Proceedings of the XXVI Iberian Latin-American Congress on Computational Methods in Engineering – CILAMCE 2005
Brazilian Assoc. for Comp. Mechanics (ABMEC) & Latin American Assoc. of Comp. Methods in Engineering (AMC),
Guarapari, Espírito Santo, Brazil, 19th – 21st October 2005

Paper CIL 01-0633

STRUCTURAL MODELLING OF VIERENDEEL BEAMS WITH SEMI-RIGID JOINTS

Alexandre Almeida Del Savio
Luiz Fernando Martha
Sebastião Arthur Lopes de Andrade
{delsavio,lfm}@tecgraf.puc-rio.br
andrade@civ.puc-rio.br
Civil Engineering Department, Pontifical Catholic University of Rio de Janeiro, PUC-RIO
Rua Marquês de São Vicente, 225, Gávea, 22453-900, Rio de Janeiro, RJ – Brazil,
Cx. Postal: 38097, Phone: +55 (0xx21) 3114-1194

Pedro Colmar Gonçalves da Silva Vellasco
Luciano Rodrigues Ornelas de Lima
{vellasco,luciano}@eng.uerj.br
Structural Engineering Department, State University of Rio de Janeiro, UERJ,
Rua São Francisco Xavier, 524, 5018A, Maracanã, 20550-900, Rio de Janeiro, RJ – Brazil,
Phone: +55 (0xx21) 2587-7537.

Abstract. *In building construction a significant advantage of vierendeel beam systems is that they can, in portal frames, take advantage of the member flexural and compression resistances eliminating, avoiding the need for extra diagonal members. For this reason, they allow greater interaction with building services, enabling a free space for pipes, ducts, etc. They are also widely used in staggered-truss systems. This work is aimed at evaluating the influence of initial stiffness variation in the joints of a vierendeel girder type beam, carried out with the inclusion of analyses of semi-rigid portal frames. FTOOL/SRC was the program used to model the semi-rigid joints by means of a simple and compact parametric analysis. The main goal of this article is to demonstrate, through a series of analyses of a vierendeel beams, the influence of semi-rigid joints in the structural response. These analyses have involved, in a first stage, fixed and simply supported beams configurations followed by three semi-rigid structures, allowing a better understanding of the force-transfer mechanism in this structural system.*

Keywords: *semi-rigid joints, vierendeel beam, non-linear analysis, steel structures, advanced analysis.*

1. INTRODUCTION

Beam-to-column joints are often subjected to a combination of bending and axial forces. Although in many regular building frames the axial force coming from the beam is usually low, it can reach significant values in many instances, such as:

- Regular frames under significant horizontal loading (seismic or extreme wind), especially sway frames;
- Irregular frames under gravity or horizontal loading, especially with incomplete storeys;
- Pitched-roof portal frames - Figure 1.

Figure 1 - Example of a pitched-roof portal frame joint.

Currently, no specific provisions are available for the analysis and design of beam-to-column joints under bending and axial forces in the context of part 1.8 of Eurocode 3 (2003). Historically, for a high M/N ratio range, a single empirical limitation is proposed on the axial force to be less than 5% of the beam's axial compression or tension plastic resistance. Below this value, the axial force could be disregarded in the analysis.

Recently, some preliminary attempts were addressed at the prediction of the behaviour of beam-to-column joints under bending and axial forces. Liège, Jaspart *et al.* (1999) and Cerfontaine (2004) have applied the principles of the component method to establish design predictions of the M-N interaction curves and initial stiffness. Based on the same general principles, Silva and Coelho (2000) have proposed analytical expressions for the full non-linear response of a beam-to-column joint under combined bending and axial forces. Unfortunately, both results were not calibrated/validated by experimental evidence. To provide a sound basis for theoretical developments, Silva *et al.* (2004) and Lima *et al.* (2004) have developed a series of experimental tests carried out at the University of Coimbra on flush and extended end-plate beam-to-column configurations, whose moment *versus* rotation curves are used in this work.

