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Single-Crossarm Stainless Steel Stayed Columns

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Abstract

Stability and strength of imperfect stayed columns are studied in 3D using ANSYS software. Following three tests of stayed columns with a reasonable geometry, the numerical modelling is validated and subsequently compared with available analytical and numerical 2D results. Arrangement and values of prestressing of ties and initial deflections of the columns affecting the nonlinear stability problem are discussed in a detail. The effect of nonlinear stress-strain relationship corresponding to common stainless steel material is shown, with respect to loading level corresponding to loss of the column stability. The assembly technique of the stayed columns is taken into account, comparing the method and stability/strengths of columns with fixed or sliding stays in the connection to the central crossarm. Finally some recommendations concerning the analysis and use of such stayed columns are given.

Keywords: stayed columns, stainless steel, prestressing, nonlinear buckling, nonlinear material, sliding stays

1. Introduction

Extremely slender compression columns are required particularly in unique structures both by architects and investors. However, the slenderness is limited by a required strength and possible deflections due to buckling. Well-known solution for the problem are frequently used prestressed stay columns, made usually from a central slender column, several lateral crossarms - each with two planar arms (arranged in a plane with the column) or crossarms in space with three (arranged in 120°) or four (arranged in 90°) arms and prestressed stays formed by cables or rods, see Fig. 1.

(a) Grande Arche, Paris (b) Parc del centre del Poblenou, Barcelona (c) Estádio Algarve, Faro

Fig. 1 Examples of the stayed columns used in famous structures

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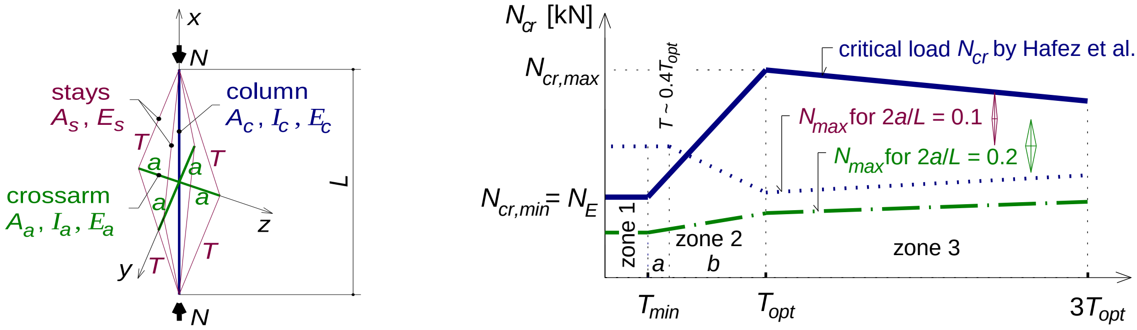
Analytical analysis of the stayed columns with multiple pin-connected crossarms and validated by tests was developed by Chu and Berge [1] in the sixtieth. Following analytical research by other authors was accomplished by Smith et al. [2] and Hafez et al. [3]. They analyzed a stayed column with one central crossarm rigidly connected (welded) to the column. The column was ideally straight and concentrically loaded, the stays were fixed to the crossarm in ideally hinge connection and the buckling was supposed to occur in the plane of the crossarm member. They analyzed planar arrangement (with two arms of the crossarm) but the solution covered also space arrangement with 4 arms positioned in 90° (Fig. 2). The analysis resulted into critical (buckling) loading for an arbitrary stays prestressing, considering symmetrical or antisymmetrical mode of buckling. However and more important, they also discovered three zones of the behavior depending on the level of the stays prestressing: zone 1 (up to T_{min}), where the prestressing in the stays disappears when the applied load is less or equal to the Euler load ($N_{cr} = N_E$); zone 2 (up to an optimal prestressing T_{opt}), where the stays remain effective until the applied load triggers a buckling; zone 3 (above T_{opt}), where all the stays remain active (in tension) even after buckling. Higher prestressing than T_{opt} increases the column loading and, therefore, decreases the critical column load N_{cr}, see Fig. 2.



