The Effect of Axial Force on the Behavior of Flush End-Plate Moment Connections

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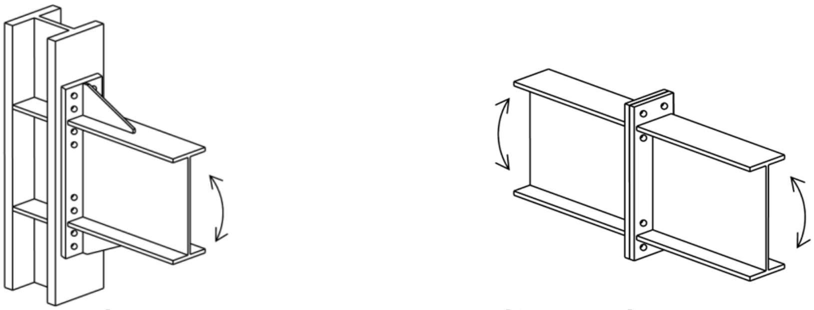
SUMMARY:
An approach, based on finite element modelling, is presented in order to numerically investigate the seismic performance of bolted steel flush end-plate moment connection by including the effect of axial forces in the connection. The methods for applying loads to the connection were considered to be only monotonic loadings. For the nonlinear finite element analysis the modelling process was carried out using general purpose computer program. The results of the finite element analysis of the connection showed that by applying the tensile axial load of the beam into the connection the ultimate bending capacity of the connection will decrease. On the other hand, by applying compressive axial load of the beam to the connection, the ultimate bending capacity of the connection will increase at first; but after the buckling of the compressive flange of the beam takes place, the total capacity of the connection tends to decrease.

Keywords: End-Plate Moment Connection, Flush End-Plate, Nonlinear Finite Element

1. INTRODUCTION

Bolted steel connections, such as T-stubs and end-plate connections, can be visualized as assemblages of components (plates, bolts and welds). Because of the large variety of connection configurations possible, many geometrical discontinuities and associated stress concentrations present in bolted connections. Also presence of frictional forces that lead to nonlinear phenomena such as slip and the need to model uplift and contact forces that lead to prying action, then these connections exhibit an overall nonlinear structural behavior commonly classified as “semi-rigid”.

Bolted end-plate connections are extensively used for connecting beams to columns or beams to beams in multi-storey steel frame buildings. These connections are divided into two categories: flush end-plate and extended end-plate. The typical uses of end-plate moment connections are illustrated in Fig. 1.1. There are two major types of end-plate connections: flush, as shown in Fig. 1.2. and extended, as shown in Fig. 1.3.



(a) Beam to column connection (b) Beam splice connection

Figure 1.1. Typical uses for end-plate moment connections

(a) Unstiffened (b) Stiffened

Figure 1.2. Flush end-plate connections

(a) Unstiffened (b) Stiffened

Figure 1.3. Extended end-plate connections

The most important structural properties of the joints that should be known prior to the analysis of frame structure and the design of its members are the moment resistance, rotational stiffness and rotation capacity. Eurocode 3 (1998) contains design rules for determining the properties of several types of connections including the bolted flush end-plate. Beam to column joints are mostly subjected to bending forces and in some instances they are subjected to combination of bending as well as axial forces. Although in many ordinary building frames the level of axial force reaching the beam and/or slab is usually low, however it can reach considerable values in many instances; such as: regular frames subjected to significant horizontal lateral loading (seismic or extreme wind) especially for sway frames, irregular frames under gravity or horizontal loading especially with incomplete floors and pitched-roof portal frames. Besides the number of influencing parameters affecting the overall behavior, the prying forces developed at the interface of column flange and end-plate intensifies the problem of understanding the behavior. The application of the axial force in the end-plate moment connection along with the existence of the bending moment due to gravity loads as well as lateral loads can result in altering the overall behavior of the entire connection. Finite element method of analysis is an ideal tool to look into such a complicated problem.

