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SEISMIC BEHAVIOUR OF BOLTED BEAM-TO-COLUMN STEEL JOINTS

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Abstract

Recent studies on the behavior of bolted extended end-plate connections designed for seismic-resistant frame have highlighted how the stress concentration produced by stiffeners on the beam flange can compromise connection performance, leading to the initiation of brittle fracture mechanisms. Therefore, a new alternative connection without the use of stiffeners was recently introduced in literature. This type of extended endplate connection features an innovative bolt arrangement around the beam flange that enables a more uniform distribution of stresses in the bolts, ensuring adequate performance under both monotonic and cyclic loads. However, the absence of stiffeners necessitates the use of thicker end plates than those required in prequalified connections, resulting in increased weight and cost. In this work a new beam-to-column design procedure was proposed for joints having the innovative bolt arrangement together with the rib stiffeners. The aim of this work is to investigate, by means of advanced numerical analyses, the performance of this new type of joints. The results show how the combination of these two aspects imply an increase of the beam-to-column joints performances representing a more economical solution.

Keywords: steel bolted joints; pre-qualified connection; seismic design; moment- rotation response; FEM analysis.

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1 INTRODUCTION

Steel structures are widely used in seismic areas as they provide excellent strength, ductility, and energy dissipation capacity [1-13]. Among them, moment-resisting frames (MRFs) offer a viable solution to exploit structural ductility without compromising architectural design. In particular, numerous research studies have been conducted in literature to examine the performance of beam-to-column joints and their influence on the whole structural behavior.

Notably, Shi et al. [14] and Abidelah et al. [15], in their respective studies, have highlighted the significance of stiffening ribs on the extended part of the end-plate. These ribs have been shown to enhance the bending capacity and ductility of the connection, thereby facilitating a more uniform stress distribution in the bolts around the beam flange. Tartaglia et al. [16], based on their findings, concluded that ribs with an angle greater than 45° do not exert a substantial influence on the capacity of the extended end-plate bolted joints. Recently, Eatherton et al. [17] and Szabo et al. [18], through experimental investigation of eight-bolt stiffened extended end-plate joints (8ES), prequalified by AISC358-16 [19], and a new twelve bolt rows stiffened extended end-plate joints realized using build-up profiles, concluded that the presence of ribs on the end-plate increases the stress concentration on the beam flange at the toe of the rib, leading in some cases to a brittle mechanism. Based on these findings, Morrison et al. [20-22] developed a new eight-bolt extended unstiffened end-plate joint (8EM) as an alternative to the 8ES joint. This was achieved without the use of stiffeners and with an innovative non-symmetric octagonal bolt arrangement around the beam flange. This arrangement was found to improve the stress distribution in the bolts and satisfy the qualifying 4% interstory drift required by AISC341 [23] under cyclic load protocol, even if greater end-plate thickness is required when compared with the prequalified joints.

The objective of the present study is to expand the findings of [22] for American beam-to-column assemblies to European ones, integrating the advantages of the new bolt arrangement in terms of stress distribution with those attributable to the utilization of stiffening ribs on the extended portion of the endplate in terms of bending capacity enhancement, with the aim of obtain a more compact and cheaper competitive connections. In order to achieve this objective, a novel design procedure has been formulated for use with European joints. This procedure is based on the Component Method and a series of numerical investigations have been conducted to determine its efficacy. The results of these investigations are discussed in the ensuing paper.

2 INVESTIGATED JOINTS

The present study investigates the performance of two beam-to-column assemblies and three distinct joints through numerical analysis. This investigation aims to extend the recently proposed 8EM joint by [22] to European joints. Additionally, it explores the integration of the new bolt arrangement with rib stiffeners on the extended part of the end-plate.

The principal geometrical characteristics of the joints under investigation are illustrated in Figure 1 and summarized in Tables 1 and 2.

The joints under investigation are identified by a label that incorporates the type of profiles utilized (i.e. "US" for the assembly with North American profiles and "EU" for the assembly with European profiles) and the type of joint (i.e. "M" for the 8EM joint, "CC" for the code complied joint and "MS" for the new 8EM joint combined with stiffening ribs on the end-plate). The beams and columns employed in the investigated European and American assemblies were properly selected to maximize the similarity in their geometric and mechanical characteristics.