(a) Geometry of the stayed column (b) Critical and maximal loadings

Fig. 2 Geometry, critical and maximal loading acc. to Wadee et al. (see later) for initial deflection $w_o = L/200$ vs stays prestress

Numerous other authors investigated influence of initial imperfections (e.g. Wong and Temple [4], Chan et al. [5]). Important findings resulted from the later, concerning recommendations for the maximal loading vs optimal pretension of imperfect columns, stay areas and crossarm lengths with respect to buckling modes and, therefore, resulting maximal loading. Another study of buckling and postbuckling behavior of "nearly perfect" prestressed stayed columns was presented by Saito and Wadee [6]. They used both analytical and numerical (Abaqus software) analysis and drew attention to stable post-buckling paths in zone 1 and initial part of zone 2, while unstable post-buckling path in zone 3. They also mentioned a danger resulting from changes in the ambient temperature, necessity of modelling in 3D and in [7] studied significance of interactive buckling in a column with one central crossarm (combination of symmetrical and antisymmetrical modes of buckling).

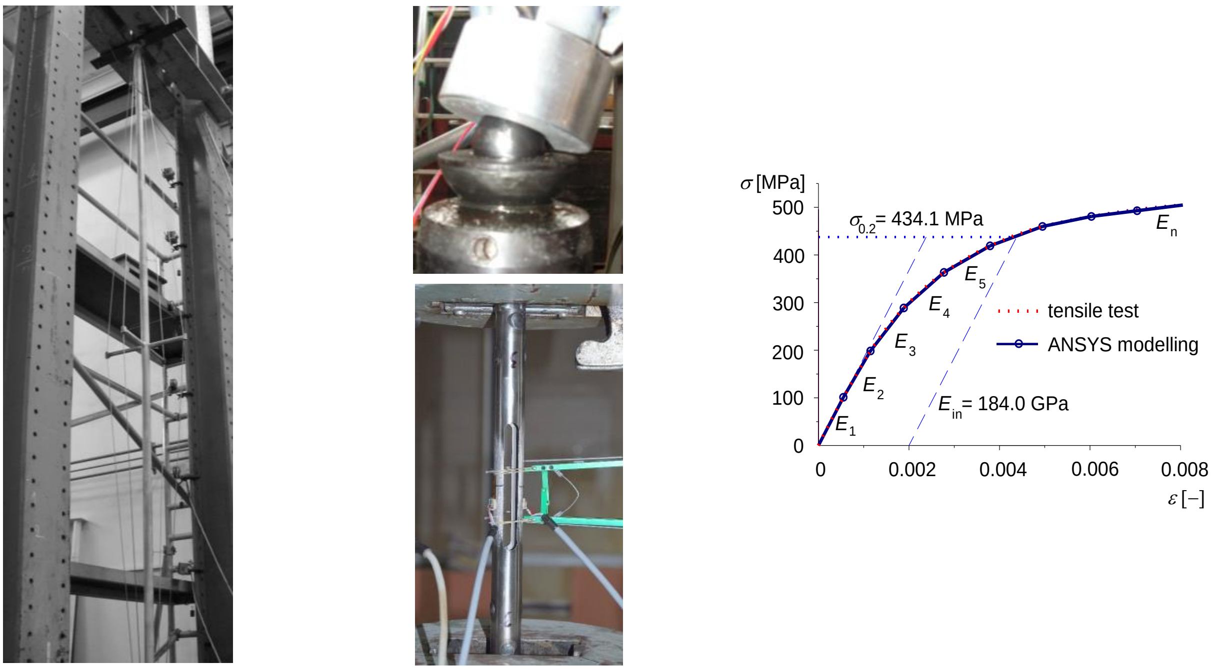
Two tests of prestressed stayed columns with a reasonable size of L= 12 m and a = 600 mm were performed by Araujo et al. [8]. The specimen were placed in horizontal position, the first one with negligible prestressing while the second with typical prestressing. Significant increase of maximal loading in comparison with the capacity of a column without any stays was affirmed. The research was accompanied with numerical analysis and parametric studies on values of initial deflections and diameter of stays (cables or rods), while using Ansys software. Extension of the studies (with a use of tests by Servitova and Machacek [9]) the authors published in [10]. Large experimental analysis of imperfect prestressed stayed columns with one central crossarm was presented by Osofero et al. [11]. Totally 18 specimens in vertical position with length of L = 2800 mm and variable arms a = 100 ÷ 420 mm were tested. A knife-edge support of the central column forced the buckling into the prescribed plane by either in symmetric or antisymmetric mode, depending mostly on ratio L/a. The tests provided the actual maximal loads N_{max} depending on the stays prestress $T \in (0, 4T_{opt})$, and pointed out to interactive buckling mode for cases where symmetric and antisymmetric buckling loads approximately coincided.