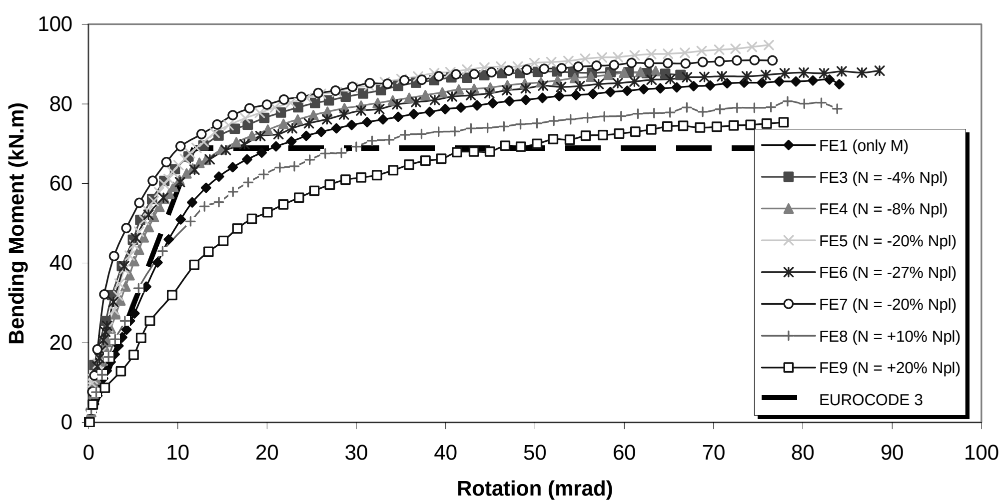


Figure 2 – Bending moment *versus* rotation curves – flush endplate joints.

With these bending moment *versus* rotation curves in hand (Figure 2), it is possible to observe that the presence of the axial force in the joints modifies their structural response. In this picture, eight flush-endplate-joint experimental tests were presented where the axial force level was considered between -27% and + 20% of the beam's plastic resistance (Silva *et al.*, 2004). With the joint bending resistance and these axial force levels, an interaction diagram may be produced such as the one presented in Figure 3, with the theoretical values obtained from the mechanical model proposed by Silva *et al.* (2004).

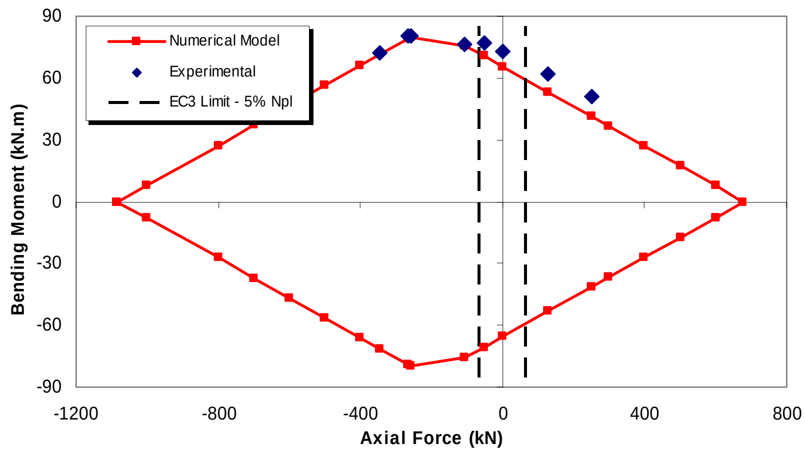


Figure 3 – Bending moment *versus* axial force diagram.

