Behaviour of steel end plate bolted beam-to-column joints

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ABSTRACT: This paper presents a numerical investigation into moment-rotation behaviour of extended, flush, and partial depth end-plate joints. Two types of steel beam-to-column joints are modelled: I-beam (IPE) to H-column (HEB) and PFC-beam (UPE) to SHS-column. The joints are designed as a single cantilever beam-to-column joint configuration. The connection details are in accordance with Eurocode 3 part 1-8 and SCI guides P358 (Simple joints) and P398 (Moment joints). Three-dimensional finite element modelling of the joints is carried out using ABAQUS. The numerical results are validated against experiments. Both material and geometric nonlinearities are considered. All joints are classified according to their stiffness as per Eurocode 3. The failure modes of different joint configurations are determined and compared with the experiments. The key contribution of this paper comes from stiffness analysis of the joints, characterisation of the joints as per EC3 and modelling nonlinear behaviour of the joints.

1 INTRODUCTION

Joints can be classed as simple or moment-resisting joints. Simple joints are nominally pinned and can transfer shear only. They offer marginal or no resistance to rotation. As such, simple joints are assumed to transfer no moment. Simple joints are used in multi-storey braced frames. Broadly, it is known as simple construction, where beams are designed as simply supported and columns take axial load only with nominal moments resulting from end reactions. Frame stability is provided by steel bracing or concrete shear wall. Flexible end plate, fin plate and web-cleated connections are the common types of simple connections. Flexible end plate connections are the most popular simple beam connections in the UK.

By contrast, moment joints transfer moments from members to the joints. They are used in multi-storey unbraced frames and single-storey portal frames. Moment connections are likely to be bolted with full or extended depth end plate connections. Welded connections also provide moment resistance. Column bases and splices use moment connections too. Lateral stability in moment frames is provided continuity of members due to fixed or rigid joints. Regardless of simple or moment frames, end plate bolted joints provide ease of fabrication, standardisation and speed of construction.

Joint's behaviour is characterised by its moment-rotation response. The conventional approach is to assume the joint's response nominally pinned or fully rigid. However, in many practical frames the moment-rotation response lies between these two theoretical extremes, introducing semi-rigid action (Qureshi & Mottram 2015). The behaviour of end plate bolted joint is in between pinned and rigid joints (Gašić et al. 2021).

The aim of this paper is to model end plate steel beam-to-column joints. General purpose finite element software ABAQUS is used to model the joint. Three joint configurations are tried: extended depth, flush or full depth and partial depth end plate joints. Two different member configurations are modelled: IPE beam to HEB column and PFC beam to SHS column. The numerical results are verified against experiments first, followed by a parametric study. Moment-rotation behaviour of joints is studied. Failure patterns are also determined. Joints are also classified, according to their stiffness using Eurocode 3 provisions, as rigid, semi-rigid and pinned.

2 EXPERIMENTAL DATA

The experimental results from previous research (de Lima et al. 2004; Simões Da Silva et al. 2004) are used to validate the finite element models. The data for flush and extended end plate bolted joints is taken from (Simões Da Silva et al. 2004) and (de Lima et al. 2004), respectively.

2.1 *Flush end plate bolted joint*

Flush or full depth end plate joints were tested by (Simões Da Silva et al. 2004) to study the joint's behaviour under combined moment and axial force. The configuration consisted of HEB 240 column, IPE 240 beam and 15 mm thick end plate with M20 class 10.9 bolts and the steel grade was S275. Figure 1 shows the joint detailing for flush end plate joint used by da Silva *et al*.(Simões Da Silva et al. 2004). The column was pinned at both ends. Nine specimens were tested using a mix of moment and axial forces. The axial load was applied as a percentage of the beam's plastic resistance. This paper uses only results from the test 'FE1', where only moment was applied with no axial force, for comparison with our FE model.

