SDSS'Rio 2010 STABILITY AND DUCTILITY OF STEEL STRUCTURES
E. Batista, P. Vellasco, L. de Lima (Eds.)
Rio de Janeiro, Brazil, September 8 - 10, 2010

NUMERICAL ANALYSIS OF ENDPLATE BEAM-TO-COLUMN JOINTS UNDER BENDING AND AXIAL FORCE

Monique C. Rodrigues*, Luciano R. O. de Lima, Sebastião A. L. de Andrade*, Pedro C. G. da S. Vellasco** and José G. S. da Silva*****

* Civil Engineering Department, PUC-RIO, Brazil
e-mails: moniquecordeirorodrigues@gmail.com, andrade@puc-rio.br

** Structural Engineering Department, UERJ, Brazil
e-mail: lucianolima@uerj.br, vellasco@uerj.br

*** Mechanical Engineering Department, UERJ, Brazil
e-mail: jgss@uerj.br

Keywords: Steel Structural, Beam-to-Column Joints, Semi-Rigid Joints, Experimental Analysis, Component Method.

***Abstract**. Steel beam-to-column joints are often subjected to a combination of bending and axial forces. Alternatively, significant axial forces can also be present at the joint in cases like: pitched-roof portal frames, sway frames or frames with partially constructed floors. Despite this fact, only very simplified design procedures are available for the analysis and design of beam-to-column joints under these actions. A single empirical limitation to the applied axial force of 5% of the beam plastic resistance under axial force is the only enforced provision present in the Eurocode 3 [1]. The main purpose of the present paper is to describe a numerical investigation developed to fully characterize the structural response of endplate beam-to-column joints subjected to bending and axial forces. Experimental results, carried out at the University of Coimbra, Portugal, were used to calibrate the finite element model. These analyses were focused on expanding the test results and enabling a complete understanding of the structural behaviour of this particular type of semi-rigid connections.*

1 INTRODUCTION

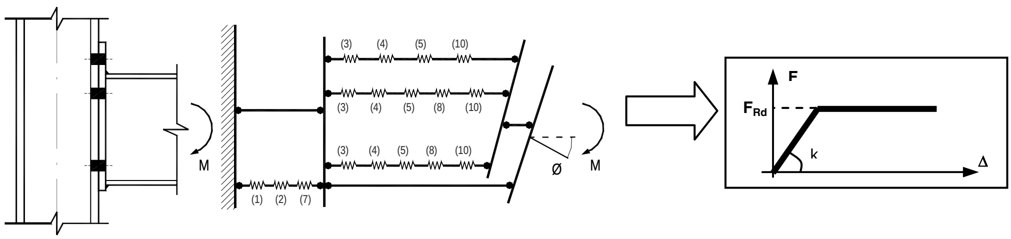
Steel beam-to-column joints are often subjected to a combination of bending and axial forces. Current specifications that take in account the steel semi-rigid joint behaviour do not consider the simultaneous presence of axial forces (tension and/or compression) acting in the joints. On the other hand, an empirical limitation of 5% of the beam plastic resistance is the only limitation suggested in Eurocode 3. In the cases where the axial force magnitude acting in the joint is less than this limit, its effects can be disregarded in the joint design. Despite this fact, the component method, proposed in the Eurocode 3, contemplate this situation since any component can be characterized, for any load type acting on the joint.

Although, the axial force transferred from the beam is usually low, it may, in some situations attain values that significantly reduce the joint flexural capacity. These conditions may be found in: Vierendeel girder systems (widely used in building construction because they take advantage of the member flexural and compression resistances eliminating the need for extra diagonal members); regular sway frames under significant horizontal loading (seismic or extreme wind); irregular frames (especially with incomplete floors) under gravity/horizontal loading; and pitched-roof frames.

On the other hand, with the recent escalation of terrorist attacks on buildings, the study of progressive collapse of steel framed building has been highlighted. The component method, Eurocode 3 [1] consists of a simplified mechanical model composed of extensional springs and rigid links, whereby the joint is simulated by an appropriate choice of rigid and flexible components as presented in Figure 1. These components represent a specific part of a joint that, dependent on the type of loading, make an identified contribution to one or more of its structural properties. The joint design must define three basic properties: bending moment resistant, $M_{j,Rd}$; initial rotational stiffness, $S_{j,ini}$ and rotation capacity, ϕ_{Cd}.

