Verification of T-stub

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1 Description

The objective of this study is a verification of component based finite element method (CBFEM) integrated in IDEA RS software with component method (CM) and research FEM model (RM) created in Midas FEA software. Two T-stubs connected with two bolts loaded in tension only are objects of study.

2 Component method

T-stub and bolt in tension are components examined in the study.

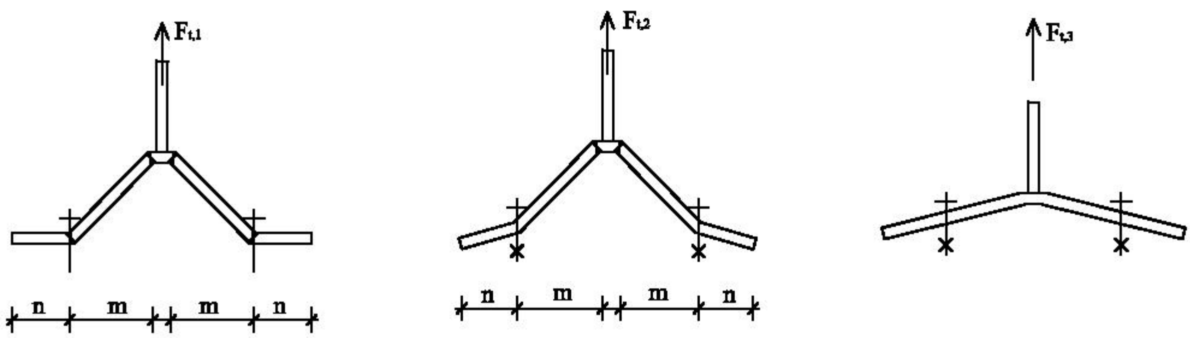
Both components are designed according to EN 1993-1-8.

2.1 T-stub

Welded T-stubs are considered. The thickness of the weld depends on the flange thickness. The welds are designed not to be the weakest component. Effective lengths for circular and noncircular failures are considered according to EN 1993-1-8 cl. 6.2.6. Only tension loads are considered.

Three modes of collapse according to EN 1993-1-8 cl. 6.2.4.1 are considered:

- 1. Mode: full yielding of the flange
- 2. Mode: two yield lines by web and rupture of the bolts
- 3. Mode: Rupture of the bolts



1. Mode   2. Mode   3. Mode

Fig. 1: Collapse modes of T-stub

2.2 Bolts

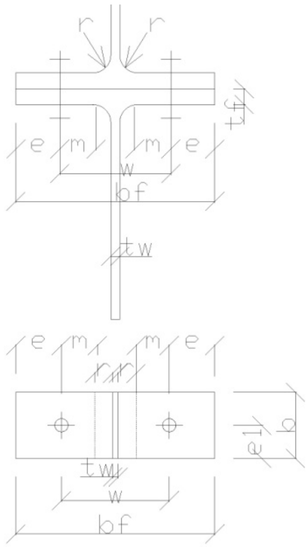
Design resistance according to EN1993-1-8 cl. 3.6.1 is calculated with considering of punching shear resistance and rupture of the bolt.

2.3 Examined samples

Overview of the considered samples is shown in the Tab. 1.

Tab. 1: Samples overview

Sample	T-stub														Bolts		
	f_y	f_u	E	γ_{M0}	t_f	t_w	b_f	a_w	b	w	e_1	m	e	n	Bolt diameter	Material	E_{bolt}
	[Mpa]	[Mpa]	[Gpa]		[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]			[Gpa]
tf10	235	360	210	1	10	20	300	10	100	165	50	61.19	67.5	67.5	M24	8.8	210
tf12	235	360	210	1	12	20	300	10	100	165	50	61.19	67.5	67.5	M24	8.8	210
tf15	235	360	210	1	15	20	300	10	100	165	50	61.19	67.5	67.5	M24	8.8	210
tf20	235	360	210	1	20	20	300	10	100	165	50	61.19	67.5	67.5	M24	8.8	210
tf25	235	360	210	1	25	20	300	13.5	100	165	50	57.23	67.5	67.5	M24	8.8	210
tf30	235	360	210	1	30	20	300	13.5	100	165	50	57.23	67.5	67.5	M24	8.8	210
tf35	235	360	210	1	35	20	300	13.5	100	165	50	57.23	67.5	67.5	M24	8.8	210
tf40	235	360	210	1	40	20	300	13.5	100	165	50	57.23	67.5	67.5	M24	8.8	210
tf45	235	360	210	1	45	20	300	13.5	100	165	50	57.23	67.5	67.5	M24	8.8	210
tf50	235	360	210	1	50	20	300	13.5	100	165	50	57.23	67.5	67.5	M24	8.8	210
M16 8.8	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M16	8.8	210
M20 8.8	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M20	8.8	210
M24 8.8	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M24	8.8	210
M27 8.8	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M27	8.8	210
M24 4.8	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M24	4.8	210
M24 5.8	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M24	5.8	210
M24 6.8	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M24	6.8	210
M24 10.9	235	360	210	1	25	20	300	10	100	165	50	61.19	67.5	67.5	M24	10.9	210
w110	235	360	210	1	20	20	300	7	100	110	50	37.08	95	46.35	M24	8.8	210
w150	235	360	210	1	20	20	300	7	100	150	50	57.08	75	71.35	M24	8.8	210
w200	235	360	210	1	20	20	300	7	100	200	50	82.08	50	50	M24	8.8	210
w240	235	360	210	1	20	20	300	7	100	240	50	102.1	30	30	M24	8.8	210
b100	235	360	210	1	20	20	300	7	100	110	50	37.08	95	46.35	M24	10.9	210
b250	235	360	210	1	20	20	300	7	250	110	125	37.08	95	46.35	M24	10.9	210
b300	235	360	210	1	20	20	300	7	300	110	150	37.08	95	46.35	M24	10.9	210
b400	235	360	210	1	20	20	300	7	400	110	200	37.08	95	46.35	M24	10.9	210



3 CBFEM Idea RS software

T-stub is modelled by 4-nodes shell elements. Every node has 6 degrees of freedom. Deformations of the element consist of membrane and flexural contributions.