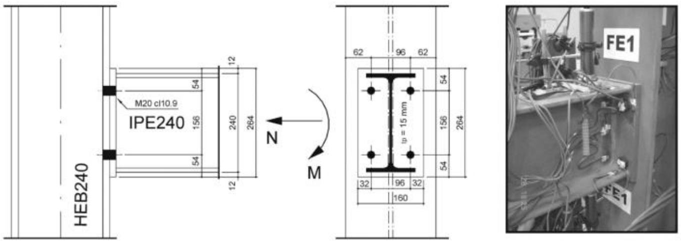


Figure 1. Connection detail for flush end plate bolted joint used by da Silva *et al*. (Simões Da Silva et al. 2004)

2.2 *Extended end plate bolted joint*

Testing on extended end plate joint was carried out by de Lima et al. (de Lima et al. 2004). The test configuration was same as in (Simões Da Silva et al. 2004), except the flush end plate was replaced with extended end plate, as shown in Figure 2. Seven specimens were tested with different moment and axial load combinations. This paper only uses experimental results from 'EE1' specimen that had only moment applied with no axial force.

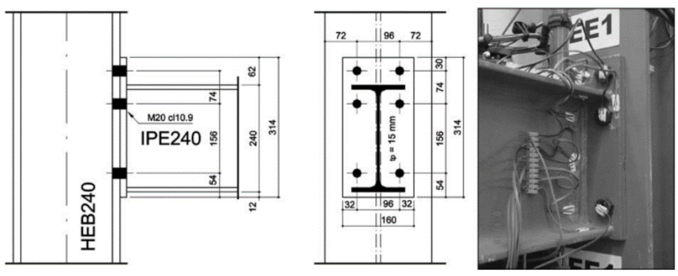


Figure 2. Joint detailing for extended end plate beam-to-column joint by de Lima *et al*. (de Lima et al. 2004)

2.3 *Partial depth end plate and PFC to SHS joints*

Partial depth end plate bolted joint was modelled using the same parameters as in flush and extended end plate joints with design and detailing from Eurocode 3 SCI guide P358 (SCI P358 2014). Similarly, the connections for PFC to SHS were detailed using Eurocode 3 SCI P358 and P398 guidelines (SCI P398 2013; SCI P358 2014).

3 FINITE ELEMENT MODEL

Finite element modelling is carried out for steel end plate bolted joints are prepared using ABAQUS. The end plate bolted (EPB) joints modelled are partial depth, full depth and extended end plate joints.

3.1 *Joint detailing*

Joint detailing for flush and extended end plate bolted joint connecting I-beam (IPE) to H-column (HEB) is obtained from experiments conducted by (de Lima et al. 2004; Gašić et al. 2021). These experimental results are used for validation of the FE model. The parametric study includes partial depth end plate joints and PFC-beam (UPE) to SHS-column joints, which are detailed as per Eurocode 3 (BS EN 1993-1-8:2005 2005). I-Beam to H-column joint details are shown in Figure 3 and PFC-beam to SHS-column details are given in Figure 4. The end plate thickness for IPE-HEB joints is 15 mm, whereas the end plate thickness for PFC-SHS is 20 mm for all the cases.

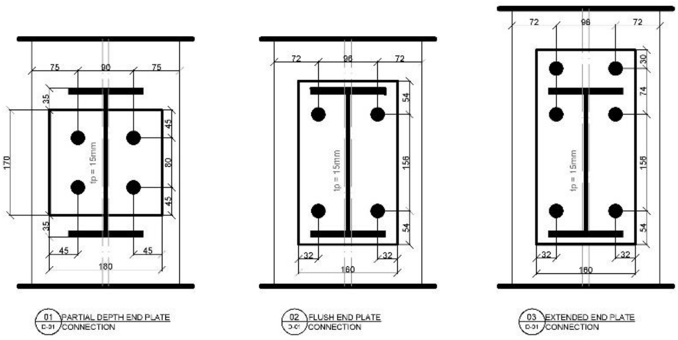


Figure 3. IPE 240 Beam to HEB 240 Column end plate bolted connection details

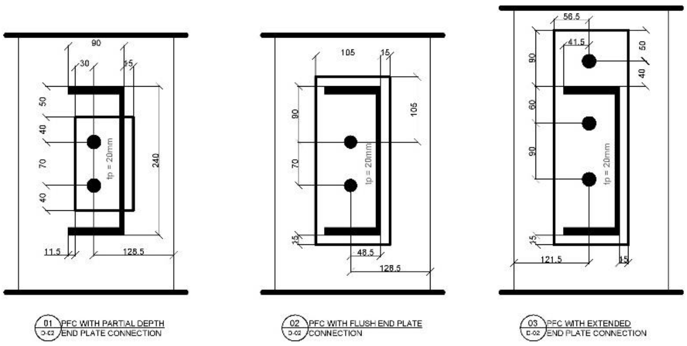


Figure 4. UPE 240 (PFC) Beam to SHS 250×250×16 Column bolted end plate connection details

3.2 *Material properties*

Material properties in Table 1 for steel IPE to HEB joints are obtained the experimental data in (de Lima et al. 2004; Simões Da Silva et al. 2004; Baei et al. 2012). While for PFC to SHS general steel properties are used for steel plates and bolts.

