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# Behaviour of stainless steel beam-to-column joints

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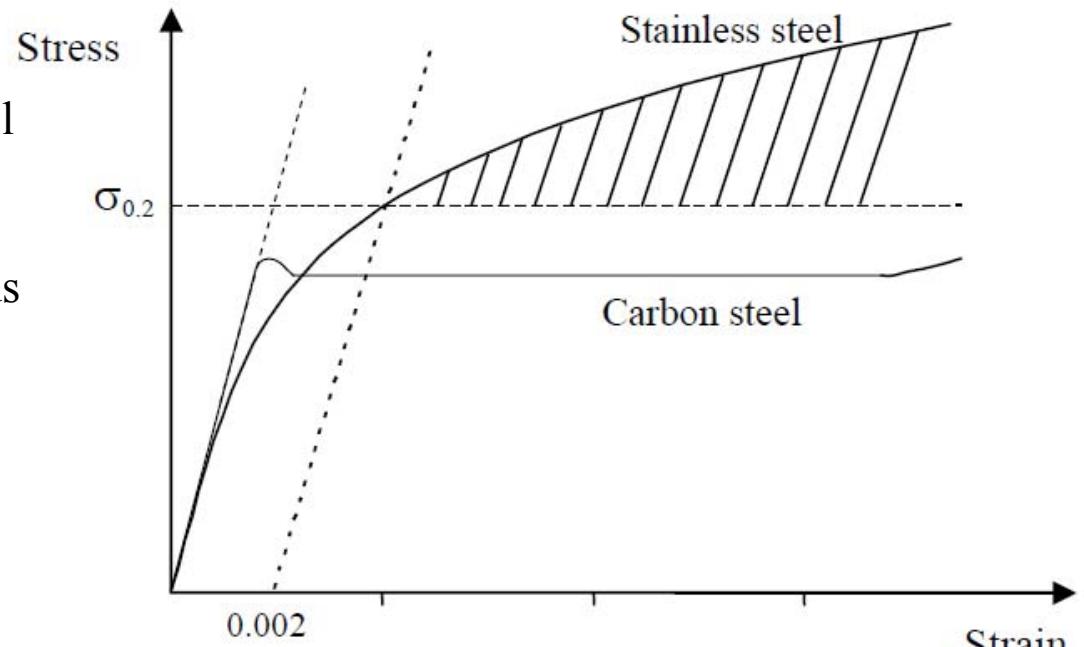
# Presentation outline

- Introduction
- Methodology
- Experimental studies
- Numerical modelling
- Discussion of results
- Conclusions & future research



# Gap in Knowledge

- material response of SS different from CS
- design based on assumed analogies with carbon steel to maintain consistency with CS design guidance
- research on SS members led to novel design methods and amendments in design codes
- connections have received far less attention
- research on SS joints mainly numerical
- limited experimental research mainly on lap joints



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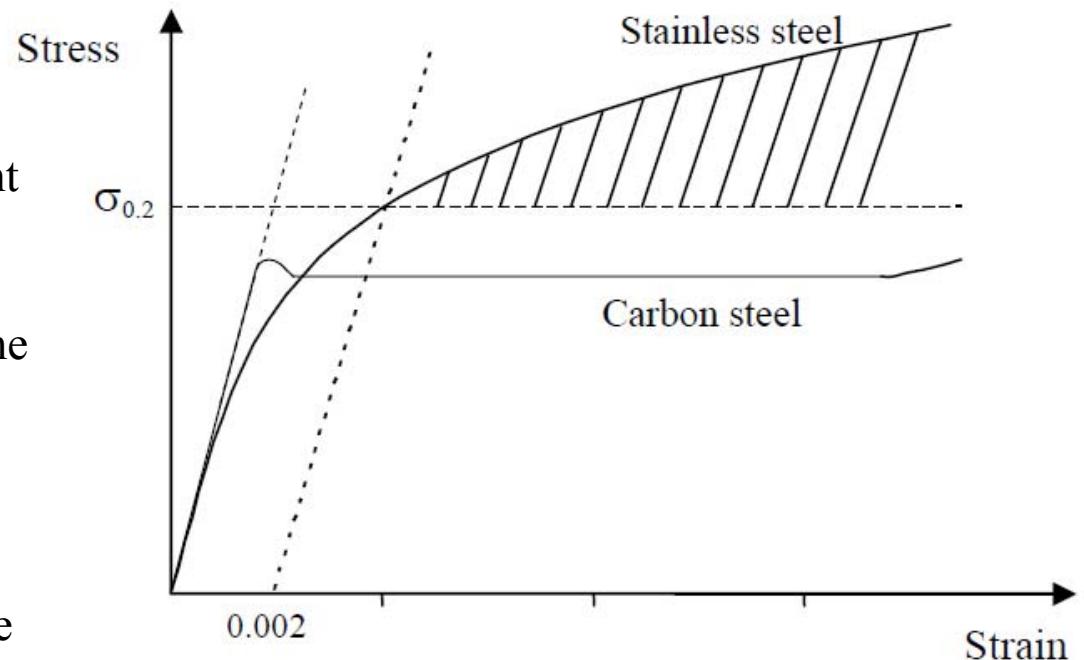
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# Gap in Knowledge

- joints: areas of high stress concentrations and high ductility demands
- several joint components in tension/shear: significant scope for the exploitation of SS strain-hardening
- material response is expected to significantly alter the response
- a research project is underway at UoB to generate experimental and numerical data on SS joints and novel design rules in line with the observed response



