Gusset plate design in IDEA StatiCa Connection

Content

Introduction

The gusset plate connection is very often used to join vertical and diagonal members in a truss or braces. The design of members loaded in tensile force and their joints is an easy task. However, members loaded in compression and their joints are susceptible to buckling. Ideally, the free lengths of gusset plates and connecting plates should be designed as small as possible, just to allow erection and manufacturing tolerances. The exception are seismic resistant joints, where yielding of gusset plates is intentional. Eccentric gusset plate connection should be designed only if completely necessary due to erection.

Symmetrical gusset plate connection

Analytical model

The buckling of a gusset plate may be simply checked by estimating boundary conditions as fixed on both ends of the gusset plate or fixed at one end and pinned at the other – see Figure

1. The plate moment of inertia about weak axis is $I = 1/12\ b\ t^3$. The length L is assumed to the centre of bolt group. Often, gusset plate is designed with variable width and the connected plate is bolted by a group of multiple bolts. Then simplifications and safe assumptions must be taken to use the simple analytical model.
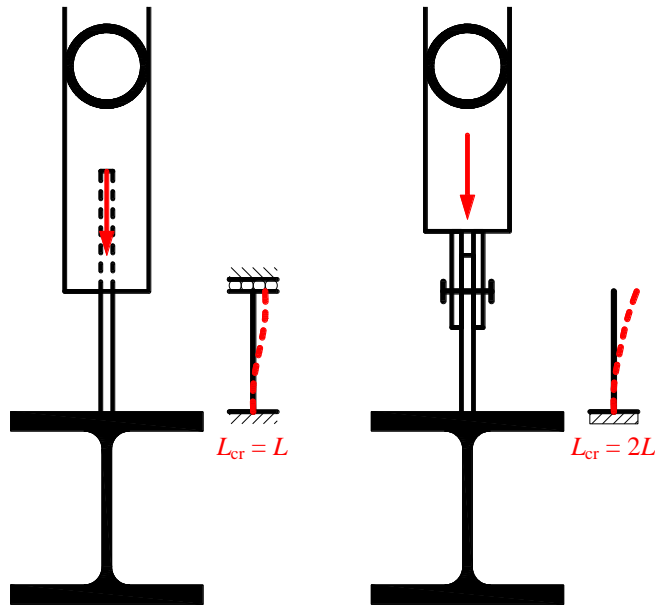

Figure 1: Gusset plate welded into a member; gusset plate connected by a pin

CBFEM model

Geometrically linear stress-strain analysis is not enough to design gusset plate connection of the compressed member. It must be complemented by linear buckling analysis and the results must be correctly evaluated.
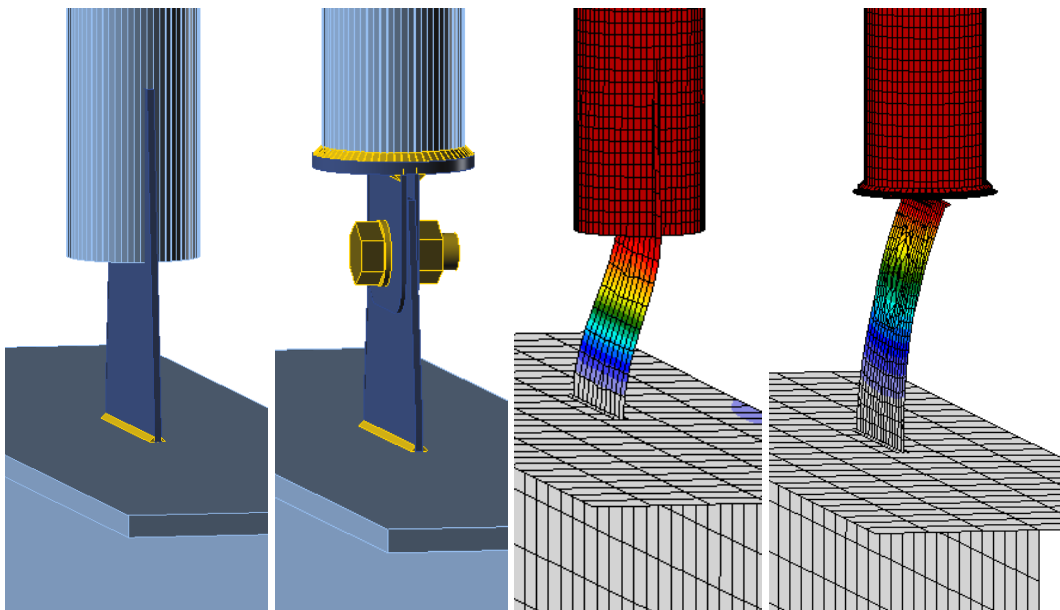

