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NON-LINEAR DYNAMIC ANALYSIS OF STAYED STEEL COLUMNS

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***Abstract**. This work describes non-linear finite element simulations made on stayed system subjected to sudden impact loads. The study aimed to determine the influence of the prestress forces magnitude and its response with and without damping effects. Various cases where the load magnitude varied from 10% up to 100% of the stayed column load bearing capacity were investigated. The performed analyses enabled an evaluation of the structural system amplification factor to be later compared to allowing horizontal deflection limits usually adopted in steel design standards.*

1 INTRODUCTION

Prestressed stayed steel columns are excellent structural systems for situations where loads have to be supported with an easy and fast erection and assembly. Its structural conception and high slender shape enable it to become a light, economic and efficient structural system [1]. Although, this structural solution dates back from the 1960's [2-9], especially when subjected to dynamic actions, is not fully understood.

This motivated a detailed study of the structural system non-linear dynamic behaviour by means of ANSYS [10] simulations when submitted to sudden loads. The current non-linear dynamic finite element analysis was performed on twelve meter length pre-stressed steel columns . These structural elements load bearing capacity was substantially increased by the additional restriction provided by the tie forces that are transferred to the main columns by means of horizontal tubes, perpendicularly welded to the column midpoint [11][16].

The parametric study main variables were the pre-stressed element shape/area (cable or reinforced bar) and the adopted element pre-stress force. These two variables substantially altered the dynamic response and proved to be key elements for a better understanding of the structural system dynamic response [12].

The load was introduced to the system by means of a concentrated load positioned at the top of the column through a rectangular pulse with five seconds to simulate a sudden impact load situation. The investigation was centred on varying the magnitude of the applied load from 10% up to 80% the stayed column capacity with and without prestress forces while considering or not the structural dampening.

2 NUMERICAL MODELLING

The same model used in a previous static analysis [12], was adopted with the aid of the ANSYS program. The prestressed stayed steel column model was divided into three parts: the central tubular column, the secondary cross bars and the tie cables. Twelve one meter length element were used in the central column while the secondary cross bars were simulated with two 300 mm elements. These dimensions delimitate a 10% inclination angle for the column ties, each modelled by a single element.

Two different materials were used in the analysis. The first type, used in the main column and secondary cross bars, possessed a 205000MPa Young´s modulus, a 20500MPa tangential modulus, a 0.3 Poisson ratio, a 380 MPa yield stress and 7850 kg/m^3 of density. The second type, used in the tie cables, possessed a 100000MPa Young´s modulus, a 10000MPa tangential modulus, a 0.3 Poisson ratio, a 750 MPa yield stress and 9100 kg/m^3 of density.

The main tubular column and secondary cross bars were modelled by PIPE20 elements while the ties were simulated with LINK10 (specified with a tension only option) elements. The geometrical characteristics are: the main column has a external diameter and thickness of 89.3 mm and 3.2 mm; the secondary cross bars have external diameter and thickness of 42.6 mm and 3 mm; and the stays have 6.35 mm diameter. An 8 mm amplitude sinusoidal initial imperfection was introduced in the numerical model to be compatible with the tests measured imperfections [13-17].

