RESPONSE OF END-PLATE JOINTS UNDER COMBINED FORCES

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Abstract. In recent years robustness assumed an important role in structural design, as the requirement to be fulfilled to prevent progressive collapse in case of accidental actions. Despite the strategies for robustness are well identified, at the moment the state of knowledge is far from being adequate for design needs. Studies have been carried on worldwide aiming at covering this gap. The senior authors were involved in a research project focused on the joint ductility as the key element to achieve a robust response of composite steel and concrete frames. This paper presents the results of a series of tests of beam-to-column steel bolted joints. The influence on the connection response of combined internal forces, of the load history and of the stiffness of the support was investigated. The main features of F.E. numerical models are also outlined, which were developed and calibrated against the experimental results as a tool for parametric analyses.

1 INTRODUCTION

In the design process of civil and industrial buildings, the vulnerability against accidental actions has recently assumed a central role. The disasters caused by terrorist attacks, such as the collapse of the Twin Towers in 2001, have clearly pointed out the inadequacy of the traditional design approaches. They overlook the possible progressive collapse, consequent to the chain reactions activated by local damages caused by accidental actions. These critical situations call for a specific design methodology enabling verification of the safety of the structure as a whole in the statically modified condition.

The ability of a structure to withstand accidental actions without disproportionate consequences is defined as Structural Robustness. In non robust structures local damages can result in the partial or complete collapse of the structure [1], [2].

Studies of robustness started in the 60's triggered by the Ronan Point collapse in London. They allowed developing design strategies for checking robustness. Two different approaches characterised by different complexity were identified: the design against specific accidental actions and the design aimed at reducing the extent of a localised failure. The first strategy requires the design analysis of the structure against the actions associated to specific scenarios. The second strategy, which is less demanding, is based on structural design requirements to be satisfied for a minimum level of robustness to be achieved [3]. The difficulties in defining the possible design scenarios and the related loads, the complexity of the structural response and of the computational needs make difficult to transfer the general strategy into specific design rules and criteria. At this aim, a number of studies of different aspects of robustness have being carried on all around the world. The state of knowledge is actually far from being adequate for design needs.

The senior authors were involved in a research project on robustness funded by the ECSC (European Coal and Steel Community) [4]. The research, which comprises of both experimental and numerical studies, focused on the behaviour of composite steel and concrete framed structures. The experimental part of the study was designed in order to investigate the effects caused by the accidental loss of a column in a framed multi-storey office building. The reference frame was designed in accordance with the

Eurocodes. The beam-to-column steel connections were bolted flush end-plate steel connections, while the flooring system used a solid concrete slab (Figure 1). The joint ductility was assumed as the key element of the design strategy to ensuring a robust response of the structure.
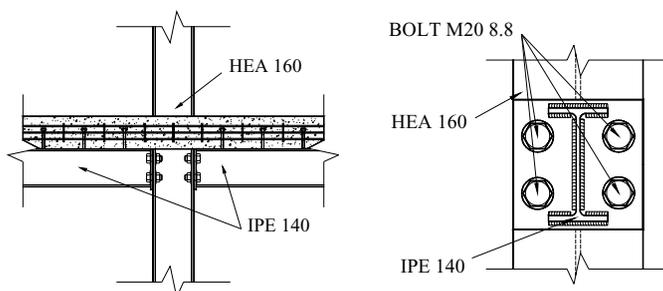

Figure 1: The investigated beam-to-column connection.

When a column is lost, a redistribution of the internal forces to the "undamaged" part of the structure occurs. This is an evolutionary phenomenon which is associated to the development of large displacements. In this context, a key role is played by the beams and the connections at the failed column. If the beams and the connections possess adequate resources in terms of resistance and ductility a catenary action can be activated allowing for the redistribution of the internal forces. Such redistribution implies the evolution of the internal forces in the beams and in the connections. At the end of the process the internal forces in the beam and the joint are substantially different from the initial ones with the axial force prevailing. Assuming the joint being the weakest component, a robust response implies that the joint possesses adequate resistance and ductility, allowing for large plastic displacements under different histories of axial force, shear force and bending moment. Fulfilment of such a requirement enables occurrence of the redistribution of the internal forces needed to reach the new equilibrium condition.

The experimental study was designed in order to investigate the behaviour of the structure at different levels. A 2-D full scale test on a sub-structure was complemented with tests on composite beam-to-column joint sub-assemblages, focused on the local performance of the joints under bending and axial force. In accordance with the philosophy of the component method, the research group of the University of Trento investigated the behaviour of the joints components in the field of large displacements when significant tensile forces build up in the floor system. The performance of both the concrete slab and the steel joint was investigated. The steel joint was analysed both at the full joint level and at the joint component level.

