EXPERIMENTAL BEHAVIOUR OF END-PLATE
BEAM-TO-COLUMN JOINTS UNDER BENDING AND
AXIAL FORCE

Database reporting and discussion of results

by

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EXPERIMENTAL BEHAVIOUR OF ENDPLATE BEAM-TO-COLUMN JOINTS UNDER BENDING AND AXIAL FORCE

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ABSTRACT

The objective of the present paper is to present the results of an experimental research project on endplate beam-to-column bolted steel joints subjected to bending and axial force currently being carried out at the University of Coimbra.

Because of the ongoing nature of this work, this paper is an updated version of a previous Document presented in Timisoara (Document TC10-01-WG2/011), 15 tests being now reported from flush and extended end-plate configurations. In addition, special emphasis is given to database reporting, to allow other research centres to use this experimental data for calibration of theoretical models.

1. INTRODUCTION

A great part of the beam-to-column connections and beams-splices are subject to axial forces, bending and shear. The interaction of these efforts modifies the behaviour of the joint with respect to its initial stiffness, bending resistance and rotation capacity.

In the Eurocode 3, [1], it is possible to evaluate the resistant capacity of a joint subject to bending moment and axial force whenever the latter is less than a maximum limit, given by the equation (1),

$$\frac{N}{N_{pl}} \leq 0.1$$

where $N$ is the beam axial force and $N_{pl}$ is the beam plastic resistance subjected to compression. Under these conditions, the axial force may be disregarded in the design of the joint.

It is important to point out that there is no background to justify this empirical limit of 10%. For connections that exceed the limit range of this equation, Eurocode 3 does not make any specific recommendation. However, the general principles of the component method contemplate this case, since any component is characterized independently of the type of applied loading to the connection. It is up to the designer to define a coherent component

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model that identifies the relevant interactions between the various components. Recent attempts to establish specific procedures for these types of connections were performed for Jaspart et al., [2], Cerfontaine, [3], Silva and Coelho, [4] and Silva et al., [5]. To provide as sound basis for further theoretical developments, a set of 15 tests was carried out at the University of Coimbra and are briefly described in the next section [6, 7]

2. DESCRIPTION OF THE EXPERIMENTAL TESTS

A series of 8 (eight) experimental tests of beam-to-column steel connections with flush endplate, typically illustrated in Figure 1, were already carried out at the University of Coimbra, within a research program on behaviour of beam-to-column joints under bending and axial force. In the first test, FE1, only bending moment was applied through a hydraulic actuator, located a meter away from the face of the column flange, Figure 1(a). For the following tests - FE3, FE4, FE5, FE6, FE7, FE8 and FE9 - constants axial forces of, respectively, -4%, -8%, -20%, -27%, -20%, +10% and 20% of the beam plastic resistance were applied to the beam.

A further series of 7 (seven) tests with extended endplate joints were also performed, Figure 1(b). As in the first test series, only bending moment was applied for test EE1. For the subsequent tests – EE2, EE3, EE4, EE5, EE6 and EE7 - constant axial forces of, respectively, -10%, -20%, -27%, -15%, +10% and +20% of the beam plastic resistance were applied to the beam.

In all tests, the columns were simply-supported at both ends and consist of a HEB240, the beams consist of an IPE240 and the endplate is 15 mm thick, all manufactured from a steel S275. The bolts are M20, class 10.9.

The compressive force application system, Figure 2(a), was composed of a hydraulic jack that applies a tension force to four cables of prestressing with diameter $\phi = 15,2$ mm. The transfer of this force for the connection was performed through a central load cell with capacity of 500kN (NOVATECH), Figure 2(c). These cables pass by a deviator constituted by a profile HEM100 to guarantee that the axial force is always parallel to the beam axis. A load cell TML with capacity of 200 kN in each cable was also used, with the purpose of to obtain the force in each cable. The transmission of the applied axial force in the connection to the reaction wall was made through a reinforced concrete footing that was connected to the reaction wall by means of a profile HEB 200, and prestressed to the reaction slab through bars DYWIDAG.