In recent years, numbers of research program have been conducted to study the prediction of the behavior of beam to column joints under bending only and without axial force. Kukreti *et al*. (1990), Bahaari and Sherbourne (1994), Bose *et al.* (1997) and Abolmaali *et al.* (*2*005) have employed finite element method to analyse end-plate joints subjected to monotonic loading. Broderick *et al.* (2002) investigated the response of flush end-plate joints under earthquake loading. da Silva *et al.* (2004) have proposed analytical expressions for the full non-linear response of a beam to column joint under combined bending and axial force. Shi *et al.* (1996) developed a tee-stub model based on beam and yield line theory for flush and extended end-plate joints. de Lima *et al.* (2004) experimentally investigated the behavior of extended end-plate beam to column joints subjected to bending and axial force. The results show that the presence of an axial force on the connection significantly modifies the joint response. Fanning *et al.* (2000) presented an ANSYS finite element model for flush end-plate joints. In this paper, the effect of axial forces on the behavior of end-plate moment connection is investigated using the ABAQUS computer program. All the nonlinear properties such as material, contact, large deformation and buckling are included in the FE model. To evaluate the accuracy of FE models for end-plate bolted connections, the numerical results are compared with experimental results were tested by da Silva *et al.* (2004). The failure mode of different components of the connection is investigated.

2. FINITE ELEMENT MODELLING

2.1. Type of elements, contact, boundary condition and loading process

The modelling is investigated with finite element ABAQUS computer program. For finite element modelling, three-dimensional solid elements have been employed to model end-plate, beam, column and the bolts. This element is an eight-node element with three translational degrees of freedom at each node (C3D8). Between the end-plate and column surface as well as the surface between the bolts surfaces with end-plate and column, contact elements are utilized with friction coefficient of 0.3. The nodes near the support located at the top and bottom section of column are restrained in all directions. The analyses is consist of 3 steps: bolts are pretentioned first with temperature so as to produce the pretentional stress of 550 Mpa in each bolt, then the axial loading applied as a tensile or compression load and finally the lateral loading is applied as a displacement type loading to the beam tip. General views of the mesh pattern for the connection detail as well as the entire bolt used in the modelling configuration are shown in Fig. 2.1.

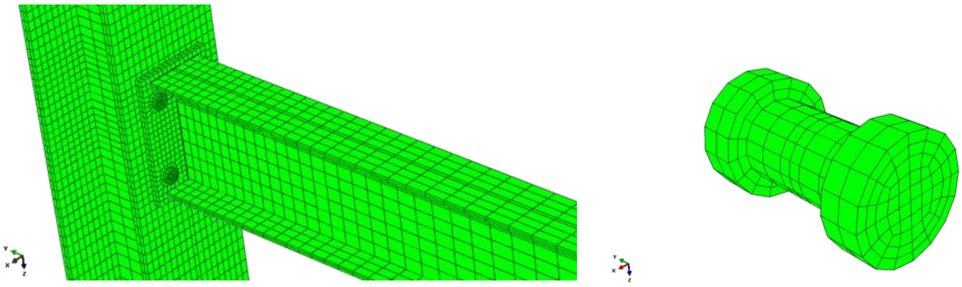
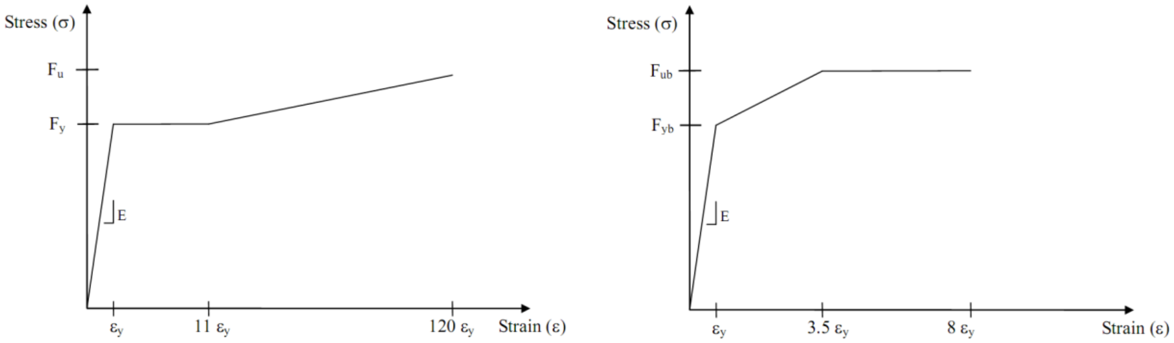


Figure 2.1. Mesh pattern of the finite element modelling

2.2. Nonlinear material properties

Steel is a ductile material that exhibits nonlinear material properties caused by plastic yielding and strain hardening. This behavior of steel has been imposed to the model by introducing two different stress-strain diagrams for beam, column and end-plate materials and bolt material. The stress-strain relationship for all connection components is represented using a multi-linear constitutive model in Fig. 2.2.



