-8:2005*, the moment resistance of the connection is determined as the sum of the products of the resistance forces of the individual bolt rows and their respective lever arms measured from the center of compression, which, in this case, is assumed to be located at the mid-depth of the lower beam flange.

The resistance of each bolt row is determined using the equivalent T-stub model. In accordance with *EN 1993-1-8:2005*, Clause 6.2.4.1, three failure modes are considered:

1. Failure mode 1: complete yielding of the flange;
2. Failure mode 2: formation of two yield lines in the flange accompanied by bolt rupture;
3. Failure mode 3: bolt rupture.

This T-stub procedure provides the effective tensile resistance of each row considered individually. However, the overall moment resistance of the connection depends not only on

these local resistances but also on how the total force is distributed among the rows. That distribution is governed by the ductility of the connection. If the end plate and column flange are sufficiently ductile, plastic redistribution may be assumed and the full effective resistances of the rows can be used in the summation. If such ductility cannot be reliably justified, the design must instead be based on an elastic distribution of forces. This is precisely the situation addressed by the triangular limit.

Design of Bolted End-Plate Connections Using the Triangular Limit (EN 1993-1-8:2005, Clause 6.2.7.2(9))

In the design of bolted end-plate connections, where plastic redistribution of forces between bolt rows cannot be justified, the method known as the “triangular limit” is applied. Its source is EN 1993-1-8:2005, Clause 6.2.7.2(9). In later editions of Eurocode 3, this approach is retained with possible refinements; however, the 2005 edition remains the basic reference.

The method is based on the elastic distribution of forces between bolt rows. In this case, the force diagram is triangular: the force in each bolt row is proportional to its distance from the center of compression. Thus, the triangle in the design model denotes elastic behavior of the connection, rather than plastic redistribution.

However, since the actual ductility of the end plate and column flange may be insufficient for full plastic redistribution, the code introduces a limitation that prevents excessive concentration of force in the outermost bolt row.

This limitation is expressed as:

“Where the effective design tension resistance $F_{tx,Rd}$ of one of the previous bolt rows x is greater than $1.9 \cdot F_{t,Rd}$, the effective design tension resistance $F_{tr,Rd}$ for bolt row r should be reduced, if necessary, in order to ensure that:

$$F_{tr,Rd} \leq F_{tx,Rd} \cdot h_r / h_x$$

where:

- h_x is the distance from bolt row x to the center of compression;
- x is the bolt row farthest from the center of compression that has a design tension resistance greater than $1.9 \cdot F_{t,Rd}$.”

Thus, the resistance assigned to each bolt row decreases in proportion to its lever arm h , measured from the center of compression. The 1.9 limit ensures that this reduction is not excessively steep.

Generation of the required parameter combinations

For this verification study, 300 unique parameter combinations were generated, with the bolt diameter, end-plate thickness, and bolt spacing being the variable parameters. The combinations were selected to produce three distinct groups of connections.

In the **first group**, the resistance of each bolt row was always below the limit of $1.9 \cdot F_{t,Rd}$. Therefore, the resistance reduction specified in EN 1993-1-8:2005, Clause 6.2.7.2(9), was not activated for any bolt row. The final moment resistance of the connection was consequently determined using the conventional approach, as the sum of the products of the calculated resistance of each bolt row, determined using the equivalent T-stub model, and its corresponding lever arm with respect to the center of compression.

In the **second group**, the limit of $1.9 \cdot F_{t,Rd}$ was reached already in the first bolt row, as bolt rupture governed the resistance of this row. Consequently, the resistance of all subsequent bolt rows was reduced proportionally in accordance with the reduction procedure specified in Clause 6.2.7.2(9).

In the **third group**, the parameters were selected such that the limit of $1.9 \cdot F_{t,Rd}$ was exceeded in the second bolt row. The reduction therefore starts at that row, not at the first. Rows 2 govern because they are the innermost rows with the shortest effective lever arms (small m_2), where the plate is strongest; the first row keeps its full resistance thanks to a longer lever arm and a two-yield-line + bolt-rupture mode (typically mode 2).

Creating models in IDEA StatiCa Connection

Using these parameter combinations, we created 300 corresponding models in the IDEA StatiCa Connection software. Examples of the models are shown in Figure 2. After running the Python script, a results table and reliability plots were obtained.

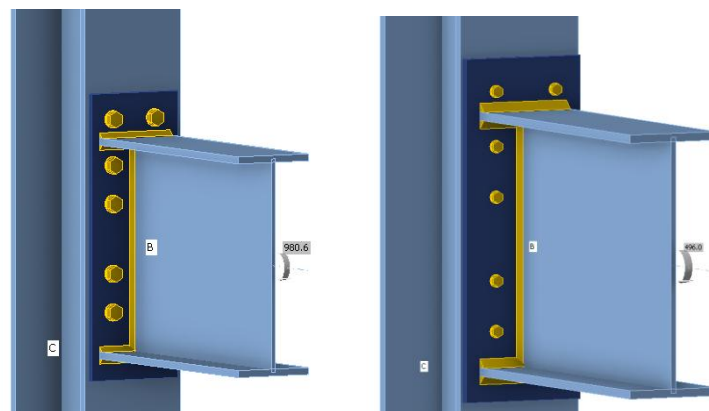


Figure 2: Model examples

Results

Based on the results, it can be observed that the resistances determined using the two methods, CM and CBFEM, are in very close agreement.

