Study on the Behavior of Steel Beam to Steel Column Connections with Extended End Plate

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Abstract

The main objective of this study is to evaluate the behavior of a typical steel beam-to-column connection with an extended end plate, isolated from a previously tested composite beam-to-steel column experimental configuration. This paper presents both analytical and numerical investigations focused on assessing the strength and stiffness of such connections. The analytical approach is based on the Component Method, while the numerical simulations were performed using Consteel and IDEA StatiCa, two finite element software tools developed for the analysis of steel structures. In Consteel, stiffness and capacity are evaluated using the Component Method, whereas IDEA StatiCa employs the Component-Based Finite Element Method (CBFEM). The results highlight the column web in shear and the end plate in tension as the most critical components. A parametric study was carried out to evaluate the influence of end plate thickness and the use of additional stiffeners on the connection's stiffness and load bearing capacity. Both analytical and numerical results confirm the semi-rigid behavior of the connection and its ability to transfer negative bending moments. This study is part of a broader research project on the performance of semi-rigid steel and composite connections, where the interaction between the steel beam and reinforced concrete slab is considered partial. The next phase includes the calibration of nonlinear models in Abaqus and an experimental program focusing on steel and composite beam-to-column connections. The research is driven by the limited guidance offered by current design codes regarding the behavior of semi-rigid connections between steel columns and composite beams with partial interaction.

Keywords: *steel and composite structures, extended end plate connections, semi-rigid connections, Component Method, CBFEM Method*

1. Introduction

Composite structures, in which steel and concrete act together to carry loads, are increasingly used in the structural systems of multi-story buildings. While the combination of steel and concrete offers significant advantages, their interaction also introduces complex structural challenges that require careful evaluation through appropriate design and analysis methods.

This study analyzes a set of steel joints isolated from composite beam-to-steel column joint specimens, previously tested as part of an experimental research program, with the corresponding results published in reference [1]. The paper presents the results of both analytical and numerical analyses conducted to evaluate the resistance and stiffness of external steel joints with extended end plates, excluding the presence of the reinforced concrete slab and the connectors.

A parametric study was also carried out to assess the impact of end-plate thickness and additional stiffeners on the load bearing capacity and stiffness of the analyzed configurations. The analytical investigation of the steel joints, isolated from the test specimens presented in reference [1], was conducted using the Component Method, as defined by the European standard SR EN 1993-1-8:2006 [2].

In parallel, a numerical analysis was performed using the Consteel and IDEA StatiCa software, which implement different approaches: the Component Method and the Component-Based Finite Element Method (CBFEM), respectively.

The tested specimens, presented in reference [1], were designed to represent isolated joints from a multi-span frame, with spans of 7.00 m and 4.00m spacing between frames, subjected to live loads up to 4 kN/m². The beams were made of IPE270 profiles, while the columns were made of HEA220 profiles. A rigid connection between the IPE270 beams and the reinforced concrete slab was achieved via full composite interaction using eight shear connectors.

The steel joint consisted of a 12 mm thick extended end plate, welded to the beam and bolted to the column flange with six M20 bolts of grade 8.8, tightened to a torque of 150Nm. The end plate was aligned with the top flange of the beam and extended downward to ensure symmetric performance under positive and negative bending moments. All steel components were made from S235 structural steel.

The experimental program detailed in [1] included four external joint tests: specimens E3 and E4 assessed the behavior of steel column and composite beam connections, while E5 and E6 focused on connections between composite column and composite beam connections. Analytical and numerical results were compared with the experimental test result of specimen E3, where the vertical loading induced a negative bending moment. The experimental configurations are illustrated in Fig. 1, and the results related to initial stiffness ($S_{j.ini}$) and

moment resistance ($M_{j.Rd}$) are summarized in Table 1.

As part of the experimental program [1], the mechanical properties and nominal dimensions of the steel components for specimen E3 were established. These characteristics are illustrated in Figures 2. and 3. The components used in the E3 configuration were fabricated from materials belonging to LOT 1.