Nonlinear elastic-plastic material status is investigated in each layer of integration point. Assessment is based on the maximum strain given according to EN1993-1-5 by value of 5%.

Bolts are divided into three sub-components. The first is the bolt shank, which is modelled as a nonlinear spring. That spring does not transmit pressure. The second sub-component transmits tensile force into the flanges. The third sub-component solves shear transmission.

Detailed information about CBFEM model is to find in chapter "Description of CBFEM model"

4 Research model

In some cases gives the CBFEM method higher resistance, initial stiffness or deformation capacity. Research FEM model (RM) from brick elements validated on experiments [3] is used to verify the CBFEM model.

RM is created in Midas FEA software of hexahedral and octahedral solid elements see Fig. 2. Mesh sensitive study was provided to get proper results in adequate time. Numerical model of the bolts is based on the model by Wu et al. (2012) [4]. The nominal diameter is considered in the shank and the effective core diameter is considered in the threaded part. Washers are coupled with the head and nut. Deformation caused by stripping of the threads in thread-nut contact area is simply modelled using interface elements. Interface elements are unable to transfer tensile stresses. Contact elements allowing the transmission of pressure and friction are used between washers and flanges of the T-stub. One quarter of the sample was modelled to use the symmetry.

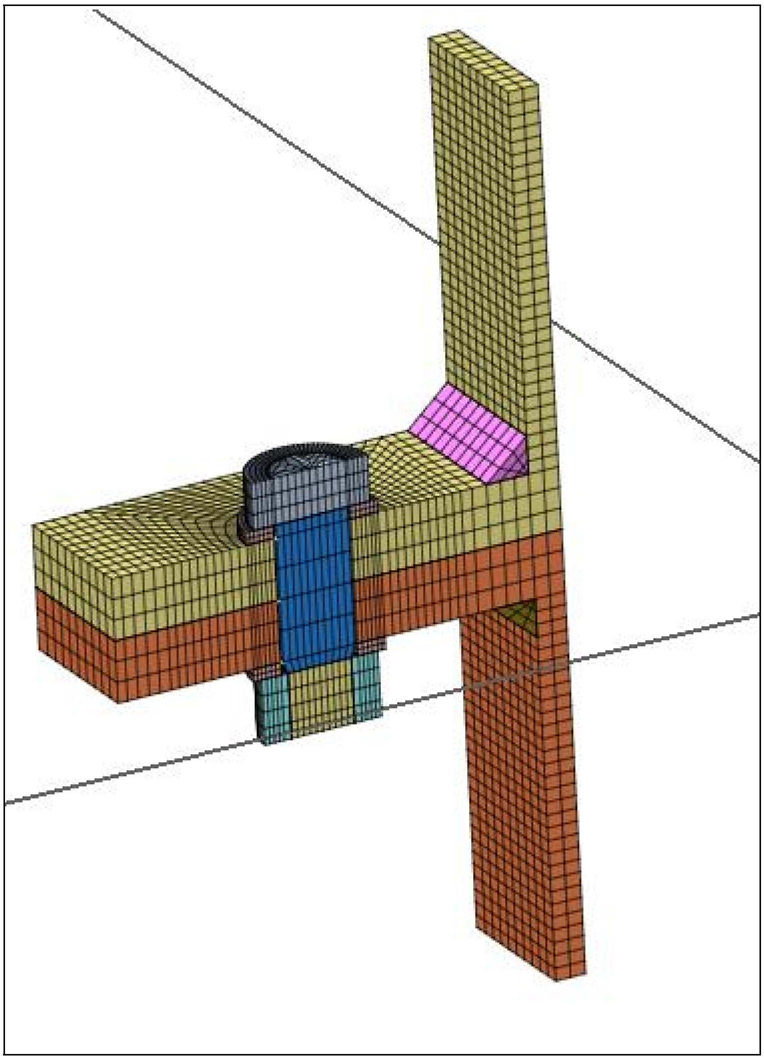


Fig. 2: Research FEM model

5 Global behaviour and verification

Comparison of the global behaviour of the T-stub described by force-deformation diagrams for all design procedures was prepared. Attention was focused to the main characteristics: initial stiffness, design resistance and deformation capacity.

Sample tf20 was chosen to present as reference, see Fig. 3 and Tab. 2. CM generally gives higher initial stiffness compared to CBFEM and RM. In all cases gives RM the highest design resistance as shown in chapter 6. Deformation capacity is compared also. Deformation capacity of T-stub was calculated according to [5]. RM does not consider cracking of the material so the prediction of deformation capacity is limited.

