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EXPERIMENTAL AND NUMERICAL STUDY OF STAYED STEEL COLUMNS

R. Pichal*, J. Machacek**

Abstract: *The numerical model of stainless steel stayed columns validated by tests is presented. 3D geometrical and material analysis including initial imperfections (GMNIA) is used for the study of nonlinear buckling and post-buckling behavior of 3 tested columns. Following study compares common 2D modelling with 3D results, elastic-plastic common steel with nonlinear stainless steel behavior and influence of the value of initial deflections. Finally significance of interconnection type between stays and central crossarm is studied with respect to possible assembly procedure. Recommendation for practical design are presented.*

Keywords: Stayed column, Experimental analysis, Nonlinear buckling, 3D analysis, Sliding stays.

1. Introduction

Stayed columns are used for decades as slender prestressed compression elements, with slenderness and strength depending on the overall geometry, number of crossarms along its length, number of stays and their prestressing (Fig. 1).

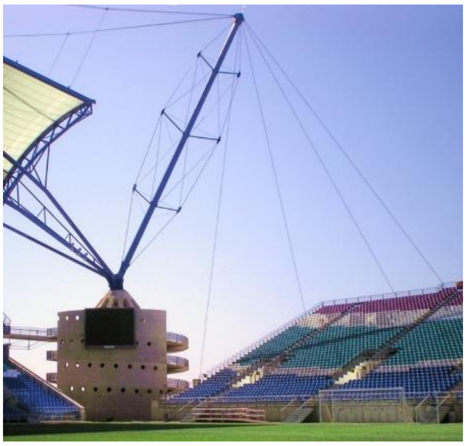


Fig. 1: Stayed column with 3 spaced crossarms (with 3 stays) supporting roof of Estádio Algarve Faro (left), planar stayed column (with 2 stays) supporting facade of a building in London (right).

Principal analytical analysis and explanation of behavior of the column with one central crossarm and stays fixed to the crossarm were presented by Smith et al. (1975) and Hafez et al. (1979). They distinguished 3 zones according to the value of the stay prestressing and derived respective formulas for critical loads (summarized by Pichal and Machacek, 2017). The formulas enable to establish minimal (T_{min}) and optimal (T_{opt}) prestressing in each of the stays and maximal external critical load for the column (Fig. 2). Recent research (Saito and Wadee, 2008, 2009, Osofero et al., 2012 and Wadee et al., 2013) introduced initial deflections to study post-buckling behavior using numerical nonlinear analysis. Based on a range of initial deflections they proposed approximate formulas for maximum capacity of the stayed columns N_{max}, depending on the element geometry and prestressing level (Fig. 2).

* Ing. Radek Píchal: Czech Technical University in Prague, Faculty of Civil Engineering, Thakurova 7; 166 29, Prague; CZ, radek.pichal@fsv.cvut.cz

** Prof. Ing. Josef Macháček, DSc.: Czech Technical University in Prague, Faculty of Civil Engineering, Thakurova 7; 166 29, Prague; CZ, machacek@fsv.cvut.cz

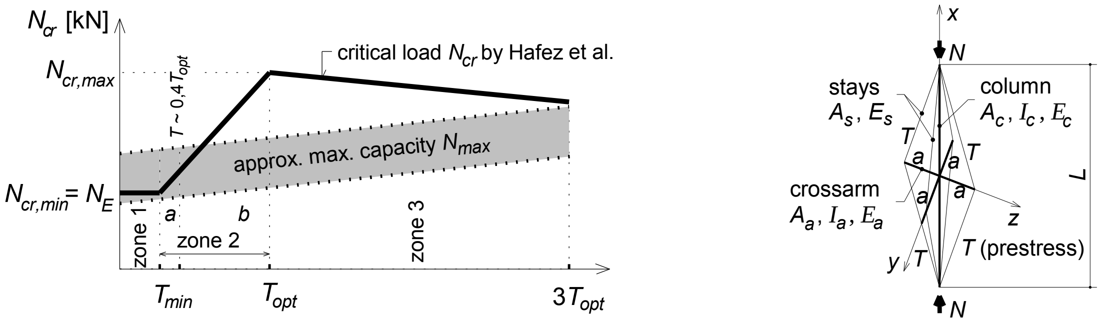


Fig. 2: Critical and maximal external load (left), geometry and terminology of the stayed column (right).