Assembly	Column	Beam	Bolt		End-Plate			Rib	Weight
			Rows	Diameter	b_p	h_p	t_p		
[-]	[-]	[-]	[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[kg]
US-M	W360X250X122 (W14X82)	W460X190X74 (W18X50)	8	29	257	734	32	-	113.6
EU-CC	HE340B	IPE450	6	30	280	870	25	20	126.1
EU-MS	HE340B	IPE450	8	27	300	790	25	15	119.9

Table 1 - Geometrical Features of investigated joints

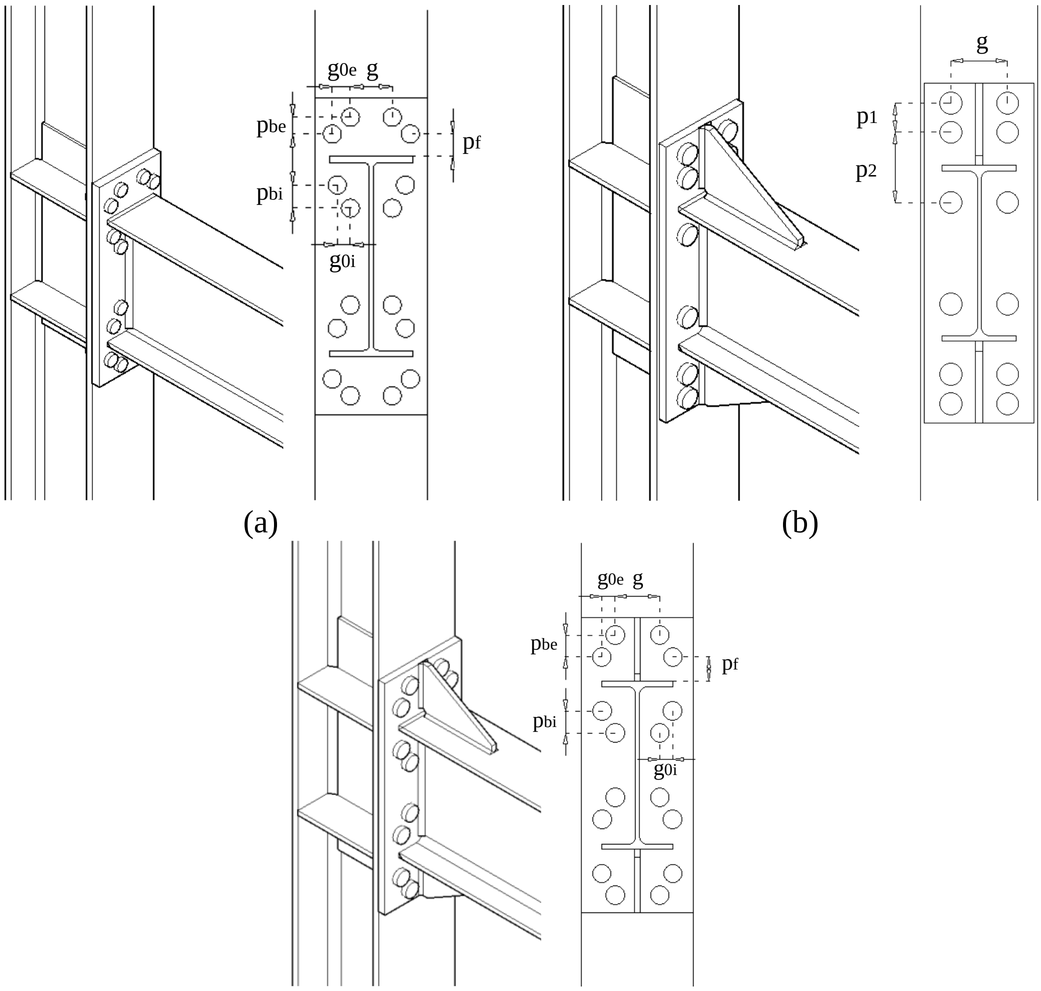


Figure 1 - Analyzed joint configurations: a) unstiffened 8EM joint; b) six-bolt rows extended stiffened joint; c) 8EM joint with stiffeners

Assembly	Bolt arrangement							
	g	g_{0e}	g_{0i}	p_f	p_{be}	p_{bi}	p_1	p_2
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
US-M	98	41	30	51	43	53	-	-
EU-CC	145	-	-	-	-	-	75	180
EU-MS	120	35	34	65	58	59	-	-

