Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

COLLAPSE AND BUCKLING OF STAINLESS STEEL PRESTRESSED STAYED COLUMNS

JOSEF MACHACEK and RADEK PICHAL

Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic

Buckling and collapse of stainless steel elements loaded in compression are studied experimentally and numerically. Based on four tests of single crossarm stayed columns the numerical analysis using ANSYS software package is validated and presented in a detail. First, for a completeness, the study refers to columns with one central crossarm, but the main emphasis is devoted to columns with two crossarms located in the thirds of the element length. The analysis employed geometrically and materially nonlinear analysis (GMNIA) to respect a change of inner energy during buckling of an "ideal" (perfect) column, initial deflections of an "imperfect" column (covering various initial deflection modes and amplitude values) and nonlinear stress-strain relationship belonging to stainless steel material. The results cover both critical buckling and maximal collapse loads of the columns in compression. Finally, the important comparisons of the load capacities concerning stayed columns in compression with one/two crossarms and ratios of critical/maximal loadings, elastic/inelastic material and fixed/sliding support of the stays at the crossarms are provided. Conclusions comprise evaluation of these results and principal recommendations for the design of stayed columns.

Keywords: ANSYS, Buckling modes, Crossarm, Imperfection, Inelastic, Prestressing.

1 INTRODUCTION

The prestressed stayed columns are used to achieve a sufficient collapse strength together with an attractive appearance in cases of very slender compression elements, see Figure 1. The most common arrangement consists of a central steel tube, single, double or triple tube crossarms and prestressed cable or rod stays. The crossarms may have two, three or four arms (arms in the angle of 180°, 120°, or 90°). Material of all these elements may be from common or stainless steel.

The principal research on the stayed columns with one central crossarm was presented by Smith *et al.* (1975) and Hafez *et al.* (1979). Using an analytical approach concerning "ideal" (perfectly straight) columns they discovered and described three zones of buckling behavior under an arbitrary prestress level of the stays including "optimal prestressing" T_{opt} leading to maximal critical load $N_{cr,max}$. Subsequent research of stayed columns with one central crossarm concerned influence of various buckling modes and, in particular, also "imperfect" columns (i.e. with initial deflections), e.g. by Chan *et al.* (2002), Saito and Wadee (2008, 2009), Pichal and Machacek (2018). The essential results, demonstrating the reduction of critical loads N_{cr} with respect to maximal collapse loads N_{max} of imperfect columns (with reasonable initial deflections), were published by Wadee *et al.* (2013) and are roughly illustrated in Figure 1.

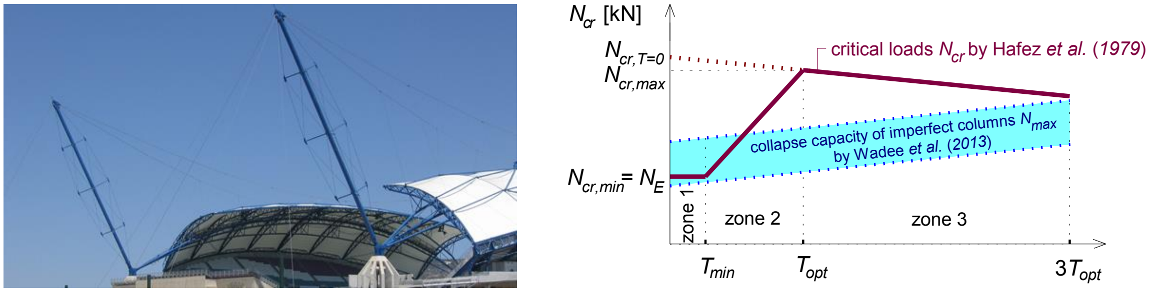


Figure 1. Stadium in Faro (Portugal) with triple crossarms, each with three in-space arms (photo J. Machacek), critical and collapse loads for stayed columns with just one central crossarm.

