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# STUDY OF THE COMPRESSION BEHAVIOR OF BUILT-UP MEMBERS COMPOSED OF CONCENTRIC HOT ROLLED CIRCULAR HOLLOW SECTIONS

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***Abstract.*** *This paper presents a study of the compression behavior of built-up members composed of concentric hot rolled circular hollow sections. The use of these composed bars is an innovative solution of practical interest for situations in which a single bar does not reach the required compressive strength. This work presents a review the elastic buckling behavior of isolated bars, the influence of geometric and physical imperfection and the plastic hinge formation when the bar instability occurs. The current compressive strength formulation according to Brazilian Standard is presented. Some technically and economically viable design and fabrication solutions to built-up members composed of concentric hot rolled circular hollow sections are presented. For validation of numerical results, models of singular hollow sections are made and compared to the ABNT NBR 16239 (2013) Standard results. A mesh sensibility test is made, and the sizes of the elements are defined. The results obtained with numerical models are satisfactory. The numerical analysis shows that, for the processed models, the connection type between the inner and outer tubes does not affect substantially the compressive strength of the composed bar.*

***Keywords:*** *Circular Hollow Sections, Axial Compression, Buckling Curve, Steel Structures, Built-up Members*

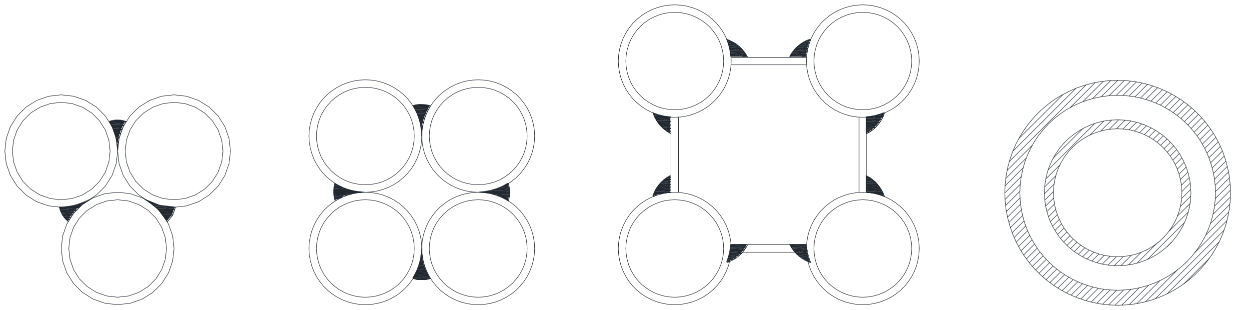
## 1. INTRODUCTION

Hollow steel sections are extensively used in urban and industrial construction in many places of the world. In Brazil, the use of such type of steel profile has grown since year 2000, when Vallourec Tubos do Brasil (previously named V&M do Brasil) raised actions focused on the increase of the use of these profiles in structural systems of civil buildings.

Circular hollow steel sections can be manufactured by hot rolling process (seamless pipe) or by welding procedure (welded pipes). The manufacture of welded tubes is made by conformation of steel plates and connecting them by welding. This process is still used, particularly for very large diameter tubes in which the hot rolling process is not feasible. Nevertheless, the hot rolling process leads to better quality bars, because of the low residual stress generated during manufacturing. However, these last types of profiles have their sizes and thicknesses limited to the capabilities of the production machines.

In some situations, it may happen that the compressive strengths of the bars are lower than the required one. In scope of hot rolled hollow sections under compression, when this situation occurs, some different alternatives can be used to solve the problem. Some of these options are the parallel assembly of tubular profiles or the assembly based on lattice bars or interconnection plates, as shown in Figure 1-a, b and c.

These solutions can cause severe impact on the architectural structure and bring complicating factors in manufacturing, erection and structural design. The welding regions in parallel built-up members are complicate to perform and the connections between beams and columns may be penalized by large eccentricities. An option, which practically does not cause impact in the architecture, is the use of composite steel and concrete structure, made by filling the inside of a tubular profile with concrete. However, this solution can strongly influence the operational viability of the construction, since it makes necessary to cast concrete at the construction site and increases the final weight of the structure. In addition, this solution raises the construction time and brings numerous difficulties such as the need of availability of concrete supply and specialized labor on the site.