Complex numerical analysis of imperfect prestressed stayed columns resulting in the design recommendations was published by Wadee et al. [12]. They analyzed planar stayed columns with three levels of initial deflection amplitudes (L/200, L/400, L/1000) for symmetrical and antisymmetrical buckling modes, using Abaqus software. After some adjustments to correlate the numerical values with test data, the results are presented for strengths of the columns in a normalized form of N_{max}/N_{cr}, symmetrical (for $2a/L < 0.175$) and antisymmetrical (for $2a/L > 0.175$) modes of buckling and four levels of the stays prestressing: zone 1 ($T < T_{min}$), zone 2a (T Є(T_{min}, 0,4T_{opt})), zone 2b (T Є(0,4T_{opt}, T_{opt})) and zone 3 (T Є(T_{opt}, 3T_{opt})). The results enabled a determination of approximations for maximal ultimate strength N_{max} for an arbitrary prestressing up to 3T_{opt} (shown for two common values of $2a/L$ in Fig. 2, but looking at the picture be aware of the relation to N_{cr} on vertical axis).

This article presents a numerical approach of prestressed stainless steel stayed columns with one central crossarm in 3D validated by own tests. The emphasis is laid on nonlinear behavior of the material, space direction of the column buckling and boundary sliding conditions of stays at the crossarm.

2. Experiments, Numerical Modelling and Model Validation

Four tests of stainless steel stayed columns with a reasonable length L = 5000 mm were performed at the lab of the Czech Technical University in Prague [9]. The main column was fitted with hinges at both ends (see Fig. 3 (a), (b)). The parameters according to Fig. 2 were identical for all tests and as follows: the central tube Ø 50x2 [mm] (L = 5000 mm, A_c = 302 mm^2, I_c = 87009 mm^4, $E_{c,ini}$ = 184 GPa), the crossarm tubes Ø 25x1.5 [mm] (a = 250 mm, A_a = 111 mm^2, I_a = 7676 mm^4, $E_{a,ini}$ = 184 GPa), the stays are Macalloy cables 1x19 stainless steel Ø 4 mm (L_s = 2513 mm, A_s = 12.6 mm^2, $E_{s,ini}$ = 200 GPa). The stays in all tested columns were sliding at steel saddles of crossarms. Material of both tubes was tested in a hydraulic testing machine on a weakened cross-section machined from the full cross sections according to Fig. 3(b). The stress-strain relationship of the stainless steel material (1.4301) was derived as an average from three such coupon tensile measurements. It should be noted that initial Youn g's modulus for the stays was accepted in the following numerical analysis due to rather low stresses at collapse loadings, while multilinear isotropic hardening according Fig. 3 (a) for the central column and crossarms.



(a) Tested column in the frame position

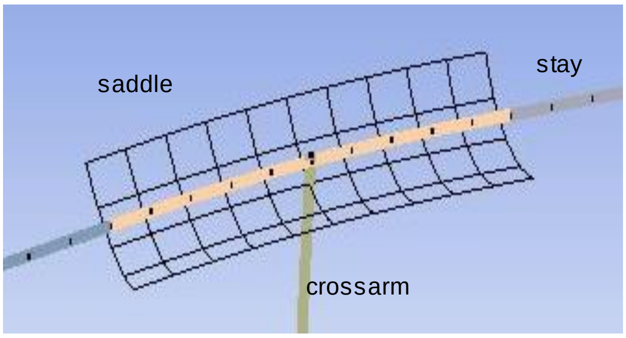
(b) Detail of the hinge at supports and central column tensile specimen

(c) Stress-strain diagram of the austenitic Grade 1.4301 stainless steel material