Figure 2: Gusset plate welded into a member; gusset plate connected by a pin – buckling analysis

The member type of the truss member should be set to N-Vy-Vz so that bending moments are restrained. Otherwise, the analysis of a member connected by a single bolt cannot be performed at all because it is free to rotate around this bolt. This model type is also correct for buckling analysis – the member is able to move laterally and sway failure mode of gusset plate is revealed – see Figure 2.

The buckling analysis provides factor α_{cr}. By multiplying factor α_{cr} by set axial load N, critical force $N_{cr,gp}$ is obtained. It is recommended to design gusset plate so that $N_{cr,gp}$ is sufficiently high, at least higher than the critical force of the member, $N_{cr,m}$. The expected buckling shape of the compressed member with pinned supports on both ends is achieved and standard design procedures may be used for this member. When $N_{cr,gp} \leq N_{cr,m}$, member sways on gusset plates and remains nearly straight – see Figure 3. The load resistance is lowered.
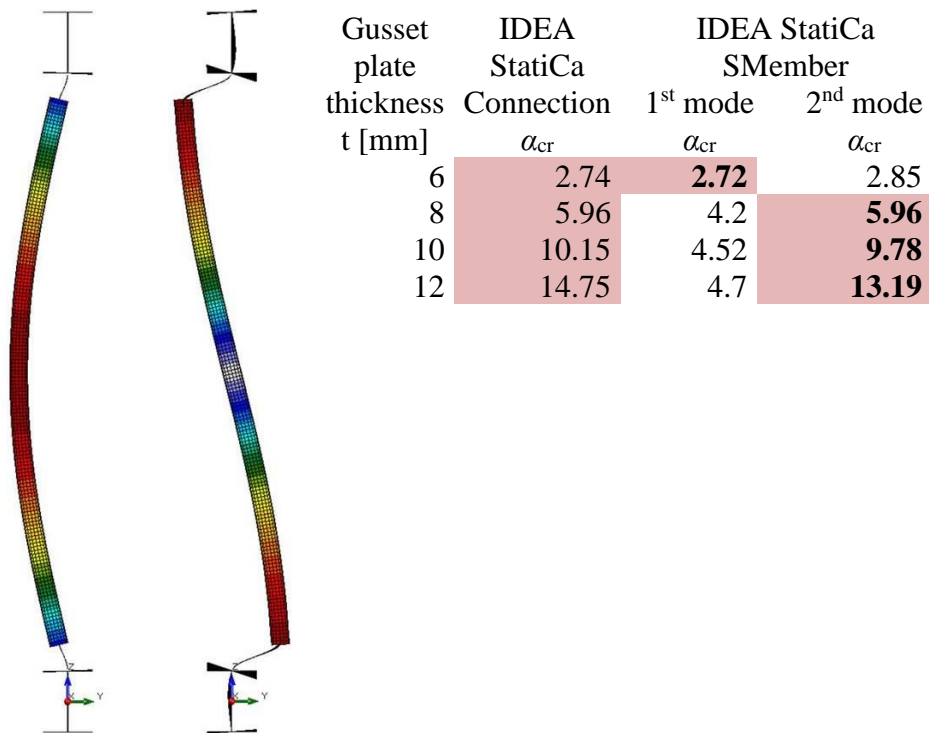
Gusset plate thickness t [mm]	IDEA StatiCa Connection α_{cr}	IDEA StatiCa SMember 1st mode α_{cr}	2nd mode α_{cr}
6	2.74	**2.72**	2.85
8	5.96	4.2	**5.96**
10	10.15	4.52	**9.78**
12	14.75	4.7	**13.19**