(a) (b) (c) (d)

Figure 1. Hollow steel sections built-up members

In this work, a different and innovate solution is proposed: the composed of concentric hot rolled circular hollow sections (Fig. 1-d). This way, it is possible to increase the compressive strength without changing the architecture and without using other materials, such as concrete.

This paper presents the numerical study of the structural behavior of the built-up members composed of concentric hot rolled circular hollow sections, henceforth called CHRCHS, to determine the compressive strength of these bars. To perform the numerical study of the CHRCHSs behavior, it was used the Finite Element Method, in ABAQUS software. In this work, there were also established technically and economically viable design solutions for the connections between the inner and outer tubes of the CHRCHSs. The concentric compound sections behavior was studied in three different connection situations along the tubes: sliding connections, fixed connections and without connections.

## 2. STRUCTURAL BEHAVIOR REVIEW

### 2.1 Structural Stability

According to Chen (1987), in the classical theory for the pinned-ended column, the differential equation that has to be solved to describe the elastic buckling is shown in Eq. (1). This theory considers a column without initial crookedness.

$$EIy'' + Py = 0 \tag{1}$$

where $E$ is Young`s modulus, $I$ is the moment of inertia of the cross section, $P$ is the load applied and $y$ is the deflection at the center of the column. Form the Elasticity Theory, is known that $EIy''$ is also the internal resisting moment (Chen 1987).

Equation (1) is a second-order linear differential equation, which leads to the critical buckling load, or Euler load, as shown in Eq. (2). The deflected shape as shown in Eq. (3) (Hibbeler, 2010).

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{2}$$

$$v(x) = C_1 \sin\left(\frac{\pi x}{L}\right) \tag{3}$$

where $P_{cr}$ is the critical buckling load, $L$ is equivalent length of the element and $C_1$ is a constant equal to deflection at the center of the column. For those perfectly straight columns the Euler load marks the bifurcation point. In real design cases, this perfectly straight column does not exist. An actual column has some geometrical imperfections

For the same pinned-ended column discussed before, if it is assumed that the initial crookedness is in the form of a half sine, this initial geometry will be described with de same Eq. (3), but considering the term $C_1$ as the amplitude of the initial crookedness at middle of the column. This condition leads to a new differential equation as shown in Eq. (4).

$$EIy'' + P(y + v_0) = 0 \tag{4}$$

where $v_0$ is the initial curvature of the column. Solving this equation, the deflected shape is described by Eq. (5).

$$v(x) = \left( \frac{1}{1 - P/P_{cr}} \right) v_0 \sin\left(\frac{\pi x}{L}\right) \tag{5}$$

where $P$ is the load applied, $v_0$ is the amplitude of the crookedness and $P_{cr}$ is the same as described in Eq. (2).

### 2.2 Residual Stresses

Residual stresses in structural steel sections are inherent from the manufacturing process. In the case of hot rolled sections, these residual stresses are induced by the differential cooling along the cross section of the element. This thermally-induced stresses produce a residual compression state in the parts that has more rapidly cooling and a residual tension state in the parts that has a slower cooling. This whole thermally induced pattern of residual stresses has to be in self-equilibrium.

The tubular steel sections produced by hot rolled process usually have small residual stresses when compared to other profiles. The only important differential cooling in these sections is the thermal gradient that exists through the thickness, due to the faster cooling outside of the tube when compared to the inside of it (Law, 2012).

According to ECCS Manual on Stability Steel Structures (1976), the tubular sections columns strength are not strongly affected by residual tensions, which commonly affect others sections, like I shapes. This ECCS publication propones that residual stresses in hot rolled steels sections have a linearly variation in thickness, from -0.15 to +0.15 of the material yield strength, as shown in Fig. 2.