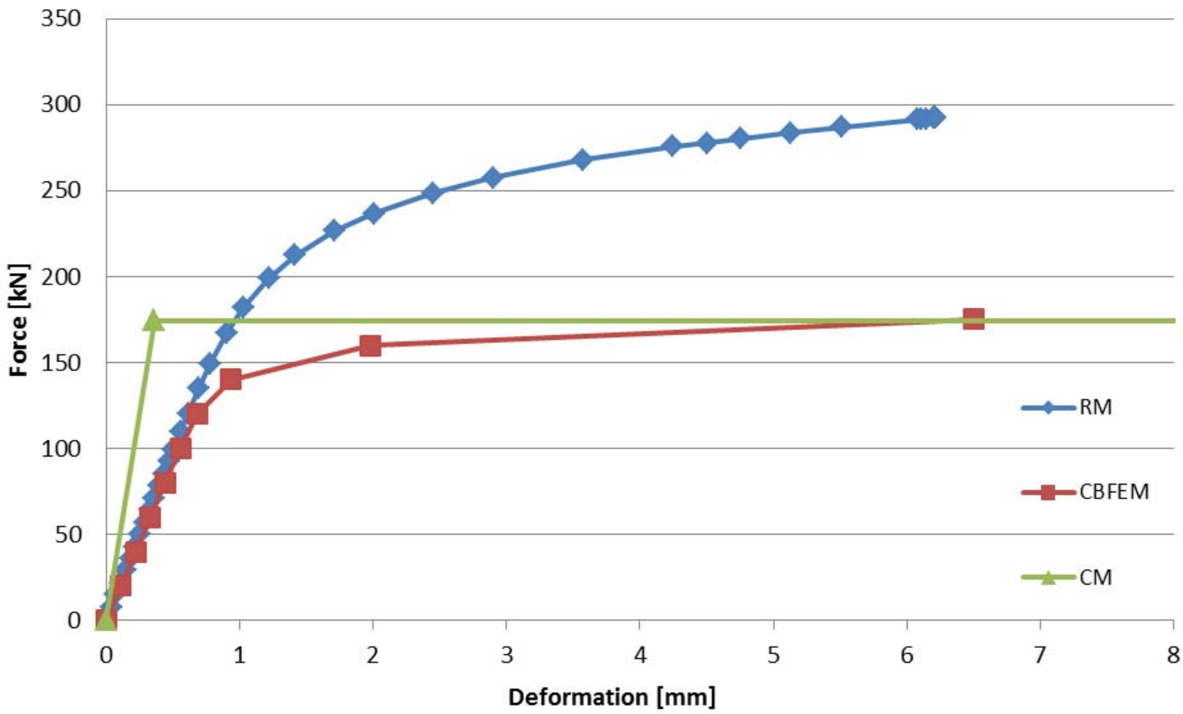


Fig. 3: Force-deformation diagram

Tab. 2: Global behaviour overview

		CM	CBFEM	RM	CM/CBFEM	RM/CBFEM
Initial stiffness	[kN/m]	484727	181818	197400	2,67	1,09
Design resistance	[kNm]	174	179.7	268.8	0,96	1,5
Deformation capacity	[mm]	24.5	6.5		3,77	

6 Verification of resistance

Design resistance calculated by CBFEM Idea RS software were compared with the results of CM and RM in the next step. The comparison was focused on the deformation capacity and determination of the collapse mode also. All results are ordered in Tab. 3.

The study was performed for five parameters: thickness of the flange, bolt size, bolt material, bolt space and T-stub width.

Tab. 3: Global behaviour overview

Sample	CM			CBFEM			RM		
	Design resistance	Collapse mode	Initial stiffness	Design resistance	Collapse mode	Initial stiffness	Design resistance	Collapse mode	Initial stiffness
	[kN]		[kN/mm]	[kN]		[kN/mm]	[kN]		[kN/mm]
Parameter: Thickness of the flange									
tf10	44	1	80.0	75	1	39.4	115	1	53.6
tf12	63	1	134.6	90	1	58.8	144	1	80.9
tf15	98	1	246.6	115	1	97.1	199.7	1	120.5
tf20	174	1	484.7	175	1	181.8	268.8	2	197.4
tf25	279	2	789.3	249	1	285.7	310.3	2	297.8
tf30	305	2	922.6	288	2	392.2	328.7	2	363
tf35	335	2	968.8	320	2	485.4	347.3	2	416.8
tf40	371	2	961.3	358	2	573.8	370.7	2	464.4
tf45	407	3	927.3	385	2	654.2	400	2	510.6
tf50	407	3	882.4	412	3	736.8	407	3	553.8
Parameter: bolt size									
M16 8.8	152	2	486.6	150	2				
M20 8.8	205	2	612.7	200	2				
M24 8.8	270	2	710.2	249	1				
M27 8.8	278	1	782.4	260	1				
Parameter: bolt material									
M24 4.8	164	2	710.2	163	2				
M24 5.8	190	2	710.2	186	2				
M24 6.8	217	2	693.6	210	2				
M24 10.9	273	1	677.8	262	1				
Parameter: bolt space									
w110	282	2	1129.7	273	1	465.1	344	2	432.5
w150	188	1	562.4	194	1	229	281	2	228
w200	129	1	237.8	144	1	111.9	222	2	112.7
w240	107	1	131.9	124	1	66.1	162.7	2	64.9
Parameter: T-stub width									
b100	314	1	1129.7	296	1	463	407	2	432.2
b250	423	2	1443.5	448	2	534.4	480.5	2	640
b300	433	2	1443.5	466	2	534.4	486	2	686
b400	433	2	1443.5	492	2	538.5	494	2	721.5