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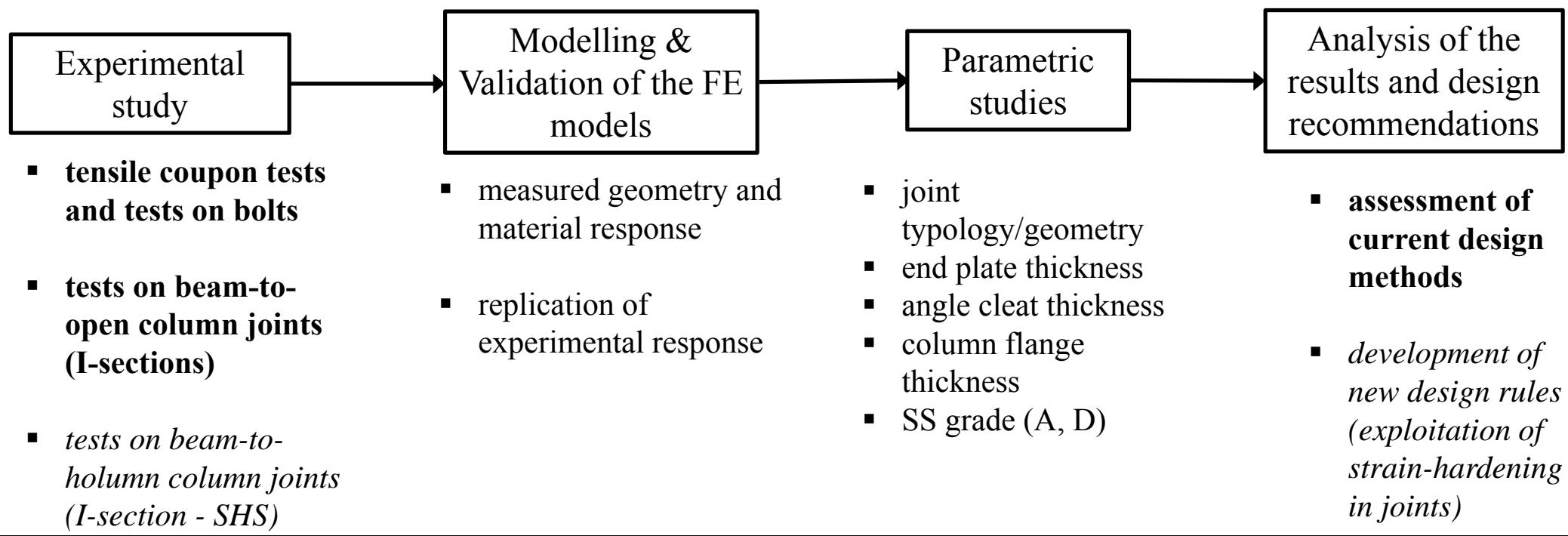
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# Methodology



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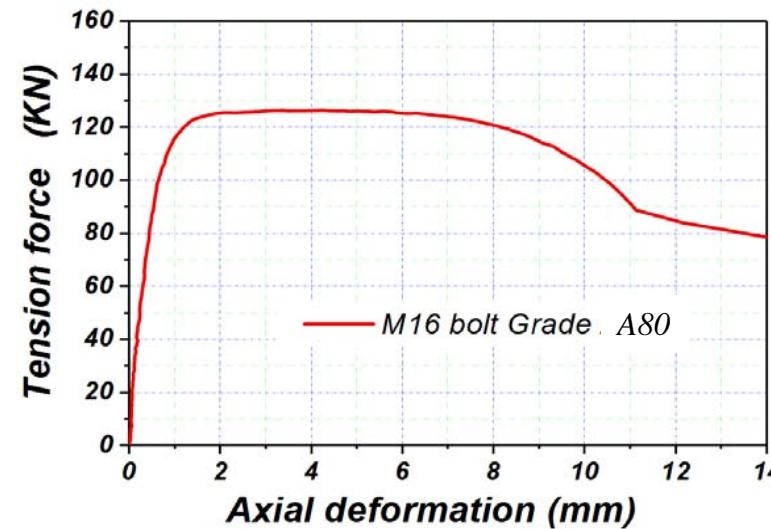
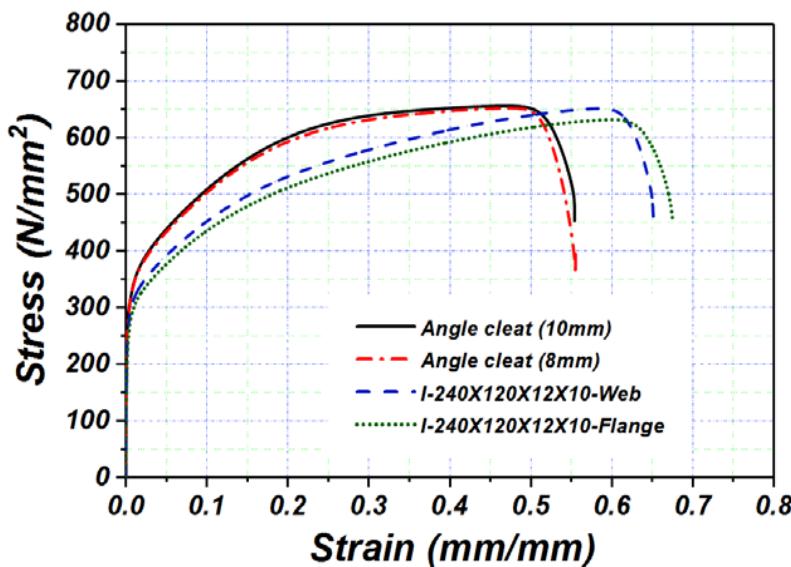
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# Material response



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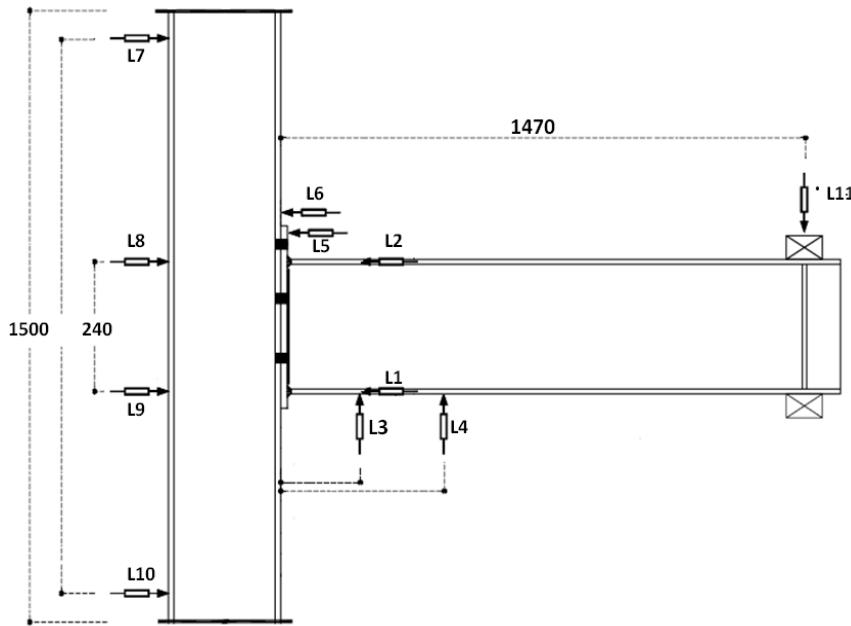
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# Test arrangement