The first step in a mechanical model development considering the component method for beam-to-column joints is the identification of the relevant components, which represent the existing deformation paths and possible ways of failure. The components are considered according to Eurocode 3 (2003).

The main objective of this paper is to present a numerical study of a flush endplate beam-column joints. The investigated joints were initially subjected only to bending moment and later joints subjected to bending moment and axial force simultaneously. The numerical results were calibrated against experimental results and to the Eurocode 3 provisions for FE01 test and Cerfontaine (2001) model to joints with bending moment and axial force.



(1) column web in shear	(5) endplate in bending
(2) column web in compression	(7) beam flange in compression
(3) column web in tension	(8) beam web in tension
(4) column flange in bending	(10) bolts in tension

Figure 1 – Mechanical Model – extended endplate joint (Lima et al, 2004)

2 NUMERICAL MODEL

The numerical model was based on tests carried out by Silva *et al.* (2003), for flush endplate beam-to-column joints. The adopted steel grade was S275. The beam was joined to the endplate (t_p = 8mm) with fillet welds (a_w = 8mm). The adopted full thread bolts were M20 (d= 19.05mm), cl. 10.9. Table 1 presents the numerical model material characteristics.

2.1 Model characteristics

The numerical simulation was performed with the finite element program ANSYS 11 package [4], using solid elements, SOLID 185, for the beam, column and bolts and shell elements, SHELL 181 for the transverse stiffeners adopted at the beam end near the load application point. In order to consider the contact between plates, contact elements TARGE 170 and CONTA 173, were used (endplate and column flange; bolt head and endplate; bolt shank and endplate hole and column flange; nut and column flange), with a 0.25 friction coefficient. Figure 1 illustrates the numerical model. Regarding the boundary conditions, the flange and column web were restricted in the x and y axis. The vertical displacement of the endplate was also prevented while the beam top flange was laterally restricted [5]. The model considered the whole length of the column following the strategy adopted in experimental programme. An elastic-plastic bilinear constitutive law was considered.

2.2 Algorithms and numerical strategies for nonlinear analysis

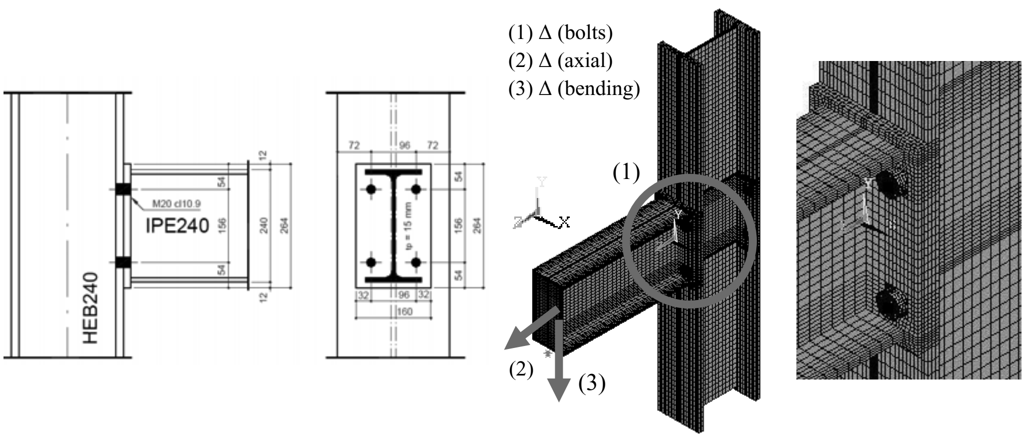
A full nonlinear analysis was performed for the developed numerical model. The geometrical and material non-linearities were considered using a Updated Lagrangean formulation and a Von Mises yield criterion associated to a bilinear stress-strain relationship and an isotropic hardening response. This procedure represents the full structural assessment of the analyzed joints, and may be summarized using the stress distributions contour plots and/or force-displacement curves for any joint node [5].

2.3 Cases studies

Table 2 presents a summary of studied cases and their respective loads where the axial force is a percentage of the beam plastic resistance (1084kN). The bending moment was applied at the beam bottom flange, the axial force along the beam cross-sectional area and the bolts pretension in the bolt head and nut. Overall loads are considered in terms of displacement application - see Figure 2.

