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Study of Inelastic Behavior of Reticular Structures of Steel Bars - Phenomena of Plastification.

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Abstract *— Technological advancement has increasingly helped solve engineering problems, but the designer who does not seek knowledge of the physical behavior of materials and mathematical techniques to solve them runs the risk of not being able to interpret the results provided by structural software. Computational techniques do not provide the exact solution of engineering problems, they provide approximations to the intervals where the solution of the differential equations governing the mechanics of the continuum are inserted. The engineer who does not know how to idealize the engineering problem in his mind will not be able to model the problem in the computer. One of the most intriguing and peculiar engineering problems is the plastification phenomenon of metallic objects.*

Keywords— Steel Bars, physical behaviour of materials, plastification.

I. INTRODUCTION

Structural analyzes are made in first-order theory in wich the equilibrium of the structure is studied in the indeslocated position, and in second-order theory where equilibrium is studied in the displaced position. The stability of the structure can only be studied in second order theory. According to Chen (et. Al., 1996) in the study of the resistence and stability of structures it is necessary to do:

- Check the inelastic behavior of the materials;
- Check the flexibility of the connections;
- Check second order effects due to geometry change.

The consideration of physical and geometric nonlinearities are pre-requisites for the beginning of the understanding of the plastification effects of steel structures.

II. ANALYSIS TYPES

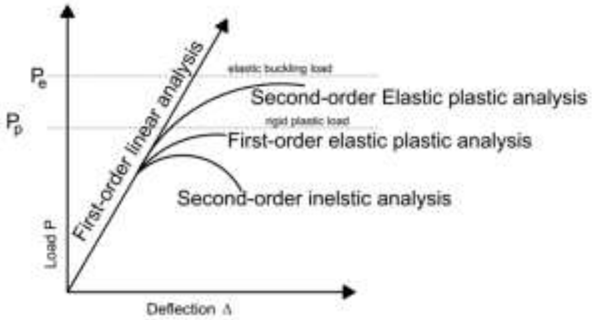

Fig.1: Load-displacement characteristics of general analysis types.

The types of structural analyses are the First and Second Order Elastic Analyses and First and Second Order Inelastic Analyses, as shown in the figure above.

In order to understand and delineate the plastification effects of steel structures, Chen (1) proposes the Advanced Structural Analysis, which consists of a technique that seeks to introduce into the behavioral models of the elements representative of the structure and its materials the closest hypotheses of reality and, together, sophisticated numerical and iterative procedures to estimate the non-linear behavior of these structures. In this way, the advanced analysis encompasses the nonlinear, physical and geometric analyzes in the studies of the structural systems and their members modeling the effects of plastification.

Three lines of thought for computacional algorithms have studied the effects of second order as follows:

1. Second order inelastic analysis with formation of plastic hinge joints and ficticious loads National Loads Chen (et al., 1996);
2. Modified Plastic Hinge Joint Method - allows smooth degeneration of stiffness;
3. Distributed plasticity - sliced discretized bar where the inelasticity is modeled with the stress state at the center of the slice, Lavall 1996.

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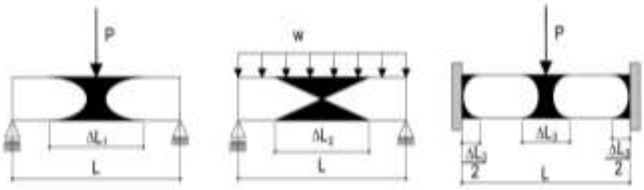

f=shape factor=$\frac{M_p}{M_y}$; Δ_{L1}=L$\left(1-\frac{1}{f}\right)$; Δ_{L2}=L$\sqrt{1-\frac{1}{f}}$; Δ_{L3}=$\frac{L}{2}\left(1-\frac{1}{f}\right)$

Fig.2: Plastic-hinge lengths in beams with different boundary conditions and load CHEN et al. 1996.

III. ATTRIBUTES NECESSARY FOR THE STUDY OF PLATIFICATION - SECOND ORDER EFFECTS.

The study of plastification in steel elements should be done by accounting for second order effects, such as loss of physical capacity of steel sheets (inertia, area, thermal expansion, etc.), and changes in geometry due to the effects of forces. These changes during the action of forces must be inserted into the model. The following are the items that should be observed in the modeling:

- Initial imperfections due to the curvature of the bars, frames and columns out of alignment, displacement of the bars.
- Residual tensions due to manufacturing and assembly processes - Welding action.
- Connection types: flexible, rigid, semi-rigid.
- Types of cross sections: symmetrical, non-symmetric, open or closed profile.
- Effects of loading: dynamic, variable, repetitive due to construction stages, etc.
- P-Δ moment: second-order moments due to axial force acting through displacements associated with member chord rotation.
- P-δ moment: second-order moments due to axial force acting through displacements associated with member curvature bending.