Figure 3: Subsystem (joint-member-joint) in application SMember compared to results of application Connection

In Figure 3, the gusset plate thickness of 6 mm is dangerous because $N_{cr,gp} \leq N_{cr,m}$. The failure mode is expected with sway mode of gusset plates, the member will remain straight and the compressive resistance of subsystem joint-member-joint will be decreased – determined by resistance of gusset plate connection. The thickness of 8 mm is sufficient and $N_{cr,gp} \geq N_{cr,m}$. Notice the rotation of the bearing member, to which the gusset plate is welded. If the rotation is not restrained at least on the span of model in IDEA Connection, the buckling factor is increasing.

Summary

Recommendation for pinned member connected by symmetrical gusset plate connection:
1. Keep free lengths of gusset plate and connecting plate as short as possible
2. Use model type N-Vy-Vz for pinned member
3. Calculate the connection using stress-strain analysis and check the results

4.   Calculate buckling analysis

5.   Consider if the member to which gusset plate is welded may rotate and increase the possibility of sway buckling mode of gusset plate:

a.   If yes, decrease the buckling factor – no general recommendation – function of member unsupported length, torsion stiffness, gusset plate bending stiffness

b.   If no, use the buckling factor of the first mode

6.   Calculate critical buckling load of the gusset plate connection: $N_{cr} = N \times \alpha_{cr}$.

7.   Make sure that the buckling load of connection is higher than the buckling load of connected member

Eccentric gusset plate connection

Analytical model

The analytical model was designed by Khoo et al. (2009). The collapse mechanism is by two plastic hinges at a gusset plate and a connecting plate.

Figure 4: Failure mode of eccentric gusset plate connection (Vesecký, 2019)

The resistance of such failure mode is linearly dependent on steel yield strength, length of the plastic hinge, free length of connecting and gusset plate and quadratically on the thickness of gusset and connecting plate.

CBFEM model

The CBFEM model comprises only the joint with stubs of connected members. The member model type is set to N-Vy-Vz so that the bending moments are restrained. The applied forces are in the position of the centre of bolt group – see Figure 5. The member is loaded by normal force N and to simulate the bending of the gusset and connected plates, eccentricities and second order effects, shear force with the magnitude of $V = N/10$.
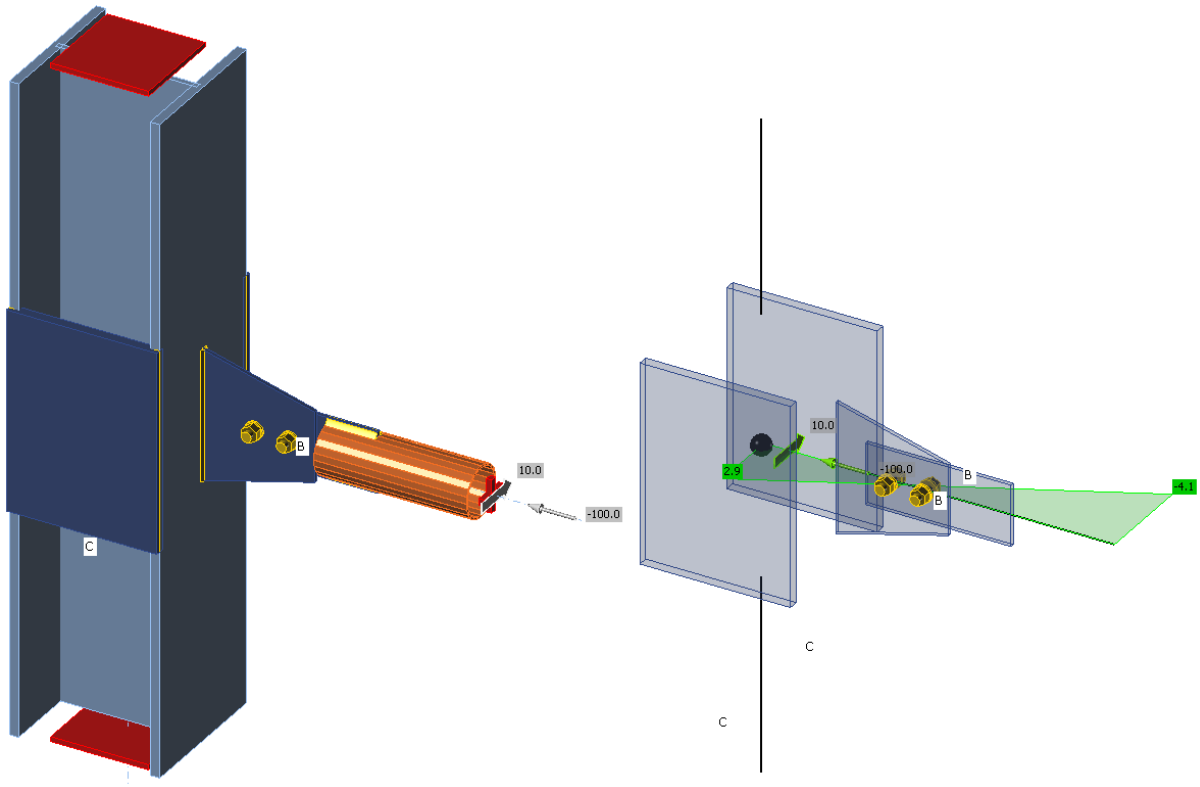