Table 2 – Main geometrical features of the investigated joints

The first assembly under investigation is composed of American W460X190X74 (W18X50) and W360X250X122 (W14X82) wide flange hot-rolled profiles, respectively for the beam and the column. In this case, the adopted joint is the 8EM (Fig. 1a) proposed by Morrison et al. [22], which has been designed in accordance with the design procedure proposed by the authors. This procedure is very close to the procedure by step proposed by AISC358-16 [19] for the prequalified 8ES joint, with some differences. The primary discrepancy between the aforementioned procedures pertains to the yielding parameters Y_p, Y_{cu} and Y_{cs}, which are utilized in the calculation of the required bolt diameter and end-plate thickness, as well as in the verification of the column flange for flexural yielding. These three parameters were modified by Morrison et al. to account for the new bolt arrangement, as illustrated in Equations 1, 2 and 3. Moreover, due to the absence of ribs, in the procedure proposed by Morrison et al. the shear yielding and the shear rupture of the extended part of the end-plate are checked as done in the AISC358 procedure for unstiffened 4E connections, using the beam flange width b_f instead the plate width b_p for gross and net area calculation. Finally, in step 9 of their procedure, Morrison et al introduced a new bolt check accounting the large elastic deformation of the end-plate as shown in [22].

Regarding the bolt arrangement of the 8EM joint (Figure 1a), to enhance stress distribution in the bolts, Morrison et al. [22] recommend positioning the two bolt rows outside the beam flange as close as possible. Furthermore, the gage between the bolts in the first row outside the beam flange should be smaller than the flange width. For the two bolt rows inside the beam flange, their alignment should form an angle of 60 degrees with the horizontal axis.

$$Y_p = \frac{1}{4}\left(\frac{b_p(2h_2+3h_3+p_f)}{p_f} + \frac{2g(-2h_3+p_{bi})}{p_{bi}+2p_f} + 8\left(\frac{h_3 p_{bi}}{g+g_{0i}} + \frac{h_2(p_{be}+p_f)}{g+g_{0e}} - \frac{p_f(p_{be}+p_f)}{g+g_{0e}} + \right.\right.$$
$$\left.\left. + \frac{p_f(h_3+p_{bi}+p_f)}{g+g_{0i}} - \frac{g_{0e}h_2}{p_{be}+2p_f} + \frac{g_{0e}p_f}{p_{be}+2p_f}\right) - \frac{2(h_3+p_f)(p_{bi}+p_f-s)}{g}\right) \tag{1}$$
$$s = \frac{g}{\sqrt{2}}$$

$$Y_{cu} = \frac{1}{2}\left(\frac{-2(g_{0e}-g_{0i})(h_2-h_3)}{c} + \frac{c\left(4g_{0i}{}^2(h_1+h_4)+g^2(2h_1+2h_2+h_3+h_4)+2gg_{0i}(3h_1+h_2+2h_4)\right)}{g(g+g_{0i})(g+2g_{0i})} + \right.$$
$$\left. + \frac{g(h_1+h_2)}{c+p_{be}} + \frac{2g_{0e}(h_1+h_2)}{c+p_{be}} + \frac{g(h_3+h_4)}{c+p_{bi}} + \frac{2g_{0i}(h_3+h_4)}{c+p_{bi}} + \frac{b_{cf}(h_1+h_4)}{s} + \frac{4(h_1(p_{be}+s)+h_4(p_{bi}+s))}{g}\right) \tag{2}$$
$$s = \frac{\sqrt{b_{cf}g}}{\sqrt{2}}$$

$$Y_{cs} = \frac{1}{2}\left(\frac{b_{cf}(h_2+h_3)}{p_f} + \frac{2(h_3+h_4)(p_{bi}+p_f)}{g+g_{0e}} + \frac{b_{cf}(h_1+h_4)}{s} + \frac{4h_4 s+4h_1(p_{be}+p_f+s)}{g}\right) \tag{3}$$
$$s = \frac{\sqrt{b_{cf}g}}{\sqrt{2}}$$

The second assembly investigated is composed of European IPE450 and HE340B hot-rolled profiles, respectively for beam and column. In this case, two distinct joints have been designed. The first joint is a six-bolt extended stiff-ended end-plate joint (Figure 1b) that has been designed in according to EN1993-1-8 [24] using the component method (CM). The second joint (Figure 1c) adopts the new bolt arrangement proposed by Morrison et al. in combination with stiffening ribs on the extended part of the end-plate. In this case, a new proper design procedure based on the CM is used.