Table 1. Material properties for IPE-to-HEB and PFC-to-SHS joints (Baei et al. 2012).

Ref	Part	Young's Modulus (E) (MPa)	Stress (σ) (MPa)	Plastic Strain (ε)	Type
IPE240 (Beam)	Flange	215222	340.14	0	Yield
			448.23	0.15	Ultimate
	Web	203713	363.40	0	Yield
			454.30	0.15	Ultimate
HEB240 (Column)	Flange	220792	342.95	0	Yield
			448.79	0.15	Ultimate
	Web	206936	372.02	0	Yield
			477.29	0.15	Ultimate
End Plate (IPE to HEB)	N/A	200248	369.44	0	Yield
			503.45	0.15	Ultimate
Bolt 10.9 (IPE to HEB)	N/A	200000	900	0	Yield
			1000	0.0875	Ultimate
S275 Steel (PFC to SHS)	N/A	205000	275	0	Yield
			430	0.147	Ultimate
Bolt 8.8 (PFC to SHS)	N/A	205000	640	0	Yield
			800	0.117	Ultimate

3.3 *Load, boundary conditions and meshing*

A single cantilever beam-to-column joint set up was used to prepare numerical model in ABAQUS, as seen in Figure 6. The column length was 2 m, and the beam length was 1 m. The beam was loaded by applying a 25 mm displacement at the free end. Three-dimensional solid elements were used to model all steel components. Surface to surface contact was assumed between connecting elements with default penalty frictional tangential behaviour and hard normal contact. Frictional coefficient was assumed to be 0.3. Figure 6 shows FE models for partial depth, full depth or flush and extended depth end plate joints.

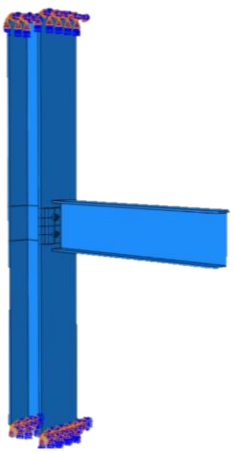


Figure 5. Finite element model with boundary conditions

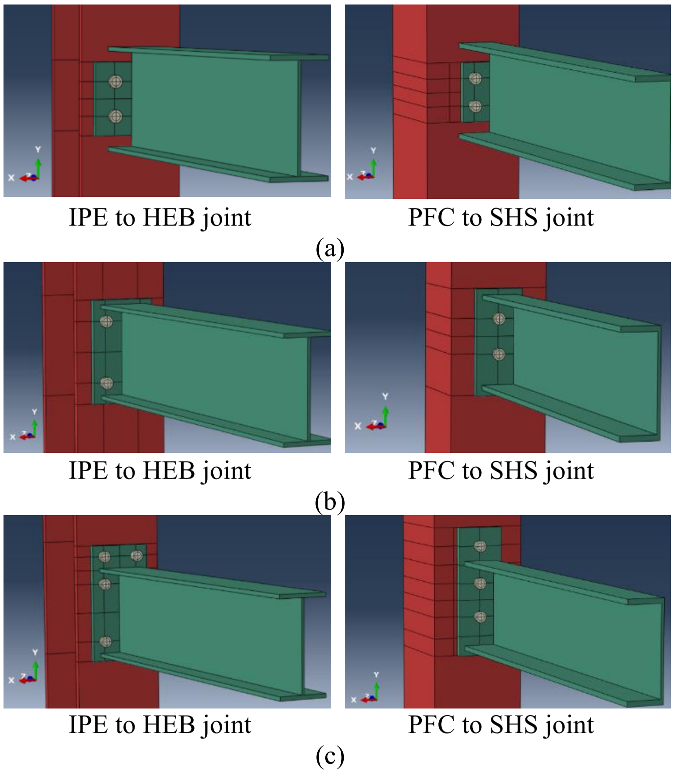


Figure 6. Assembled ABAQUS beam-to-column models (a) Partial depth end plate (b) Flush end plate (c) Extended end plate

3.4 *Mesh sensitivity analysis*

Table 2 presents the mesh sensitivity analysis for IPE to HEB partial depth end plate model. Hex-dominated brick elements were used for FE analysis. Table 3 shows difference in moment for different models.