The theoretical research was accompanied by laboratory tests by Araujo *et al.* (2008), Servitova and Machacek (2011), Osofero *et al.* (2012), and Serra *et al.* (2015). Stayed columns with two and three crossarms were investigated in recent years, following some first attempts in the 80s of the 20th century. The stability of these "ideal" columns was investigated by Martins *et al.* (2016), Yu and Wadee (2017) and Lapira *et al.* (2017). Lastly, Machacek and Pichal (2018) investigated numerically both "ideal" and "imperfect" stayed columns with two crossarms.

This paper will focus on comparisons of critical and collapse loads of prestressed stayed columns with either one or two crossarms and effectiveness of the second crossarm in a case of otherwise the same column (with the same geometrical and material properties). The numerical values were received using ANSYS software, followed by proper and successful validation of the modelling via four stayed column tests.

2 NUMERICAL ANALYSIS

The analyzed stayed columns are shown in Figure 2 and correspond to the tested ones with just one central crossarm by Servitova and Machacek (2011). The entry characteristics (length, area and second moment of area) are as follows:

- Central stainless steel tube Ø 50x2 [mm]: L = 5000 mm, A_c = 302 mm^2, I_c = 87009 mm^4,
- Crossarm stainless steel tubes Ø 25x1.5 [mm]: a = 250 mm, A_a = 111 mm^2, I_a = 7676 mm^4,
- Stays as cables or rods Ø 4 mm: L_s = 2513 mm, A_s = 12.6 mm^2.

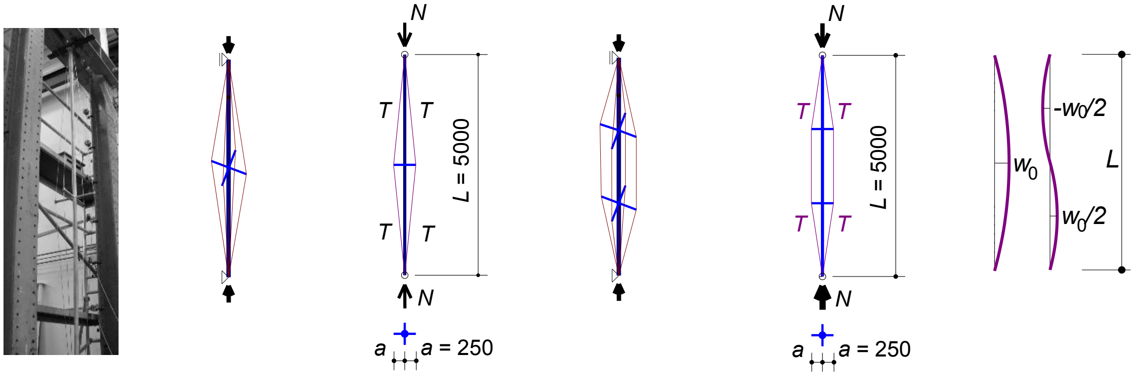


Figure 2. Photo of tested stayed columns, geometry of analyzed columns with just one central crossarm or two crossarms located in the thirds of the column length and considered initial deflection modes.

Tensile tests of full tube cross section stainless steel (grade 1.4301) specimens for both central column and crossarm tubes resulted into the average nonlinear stress-strain relationship as shown in Figure 3, with the initial elastic modulus of 184 GPa.