In the CM the behavior of the joint is defined as a combination of simply components, modelled as non-elastic springs and investigated individually. In this method, the equivalent T-stub analogy is a key element in the evaluation of the capacity of components that act in bending (i.e. the end-plate in bending or the column flange in bending). In the T-stub analogy, the capacity of these components is obtained as a function of the yielding patterns and their effective length. EN1993-1-8 [24] provides all the information on the possible yielding patterns available in traditional extended end-plate bolted joints, that are used in this paper for the design of the six bolt rows joint and modified for accounting of the new bolt arrangement in the new proposed EU-MS joint.

As shown in Table 1, the design of the two EU connections indicates that adopting the new bolting arrangement proposed by Morrison et al. leads to a lighter and more economical joint compared to traditional configurations.

3 NUMERICAL MODEL

3.1 Modelling assumption

Advanced finite element (FE) software Abaqus is utilized to undertake numerical analyses. The geometry of the analyzed assemblies is defined sub-structuring the beam-to-column connection from two different MRF's structures at the null point of the deformed shape due to shear loads as reported by [25-26]. The adopted boundary conditions remain consistent with this sub-structuring; specifically, pinned end column sections and lateral-torsional restraints outside the expected plastic hinge formation zone on the beam are imposed.

C3D8I elements and a mesh size of 15 mm are employed to discretize the models.

Regarding the materials, an S355 steel is adopted for the European assemblies while an ASTM992 steel is adopted for the American investigated joint. 10.9 and 12.9 bolts used in the European joints, while A325 high resistant bolts are adopted in the American one.

The interactions between the welded elements are modelled by Tie-Constraints, while those between adjacent elements are modelled with surface-to-surface interactions, with a friction coefficient of 0.4 and a "Hard" Contact.

A two-step dynamic implicit analysis is conducted on the models. Initially, clamping is applied to the bolts, and subsequently, a vertical monotonic load is applied at the free end of the beam.

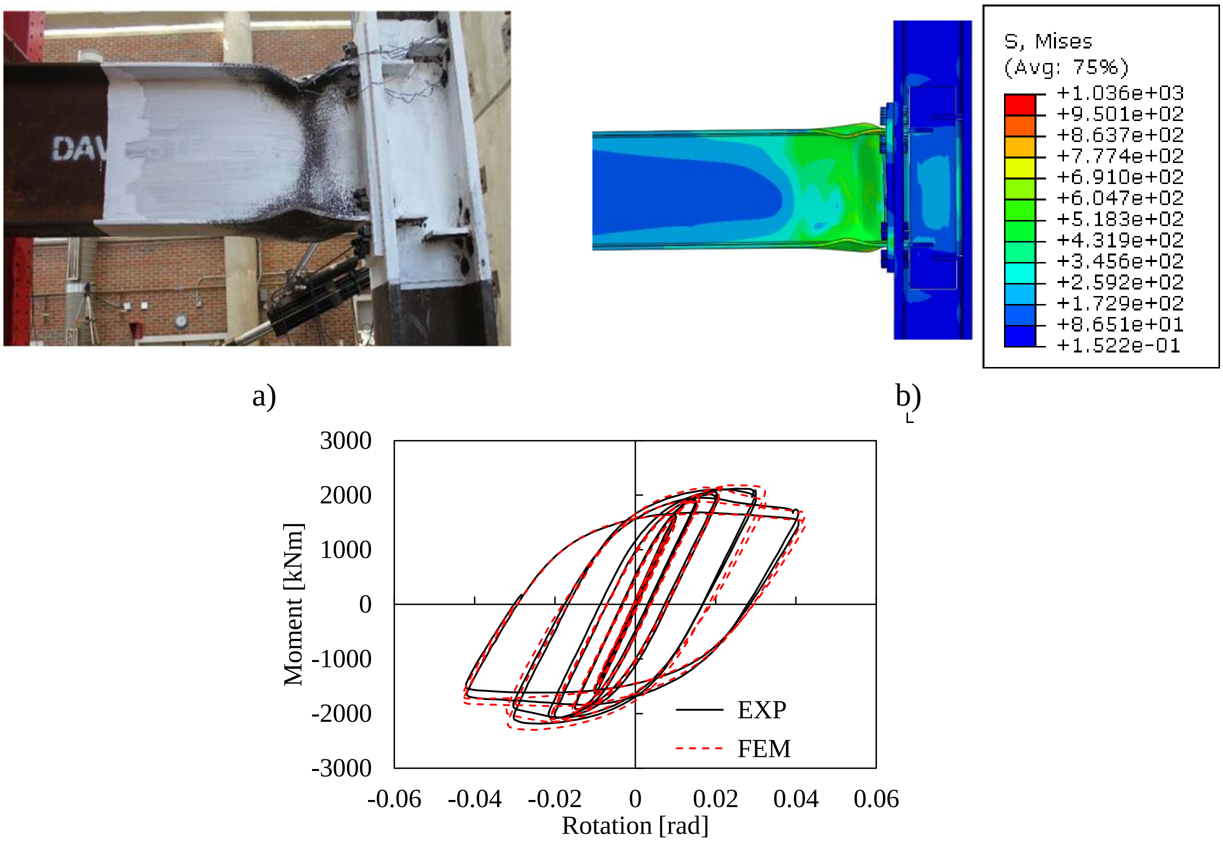
The results of these analyses, in terms of the moment-rotation curve and PEEQ (equivalent plastic strain index), are discussed subsequently.