IV. FORMULATION

Engineering strains and stress:

$$\varepsilon = \lambda - l = \frac{l_c - l_r}{l_r} = \frac{\Delta l}{l_r} \quad ; \quad \sigma = \sigma_N = \frac{N}{A_r} \qquad (1)$$

$$\sigma = \sigma(\varepsilon) \;\therefore D = \frac{d\sigma}{d\varepsilon} \qquad (2)$$

Stiffness module or angular coefficient or slope of the strain-stress curve

Elastic phase: (load e unload);

$$\left(\sigma - \sigma_y\right) \leq 0 \quad \therefore \quad D = D^e = d\sigma/d\varepsilon \qquad (3)$$

Plastic phase: (unload)

$$\left(\sigma - \sigma_y\right) > 0 \quad \therefore \quad D = D^e \qquad (4)$$

(load)

$$D = D^{ep} \qquad (5)$$

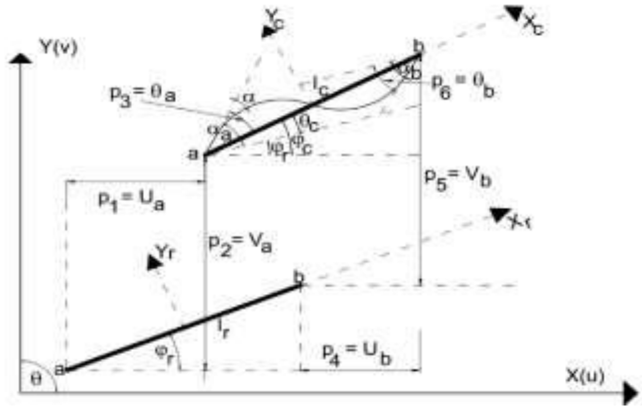

Fig.3: Coordinate system and degrees of freedom.

Corrotational local system:

$$q_\alpha = \{q_1 \quad q_2 \quad q_3\} \;\therefore\; q_1 = l_c - l_r \;; \quad (6)$$

$$q_2 = \alpha_a \;;$$

$$q_3 = \alpha_b$$

Cartesian degrees of freedom: global system

$$p_i = \{u_a \quad v_a \quad \theta_a \quad u_b \quad v_b \quad \theta_b\} \quad (7)$$

The structural theory used in this work is based on the hypothesis attributed to Bernoulli-Euler, which states that: "The cross-sections flat and orthogonal to the axis of the bar remain flat, indeformable and orthogonal to the axis after deformation." The displacements u_c and v_c of a section point in the corrotational system (x_c , y_c) are then determined by:

$$u_c(x,y) = \overline{u_c}(x) - y_r sen\alpha \quad \therefore \qquad (8)$$

$$v_c(x,y) = \overline{v_c}(x) - y_r(1 - cos\alpha) \qquad (9)$$

$$\varepsilon = (1 + \overline{u_c})sec\alpha - 1 - y_r\alpha \qquad (10)$$

Equilibrium Equations: PVW

$$P_i = Q_\alpha \, q_{\alpha i} \qquad (11)$$

$$Q_\alpha = \int v_r \sigma \varepsilon_\alpha dV_r \qquad (12)$$

$$\frac{\partial P}{\partial p} = K_t \quad \therefore \qquad (13)$$

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$$k_{i,j} = q_{\alpha,i} D_{\alpha,\beta} q_{\beta,j} + q_{\alpha,i} H_{\alpha,\beta} q_{\beta,j} + Q_\alpha q_{\alpha,ij} \quad (14)$$

$$D_{\alpha,\beta} = \int v_r \varepsilon_\alpha D \varepsilon_\beta \, dV_r \quad \therefore \; H_{\alpha,\beta} = \int v_r \sigma \varepsilon_{\alpha\beta} \, dV_r \quad (15)$$

Constitutive Stiffness Matrix: Physical and Geometric

$$K_M = B^T DB \quad \textit{Physical part} \quad (16)$$

$$K_G = B^T HB + Q_\alpha G_\alpha \quad \textit{Geometric part} \quad (17)$$

$$\begin{cases} \sigma = E\varepsilon & \rightarrow \quad \textit{Elastic Regime} \\ \sigma = D\varepsilon & \rightarrow \quad \textit{Elastic} - \textit{plastic Regime} \end{cases}$$

V. COMPUTATIONAL ALGORITHM

In 1996, Lavall proposed a computational algorithm for the study of the plasticity distributed in steel plates constituent of beam and frames members. This method was known as slicing method based on the formulation of item 4.