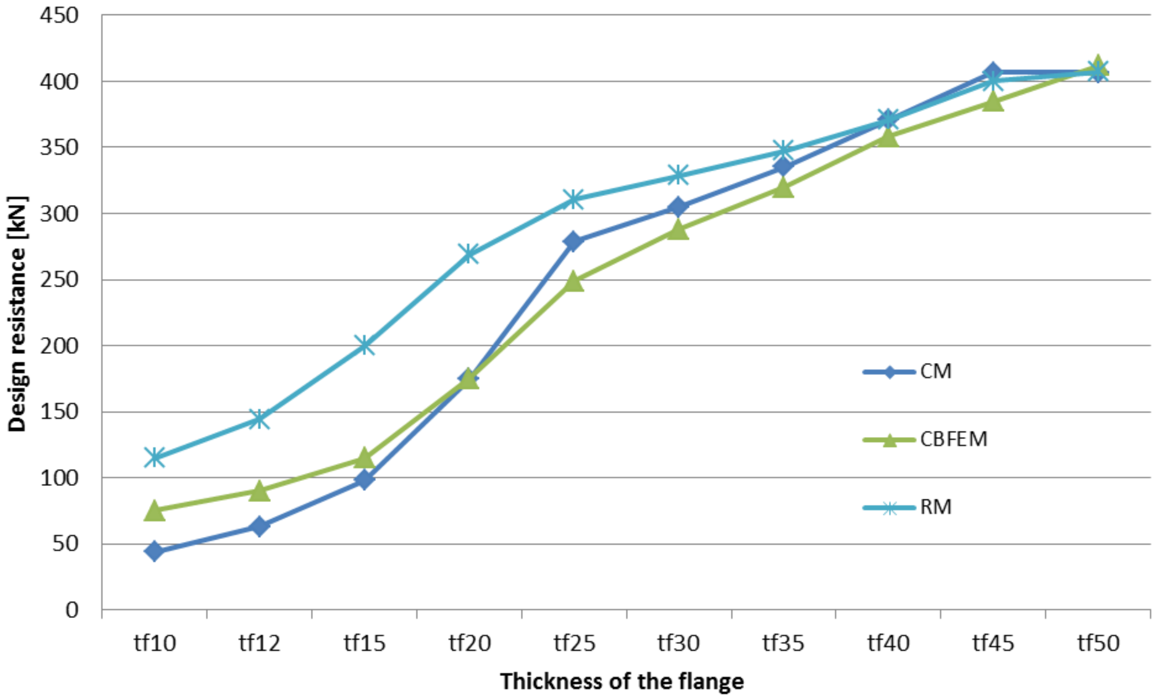


Fig. 4: Parametric study – flange thickness parameter

First parametric study with thickness of the flange shows higher resistance according to CBFEM compared to CM for samples with flange thicknesses up to 20 mm. RM gives for that samples even higher resistance, see Fig. 4. Higher resistance of both numerical models is reasoned by neglecting of membrane effect in CM.

In the second and third case with parameters bolt diameter (Fig. 5) and bolt material (Fig. 6) respectively correspond results of CBFEM and CM. Due to a good agreement of both methods, results of RM are not required.