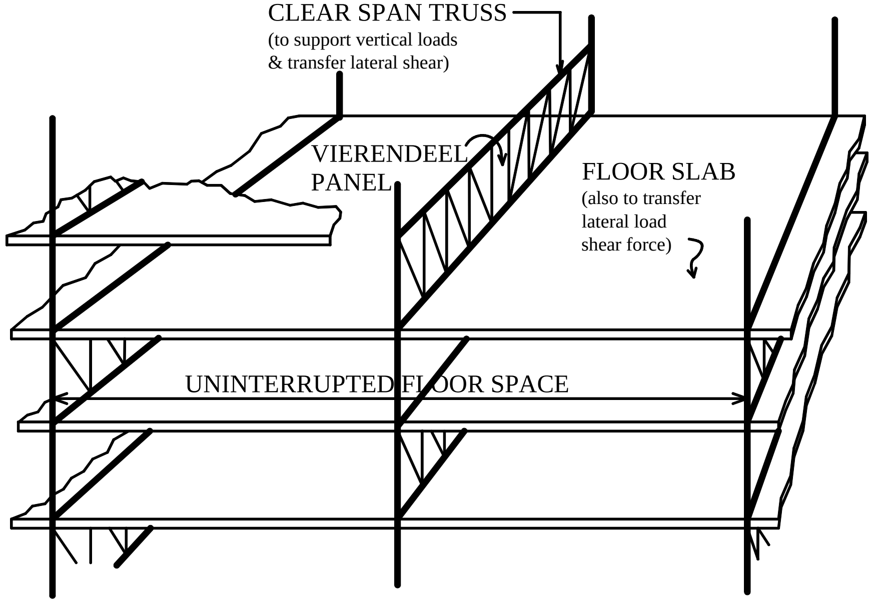
The axial force may significantly reduce the flexural capacity of some steel structure joints, therefore not considering it can lead to unsafe structural designs. Typical examples of these are vierendeel girder systems with semi-rigid joints. In the portal frames here presented, semi-rigid joints were firstly selected because they lead to more economic and efficient solutions.

2. IDEALIZED STRUCTURAL MODEL

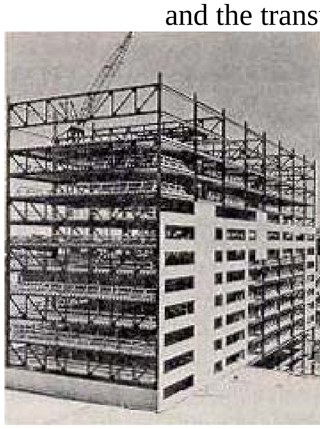
A significant advantage of vierendeel beam systems is that they can, in portal frames, take advantage of the members flexural and compression resistances eliminating the need for extra diagonal members. Therefore, this structural solution allows more flexibility in the execution of installations, leaving a free space for pipes, people, etc. They can also be used, for example, in staggered-truss systems, as presented in Figure 4.

The beam modelling considered a number of different joint configurations, with five different beam-to-column joint stiffness values. These analyses have involved, in a first stage, two limit configurations for the structural joints: the first completely fixed (Figure 5a) and the second pinned (Figure 5b). Subsequent analyses, also adopted three different semi-rigid joint configurations.

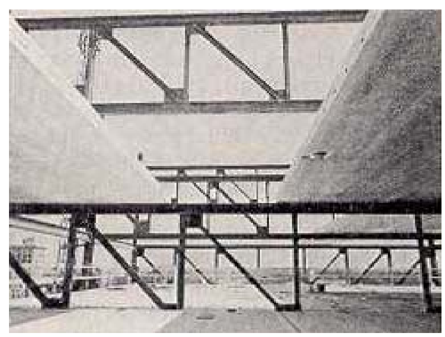
The structures were modelled by a linear elastic analysis in the FTOOL/SRC program. FTOOL/SRC (Del Savio *et al.*, 2004 e Del Savio, 2004) can be used to model semi-rigid joints by means of a simple and compact parametric analysis. Internally, the program models the semi-rigid joint using a non-linear joint finite element whose formulation was developed in a Lagrangian reference, also using the co-rotational approach for the displacements. The dimensions and the configurations of each case studied are detailed in the following section.



(a) Schematic illustration of a typical truss-stagger pattern and the transverse load-distribution mechanism.

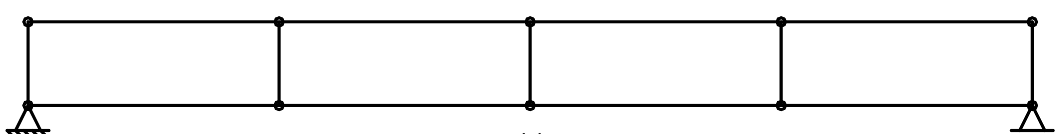


(b) Typical structural system.

