

BOLTED END-PLATE BEAM-TO-COLUMN JOINTS USING HAMMER-HEAD BEAMS

Experimental tests and proposal of design guidelines

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INTRODUCTION

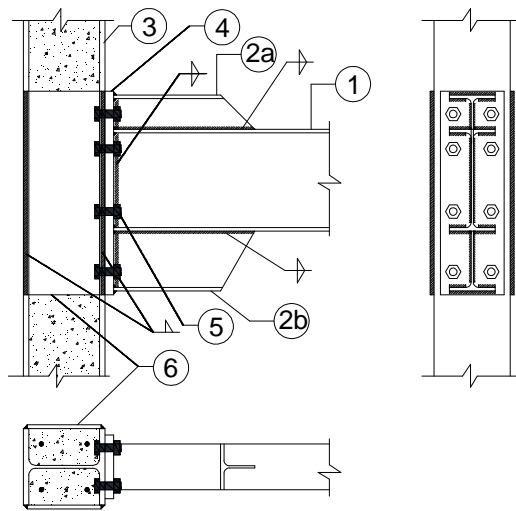
When considering the capacity design for a frame in seismic area, Eurocode 8 imposes to have full strength beam-to-column joints (with account of possible overstrength effects). This requirement leads generally to uneconomical joint configurations. Within the European RFCS project HSS-SERF - “High Strength Steel in Seismic Resistant Building Frames”, it is intended to propose more economical solutions for such joints using a combination of high strength steel elements for some parts and normal carbon steel for others. At the University of Liege, as partner of this project, innovative solutions of joints using hammer-head to reinforce beam components has been experimentally, numerically and analytically investigated. The proposed solution allows performing some economies at the joint level and allows satisfying all the recommendations from Eurocode 8. This paper summarises the main results, from the experimental tests to the developed design guidelines, for this innovative joint configuration.

1 INVESTIGATED JOINT CONFIGURATIONS

Within the framework of the RFCS European project HSS-SERF – “High Strength Steel Seismic Resistant Building Frames”, the University of Liege contribution was devoted to the investigation of innovative bolted beam-to-column joints in moment-resisting dual-steel frames susceptible to be loaded by significant seismic actions. Respecting the capacity design approach, the structural joints should be full strength ones, taking into account the possible overstrength as recommended in Eurocode 8. One of the specificities of the HSS-SERF project was that the proposed joints were intended to be used in moment resistant dual-steel frames where the beams are made of S355 steel grade while steel grades from S460 to S700 are used for the steel profiles/tubes in the composite columns.

Three bolted end-plate joint configurations were proposed: (1) Bolted hammer head end-plate to wide flange column joint (B-EP-H - *Fig. 1*): the end-plate welded to the hammer head beam is directly bolted to the flanges of partially-encased wide-flange columns reinforced by lateral plates (pieces 6 in *Fig. 1*); (2) Bolted hammer head end-plate to RHS column joint with U channel (B-EP-U - *Fig. 2*): the end-plate welded to the hammer head beam is connected to a concrete-filled tube column through a reverse U channel (pieces 6 in *Fig. 2*); and (3) Bolted extended end-plate to RHS column joint with long bolts and reduced beam section (B-EPL-RBS - *Fig. 3*): extended end-plates are bolted to concrete-filled tube column using long bolts passing through the column.

The specificity of the proposed solution with the hammer-heads is that the hammer-heads are directly extracted from the same profile than the one used for the beams. Accordingly, no overstrength coefficient needs to be considered for the components associated to these hammer-heads, what leads to a global economy of the proposed solutions as demonstrated in [1] and [2].