Table 1 – Material mechanical properties (in MPa)

		f_y	f_u	E
PLATES	beam web	364.08	545.10	203714
	beam flange	340.68	537.89	215222
	column web	372.69	572.76	206936
	column flange	343.48	538.55	220792
	endplate	370.12	604.14	200248
BOLTS	M20	943.88	1222.40	210000
STIFFENER	t = 10 mm	1000		210000



(a) joint geometrical parameters (b) numerical model (c) detail

Figure 2 – Flush endplate joint specifications

Table 2 – Considered experimental tests (Silva *et al.*, 2003)

ID	Bending Moment kN.m	Axial Force Levels ($\%N_{pl,beam}$)	Axial Force Levels (kN)
FE1	72.2	-	-
FE3	77.2	-4%	-52.7
FE5	80.5	-20%	-265.0
FE6	72.3	-27%	-345.0
FE8	61.7	+10%	+130.6

3 APLICATION OF COMPONENT METHOD

In order to compare the theoretical, experimental and numerical results, the FE01 joint was used considering the bending moment application only. The partial safety factors were considered equal to 1.0. Table 3 presents the individual values of resistance and stiffness coefficients of each component. It can be observed that the component that controls the joint design in tension zone is the endplate in bending (5) and in the compression region, the beam flange in compression (7).

Table 3 – Individual resistances - component method (Eurocode 3, 2003) - Test FE01

	Component		F_{Rd} (kN)	k/E (mm)
Components on the area in compression	(1)	column web in shear	494.8	8.43
	(2)	column web in compression	690.7	10.40
	(7)	beam flange in compression	444.3	∞
First bolt row (h=193.1mm)	(1)	column web in shear	642.6	8.43
	(2)	column web in compression	690.7	10.40
	(7)	beam flange in compression	542.3	∞
	(3)	column web in tension	533.3	7.03
	(4)	Column flange in bending	408.3	40.47
	(5)	endplate in bending	339.3	13.35
	(8)	beam web in tension	483.0	∞
	(10)	bolts in tension	441.0	7.76
Second bolt row (h=37.1mm)	(1)	column web in shear	303.2	8.43
	(2)	column web in compression	351.4	10.40
	(7)	beam flange in compression	203.0	∞
	(3)	column web in tension	533.3	7.03
	(4)	Column flange in bending	408.3	40.47
	(5)	endplate in bending	339.3	13.35
	(8)	beam web in tension	483.0	∞
	(10)	bolts in tension	441.0	7.76
$M_{j.Rd}$=339.3x0.193+203x0.037=73.05kN.m $S_{j.ini}$=11152.2kN.m/rad e $S_{j.ini}/\eta$=5576.1 kN.m/rad				

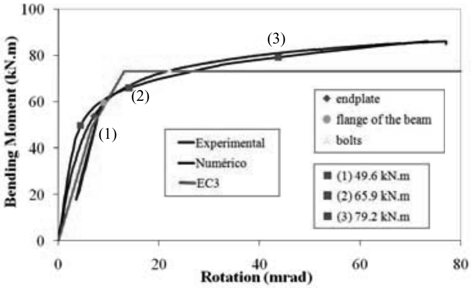
4 RESULTS AND DISCUSSION

4.1 Joint only subjected to bending moment

Figure 3 presents the bending moment versus rotation curves for the FE01 joint (Luis *et al.,* 2003*)* where it is possible to observe that a good agreement between the numerical and experimental results was reached. This figure also presents, the progressive sequence of yielding of the experimental components obtained from the strain gauges results: endplate in bending, beam flange in compression and bolts in tension. In the numerical curve, it can be observed that from a bending moment level of 49.6kN.m, the initial stiffness is no longer linear, indicating that the beginning of the endplate in bending component yielding, Figure 3, confirming the results obtained from the experiments. From this figure it is also possible to observe that the beam flange in compression component yield at a 65.9 kN.m level, according to Von Mises criteria, Figure 4.

4.2 Joints subject to bending moment and axial force

This section presents the results for joints simultaneously subjected to bending moment and axial force. In order to reproduce the experimental test loading sequence, first the axial force was applied followed by the bending moment application. The individual and global bending moments *versus* rotation curves are presented in Figures 5 and 6, respectively.