The tensile axial force application system is shown in Figure 3. Four hydraulic jacks placed in one of the extremities of a circular profile transmit the tension axial force. These circular profiles are simply supported in the other extremity for allow the rotation of these profiles and to guarantee that the axial force is applied always parallel to the beam axis.
Figure 1 – Endplate joints layout

Figure 2 – (a) Frame of application loading, (b) hydraulic jack and (c) central load cell

Figure 3 – Experimental test layout for tests subjected to bending and tension axial force
All tests were instrumented as shown in Figure 4 and Figure 5 with single strain gauges (FLK 6-11-TML), rosettes to 45° (FRA 5-11-TML), bolts axial strain gauges (BTM 6-C-TML), and displacements transducers (LVDT’s), in order to evaluate the main characteristics of the connection, such as, bending moment resistance, initial stiffness and rotation capacity. The registration of measurements was done with a data acquisition system TDS602-TMIL.

For all tests, a constant axial force was applied first, maintained constant throughout the test, with subsequent application of a bending moment incremented to failure. Two unloadings were performed, the first for a bending moment of 25 kNm (down to 5 KNm, to eliminate possible slack in the joint) and the second for a rotation of 20 mrad. Force control was used in the first part of each test, subsequently changed to displacement control.

Tensile tests on coupons extracted from the beams were carried out, aiming at characterizing the actual properties of the material. Then, it was possible to calculate the beam plastic resistance and to determine which the true level of applied axial force to the beam for the other tests. These tensile tests were accomplished according to the following specifications, EN10002 [6], EN10020 [7] and EN10025 [8], yielding the results of Table 1.
Table 1 – Steel mechanical properties (beam of the first test - FE1)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$f_y$ (MPa)</th>
<th>$f_u$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange3A</td>
<td>312.1</td>
<td>439.2</td>
</tr>
<tr>
<td>Flange3B</td>
<td>319.7</td>
<td>459.2</td>
</tr>
<tr>
<td>Flange average</td>
<td>315.9</td>
<td>449.2</td>
</tr>
<tr>
<td>Web2B</td>
<td>345.1</td>
<td>451.4</td>
</tr>
<tr>
<td>Web3B</td>
<td>332.3</td>
<td>443.4</td>
</tr>
<tr>
<td>Wen3A</td>
<td>350.0</td>
<td>457.9</td>
</tr>
<tr>
<td>Web average</td>
<td>342.5</td>
<td>450.9</td>
</tr>
</tbody>
</table>

3. ANALYSIS OF THE EXPERIMENTAL RESULTS FOR THE FLUSH ENDPLATE JOINTS

3.1. Moment vs. Rotation Curves and Application of the Axial Force

The moment vs. rotation curves of the seven tests are presented below where it may be observed that even for a level of equivalent axial force of 20% of the beam plastic resistance, the bending moment is still higher than the Eurocode 3. This is due to the fact that the components in tension for two bolt row are alleviated by the compression axial force and the components in compression, even increased, don't reach the strength, even in presence of the axial force, Figure 6. The results of test FE9 (applied axial force of + 20% of the beam plastic resistance) will be added to the results shortly.

Figure 6 – Moment vs. rotation curves

With the purpose of calibrating the axial force application system, a initial test was performed (FE2) in elastic regime. It was verified that the applied axial load with the cables
was transmitted by the central load cell to the connection as shown in Figure 7. In this graph, it was verified that the axial force applied to the connection, measured through the strain gages located in the web and flange beam and measured by the central load cell is similar.

For higher levels of bending moment, it was verified that the rotation of the beam provoked a reduction of the force in the lower cables and an increment of load of the top cables. Consequently, hydraulic jacks were placed in the lower cables to make the correction of the axial force as the test is being performed. In Figure 8, the variation of the axial force is exemplified in the four individual cables with the moment applied for each test, as well as a detail of the hydraulic jacks. The correction can be observed in item (c).

The Table 2 presents the values obtained for the bending moment resistance and for the initial stiffness of the tests connections. The values of the initial stiffness were obtained from slope of the unloading part of the moment vs. rotation curves. The theoretical values calculated according to Eurocode 3 were respectively, 68.9 kN.m and 5915.7 kN.m/rad being disregarded the presence of the axial force.