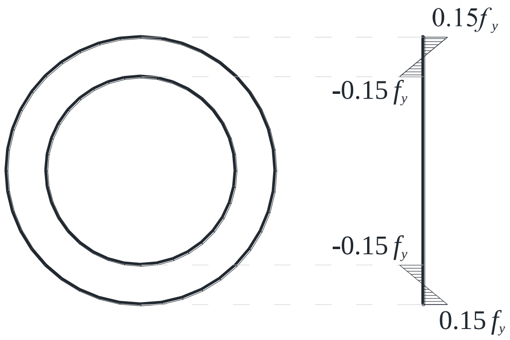



Figure 2. Residual stresses

European Standard EN 1993-1-1 (2005) recommends increasing the initial curvature to consider the effect of residual stresses for global structural analysis of frames. For low residual stresses sections, as hot rolled circular hollow sections, the recommended total curvature is $L$/300, where $L$ is the length of the bar.

Brazilian Standard ABNT NBR 8800 (2008) and American Standard ANSI/AISC 360 (2010) recommend to use a reduced Young's modulus to consider residual stresses effects. According to these standards, the Young's modulus of all types of steel sections should be reduced by 0,8 in structural analysis.

### 2.3 Elasto-plastic Behaviour

Some materials, as steel, tend to have a perfectly plastic behavior when reach stresses above yield strength. A section that starts to yield at extremity fiber starts to form a plastic hinge, and when all of the transversal section gets yielded, the plastic hinge is completely formed, and reaches a plastic collapse. On this situation, the structure becomes a mechanism, and depending on the conditions, it becomes unstable (Chen, 2007).

For a simple supported beam, the critical moment plastic load can be calculated by a simple equilibrium of areas and loads. When it comes to columns with initial crookedness, the load nature is an axial load plus a bending moment, and the plastic hinge form is affected by the neutral axis displacement. The equilibrium can still be made, but the moment has to be computed and the distribution of the yielded parts along the cross section is no more symmetric.

The design of slender steel structures is basically a combination of elastic buckling and plastic hinge formation in a transversal section. The deflection caused by the axial load in the columns with initial crookedness increases in elastic behavior until reaches the initial yielding of the material in some points of the transversal section. At this point, the elasto-plastic behavior controls the phenomena and a plastic hinge begins to form, decreasing the gain of load capacity of the column. When the cross section is totally yielded, the plastic hinge is formed and the structure reaches its critical load and collapses.

## 3. STANDARDS BUCKLING CURVES CURRENT FORMULATION

Bars with low residual stress or more favorable distributions of this stress present buckling curves that lead to greater compressive strength. In spite of this, the American Standard ANSI/AISC 360 (2010) and the Brazilian Standard ABNT NBR 8800 (2008), in a simplified manner, provide only one buckling curve, assuming the same influence of residual stress to all the cross sections. The Canadian Standard CAN/CSA-S16 (2005) is stricter and provides two curves, one for the cross sections with little influence of the residual stresses, and another for those sections in which the residual stress has a more significant influence on the compressive strength. On the other hand, the European Standard EN 1993-1-1 (2005), in an even more strict way, provides five curves with gradual variation according to the level of influence of residual stresses on the value of the compressive strength. Moreover, Brazil's ABNT NBR 16239 (2013) Standard provides a specific buckling curve to hot rolled circular hollow sections, in which the influence of residual stresses is highly reduced, identical to the equivalent curve from CAN/CSA-S16 (2005).

### 3.1 Brazilian Standard

Brazilian Standard ABNT NBR 16239 (2013) provides compressive strength $N_{c,Rd}$ value by Eq. (6).

$$N_{c,Rd} = \frac{\chi A_g f_y}{\gamma_{a1}} \tag{6}$$

where $\chi$ is a reduction factor associated with compression, $A_g$ is the cross section area, $f_y$ is the yield strength of steel and $\gamma_{a1}$ is the design resistance safety factor.

The value of $\chi$ is determined by Eq. (7).

$$\chi = \frac{1}{\left(1 + {\lambda_0}^{4.48}\right)^{1/2.24}} \tag{7}$$

where $\lambda_0$ is the reduced slenderness factor, which should be calculated by Eq. (8).

$$\lambda_0 = \sqrt{\frac{A_g f_y}{N_e}} \tag{8}$$

where $N_e$ is the critical elastic force for the relevant buckling mode, based on the gross cross sectional properties.