In this paper the numerical model of the column with one central crossarm in ANSYS software is proposed and validated using tests results by Servitova and Machacek (2011). The following studies concern influence of the mode and amplitude values of initial deflections on maximal strength of the column and significance of connection type between the stays and the central crossarm.

2. Tests, numerical modelling and validation of results

Three tests of stainless steel stayed columns with one central crossarm and the same geometry were performed at the CTU of Prague. For the central column was used tube Ø 50 x 2 [mm] (L = 5000 mm, A_c = 302 mm^2, I_c = 87009 mm^4, $E_{c,ini}$ = 184 GPa), for the crossarm tube Ø 25 x 1.5 [mm] (a = 250 mm, A_a = 111 mm^2, I_a = 7676 mm^4, $E_{a,ini}$ = 184 GPa) and for the stays Macalloy cable 1 x 19 stainless steel Ø 4 mm (L_s = 2513 mm, A_s = 12.6 mm^2, $E_{s,ini}$ = 200 GPa). The stress-strain relationship of the stainless steel tubes was derived as an average from the three full cross-section measurements and is presented in Fig. 3. The stays run continuously over crossarm at saddles, while the Column 3 was tested also without any stays.

Initial deflections of the columns and deflection under loading were monitored by total station (3D scanning) and local potentiometers together with strain measurements in stays by strain gauges located in turnbuckles. The prestressing of the stays needed to be uneven in the 4 stays to receive initial deflection in accord with EN 10219-2 (i.e. amplitude < L / 500 = 10 mm). This requirement was fulfilled in the Column 1 under total prestressing $4T$ = 5.44 kN (w_{0y} = 1.9 mm, w_{0z} = 8.3 mm) and Column 3 (w_{0y} = 0.5 mm, w_{0z} = 2.2 mm), but not in Column 2 with $4T$ = 4.54 kN (w_{0y} = 3.8 mm, w_{0z} = 19.9 mm). Loads were applied in steps of 2.5 kN followed by unloading up to termination of tests, usually due to large central deflection.

Numerical model in ANSYS was arranged in 3D with BEAM188 elements used for the central column and all crossarms, LINK180 for cable stays and SHELL281 for saddles (all covering large deflection and material nonlinearity), after assessing suitable meshing (finally L / 250, a / 25, for shell elements 23.0 mm^2). Loading was applied by axial displacement Δx, and the stay's prestressing by a thermal change.

Comparison of test and numerical results for Column 1 is shown in Fig. 3-right. The test was terminated under loading of 17.7 kN and the agreement of numerical results with test is very good. Test of the Column 2 (with rather large initial deflection) terminated under loading of 14.9 kN. Numerical analysis gives maximal loading 16.2 kN (exceeding test value by 8.7 %), see Fig. 4-left.