- all beams and columns I 240X120X10X12
- all bolts A80 M16

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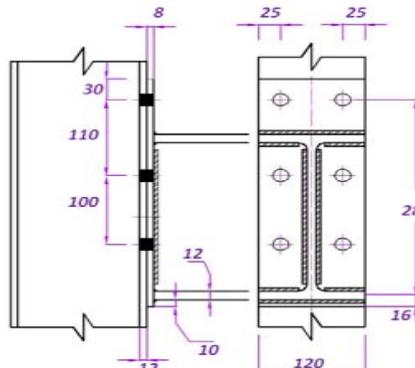
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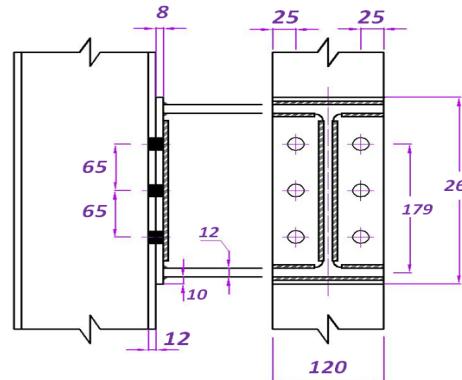
# Joint configuration



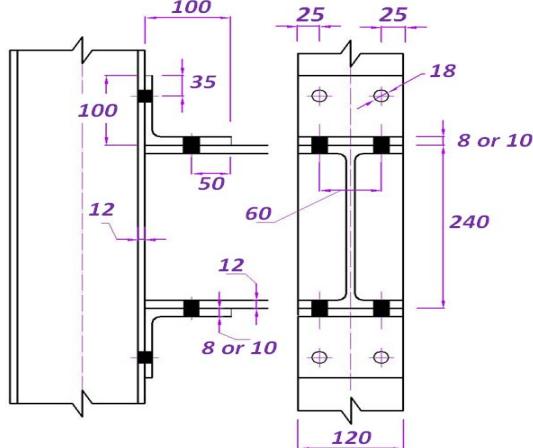
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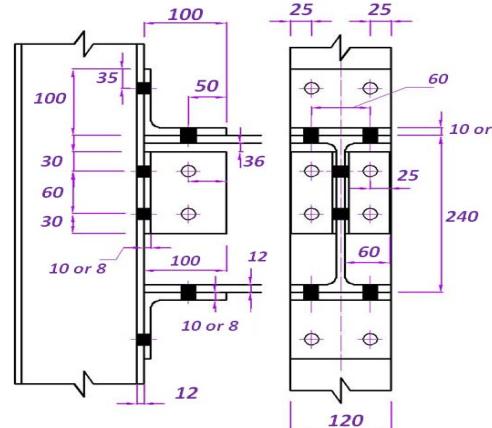
(a) Extended End Plate (EEP) connection



(b) Flush End Plate (FEP) connection



(c) Top and Seat Angle Cleat  
connection (TSAC)



(d) Top, Seat and double Web Cleat  
(TSWAC) connection

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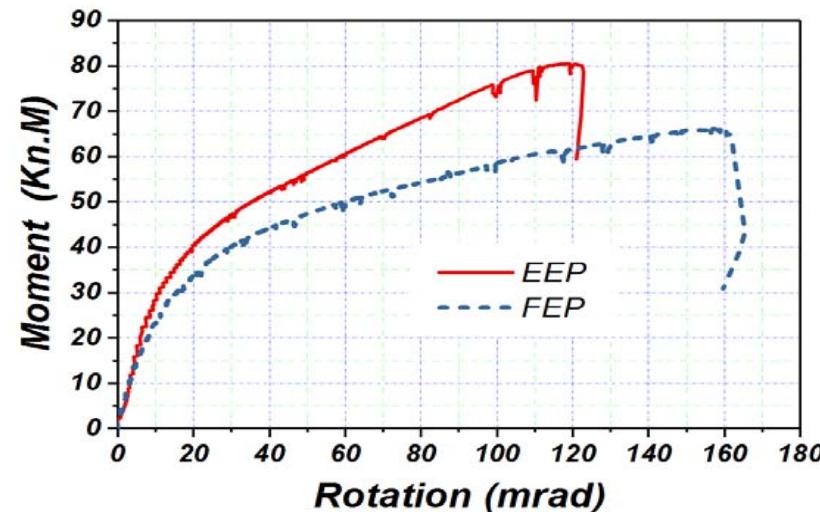
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# Test results – end plate joints



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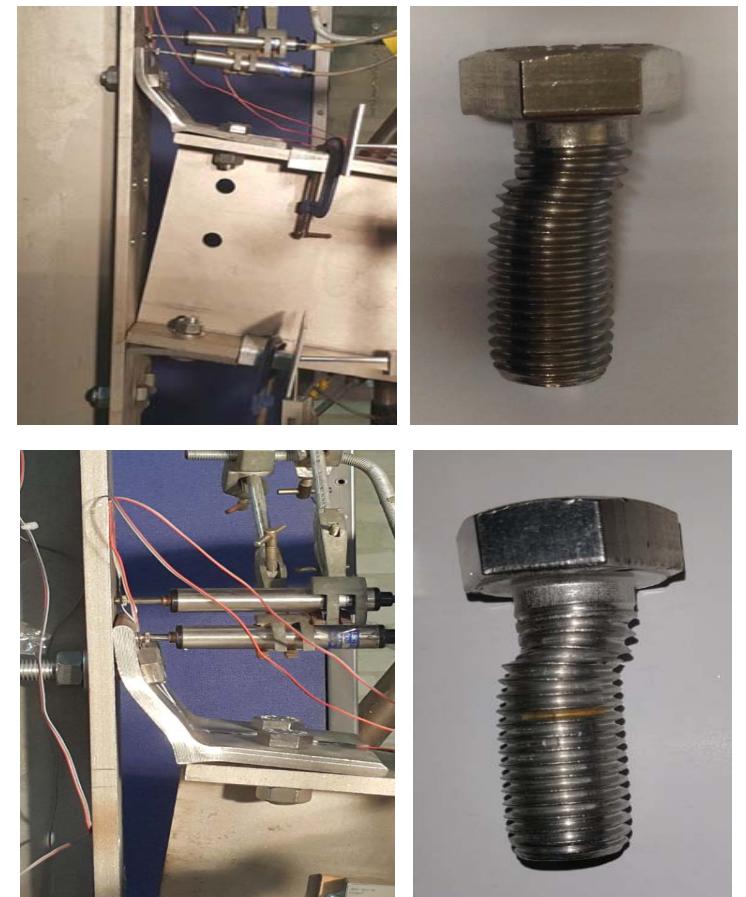
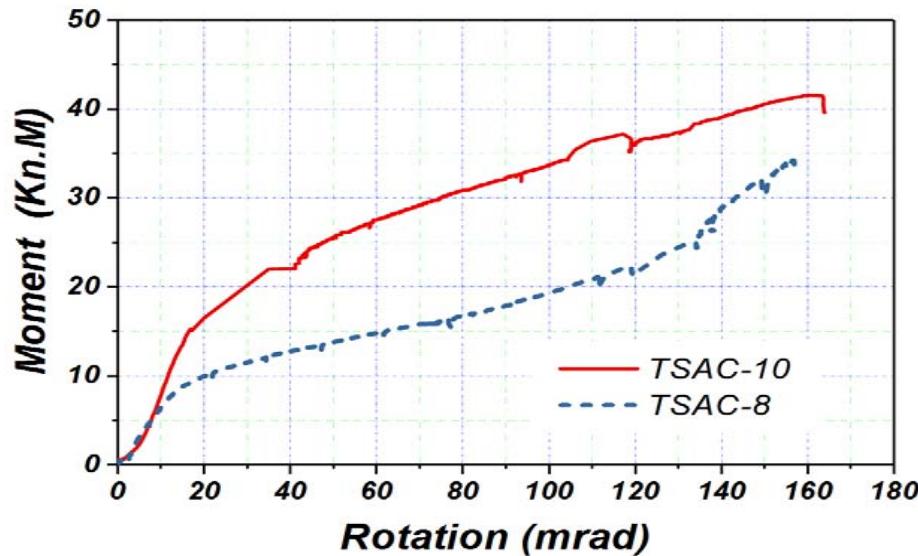
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# Test results – top and seat cleats