Table 2 - Experimental values of bending moment resistance and initial stiffness

<table>
<thead>
<tr>
<th>Test</th>
<th>N (kN)</th>
<th>MRd (kN.m)</th>
<th>SI (kN.m/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE1 (only M)</td>
<td>-</td>
<td>67.8</td>
<td>5785</td>
</tr>
<tr>
<td>FE3 (- 4% Npl)</td>
<td>52.7</td>
<td>72.0</td>
<td>5947</td>
</tr>
<tr>
<td>FE4 (- 8% Npl)</td>
<td>105.6</td>
<td>74.0</td>
<td>6250</td>
</tr>
<tr>
<td>FE5 (- 20% Npl)</td>
<td>265.0</td>
<td>75.5</td>
<td>6163</td>
</tr>
<tr>
<td>FE6 (- 27% Npl)</td>
<td>345.0</td>
<td>72.4</td>
<td>7869</td>
</tr>
<tr>
<td>FE7 (- 20% Npl)</td>
<td>265.0</td>
<td>76.4</td>
<td>5914</td>
</tr>
<tr>
<td>FE8 (+ 10% Npl)</td>
<td>130.6</td>
<td>58.9</td>
<td>6095</td>
</tr>
<tr>
<td>FE9 (+ 20% Npl)</td>
<td>264.9</td>
<td>49.9</td>
<td>5488</td>
</tr>
</tbody>
</table>
Experimental behaviour of endplate beam-to-column joints under bending and axial force

3.2. Analysis of Individual Components

The Table 3 presents the theoretical values of the bending moment resistance and initial stiffness for all components of the connection in study, calculated in agreement with Eurocode 3.

<table>
<thead>
<tr>
<th>Component</th>
<th>Resistance (kN)</th>
<th>Stiffness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column web in tension (3)</td>
<td>458.7</td>
<td>7.03</td>
</tr>
<tr>
<td>Column flange in bending (4)</td>
<td>397.2</td>
<td>38.22</td>
</tr>
<tr>
<td><strong>Endplate in bending (5)</strong></td>
<td><strong>321.7</strong></td>
<td><strong>13.35</strong></td>
</tr>
<tr>
<td>Beam web in tension (8)</td>
<td>455.2</td>
<td>∞</td>
</tr>
<tr>
<td>Bolts in tension (10)</td>
<td>441.0</td>
<td>7.76</td>
</tr>
<tr>
<td>Compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column web in shear (1)</td>
<td>552.7</td>
<td>7.52</td>
</tr>
<tr>
<td>Column web in compression (2)</td>
<td>598.2</td>
<td>10.40</td>
</tr>
<tr>
<td><strong>Beam flange in compression (7)</strong></td>
<td><strong>503.6</strong></td>
<td><strong>∞</strong></td>
</tr>
</tbody>
</table>

In Figure 9, the moment vs. rotation curves of the four tests can be observed with the experimental identification of the yielding sequence of the several components. It is clearly noticed that application of the compression axial force benefits the critical component of the tension zone (endplate in bending) and it decreases the capacity of the critical component of the compression zone (beam flange in compression).
In the graph presented in the Figure 10 it can be observed that, for all the tests, the column flange in bending presented deformations according to mode 1, that is, complete yielding of the flange. The measured displacements for this component are presented in Figure 11 where it is noticed that the behaviour of the component is similar for all the tests, independently of the applied axial force.
In agreement with the design rules of Eurocode 3, the resistance of the endplate in bending is equal to 321.7 kN. In the graph of the Figure 12, this component, in test FE1 reaches the yielding strain for a bending moment of, approximately, 45 kN.m. For this bending moment level, the tension load in the first bolt row, evaluated in agreement with the strain gages located in the beam flange, it is equal to 333.4 kN. However, for the test FE5, due to the contribution of the applied axial force, the endplate reached the yield strain for a higher level of applied moment. In Figure 13 the moment vs. displacements curves for this component are presented.
Analysing the curves presented in Figure 14, it is clearly noticed that the beam flange also reaches yielding. According to Eurocode 3, the beam flange in compression resistance is 529.3 kN. For this bending moment level, the average of the measured strains in the inferior beam flange was 2300 µε, that it, is equal to a force of 570.0 kN, higher than the 529.3 kN presented above, fact that can be explained through the hardening of the steel. However, it is worthwhile to point out that for the first test, where the compression axial force was not applied to the beam, beam flange yielding occurred for a larger value of bending moment than in the other tests.
As it can be seen in Figure 15 the column web in compression component did not reach yielding for any of the tests.