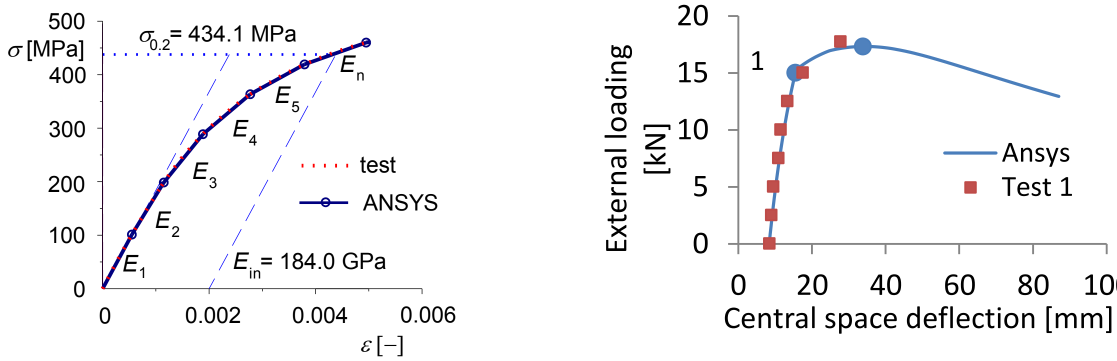
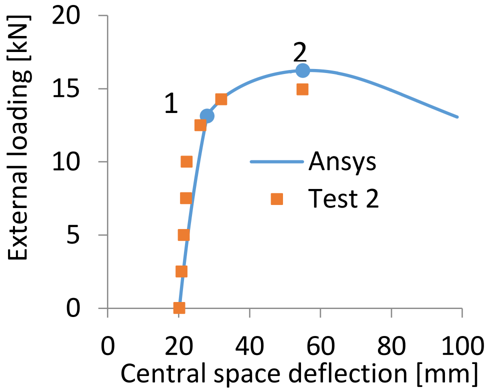


Fig. 3: Stainless steel stress-strain relationship (left), Column 1 comparison (right).



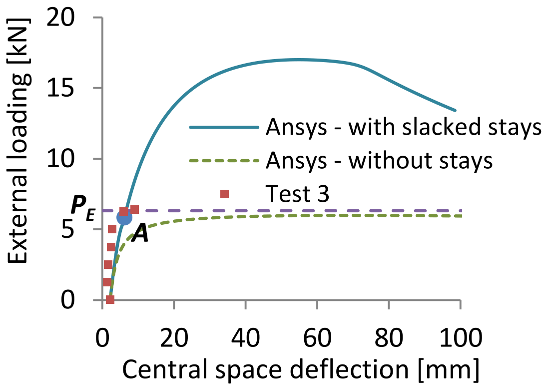


Fig. 4: Column 2 comparison (left), Column 3 comparison (right).

Column 3 was tested without any stays (as a comparative sample) and later the same one with very slightly prestressed stays. Euler's critical load is P_E = 6.3 kN while the test value of imperfect column was detected surprisingly somewhat higher as N_{test} = 6.5 kN, when the column started to deflect rapidly, see Fig. 4-right. This difference (2.8 %) is however negligible and may be assigned to rather questionable determination of the cross-section average modulus of elasticity. The numerical analysis in this case was performed for both arrangements. The first one for simple initially deflected column without any stays, giving maximal load N_{max} = 6.0 kN, the second one with unprestressed stays and giving N_{max} = 17.0 kN (see Fig. 4-right). The latter value is approaching the maximal test loading of the column with initially slacked stays of N_{test} = 16.2 kN. The mechanism of this behavior was revealed from the numerical analysis, when the stays on concave side after buckling were activating (approx. at loading of 12.2 kN) to change the simple column into stayed column. Such behavior was discovered also by Wadee et al. (2013), see Fig. 2.

The described numerical modelling in ANSYS software can therefore be considered as successfully validated.

3. Parametrical studies

Former studies concerning differences between in-plane and space buckling (2D and 3D analysis) by Pichal and Machacek (2017) resulted into conclusion that the stayed columns buckle into space (in between the arms of the crossarm) but the critical and maximal loading for both analyses are nearly identical. Results of preliminary studies in 3D concerning influence of the initial deflection amplitude values w_0 with shapes acc. to Fig. 5 for the stayed column analyzed in Chapter 2 is given in Tab. 1. It should be noted, that obtaining optimal prestressing T_{opt} requires a number of solutions with different prestressing of stays. The decisive mode of buckling for the shallow amplitudes is antisymmetrical (while for reasonable amplitudes > L / 1000 and ratio 2 a / L < 0.175 in acc. with Wadee et al. 2013 is expected to be symmetrical). The enormous influence of the deflection amplitude value is obvious.