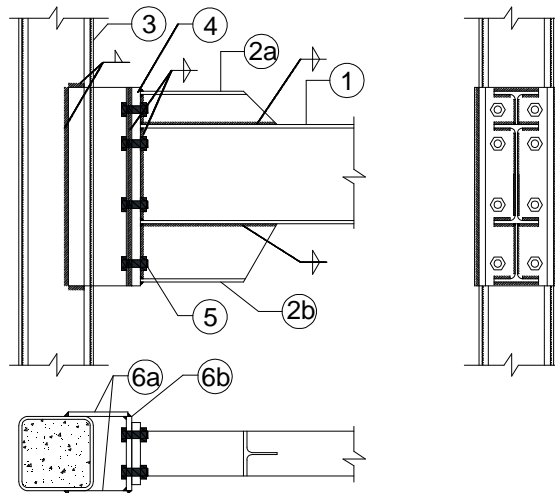
Elements

- 1 Double-T steel beam
- 2a, 2b Top and bottom hammer-heads
- 3 Partially-encased wide-flange column
- 4 End-plate
- 5 Bolts
- 6 Lateral plates

Steel materials

- S355
- Extracted from the beam profiles
- S460 / S700
- S355
- 10.9
- Same grade with the column profiles

Fig. 1: B-EP-H joint configuration



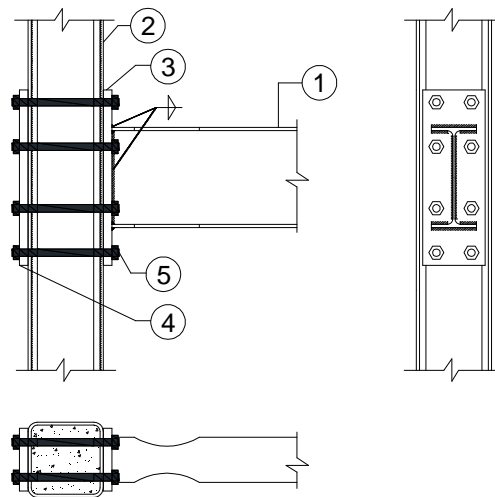
Elements

- 1 Double-T steel beam
- 2a, 2b Top and bottom hammer-heads
- 3 Concrete-filled RHS column
- 4 End-plate
- 5 Bolts
- 6a, 6b Lateral faces and front face of U channel

Steel materials

- S355
- Extracted from the beam profile
- S460 / S700
- S355
- 10.9
- Same grade with column tube

Fig. 2: B-EP-U joint configuration



<i>Elements</i>		<i>Material</i>
1	Double-T steel beam with dog-bone	S355
2	Concrete-filled RHS column	S460 / S700
3	End-plate	The same grade with the beam
4	Repartition plate	The same grade with the beam
5	Long bolts	10.9

Fig. 3: B-EPL-RBS joint configuration

Within the proposed joint configurations, new components not yet covered by the Eurocodes (in particular, by EN1993-1-8 devoted to joints) and so for which further investigations are required, can be identified:

- the compression zone (and its associated lever arm) of the B-EP-H and B-EP-U joints using hammer head beams;
- the hammer head component in compression/tension for B-EP-H and B-EP-U joints;
- the column flange in bending component with plates welded to the flanges in B-EP-H joints;
- the reverse U channel component in B-EP-U joints and;
- long bolt component with bolt preloading, the latter significantly affecting the prediction of the stiffness of the B-EPL-RBS joints.

These new components were investigated experimentally and analytically in the framework of the previously mentioned HSS-SERF project. Within the present paper, the investigations conducted on the joint configurations using the hammer head solution are briefly summarised. All the details about the conducted investigations can be obtained in [3] (freely available on request to the authors).

2 CONDUCTED EXPERIMENTAL TESTS AND OBTAINED RESULTS

16 large scale specimens were tested within the test campaign conducted at the University of Liege (Table 1): 8 B-EP-H joints and 4 B-EP-U joints. The tested specimens were extracted from reference buildings designed within the HSS-SERF project. HEB320/260 profiles and 300x10/250x10 square hollow sections are used for the columns made of S460/S700 steels while IPE400 with S355 steel grade is used for the beams in all specimens. As the joints have been designed to be full strength, the beams in some specimens are reinforced by welding vertical plates between the flanges to be able to reach the resistance of the joints during the tests and, so, to characterise the behaviour of the joints and to validate the proposed design guidelines for the investigated joint configurations (see Section 3).