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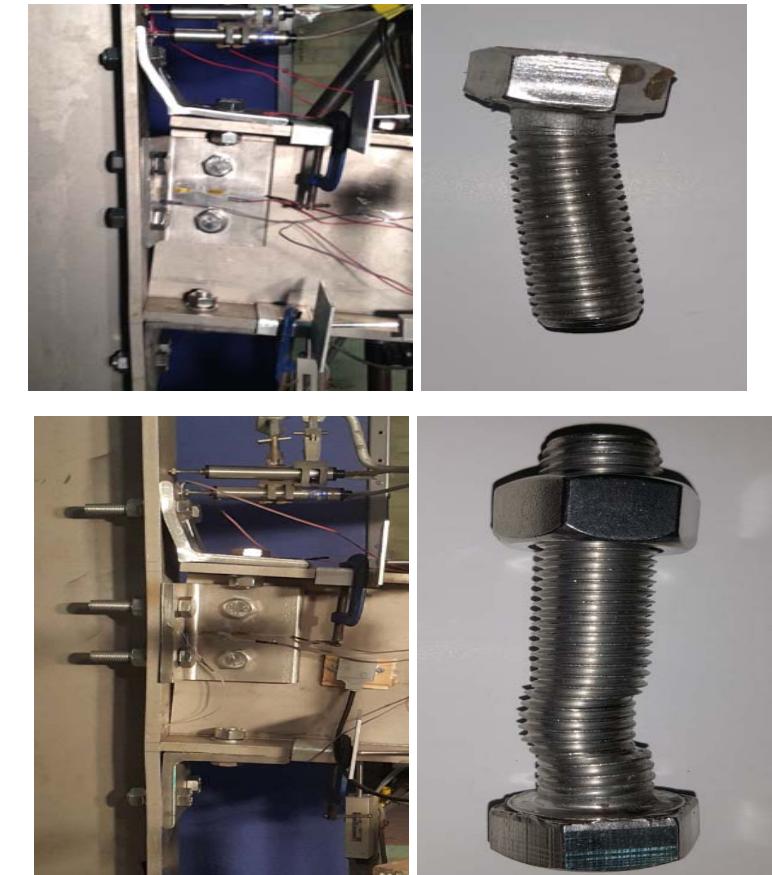
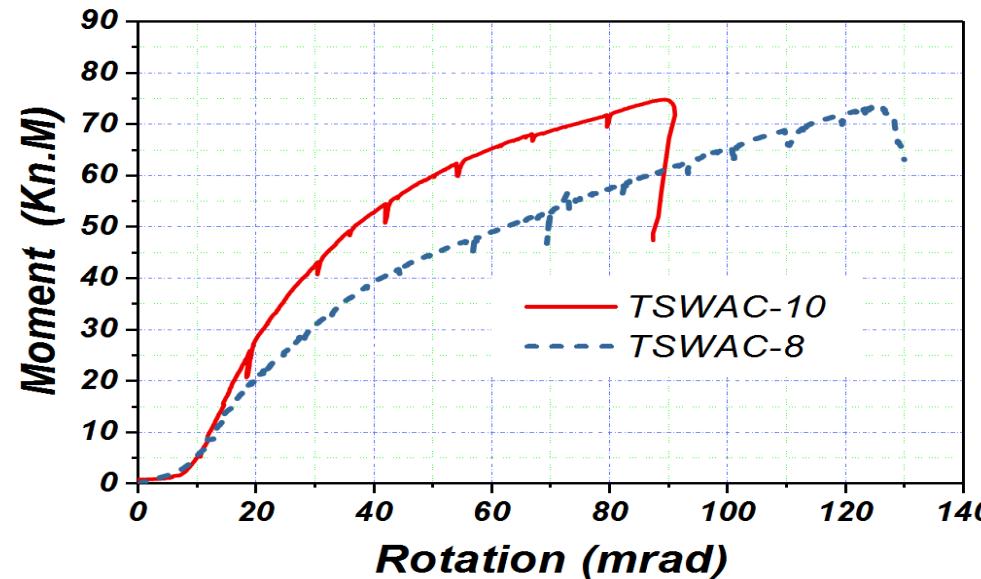
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# Test results – top, seat and web cleats



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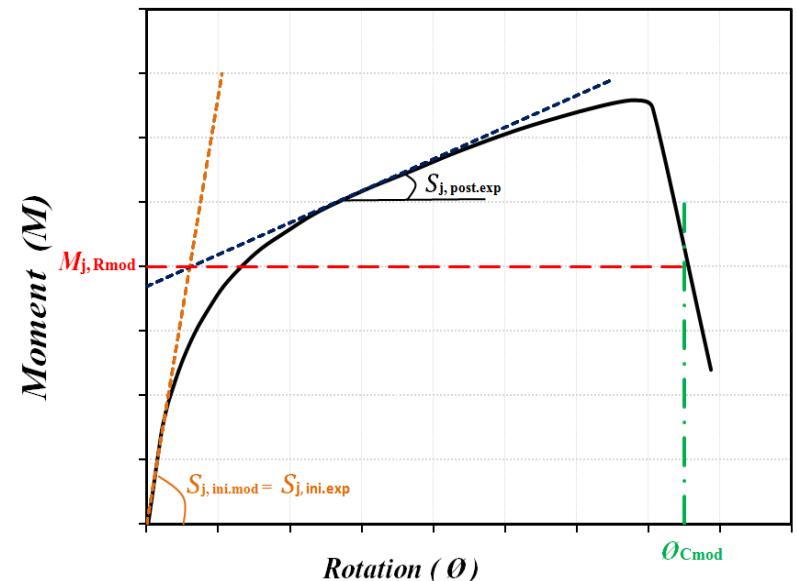
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# Test results – Summary