Additionally, the results include plots showing, on the x -axis, the force distribution obtained from the *EN 1993-1-8:2005* of each bolt row, together with the bolt forces from IDEA StatiCa grouped by bolt row; the y -axis shows the lever arms of these forces — the distance to the center of compression, located at the mid-thickness of the beam's bottom flange. Next to each graph, a front view and a side view of the connection are displayed, illustrating its geometry (plate dimensions, bolt positions, beam and column cross-sections).

Considering **Group 1**, the connection is plate-governed, so the triangular reduction rule of *EN 1993-1-8* never activates. The hand-calc bars (grey = unreduced F_r , blue = reduced $F_{tr,Rd}$) are therefore identical and show a nearly uniform distribution along the height, whereas the IDEA diamonds (orange, $F_{t,Ed}$ per row) typically decrease from the top to the bottom. The reason the two sets of values differ is fundamental: the hand-calc bars are resistances calculated from T-stub theory, while the IDEA diamonds are bolt forces including prying to the contact force just next to the bolt. The figure with the graph and geometry for one of the connections from Group 1 can be seen in Figure 3.

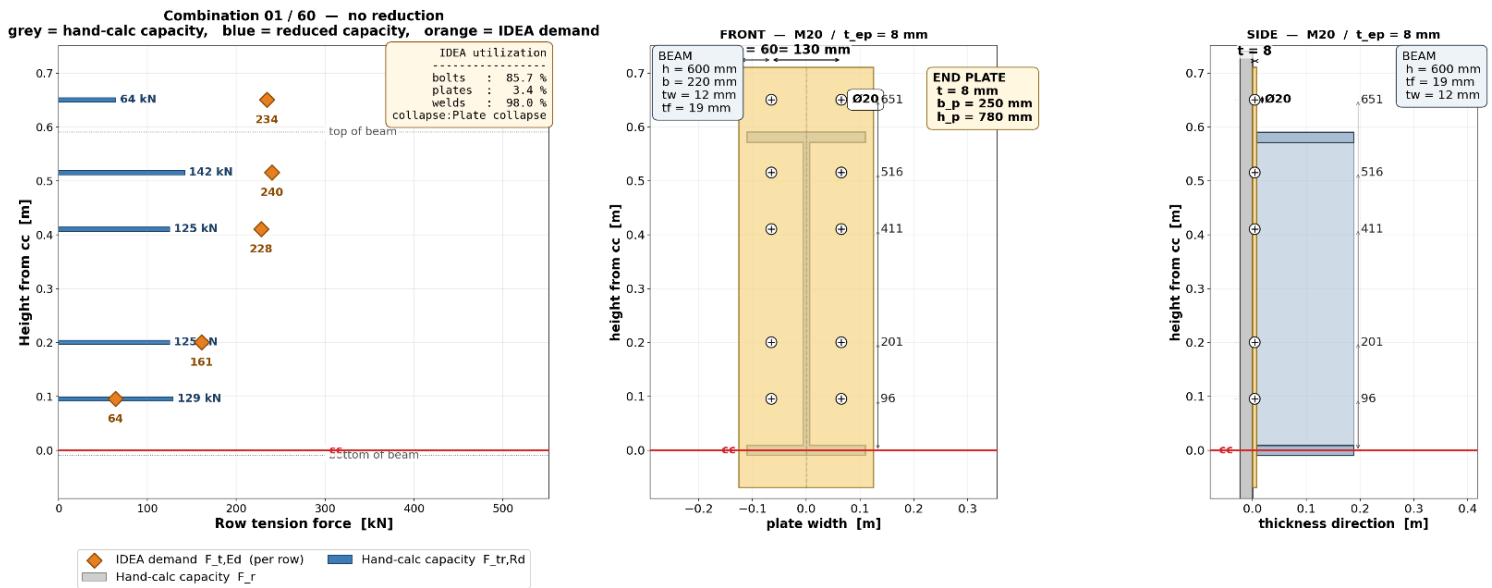


Figure 3: Joint from group 1

In **Groups 2 and 3**, the hand-calc and IDEA forces are much closer than in Group 1, because here the connection is no longer plate-governed and prying forces are much smaller or non-existent — the triangular reduction actually activates, so both methods describe the same

physical mechanism. In Group 2 the pivot sits at Row 1, so the top bolt row governs and both models cap it at the same value, making the whole distribution nearly identical. In Group 3 the pivot sits at Row 2: the top row is still plate-controlled, but thanks to longer yield length, second bolt row is mode 3 with nearly identical resistance for both methods. This is why Groups 2 and 3 show much better agreement in terms of bolt forces than Group 1. The figures with the graph and geometry for one of the connections from Group 2 and Group 3 can be seen in Figures 4 and 5, respectively.