$M_{EXPj.Rd}$ = 72.20 kN.m

$M_{NUMj.Rd}$ = 70.04 kN.m

$M_{EC3j.Rd}$ = 73.05 kN.m

$S_{EXPj.ini}$ = 8564.0 kN.m/rad

$S_{NUMj.ini}$ = 9940.0 kN.m/rad

$S_{EC3j.ini}$ = 11152.2 kN.m/rad

Figure 3 – Moment versus rotation curve – Test FE01 – only for bending M

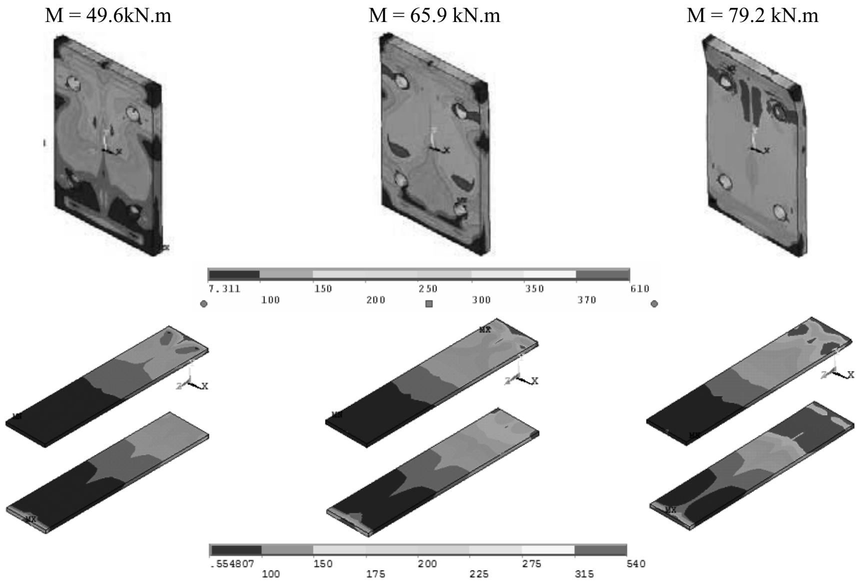
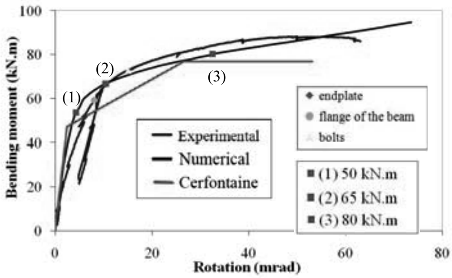


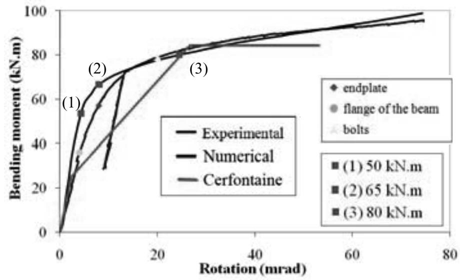
Figure 4 –Von Mises stress distribution – FE01 (in MPa)

Figure 6 indicates that in all the numerical model bending moment *versus* rotation curves an increase of the compression axial force levels applied to the joint also led to an increase of the joint flexural resistance. The previous conclusion was also valid for the case with axial force corresponding to 20% of the beam plastic resistance, fact corroborated by the experiments, despite differences in the individual bending moment *versus* rotation curves. This is due to the fact that the components in the compression region, even with an increase of applied force, did not reach their resistance limits and, therefore, the components in tension were relieved by the compressive axial force. Small changes in initial stiffness of these curves were also observed. For tests with tension axial force, the bending moment resistance was reduced because the compression components reached the yielding for early bending moment levels.

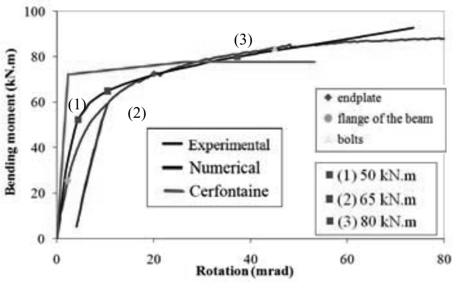
The numerical initial stiffness presented values larger than their experimental counterparts but in terms of the bending moment resistance, the values were very similar. It could be verified that, increasing the joint axial forces, the endplate in bending component was not the controlling factor leading the joint design to be controlled by beam flange in compression component, fact that was also observed experimentally. Table 4 presents the values of bending moment resistance, $M_{j,Rd}$, and initial rotational stiffness, $S_{j,ini}$, for all the tests investigated.