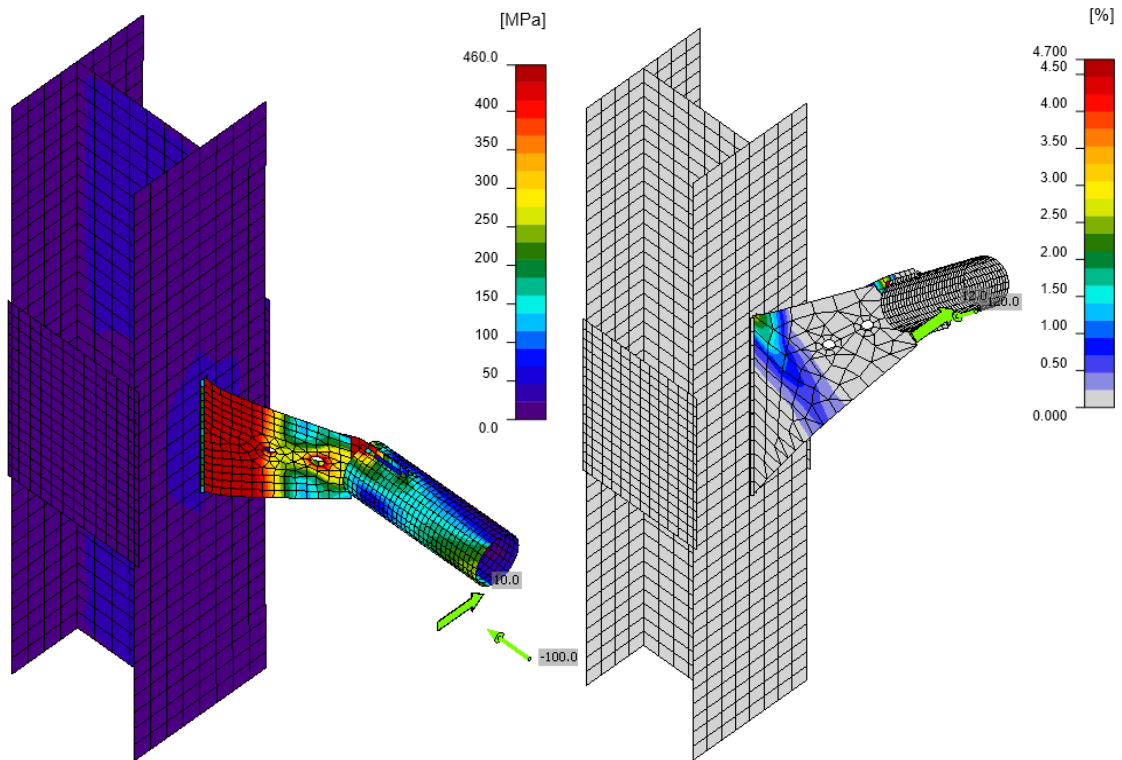Figure 5: CBFEM model with supports and bending moment diagram