![Figure 15 - Moment vs. displacements curves for column web in compression component](image1)

The column web in shear component reached yielding for all tests, Figure 16. This graph was obtained through a rosette positioned in the centre of the column web panel where the used component was the $\varepsilon_{45^\circ}$.

![Figure 16 - Moment vs. strain curves for column web in shear component](image2)
4. ANALYSIS OF EXPERIMENTAL RESULTS FOR EXTENDED ENDPLATE JOINTS

4.1. Moment vs. Rotation Curves and Application of the Axial Force

The moment vs. rotation curves of the seven tests are presented below where it may be observed that even for a level of equivalent axial force of -10% of the beam plastic resistance, the bending moment is still higher than the Eurocode 3. This is due to the fact that the components in tension for the two bolt rows are alleviated by the compression axial force and the components in compression, even increased, don't reach the strength, even in presence of the axial force, Figure 17. The results of test EE6 (applied axial force of + 10% of the beam plastic resistance) show that the bending moment was reduced by 10%. In Figure 18 some deformations that occurred in these tests may be observed.

![Figure 17 – Moment vs. rotation curves](image1.png)

![Figure 18 – Column flange, beam flange and endplate deformations](image2.png)
5. DATABASE REPORTING

Currently, all tests performed at the University of Coimbra are organised in EXCEL sheets with the general organisation of Figure 19.


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Figure 19 – DATABASE information
The detailed organisation of the information is as follows:

(i) \textbf{Geometrical and Mechanical Properties.xls} - This file described data for the complete experimental program (15 tests) in the following way:

(i.1) \textbf{FLUSH ENDPLATE TESTS} - These worksheets include nominal values and all measured quantities

(i.1.a) Geometrical Properties
- End-plate and beam \(\text{[Figure 20]}\)
- Column

(i.1.b) Mechanical Properties

(i.1.c) Joint details

(i.1.d) Test arrangement

(i.1.e) Instrumentation - This worksheet identifies the relevant positions within the test arrangement

(i.2) \textbf{EXTENDED ENDPLATE TESTS} * - These worksheets include nominal values and all measured quantities

(i.2.a) Geometrical Properties
- End-plate and beam \(\text{[Figure 20]}\)
- Column

(i.2.b) Mechanical Properties

(i.2.c) Joint details

(i.2.d) Test arrangement

(i.2.e) Instrumentation - This worksheet identifies the relevant positions within the test arrangement

(ii) \textbf{FE1.xls to FE9.xls and EE1.xls to EE7.xls} ** - These files, all sharing the same structure, contain all the results for each individual test, organised in the following way:

(ii.1) \textbf{DATALOGGER READINGS} - This worksheet contains all readings from datalogger, for the various channels already identified in file (i) Geometrical and Mechanical Properties.xls

(ii.2) \textbf{INDIVIDUAL GRAPHS (CE… to CE…)} - These worksheets contain graphical information for each channel, plotted against load increments

* Incomplete
** Not all available at this stage
The experimental results obtained to the moment for beam-to-column connections with flush endplate allow the elaboration of a moment vs. axial force interaction curve corresponding to the elastic resistance of the connection, just as it illustrates [Figure 21].

From the analysis of the Table 3 that illustrates the resistance and elastic stiffness of the all components of the connection in study, calculated in agreement with Eurocode 3, it is possible to conclude that, for this connection, the tension zone presents a resistance of the critical component that is equal at 63% of the component of the compression zone. Thus, the compression axial force results in an increase of the bending moment resistance of the connection, as it is verified. The results evidence the need to prepare specific clauses for the design of connections subjected to axial forces and bending moment.
7. REFERENCES


Figure 21 – M-N interaction diagram for flush endplate joints