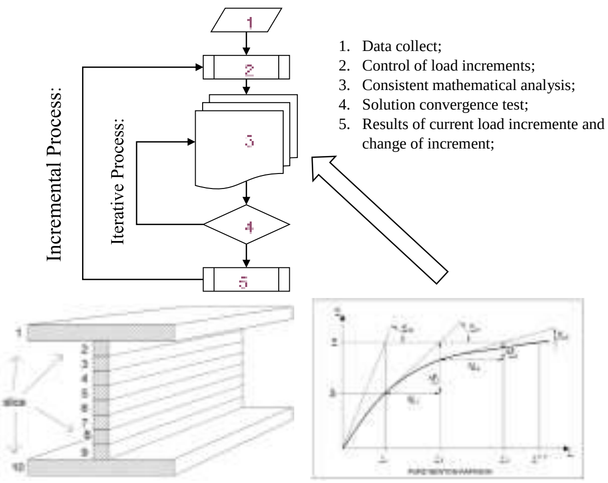

Figure 4 – Computational tool for evaluating plasticity.

VI. EXEMPLES

A static foundation pile test was carried out in the city of Rio de Janeiro in 2011 in which the reaction beam was a W1000x217 (ASTM A36, fy = 250MPa) with 5 meters in length. The test load was 1697kN and so it was done. As a research objective to plasticize the bar, the load was increased to 2001 kN where from this point the lateral buckling mechanism started and the test was stopped. This reaction system (W1000x217) is studied in four different models:

1. Model 1 - Strength of materials;
2. Model 2 - Computational Algorithm of Nonlinear Analysis Lavall 1996;
3. Model 3 - SAP2000 v19;
4. Model 4 - Ansys 16.

6.1 Model 1 - Strength of materials:

$$M_{max} = \frac{PL}{4} = M_{pl} = Z_x * f_y$$

$$E = 20000 kN/cm^2 \quad f_y = 25 kN/cm^2$$

$$P = \frac{4 * M_{pl}}{L} \cong 2341 kN$$

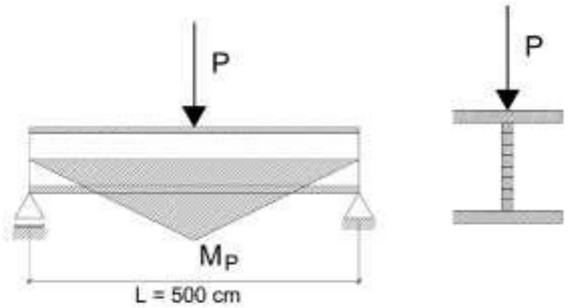

Fig.5: Maximum Plastic concentrated Load Beam

6.2 Model 2 - Computational Algorithm of Nonlinear Analysis Lavall 1996; – Plastic slices:

Fig.6: Interface Data Entry Lavall 1996

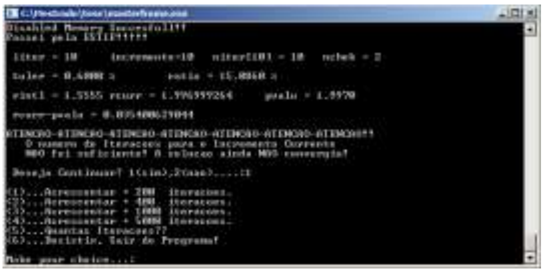

Fig.7: Processing Data, Lavall 1996

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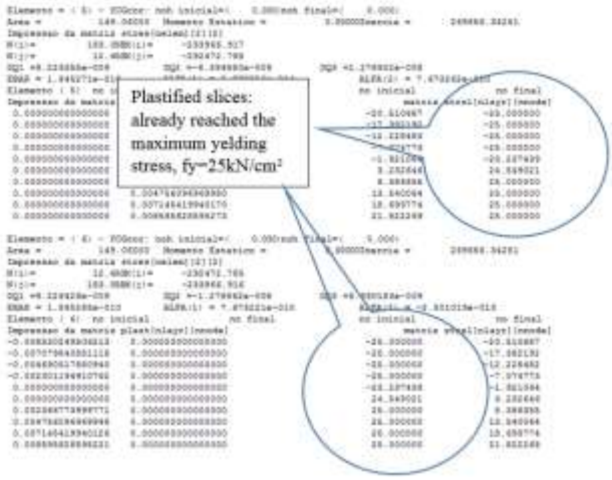

