Experimental Behaviour of I Beam – SHS Column Steel Joints with Hollo-bolts

Mesquita, A.B. ¹, Simões da Silva, L.A.P. ², Jordão, S. ³

¹Assistant, Civil Engineering & Architecture Department, University of Beira Interior, Covilhã, Portugal
²Full Professor, Civil Engineering Department, University of Coimbra, Coimbra, Portugal
³Assistant Professor, Civil Engineering Department, University de Coimbra, Coimbra, Portugal

ABSTRACT: The main objective of this paper is to present the results from an experimental analysis aiming at the characterization of the behaviour of a new feature steel bolted joint, that is not yet considered in Eurocode 3. The referred joint is I Beam – SHS Column using an innovative fastening solution with the commercial designation of hollo-bolt. This kind of device is a pre-assembled unit that allows fixing and fastening when access is possible from one side only. This is particularly useful for nodes in which the column is a hollow profile, which has recently become an increasingly popular design solution. The test programme is currently being undertaken at the Civil Engineering Department of the University of Coimbra and encompasses 17 tests, accounting for external, corner and internal façade node configurations, flush and extended end-plate type, on full scale prototypes. Some preliminary isolated hollo-bolt tests were also performed in order to fully characterize its behaviour when subjected to tension and shear. The results are presented in terms of characterization of initial stiffness and resistance for each configuration. A comparison is established, for the referred parameters, between nodes with the same typology. Some preliminary conclusions concerning the main parameters and phenomena influencing the behaviour of the new feature joints are presented and discussed. Three main phenomena are in evidence: i) membrane behaviour response of the tubular column wall; ii) influence of hollo-bolts on the column holes area yielding; iii) three-dimensional effect when an orthogonal cantilever beam is added.

1 INTRODUCTION

In recent years, steel structures with hollow section elements have been an attractive choice for several design solutions because of its structural and architectural potential. According to CORUS® Group, the structural utilization of SHS profiles, comparatively to the open sections profiles (I, H, U, L, T), presents several advantages: i) A very good resistance to the axial compression and torque; ii) A good behaviour to the corrosion, due to the absence of alive edges; iii) A larger easiness in the painting of the surfaces, taking into account the need of maintenance and consequent economy. From the architectural point of view, the advantage is that hollow profiles can produce fluid and slender surfaces with metallic texture.

Although the structural connections, that involve tubular profiles, can be majorly classified as partial-strength and possess a simple geometry, the distribution of stresses and behaviour are more complex comparatively to the profiles with rigid central web. The referred complexity requires the definition of methods and calculation rules tailored for this type of joint, including formulation for assessing resistance and rotational stiffness. In the particular case of the joint studied, it is also necessary to develop formulation for the new component “hollo-bolt in combined bending, tension and shear”. In fact, the inexistence in Part 1.8 of EC3 (2005) of calculation rules for tubular sections compatible with column and beam sizes typical of current steel frames including the fixation system problem, have been leading to the need of research on the behaviour of that type of cross-sections. Some international institutions as International Institute of Welding (IIW) and Comité International
pour le Développement et l’Étude de la Construction Tubulaire (CIDECT), have been trying to tackle the problem aiming at the uniformity of the calculation rules.

The main objective of the research work presented branches in this goal, since it aims at characterising the structural behaviour of I beam - SHS column steel joints with an innovative fastening solution, the hollo-bolts, as referred in Simões da Silva et al (2003).

2 CONFIGURATION AND TYPOLOGY OF PROTOTYPES

2.1 Joints configurations

Full-scale prototypes were used representing external (Figure 1a)) and corner (Figure 1b)) joint configurations. Beams are welded to the end-plates, flush or extended, which are bolted to columns using hollo-bolts.

![Figure 1. Prototypes configurations](image)

2.2 Connections typologies

It was decided to use typologies that are considered in Eurocode 3 in order to enable future comparisons with tests performed by other authors. Furthermore, it was intended to keep the number of unknown variables to a minimum since the new joint encompasses a new uncertainty related with the behaviour of the hollo-bolt. Figure 2a) shows the flush end-plate A configuration, and Figure 2b) exhibits the extended end-plate used for the tests with typology B, (A/B, detailed in Table 1).

![Figure 2. Connections’ typologies: Front view](image)
The values chosen for the distance between the middle lines of bolt holes, either vertical or horizontal (\(e_1, e_2, p_1\) or \(p_{12}\), referred on EC3), were obtained from a previous optimization calculation. The Figure 3a) illustrate a 3D view of the corner joint and a cross section through the hollo-bolt middle plane. Accordingly with the manufacturer information (Lindapter), hollo-bolts are a pre-assembled five part fitting including a standard bolt, a cylindrical body with 4 legs, a collar, a washer and a tronco-conical nut, as shown on Figure 3b).