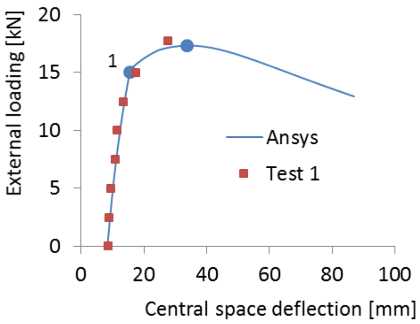
Fig. 3 Assembly and material testing

After assembly of each of the stayed columns a careful measurements of the space initial deflections was recorded using 3D scanning and electric potentiometers (for more details see [9]). Because the initial deflection values of the unprestressed columns exceeded in some columns the limits prescribed by EN 10219-2 (i.e. L/500), the imposed prestressing was slightly uneven in the four stays to result in the later shown acceptable final initial deflections under each of the selected prestressing.

ANSYS software was used for numerical analysis of both tests and in the following parametrical studies. 3D model was formed using for the central and crossarm tubes BEAM188 and for cable stays LINK180 (and no-compression option) elements, all embodying large deflections and material nonlinearity. The steel saddles at tips of the crossarms were modelled using SHELL281 elements (Fig. 4 (a)) with various frictions coefficients between the saddles and cable stays. After FE meshing the division employed in the analysis was L/250, a/25 and shell elements with area of approx. 23 mm^2. Prestressing of the stays was achieved by a respective thermal change and external loading of the column by an axial displacement Δx.



(a) FE modelling of saddles



(b) Column 1: comparison of test and ANSYS analysis

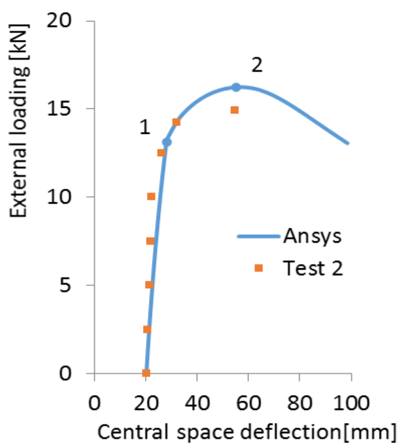
Fig. 4 Ansys detailed modelling and validation

With ratio $2a/L = 0.1$ and initial deflections roughly in one half wave shape, all the final deflections at the tests and numerical analysis followed the first buckling mode, i.e. one half wave. Results of tests and validation of numerical approach is shown for all 4 tests, using friction coefficient between the saddles and cable stays $\nu = 0.1$ (common for steel-steel friction).

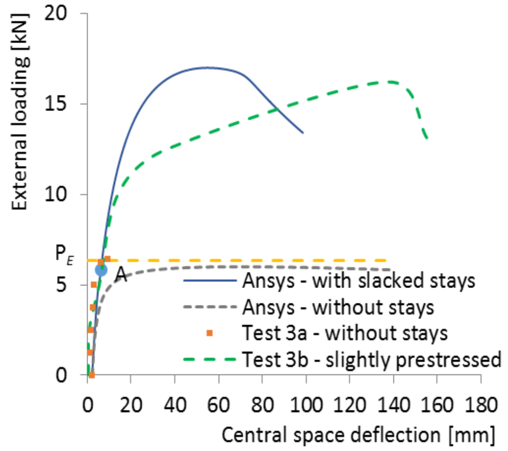
Column 1: The total applied prestressing in all four stays was $4T = 5.44$ kN. The prestressing in each of the 4 stays was slightly different to receive required global imperfection, which in this case had amplitudes at midspan of $w_{0y} = 1.9$ mm and $w_{0z} =$ 8.3 mm. The test exhibited linear behavior up to approx. 15 kN, followed by a rapid growth of deflection up to maximal ultimate loading of $N_{max,exp} = 17.7$ kN and terminated due to enormous deflection, see Fig. 4 (b). Numerical analysis in 3D covered the initial deflections of one half-sine shape with the above given amplitudes and initial total prestressing $4T$, requiring slightly different prestressing in each of the four stays. The comparison of test and numerical analysis is shown in Fig. 4 with good agreement.