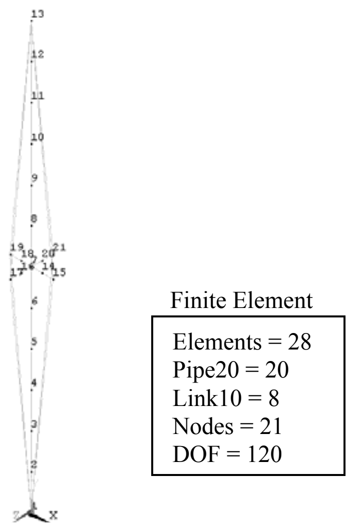


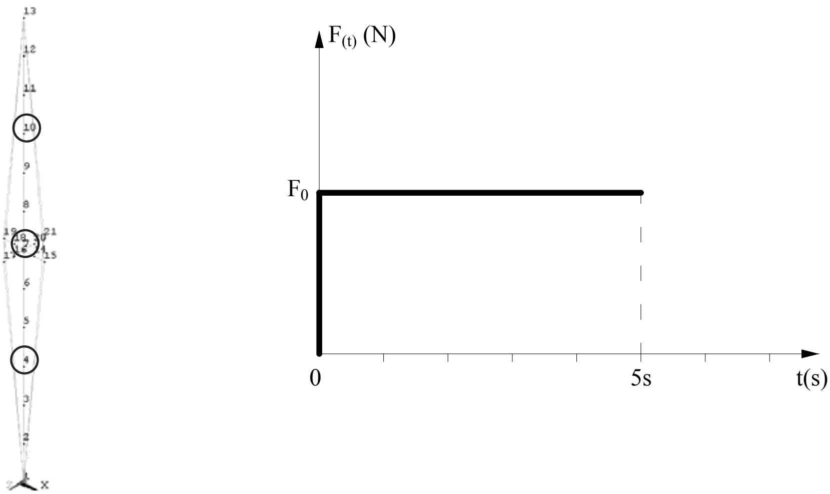
Figure 1: Finite element model used to represent the prestressed stayed steel column.

3 DYNAMIC ANALYSIS

The prestressed stayed steel column was modelled with cables and bars as stays. In this case only cables were modelled. The non-linear dynamic analysis considered a rectangular pulse to represent an impact load case, applied on the top of the structural system, in order to simulate a sudden load. In this analysis the time of the dynamic loading application was considered equal to five seconds.

The investigation was centred on varying the magnitude of the applied dynamic load from 10% up to 80% of the stayed column capacity with and without prestress forces while considering or not the structural damping. The time step used in this investigation was equal to 0.001s ($\Delta t = 10^{-3}$ s). The analysis enable the determination of the amplification factors for the studied prestressed stayed steel columns using cables as stays.

Three nodes were chosen in the main column at 1/4, 1/2 and 3/4 span to enable a comparison to the recommendations present in the Brazilian Standard [18] and Eurocode [19]. Lateral displacements were evaluated at and compared to the suggested limit of L/500 (24 mm - Brazilian Standard [18]) and L/300 (40 mm - Eurocode [19]), where L is the main column length (12 m).



(a) Nodes Location (b) Impact loading

Figure 2: Prestressed stayed steel column: nodes location and impact loading.

3.1 Structural damping

In this investigation, the structural damping was considered according to the Rayleigh proportional damping formulation [20]. The bridge structure damping matrix is defined by the parameters α and β, determined in function of the damping modal coefficient. According to this formulation [20], the structural system damping matrix [C] is proportional to the mass and stiffness matrix, as shown in Equation (1):

$$[C] = \alpha [M] + \beta [K] \tag{1}$$

The expression above can be rewrite in terms of the modal damping coefficient and the natural frequency, leading to the Equation (2):

$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \tag{2}$$

Where ξ_i is the modal damping coefficient and ω_i is the natural frequency associated to the mode shape "i". Isolating the parameters α and β of the Equation (2) for two natural frequencies, ω_{01} and ω_{02}, adopted according to the relevance of the corresponding vibration mode for the structural system dynamical response, it can be written:

$$\alpha = 2\xi_1\omega_{01} - \beta\omega_{01}\omega_{01} \tag{3}$$

$$\beta = \frac{2(\xi_2\omega_{02} - \xi_1\omega_{01})}{\omega_{02}\omega_{02} - \omega_{01}\omega_{01}} \tag{3}$$

With two values of natural frequencies is possible to evaluate the parameters α and β de-scribed before, see Equations (3) and (4). The reference frequencies ω_{01} and ω_{02} are generally taken as the extreme frequencies of the structure spectrum. In this paper, the frequency ω_{01} adopted will be the structure fundamental frequency (2.80 Hz: without prestress and 2.71 Hz: with prestress [12]) and the frequency ω_{02} considered will be the system tenth natural frequency (39.23 Hz: without prestress and 38.58 Hz: with prestress [12]). The modal damping coefficient adopted in this investigation is equal to 0.005 (ξ=0.5%) [1].