The testing set-up for the beam-to-column joints is presented in Figure 6. Fixed hinges at the bottom and hinges allowing a vertical displacement at the top are used at the column extremities. Possible displacements of the hinges have been anyway recorded during the tests. A vertical load is applied at the free end of the beam introducing a bending moment and a shear force in the joints.

The main test results (i.e. the resistance, the initial stiffness and the failure modes) are presented in Table 2. Additional information such as the coupon tests for the material characterisation, the geometrical measurement, the instrumentation, the bolt tightening, etc. can be found in [3].

All the moment rotation curves are not reported herein; two examples are reported in Figure 10. All the detailed curves recorded during the tests can be found in [3]. The following remarks can be drawn from the test results: (1) all the joints are full strength ones; (2) B-EP-H joints have a higher stiffness than B-EP-U joints due to the deformability of the reverse U channel in the latter; (3) different failure modes have been observed allowing validating the developments related to the new joint components.

Table 1: description of the tested specimens

N ^o	Test	Joint type	Column	Details	Reinforcement degree	Loading ^(a)
1	A1	B-EP-H	HEB 320, S460	Figure 4	reinforced	Monotonic M ⁺
2	A2				reinforced	Monotonic M ⁻
3	A3				not reinforced	Monotonic M ⁺
4	A4				not reinforced	Cyclic
5	B1		"HEB260", S690		reinforced	Monotonic M ⁺
6	B2				reinforced	Monotonic M ⁻
7	B3				not reinforced	Monotonic M ⁺
8	B4				not reinforced	Cyclic
9	C1	B-EP-U	SHS 300x300x12.5, S460	Figure 4	reinforced	Monotonic M ⁺
10	C2			Figure 5	reinforced	Monotonic M ⁻
13	E1	B-EP-U	SHS 250x250x10 S700	Figure 4	reinforced	Monotonic M ⁺
14	E2			Figure 5	reinforced	Monotonic M ⁻

^(a): M⁺ and M⁻ are hogging and sagging moments, respectively; ANSI/AISC 314-10 protocol is used in the cyclic tests.