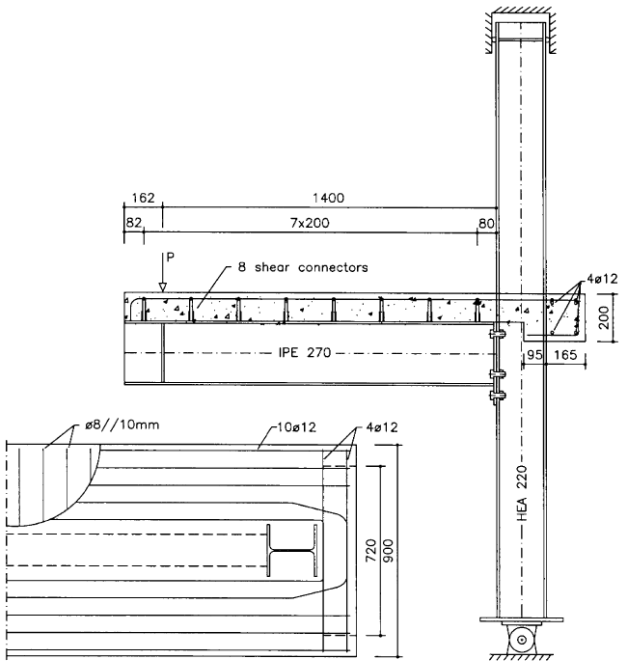

Fig. 6. External node, steel column.

Fig. 1. Specimen E3 tested as part of the experimental program (used with permission from [1])

	Element		Yield strength (MPa)	Ultimate strength (MPa)	Yield strain (%)	Ultimate strain (%)	Modulus of elasticity (MPa)
Lot 1	Beam	Web	306	439	23.9	31.8	198
	(IPE270)	Flange	267	415	24.4	36.1	203
	Column	Web	328	476	22.1	31.5	198
	(HEA220)	Flange	303	459	20.6	34.5	211
	End-plate		283	437	23.7	31.0	206
	Bolts		–	939	–	–	219
Lot 2	Beam	Web	345	508	21.3	31.8	203
	(IPE270)	Flange	311	493	20.9	34.9	208
	Column	Web	495	589	17.5	25.6	204
	(HEA220)	Flange	479	578	13.9	21.2	213
	End-plate		304	460	23.7	36.6	217
	Bolts		–	1008	–	–	209
Connectors			376	645	17.1	33.3	175
Rebar ∅12 mm			541	639	15.0	25.6	205
Rebar ∅8 mm			513	600	16.4	23.2	212
Rebar ∅6 mm			470	614	13.6	17.6	208

Fig. 2. Mechanical properties of the steel parts investigated within the experimental program (used with permission from [1])

Nominal dimensions and average of the real dimensions (mm)

	Column (HEA 220)		Left beam (IPE 270)		Right beam (IPE 270)		Left end-plate		Right end-plate	
	Height	Width	Height	Width	Height	Width	Height	Width	Height	Width
Nominal	210	220	270	135	270	135	350	160	350	160
LOT 1 (E1 to E4)	208.5	219.8	270.8	136.0	270.5	135.5	350.0	160.0	350.0	160.0
LOT 2 (E5 to E8)	212.2	222.5	270.0	135.8	270.2	135.9	348.4	160.3	348.6	160.3

Average of the real thicknesses (mm)

	Column (HEA 220)			Left beam (IPE 270)			Right beam (IPE 270)			End-plate	
	Web	Flanges		Web	Flanges		Web	Flanges		Left	Right
		Top	Bottom		Top	Bottom		Top	Bottom		
Nominal	7.0	11.0	11.0	6.6	10.2	10.2	6.6	10.2	10.2	12.0	12.0
LOT 1 (E1 to E4)	7.1	10.4	10.5	6.8	9.8	9.8	6.8	9.7	9.7	12.0	11.9
LOT 2 (E5 to E8)	7.2	10.5	10.6	6.9	9.9	10.0	6.9	9.9	10.1	12.4	12.4

Fig. 3. Nominal dimensions of the steel parts investigated within the experimental program (used with permission from [1])

Tab. 1. Experimental results of specimen E3 from the research program presented in [1].