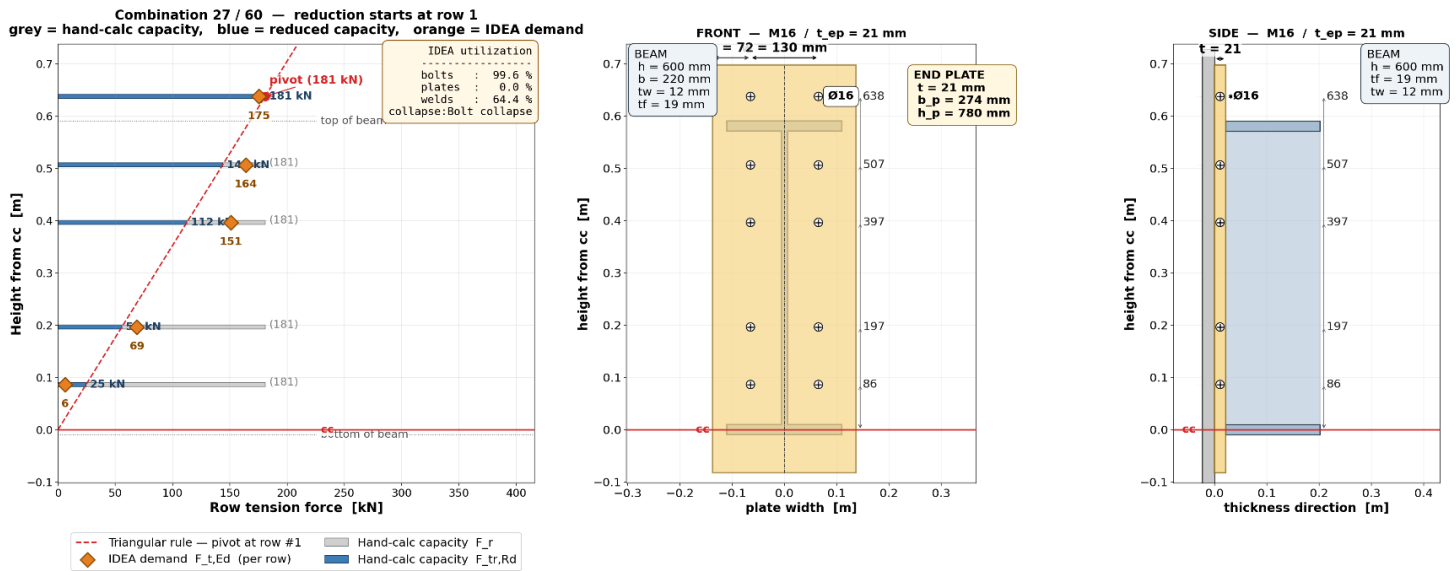


Figure 4: Joint from group 2

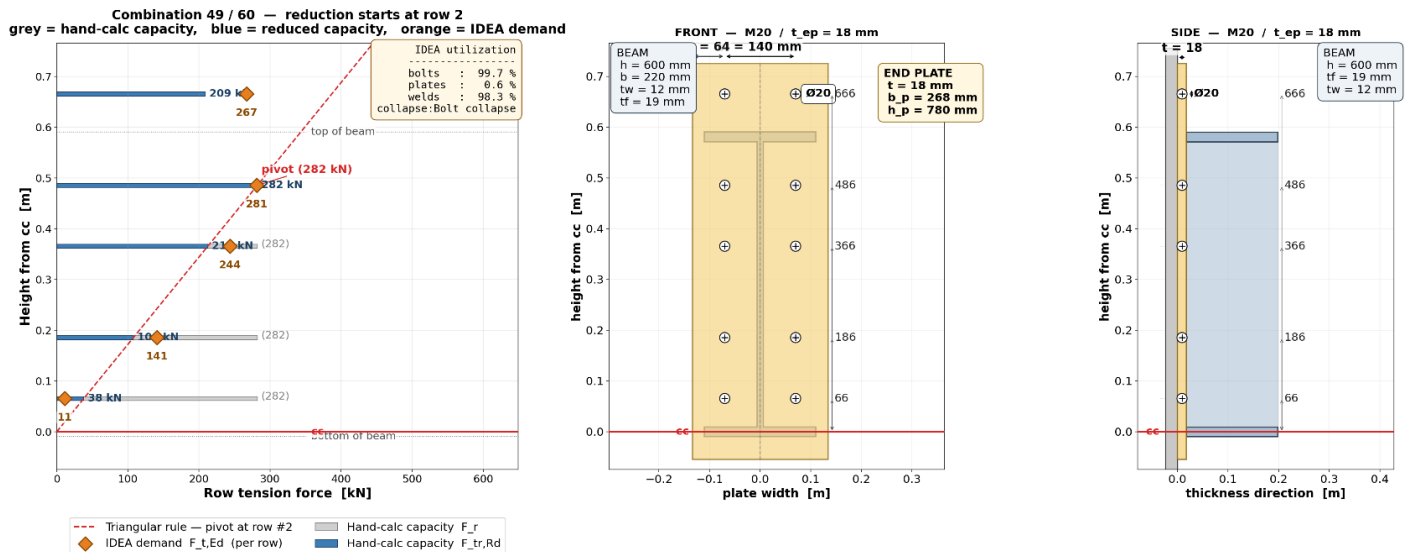


Figure 5: Joint from group 3

The geometries of all remaining combinations, along with the plots illustrating the relationship between the resistance of each bolt row calculated according to EN 1993-1-8:2005 together with the bolt forces from IDEA StatiCa grouped by bolt row and its corresponding lever arm, are provided in the appendices to this study.

The reliability plot is shown in Figure 6. The coefficient of variation is 0.095, while the mean resistance ratio (CBFEM/CM) is 0.973.