Table 2. Mesh sizes for different models

Reference	Mesh seed size (mm)			
	Column	Beam	End Plate	Bolt
Model 1	35	35	20	8
Model 2	25	25	15	5
Model 3	20	20	13	3
Model 4	15	15	8	3

Figure 7 shows moment-rotation response of FE models. Based on computational efficiency and reasonable accuracy, model 3 is chosen for further analysis.

Table 3. Mesh sensitivity analysis

Rotation (mrad)	Moment (kNm)				% Difference between models		
	Model 1	Model 2	Model 3	Model 4	1 and 2	2 and 3	3 and 4
20	23.30	22.50	22.30	22.30	-3%	-1%	0%
40	26.90	25.90	25.90	25.90	-4%	0%	0%
60	29.10	28.00	27.80	27.80	-4%	-1%	0%
80	31.20	30.00	29.70	29.70	-4%	-1%	0%
100	33.20	31.80	31.30	31.30	-4%	-2%	0%
120	35.00	33.40	33.00	33.00	-5%	-1%	0%
				Average	-4%	-1%	0%

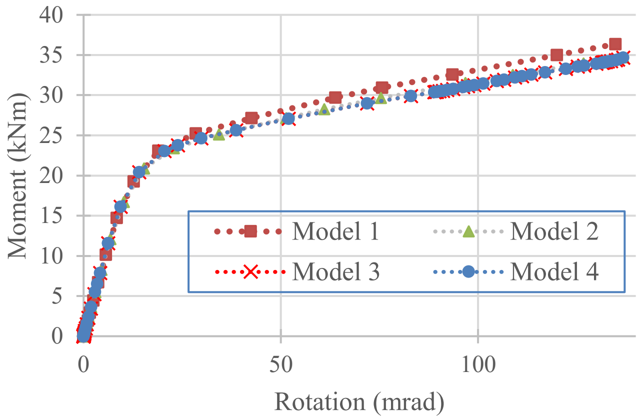


Figure 7. Mesh sensitivity analysis: moment-rotation response.

4 RESULTS AND DISCUSSION

First, the finite element model is verified against the flush and extended end plate joints between IPE and HEB from (Simões Da Silva et al. 2004) and (de Lima et al. 2004), respectively. Failure modes are compared too. The validated model is used to create IPE-HEB partial depth end plate joint and PFC-SHS joints (partial, flush and extended end plate).

4.1 *Validation of FE model*

Moment-rotation response and failure modes from experiments in (de Lima et al. 2004; Simões Da Silva et al. 2004) are compared with numerical models.

4.1.1 *Moment-rotation response: Flush end plate joint*

Moment-rotation response from experiment in (Simões Da Silva et al. 2004) and FE model is compared in Figure 8. The numerical results show a good correlation with experiments.