Figure 6: Von Mises stress on specimen C2 and plastic strain on specimen D4, deformation scale 3

Verification and validation of resistance

Design resistances calculated by CBFEM were compared with results of analytical model, experiments, and research oriented finite element model (Vesecký, 2019). The experiments were performed at ČVUT in 2018 and comprised six specimens. All members were tubes CHS 102×4 eccentrically connected via gusset plates and connecting plates with the thicknesses of 8 mm – see Figure 7. The research oriented finite element model was made in Abaqus software and validated on the experiments. ROFEM - DIC is using digital image correlation to apply the real imperfections; ROFEM – EN is using imperfections according to EN 1993-1-5 and EN 1090-2. The analytical models are labelled KPA1 and KPA2. Model KPA1 is Khoo-Perera-Albermani with minimal lengths of plastic hinges and minimal moments of inertias of gusset and connecting plates; model KPA2 is using average moments of inertia. The measured strengths of gusset plates and connecting plates were used in all models.
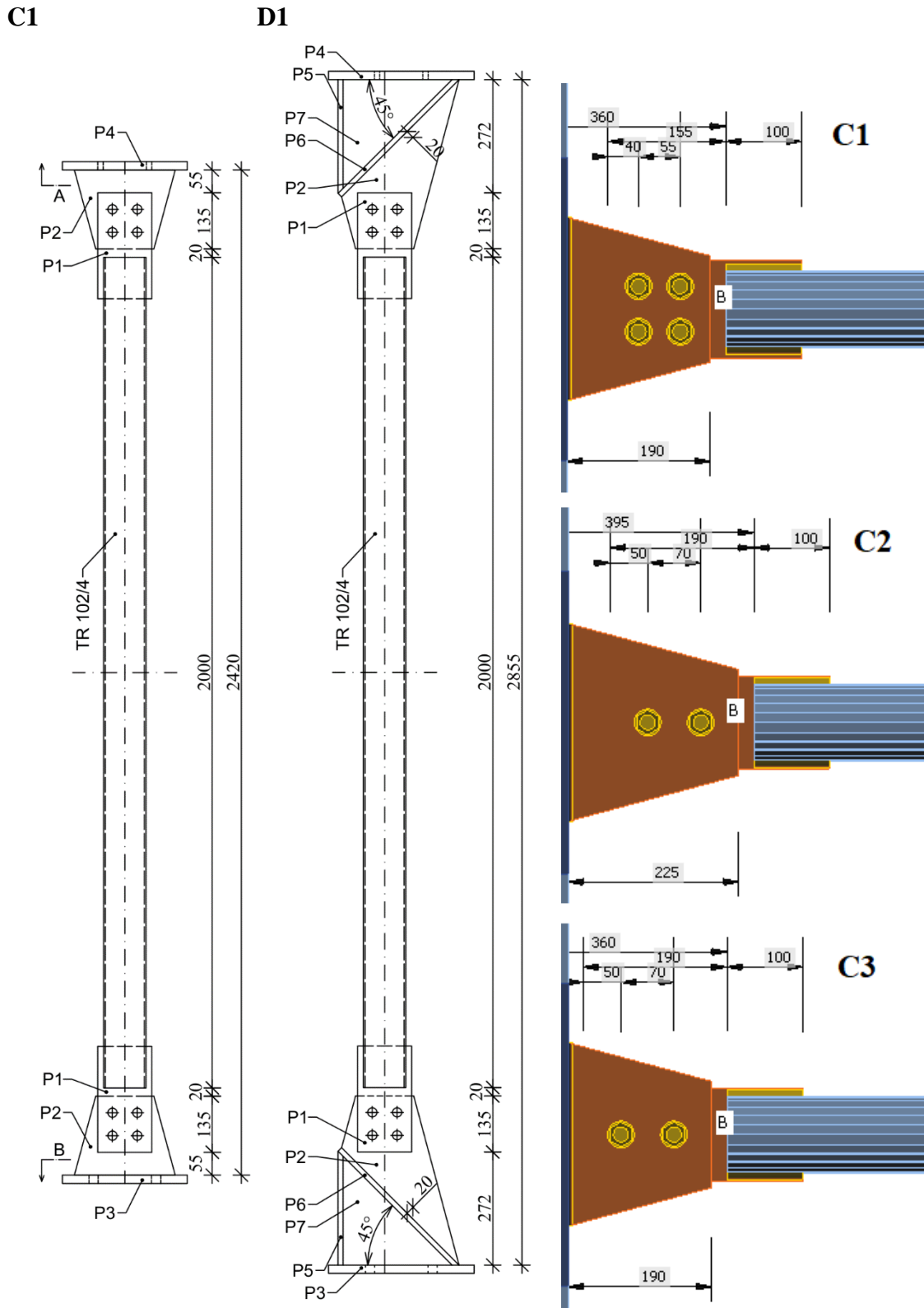
Figure 7: Specimens of circular hollow sections connected via eccentric gusset plates (Vesecký, 2019)