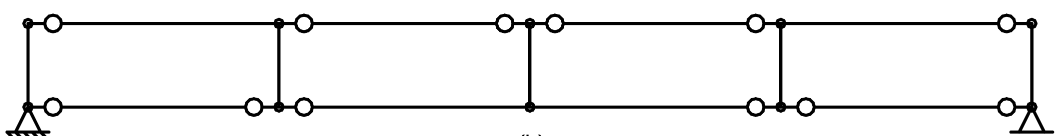


(c) Typical structural system.

Figure 4 – Staggered-truss system (Ritchie and Chien, 1979).



(a)



(b)

Figure 5 - Idealized structural model: vierendeel girder system: (a) rigid and (b) pinned.

3. NUMERICAL EXAMPLES: A Vierendeel Girder Semi-Rigid Structural System

The vierendeel system considered has a twelve-meter span divided in four, three meters long and one meter high, segments. The beams were subjected to four concentrated loads of 35, 30, 10 and 20 kN, respectively applied to the nodes 3 (P_3), 4 (P_4), 8 (P_1) and 9 (P_2). The purpose of this non-symmetric loading was to generate non-linear geometric disturbances in the structure and to "overload" element twelve, which will be the main target for the comparisons among the results obtained in the variations of the joints' stiffness values. A similar analysis could be made with the use of lateral loads, which are often found in these structures due to wind forces.

Figure 6 presents the structural model conceived for the vierendeel beams. This image shows the applied load, the numbers of the nodes and elements (inscribed in a rectangle), the dimensions and identifications of the joints represented by S_i (i varying from 1 to 16).

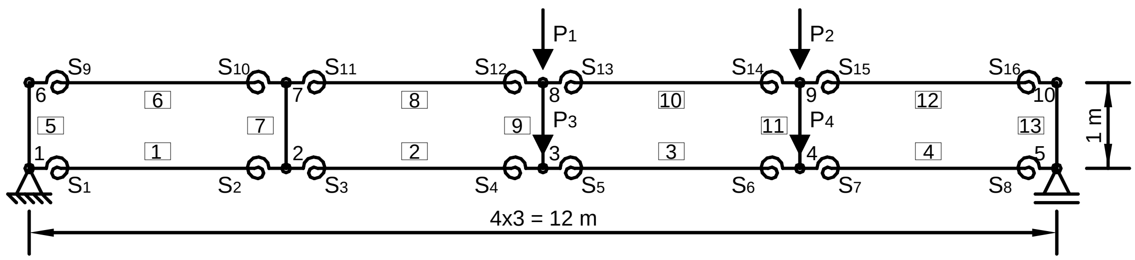


Figure 6 - Idealized structural model: vierendeel girder system.

The beams elements (horizontal members), used an IPE 240 steel profile, while the columns adopted a HEB 240 steel section. The adopted steel section dimensions are presented in Table 1.

Table 1 – Steel Profile Geometry.

Member	Section	d (mm)	b (mm)	tw (mm)	tf (mm)	A (mm^2)	I (mm^4)
1 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
2 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
3 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
4 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
5 (column)	HEB 240	240	240	10	17	1.0e+4	1.1e+8
6 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
7 (column)	HEB 240	240	240	10	17	1.0e+4	1.1e+8
8 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
9 (column)	HEB 240	240	240	10	17	1.0e+4	1.1e+8
10 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
11 (column)	HEB 240	240	240	10	17	1.0e+4	1.1e+8
12 (beam)	IPE 240	240	120	6	10	3.7e+3	3.7e+7
13 (column)	HEB 240	240	240	10	17	1.0e+4	1.1e+8

The steel grade used in all elements of the beam has an Young´s modulus of 205000 MPa and specific weight of 78.5 kN/m^3.

Figure 7 presents the bending moment *versus* rotation curves for the studied situations, varying from the fixed to the pinned condition and including the semi-rigid configurations. A bi-linear moment *versus* rotation curve adopted in the semi-rigid joints was tested by Lima *et al*. (2004) and is illustrated in Figure 8.