Stress-strain diagram for steel beam, column and end-plate

Stress-strain diagram for bolts

Figure 2.2. Stress-strain diagram for components

2.3. Test cases chosen for calibration of the numerical model

Several specimens of flush end-plate connections have been tested and subjected to monotonic loading da Silva *et al.* (2004). In this research, in order to calibrate the numerical models the following specimens tested previously by da Silva *et al.* (2004) were used as benchmark cases of the study; FE1 specimen that was subjected to bending forces without axial loading, FE5 specimen that was subjected to bending forces and compressive axial loading with 20% Npl (axial beam plastic resistance), FE6 that was subjected to bending forces and axial compressive loading with 27% Npl and FE9 with bending forces and axial tensile loading with 20% Npl. Also another extra numerical model (NUM) with 35% Npl compressive axial loading is implemented in to the computer model and analysed by means of finite element method. The specimen's geometrical characteristics and material that were used are shown respectively in Fig. 2.3. and Table 2.1.

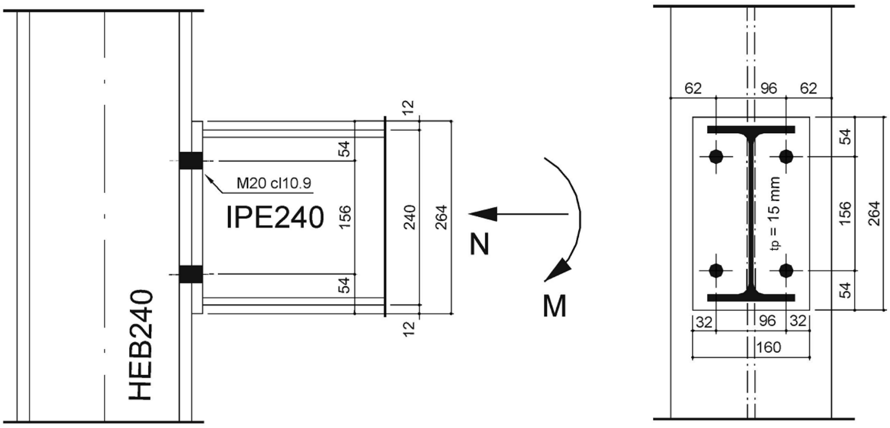


Figure. 2.3. Typical end-plate, beam and geometry (da Silva *et al.* 2004)

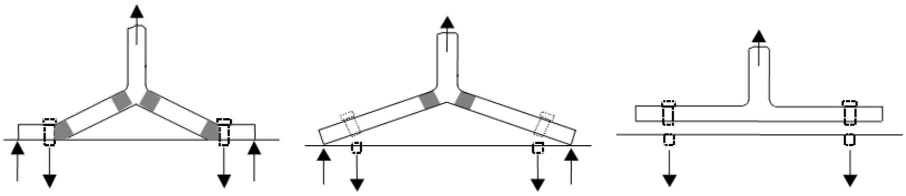
Table 2.1. Material Properties (de Silva *et al.* 2004)

Material	Application	Yielding stress (MPa)	Ultimate stress (Mpa)	Young's modulus (MPa)
Steel grade S275	Beam web	363.4	454.3	203,713
Steel grade S275	Beam flange	340.14	448.23	215,222
Steel grade S275	Column web	372.02	477.29	206,936
Steel grade S275	Column flange	342.95	448.79	220,792
Steel grade S275	End-plate	369.44	503.45	200,248
M20	Bolts	900	1000	200,000

2.4. Failure modes

The three main failure modes for a bolted end-plate connection proposed by Eurocode 3 (1998) are considered in this study and they are illustrated in Fig. 2.4. These modes are defined, as follows:

Mode 1: plastic hinges form at the bolt-line and at the beam web.
Mode 2: plastic hinges form at the beam web followed by yielding of the bolts.
Mode 3: yielding of the bolts only while the end-plate remains elastic.