	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)
E3	27000	111.3

2. Analytical evaluation

The analytical methods were conducted in accordance with the provisions of the European standard SR EN 1993-1-8:2005 [2], by applying the Component Method, where each component is characterized by a nonlinear force–deformation curve, as also noted by J. Jaspart [3]. The analysis focused on determining key mechanical properties relevant for characterizing the joint, namely the initial stiffness ($S_{j.ini}$) and the moment resistance ($M_{j.Rd}$).

$$S_{j.ini} = \frac{Ez^2}{\sum_i \frac{1}{k_i}} \tag{1}$$

where E is the modulus of elasticity, z is the lever arm, and k_i is the stiffness coefficient of component i.

$$M_{j.Rd} = \sum_r (h_r F_{tr.Rd}) \tag{2}$$

where $F_{t.Rd}$ is the tensile resistance of bolt row r, h_r is the distance between bolt row r and the center of compression, and r is the number of bolt rows.

Based on the analytical approach, the most critical components influencing the behavior of the studied steel joint were identified as the end plate and the column web. Considering these findings, a parametric analysis was performed to evaluate the influence of the end plate thickness and the effect of additional stiffeners. The results indicated that increasing the end-plate thickness did not lead to a significant improvement in moment resistance, whereas a slight increase in joint stiffness was observed.

Table 2. presents the analytically determined values of initial stiffness ($S_{j.ini}$) and bending moment resistance ($M_{j.Rd}$) for the investigated joint configuration, as a function of end-plate thickness. Additionally, the table highlights the difference in percentages in initial stiffness ($S_{j.ini}{}^{12}+$), compared to the reference configuration with a 12 mm thick end plate.

Tab. 2. Analytical results of the investigated joint [1] as a function of end plate thickness.

	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$S_{j.ini}{}^{12}+$ (%)
A-p12mm	9642.34	48.59	0
A-p14mm	9970.42	48.59	3.40
A-p16mm	10152.51	48.59	5.29
A-p18mm	10255.21	48.59	6.35
A-p20mm	10312.32	48.59	6.95
A-p22mm	10341.87	48.59	7.25

Table 3. presents the analytically determined values of initial stiffness ($S_{j.ini}$) and bending moment resistance ($M_{j.Rd}$) for the studied joint, as a function of stiffener configuration: without stiffeners (A-wos), with horizontal stiffeners at the top and bottom flanges of the beam (A-ulhs), with only upper stiffeners (A-us), and with only lower stiffeners (A-ls). In addition, the table includes the percentage variations in initial stiffness ($S_{j.ini}{}^{wos}+$) and moment resistance ($M_{j.Rd}{}^{wos}+$), relative to the configuration without stiffeners.

It should be noted that the values presented in Tables 2. and 3. were obtained using the theoretical mechanical properties of S235 structural steel.

Tab. 3. Analytical results of the investigated joint [1] as a function of stiffeners.

	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$S_{j.ini}{}^{wos}+$ (%)	$M_{j.Rd}{}^{wos}+$ (%)
A-wos	9642.34	48.59	0	0
A-ulhs	14552.30	49.99	50.92	2.88
A-us	14552.30	49.99	50.92	2.88
A-ls	14514.02	49.73	50.52	2.35

3. Numerical evaluation

Numerical models were developed using the IDEA StatiCa and Consteel softwares to evaluate the steel joint corresponding to configuration E3. While configuration E3 originally consisted of a steel column and a composite beam, the numerical analyses focused on the connection between a steel column and a steel beam. In Consteel, joint behavior is assessed using the Component Method, while IDEA StatiCa applies the Component-Based Finite Element Method (CBFEM).