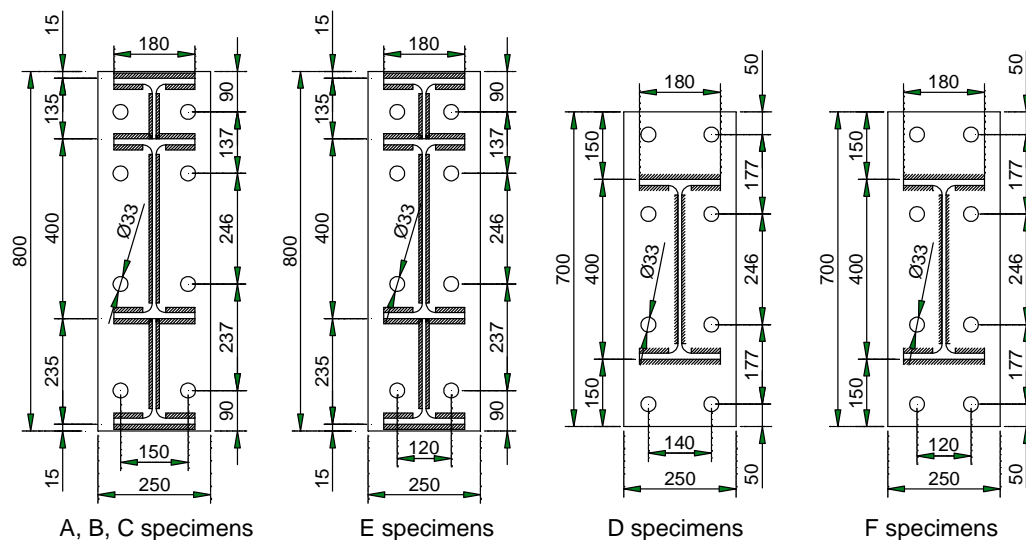


Figure 4: end-plate details

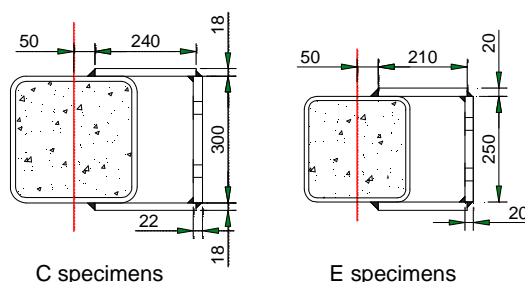


Figure 5: reverse U channel details

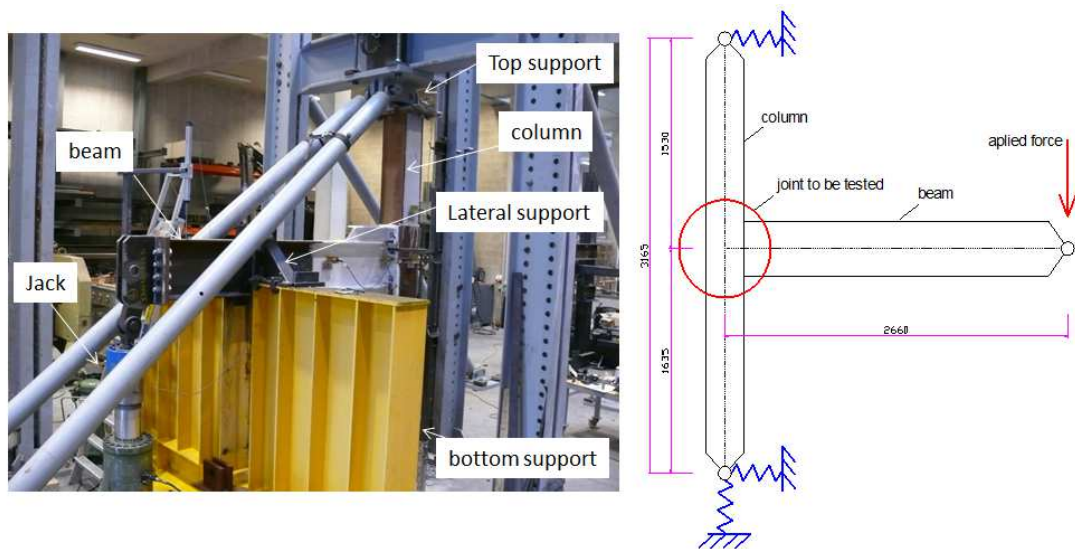


Figure 6: test set-up

Table 2: test results

Test	$M_{\max}^{(a)}$ (kNm)	Stiffness ^(b) (kNm/rad)	Failure modes
A1	820	193 000	Plastic hinge in the hammer head zone - Figure 7
A2	1187	187 000	Joint failure (bolts + hammer head) - Figure 8
A3	550	210 100	Plastic hinge in the beam - Figure 7
A4	575	182 400	Plastic hinge in the beam - Figure 7
B1	1160	154 500	Joint failure (bolts + hammer head) - Figure 8
B2 ^(c)	944	177 700	
B3	550	214 000	Plastic hinge in the beam - Figure 7
B4	566	144 000	Plastic hinge in the beam - Figure 7
C1	980	82 027	Yield mechanic in reverse U channel - Figure 9
C2	877	80 000	Yield mechanic in reverse U channel - Figure 9
E1	972	70 100	Yield mechanic in reverse U channel - Figure 9
E2	946	68 300	Yield mechanic in reverse U channel - Figure 9

Remarks:

(a): maximal bending moment at the critical section.

(b): in the cyclic tests, the stiffness under hogging moment is reported.

(c): the weld between the beam and the reinforcing plate failed and the test was stopped.