Column 2: The total applied prestressing in this case was $4T = 4.54$ kN, arranged in the similar procedure as for the column 1, resulting in initial deflections with the mid-span amplitudes $w_{0y} = 3.8$ mm and $w_{0z} = 19.9$ mm. Up to the external load of 12.5 kN the behavior was nearly linear, followed by enormous increase of deflections and maximal ultimate load of 14.9 kN, when the test was terminated. Here the numerical maximal loading exceeded the test value of approx. 9 %, which was assigned to difficulties with modelling of various prestressing of the 4 stays and keeping the deflections as in the test.

Column 3: First, column 3a was tested without stays (in the lab reality with attached, but slacked stays). The amplitudes of initial deflections at midspan were $w_{0y} = 0.3$ mm and $w_{0z} = 1.4$ mm. The test was terminated due to sudden increase of central deflection (see Fig. 5 (b)) under loading $N_{max,exp} \approx 6.5$ kN, while common Euler's critical load is $N_E = 6.3$ kN (the difference amounts for 2.8 %). Numerical analysis of initially deflected column without stays gives $N_{max} = 6.0$ kN $< N_E$.



(a) Comparison of test and ANSYS analysis for column 2



(b) Comparison of test and ANSYS analysis for column 3

Fig. 5 Comparison of test and ANSYS analysis

Second, the stays in the column 3b were slightly prestressed with total value of $4T$ = 3.9 kN and resulting final central amplitudes of initial deflections were w_{0y} = 0.5 mm and w_{0z} = 2.2 mm. This test was terminated due to enormous deflections, giving maximal ultimate load N_{max} = 16.2 kN. Instead of numerical analysis of the slightly prestressed column the results of the column with fully slacked (unprestressed) stays is shown for comparison in Fig. 5 (b). The numerical results with N_{max} = 17.0 kN revealed a small "jump" at point A on the load-deflection curve at the level of critical loading, when a buckling activated initially slacked stays on the concave side of the column. The positive influence of the unprestressed stays on the ultimate loading is, therefore, confirmed in agreement with results of [12].

Comparison of results of the three tests with the proposed numerical modelling is satisfying and justifies use of the model for the following numerical studies.

3. Critical and Maximal Loading in 2D and 3D, Material Nonlinearity

Numerical analysis of the prestressed stayed columns needs to respect the 3 zones according to the prestress of stays (see Fig. 2). As explained in the Introduction, the behavior in the zone 2 involves sudden change of the assembly inner energy due to the central column buckling and instant activating of stays on convex side of the column. Therefore, linear buckling analysis can't be used and geometrically nonlinear one is necessary. However, in such case GNIA (geometrically nonlinear analysis with imperfections) need to be used, with negligible initial deflections. In the study were considered values of $w_{0y} = w_{0z} = L/500000$ = 0.01 mm.

Direction of maximal deflections in all former described tests was into space (i.e. between the axes y, z). The question arose, whether solution in 3D with the corresponding initial deflections in both axes y, z gives lower critical/maximal loadings. The studied stayed column had the same geometry as in Chapter 2, but with fixed stays at the crossarms: the central tube Ø 50x2 [mm], the crossarm tubes Ø 25x1.5 [mm] the stays as Macalloy cables Ø 4 mm. Stainless steel material with E = 200 MPa was considered for all the central tube, crossarms and stays (here as an initial value due to low stresses). Comparison of results for 2D analysis according to [3] and FEM in 3D with four amplitudes of initial deflections (w_0 = 0.01 mm, 0.05 mm, 0.10 mm and 25 mm) is shown in Table 1. The greatest amplitude corresponds to the design recommendation of Eurocode EN 1993-1-1 for cold-formed tubes and elastic analysis (L/200 = 25 mm). Both symmetric (one half wave initial deflection) and antisymmetric (two half waves with half amplitudes of initial deflection) were analyzed to determine T_{opt} and corresponding maximal critical loading or maximal strength N_{max} of imperfect column in the prestressing range up to $3T_{opt}$, Fig. 6.