3.2 Numerical validation

The modelling assumptions are validated against the experimental tests results provided by Morrison et al. [22]. In this study, four large-scale, bare-steel, single-cantilever beam-to-column assemblies with 8EM joints were tested under the ANSI/AISC341 chapter K cyclic loading protocol. Two of the four specimens tested by Morrison et al. utilized W690x140 wide flange beams, while the others employed W840x193 beams. For all specimens, a single W360x382 column, accurately reinforced with doubler plates and half-depth continuity plates to avoid yielding, was utilized. The beam flange was welded to the end-plate through full penetration weld, without access hole and with a 9.5mm backing fillet weld, while the beam web was welded to the plate with fillet welds designed to develop the beam web strength in tension.

The column height was imposed as 3.66m, while a 3.4m beam length was utilized. The ends of the column were pinned, a lateral-torsional restraint was adopted on the beam at 2.13m from the column flange and the load was applied on the beam free end.

As shown in Figure 2 the numerical assumptions adopted in this paper are perfectly able to reproduce the experimental results.



c)

Figure 2 – Comparison between experimental and numerical results

4 NUMERICAL RESULTS

As illustrated in Figure 3, a comparison is presented of the moment-rotation curves obtained from numerical analyses conducted for the three joints under investigation (i.e. US-M, EU-CC and EU-MS).

It is evident that all the designed joints perform as full-strength joints, exhibiting a high bending capacity relative to the connected beam, where a plastic hinge is formed. It can be observed that the EU-CC joint, designed using the latest version of the EN 1993-1-8 code [24], and the EU-MS joint, designed using a new bolt arrangement proposed by Morrison et al., in conjunction with ribs on the extended part of the end plate, demonstrate very similar behavior regarding resistance, initial stiffness and ductility. Conversely, the US-M unstiffened joint, which was designed according to the procedure outlined by Morrison et al. for the 8EM joint, exhibits a lower bending capacity and initial stiffness due to the absence of stiffening ribs.

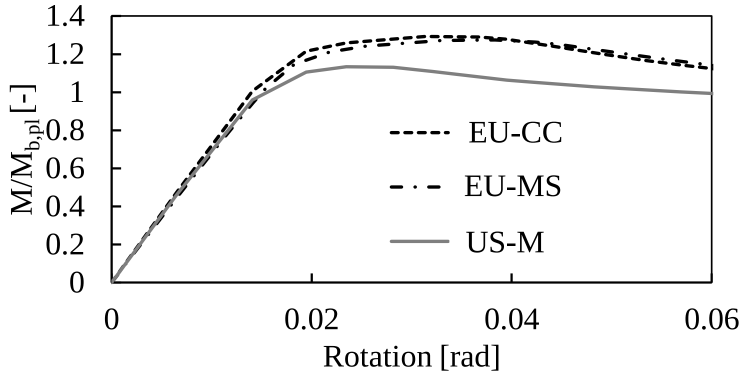


Figure 3 - Comparison between the Moment-Rotation curves of the investigated joints

The PEEQ distribution obtained in ABAQUS for the three investigated joints shown that in all the investigated solutions the plastic hinge is formed in the beam, while the connection remains in the elastic range (Figure 4).