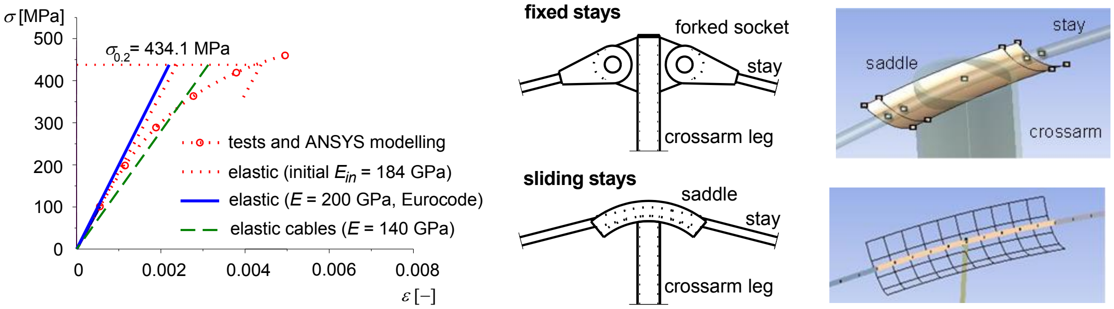


Figure 3. Stress-strain relationships used in the following analyses. Arrangements of stay-crossarm connections (commonly fixed, sliding over saddles at tests) and FEM modeling of the saddles in ANSYS.

Three-dimensional (3D) FEM in ANSYS used elements BEAM188 for the central column and all crossarms (2x6 = 12 DOF, embodying large deflections and material nonlinearity) and LINK180 for cable/rod stays (2x3 = 6 DOF, large deflections, material nonlinearity and adopting tension forces only). In the case of sliding stays the cylindrical and toroidal parts of the saddles was formed from SHELL281 elements according to Figure 3, with friction coefficients between stay and saddle ranging from ν = 0.01 to 0.1. The contact between the saddle and the stay provided elements TARGE170 and CONTA175. The stay's prestress was imposed by a relevant thermal change and following external loading via axial displacement of the column, using standard Newton-Raphson iteration. The FE meshing was tested for various divisions with resulting satisfactory element lengths L/250, a/25 and area of shell elements 23.0 mm^2.

Finite element (FE) model was validated using results of the four tests by Servitova and Machacek (2011). The tests with otherwise identical arrangement differed in initial deflections of the central column and level of the stays prestress. The stays, each with the prestress of T [kN], were continuous over the saddles and friction coefficient 0.1 was considered. Geometrically and materially nonlinear analysis with imperfections in 3D (GMNIA) was employed. The validation for all four tests was successful, but here only the tests No. 1 and No. 2 are shown in Figure 4.

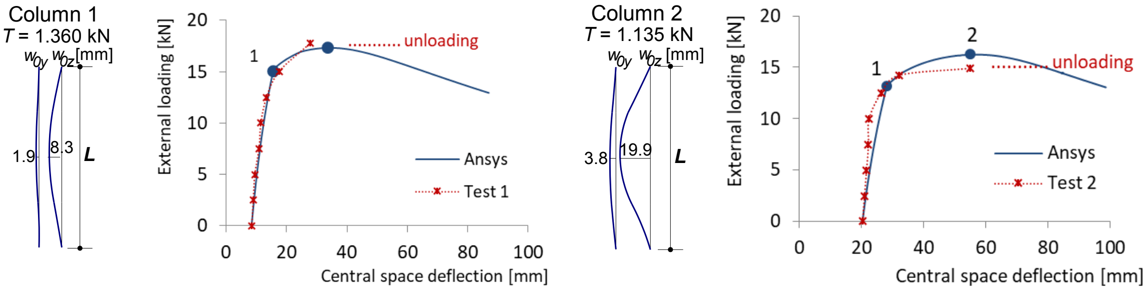


Figure 4. Initial deflections along the columns lengths and comparison of tests and 3D GMNIA results.