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Specimen	Initial stiffness $S_{j,ini}$ (kNm/rad)	Maximum moment $M_{j,max}$ (kNm)	Plastic Moment resistance $M_{j,R}$ (KN.m)	Rotation $\Phi$ (mrad)	
				at maximum moment $\Phi_{j,u}$	maximum recorded $\Phi_c$
FEP	3913	65.40	40	157	165
EEP	4464	80.40	42	119	121
TSAC-8	1237	34.10	12	157	157
TSAC-10	1521	41.50	23	162	162
TSWAC-8	1920	73.30	39	125	131
TSWAC-10	2769	74.70	55	91	95



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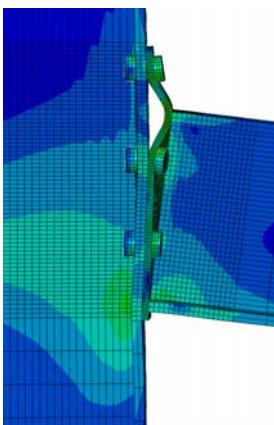
# FE Modelling

- Reduced integration 1<sup>st</sup> order solid elements
- Mesh density: at least 3 elements through thickness of plated elements, fine mesh in the vicinity of the joint, coarser mesh further away
- **Measured geometric dimensions and material properties** incorporated
- Contact definition
  - normal direction: hard contact
  - tangential direction: friction coefficient 0.3
- Quasi-static explicit dynamic analysis to overcome convergence difficulties
- BC replicating experimental BC

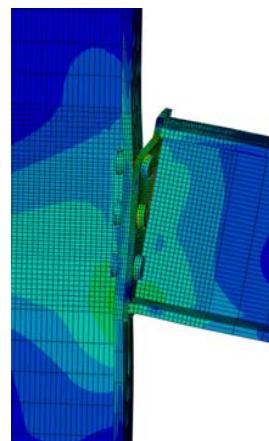
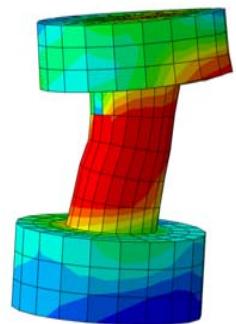
# Validation – Failure modes



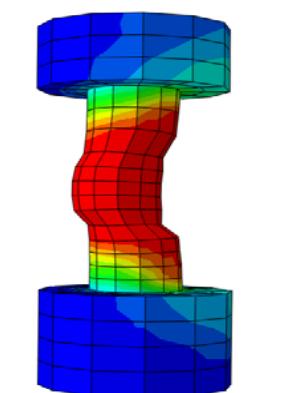
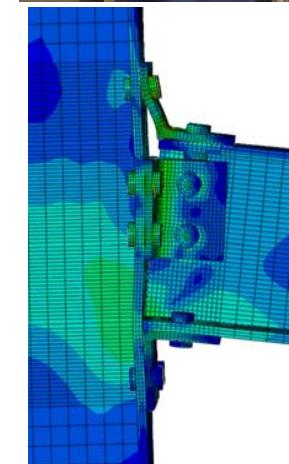
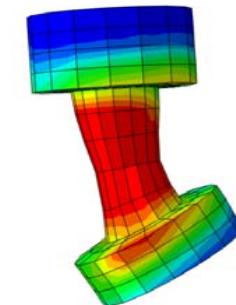
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(a) Extended End Plate (EEP) connection failure mode and deformed top bolt



(b) Flush End Plate (FEP) connection failure mode and fractured top bolt



(c) Top, seat, web cleat 10 mm angle cleats

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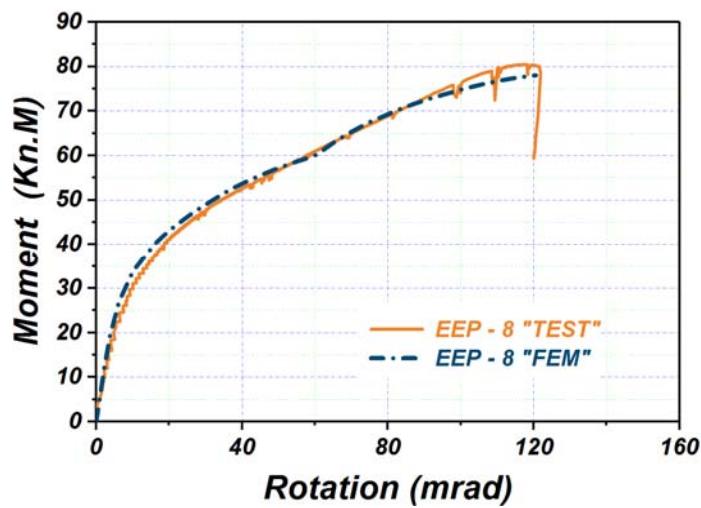
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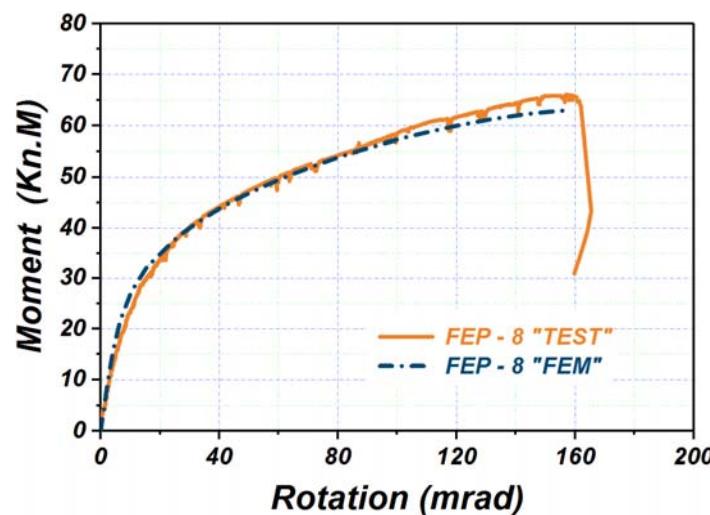
# Validation – Failure modes