## 4. DESIGN SOLUTIONS

To make practical sense to develop the study of the behavior of built-up sections formed by concentric tubular sections, the possible ways of assembling this type of composition should be studied. The end flange joints do the compatibility of the displacements at the extremities of the bars, but may be necessary to match the transverse displacement of the inner and outer tubes, in some points, along the bars. From the viewpoint of designing and manufacturing, the problem of these connections design between the tubes should be solved.

To ensure that each bar of built-up sections works structurally together with the other bar of the assembly, the Brazilian Standard ABNT NBR 8800 (2008) recommends that the connecting elements along the bars respect Eq. 9.

$$\frac{L_{trav}}{r_{min}} \leq \frac{\lambda}{2} \tag{9}$$

where $r_{min}$ is the minimum radius of gyration of individual component, $\lambda$ is the slenderness parameter for built-up section and $L_{trav}$ is the connections distance. In this paper, the simulations were performed considering three types of assemblies: without connections, with rigid connections and with sliding connections, that can be manufactured as described in the following items.

### 4.1 Rigid Connections

One of the proposed options for engaging the tubes together is the use of connection parts welded on tubes. In the production of CHRCHSs, the steps for placing the connections can be divided into three. In the first stage, the connectors must be fixed with a fillet weld on the outer face of the inner tube, as shown in Fig. 3-a. In the second stage, the outer tube must be drilled at the points above the places where the connecting pieces will be and then, the assembly should be mounted. In the third step, a butt weld should be performed, welding the connecting pieces to the outer pipe, as shown in Fig. 3-b.

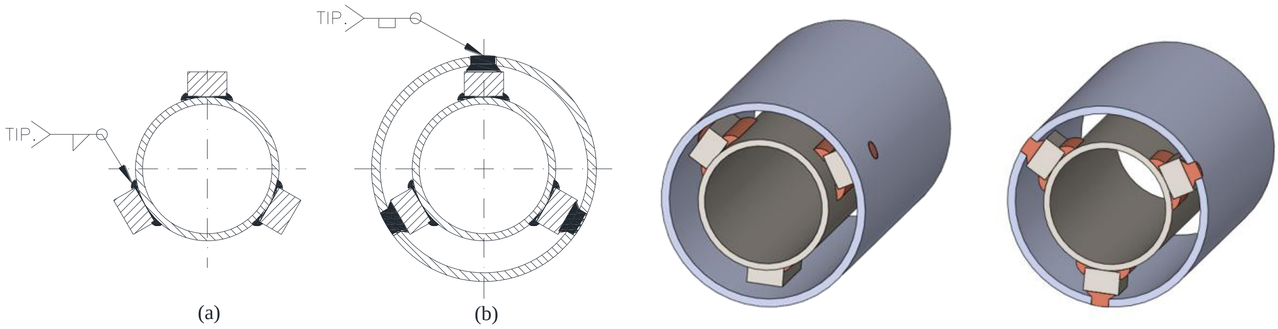



Figure 3. Rigid connections between tubes

### 4.2 Sliding Connections

The second option for engaging the tubes together is the use of sliding connections. In this case, the connection parts are fixed to the outer tube and leaning against the inner tube. To assemble this type of connection, initially the outer tube should be drilled in the positions of the connections. In the second stage, the tubes should be concentrically positioned and the pins should be placed in the holes, resting against the inner tube. After this step, a fillet weld should be performed, welding the pins and the outer tube. The assembly is shown in Fig. 4.