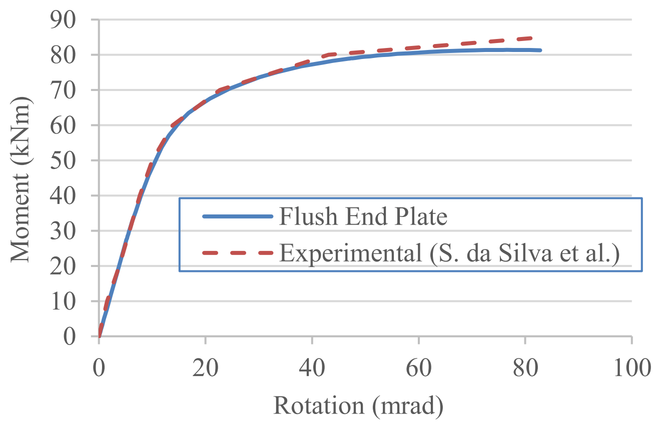
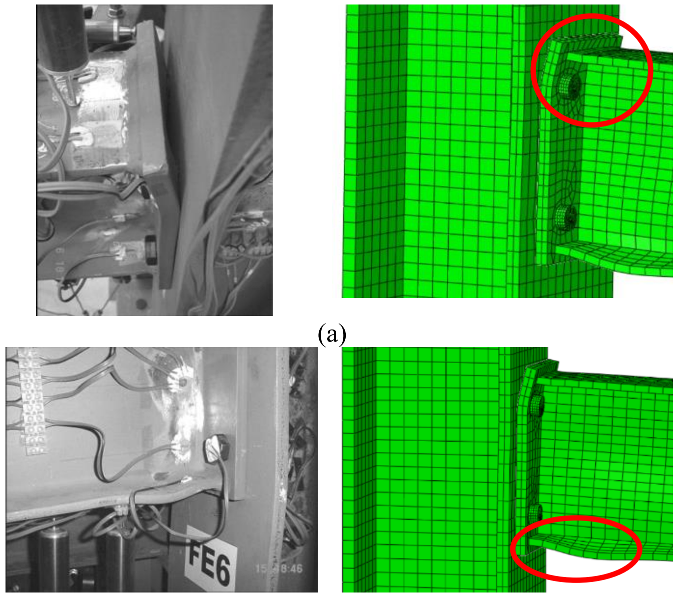


Figure 8. IPE to HEB flush end plate joint FE model comparison with experimental results

4.1.2 *Failure modes: Flush end plate joint*

Figure 9 shows the comparison of failure modes obtained from numerical model with experiments. It indicates that end plate near top flange and the beam's bottom flange fail in a similar manner both in experiments and numerical model.



(a)

(b)

Figure 9. Comparison of failure modes for flush end plate joint with experiments in (Simões Da Silva et al. 2004): (a) End plate bending; (b) Beam bottom flange bending

4.1.3 *Moment-rotation response: Extended end plate joint*

Figure 10 presents moment-rotation (M-R) behaviour of IPE to HEB extended end plate joint from both experiments (Simões Da Silva et al. 2004) and numerical model. It indicates that experiment M-R curve is stiffer than FE curve. This might be due residual stresses and geometric imperfections in the experiment, which are not accounted for in the numerical model. Bolt tightening and friction coefficients could be different too in FE model and experiment. However, a good match can be seen for the joint's ultimate moment capacity between FE and test results.

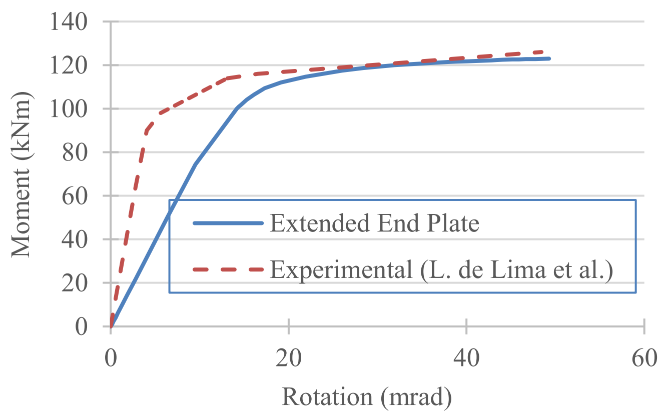


Figure 10. IPE to HEB extended end plate joint FE model comparison with experimental results

4.1.4 *Failure modes: Extended end plate joint*

Failure patters for IPE to HEB extended end plate joints are shown in Figure 11. A close match can be observed in both end plate bending and the beam's bottom flange buckling.