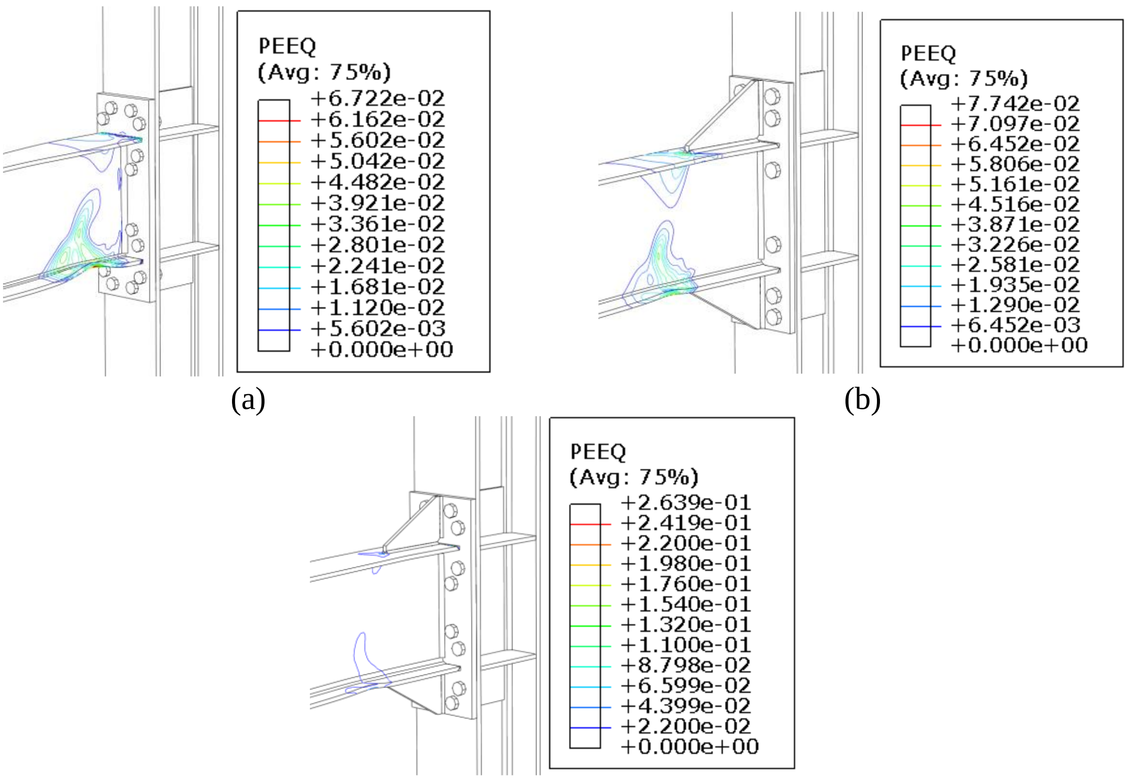


Figure 4 - PEEQ distribution for a rotation equal to 4%: a) US-M; b) EU-CC; c) EU-MS

To establish the true capacity of the joints under investigation, without the influence of beam plasticization, an additional set of models was created in ABAQUS, thereby ensuring elastic behavior for the beam steel.

In Figure 5, the moment-rotation curve obtained for the three joints under investigation is compared with the results obtained from the model with an elastic beam (BElastic). As expected, given that the joints are designed to act as a full-strength joint, the BElastic models consistently exhibited higher capacity compared to the models with real beams. Specifically, as presented in Table 3, the US-M joint with the elastic beam exhibited an $M_{BElastic,Rd}/M_{Rd}$ ratio of 1.63, where $M_{BElastic,Rd}$ denotes the bending capacity of the connection with the elastic beam, and M_{Rd} represents the joint's bending capacity. In contrast, the EU-CC and EU-MS joints demonstrated $M_{BElastic,Rd}/M_{Rd}$ overstrength ratios of 1.56 and 1.48, respectively. A comparison of the two joints designed for European assembly reveals that utilizing the new bolt configuration defined by Morrison et al. and stiffening ribs on the end-plate enables the fabrication of a more compact and economical joint compared to the EU-CC. However, this joint exhibits a substantially similar behavior to that of the EU-CC, yet it has a smaller $M_{BElastic,Rd}/M_{Rd}$ overstrength ratio.