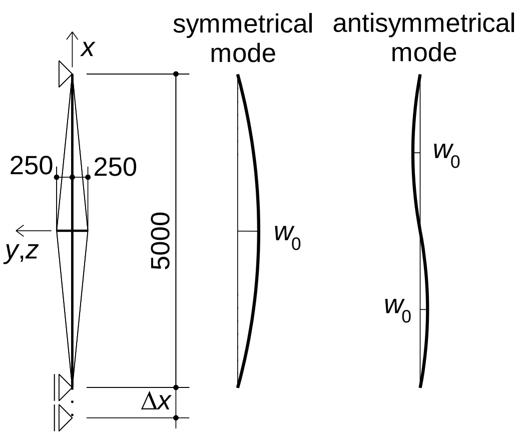
Table 1 Influence of initial deflection w_0, comparison of 2D and 3D analysis, material nonlinearity

w_0 [mm]	Symmetrical initial deflections		Antisymmetrical initial deflections		N_{max} [kN]
	T_{opt} [kN]	$N_{max,sym}$ [kN]	T_{opt} [kN]	$N_{max,anti}$ [kN]	
0 (2D)	1.41	39.79	1.30	36.79	36.79
0.01 (3D)	1.51	39.73	1.35	36.18	36.18
0.05 (3D)	1.58	39.25	1.43	35.77	35.77
0.10 (3D)	1.61	38.62	1.52	35.43	35.43
25.0 (3D)	-	22.74	-	24.84	22.74
0.01 (stainless steel)	1.51	36.54	1.27	31.58	31.58
25.0 (stainless steel)	-	19.57	-	19.92	19.57

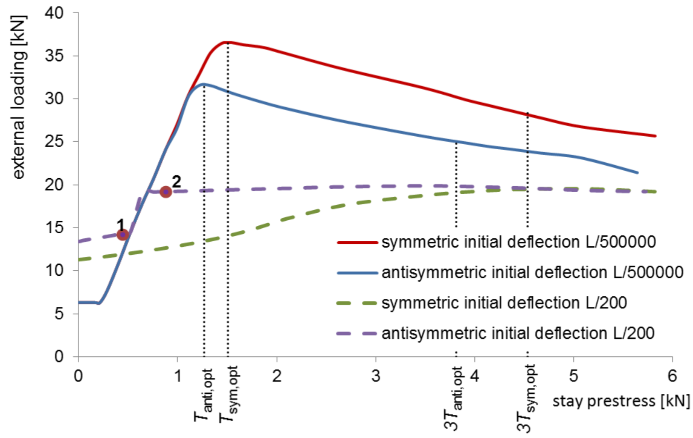
After analysis of the results, it was concluded (see the first two rows in Table 1), that 2D and 3D results, in spite of various directions of buckling (in direction of arms for 2D and into the space in 3D), provide nearly identical critical/strength values. This conclusion may be considered not only for the "ideal" column (i.e. for critical loading), but also for maximal ultimate loading (strength of imperfect stayed columns).

The last row of the Table 1 presents results for the same stayed column as above but made from stainless steel material as in the tests (see Chapter 2). It means that for central column and crossarms instead of constant E = 200 MPa the respective values of E_1 = 184 MPa, E_2 etc. (see Fig. 3) were employed. The results for N_{max} are significantly lower for the stainless steel material and simple reduction from elastic behavior using initial ratio $E_1/E \approx 0.92$ is not sufficient.

The GMNIA results for stainless steel material are shown in Fig. 6 (b). It is obvious that for the given geometry, design initial deflections $L/200$ and decisive role of symmetric initial deflections (because $2a/L = 0.1 < 0.175$), the ratio N_{max}/N_{cr} is similar to the one given in [12].



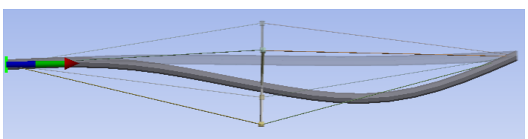
(a) Initial deflection shape



(b) Comparison of values for "ideal" ($w_0 = L/500000$) and initially deflected ($w_0 = L/200$) stainless steel stayed column

Fig. 6 GMNIA results for "ideal" and imperfect stayed column

The changes in deflection shape for such large antisymmetric initial deflections with an increase of prestressing are highlighted by points 1 and 2 in Fig. 6. The antisymmetric initial mode (however not decisive in this geometry) is changed after prestressing to an interactive one up to the point 1 and then, from point 2, to antisymmetric one again (see Fig. 7).

