

FULL SCALE TESTS ON BOLTED BEAM-TO-BEAM END-PLATE CONNECTIONS UNDER BENDING

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Abstract

The paper presents the details and results of an experimental study on bolted end-plate joints of industrial type steel buildings. The investigated types of joint are common used by Lindab-ASTRON-Butler Co. and these are optimized from the manufacturing, erection and durability point of view.

The aim of the research was to provide with an experimental background of design model development by measuring the load bearing capacity of the joints, determining the bolt force distribution, and the end-plate deformations. Because of the special joint arrangement the Eurocode 3 component model was improved to complete the design resistance calculation.

In the experimental programme 18 full scale specimens were studied and covered eight different end-plate and bolt arrangements with different end-plate thicknesses. The specimens were investigated under pure bending conditions, applying a four-point-bending arrangement, in which the test specimens were changed.

During the tests the typical global and relative displacements were measured by inductive transducers under the loads and in the cross-section of the tested joint. The evolved bolt force distribution was measured during the test by load cells. The end-plate deformations were determined during and after the tests by specially developed methods. The experimental data were presented and evaluated by the following diagrams: moment-bolt-row force diagrams, moment-deflection diagrams furthermore by the deformed end-plate contour-lines and surfaces.

On the basis of the evaluated test results the ultimate behaviour and the failure modes were determined and classified.

In parallel with the tests analytical simulation was completed and the developed Eurocode 3 based design method compared and verified by the experimental results.



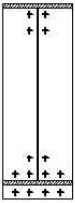

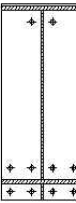
Keywords: Bolted end-plate joint, Beam-to-beam connection, Full-scale test, End-plate deformation

1. Introduction

The purpose of the research was to perform experimental and analytical studies on different bolted, end-plate joint arrangements. The tested joint arrangements are used in the industry and, because of the innovative arrangements, in some aspects there are uncertainties in their behaviour which are not supported by standardized design rule. The investigated joint types are shown in Table 1.

The research concentrated first on the physical phenomena and resulted in practically applicable design information. In the research strategy interacting experimental, analytical and numerical tools were used.

Table 1. Details of the investigated joints

				
<p>a.) standard joint arrangement</p>	<p>b.) HammerHead joint arrangement</p>	<p>c.) joint with four bolts in one row</p>	<p>d.) HammerHead joint arrangement and joint with four bolts in one row</p>	<p>e.) joint with four bolts in one row and an additional stiffener in the first bolt-row</p>
<p>The joint can be designed, the EC3 component model method can be used, without adjustment.</p>	<p>In the extended tension zone the end-plate has two bolt-rows and an additional flange.</p>	<p>In the end-plate the bolt-rows contain four bolts in the first and second bolt-rows.</p>	<p>The design problems indicated in b.) and c.) are combined in this joint.</p>	<p>The design problem indicated in c.) and an additional stiffener in the first (extended) bolt-row.</p>

The aim of the theoretical study was to develop design methods compatible with the Eurocode 3 based component model, to calculate the failure mode and the load bearing capacity of the tested joints [1], [2]. The developed methods were validated by the experimentally determined behaviour modes and load bearing capacities of the joints.

2. Research programme

2.1 Test specimens

In the experimental programme 18 full scale specimens were studied and covered eight different end-plate and bolt arrangements with different end-plate thicknesses. The investigated types of joint are common used by Lindab-ASTRON-Butler Co. and are optimized from the manufacturing, erection and durability point of view.

Table 2. Test specimens in series I





end-plate arrangement												
end-plate type	I			II			III			IV		
test specimen	TB2	TB6	TB10	TB3	TB7	TB11	TB4	TB8	TB12	TB5	TB9	TB13
end-plate thickness t_{ep} [mm]	12	15	20	12	15	20	12	15	20	12	15	20

Table 2 and Table 3 show a summary of the test specimens with their bolt arrangements, end-plate type and end-plate thickness.

Table 3. Test specimens in series II

end-plate arrangement							
test specimen	TA	TB	TC	TD	TE	TF	
end-plate thickness t_{ep} [mm]	16	20	20	16	20	24	

Figure 1 gives the short explanation of the so called HammerHead arrangement. This is an additional short web and flange, which are extended on the tension side of the girder.