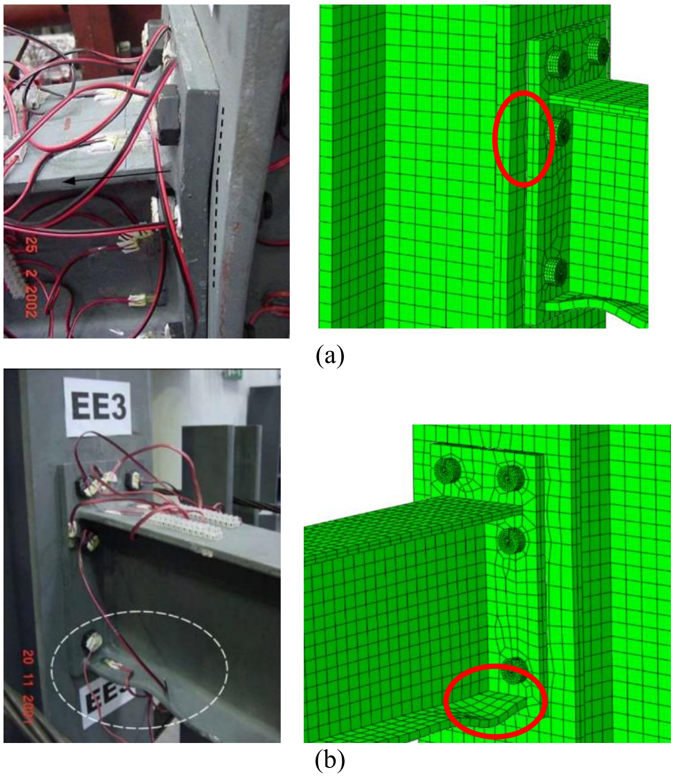


Figure 11. Comparison of failure modes for extended end plate joint with experiments in(de Lima et al. 2004): (a) End plate bending; (b) Beam bottom flange bending

4.2 *Parametric study*

The validated model is used to conduct a parametric study. This involves IPE-HEB partial depth end plate joint, and PFC-SHS partial, flush and extended joints.

4.2.1 *Moment-rotation response: IPE-HEB joints*

The moment-rotation response of partial, flush and extended depth end plate IPE-HEB joints is presented in Figure 12. The moment resistance of flush end plate and partial depth end plate is about 37% and 79% of the moment in extended end plate joints.

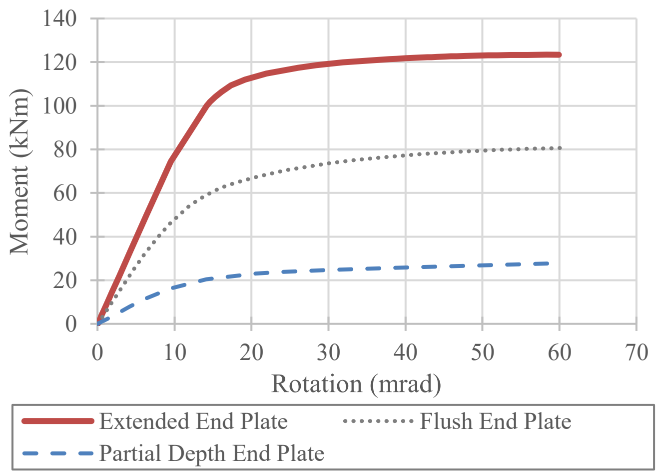


Figure 12. Moment-rotation behaviour of IPE to HEB end plate bolted joints (joint rotation limited to 60 mrad for comparison)

4.2.2 *Moment-rotation response: PFC-SHS joints*

Presented in Figure 13 is the moment-rotation behaviour of PFC-SHS partial depth, flush and extended end plate joints. The results indicate a difference of 41% between extended and flush end plate joints and 79% between extended and partial depth joints for their moment capacity.

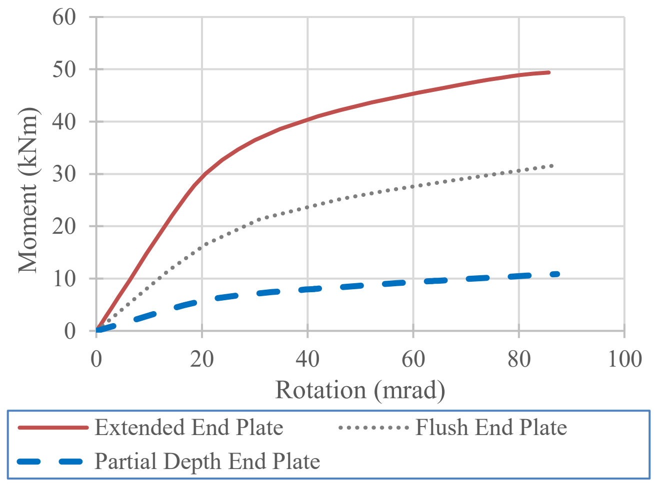


Figure 13. Moment-rotation behaviour of PFC-SHS end plate bolted joints (Joint rotation limited to 85 mrad for comparison)

4.3 *Joint classification*

All joints are classified according to their stiffness as per Eurocode 3 (BS EN 1993-1-8:2005 2005). Figure 14 and 15 present the joint classification for IPE-HEB and PFC-SHS joints, respectively. Figure 14 shows that IPE 240 beam to HEB 240 column joint with extended and flush end plate connections are classified as semi-rigid, whereas the partial depth end plate connection is categorised as pinned.