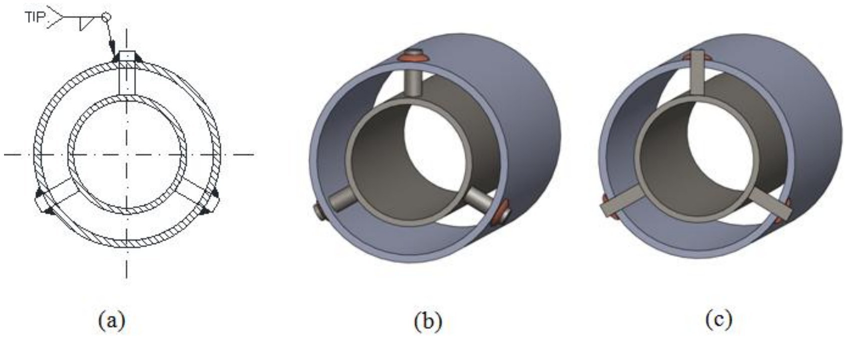



Figure 4. Sliding connections between tubes

## 5. CALIBRATION OF NUMERICAL MODELS

The development of the numerical models was primarily made from isolated circular hollow sections with an initial crookedness under compression, simulated in ABAQUS software, by Finite Element Method. Different types of elements and meshes were tested, and the results were compared with ABNT NBR 16293(2013) design procedures for bars under axial compression.

The software ABAQUS uses the iterative incremental Newton-Rapson method in non-linear analysis to obtain the solutions for the equation systems. When performing a stability and critical load analysis, as in the case of the study presented here, the ABAQUS uses the Modified Riks Method, also named Arc Length Method, which allows obtaining static equilibrium states during unstable phase of structure (CASTRO E SILVA, 2006). To study the plastic behavior of the steel, this software allows informing the material stress-strain curve points. On this study, a bi-linear stress-strength curve was considered, with yield strength of 350 MPa and Young`s modulus of 200 GPa. On the plastic parcel of the stress-strength material curve, an inclination of 1/10,000 was considered to avoid possible computational difficulties to converge the structural analysis, as suggested in ENV 1993-1-1(1992).

After testing different elements in the software, the S8R element was selected, which is an 8-node quadratic doubly curved shell, with reduced integration. To represent the stress and strength non-linear behavior of the material, five points of integration were set along the thickness, and the integration was solved by the Simpson Rule.

The models were made considering the geometric imperfections by inputting an initial crookedness of L/1,000. This value was selected to enable the comparison of the numerical results with the buckling curve of the Brazilian Standard ABNT NBR 16239(2013), once this is the value in which the initial crookedness of the Standard buckling curve is based on.

The materials imperfections were neglected in the numerical model. The ABAQUS software is not prepared to input an initial stress along the thickness of the shells. Additionally, the residual stresses are very low and act just along the thickness, leading its influence to be negligible.

A mesh sensitivity test was performed, varying the number of the elements in the cross section according to the bar diameter. The test was made with sections TC 73x3,6 (D/t = 20) and TC 323,8x6,4, for the slenderness ratios of 60 and 120.

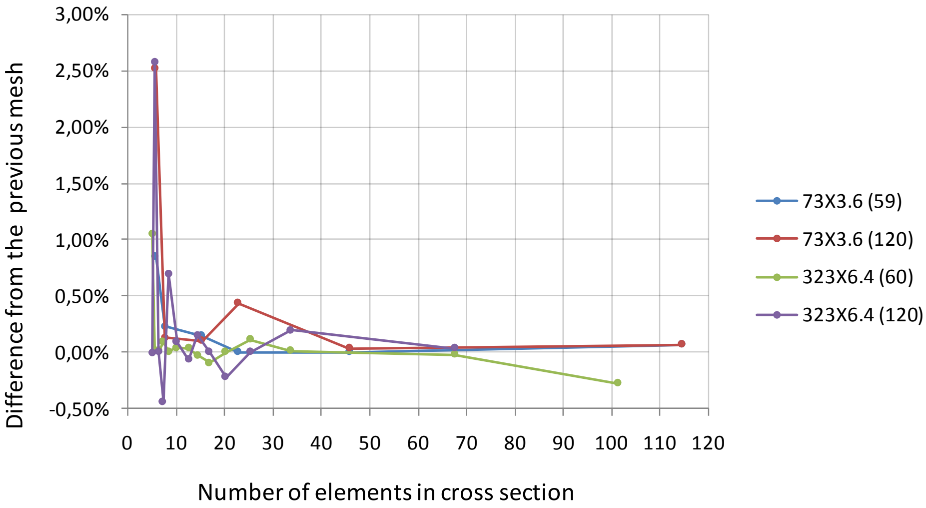



Figure 5. Mesh sensitivity test

As shown in Fig. 5, from 10 elements in cross section, the difference between the values is almost negligible in all models tested. In order to reduce to a minimum error of the numerical model, the number of 15 elements in the cross section was adopted as reference in this work.