The tests on the joint were carried out on the full steel connection (beam and end-plate) on rigid support and on the complete steel joint (including beam and column stubs), so allowing investigation of the influence of the column's deformation on the connection response. The tests at the joint component level focus on the response of the tensile zone, which is the main source of joint deformability.

The evolution of internal actions experienced by the beam and the joint in case of the loss of a column is fairly complex, and difficult to be simulated when considering the connection in isolation. However, some interesting information on the response of the steel joint subject to combined forces (N, V, and M) can be obtained simulating a simpler load history. Therefore, tests were performed under different combination of N, V and M. Experimental results were used to develop and validate F.E. numerical models.

This paper reports the main results of the experimental study carried out on the full steel connection and joint. The key features of the numerical model are also outlined.

2 THE EXPERIMENTAL STUDY

In framed structures the joints can play a fundamental role in ensuring a robust response. The redistribution of the internal forces and hence the activation of alternative load paths when local damage occurs requires an "adaptive capacity" of the joints to all the intermediate equilibrium configurations and up to the new and final one. The "robust design" of the joints requires checking the joint capacity to withstand the different combinations of internal actions and to sustain large displacements. The complexity of the load history and its dynamic nature further complicates joint design.

The experimental study investigated the joint performance when subject to load histories combining axial force (N), shear force (V) and bending moment (M). The loading history considered in the tests simulates in a simplified way the one a beam-to-column joint would experience in the case of sudden collapse of a column.

The specimens comprised of a beam stub made of a section IPE 140 of nominal length 950mm and a flush endplate steel connection of thickness 8mm. The end-plate was connected to two different 'supports' by means of four bolts M20 class 8.8 preloaded with a torque moment of 350Nm. The supports were either a rigid support or a column stub (HEB 160) with a length of 1000mm. This allowed investigating the influence of the column deformation on the joint response. The latter configuration will be referred to as the 'complete joint'.

For both test configurations the load was applied to the free end of the beam with an initial inclination angle (β) (Figure 2a). The nominal values of β were 0°, 11°, 20°. As soon as the load increases, a rotation of the beam occurs leading to a progressive alignment between the actuator and the beam. At collapse, it was expected the complete beam-actuator alignment if compatible with the deformation capacity of the connection/joint (Figure 2b). In this way tests under pure tension, $\beta = 0°$, and under different combinations of N, V and M were performed.
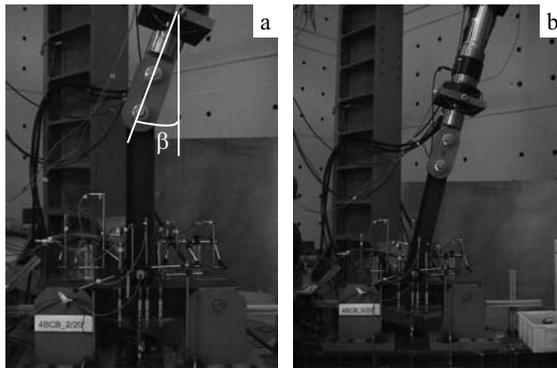

Figure 2: Test configuration for the complete joint.

A typical load history in terms of internal forces applied to the connection is plotted in Figure 3. The applied force's components (axial and shear forces) were computed with respect to the longitudinal axis of the beam in the deformed position; i.e., the force applied by the actuator was projected along the normal and the parallel directions with respect to the longitudinal beam axis. To this aim the inclination angles were measured by clinometers located on the beam web and on the actuator. The displacements of the flange at different points and of the bolts were also recorded. In the tests on the complete joint also the column deformation was measured.

In all the tests the load was applied by a hydraulic actuator in displacement control. The load history comprises of a pre-loading cycle followed by the application of the displacement at a speed of 0.015mm/s up to the collapse of the specimen.

Tables 1 and 2 provide the values of the load and of the internal forces applied to the connection at collapse. They are related to the connection on rigid support and to the complete joint, respectively. The results show that at collapse a 'substantial' alignment between the beam and the actuator was achieved only in the case of full connection with an initial inclination angle of 11°. In the remaining tests a non negligible bending moment was still acting on the connection at failure.
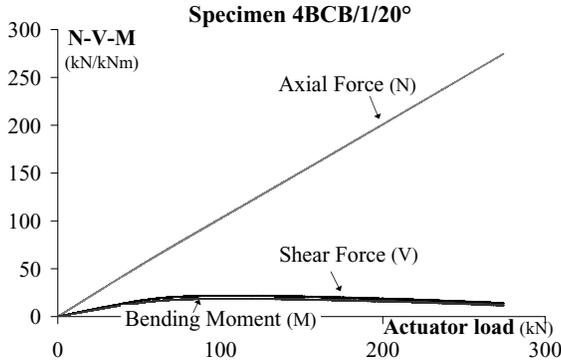

Figure 3: Internal forces at the connection vs. applied load.