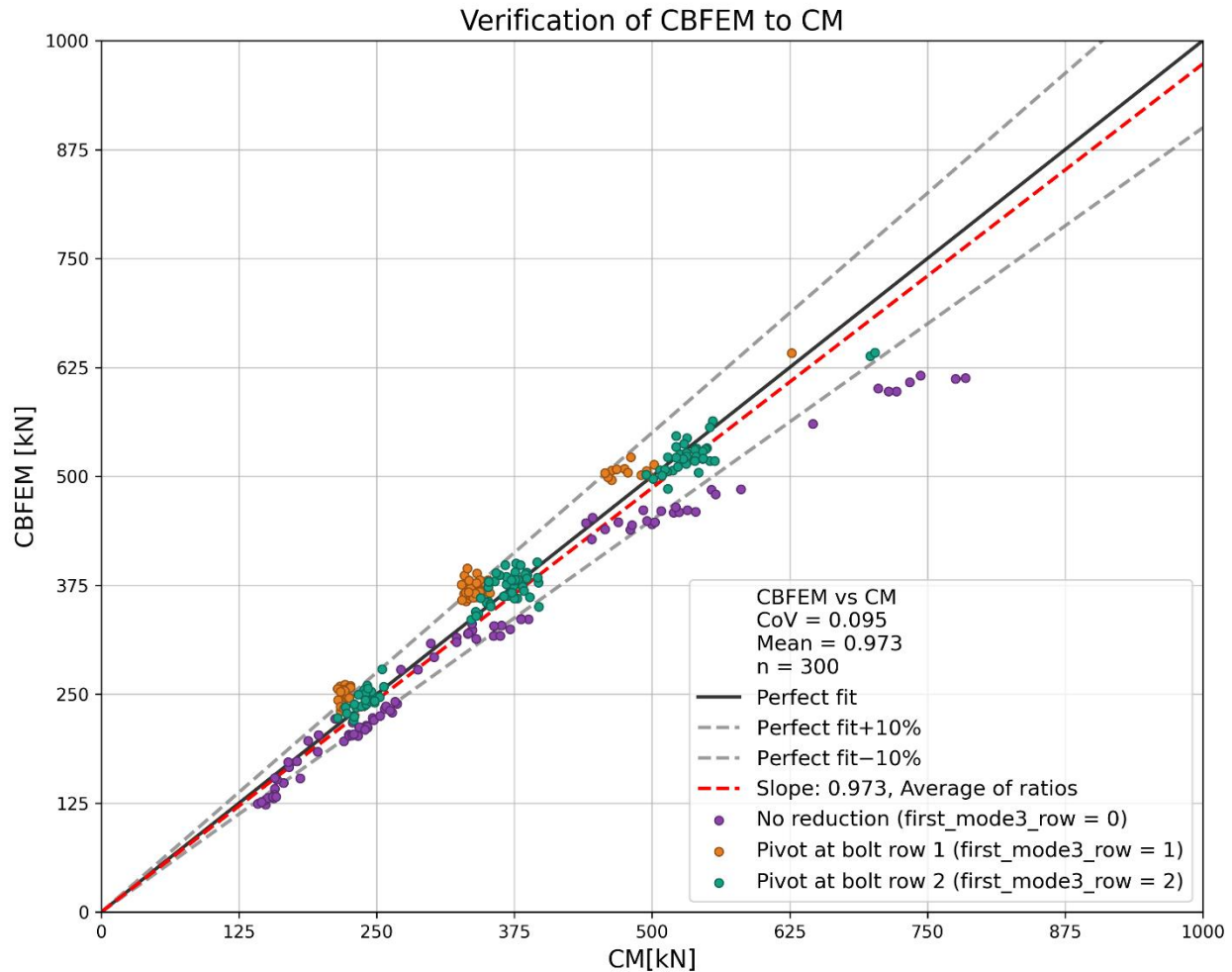


Figure 6: Reliability plot for all geometries

On the reliability plot, the points are divided into three groups, each shown in a different color corresponding to the three combination groups. It can be seen that the results differ for each group. The purple points (plastic redistribution) lie mostly below the perfect-fit line, which means that the hand calculation generally provides higher resistance compared with CBFEM. The orange points (pivot at bolt row 1) lie above the perfect-fit line, indicating that the hand calculation is conservative. The teal points (pivot at bolt row 2) lie closest to the

perfect-fit line, showing the best agreement between the two methods. This behavior follows directly from the governing mechanism in each group: Group 1 is plate-governed; Group 2 is bolt-governed, where the hand calculation caps the top row at the bolt resistance while CBFEM still finds additional reserve; and Group 3 combines a plate-controlled top row with a bolt-governed pivot at Row 2. The corresponding results are provided in the attached Excel file.

We also divided the data into 3 separate reliability plots. You can see them in Figures 7, 8, and 9.