CBFEM combines the principles of the Component Method with those of Finite Element Method, dividing the joint into distinct components. This approach allows for the interaction between components to be captured, directly influencing the joint's moment resistance and stiffness, as emphasized by Lubomír Šabatka [4]. IDEA StatiCa uses an automatic mesh discretization with shell elements, featuring a minimum element size of 8 mm and a maximum of 50 mm.

In IDEA StatiCa, three different models were developed based on specimen E3. The model IS–Lot1-bweld features butt weld between the top flange of the beam and the end plate, with the top edge of the end plate perfectly aligned with the top flange. This model incorporates the actual mechanical properties of the materials, determined through tensile testing. The IS-S235-bweld and IS-S235-fweld models employ theoretical mechanical properties of S235 structural steel. The difference between these two lies in the weld type used between the top flange and the end plate: one uses a butt weld, the other a fillet weld. Standardized dimensions from steel catalogs were used for all models, disregarding nominal manufacturing tolerances.

The Consteel software presents certain limitations. One key restriction is the inability to assign different steel grades to the flanges

and web of a cross-section. As a result, the CS-S235-fweld model in Consteel uses theoretical mechanical properties of S235 structural steel. Additionally, Consteel does not support butt welds, requiring the use of fillet welds between the top flange of the IPE270 beam and the end plate. This limitation leads to an automatic offset of approximately 10 mm between the top flange and the end plate, meaning the Consteel model does not accurately replicate the E3 test configuration.

An identical model was created in IDEA StatiCa with the same assumptions as in Consteel to enable a direct comparison between the numerical results obtained from the two software. Numerical analysis results are summarized in Table 4.

Tab. 4. Numerical analysis results of the studied joint, according to [1].

	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)
E3 [1]	27000	111.30
IS-S235-bweld	8776.53	48.30
IS-S235-fweld	8684.66	47.80
IS-Lot1-bweld	8099.42	57.50
CS-S235-fweld	9307.98	46.48

The studied steel joint was analyzed parametrically in IDEA StatiCa by varying the end-plate thickness and the types of stiffeners applied. The investigated configurations included: no stiffeners (N-wos), horizontal stiffeners at both top and bottom flanges (N-ulhs), upper stiffeners only (N-us), lower stiffeners only (N-ls), combined horizontal and vertical stiffeners (N-hvs), and doubler plates for stiffening the column web (N-ds). The corresponding results are presented in Tables 5–8.

It was observed that vertical stiffeners used in IDEA StatiCa cannot be modeled in Consteel. For the configuration without stiffeners, both software tools produced comparable results, with differences of less than 10%. However, for configurations with stiffeners (excluding N-wos), the discrepancies between the results obtained from the two software packages ranged from -16.67% to 43.97% for initial stiffness ($S_{j.ini}$), and from 5.45% to 30.13% for bending moment resistance ($M_{j.Rd}$). The numerical models developed in IDEA StatiCa are illustrated in Figures 4–11.

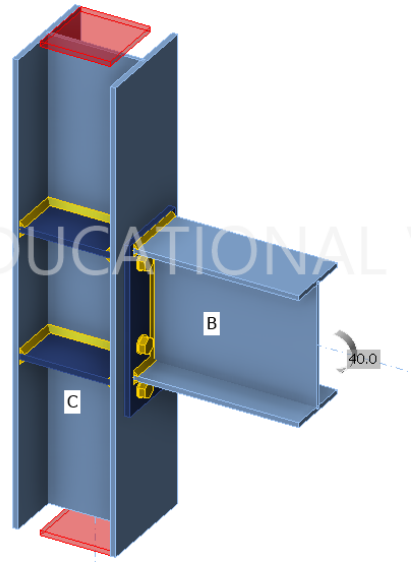

Fig. 4. N-ulhs joint configuration in IDEA StatiCa.