Table 1: Internal forces and applied load at collapse: full connection on rigid support.

Specimen	Actuator initial angle Deg	Maximum load kN	Axial component kN	Shear component kN	Bending moment kNm
4BA/2	0°	533.840	533.840	0	0
4BB/3/11°	11°.10	453.480	453.480	-0.633	-0.537
4BB/4/11°	10°.98	441.560	441.556	1.950	1.658
4BB/1/20°	19°.51	293.640	293.299	14.139	11.998
4BB/2/20°	19°.34	307.960	307.823	9.168	7.782

Table 2: Internal forces and applied load at collapse: complete joint.

Specimen	Actuator initial angle deg	Maximum load kN	Axial component kN	Shear component kN	Bending moment kNm
4BCA/1	0°	375.520	375.520	0	0
4BCA/2	0°	382.160	382.160	0	0
4BCB/3/11°	11°.70	372.640	372.627	3.141	2.665
4BCB/4/11°	12°	383.520	383.418	8.828	7.496
4BCB/1/20°	20°	274.680	274.354	13.385	11.462
4BCB/2/20°	19°	319.880	319.831	5.583	4.745

As to the load ultimate capacity, the results in tables 1 and 2 indicate that:
- full connection on rigid support (Table 1): the connection's "loading" history affects remarkably the connection response, and the ultimate axial load capacity is significantly reduced with respect to the pure tensile condition: such a decrease is of 16% for an initial inclination angle of approximately 11°, and of 44% for an inclination angle of 20°;
- complete joint (Table 2): it appears that a moderate initial inclination of the applied load seems not to affect the joint response and performance. When the initial inclination angle increases, the influence of the joint's "loading" history becomes more important;

- the type of support (rigid support vs. column, Table 1 vs. Table 2) remarkably affects the joint response and strength in case of tension tests and of moderate initial inclination angle. Assuming as a reference the case of connection on rigid support, the collapse load of the full joint reduces of an average of 29% and 16% in case of tension test and for an initial inclination angle of 11°, respectively.

A first appraisal of the severity of the load history applied to the connection/joint can be achieved by comparing the maximum value of the internal forces N, V and M developed in the tests to the plastic resistance of the beam V_{pl}, N_{pl}, M_{pl}. Test results showed maximum values of the ratios V/V_{pl}, N/N_{pl} and M/M_{pl} of 0.126, 0.623 and 0.609, respectively, in the case of the connection on rigid support and of 0.114, 0.527 and 0.553, respectively, in the case of the complete joint. These data indicate that tests were carried out under a 'prevailing' combination of axial force and bending moment, i.e, under loading condition similar to that developing in case of the collapse of a column. A further appraisal of the 'severity' of the loading history can be achieved by comparing the maximum bending moment applied in tests (M_{max}) with the ultimate bending moment of the joint (M_u). This one was evaluated in accordance with the simplified and conservative procedure proposed by the Eurocode 3 [5]. Tests results showed ratios M_{max}/M_u in the range 0.855-1.185 in the case of tests on rigid support, and 0.814-1.076 in the case of the tests on the complete joint. The figures greater than one may be justified by the conservativeness of the Eurocode 3 approach [5]. However, the results point out that the connection/joint in all tests was stressed under combined action at level close to its ultimate resistance.

The experimental response in all the tests was characterized by a remarkable inelastic deformation of the end-plate (Fig. 4a). Significant plastic deformation also occurred in the column flange in case of tests on the complete joints (Fig. 4b). Such inelastic deformation capacity has a key role in making the load alignment possible. A first appraisal of the joint deformation capacity as influenced by the load condition and history can be obtained by considering the average deformation of the joint zone at the maximum load. At this aim, the attention was focused on the displacement evaluated in correspondence of the axis of the beam (i.e., the geometrical centre of the connection), which are summarized in Table 3. In the case of the connection on rigid support the displacements are related to the sole end-plate, while for the complete joint the displacements take into account the contribution of both the end-plate and the column flange and web.

Table 3: Displacement in correspondence of the axis of the beam at the maximum load.