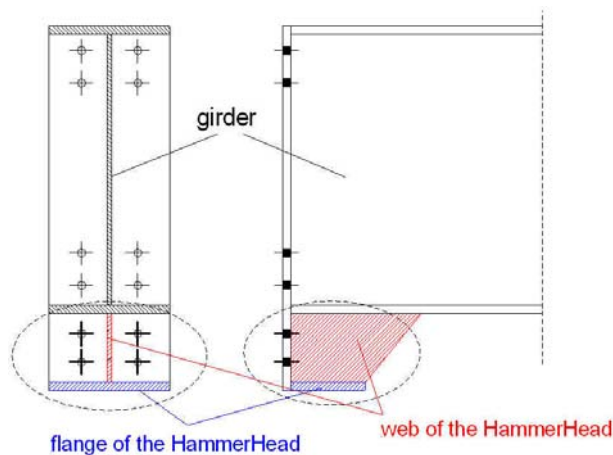


Figure 1: The HammerHead arrangement.

2.2 Test arrangement

The specimens were investigated under pure bending conditions, applying a four-point-bending arrangement, in which the test specimens were changed. The specimens were erected between so called fixed girders as shown in Fig. 2. These supporting beams served the economy of the fabrication of the specimens. The two concentrated loads were applied by hydraulic jacks with capacities of 400 kN.

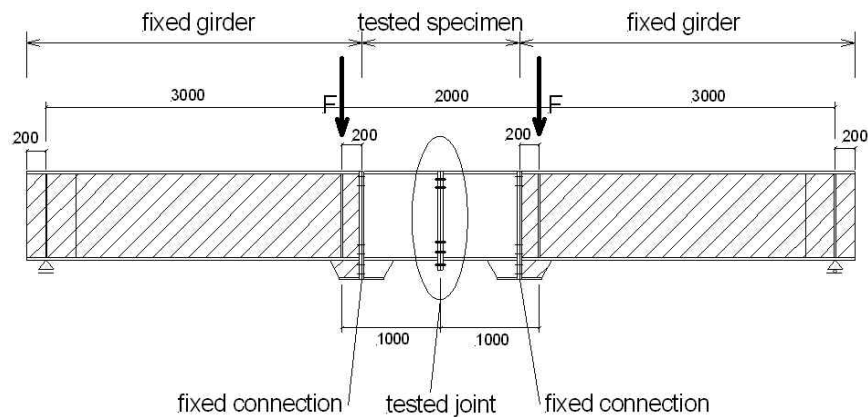


Figure 2: The test arrangement.

Because of this load configuration the tested part, including the investigated joint, was loaded under pure bending. To prevent lateral buckling of the beam, both flanges were restrained close to the load introduction point.

2.3 Measuring system

2.3.1 Measuring of displacements and bolt forces

During the tests representative displacements were measured by inductive transducers placed under the loads and in the cross-section of the investigated joint. The distribution of the bolt forces was registered by load cells, developed for this purpose. The measured data were collected in each second, by two HBM Spider (Hottinger Baldwin Messtechnik) data collection systems. Figure 3 shows schematically the locations of the transducers and the load cells.

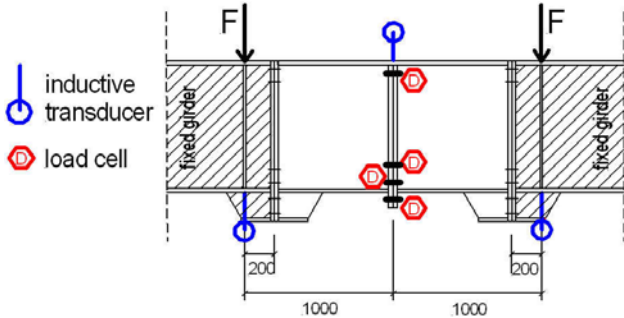
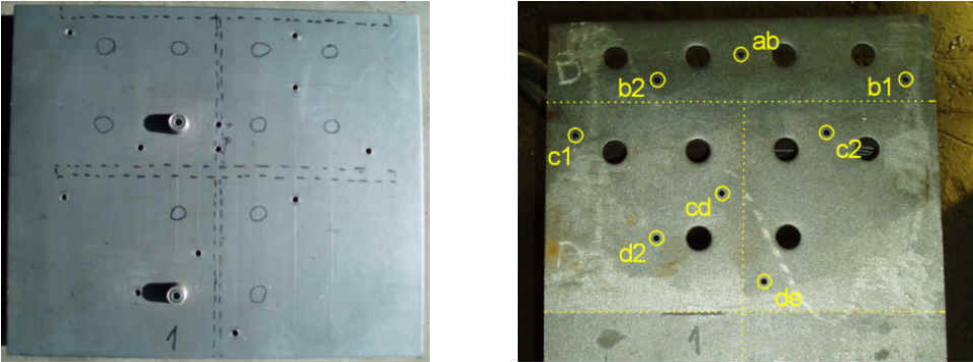


Figure 3: Locations of transducers and load cells.