### 5.1 Numerical results from calibration models

To study the calibration of the numerical models, 60 tests were done by using 3 different cross sections of isolated steel circular hollow sections. These cross sections were chosen to contemplate the variation of the *D/t* relation in the sections manufactured in Brazil.

The following cross sections: 73x3,6 (*D/t* = 10), 73x7,1 (*D/t* = 20), 323,8x6,4 (*D/t*=50), were tested numerically, varying the slenderness ratios by 10 to 10, from 10 to 200. For these three sections, the buckling curves ($\lambda$ versus $\chi$) were obtained and compared to ABNT NBR 16239 (2013) buckling curves, as shown in Figure 6.

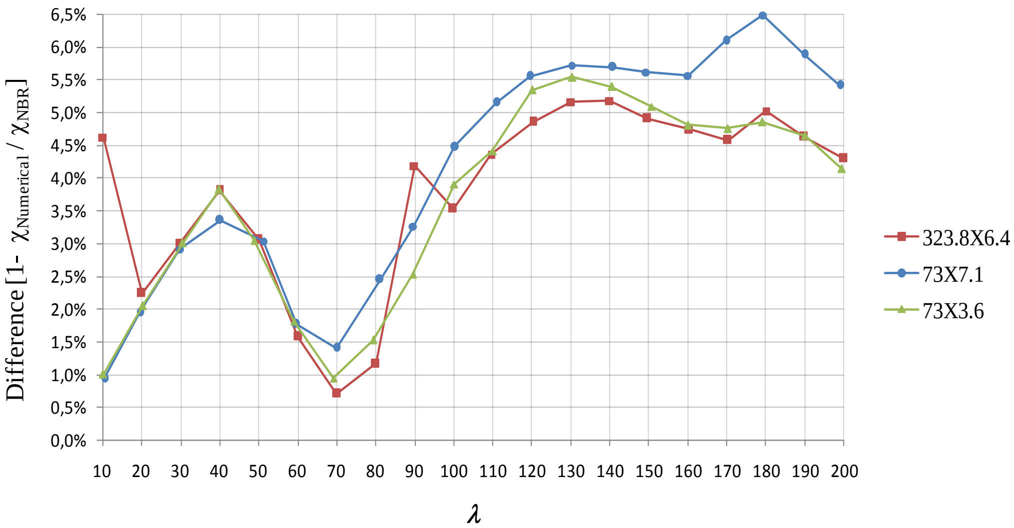



Figure 6. Buckling curve difference (Numerical / ABNT NBR 16239 (2013))

As can be inferred from the Figure 6, the variation between the numerical models and the results obtained in accordance with ABNT NBR 16293 (2013) were below 6.5%. Regarding these differences, the following assessments can be performed:

1) The Standard buckling curve was made by using a statistical treatment based on laboratory tests, being subjected to variability. In addition to this, the Standard buckling curve was mathematically adjusted, which is a source of deviations.
2) All the results obtained numerically by FEM models were conservative, even neglecting the residual stresses.

Considering these aspects, the adopted numerical simulation process was considered adequate for this study of CHRCHS.