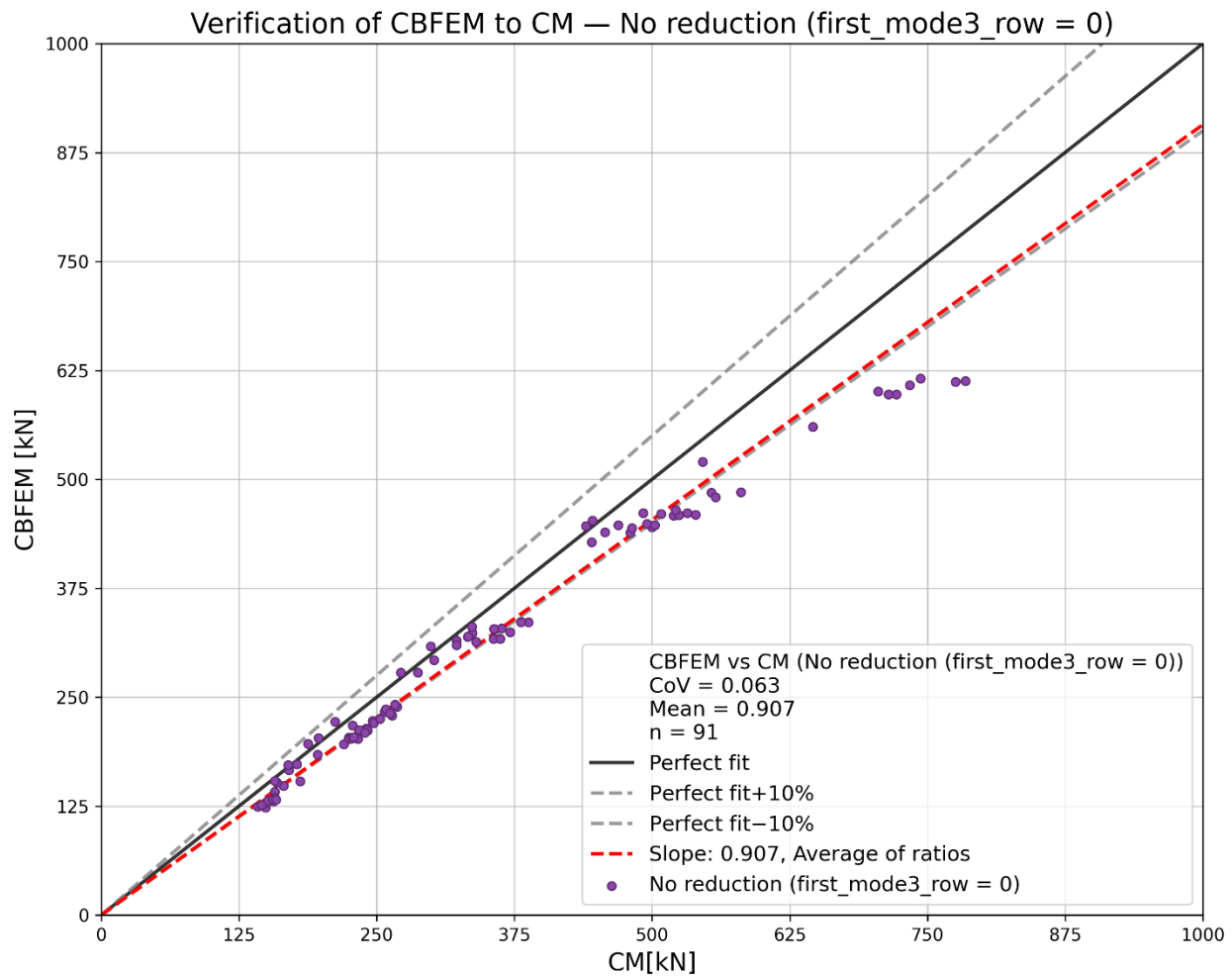


Figure 7: Reliability plot Group A

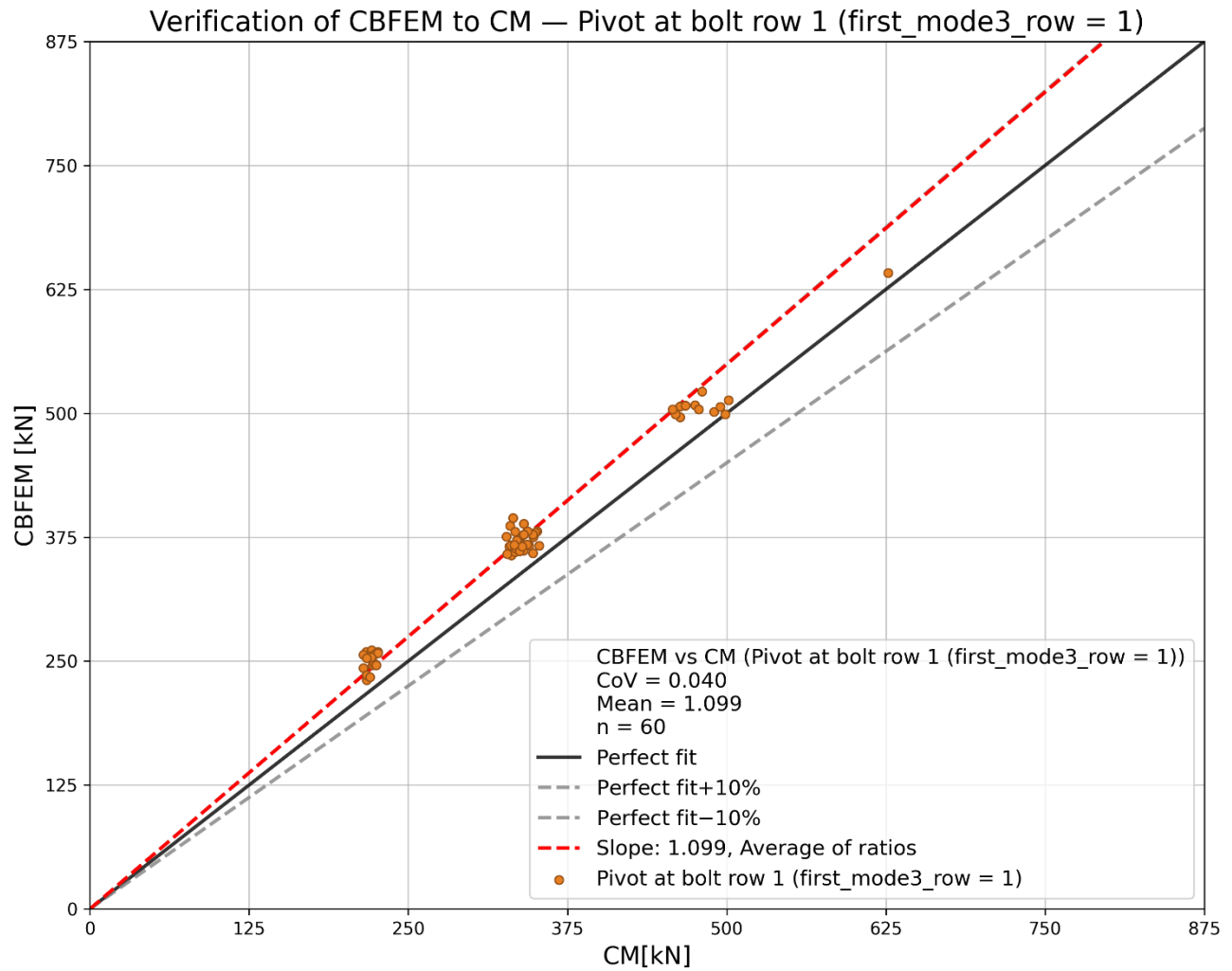


Figure 8: Reliability plot Group B

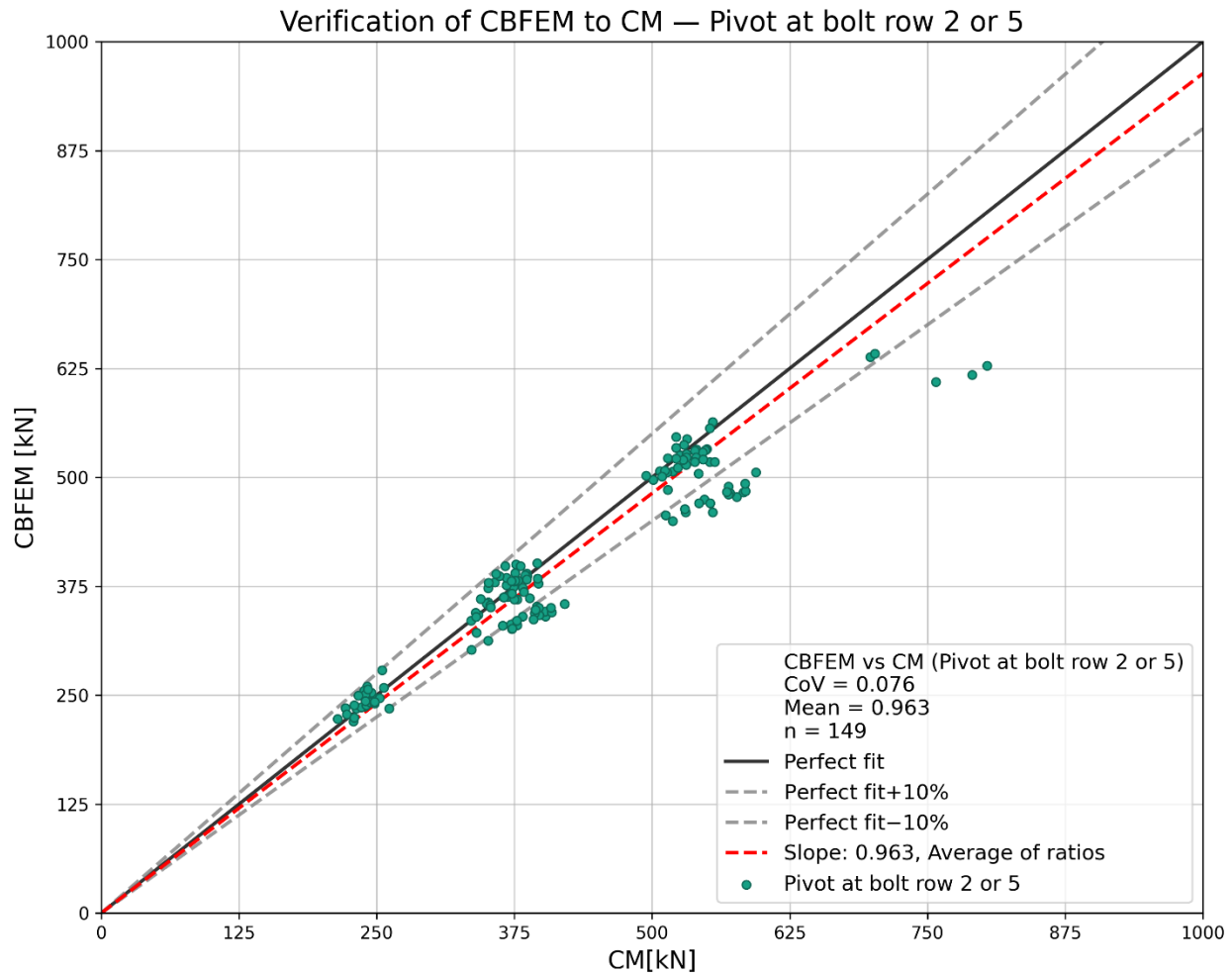


Figure 9: Reliability plot Group C

Another graph we produced shows the percentage utilization of the plate and the bolts for each of the three groups. The values are plotted on two independent axes: on the left, the plastic strain of the end plate or the flange (0–5 %); on the right, the bolt utilization (0–100 %). The rectangle spans the full range from the minimum to the maximum value within a group, and the dashed line inside marks the median. The graph can be seen in Figure 10.