Tab. 1: Optimal prestressing and corresponding maximal loading.

w_0 [mm]	Symmetrical initial deflections		Antisymmetrical initial deflections		$N_{cr,max}$ [kN]
	T_{opt} [kN]	$N_{max,sym}$ [kN]	T_{opt} [kN]	$N_{max,anti}$ [kN]	
0.01 (L/500000)	1.51	39.73	1.35	36.18	36.18
0.05 (L/100000)	1.58	39.25	1.43	35.77	35.77
0.10 (L/50000)	1.61	38.62	1.52	35.43	35.43

Another study concerned comparison of GNIA (geometrically nonlinear analysis with imperfections) and GMNIA (incl. material nonlinearity of stainless steel in acc. with Fig. 3). For the above geometry the tangent modules E_1 and E_2 up to the maximal loading values needed to be used only and the differences of both analyses were therefore negligible. The prestressing of cable stays is usually very low with respect to 0.2 % proof yield and initial elastic modulus (such as nominal one) is a reasonable choice.

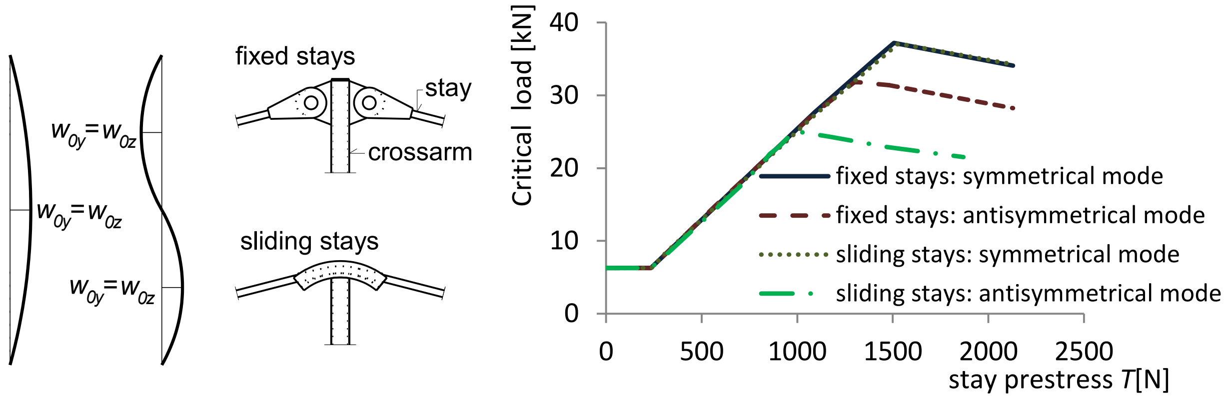


Fig. 5: Amplitudes of initial deflections (left), influence of conditions at crossarm (right).

Finally the boundary conditions at the crossarms were studied. In the tests the saddles and sliding stays were applied (Fig. 5), considering a very low friction coefficient 0.01 (whilst common friction between steel-steel is expected to be 0.1). Frequent arrangement represents hinged (fixed) connection of the stays, analyzed by other authors in the References. Nevertheless, from assembly view the sliding stays are more advantageous and were used in our tests. As obvious from a comparison between the two (Fig. 5-right, with initial deflection of the central column $w_0 = L / 500000$) the different behavior arises at antisymmetrical mode of buckling only, were reduction of maximal critical load is substantial.

4. Conclusions

Tests and validated numerical modelling of the three stayed prestressed columns made of stainless steel is presented. The numerical analysis of critical load and optimal prestressing in zone 2 according to Fig. 2 requires GMNIA with an arbitrary infinitesimal initial deflection, as LBA (linear buckling analysis) can't be used due to sudden change of the column axial energy at the instant of buckling.

The following numerical studies with the given geometry proved a little impact of a nonlinear column/stay material properties such as has stainless steel. On the contrary the influence of initial deflection value and mode is substantial as expected. Also boundary conditions at crossarm concerning possible slip of stays may lead to strong reduction of the final strength of the column. This will, however, happen for antisymmetric modes of buckling only, which are expected at large aspect ratios $2\,a / L$.

Acknowledgement

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