![3D view of the corner joints](image1)

![Components of the hollo-bolt](image2)

![Hollo-bolt](image3)

Figure 3. Hollo-bolt: pre-assembled unit inserted in the column wall hole

Table 1 summarizes the data for each test in the experimental programme, describing the type of node, details on the joint typology, number, diameter and tightening torque of the hollo-bolts and loading strategy.

<table>
<thead>
<tr>
<th>Nº</th>
<th>Column / beam / end-plate</th>
<th>Configuration</th>
<th>Typology</th>
<th>Hollo-Bolts</th>
<th>Torque [Nm]</th>
<th>Monotonic loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>E01_1</td>
<td>SHS 200 x 8 / IPE 330 / A</td>
<td>External joint</td>
<td>Flush</td>
<td>M16</td>
<td>190</td>
<td>(P_1(\downarrow))</td>
</tr>
<tr>
<td>E01_2</td>
<td>SHS 200 x 8 / IPE 330 / A</td>
<td>External joint</td>
<td>Flush</td>
<td>M20</td>
<td>480</td>
<td>(P_1(\downarrow))</td>
</tr>
<tr>
<td>E01_3</td>
<td>SHS 200 x 8 / IPE 330 / A</td>
<td>External joint</td>
<td>Flush</td>
<td>M20</td>
<td>550</td>
<td>(P_1(\downarrow))</td>
</tr>
<tr>
<td>E03_1</td>
<td>SHS 200 x 12 / IPE 330 / B</td>
<td>External joint</td>
<td>Extended</td>
<td>M20</td>
<td>550</td>
<td>(P_1(\downarrow))</td>
</tr>
<tr>
<td>E03_2</td>
<td>SHS 200 x 8 / IPE 330 / B</td>
<td>External joint</td>
<td>Extended</td>
<td>M20</td>
<td>550</td>
<td>(P_1(\downarrow))</td>
</tr>
<tr>
<td>E04_1</td>
<td>SHS 200 x12 / IPE 330 (2)/ A</td>
<td>Corner joint</td>
<td>Flush</td>
<td>M20</td>
<td>500</td>
<td>(P_1 + P_2 (\downarrow))</td>
</tr>
<tr>
<td>E05_1</td>
<td>SHS 200 x 12 / IPE 330 (2)/ B</td>
<td>Corner joint</td>
<td>Extended</td>
<td>M20</td>
<td>500</td>
<td>(P_1 + P_2 (\downarrow))</td>
</tr>
</tbody>
</table>

A – Flush: 370x170x20; B – Extended: 425x170x20

2.3 Material properties

The steel grade of the columns is S355 J2 H; for beams and end-plates the steel grade is S355 J0. The bolts are 8.8 grade. Coupon tests are being prepared, to assess the full nonlinear material behaviour curve. Considering a previous set of push-out tests of hollo-bolts, contemplating simultaneously M16 and M20, it was obtained a tensile strength capacity of 92,5 kN and 188,5 kN respectively for each bolt. These values were obtained for a 190 Nm (M16) and 500 Nm torque (M20).

3 EXPERIMENTAL SET UP

3.1 Layout

Figure 4 shows some views of the experimental layout for external and corner nodes. The layout accounts for two orthogonal directions, needed for the corner nodes testing. The upper and lower supports of columns are simulated by pinned joints, allowing that the rotations occur on the same plane of the reaction wall, considering bolted plates on top and bottom connected do that pinned joints, according to Figures 1 and 4.
3.2 Measuring devices

The main purpose of the measuring devices is to obtain information on the behaviour of the node and to obtain values for the calibration of the numerical model. Displacement transducers were used to characterize the relevant node rotation components, so that the joint rotation could be precisely assessed. They were also used to measure key displacements throughout the structure that will bring in useful information on local and global structural behaviour. Strain gauges were used to characterize the stress field in key points throughout the structure. The beam tip displacement, for each test, was measured by a LVDT positioned at 1.0 m from column face under bottom beam’s flange (Figure 1). Horizontal displacements were measured on heads bolts. Figure 5a) illustrate a schematic disposition of displacement transducers adopted for tests with extended end-plates, while Figure 5b) shows a photo of the first corner joint test.