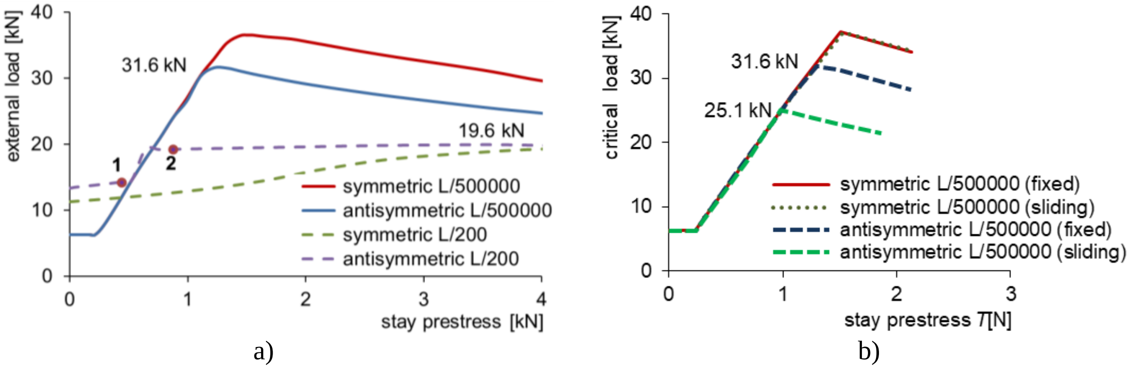
3 COMPARATIVE STUDIES

Columns with symmetrical and antisymmetrical initial deflections were investigated (Figure 2).

Saito and Wadee (2008) confirmed that in prestressed stayed columns linear buckling analysis (LBA) doesn't give the relevant critical loads in the full range of prestressings due to a sudden change of the column inner energy under buckling. Therefore, initial deflections have to be introduced and GMNIA or in an elastic region GNIA need to be used. In the current studies the infinitesimal initial deflection amplitude $w_0 = L/500000 = 0.01$ mm was used for the "ideal" columns to determine critical loads and value of $w_0 = L/200 = 25$ mm for the "imperfect" columns to determine maximal (collapse) loads. The latter value corresponds to Eurocode EN 1993-1-1 for cold-formed tubes and elastic analysis and covers all kinds of initial imperfections.

3.1 Columns with One Central Crossarm

The spatial direction of initial deflections (in between the crossarm arms) and up to 20 different prestressings were imposed to the columns. The results of 3D GMNIA are shown in Figure 5. Note that in a low prestress the maximal load is higher than the critical one due to activating of stays on convex sides of the buckling column (while at concave sides the stays slacken). The maximal critical load $N_{cr,max} = 31.6$ kN is given by antisymmetric buckling (with antisymmetric initial deflections), while maximal collapse load for the imperfect column $N_{max} = 19.6$ kN can be reached for a great prestress only. The buckling modes at collapse for different prestress levels between point 1 and 2 are changing from antisymmetric to interactive and back to antisymmetric ones.



a) b)

Figure 5. a) GMNIA results for critical load (with $w_0 = L/500000$) and maximal collapse load (with $w_0 = L/200$). b) Influence of sliding stays over crossarm saddles.

Using 3D GNIA (i.e. elastic analysis with $E = 200$ GPa recommended by Eurocode) gives results on unsafe side with $N_{cr,max} = 36.2$ kN and $N_{max} = 22.7$ kN (not shown in this paper). Influence of the support arrangement of stays at crossarms (see Figure 3) was studied with several friction coefficients between stays and saddles. Results for critical loads under very low friction $v = 0.01$ are shown in Figure 5. The sliding support may give more economical solution (less stay pieces and forked sockets), but the antisymmetric buckling results in substantial decrease of both critical and maximal loads.

3.2 Columns with Two Crossarms

The similar 3D GMNIA studies concerning "ideal" and "imperfect" columns with two crossarms were performed (see Figure 6). For the given entry data the antisymmetric initial deflections are deciding for both critical (40086 N) and maximal collapse (25040 N) loads. Again, in a low prestress the maximal load is higher than the critical one due to activating of the convex stays.