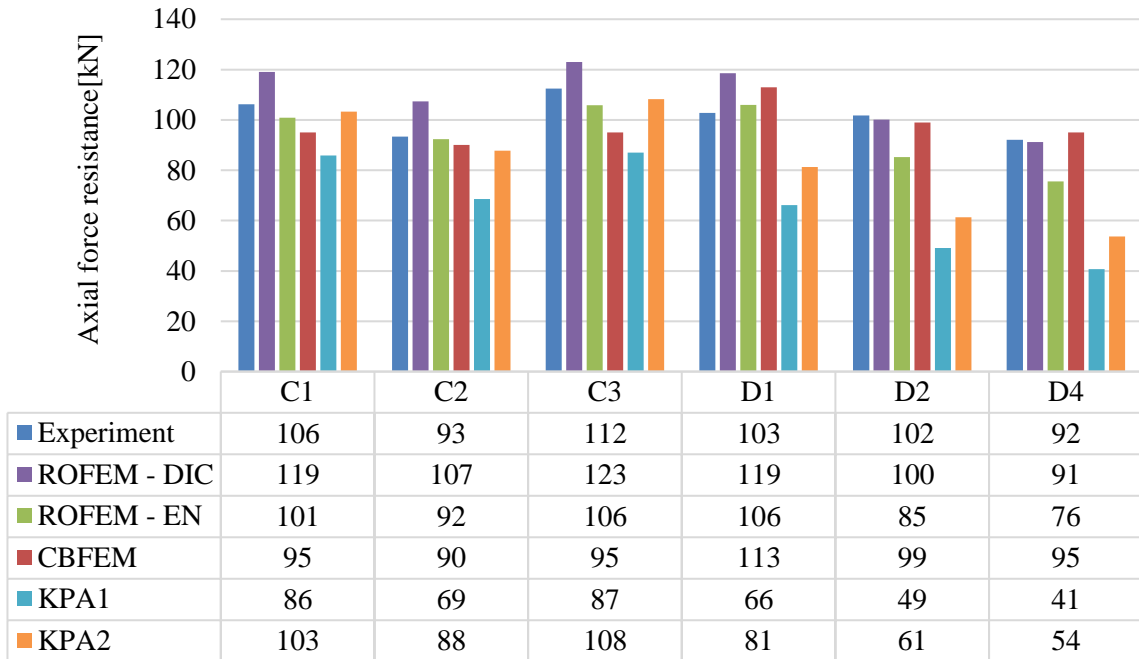The results are summarised in Figure 8.

	C1	C2	C3	D1	D2	D4
■ Experiment	106	93	112	103	102	92
■ ROFEM - DIC	119	107	123	119	100	91
■ ROFEM - EN	101	92	106	106	85	76
■ CBFEM	95	90	95	113	99	95
■ KPA1	86	69	87	66	49	41
■ KPA2	103	88	108	81	61	54

Figure 8: Comparison of experimental, FEM and analytical models of tested specimens

Sensitivity analysis

The ROFEM was further used for parametric study. The steel grade S355 and geometry parameters of specimen C2 were used unless stated otherwise. Always only one parameter was variable.