## 6. NUMERICAL RESULTS OF NUMERICAL CHRCHS MODELS

Once the numerical simulation process was validated by the isolated tubes model, simulations were performed with the CHRCHSs models. Nine different combinations of cross sections were simulated, each one with the tree different types of connections between the inner and outer tubes, considering rigid connections, sliding connections and without connections along the tubes. In all models, the extremities of the tubes were considered rigidly coupled between them. This consideration assumes that the connection flange made a perfect transfer of the load to the inner and outer tubes, without deformation between them. All the models were made considering an initial crookedness of $L$/1,000. Each section of CHRCHS was simulated with different slenderness ratios, varying the length of the bars. The tested numerically models are presented in the Fig. 7.

| Model | Inner Tube | | Outer Tube | |
|---|---|---|---|---|
| | Section | *D/t* | Section | *D/t* |
| 1 | 73X3,6 | 20 | 114,3X4,5 | 25 |
| 2 | 273X30 | 9 | 356,6X10 | 36 |
| 3 | 273X30 | 9 | 355,6X25 | 14 |
| 4 | 273X20 | 14 | 356,6X25 | 14 |
| 5 | 273X10 | 27 | 356,6X25 | 14 |
| 6 | 273X8 | 34 | 356,6X25 | 14 |
| 7 | 273X8 | 34 | 356,6X16 | 22 |
| 8 | 273X8 | 34 | 356,6X12,5 | 28 |
| 9 | 273X8 | 34 | 356,6X8,8 | 40 |

Figure 7. Sections of the CHRCHSs numerical models

The results obtained with ABAQUS were considered consistent. There as presented two curves for each model. Curve A presents the difference between the model with sliding connections and the model with rigid connections. Curve B presents the difference between the model without connections along the bars and the model with rigid connections. These results are shown in Fig. 8 and 9.

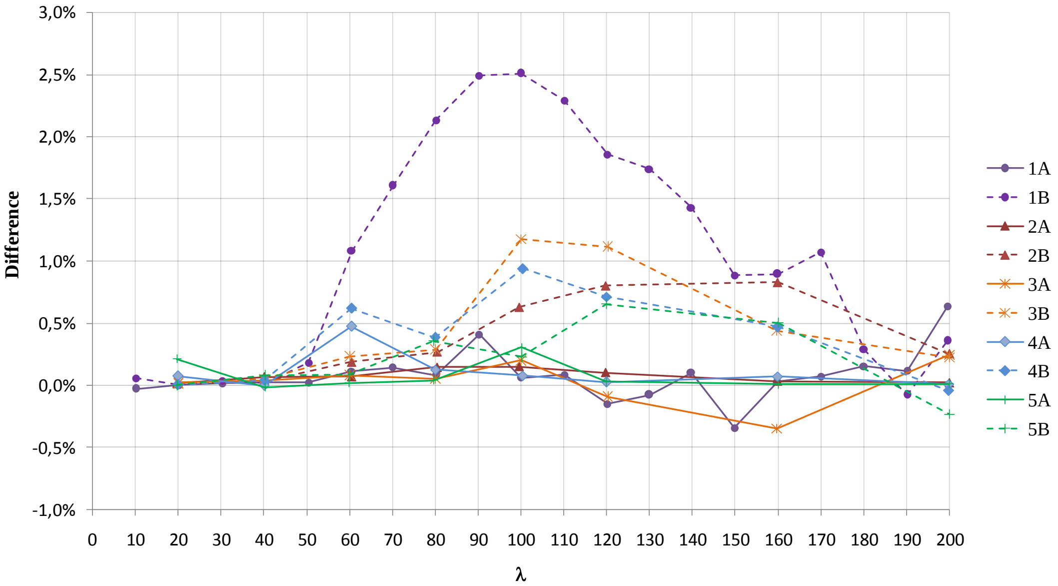



Figure 8. Numerical results (models 1 to 5)