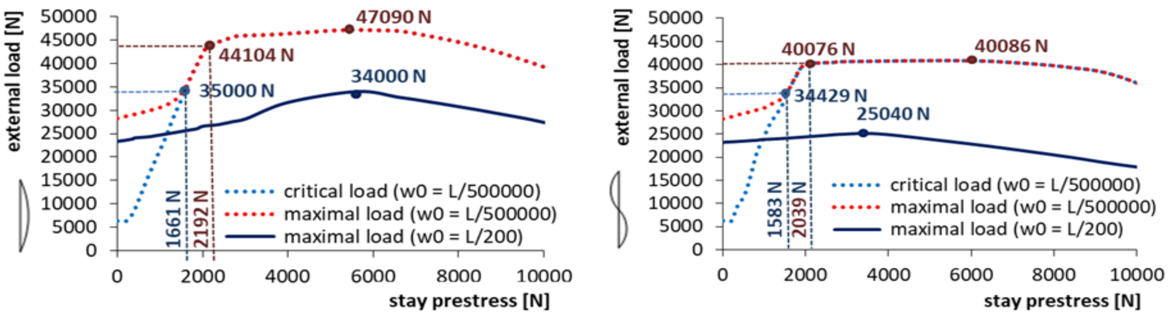


Figure 6. GMNIA results for critical and maximal collapse loads of columns with two crossarms: left for symmetric initial deflections, right for antisymmetrical initial deflections.

Rather interesting is behavior of the "ideal" column in a low prestress. While the critical load is given by buckling resulting in slackening of the concave side stays, the column may carry higher maximal load by activating of the convex side stays, see Figure 6 (this is valid also for unprestressed column, with the prestress *T* = 0). For higher prestress both the critical and maximal loads of the "ideal" column merge together.

The significance of the material nonlinearity concerning stainless steel follows from the results of elastic geometrically nonlinear analysis with imperfections (GNIA) shown in Figure 7. In the analysis the elastic Young's modulus *E* =200 GPa was employed (see also Figure 3).

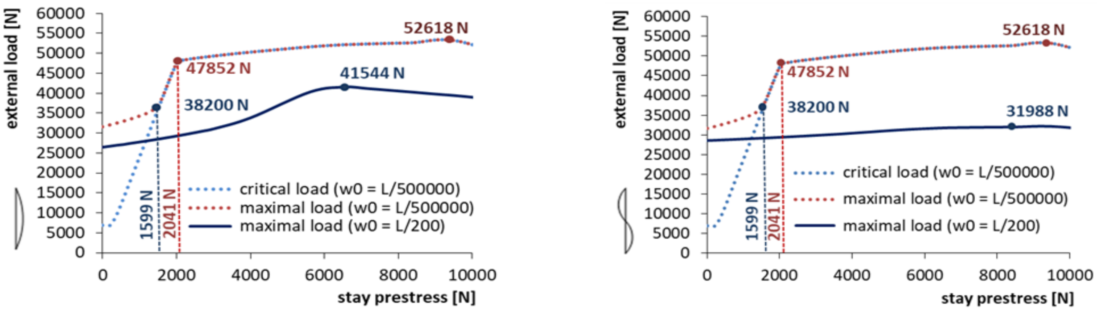


Figure 7. GNIA results for critical and maximal collapse loads of columns with two crossarms: left for symmetric initial deflections, right for antisymmetrical initial deflections.

Comparison of both critical and maximal loads indicates the substantial relevance of proper modeling of the material nonlinear behavior.

4 CONCLUSIONS

The investigation of the prestressed stayed columns with one central crossarm and two crossarms located in the thirds of the column length are presented. The study covers both "ideal" (perfectly straight) and "imperfect" (real) columns to find critical or maximal collapse loads. While the uniform main geometrical entry data are used, the initial imperfections and level of prestress are variable. The results therefore enable comparison of the relevant factors influencing the column behavior and recommend taking them into account in a practical design.