3.2 Dynamic amplification factor

With these values the numeric study proceeded with the non-linear dynamic analysis to determine the sudden load amplification factors for the two investigated cases. The following tables can be better understood with the knowledge of the following adopted abbreviations: P_{cr} is the critical load of the structural system with and without prestress forces; Δ is the axial displacement at the top of the structural system; Δ_e is the static displacement; Δ_d is the dynamic displacement and DAF is the dynamic amplification factor.

Table 1 depicts the dynamic amplification factors (DAF) for the structural system without prestress forces and also presents the translational horizontal (Axis X) and vertical (Axis Y) displacements at node 7, see Figure 2, for the applied sudden loads, see Figure 2.

It should be stressed that the displacement at node 7, see Figure 2, exceeds the L/500 (24 mm) limit suggested by the Brazilian Standard [18] for all the cases where the sudden impact load was higher or equal to 60% of the system critical load and exceeds the L/300 (40 mm) limit suggested by the Eurocode [19] for all the cases where the sudden impact load was higher or equal to 80% of the system critical load.

Table 1: Dynamic amplification factors for structural systems without prestress forces.

Without Prestress forces						
P_{cr} 21086,8 N	Axis X (mm)		Axis Y (mm)		DAF - X	DAF - Y
	Δ_e	Δ_d	Δ_e	Δ_d	Δ_d/Δ_e	Δ_d/Δ_e
P_{cr} 10%	1.17	2.17	0.074	0.13	1.86	1.82
P_{cr} 20%	2.58	4.83	0.15	0.27	1.87	1.80
P_{cr} 30%	4.33	8.15	0.22	0.40	1.88	1.79
P_{cr} 40%	6.55	12.40	0.30	0.54	1.89	1.77
P_{cr} 50%	9.47	18.04	0.39	0.67	1.90	1.73
P_{cr} 60%	13.50	25.89	0.48	0.80	1.92	1.69
P_{cr} 70%	19.44	37.53	0.58	0.94	1.93	1.61
P_{cr} 80%	29.17	56.89	0.73	1.07	1.95	1.47

Figures 3 and 4 presents the structural system non-linear dynamic response for the cases where a sudden load magnitude of 10% and 60% of the system critical load was applied to the column top, respectively.

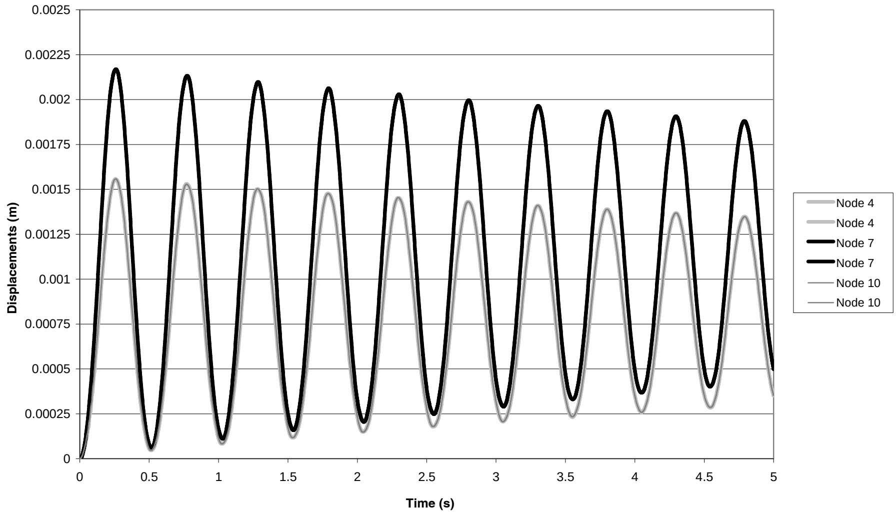


Figure 3: Displacements related to a 10% P_{cr} force applied to a structural system without prestress forces.