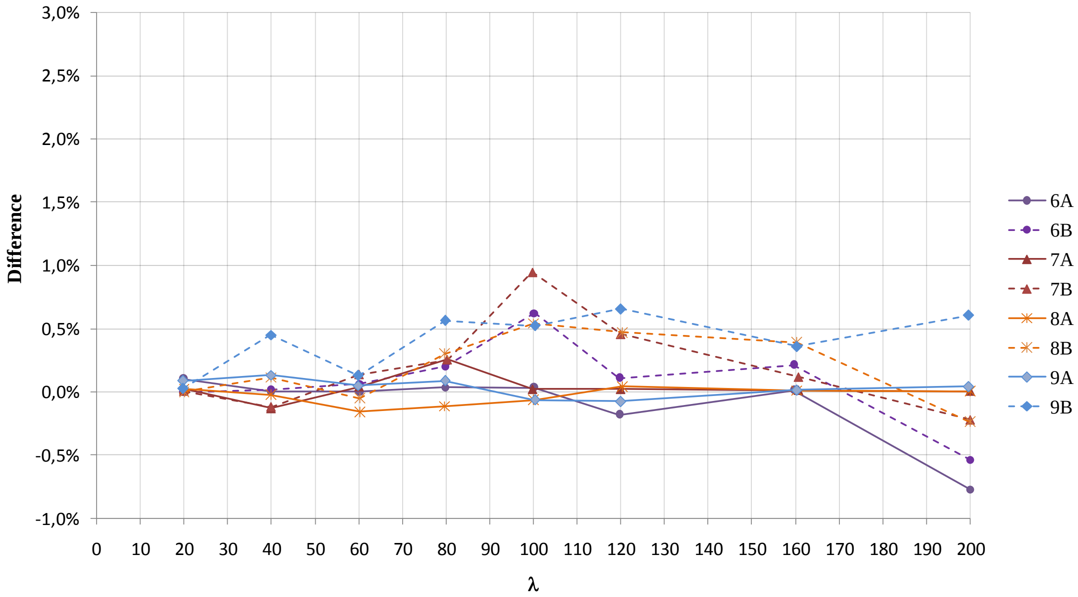



Figure 9. Numerical results (models 6 to 9)

## 7. RESULTS ANALYSIS AND CONCLUSIONS

According to the results shown in fig. 8 and 9, the interchange of the connection types between the inner and outer tubes makes the CHRCHS compressive strength varies only 2,5%. For the models tested, these results demonstrate that the connection between the tubes can be neglected. In these cases, the CHRCHS can be manufactured merely by making the inner and outer tubes extremities displacement compatible, using the connection flanges. The loss of compressive strength caused by the absence of the connections along the tubes is insignificant for the tested models.

Other combinations of the inner and outer cross sections should be analyzed to determine the CHRCHSs global behavior variation associated to the connection types along the tubes.

## 8. ACKNOWLEDGEMENTS

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## 9. REFERENCES

ABNT, 2008. *NBR 8800 – Projeto de Estruturas de Aço e de Estruturas Mistas de Aço e Concreto de Edifícios*. Rio de Janeiro.

ABNT, 2013. *NBR 16239 – Projeto de Estruturas de Aço e de Estruturas Mistas de Aço e Concreto de de Edificações com Perfis Tubulares*. Rio de Janeiro.

ANSI, 2010. *American Institute of Steel Construction 360-10 – Specification for Structural Steel Buildings*. Chicago.

CASTRO E SILVA, A. L. R. *Análise Numérica Não-Linear da Flambagem Local de Perfis de Aço Estrutural Submetidos à Compressão Uniaxial*. Tese de Doutorado, Universidade Federal de Minas Gerais, 2006.

CAN/CSA, 2003. *S16-01 – Limit States Design of Steel Structures*.Ottawa.

Chen, W.F., Han, D.J., 2007. *Plasticity for Structural Engineers*. Springer-Verlag, New York, 1st Edition.

Chen, W.F., Lui, E.M., 1987. *Strutural Stability. Theory and Implementation*. Prentice-Hall, NewJersey, 1st Edition.

ECCS, 1976. "Manual on Stability of Steel Structures". *European Convention for Constructural Steelwork - Committee 8*. 2nd edition.

EN1993-1-1 : *Design of steel structures - Part 1-1: General rules and rules for buildings* – Eurocode 3, 2005.

ENV1993-1-1: *Design of steel structures - Part 1-1: General rules and rules for buildings* – Eurocode 3, 1992.

Hibbler, R.C., 2010. *Resistência dos Materiais*. Pearson Prentice Hall, São Paulo, 7th edition.

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