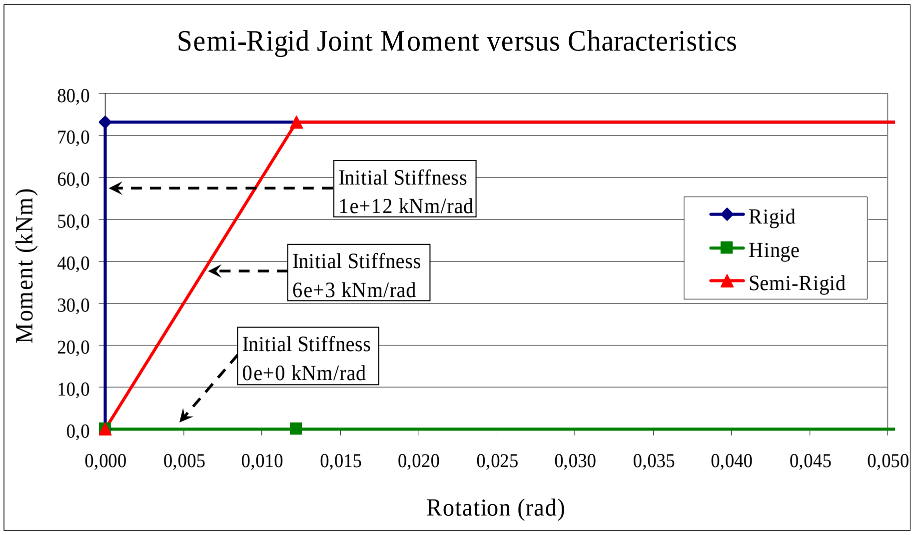


Figure 7 - Moment-rotation characteristics spring elements.

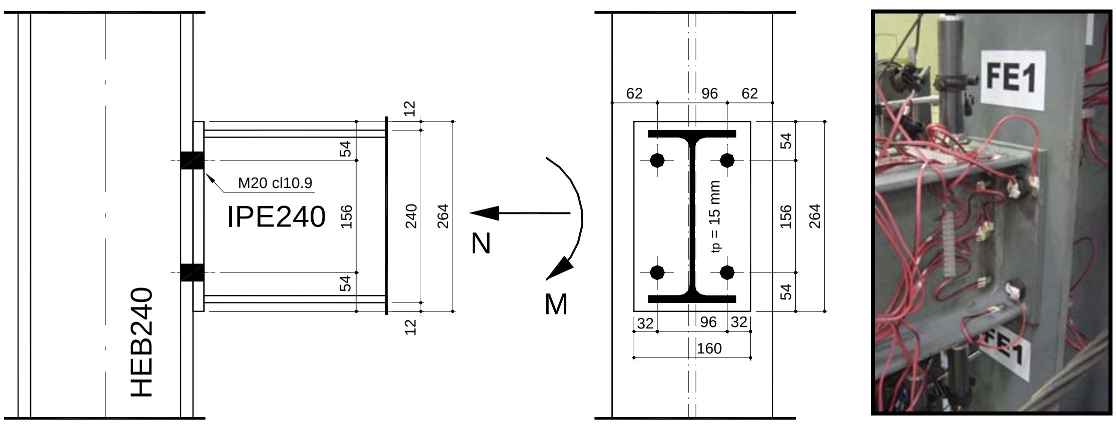


Figure 8 – Flush endplate joint layout.

Table 2 presents five different configurations for the joint initial stiffness values (S_i) of the vierendeel systems. The considered hypotheses were:

1) rigid behaviour, in which all joints have a stiffness of 1.0e+12 kN.m/rad;
2) pinned configuration hypothesis;
3) first semi-rigid hypothesis, in which the hinges in the second hypothesis were replaced with semi-rigid joints with a stiffness of 6000 kN.m/rad;
4) second semi-rigid hypothesis, in which the hinges in the second hypothesis were maintained while the remaining joints were replaced with joints stiffness of 6000 kN.m/rad;
5) third semi-rigid hypothesis, in which all joint were considered semi-rigid with a 6000 kN.m/rad stiffness.

Table 2 – Joint initial stiffness values.