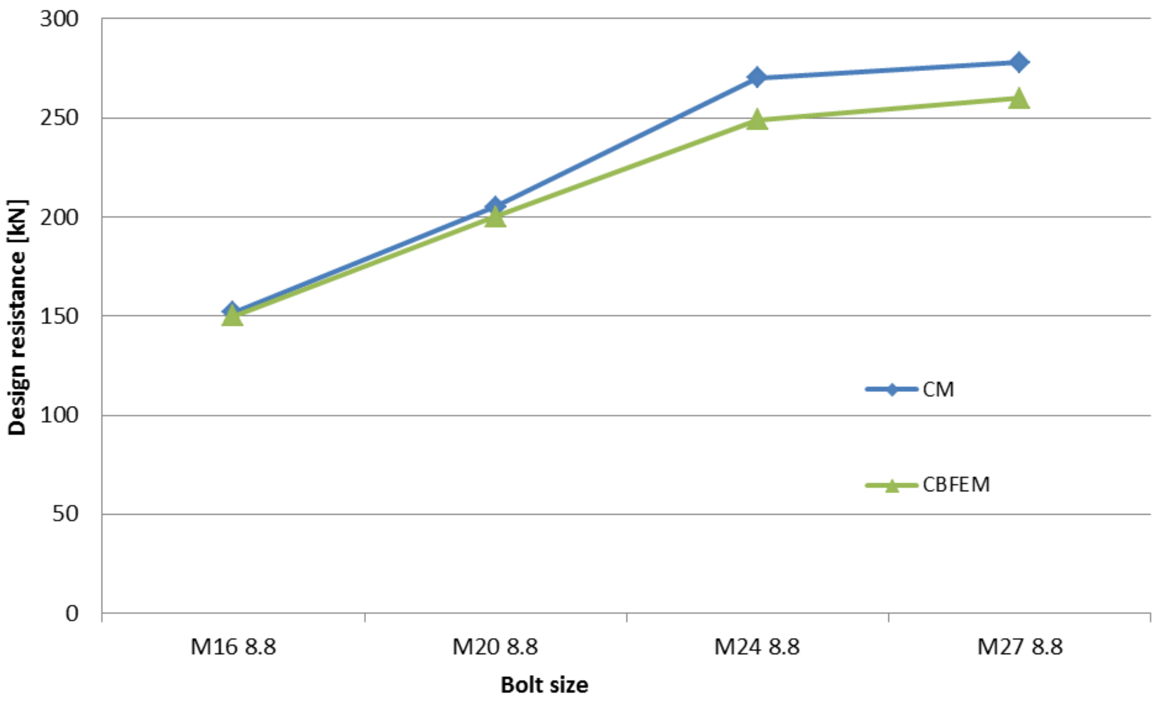


Fig. 5: Parametric study – bolt size parameter

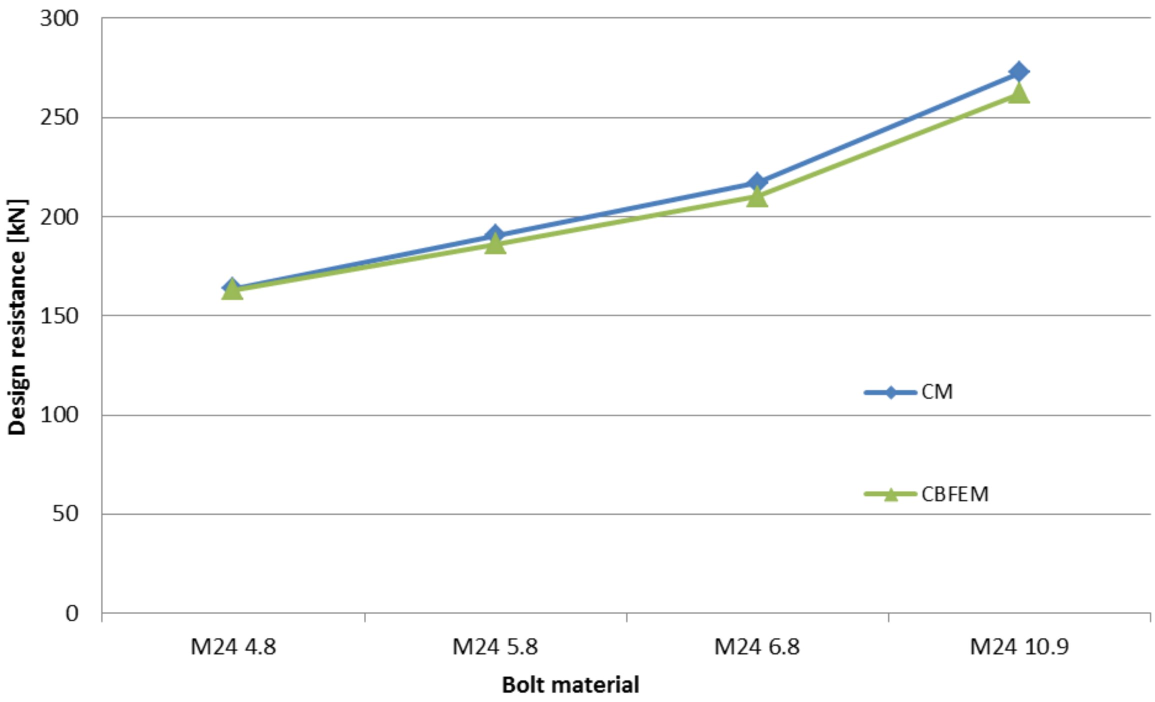


Fig. 6: Parametric study – bolt material parameter

In the fourth case with bolt space parameter shows results of CBFEM and CM generally good agreement, see Fig. 7. With increase of bolt space give CBFEM slightly higher resistance compared to CM. For that reason, results of RM are showed also. RM gives the highest resistance in all cases.

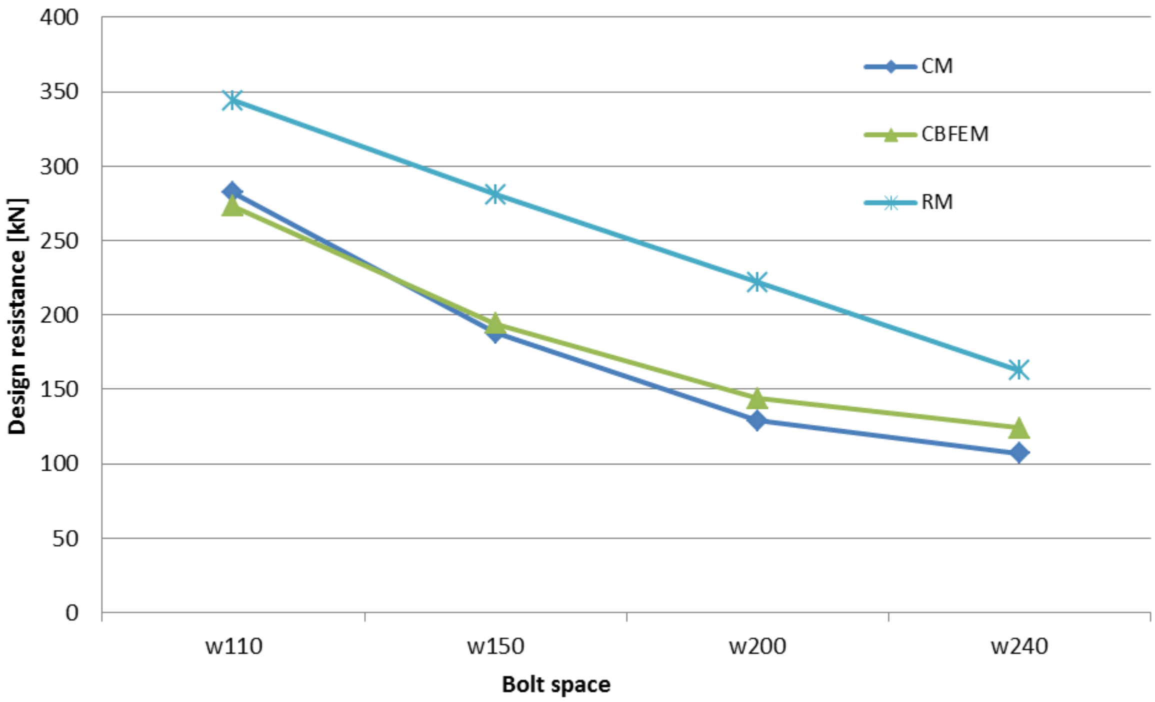


Fig. 7: Parametric study – bolt space parameter

In the fifth study with T-stub width parameter shows CBFEM slightly higher resistance compared to CM with increase of width. For that reason, results of RM were estimated also and RM gives again the highest resistance in all cases, see Fig. 8.