(a) Mode 1 (b) Mode 2 (c) Mode 3

Figure 2.4. Failure modes for a bolted end-plate connections (Eurocode 3)

3. FINITE ELEMENT RESULTS AND COMPARISON WITH TEST RESULTS

The experimental moment vs. rotation curves for the FE1, FE5, FE6, FE9 and Eurocode 3 are all presented in Fig. 3.1. Results from finite element analyses in terms of moment vs. rotation for different test specimens are also illustrated in Fig. 3.2. As shown, the numerical results have good correlations with the experimental results.

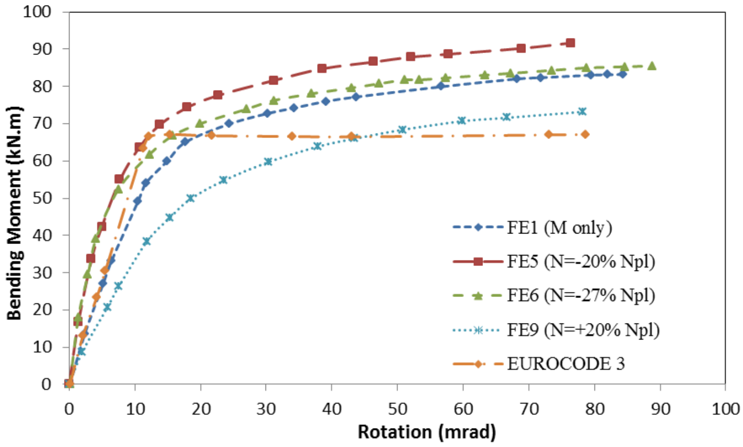


Figure 3.1. Moment vs. rotation curves of the experimental tests (da Silva *et al.* 2004)

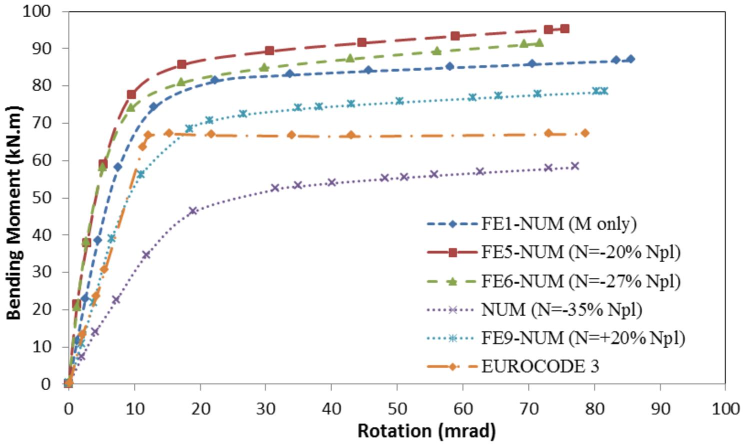


Figure 3.2. Moment vs. rotation curves of the finite element models

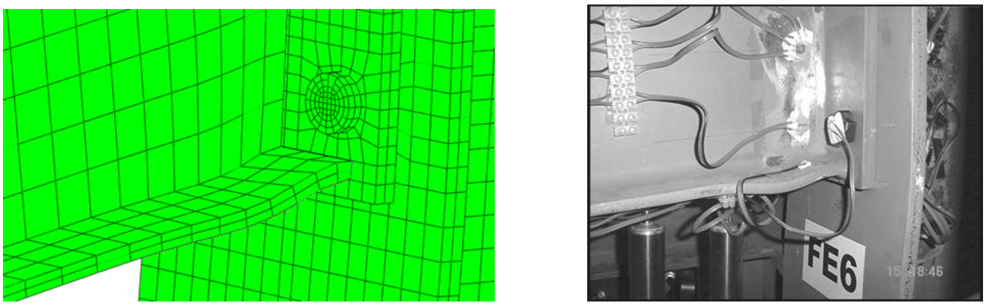
Some of the findings and observations drawn from the two figures are as follows. With certain level of compressive axial forces along with bending moment the capacity of the connections may increase to some extent. It may be observed that with 20% axial compressive forces of the axial beam plastic resistance with the bending moment, the ultimate moment will be reached and beyond 20% of the compressive forces the ultimate moment reduces due to excessive deformations which results in beam flange buckling. Results obtained from numerical model NUM with 35% axial compressive forces of the beam plastic resistance show the flange beam bucking and the moment deterioration. Also for a level of 27% axial compressive forces of the beam plastic resistance, the ultimate bending moment becomes almost similar to the case with moment only and without any axial forces applied. The application of axial tensile force along with the bending moment in the connection results in decreasing of the bending resistance of the joint. As expected, by applying the axial forces in to the connection, the bending moment behavior was changed. The axial tensile force along with the moment forces reduces the overall capacity of the connection.