2.3.2 End-plate deformation measurement in the elastic phase of the test

The purpose of measuring the end-plate deformations in the elastic phase was to analyze the load vs. deformation relationship and to find out how plate deformations develop up until the ultimate limit state. Note that the surface deformation of the end-plates can hardly be measured during the tests; in the previous research this measurement is usually focused only on the edges of the end-plates.

In the completed tests, in the elastic phase of joint behaviour, the end-plate deformations were measured by portable inductive transducer. The measuring points - drilled holes in the plate - were placed so as to give representative points of the expected deformation but at the same time not to disturb the development of yield lines or the load bearing capacity of the joint. Therefore, on the one hand, an appropriate number of measuring points needed to be defined so as to achieve an adequate accuracy of the deformation values determined, while on the other hand, one needed to be careful not to place too many such points so as not to disturb the yield line pattern to develop.



a.) the pattern tool applied b.) the prepared end-plate of test specimen TBS

Figure 4: Pattern tool and prepared specimen.

For this reason half of the measuring points were placed in one end plate, and the other half in the other plate, following a pattern symmetrical to the web. Figure 4 a.) shows the fabricated pattern tool, which contained the holes, and which was then applied in both end-plates making use of the symmetry of the bolt arrangement with respect to the web. For the exact positioning the tool to the end-plates two positioning bars were used, as shown in Fig. 4 a.). Figure 4 b.) presents an example of an end-plate as prepared for the test.

2.3.3 End-plate deformation measurement after the test

Special equipment was developed to measure the deformation of the end-plates after the test, as shown in Fig. 5.



a.) specimens with the testing bar b.) measuring wheel with inductive transducer

Figure 5: Measuring the plastic deformation of the end-plate.

After the test the plastic end-plate deformations were measured by an automatically running and sensing device and the benchmark data are collected in the web direction in each 0.25 mm at the 0.001 mm accuracy. The zero altitude level was chosen for all end-plates at the intersection of the web and the compression flange, as shown in Fig. 6. On each end-plate the deformations were collected as illustrated in the figure.

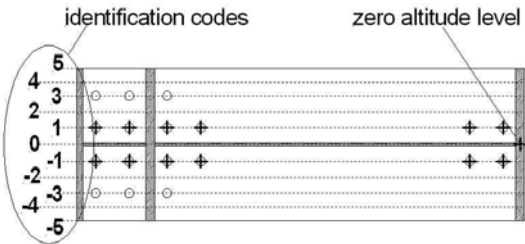


Figure 6: End-plate deformation measurement lines.

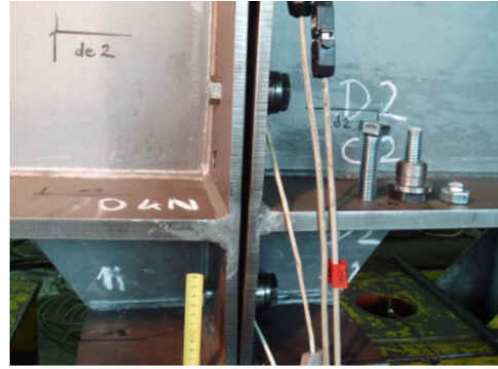
3. Test results

The data collected during the tests were prepared and presented by the following diagrams: moment-bolt-row force diagrams, moment-deflection diagrams furthermore figures of the deformed end-plate surfaces. In the followings the results are shown for a typical joint.

Figures 7 a.) and b.) illustrate the selected test specimen TB2 before the test and the deformed tension zone after the test, respectively. The observed ultimate behaviour of the joint was dominant plate failure. The plate deformations, especially those close to the tension bolts, are shown in Fig. 7 b.).



a.) specimen TB2 before test



b.) the tension zone after failure

Figure 7: Specimen TB2 - arrangement and failure mode.

The moment vs. bolt-row force diagrams show the relationship of the measured force in the bolt-rows and the moment in the tested joint. Figure 8 illustrates, as an example, the moment and bolt-row force relationships of test TB2.