- Adding the second crossarm into otherwise the same prestressed stainless steel stayed column increases significantly both critical and maximal collapse loads. In the

investigated column the increase of critical load was 27 % (40086 N/31600 N) and that of maximal collapse load was 28 % (25040 N/19600 N).
- The critical loads of “ideal” columns can’t be used in a practical design as the influence of initial imperfections is enormous. In the studied columns the decrease due to imperfections was to 62 % for both columns with one or two crossarms.
- Material nonlinearity of stainless steel needs to be carefully taken into account. In the investigated column the decrease of maximal load due to the nonlinearity is to 78 %.
- Sliding of stays over saddles decreased the maximal load to 79 %.

Acknowledgments

The work was supported by the Czech Grant Agency under grant GACR No. 17-24769S.

References

Araujo, R. R., Andrade, S. A. L., Vellasco, P. C. G. S., Silva, J. G. S., and Lima, L. R. O., Experimental and Numerical Assessment of Stayed Steel Columns, *Journal of Constructional Steel Research*, 64(9), 1020-1029, 2008.

Chan, S. L., Shu, G., and Lü, Z., Stability Analysis and Parametric Study of Pre-Stressed Stayed Columns, *Engineering Structures*, 24(1), 115-124, 2002.

Hafez, H. H., Temple M. C., and Ellis, J. S., Pretensioning of Single-Crossarm Stayed Columns, *Journal of the Structural Division*, 14362(ST2), 359-375, 1979.

Lapira, L., Wadee, M. A., and Gardner, L, Stability of Multiple-Crossarm Prestressed Stayed Columns with Additional Stay Systems, *Structures*, 12, 227-241, 2017.

Machacek, J., and Pichal, R., *Stability and Strength of Stainless Steel Stayed Columns with One and Two Crossarms*, Proceedings 8th International Conference on Thin-Walled Structures 2018 (ICTWS 2018), Camotin, D. (ed.), 1-12, Lisbon, 2018.

Martins, J. P., Shahbazian, A., Silva, L. S., Rebel, C., and Simoes, R., Structural Behavior of Prestressed Stayed Columns with Single and Double Cross-Arms Using Normal and High Strength Steel, *Archives of Civil and Mechanical Engineering*, 16, 618-633, 2016.

Osofero, A. I., Wadee M. A., and Gardner, L., Experimental Study of Critical and Post-Buckling Behaviour of Prestressed Stayed Steel Columns, *Journal of Constructional Steel Research*, 79, 226-241, 2012.

Pichal, R., and Machacek, J., Single-Crossarm Stainless Steel Stayed Columns, *Advances in Technology Innovation*, 3(1), 9-16, 2018.

Saito, D., and Wadee, M. A., Post-Buckling Behaviour of Prestressed Steel Stayed Columns, *Engineering Structures*, 30, 1224-1239, 2008.

Saito, D., and Wadee, M. A., Numerical Studies of Interactive Buckling in Prestressed Steel Stayed Columns, *Engineering Structures*, 31(2), 432-443, 2009.

Serra, M., Shahbazian, A., Silva, L., S., Marques, L., Rebelo, C., and Vellasco, P. C. G. S., A Full Scale Experimental Study of Prestressed Stayed Columns, *Eng. Structures*, 100, 490-510, 2015.

Servitova, K., and Machacek, J., *Prestressed Stainless Steel Stayed Columns*, Proceedings EUROSTEEL 6th European Conf. on Steel and Composite Structures, Dunai, L. *et al.* (eds.), 1767-1722, Budapest, 2011.

Smith, R. J., McCaffrey, G. T., and Ellis, J. S., Buckling of a Single-Crossarm Stayed Column, *Journal of the Structural Division*, 11071(ST1), 249-268, 1975.

Wadee, M. A., Gardner, L., and Osofero, A. I., Design of Prestressed Stayed Columns. *Journal of Constructional Steel Research* 80, 287-298, 2013.

Yu, J., and Wadee, M. A., Mode Interaction in Triple-Bay Prestressed Sayed Columns, *International Journal of Non-Linear Mechanics*, 88, 47-66, 2017.