The resistance of the joint for varying free length is shown in Figure 9. CBFEM follows the same slope as ROFEM. The resistance is linearly dependent on the free length.
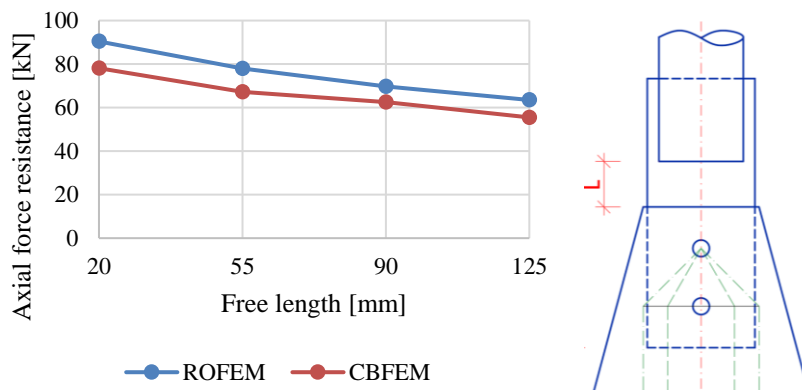
Figure 9: Effect of free length of the connecting plate

The effect of varying thickness of gusset and connected plates is shown in Figure 10. The CBFEM is slightly underestimating the resistance with higher thickness of the plates compared to the ROFEM.
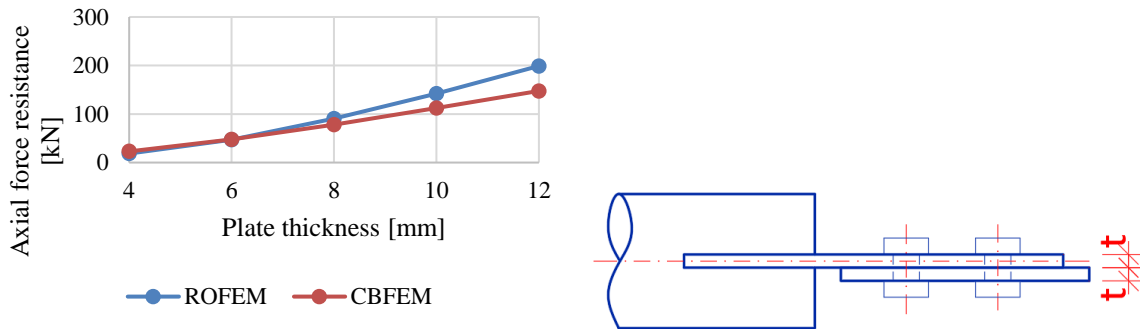
Figure 10: Effect of thicknesses of gusset plate and connected plate

The number of bolts nearly do not affect the resistance of the connection – see Figure 11. The effect was investigated on connection C2 and D4.
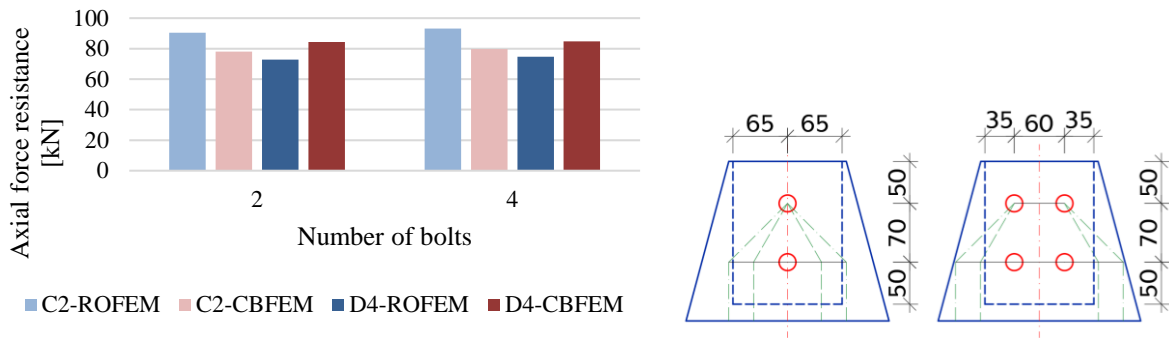