Table 3.1 show experimental values presented by da Silva *et al.* (2004) along with results obtained from finite element method. Parameters like bending moment resistance as well as initial stiffness are the quantities that are compares and illustrated in the table. As shown, the numerical results are relatively close to the experimental values and the maximum difference is about 11.98% for flexural resistance and 11.46% for initial stiffness of the connection.

Table 3.1. Experimental Values vs. Finite Element Results

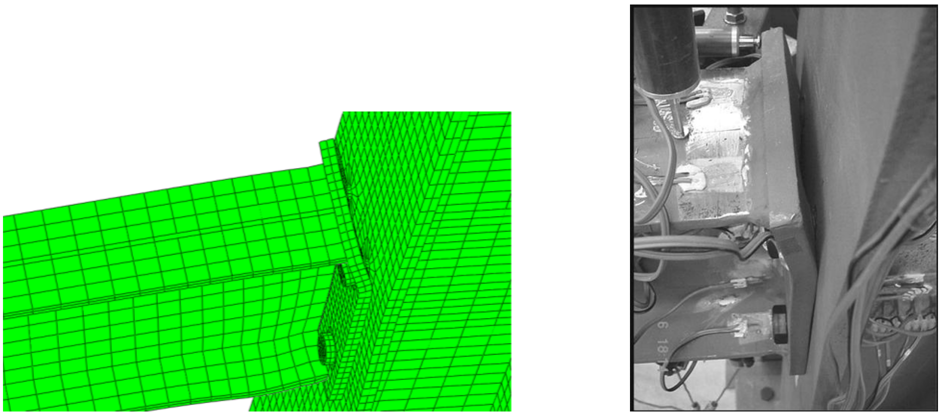
Test Specimen	Axial force (kN)	Connection flexural resistance (kN.m)		Connection initial stiffness (kN.m/rad)	
		FE Model	Experimental	FE Model	Experimental
FE1 (M only)	-	76.6	68.4	7361	7244
FE5 (N=-20% Npl)	265.0	81.6	78.5	11038	10610
FE6 (N=-27% Npl)	345.0	77.2	72.4	11065	9927
FE9 (N=+20% Npl)	264.9	62.11	52.3	5961	9084

Figs. 3.3. and 3.4. present the graphical deformations of beam bottom flange buckling obtained from numerical analysis as well as experiment and deformation at the top of the end-plate. As shown, the deformations predicted by finite element method are almost identical to the deformations visualized in experiments.