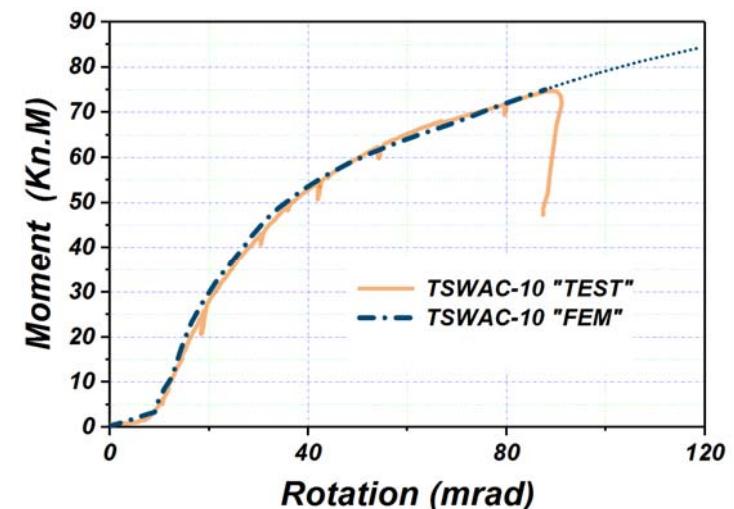
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(a) Extended End Plate (EEP) connection failure mode and deformed top bolt



(b) Flush End Plate (FEP) connection failure mode and fractured top bolt



(c) Top, seat, web cleat 10 mm angle cleats

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# Parametric Studies – investigated parameters

- *Angle / Endplate thickness ( $t_a$  or  $t_p$ )*
- *Column flange flexibility ( $t_c$ )*
- *Edge instance ( $e_1$ )*
- Depth of the leg of the cleats parallel ( $L_1$ )
- Gap  $g$  between the beam and the column flange ( $g$ )
- Stainless steel grade considered (austenitic and lean duplex)

132 analyses in total

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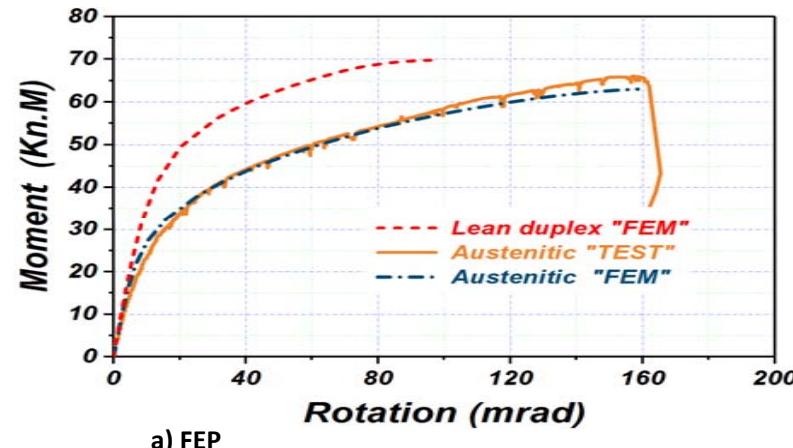


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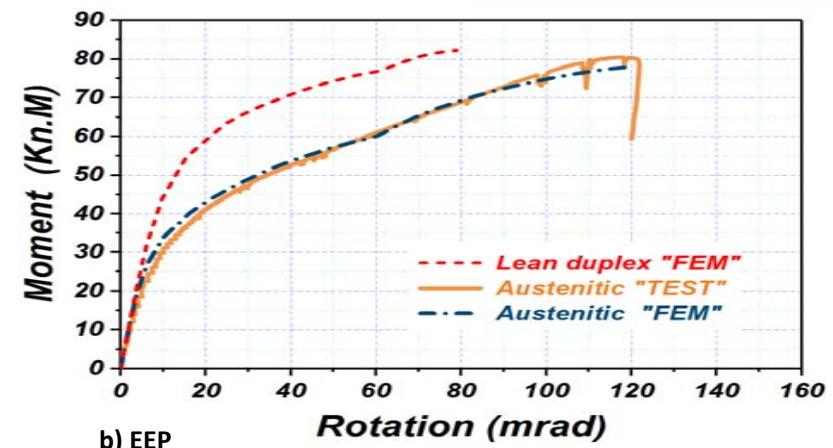
# Parametric Studies: Effect of material



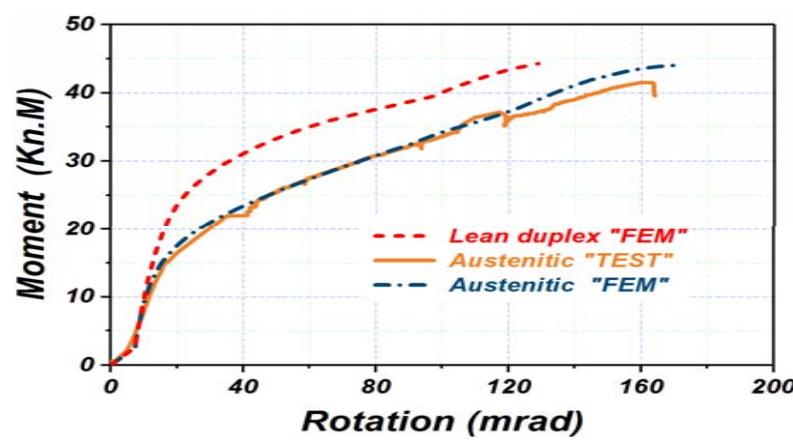
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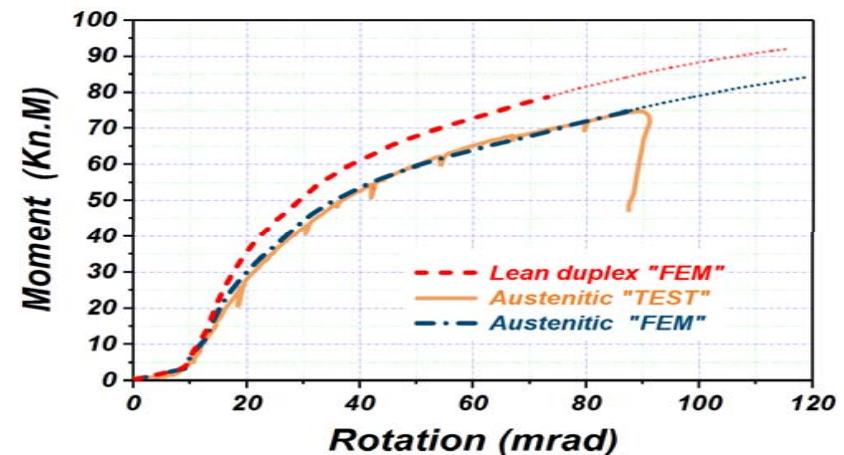
a) FEP