4 TEST PROCEDURES

A load, unload and reload history was in general considered for the performed tests. The load in elastic range varies from 30 kN to 50 kN in some tests. For other tests, considering a more significant plastic deformation, the value of 70 kN was selected. The control of equipment load was done in terms of displacement considering velocities between 0.02 mm/s and 0.03 mm/s for the final reload until the end of external joints tests. For corner joints tests, where two load equipments were involved the experimental procedure requires an incremental load applying in terms of displacement control verifying in permanence the values of the beams tip displacements in order to adjust as quickly as possible load P1 and load P2, once the electromechanical equipment controls are different, respectively Servosis system and Dartec system.
5 EXPERIMENTAL RESULTS

5.1 Load-displacement diagrams - $F-d$

Figure 6a) shows the load-horizontal displacement diagram for external joint test E01_3 (flush end-plate). On Figure 6b) it can be seen the correspondent hollo-bolts $F-dx$ diagram. Figure 6c) shows the load-vertical displacement diagram for the test E03_1 (extended end-plate).

These three diagrams are selected from the other cases in order to illustrate the general graphical evolution of the load-displacement curves that represents the behaviour of tested SHS columns and beams as well as hollo-bolts (upper and lower rows). The respective coherence with the moment-rotation curves is observed in next paragraph.

5.2 Moment-Rotation diagrams - $M-\Phi$

5.2.1 External Joints (flush and extended end-plate)

The experimental moment-rotation characteristic curves obtained from tests corresponding to external joints with flush end-plates are summarized on Figure 7.
With tests E01_1/2/3, it could be verified a deformability on SHS section wall and a rigid body rotation of the flush end-plate when hollo-bolt legs failure happened, typical in all tests. It can be observed on Figures 10a), d). A bigger deformability occurred on tests E01_2 and E01_3, considering the higher hollo-bolt diameter in these last cases, according with Table 1, comparing with E01_1. Figure 8 shows the experimental curves for extended end-plates on external joints.

![Figure 8](image1)

Figure 8. \( M-\Phi \) diagrams for external joints with connections by extended end-plate

For the test E03_1, considering the major value of thickness wall of tubular profile (12mm) comparing with the first three tests (8 mm), it occurred also the failure of the hollo-bolt legs simultaneously with the bending of the extended end-plate and a very small deformability on the SHS column, according to Figure 10b). On the case of test E03_2, Figure 10c), even though this test presents the same typology of test E03_1, the column has only 8 mm of thickness, lower than the previous test. So, it could be verified a bigger deformability on the SHS wall and an almost rigid body rotation of respective extended end-plate. The plastic deformations near of column upper holes shows the tendency to the membrane behaviour of the load face column for sections with 8 mm of thickness.

5.2.2 Corner Joints

Figure 9 presents the moment-rotation diagrams for both corner tested joints.

![Figure 9](image2)

Figure 9. \( M-\Phi \) diagrams for corner joints with connections by flush and extended end-plate

As in the other cases of configuration and typology, the rotation can be calculated according to the expression,

\[
\theta_{\text{joint}} = \theta_{\text{node}} - \theta_{\text{web column}}
\]  

(1)

where rotation of the node was obtained from difference between horizontal displacements on heads bolts divided by the distance between their axis (LVDT 5 and 6 from Figure 5a)), and the rotation on web column calculated from the difference between displacements measured on the oppo-
site loaded face (LVDT 9 and 10 from the Figure 5a)). Alternatively, rotation of the node can be obtained taking into account LVDT 15 or 16 under flange beam as indicated on the same figure.

### 5.2.3 Deformabilities sources

Figure 10 shows the principal sources of deformability observed after laboratorial tests witch represents the general kinds of behaviour of the external joints also presented by corner joints.

![Figure 10. Deformabilities verified during the execution of tests](image)

**a) Tests E01_1/2/3/04_1**, **b) Tests E03_1 and E05**, **c) Test E03_2**, **d) Failure legs of Hollo-bolts**

### 5.3 Initial Rotational Stiffness and Plastic Moment for external and corner joints

Table 2 summarizes the values of the initial rotational stiffness, the plastic moment and the ultimate moment for each tested joint, obtained from the experimental curves, by means of a graphical method proposed by Jaspart (1991).