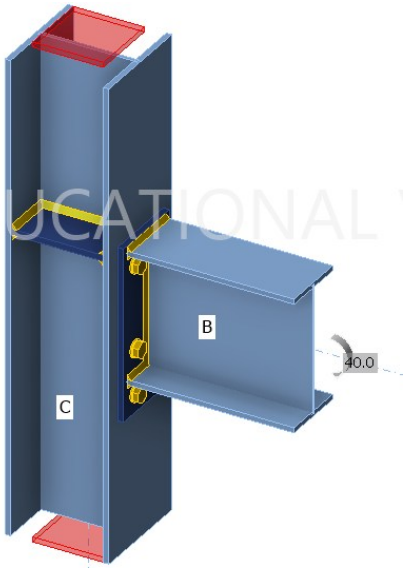

Fig. 5. N-us joint configuration in IDEA StatiCa.

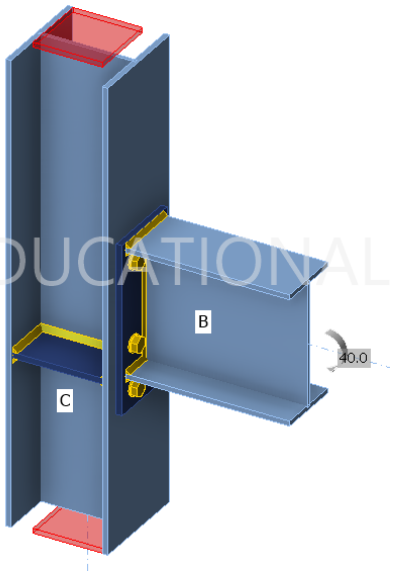

Fig. 6. N-ls joint configuration in IDEA StatiCa.

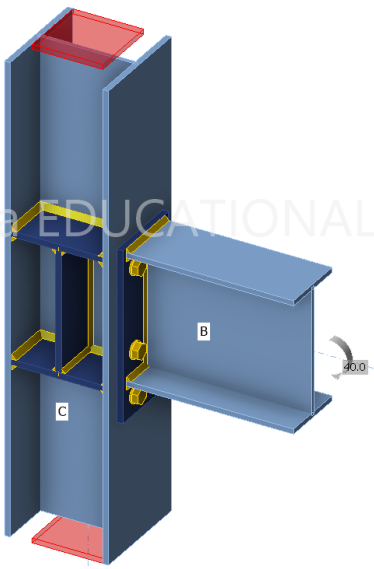

Fig. 7. N-hvs joint configuration in IDEA StatiCa.

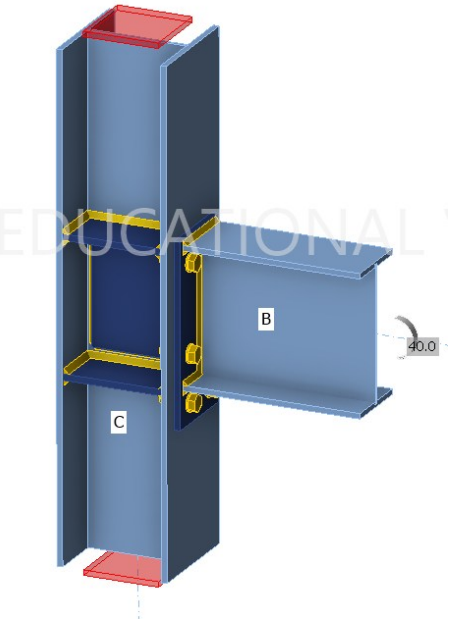

Fig. 8. N-ds joint configuration in IDEA StatiCa.

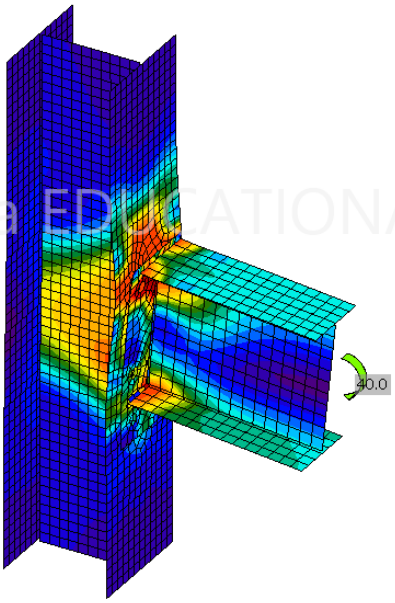

Fig. 9. Numerical analysis of specimen IS-S235-fweld.