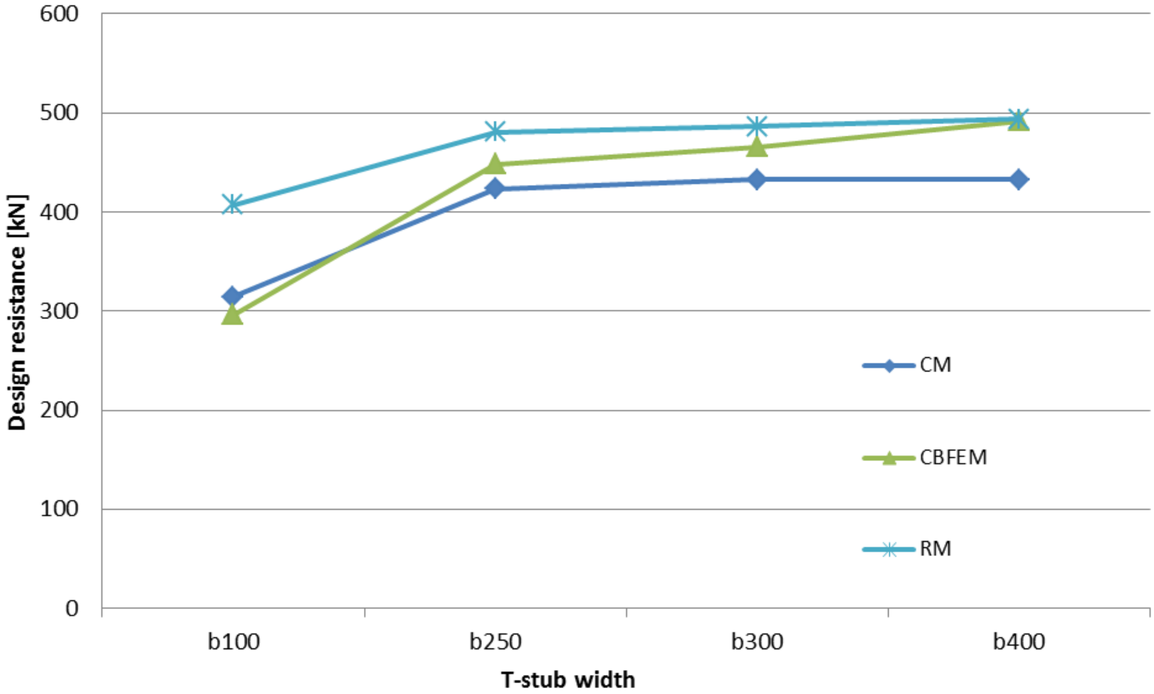


Fig. 8: Parametric study – T-stub width parameter

To illustrate the accuracy of the CBFEM model, results of the parametric studies were summarized in graph comparing resistance by CBFEM and component method, see Fig. 9. The results show that the difference of the two calculation methods is in most cases up to 10%, which is a generally acceptable value. In cases with CBFEM/CM > 1,1 correctness of CBFEM was verified on the results of RM which gives highest resistance in all cases.