Joints (kN.m/rad)	Rigid	Hinge	Semi-Rigid (partial)	Semi-Rigid (hinge)	Semi-Rigid (full)
S_1	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_2	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_3	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_4	1.0e+12	1.0e+12	1.0e+12	6.0e+03	6.0e+03
S_5	1.0e+12	1.0e+12	1.0e+12	6.0e+03	6.0e+03
S_6	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_7	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_8	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_9	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_{10}	1.0e+12	1.0e+12	1.0e+12	6.0e+03	6.0e+03
S_{11}	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_{12}	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_{13}	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_{14}	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03
S_{15}	1.0e+12	1.0e+12	1.0e+12	6.0e+03	6.0e+03
S_{16}	1.0e+12	0.0e+00	6.0e+03	0.0e+00	6.0e+03

The results obtained in each of the cases analyzed are presented below, in Table 3 and Table 4, respectively, in terms of node number three displacements of and element twelve structural forces and moments.

Table 3 – Comparison: displacements in node 3.

Displac.	Rigid	Hinge	Semi-Rigid (partial)	Semi-Rigid (hinge)	Semi-Rigid (full)
d_x (mm)	0.7939	0.4132	0.7301	0.4132	0.8084
d_y (mm)	-18.7200	-93.5000	-33.3000	-198.5000	-45.1500
r_z (rad)	-0.0003	-0.0010	-0.0004	-0.0010	-0.0003

Table 4 – Comparison: forces and moments in element 12.

Internal Forces	Rigid	Hinge	Semi-Rigid (partial)	Semi-Rigid (hinge)	Semi-Rigid (full)
N_9 (kN)	-86.80	0.00	-72.00	0.00	-88.20
N_{10} (kN)	-86.60	0.00	-72.00	0.00	-88.20
Q_9 (kN)	-30.00	-60.00	-38.10	-60.00	-30.00
Q_{10} (kN)	-30.00	-60.00	-38.10	-60.00	-30.00
M_9 (kNm)	46.60	180.00	74.30	180.00	45.90
M_{10} (kNm)	-43.40	0.00	-40.10	0.00	-44.10

When evaluating the obtained forces and moments for each configuration, the hinge and semi-rigid configurations can be discarded since they violate the semi-rigid joint capacity, which is 73.1 kN.m. Moreover, in both configurations, the vertical displacements strongly violate the vertical displacement serviceability limit at midspan, which is L/250, i.e., 48 mm.

The three remaining configurations (rigid, partial semi-rigid and complete semi-rigid) were evaluated according to the levels of axial forces and bending moments present in the element twelve, since these configurations have not surpassed the flexural capacity of the semi-rigid joint and the serviceability limitation.

Figure 9 depicts the axial force *versus* bending moment interaction diagram presented in Figure 3 but, for clarity, only the mechanical model (highlighting the safe structural design region) is presented together with the points obtained by the rigid, partial semi-rigid and complete semi-rigid configurations, respectively.

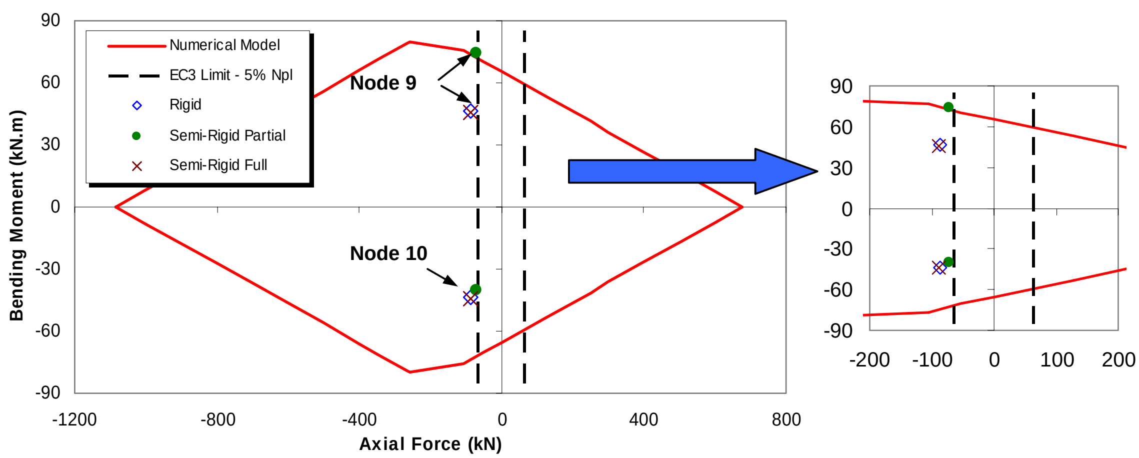


Figure 9 - Bending moment *versus* axial force interaction diagram.