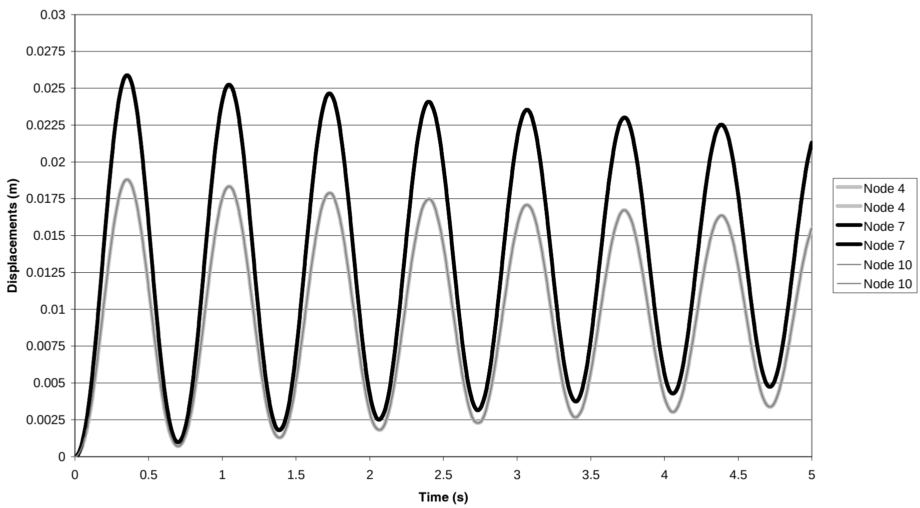


Figure 4: Displacements related to a 60% P_{cr} force applied to a structural system without prestress forces.

Table 2 depicts the dynamic amplification factors (DAF) for the structural system without prestress forces and also presents the translational horizontal (Axis X) and vertical (Axis Y) displacements at node 7, see Figure 2, for the applied sudden loads, see Figure 2.

It should be stressed that the displacement at node 7, see Figure 2, exceeds the L/500 (24 mm) limit suggested by the Brazilian Standard [18] for all the cases where the sudden impact load was higher or equal to 70% of the system critical load and exceeds the L/300 (40 mm) limit suggested by the Eurocode

[19] for all the cases where the sudden impact load was higher or equal to 80% of the system critical load.

Table 2: Dynamic amplification factors for structural systems with prestress forces.

With Prestress Forces						
P_{cr} 21086,8 N	Axis X (mm)		Axis Y (mm)		DAF - X	DAF - Y
	Δ_e	Δ_d	Δ_e	Δ_d	Δ_d/Δ_e	Δ_d/Δ_e
P_{cr} 10%	1.15	2.39	0.42	0.78	2.08	1.85
P_{cr} 20%	2.11	4.26	0.52	0.96	2.02	1.85
P_{cr} 30%	3.30	6.65	0.63	1.15	2.01	1.84
P_{cr} 40%	4.83	9.70	0.73	1.34	2.01	1.84
P_{cr} 50%	6.86	13.69	0.84	1.53	1.99	1.83
P_{cr} 60%	9.70	19.20	0.95	1.72	1.98	1.81
P_{cr} 70%	13.93	27.58	1.07	1.91	1.98	1.78
P_{cr} 80%	20.94	41.32	1.21	2.09	1.97	1.73

Figures 5 and 6 presents the structural system non-linear dynamic response for the cases where a sudden load magnitude of 10% and 70% of the system critical load was applied to the column top, respectively.