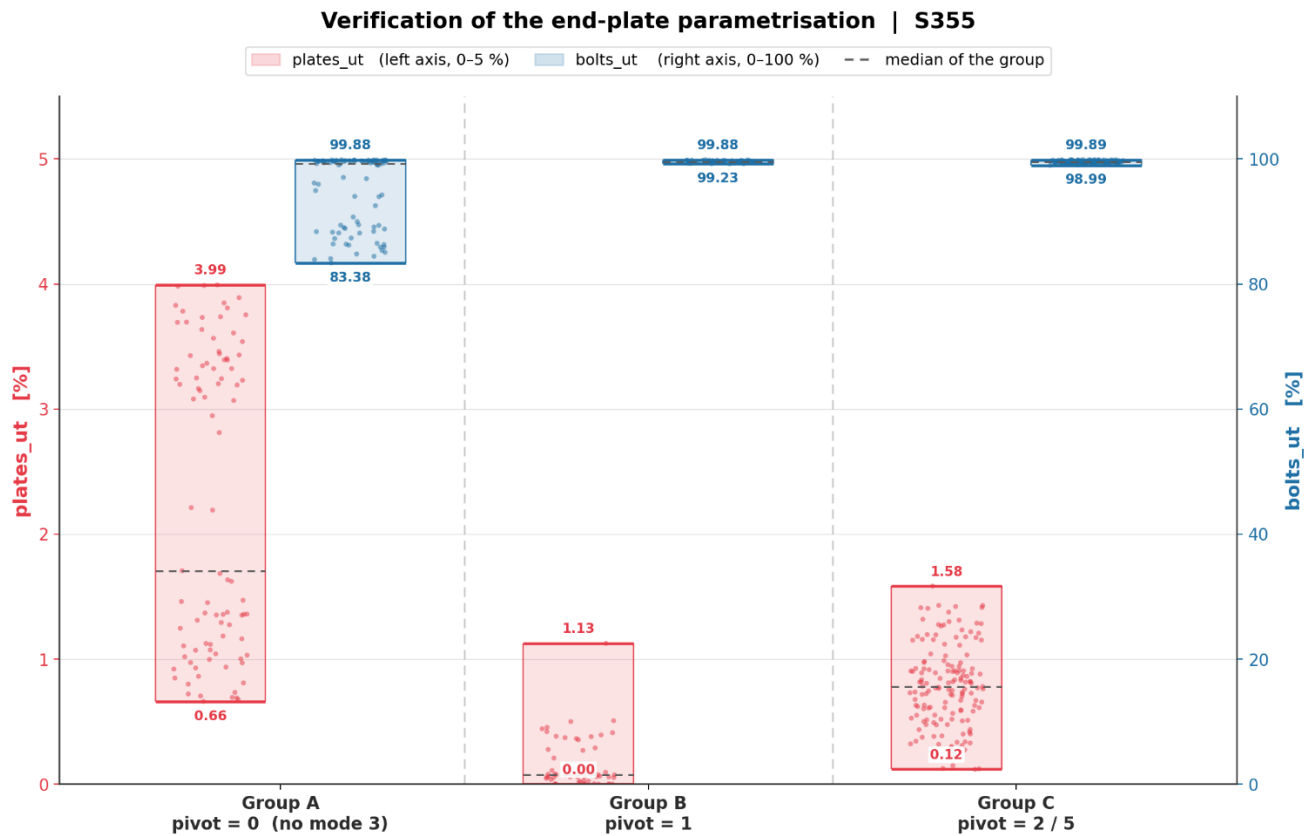


Figure 10: Utilization of plates and bolts

In group A, we see the highest plate plastic strain (up to 3.99 %) and the lowest bolt utilization values (from 83.4 %). This is exactly the expected behavior: since the end plate is the weakest compared to the bolt tensile strength and yields while the bolts retain a reserve.

In group B, on the contrary, the plates barely deform (up to 1.13 %), while the bolts reach 99.2–99.9 % — because the pivot starting from the first row forces the bolt to fail before the end plate or flange can yield.

In group C, the values are intermediate: the plates show moderate deformation (up to 1.58 %), and the bolts reach almost 100 % (98.99–99.89 %), which corresponds to the pivot being activated at the inner rows and mode 2 achieved in the top bolt row.

Overall, the distribution across the groups came out exactly as intended: each group exhibits its own characteristic behavior mode, and all three behave predictably and logically.

Validation

To verify the accuracy of the obtained results, the two methods were further validated against experimental data. For this purpose, the experimental study by Matthew R. Eatherton (2026), entitled *Seismic Testing of an Eight-Bolt Extended Unstiffened End-Plate Moment Connection* [1], was selected. Specimen 8E-1.375-1.5-24 was considered for the validation. The geometry of the specimen is shown in Figure 11. Measured plate and bolt material strengths were used in the component method and CBFEM calculations.