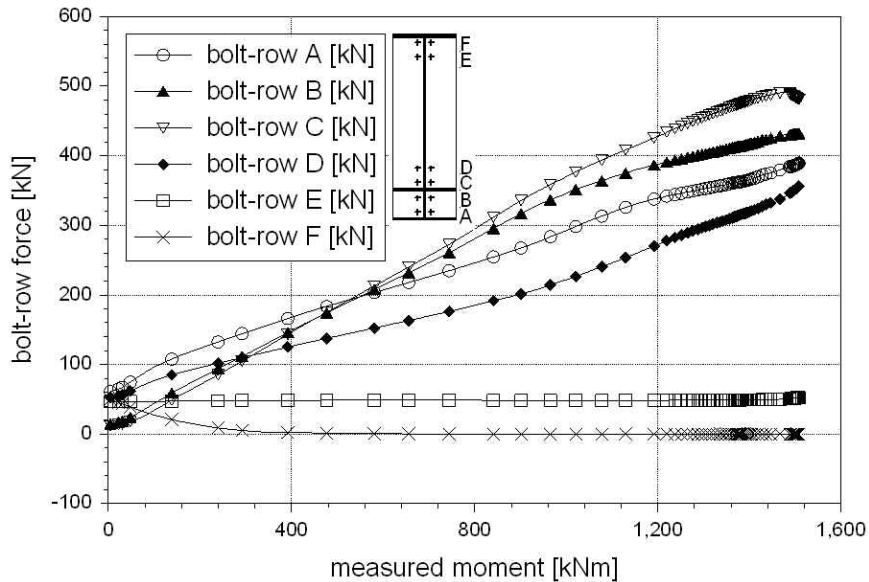


Figure 8: Moment vs. bolt-row force diagrams of specimen TB2.

Because of previous load steps and different pre-tensioning levels of the bolts, the presented bolt-force curves have different starting points. For reasons of clarity, in each diagram of the measured bolt forces presents the force for the whole bolt-row.

The moment vs. bolt-row force diagrams show how changes the force increment in the bolt-rows and in which part of the joint i.e. in which bolt-row accumulate higher forces. The diagrams show in the given case of specimen TB2, that the highest force increment in bolt-row C, below the members tension flange, was obtained. Which phenomenon was explained by the non-homogenous stiffness distribution of the end-plate.

The end-plate deformations of specimen TB2 in the elastic phase are shown in Figs. 9 a.) and b.), while the plastic deformations can be seen in Fig. 9 c.).

The Eurocode 3 standard gives calculation methods to determine the end-plate deformations, i.e. the yield line pattern, in the ultimate limit state, but it does not inform about the load-deformations

equilibrium in the phases when the behaviour is still elastic. This study aims at identifying the “path” that leads from elastic to plastic deformations and finding the relationships among these deformations.

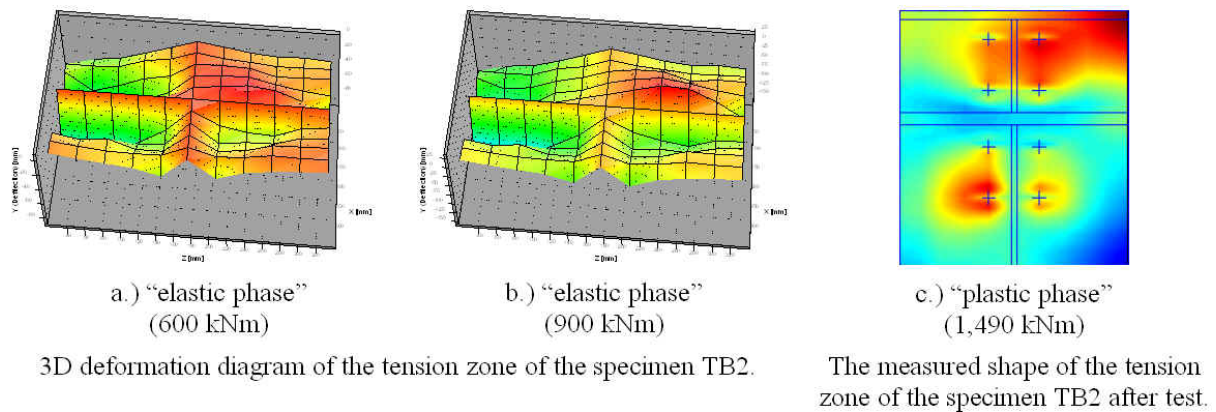


Figure 9: The end-plate deformations in elastic and in plastic phases of the specimen TB2.

The deformation diagrams presented in Figs. 9 a.) and b.) show relative deformations. The initial deformations due to the welding process and the erection were measured and taken into consideration as the reference surface for the purposes of further measurements. The surfaces presented in the diagrams above have been obtained by interpolation between the measured points.