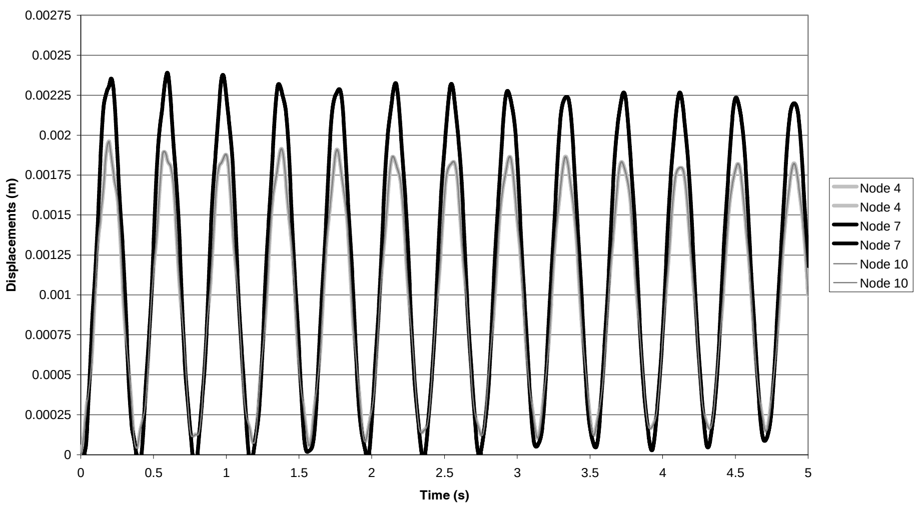


Figure 5: Displacements related to a 10% P_{cr} force applied to a structural system with prestress forces.

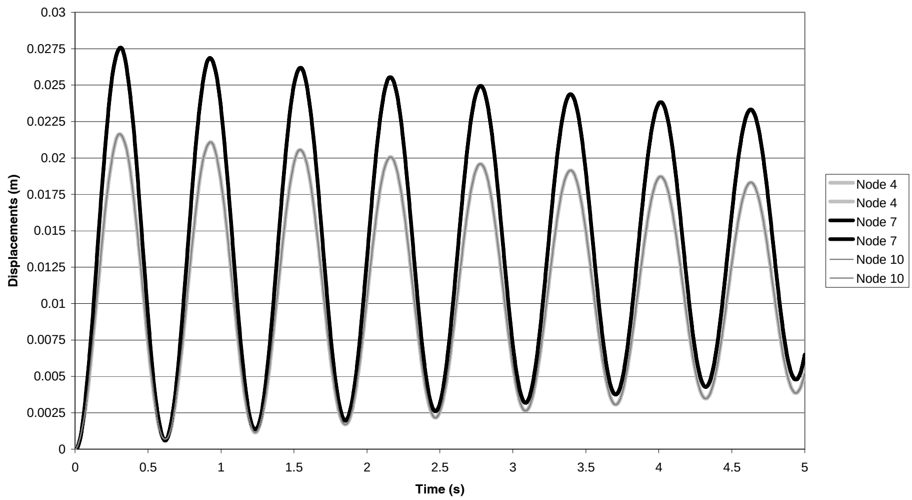


Figure 6: Displacements related to a 70% P_{cr} force applied to a structural system with prestress forces.

4 FINAL REMARKS

The current non-linear dynamic finite element analysis was performed on twelve meter length pre-stressed steel columns. These structural elements load bearing capacity was substantially increased by the additional restriction provided by the tie forces that are transferred to the main columns by means of horizontal tubes, perpendicularly welded to the column midpoint. The parametric study main variables were the prestressed element shape/area (cable or reinforced bar) and the adopted element pre-stress force. These two variables substantially altered the non-linear dynamic response and proved to be key elements for a better understanding of the structural system dynamic response.

Along the present investigation it was observed that a magnitude over 60% of structural system critical load without prestress forces and a magnitude over 70% of the structural system critical load with prestress forces led to horizontal displacements values that exceeded the limit suggested by the Brazilian Standard (horizontal displacements: L/500 = 24 mm). On the other hand, in the Eurocode this limit (horizontal displacements: L/300 = 40 mm) increases to 80% of structural system critical load with and without prestress forces. Another important outcome of the present investigation was that the stay prestress force magnitude directly influences the model displacements results altering the above mentioned limits.

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