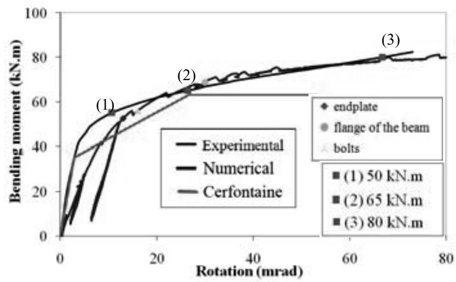
(a) Test FE03 – N= - 52.7kN



(b) Test FE05 – N= - 265.0kN



(c) Test FE06 – N= - 345.0 kN



(d) Test FE08 – N= + 130.6 kN

Figure 5 – Bending moment *versus* rotation curves

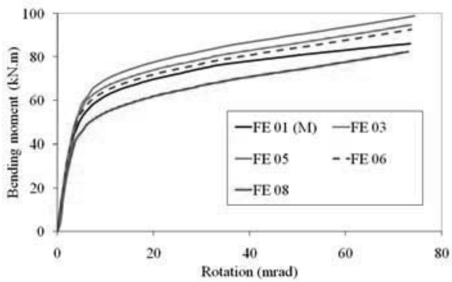


Figure 6 – Moment *versus* rotation curve – Numerical Model

Table 4 – Value of $M_{j.Rd}$ and $S_{j.ini}$

Test	$M_{j.Rd.ex}$ kN.m	$M_{j.Rd.num}$ kN.m	$\frac{M_{j.Rd.num}}{M_{j.Rd.ex}}$	$S_{j..ini.exp}$ kN.m/ rad	$S_{j..ini.num}$ kN.m/ rad	$\frac{S_{j..ini.num}}{S_{j..ini.exp}}$
FE1	72.20	70.04	0.97	8564	9940	1.16
FE3	77.20	70.20	0.91	9713	11128	1.14
FE5	80.50	75.20	0.93	10763	11351	1.05
FE6	72.30	69.10	0.96	9379	10800	1.15
FE8	61.70	57.50	0.93	7185	8474	1.18

Figures 7 and 8 present the Von Mises stress distribution for three different bending moment levels, i.e., 50 kN.m, 65kN.m and 80 kN.m, respectively. Once again, comparing the results, it could be observed that increasing the applied axial force, the beam flange in compression component reached the yielding before.

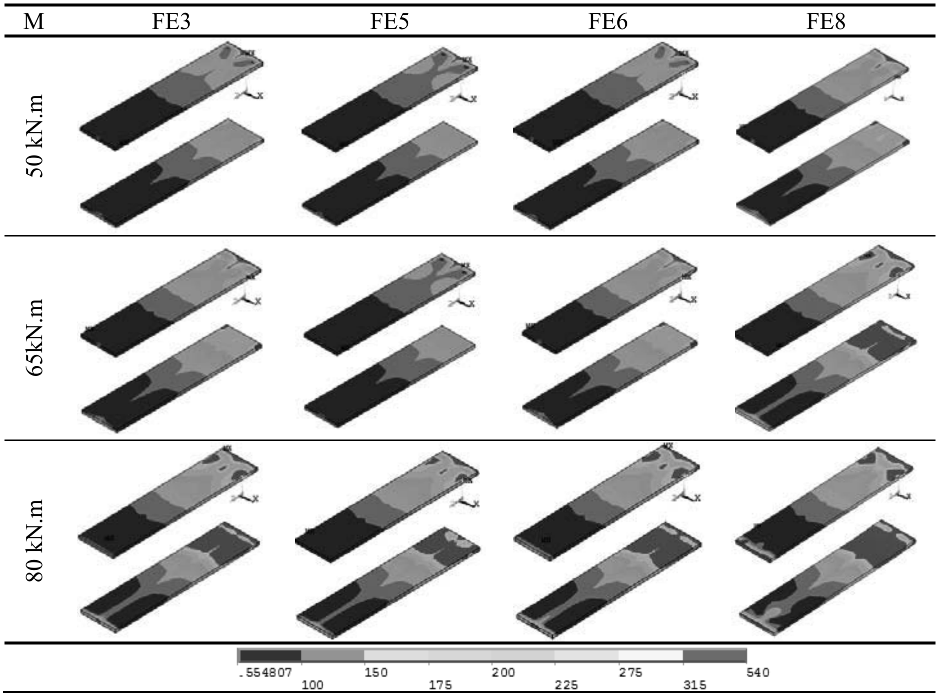


Figure 7 –Von Mises stress distribution – bottom beam flange (in MPa)

In FE06 test a compressive axial load magnitude corresponding to 27% of the beam plastic resistance was applied but the joint bending resistance was less than its correspondent to the FE05 test. This was due to the fact that in the FE06 test, the compressive axial load level led to an early yielding of the beam flange in compression component. Comparing the results for the individual bending moment *versus* rotation curves presented in Figure 5, it could be observed that for the numerical and experimental results related to FE03, FE05 and FE08 tests, the values obtained from the use of Cerfontaine model represent a lower bound for the bending moment resistance. Alternatively in FE06 test, the Cerfontaine model use led to an unsafe prediction.