Connection on rigid support		Complete joint			
Specimen	Displacements mm	Specimen	Displacements		
			end-plate mm	web of the column mm	Total mm
-	-	4BCA/1	NA	NA	22.875
4BA/2	24.503	4BCA/2	14.225	8.880	23.105
4BB/3/11°	18.930	4BCB/3/11°	19.666	9.946	29.612
4BB/4/11°	16.419	4BCB/4/11°	19.986	9.009	28.995
4BB/1/20°	14.044	4BCB/1/20°	15.504	8.971	24.475
4BB/2/20°	15.257	4BCB/2/20°	15.895	7.074	22.969

NA: not available

In case of rigid support, the results indicate a substantial reduction of the end-plate deformation at collapse due to the presence of combined forces: the deformation capacity is reduced up to 40% for an initial inclination angle of 20°. In the case of the complete joint, it can be noted the non negligible contribution of the column to the total deformation of the joint, which represents on average the 34%. In addition, it can be observed the negligible influence of the load condition and history on the deformation of the column. The influence of the support condition can be appraised by comparing the displacement at failure of the connection and of the complete joint: in the cases of inclination angle of 11° and 20° the displacement of the complete joint is on average greater of about 65% and 62%, with respect to the case of rigid support. This is due, as expected, to the contribution of the column deformation. In the case of

the tensile tests, the deformation is almost the same. These results should be analysed in conjunction with the maximum load reached in the tests (Table 1 and 2): the greater deformations showed by the complete joint are associated to lower collapse loads if compared with the corresponding connection on rigid support. In the case of tensile tests similar deformations are attained for a collapse load which differs of 30% on average.

Bolts were always subjected to significant bending and in all the tests the collapse was associated with the failure of the bolts (Fig. 4a-4b). However, for the specimens tested under a combination of axial and shear force cracks initiated just before failure at the toe of the weld between the beam stub and the end-plate in the more stressed zone in tension (Fig. 4c). The type of deformations observed, in the complete joints, for the end-plate and the column flange tends to increase such a bending, leading to a decrease, with respect to the connection tests on rigid support, of the ultimate loading capacity. This reduction is significant in particular for the case of pure tension. The influence of the bending of the bolts is neglected in the T-stub models usually adopted in design. The results seem hence to point out the need for deeper understanding of this issue.

Figure 4: Deformation at collapse.

A contribution to the analysis of the 'collapse' mechanisms comes from the deformed shape of the connection at collapse. At this aim, the deformed shapes of the end-plate and of the column flange were obtained by means of a laser scanner. In order to investigate the potential collapse mechanism the data were analysed with the program Surfer [6]. In order to identify the regions of the plate characterised by strain concentration, the maximum local slope of the displacements' were computed (i.e., the 'yield lines'). The figures 5 and 6 show the slope contour maps of the end-plate associated with the tests on rigid support and on the complete joint. The figures 5a and 6a are associated to the tension tests, while the figures 5b-6b and 5c-6c are associated to tests with initial inclination angle of 11° and 20°, respectively.
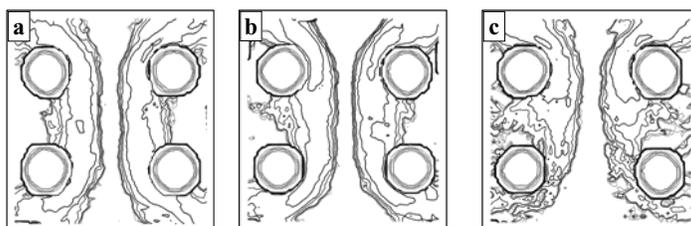

Figure 5: Slope contour map of the end-plate: connection on rigid support.

The slope contour lines identify in general a mechanism of collapse which involves two yield lines: one at the end plate-to-beam weld and a second 'connecting' the bolts. In no case, the mechanism does appear completely developed. In case of tests under combined actions the collapse mechanism still involves the bolts' area. However, the contour lines are less pronounced and get closer around the "compressed" bolt. In addition, contour lines appear in between the bolts. This effect becomes more

evident in case of tests with an initial inclination angle of 20° (Fig. 5c and 6c). Besides, the mechanism of collapse indicated by the slope contour lines show spreading of plasticity also in between the bolts.
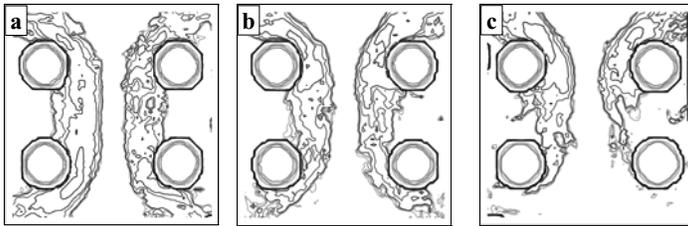

Figure 6: Slope contour map of the end-plate: complete joint.