Figure 11: Effect of number of bolts

The load resistance is linearly rising with increasing yield strength – see Figure 12. The effect was investigated on connection C2 and D4.
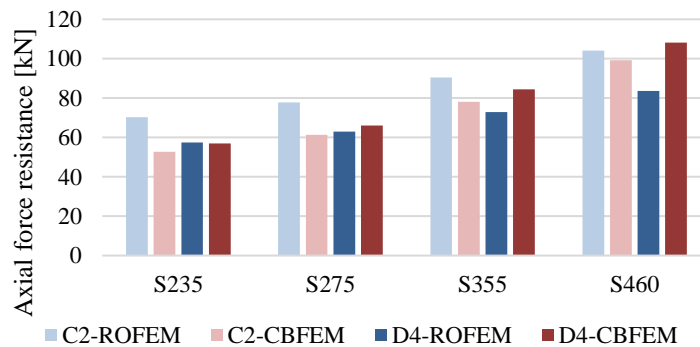

Figure 12: Effect of steel grade

The comparison of load resistances using ROFEM and CBFEM is plotted in Figure 13. The CBFEM is usually conservative except for specimens D2 and D4. However, for these specimens, the ROFEM is conservative compared to the experiments. The CBFEM model is much simpler and uses geometrically linear analysis but the accuracy of its results is comparable to ROFEM and exceeds analytical models.
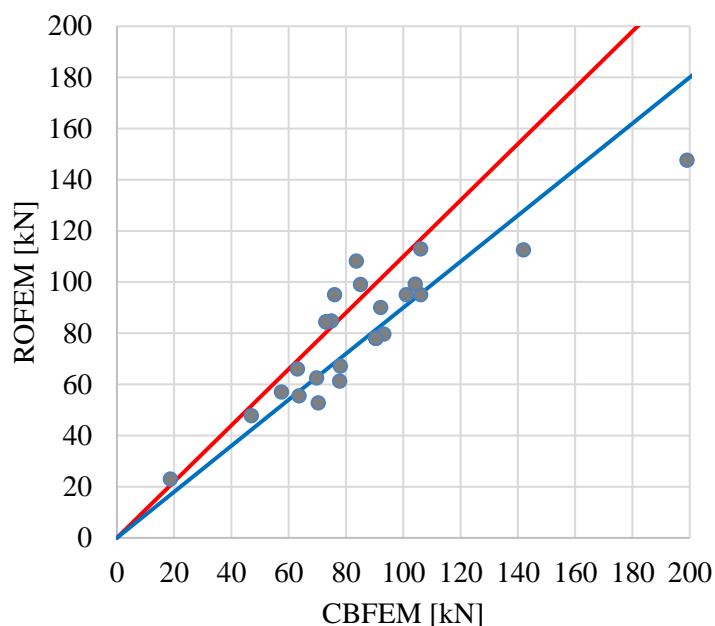
Figure 13: Comparison between ROFEM and CBFEM

Summary

Recommendation for pinned member connected by unsymmetrical gusset plate connection:
1.   Keep free lengths of gusset plate and connecting plate as short as possible
2.   Use model type N-Vy-Vz for pinned member
3.   Set shear load perpendicular to the gusset plate as a disruptive force due to eccentricities with the magnitude of $V = N / 10$ in the location of bolt group centre
4.   Calculate the connection using stress-strain analysis and check the results

References:

- EN 1993-1-5, *Eurocode 3, Design of steel structures, Part 1-5: Plated structural elements,* CEN, Brussels, 2006.
- EN 1090-2, *Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures*, CEN, Brussels, 2008.
- EN 1993-1-8, *Eurocode 3, Design of steel structures, Part 1-8: Design of joints*, CEN, Brussels, 2005.
- Khoo X.E., Perera M., Albermani F.; Design of eccentrically connected cleat plates in compression; In: *Advanced Steel Construction*; August 2009, Vol. 6, No. 2, pp. 678–687.
- Vesecký, J., *Buckling resistance of gusset plates,* diploma thesis, ČVUT, Prague, 2019.