(a) Numerical (b) Experimental

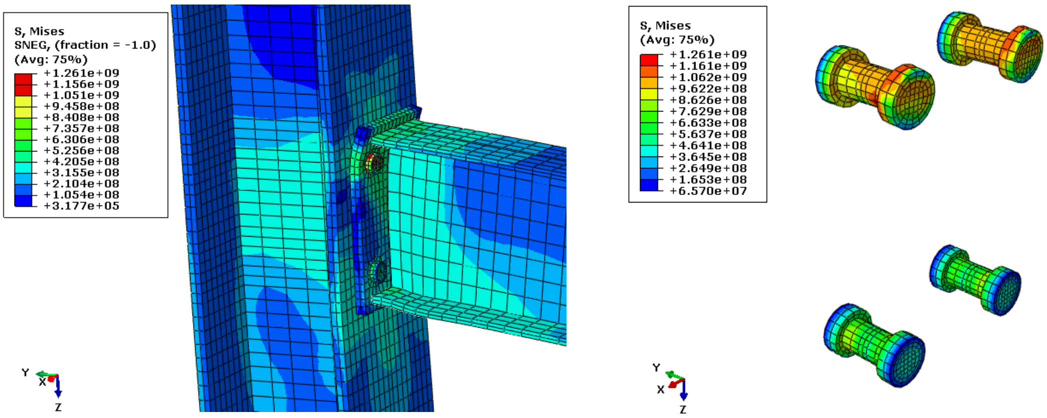
Figure 3.3. Bottom flange buckling



(a) Numerical (b) Experimental

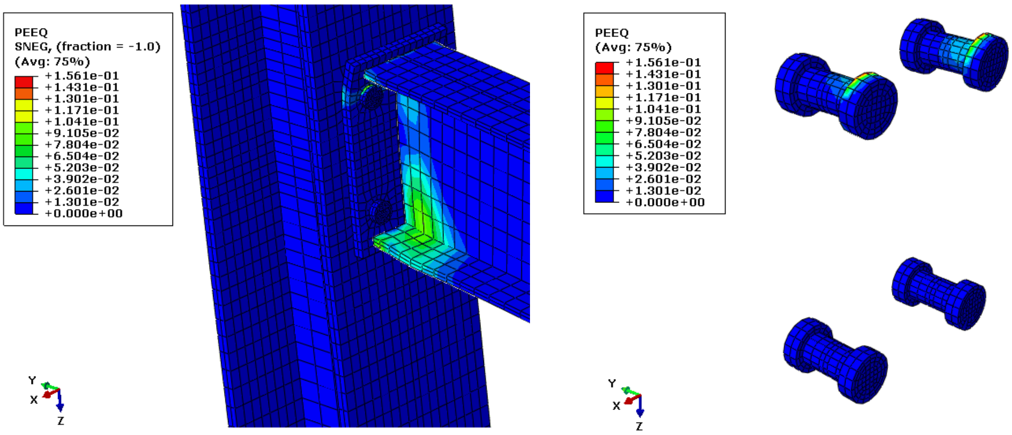
Figure 3.4. Deformation of top of end-plate

Von-mises stress contours as well as contour of plastic strain equivalent (PEEQ) are shown for the overall finite element modelling and bolts at the end time step of the analysis for the FE6 specimen (FE6-NUM); respectively in Figs. 3.5. and 3.6.



Von-mises stress for the entire mesh (Pa) Von-mises stress for bolts (Pa)

Figure 3.5. Von-mises stress for FE6 specimen



PEEQ for the entire mesh PEEQ stress for bolts

Figure 3.6. PEEQ for FE6 specimen

The results from finite element method emphasize that since the tensile bolts may control connection failure so for tensile force in these models mode 3 is the main failure mode. In case, the compressive axial force is applied along with bending moments, connection moment capacity is initially increased by increasing the axial force and after a while the beam flange buckling may take place and therefore for these models the main failure mode is considered to be mode 2 which means that plastic hinge forms at the beam web followed by yielding of the bolt.

4. CONCLUSION

In this study, a finite element model is introduced in order to study the behavior of flush end-plate moment connection subjected to bending as well as axial forces. Characteristics of the connection indicate that the results obtained from the numerical model and analysis by the finite element method is in close agreement with the test results. An increase of the moment resistance was noted for compressive axial force below 25% of the beam axial plastic resistance. Beyond this point, flange buckling was observed in all of the compressive axial with bending moment load combinations. It means that by increasing compressive axial force, initially the moment capacity increases but in continue, the moment capacity decreases due to occurrence of different failure mode in type of beam flange bulking. The modes of failure that exists in connection and was suggested Eurocode 3 are predicted very well by the finite element model. The results obtained from this study suggests that it is needed to review the current 10% limitation considered by Eurocode 3 for joints subject to bending moment and axial forces. Thus in the case of the end-plate moment connection subjected to bending moments along with the axial forces, the influence of axial force must definitely be considered on assessment of ultimate moment capacity of connection.

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