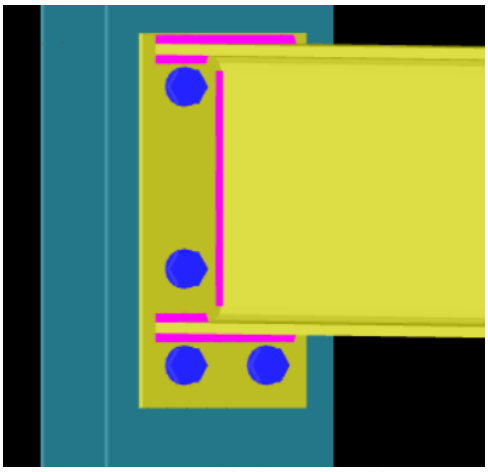

Fig. 10. 3D model of CS-235-fweld.

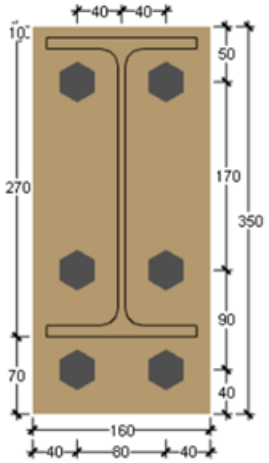

Fig. 11. 2D model of CS-S235-fweld.

Tab. 5. Numerical results of the investigated joint as a function of end-plate thickness. Comparison between the results obtained from Consteel and Idea StatiCa software.

	CS-S235-fweld		IS-S235-fweld		Difference	
	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$\Delta S_{j.ini}$ (%)	$\Delta M_{j.Rd}$ (%)
N-12mm	9307.98	46.48	8684.66	47.80	-6.70	2.84
N-p14mm	9770.24	47.90	9023.85	48.60	-7.64	1.46
N-p16mm	10049.26	47.97	9237.46	49.50	-8.08	3.19
N-p18mm	10222.49	48.05	9403.29	50.40	-8.01	4.89
N-p20mm	10332.3	48.08	9535.78	51.40	-7.71	6.91
N-p22mm	10402.49	48.08	9659.03	52.40	-7.15	8.99

Tab. 6. Numerical results of the investigated joint as a function of stiffeners. Comparison between the results obtained from Consteel and Idea StatiCa software.

	CS-S235-fweld		IS-S235-fweld		Difference	
	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$\Delta S_{j.ini}$ (%)	$\Delta M_{j.Rd}$ (%)
N-wos	9307.98	46.48	8684.66	47.8	-6.70	2.84
N-ulhs	11327.43	48.03	13581.78	62.5	19.90	30.13
N-us	9158.5	46.44	11598.91	60	26.65	29.20
N-ls	11534.64	46.75	9612.05	49.3	-16.67	5.45
N-hvs	-	-	13962.67	62.8	-	-
N-ds	13272.48	54.49	19108.16	62.8	43.97	15.25

Tab. 7. Parametrical analysis results of the studied joint and comparative evaluation with respect to end-plate thickness.

Configuration Idea StatiCa	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$S_{j.ini}^{12}$+ (%)	$M_{j.Rd}^{12}$+ (%)
N-p12mm	8684.66	47.8	0	0
N-p14mm	9023.85	48.6	+3.91	+1.67
N-p16mm	9237.46	49.5	+6.37	+3.56
N-p18mm	9403.29	50.4	+8.27	+5.44
N-p20mm	9535.78	51.4	+9.8	+7.53
N-p22mm	9659.03	52.4	+11.22	+9.62

Tab. 8. Numerical analysis results of the studied joint and comparative assessment with respect to stiffeners.