b) EEP



c) TSAC-10



d) TSWAC-10

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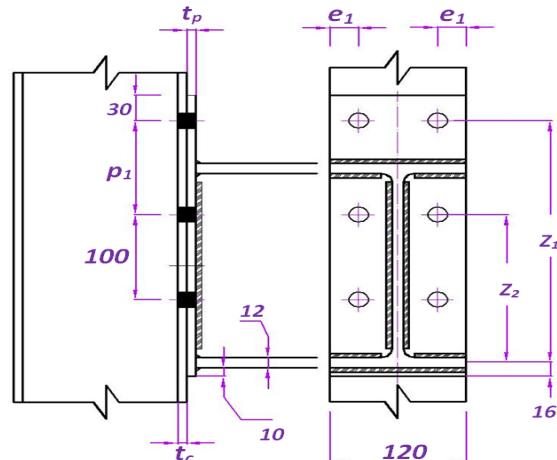
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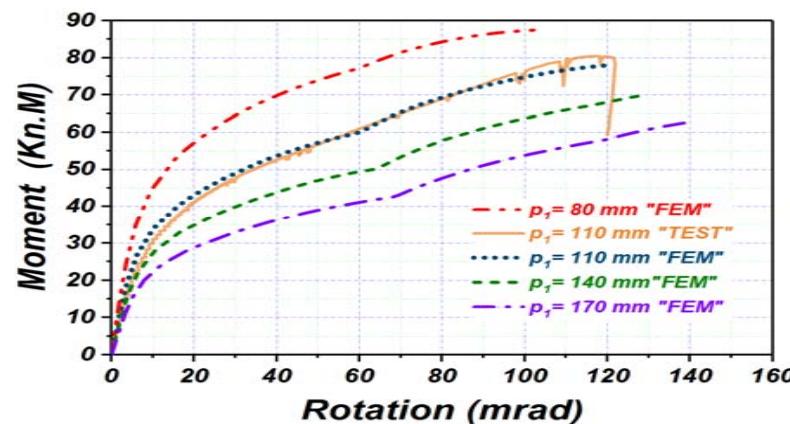
# Parametric Studies: Various effects



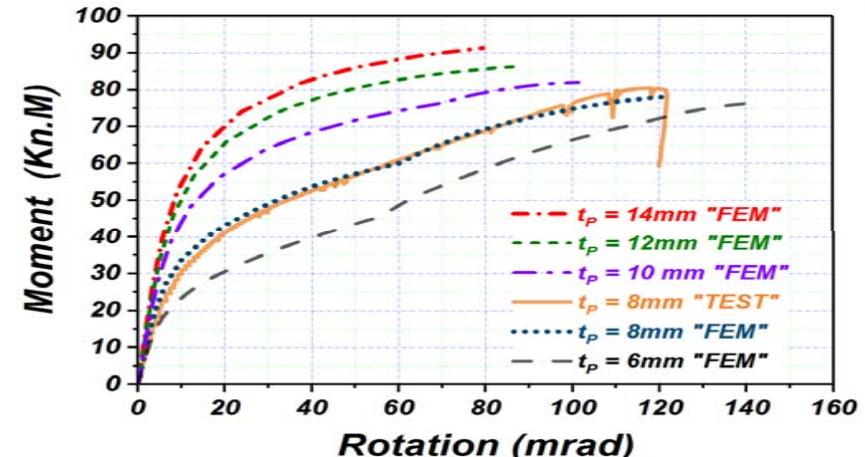
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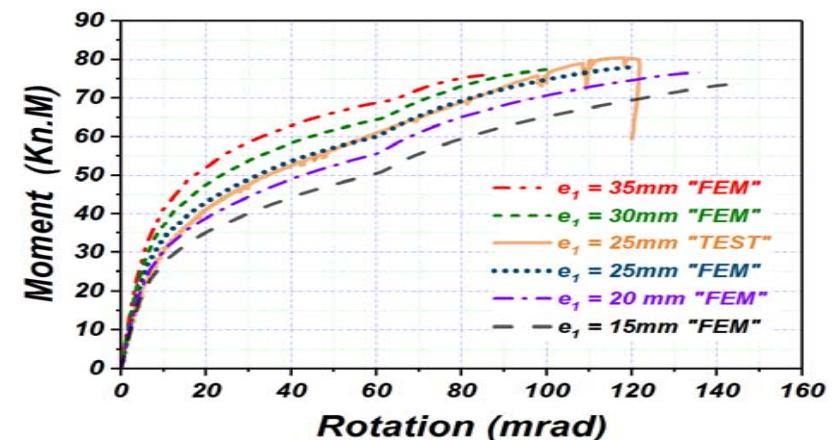
(a) Extended End Plate (EEP) connection



(c) M-Φ curves for different spacing of the first bolt row



(b) M-Φ curves for different plate thicknesses  $t_p$



(d) M-Φ curves for different bolt edge distances  $e_1$

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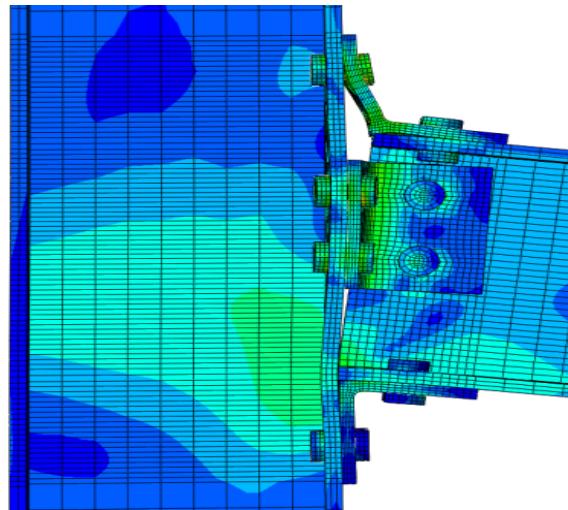
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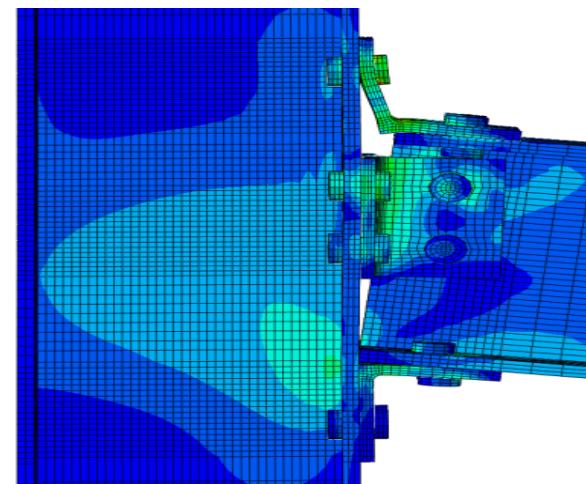
# Parametric Studies: Effect of gap