3   THE NUMERICAL MODEL

In order to investigate in depth the complex behaviour of the connection F.E. models were developed and calibrated against the experimental results. At this aim the program ABAQUS ver. 6.8-1 [7] was adopted. The different support conditions (i.e, rigid support and column) and the different loading condition (i.e., tension tests and combined action) required the development of six F.E. models. The complexity of the models in terms of geometry and number of elements and the results of preliminary analyses suggested the use of brick linear elements type C3DR8 with reduced integration. The built up of the meshes was manually controlled allowing its refinement in correspondence of the zones of stress concentration, (i.e., the connection/joint, the bolts, the welds). The dimensions of the F.E. elements range between a minimum of 1mm, which is adopted in the connection area, to a maximum of 20mm, for the less stressed zones. The meshes comprise a minimum number of nodes of 98000 for the case of tensile tests on rigid support and a maximum of 229000 nodes in the case of the complete joints under combined action.

In order to reproduce the load history applied during the tests under combined action, for both the support conditions, the F.E. models comprise also of the actuator which was modelled as a rigid element.

Particular attention was devoted to model the contacts between the surfaces, such as the contacts between the end-plate and the support, between the bolt and the support, the nut and the washer. At this aim, a Coulomb like formulation was adopted in the form of 'finite sliding' which allows the sliding and the separation between the surfaces. The material properties were implements as true stress-true strain relationships evaluated on the basis of the results of 'ad hoc' tensile tests. The load is applied as a uniform pressure applied to the end of the beam for the case of tension tests and to the end of the rigid element which reproduce the actuator in the case of tests under combined action. Second order non linear analyses in large displacements were carried out. The load history comprised of two phases: in the first the bolts are preloaded, and in the following one the load is increased up to the collapse of the specimen. Unload to zero is then simulated so as to identify the residual plastic deformations.

For all the considered cases, the comparison between experimental and numerical results in terms of collapse load, displacements of the end-plate and of the column and residual plastic deformation shows a general good agreement. An example is shown in figure 7 which compares the slope contour maps for a complete joint with an initial inclination angle of 20° (test 4bcb/2/20°). The outcomes of the numerical analysis are on the left, while the experimental ones are on the right. The comparison proposed in figure 7 shows the good agreement of the results and points out the ability of the F.E. model in catching also the spread of plasticity in both the column flange and the end-plate.

The F.E. numerical models provide hence a useful tool for further studies of the effect of joint geometry, of mechanical properties of the steel as well as of the loading history. Preliminary analyses devoted to the investigation of the influence of the load history have been already performed. The results are at the moment under evaluation.
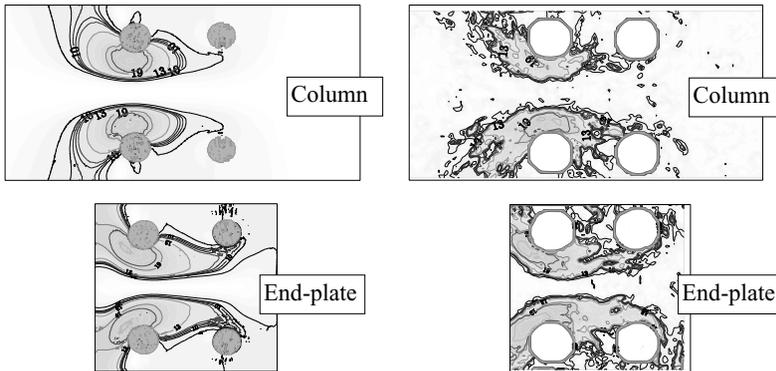
Figure 7: Slope contour lines for test on the complete joint with inclination angle of 20°.

4   CONCLUDING REMARKS

The paper presents and discusses the results of the experimental study of the performance of end-plate connections under combined forces. The tests were carried out on the sole connection on a rigid support and the complete joint, incorporating the column

Both series of tests confirmed the potential ductility of end-plate joints. However, the tests pointed out the negative influence of a loading history which combines shear, moment and axial force on both the ultimate load and deformation capacities. Besides, the importance of bolt bending is underlined. The main features of F.E. models calibrated against the experimental results were also presented. These models will provide a useful tool for extending the related knowledge via a parametric study of the effect of different geometries and mechanical properties as well as of the loading process.

ACKNOWLEDGEMENT

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