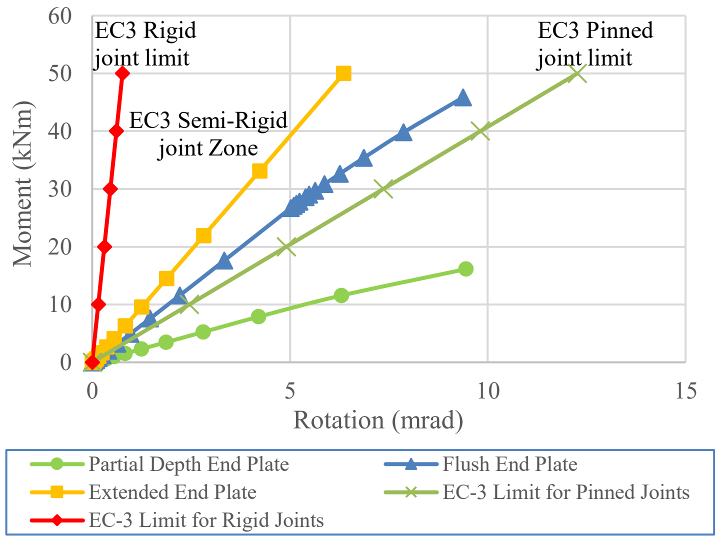


Figure 14. Joint classification as per EC 3 for IPE-HEB joints

Unlike for IPE to HEB joints, PFC to SHS joints are all classified as pinned, as indicated in Figure 15. The depth of connecting beams was same for both cases. However, material properties were different, as shown Table 1. The lower cross-sectional area of PFC and less bolts in PFC-SHS joints could have contributed to their less moment than IPE-HEB joints.

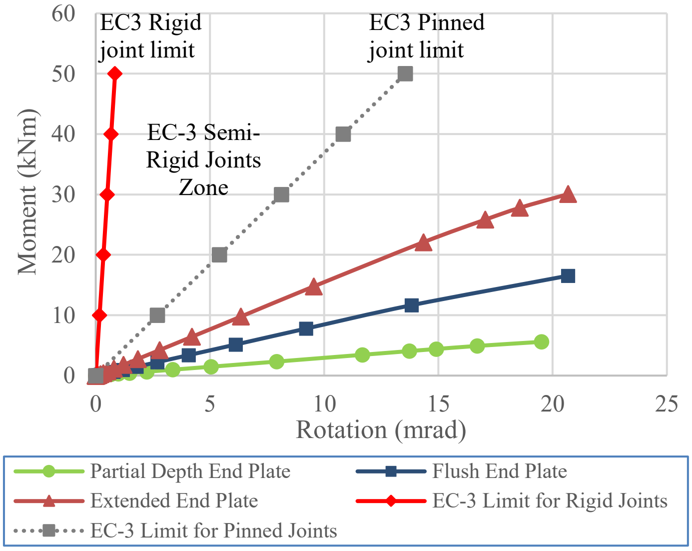


Figure 15. Joint classification as per EC 3 for PFC-SHS joints

5 CONCLUSIONS

Three-dimensional nonlinear finite element modelling is carried for partial depth, full depth or flush and extended depth end plate joints between IPE beam and HEB column, and PFC beam and SHS column. Moment-rotation behaviour and failure modes are determined. Joints are also classified according to stiffness as rigid, semi-rigid and pinned using EC3 provisions. Following conclusions can be drawn:

- Finite element model matched with experimental moment-rotation response and failure modes.
- Extended end plate joints take about 40% and 80% more moment than flush and partial depth end plate joints.
- IPE beam to HEB column extended depth and flush end plate joints are classified as semi-rigid. However, partial depth end plate joints are classed as nominally pinned.
- All PFC beam and SHS column joints are classified as nominally pinned.

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