<table>
<thead>
<tr>
<th>Nº</th>
<th>Column / beam / end-plate</th>
<th>HB Torque [Nm]</th>
<th>$S_{ini}$ [kNm/rad]</th>
<th>$M_{Rd}$ [kNm]</th>
<th>$M_{uexp}$ [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E01_1</td>
<td>SHS 200 x 8 / IPE 330 / A</td>
<td>190 (M 16)</td>
<td>2807,1</td>
<td>32,0</td>
<td>54,3</td>
</tr>
<tr>
<td>E01_2</td>
<td>SHS 200 x 8 / IPE 330 / A</td>
<td>480 (M 20)</td>
<td>4650,5</td>
<td>53,0</td>
<td>64,8</td>
</tr>
<tr>
<td>E01_3</td>
<td>SHS 200 x 8 / IPE 330 / A</td>
<td>500 (M 20)</td>
<td>3362,5</td>
<td>42,0</td>
<td>74,5</td>
</tr>
<tr>
<td>E03_1</td>
<td>SHS 200 x 12 / IPE 330 / B</td>
<td>550 (M 20)</td>
<td>12335,0</td>
<td>87,5</td>
<td>161,9</td>
</tr>
<tr>
<td>E03_2</td>
<td>SHS 200 x 8 / IPE 330 / B</td>
<td>550 (M 20)</td>
<td>11388,0</td>
<td>77,0</td>
<td>120,5</td>
</tr>
<tr>
<td>E04_1</td>
<td>SHS 200 x12 / IPE 330 (2) / A</td>
<td>500 (M 20)</td>
<td>14276 - J1</td>
<td>79,0</td>
<td>101,7 (M1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17180 - J2</td>
<td>85,0</td>
<td>113,5 (M2)</td>
</tr>
<tr>
<td>E05_1</td>
<td>SHS 200 x 12 / IPE 330 (2) / B</td>
<td>500 (M 20)</td>
<td>15898 - J1</td>
<td>112</td>
<td>155,6 (M1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>27262,5- J2</td>
<td>141,5</td>
<td>204,9 (M2)</td>
</tr>
</tbody>
</table>

The referred method considers that the initial stiffness is obtained from the slope of the elastic portion of the curve, and that the plastic moment is obtained from the intersection of two lines ("a" and "b"), represented in Figure 11.

![Figure 11. Graphical determination of structural experimental properties: general consideration](image)
Line “a” intersects the axes origin and its slope is the initial rotational stiffness (elastic stiffness). Line “b” is obtained by linear regression adjusting to a portion of the curve, in the after yielding range, starting on point P, represented in Figure 11. Point P is defined by the intersection of the experimental curve with a line with a slope of $S_{j,ini}/\eta$ ($\eta = 2$, bolted connection – EC3). Taking into account the moment-rotation diagrams for the first tests as well as the results listed in Table 2, it can be concluded that the values of $S_{j,ini}$ and $M_{j,Rd}$ increase with the hollo-bolt diameter and respective torque applied. On tests E03_1 and E03_2 the values of initial stiffness and plastic moment are considerably superior to those obtained with the series E01. This fact occurs due to the use of the extended end-plate. However, in the second of these last tests, the lower thickness of SHS wall originated a decrease of structural properties. These same properties are higher on test E04_1, relatively to the previous tests. Analogous conclusion can be verified between this one and test E05_1. For the corner joints connections, we can verify different results for initial rotational stiffness and plastic moment between beam 1 and beam 2 for each test.

It is interesting to state that the different behaviour of the two beams and the correspondent orthogonal hollo-bolts results also of the different static loads applied in several steps of the incremental process, inspite the intention to minimize the displacements difference during the execution of tests. When the load 1 is applied on beam 1, the second beam moves due to the instantaneous unbalance between orthogonal loaded SHS faces. Considering the relation $M_{j,rd 1}/M_{j,rd 2}$ we obtain 93% for test E04_1 and 79% for test E05_1.

6 CONCLUSIONS

With the performed group tests it is possible to verify the failure of the hollo-bolt legs under tension and shear introduced by the bending on beam as well as the increase of $S_{j,ini}$ and $M_{j,Rd}$ values not only with the hollo-bolt diameter and respective torque applied but also with an extended end-plate. On the other side, the membrane behaviour effect, typical of tubular columns under orthogonal forces on loaded faces (Neves, 2004) will be more visible on the SHS sections with smaller thickness, which will be taken into account in the second part of experimental programme. However, such tendency can be observed on prototypes with columns of 8 mm of thickness and M20 hollo-bolts. Also the influence of a second orthogonal cantilever beam can produce a modification in the structural joint behaviour, as the example between tests E03_1 and E05_1: equal sections, equal hollo-bolts, similar torque, but higher values for the last test in both directions, in what concerns to strength and stiffness.

7 REFERENCES

CORUS Tubes library publication.