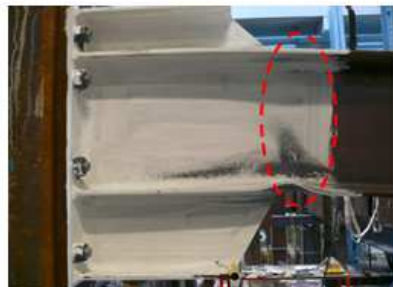


Figure 7: development of a plastic hinge close to the hammer head

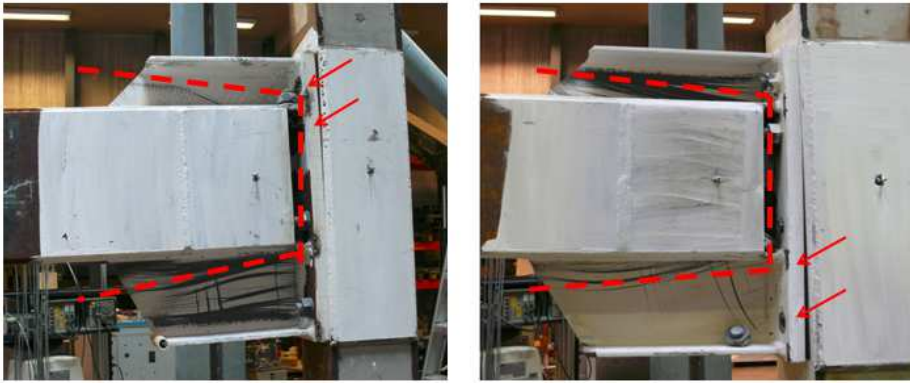


Figure 8: B-EP-H joint – failure in the connection
(4 bolts in the tension zone failed and the hammer head in compression yielded)



Figure 9: failure mode of the B-EP-U joints (reverse U channels yielded)

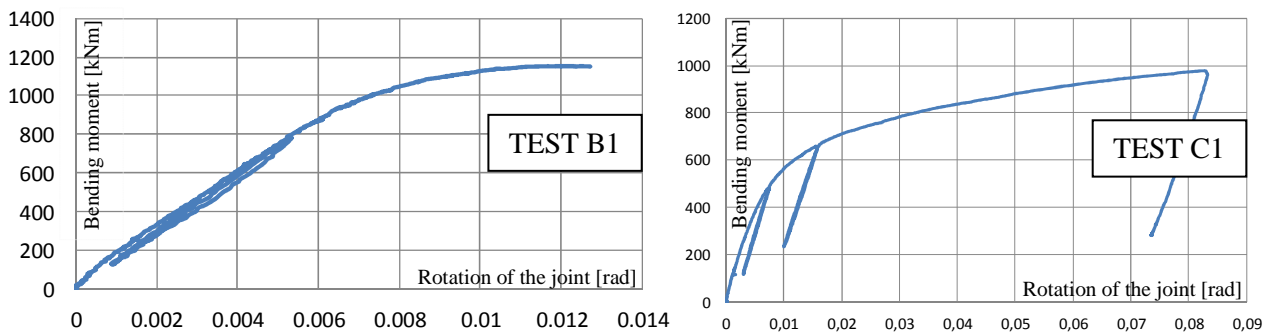


Figure 10: Examples of moment-rotation curves at the joint level obtained through the experimental tests

3 DESIGN GUIDELINES

The component method is recommended in EN1993-1.8 for the design of structural joints; Table 3 presents the different components met in the investigated joints and references to Eurocode design rules when available. The new components not yet covered are also identified; for each of them, analytical models for their mechanical characterisation are proposed and validated through comparison to the experimental results in [3].