Configuration Idea StatiCa	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$S_{j.ini}^{wos}$+ (%)	$M_{j.Rd}^{wos}$+ (%)
N-wos	8684.66	47.8	0	0
N-ulhs	13581.78	62.5	+56.39	+30.75
N-us	11598.91	60	+33.56	+25.52
N-ls	9612.05	49.3	+10.68	+3.14
N-hvs	13962.67	62.8	+60.77	+31.38
N-ds	19108.16	62.8	+120.02	+31.38

4. Discussions and Results

IDEA StatiCa not only enables the direct extraction of the initial rotational stiffness of a joint but also provides an automatic classification in accordance with the limits set out in EN 1993-1-8 [2]. The isolated steel joint from the configuration presented in reference [1] can be classified as semi-rigid, based on the results obtained from the analyses. This conclusion is supported by the values listed in Table 9. and the diagram shown in Fig. 10. It is observed that the initial stiffness ($S_{j.ini}$) falls between the boundaries defined for a rigid joint ($S_{j.R}$) and those for a pinned joint ($S_{j.P}$). The initial rotational stiffness ($S_{j.ini}$) is more than double the upper bound for a pinned joint ($S_{j.P}$), so the connection cannot be regarded as ideally pinned. At the same time, it reaches less than 5 % of the rigid-joint threshold ($S_{j.R}$), falling below of the fully rigid criterion. Together, these ratios confirm that the joint should be classified as semi-rigid.

The classification obtained in IDEA StatiCa corresponds to the analytical evaluation results, confirming that the extended end-plate connection can transmit negative bending moments. In practice, recognizing this behavior supports more economical designs by avoiding unnecessarily conservative/dangerous assumptions of either perfectly rigid or pinned behavior.

Tab. 9. Joint classification based on stiffness according to the analysis in IDEA StatiCa.

	$S_{j.ini}$ (kNm/rad)	$S_{j.R}$ (kNm/rad)	$S_{j.P}$ (kNm/rad)	Category
IS-S235-fweld	8684.66	182020.96	3640.42	semirigid

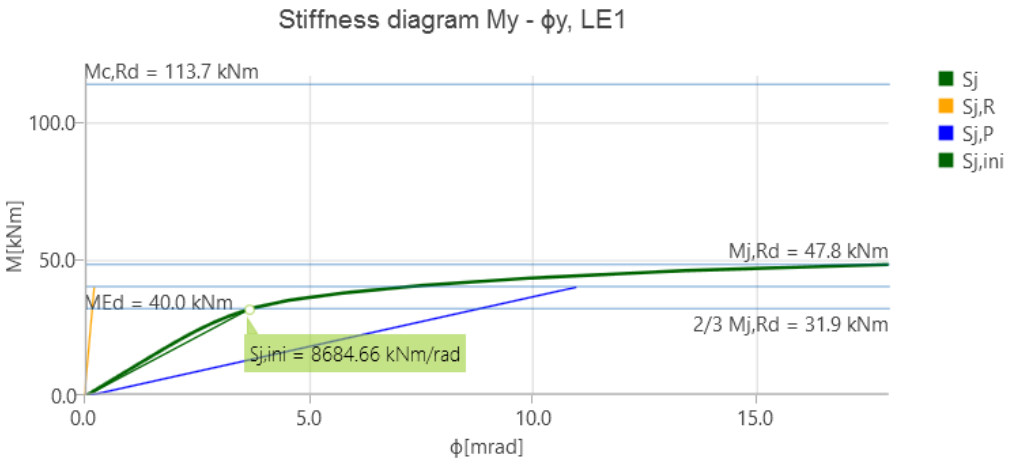

Fig. 10. Stiffness diagram of the investigated steel joint (used with permission from [1])

Tab. 10. Analytical and numerical results of the investigated joint as a function of end-plate thickness.