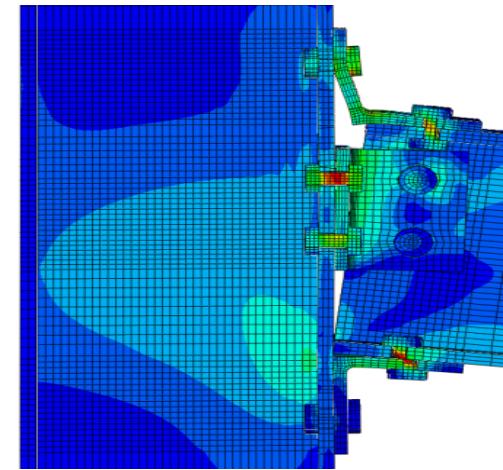
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a) TSWAC ( $g = 0 \text{ mm}$ )



b) TSWAC ( $g = 9 \text{ mm}$ )



c) TSWAC ( $g = 9 \text{ mm}$ )

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# Results and discussion: Tests



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Specimen	Initial stiffness $S_{j,ini}$ (KN.m/mrad)			Moment Capacity $M_j$ (KN.m)		
	$S_{j,ini}$ (EC3)	$S_{j,ini}$ (TEST)	EC3/Test	$M_{j,R}$ (EC3)	$M_{j,R}$ (TEST)	EC3/Test
FEP	5740	3913	1.47	18.6	40	0.47
EEP	9360	4464	2.10	27.2	42	0.65
TSAC-8	1800	1237	1.48	6.6	12	0.55
TSAC-10	2520	1521	1.68	11.1	23	0.48
TSWAC-8	5240	1920	2.73	19.25	39	0.49
TSWAC-10	6140	2769	2.22	30.3	55	0.55
MEAN			1.94			0.53
COV			0.49			0.13

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# Results and discussion: FE – EEP (A)



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Model No.	Distances according to Fig.1 (mm)						Initial stiffness $S_{j,ini}$ (KN.m/mrad)		Moment Capacity $M_{j,R}$ (KN.m)		Maximum (FEM)		yield zone pattern		
	$t_c$	$t_p$	$e_I$	$p_I$	$p_2$	$z$	$S_{j,ini}$ , (EC3)	$S_{j,ini}$ , (FEM)	EC3/ FEM	$M_{j,R}$ , (EC3)	$M_{j,R}$ , (FEM)	EC3/ FEM	$M_{j,u}$ (KN.m)	$\Phi_{j,u}$ (mrad)	
Model-1	12	8	25	65	65	179	5739	3995	1.44	18.6	40.5	0.46	63.0	158.5	3
Model-2	12	<u>14</u>	25	65	65	179	7788	5477	1.42	28.7	56.8	0.51	69.3	77.8	3
Model-3	12	<u>12</u>	25	65	65	179	7406	5354	1.38	28.7	54.1	0.53	68.7	89.2	3
Model-4	12	<u>10</u>	25	65	65	179	6786	4948	1.37	26.4	50.4	0.52	66.1	103.9	3
Model-5	12	<u>6</u>	25	65	65	179	4031	3562	1.13	10.5	26.7	0.39	60.3	201.1	2
Model-6	12	8	<u>35</u>	65	65	179	7611	5806	1.31	23.7	52.9	0.45	68.7	82.1	3
Model-7	12	8	<u>30</u>	65	65	179	6697	5014	1.34	20.5	48.7	0.42	66.5	111.7	3
Model-8	12	8	<u>20</u>	65	65	179	4743	3816	1.24	16.5	37.8	0.44	59.6	176.0	1
Model-9	12	8	<u>15</u>	65	65	179	3912	3353	1.17	15.3	32.5	0.47	55.6	195.1	1
Model-10	<u>16</u>	8	25	65	65	179	6288	4746	1.32	18.6	45.5	0.41	65.7	134.7	3
Model-11	<u>14</u>	8	25	65	65	179	6053	4674	1.30	18.6	44.2	0.42	64.8	136.7	3
Model-12	<u>10</u>	8	25	65	65	179	5290	3852	1.37	18.6	41.8	0.45	60.8	162.2	3
Model-13	<u>8</u>	8	25	65	65	179	4591	3650	1.26	16.1	37.5	0.43	58.0	175.9	3
Model-14	12	8	25	65	65	<u>204</u>	7585	6753	1.12	24.7	59	0.42	75.6	83.0	1
Model-15	12	8	25	65	65	<u>191.5</u>	6554	5387	1.22	20.5	49	0.42	69.7	120.5	1
Model-16	12	8	25	65	65	<u>166.5</u>	4956	3706	1.34	16.7	36	0.46	57.0	162.8	3
Model-17	12	8	25	65	65	<u>154</u>	4245	3120	1.36	15.1	31	0.49	50.7	182.4	3
MEAN								<b>1.30</b>				<b>0.45</b>			
COV								<b>0.07</b>				<b>0.09</b>			

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# Conclusions and future research



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- **The plastic moment resistance** was found to be **underestimated by 44% and 34%** on average for austenitic and lean duplex stainless steel joints
- The stiffness predictions are scattered
- The strength of FEP, EEP and TSAC joints is consistently underpredicted by EN1993-1-8 with COV between 0.06 and 0.11
- The predictions for TSWAC are less conservative and more scattered
- Material non-linearity and strain-hardening affect the response
- *Based* on the results the development of a design model in agreement with the observed structural response is warranted.

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- Maintain the component-based approach of EN 1993-1-8
- Exploitation of strain-hardening in the determination of the strength of ductile joint components (t-stubs, web panel in shear)
- Use of the CSM (with a strain limit of 0.15) for the determination of the strength of equivalent t-stub for the column flange and end plates/angle cleats
- Test individual SS t-stubs in tension to validate the approach

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Thank you for your attention