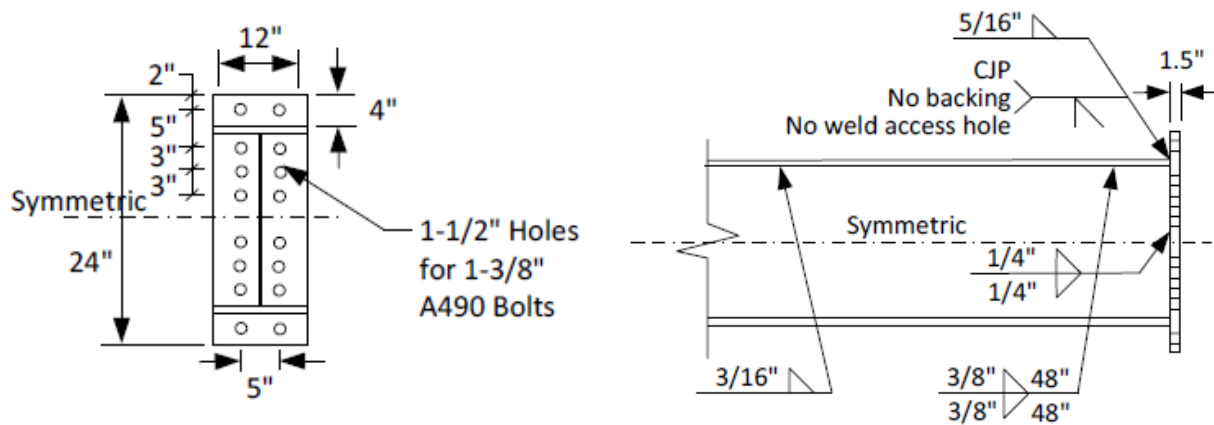


Figure 11: Specimen 8E-1.375-1.5-24 geometry

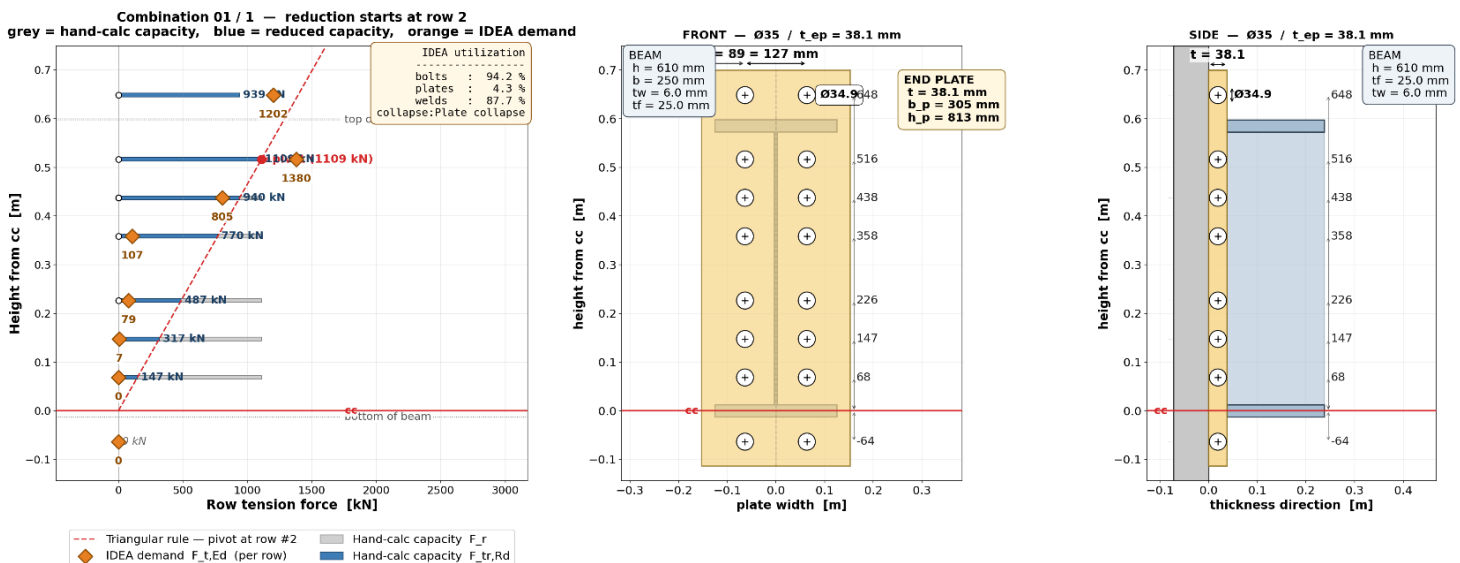


Figure 12: Bolt forces by CM and CBFEM

According to the results of the hand calculation for this connection, the resistance reduction started from the second bolt row, where the $1.9 \cdot F_{t,Rd}$ criterion was reached. The plot showing the distribution of the forces and their corresponding lever arms is presented in Figure 12.

After creating the model in IDEA StatiCa and performing the analysis using the CBFEM method, the following relationship was obtained between the results of the CM and CBFEM methods and the experimentally determined resistance. The comparison is presented in Table 1.

Table 1: Validation results

Resistance CM [kN]		Resistance CBFEM [kN]		Resistance Experiment [kN]
2036		1830		2474
Bolts Ut [%]	Welds Ut [%]	Plates ε_{pl} [%]	CM/CBFEM	EXP/CBFEM
94.17	87.69	4.25	1.11	1.35

Based on the results of this comparison, the difference between the calculated and experimental resistances is relatively small, while the CBFEM results show a conservative deviation.

References:

[1] Matthew R. Eatherton and Abdelrhman A. Ramadan, *Seismic Testing of an Eight Bolt Extended Unstiffened End-Plate Moment Connection*. Proceedings of the Connections Workshop X; 2026 Jul 8–10; Cincinnati, OH, USA.