From the measuring results, in the elastic phase, it is concluded that the 3D deformation diagrams show similar failure modes as those corresponding to the ultimate failure already at relatively low load levels that correspond to the elastic phase of joint behaviour. This shows that the governing end-plate deformations can already be identified in the phase of elastic behaviour. This observation, together with the measuring method developed could be useful for forecasting failure modes.

Figure 10 shows the results of the measurements of the deformed end-plate of specimen TB2 after test and presents the deformations by contour-lines and from the contour-lines derived deformed surface of the end-plate which was calculated by linear interpolation between the contour-lines.

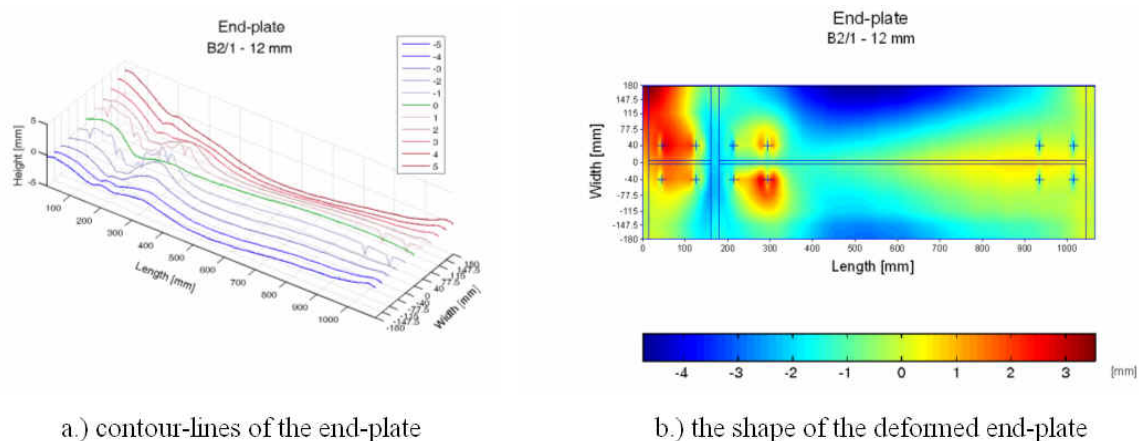


Figure 10: Evaluated results of the measurement on the deformed end-plate of specimen TB2.

In Fig. 10 it can be seen that the end-plate in height of the flange of the HammerHead arrangement deforms too, which deformations were in the moment vs. bolt-row force diagrams (Fig. 8) mirrored. And this deformation was the reason why the highest bolt-row force in bolt-row C, followed from bolt-row B, was measured.

4. Concluding remarks

In the paper an experimental study is presented on full-scale beam-to-beam end-plate joints. Despite these type of joints were widely studied in previous research and standardized methods exist for the design, the investigated novel joints have such specialities which cannot be handled on the basis of existing results.

Essential aspect of the experimental study is the surface measurement of the end-plate deformation during and after the tests. Important finding of these measurements that in the elastic phase the governing end-plate deformations can already be identified; this observation can be used for forecasting the failure mode. The measured plastic deformation of the end-plates provide with major background for the standardized classification of the joint behaviour.

On the bases of the experimental observations practical design rules were derived using the component model of the Eurocode 3 standard. The developed design methods can be used to calculate the failure mode and the load bearing capacity of HammerHead type structural joints and four bolts in one row type end-plate joints which are out-of the scope of the standard.

The developed design method is validated by the experimental results both qualitative and quantitative sense.

The results of the research are directly applied in the ongoing software and product develop project of the company Lindab-ASTRON-Butler.

More details on the tests can be found in [3] and [4]; the developed design method is detailed in [5].

5. Acknowledgement

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6. References

- [1] EN 1993-1-1 (2004). Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings.
- [2] EN 1993-1-8 (2005). Eurocode 3: Design of steel structures - Part 1-8: Design of joints.
- [3] L. Dunai, L. Katula, L. Kaltenbach, M. Kálló, A. Tóth: Full scale tests on bolted beam-to-beam end-plate connections under bending, *Technical Report*, BME Department of Structural Engineering, Budapest, March 2006, p. 73.
- [4] L. Dunai, L. Katula, L. Kaltenbach, M. Kálló, A. Tóth: Full scale tests on typical ASTRON end-plate connections under bending, *Technical Report*, BME Department of Structural Engineering, Budapest, May 2006, p. 43.
- [5] L. Katula: Bolted end-plate joints under static and fatigue loading, *PhD Dissertation*, Budapest University of Technology and Economics, Budapest, 2007.