	Analytical analysis results		Numerical analysis results IS-S235-fweld		Difference	
	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	$S_{j.ini}$ (kNm/rad)	$M_{j.Rd}$ (kNm)	Δ $S_{j.ini}$ (%)	Δ $M_{j.Rd}$ (%)
A-12mm	9642.34	48.59	8684.66	47.80	-9.93	-1.63
A-p14mm	9970.42	48.59	9023.85	48.60	-9.49	0.02
A-p16mm	10152.51	48.59	9237.46	49.50	-9.01	1.84
A-p18mm	10255.21	48.59	9403.29	50.40	-8.31	3.59
A-p20mm	10312.32	48.59	9535.78	51.40	-7.53	5.47
A-p22mm	10341.87	48.59	9659.03	52.40	-6.60	7.27

For the isolated steel joint from the configuration presented in reference [1], the comparison between analytical and numerical results indicated differences of less than 10% in both the initial stiffness and the moment resistance of the investigated joint. Table 10. presents the comparison between the analytical and numerical results.

The conducted parametric analysis revealed that the end plate and the column web are the most critical components affecting joint behavior. These estimates are consistent with the observations made during the E3 test in reference [1], where even in the case of the composite solution, the initial failure occurred at the web of the column. This failure mode was subsequently followed by yielding of the longitudinal reinforcement located closer to the column, as well as cracking of the concrete slab in the anchorage area. Parametric studies indicated that increasing the end-plate thickness beyond 14 mm leads to negligible improvements in both stiffness and load bearing capacity. Based on the IDEA StatiCa simulations, it was observed that stiffeners significantly enhance joint stiffness: using both top and bottom stiffeners resulted in a 56% increase, while applying doubler plates as stiffeners on the column web led to an improvement of up to 120%.

According to reference [1], the load bearing capacity of the composite joint corresponding to configuration E3 was 111.30 kNm. In contrast, the steel connection analyzed in this study exhibited a significantly lower capacity of 57.5 kNm, representing a 48.33% reduction attributed to the absence of composite action. The initial stiffness of specimen E3, determined experimentally, was 27,000 kNm/rad, considerably higher than the values predicted by numerical models for joints composed exclusively of steel elements. For the IS-Lot1-bweld model, the initial stiffness reached only 8,099.42 kNm/rad, which is just 29.99% of the experimentally measured value—representing a 70.01% reduction.

5. Conclusion

The analytical and numerical methods carried out in Consteel and IDEA StatiCa confirmed that the investigated steel beam-to-column joints exhibit semi-rigid behavior and can transfer negative bending moments. Both the Component Method and CBFEM yielded similar results for moment resistance and joint stiffness, with differences remaining within acceptable limits for unstiffened configurations. However, larger deviations were observed for stiffened configurations.

The results presented highlight the advantages of composite joints, which demonstrate higher stiffness and load bearing capacities compared to joints composed exclusively of steel elements.

The next stage of the research program involves calibrating ABAQUS models for both steel and composite joints, using the experimental data provided in reference [1]. This will be followed by the development of an experimental program aimed at analyzing two types of connections: joints between steel columns and steel beams and joints between steel columns and composite beams, where the interaction between the steel beam and the reinforced concrete slab will be considered partial.

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References

1. da Silva L. S., Simoes R. D., Cruz P. J. S., "Experimental behavior of end-plate beam-to-column composite joints under monotonical loading", Engineering Structures. 23 (11), pp. 1383-1409 (2001).
2. SR EN 1993-1-8:2005: Design of steel structures-Part 1-8: Design of joints, 2005.
3. Jaspart J.-P., Weynand K., "Design of joints in steel and composite structures." ECCS-European Convention for Constructional Steelwork, Ernst & Sohn, Brussels, (2016).
4. J Šabatka L., Wald F., Kabeláč J., Kolaja D., Pospíšil M., "Structural Analysis and Design of Steel Connections Using Component-Based Finite Element Model." Journal of Civil Engineering and Architecture, 9(8), (2015).