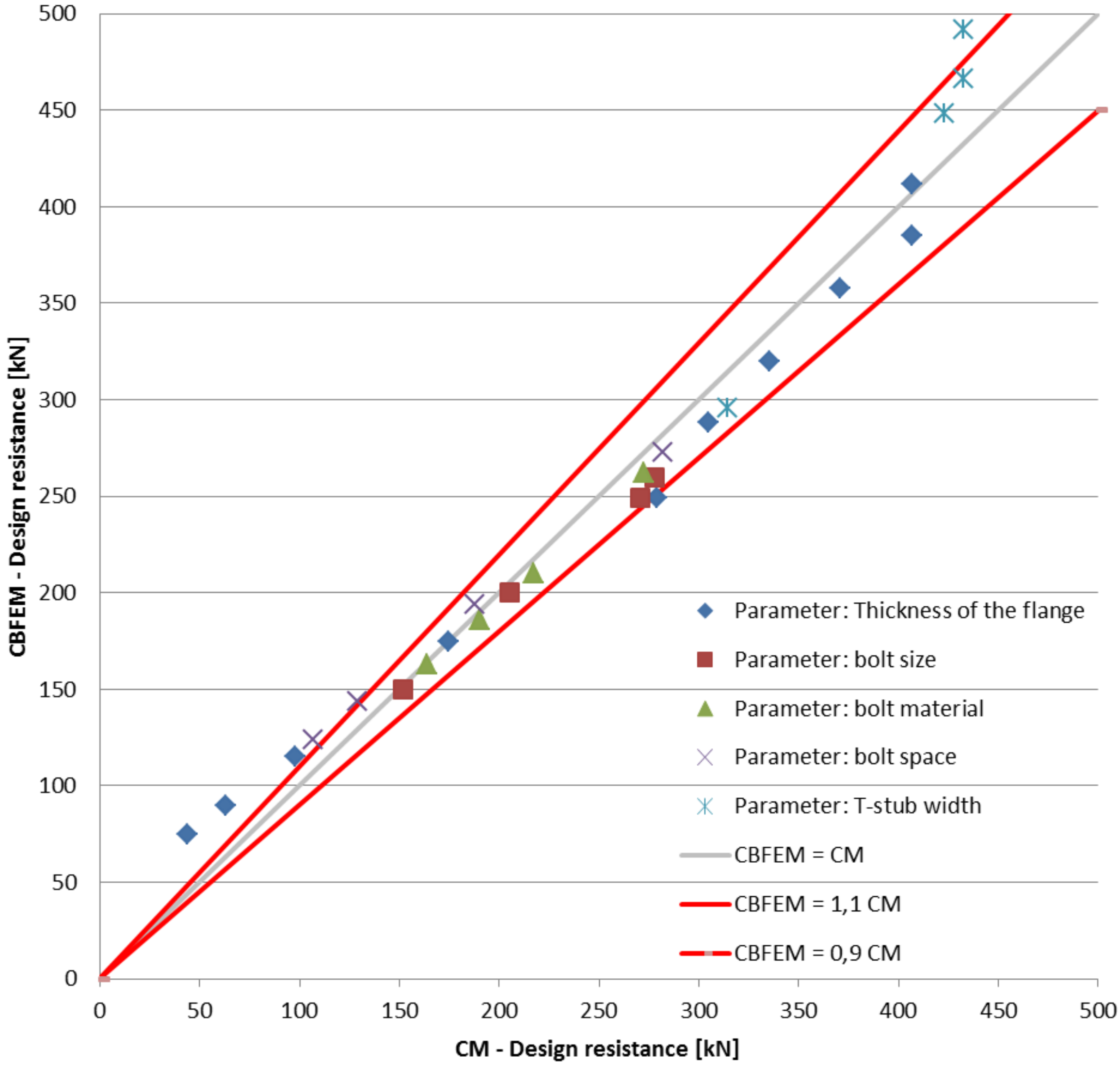


Fig. 9: Verification of CBFEM to CM

7 Scope of validity

CBFEM was verified for usually used T-stub geometries. Scope of validity is defined in boundaries:

- Minimal thickness of the flange 8 mm
- Maximal distance of the bolts to bolt diameter ratio: $p/d_b \leq 20$
- Maximal ratio distance bolt line – web to bolt diameter: $m/d_b \leq 5$

Verification study is necessary for using of CBFEM out of defined scope.

8 Résumé

Verification studies confirmed the accuracy of the CBFEM IDEA RS software for prediction of T-stub behaviour. Results of that software were compared with the results of the CM and RM. All procedures predict similar global behaviour of the joint. Except few cases is the difference in design resistance of the CM and CBFEM up to 10%, which is a generally acceptable value. Higher resistance by CBFEM IDEA RS software compared to CM is caused by conservative calculation of component method neglecting membrane effects. Correctness of CBFEM was verified on the results of RM which gives highest resistance in all cases.

Reliability of CBFEM software is provided in accordance with the strategy of EC considering partial safety factors.

9 Benchmark example

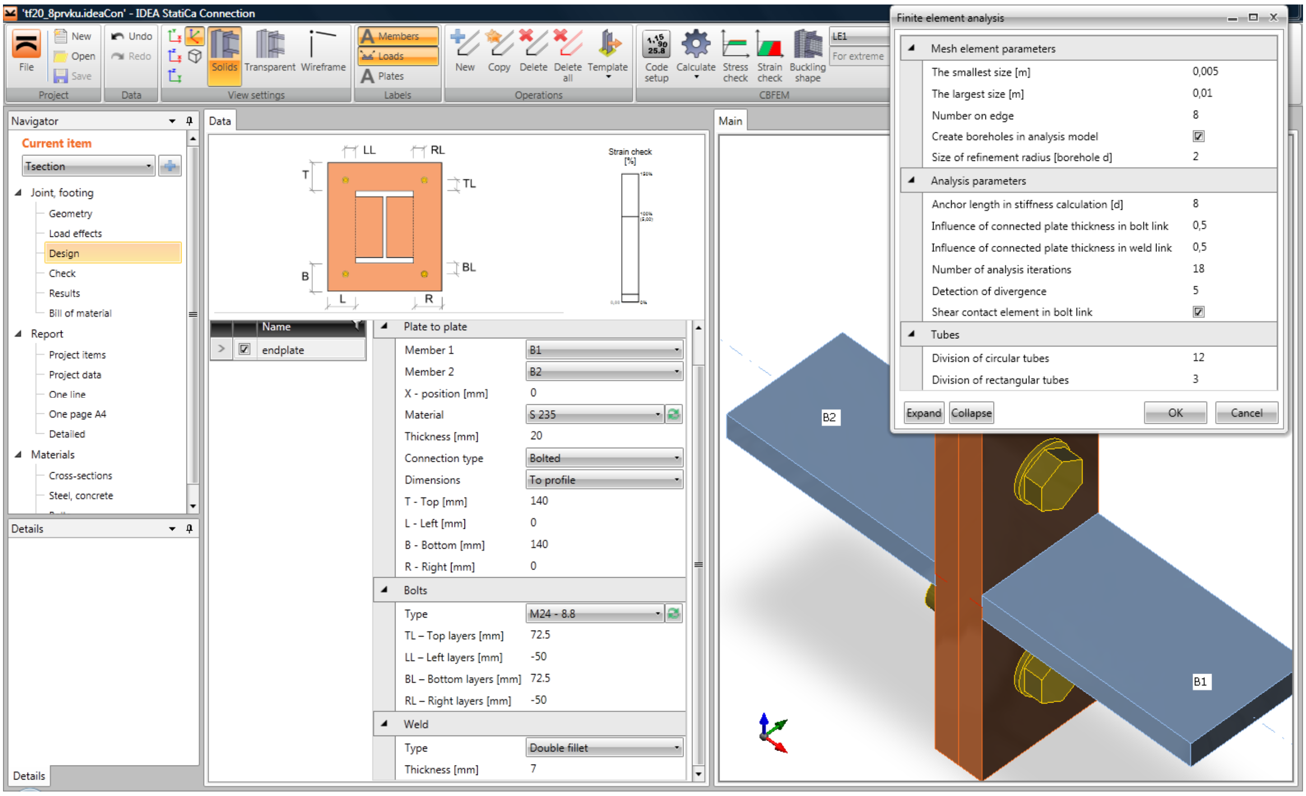
Inputs:

T-stub:

- Steel: S235
- flange thickness t_f = 20 mm
- web thickness t_w = 20 mm
- flange width b_f = 300 mm
- length b = 100 mm
- double fillet weld a_w = 10 mm

Bolts:

- 2 x M24 8.8
- distance of the bolts w = 165 mm



Outputs:

- Design resistance in tension: $F_{T,Rd}$ = 175 kN
- Collapse mode: full yielding of the flange
- Utilization of the bolts: 88,4 %
- Utilization of the welds: 49,1 %

Tsection

Bolts/ Anchors

Name	Bolt assembly	Diameter [mm]	fu [MPa]	Gross area [mm^2]
M24 - 8.8	M24 - 8.8	24	800,0	452

Load effects

Name	Member	Pos.	N [kN]	Vy [kN]	Vz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
LE1	B1	End	20,0	0,0	0,0	0,0	0,0	0,0
	B2	End	20,0	0,0	0,0	0,0	0,0	0,0
LE2	B1	End	40,0	0,0	0,0	0,0	0,0	0,0
	B2	End	40,0	0,0	0,0	0,0	0,0	0,0
LE3	B1	End	60,0	0,0	0,0	0,0	0,0	0,0
	B2	End	60,0	0,0	0,0	0,0	0,0	0,0
LE4	B1	End	80,0	0,0	0,0	0,0	0,0	0,0
	B2	End	80,0	0,0	0,0	0,0	0,0	0,0
LE5	B1	End	100,0	0,0	0,0	0,0	0,0	0,0
	B2	End	100,0	0,0	0,0	0,0	0,0	0,0
LE6	B1	End	120,0	0,0	0,0	0,0	0,0	0,0
	B2	End	120,0	0,0	0,0	0,0	0,0	0,0
LE7	B1	End	140,0	0,0	0,0	0,0	0,0	0,0
	B2	End	140,0	0,0	0,0	0,0	0,0	0,0
LE8	B1	End	160,0	0,0	0,0	0,0	0,0	0,0
	B2	End	160,0	0,0	0,0	0,0	0,0	0,0
LE9	B1	End	175,0	0,0	0,0	0,0	0,0	0,0
	B2	End	175,0	0,0	0,0	0,0	0,0	0,0

Results

Summary

Name	Value	Check status
Analysis	Applied loads : 100,0%	OK
Plates	5,0 < 5%	OK
Bolts	88,4 < 100%	OK
Welds	49,1 < 100%	OK

Plates

Name	Thickness [mm]	Load case	σ_{Ed} [MPa]	ε_{Pl} [1e-4]	Check status
B1-bfl 1	20	LE9	211,4	1,8	OK
B2-bfl 1	20	LE9	211,4	1,8	OK
endplate	20	LE9	245,5	498,6	OK
endplate	20	LE9	245,5	498,6	OK

Design data

	fy [MPa]	ε_{lim} [1e-4]
S 235	235,0	500,0

Symbol explanation

Symbol	Symbol explanation
ε_{Pl}	Strain
σ_{Ed}	Eq. stress

Bolts

Name	Load case	$F_{t,Ed}$ [kN]	V [kN]	Ut_t [%]	Ut_s [%]	Ut_{ts} [%]	Check status
B1	LE9	179,7	0,0	88,4	0,0	63,1	OK
B2	LE9	179,7	0,0	88,4	0,0	63,1	OK

Design data

Name	$F_{t,Rd}$ [kN]	$B_{p,Rd}$ [kN]	$F_{v,Rd}$ [kN]	$F_{b,Rd}$ [kN]
M24 - 8.8 - 1	203,3	390,9	135,6	345,6

Symbol explanation

Symbol	Symbol explanation
$F_{t,Rd}$	Bolt tension resistance EN 1993-1-8 tab. 3.4
$B_{p,Rd}$	Punching shear resistance
$F_{t,Ed}$	Tension force
V	Resultant of shear forces Vy, Vz in bolt.
$F_{v,Rd}$	Bolt shear resistance EN_1993-1-8 table 3.4
$F_{b,Rd}$	Plate bearing resistance EN 1993-1-8 tab. 3.4, Assumption $\alpha 1 = 1$
Ut_t	Utilization in tension
Ut_s	Utilization in shear
Ut_{ts}	Utilization in tension and shear EN 1993-1-8 table 3.4

10 References

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