	US-M	**EU-CC**	**EU-MS**
$M_{BElastic,Rd}/M_{Rd}$	1.63	1.56	1.48
MS / CC	-	0.95	

Table 3 - Investigated joints overstrength ratio

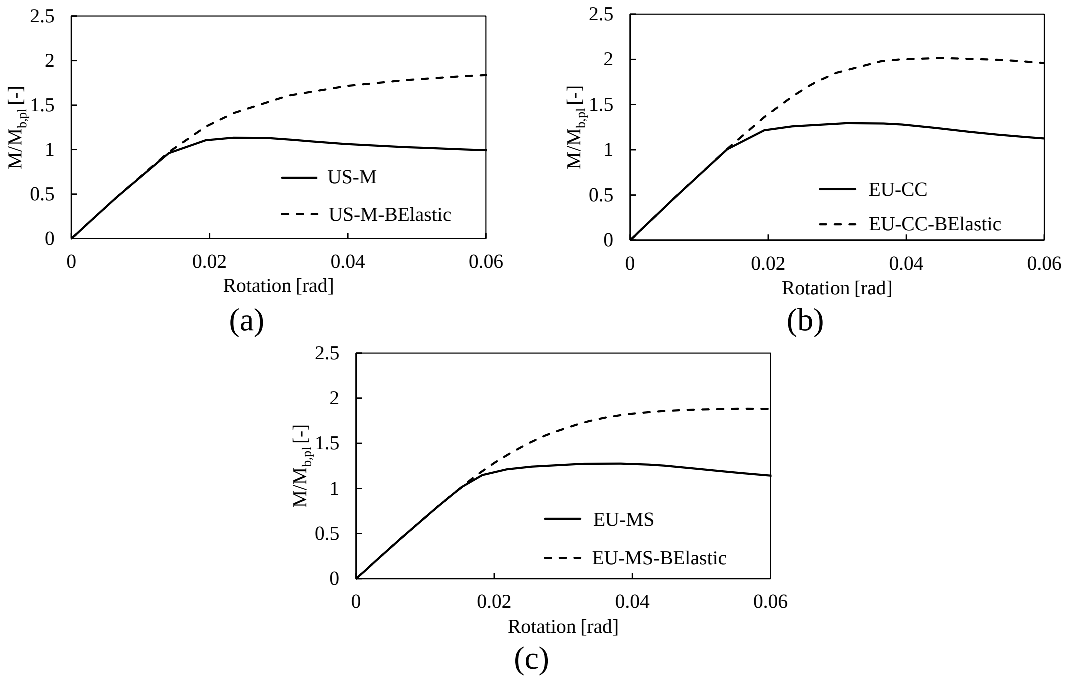


Figure 5 - Comparison between the behaviour of the investigated joints modelled with real beam and elastic beam: a) US-M; b) EU-CC; c) EU-MS

5 CONCLUSIONS

The following conclusions can be pointed out from the results of the numerical analyses conducted on the investigated joints:

- The adopted numerical assumptions allows for the simulation of the experimental results presented by Morrison et al. [22] and for the replication of the real behavior of the investigated joints.
- The advanced design procedure developed for the European MS joint, integrating the innovative bolt arrangement with end-plate stiffeners, allow to obtain ductile, full-strength joint, in which the plastic hinge is mainly concentrated within the connected beam, while the connection remains in elastic range
- The utilization of the innovative bolt configuration, in conjunction with the ribs on the endplate, allows for more economical joints. Indeed, when comparing the EU-MS with

the EU-CC joints, it can be observed that despite a reduction in steel weight, the two joints exhibit comparable capacity and ductility.

- As expected, due to the absence of ribs on the end-plate, the US-8EM joint depicts lower value of both resistance and stiffness in comparison to stiffened joints.

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