5 CONCLUSION

The present paper aimed to evaluate the structural response of beam-to-column joints subjected to bending moments and compressive axial forces. The adopted methodology first considered the available component method introduced in the Eurocode 3 (2003). Afterwards, a numerical model based on finite element simulations was developed, using Ansys 11.0 package [3], considering a full nonlinear analysis (material and geometric) followed by the application of the Cerfontaine model (2001). The numerical model calibration was performed against experimental evidence in terms of bending moment versus rotation curves and stress distribution patterns. A numerical and experimental results comparison indicated a good agreement in terms of bending moment resistance, initial stiffness and component yielding sequence. For the studied cases, the presence of a compressive axial force in the joint led to an approximate 10% increase in the joint bending moment resistance, i.e., from M_{jRd}=80,5kN.m to $M_{j,Rd}$=72,2kN.m for the FE01 joint [2] where only bending moments were applied to the joint. On the other hand, when tensile axial force was applied to the joint, a reduction of 15% was verified in the joint bending moment resistance.

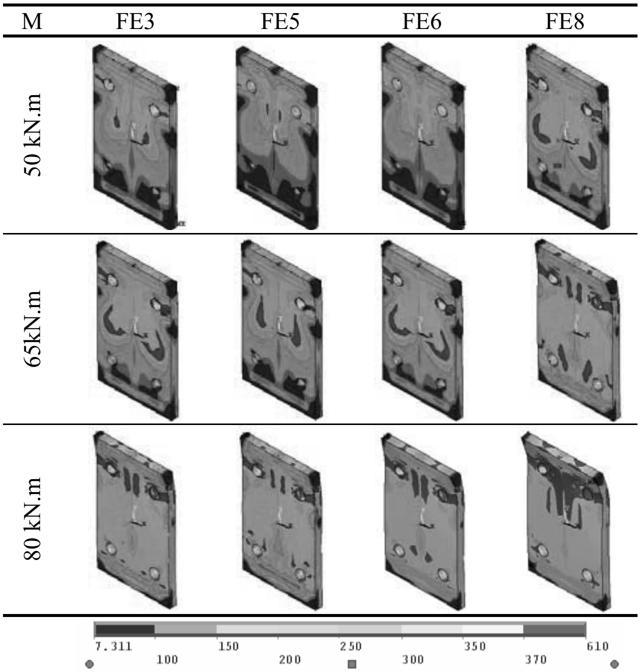


Figure 8 – Distribution of the Von Mises stress - endplate (in MPa)

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge the Brazilian National and State Science Support Agencies: CAPES, CNPq and FAPERJ for the financial support granted to this research program.

REFERENCES

[1] Ansys. Inc. Theory Reference (version 11). 2008.

[2] Bursi. O. and Jaspart. J. P.. 1997. Calibration of a Finite Element Model for Isolated Bolted End-Plate Steel Connections. Journal of Constructional Steel Researchers. vol. 44. nº 3. pp. 225-262.

[3] Cerfontaine, F, 2001. Etude analytique de l'interaction entre moment de flexion et effort normal dans les assemblages boulonnés. In: Construction Méttalique, nº 4, p. 1-25.

[4] Eurocode 3. prEN 1993-1.8. 2003. Design of steel structures – Part 1.8: Design of joints ("final draft"). CEN. European Committee for Standardisation. Brussels.

[5] Rodrigues. M.C.. 2009. Numerical Modeling of Beam-Column Joints in Steel under Bending Moment and Axial Force. 178f. Dissertation - Civil Engineering Department. UERJ. Rio de Janeiro. 2009.

[6] Silva, L. S. da, Lima, L. R. O. de, Vellasco, P. C. G. da S. and Andrade, S. A. L. de, 2004. Behaviour of Flush Endplate Beam-to-Column Joints Under Bending and Axial Force. International Journal of Steel and Composite Structures, vol. 4, nº 2, pp. 77-94.