Table 3: identified joint components and availability of design rules

Individual component					Design rules
N°	Components	concerned joint types			
		B-EP-H	B-EP-U	B-EPL-RBS	
1	Column panel in shear	x	x	x	Covered in EN-1993-1.8 and EN-1994-1.1.
2	Column in transverse compression	x		x	
3	Beam web in tension	x	x	x	
4	Bolt in tension	x	x	x	
5	End-plate in bending	x	x	x	
6	Column web in tension	x			
7	Beam flange and web in compression	x	x	x	
8	Column flange in bending	x			Not yet covered
9	Hammer head in compression/tension	x	x		Not yet covered
10	U channel in bending		x		Not yet covered
11	Resistance of beam in the hammer head zone	x	x		Not yet covered
Component assembly					
1	B-EP-H and B-EP-U joints				Not yet covered
2	B-EPL-RBS joints				Not yet covered

4 SUMMARY AND ACKNOWLEDGMENT

Within the present paper, three innovative beam-to-column joint configurations for moment resisting building frames in seismic area are briefly introduced. A test campaign on 16 full-scale specimens was performed, demonstrating the appropriate behaviours of the proposed joint solutions. Also, new joint components, i.e. not yet covered in the design codes, are identified within the proposed joint configurations; analytical design rules for these specific joint components have been developed and validated through comparisons to experimental results.

Using the so-developed analytical models, the proposed joint configurations can be fully characterized (in terms of resistant bending moment and stiffness) using the component method as recommended in the Eurocodes.

The authors are grateful to the European Union for its financial support under the project HSS-SERF RFSR-CT-2009-00024 and to the partners of the project for the fruitful collaboration in the framework of this project.

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KEYWORDS: full-strength joints, hammer-head beams, new joint components

ABSTRACT

When considering the capacity design for a frame in seismic area, Eurocode 8 imposes to have full strength beam-to-column joints (with account of possible overstrength effects). This requirement leads generally to uneconomical joint configurations. Within the European RFCS project HSS-SERF - “High Strength Steel in Seismic Resistant Building Frames”, it is intended to propose more economical solutions for such joints using a combination of high strength steel elements for some parts and normal carbon steel for others. As partner of this project, the University of Liege proposed and investigated innovative bolted beam-to-column joints in moment-resisting dual-steel frames susceptible to be loaded by significant seismic actions. Respecting the capacity design approach, the structural joints are full strength ones, taking into account the possible overstrength as recommended in Eurocode 8. One of the specificities of the HSS-SERF project was that the proposed joints were intended to be used in moment resistant dual-steel frames where the beams are made of S355 steel grade while steel grades from S460 to S700 are used for the steel profiles/tubes in the composite columns.

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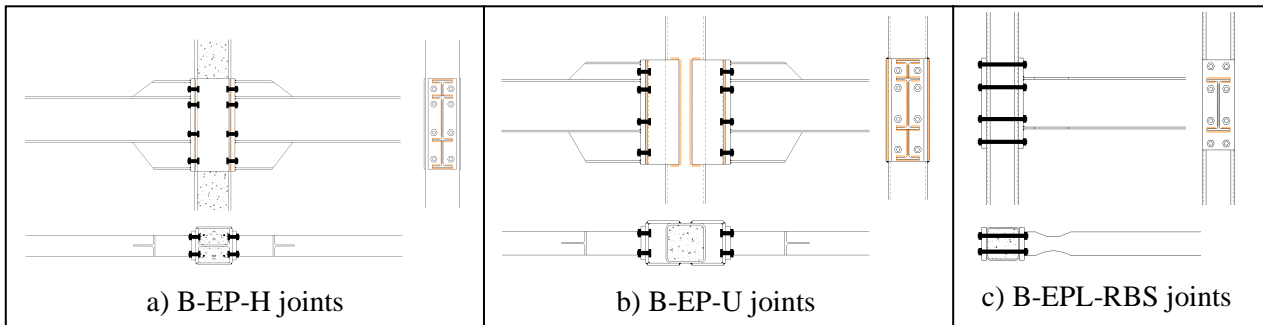


Fig. 1: Proposed and investigated joint configurations

CONCLUSIONS

Within the presented paper, three innovative beam-to-column joint configurations for moment resisting building frames in seismic area are briefly introduced. A test campaign on 16 full-scale specimens was performed, demonstrating the appropriate behaviours of the proposed joint solutions. Also, new joint components, i.e. not yet covered in the design codes, are identified within the proposed joint configurations; analytical design rules for these specific joint components have been developed and validated through comparisons to experimental results.

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