The evaluations of the three configurations in terms of the bending moment *versus* axial force diagram are important because it is well know that the axial force can significantly reduce the joint flexural capacity. Therefore, its interaction with the bending moment must be always considered.

In the three cases, two joint configurations are within the boundaries of the safe design region for the investigated interaction levels and very close to the maximum range of +/-5% of the axial force capacity, in which the component method can be safely applied (Eurocode 3, part. 1.8, 2003). It is worth noting that a point referent to the partial semi-rigid configuration, in node 9, is exactly at the safe boundary limit of the interaction graph. Outside the range, as established by Eurocode 3, more advanced methods have to be used, such as the one proposed by Cerfontaine (2004).

4. CONCLUSIONS

The main purpose of this article was to demonstrate, through a series of analyses of a vierendeel beam systems, the influence of semi-rigid joints in the structural forces and displacements, enabling a better understanding of the force transfer mechanism within the system structural elements.

Based on the results obtained and analyzed in the previous section, the advantages of employing a complete semi-rigid solution in relation to the other evaluated configurations can be highlighted. This could be seen, for instance, when comparing the complete semi-rigid hypothesis with the rigid hypothesis: The semi-rigid solution presented practically the same forces as in the rigid system, but it has satisfied all the acceptable force levels and had stiffness well below the rigid hypothesis (a reduction from 1.0e+12 kN.m/rad to 6.0e+03 kN.m/rad). The natural consequence of this structural solution is a more economic structure, as semi-rigid joints are cheaper and the structure is lighter.

The present work represents the initial stage in an investigation that seeks to evaluate vierendeel beam systems by varying the joint stiffness conditions. At the present stage, the structure was evaluated by a linear elastic procedure, later to be changed to an analysis that could incorporate the geometric and material non-linearities of the structural elements and joints these last represented by typical moment *versus* rotation curve. Subsequently, this study it is aimed to consider the joint forces and moments interactions in order to evaluate this fundamental aspect in the global structural response.

Acknowledgements

The authors would like to acknowledge the financial support provided by the Brazilian Foundations: CAPES, CNPq and Faperj.

REFERENCES

Cerfontaine, F. (2004), "Etude de l'interaction entre moment de flexion et effort normal dans les assemblages boulonnés" (in french), Thèse de Docteur en Sciences Appliquées, Faculté des Sciences Appliquées, University of Liège, Belgium.

Del Savio, A.A., Andrade, S.A. de, Vellasco, P.C.G.S., Martha, L.F.C.R, 2004. A Non-Linear System for Semi-Rigid Steel Portal Frame Analysis, *Proceedings of the Seventh International Conference on Computational Structures Technology - CST2004*, vol.1, pp. 1-12.

Del Savio, A.A., 2004. *Computer Modelling of Steel Structures with Semi-rigid Connections*. MSc. Dissertation, Civil Eng. Depart. – PUC-Rio, Brazil, (in Portuguese), 152p.

prEN 1993-1.8, 2003. *Design of steel structures – Part 1.8: Design of joints ("stage 49 draft")*, CEN, European Committee for Standardisation, Brussels.

Jaspart, J.P., Braham, M. and Cerfontaine, F. (1999), "Strength of joints subjected to combined action of bending moment and axial force", in Proceedings of the Conference Eurosteel '99, CVUT Praha, Czech Republic, May 26-29, 465-468.

Lima, L. R. O. de, Silva, L. S. da, Vellasco, P. C. G. da S. and Andrade, S. A. L. de, 2004. Experimental Evaluation of Extended Endplate Beam-to-Column Joints Subjected to Bending and Axial Force. *Engineering Structures*, vol. 46, nº 7, pp. 1-15.

Ritchie, J. K. and Chien, E. Y. L., 1979. Innovative Designs in Structural Systems for Buidings. *Canadian Journal of Civil Engineering*, vol. 6, nº 1, pp. 139-167.

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.

Simões da Silva, L. and Coelho, A.G. (2000), "An analytical evaluation of the response of steel joints under bending and axial force", Computers & Structures 79, 873-881.