Fig.8: Results Data, Lavall 1996

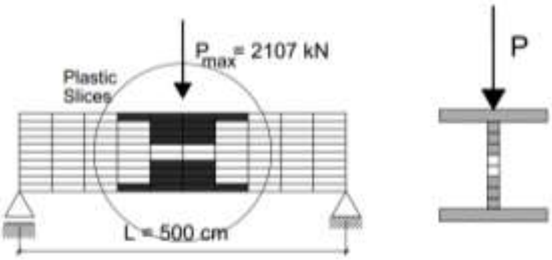

Fig.9: Plastified slices zone.

6.3– Model 3 - SAP2000 v19:

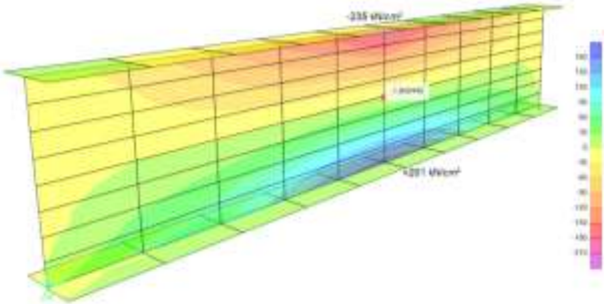

Fig.10: Longitudinal stress σxx web beam.

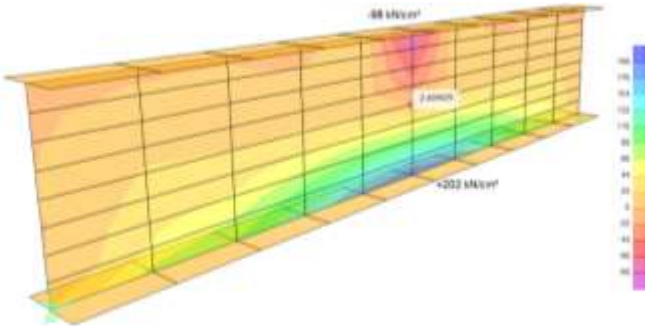

Fig.11: Shear stress τxy web beam.

6.4 Model 4 - Ansys computer program 16.

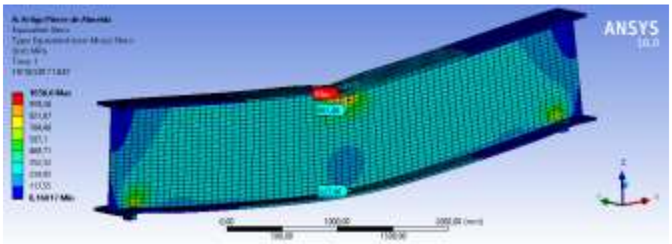

Fig.13: Maximum Von-Mises stress web beam.

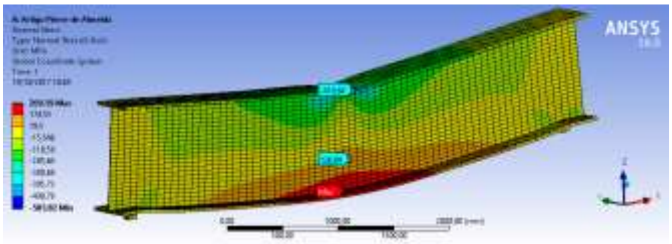

Fig.14: Longitudinal stress σxx web beam.

VII. RESULTS ANALYSIS

	Real Test	Materials Resistence	Lavall 1996
Maximum Load	**2001 kN**	**2341 kN**	**2106,9 kN**
Observations	beginning of lateral buckling and interruption of the test		Result until the ninth increment of load, from there the beam breaks due to plastification where the limit of the stress is of 25 kN/cm² and the processing is interrupted.

	SAP2000 v19	Ansys 16.0
Maximum Load	**2335 kN**	**2341 kN**
Observations	Resolution of the problem up to the maximum load, however, elements with stress above the yielding are shown, ex. 235kN / cm² (2350MPa), which does not occur in a real test.	Solving the problem up to the maximum load and the maximum stresses at the top and bottom of the beam are shown, however the stresses went beyond the ultimate tensile stress 550MPa.

Table 1 – Comments about the results.

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