Point 1


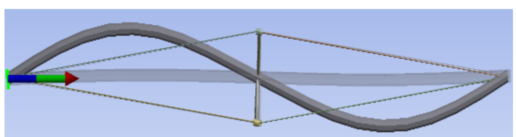
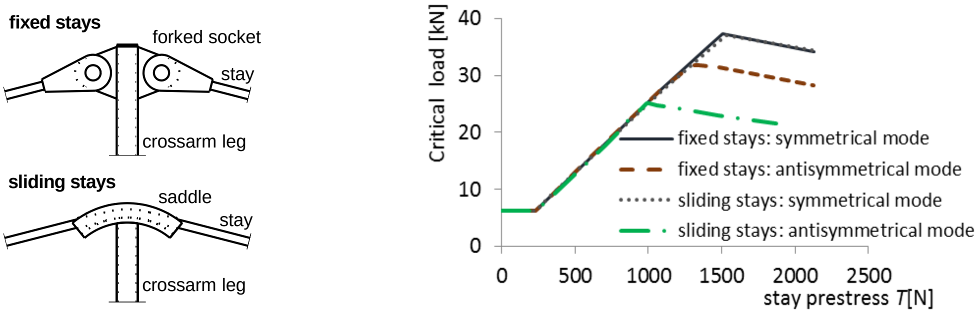
Point 2


Fig. 7 Deflection shapes for antisymmetric initial deflections and prestressing corresponding to points 1, 2

4. Support of Stays at Crossarms

The stays are formed either by rods or cables. Using rods naturally requires fixed fastening to the crossarms, but cables may be fastened either by forked terminal (i.e. fixed) or run continuously over saddles. In the tests described in Chapter 2, the saddles were used, enabling balancing tension in both parts of the respective stay after exceeding friction between the saddle and the cable, see Fig. 8 (a). Such arrangement is advantageous from assembly point of view and saving cable sockets, but obviously reduces in some way strength of the stayed column system.



(a) Support at crossarm (b) Influence of cable slip at saddles

Fig. 8 Alternatives and value of support conditions at crossarm

The friction between the saddles and cables may vary between from nearly zero (when using Teflon -like lining) and common value for steel-steel contact of $\nu = 0.10$. To analyze the influence of the cable slip at saddles safely, very low friction coefficient $\nu = 0.01$ was used and results are shown in Fig. 8 (b). The columns with geometry given in Chapter 3 and initial deflection of the central column $w_0 = L/500000$ were analyzed using GMNIA. From comparison of results is obvious that the different behavior arises at antisymmetrical mode of buckling only, were reduction of maximal critical load is substantial. Extensive studies concerning prestressed stayed columns with sliding stays and required necessary initial deflections are in progress.

5. Conclusions

The proposed numerical ANSYS model was successfully validated by comparison with the four tests of stainless steel stayed columns of reasonable geometry and various prestressing of stays.

The detailed studies resulted into the following conclusions:

(1) The stayed column even with unprestressed stays (slacked stays) provides significantly higher maximal ultimate loading in comparison with simple column without stays due to activating of stays at the concave side of the column during the buckling.

(2) The 2D planar analysis (FE or analytical one) with a buckling in the direction of the arms supplies nearly identical results concerning optimal prestressing, maximal critical and maximal ultimate loading as the 3D space analysis with buckling into space (in between the arms of the crossarm).

(3) Using nonlinear (stainless steel) material in stayed columns requires GMNIA and proper introduction of stainless steel stress-strain relationship.

(4) Maximal ultimate loading (strengths N_{max}) of a stayed column must be analyzed with initial deflections of appropriate amplitude and shape. With reasonable amplitudes (e.g. $L/200$ for cold-formed tubes required by Eurocode 3) and common ratios $2a/L$, both symmetric and antisymmetric initial deflections may be decisive and corresponding ratios N_{max}/N_{cr} be greater (for low prestressing) or much lower (for great prestressing) than 1.

(5) Continuous stays, running over saddles, may be advantageous for assembly, but when antisymmetric buckling is predominant, a strong reduction in maximal ultimate loading need to be expected.

Acknowledgement

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References

[1] K. H. Chu and S. S. Berge, “Analysis and design of struts with tension ties,” Journal of the Structural Division ASCE, vol. 89, no. ST1, pp. 127-163, February 1963.

[2] R. J. Smith, G. T. McCaffrey, and J. S. Ellis, “Buckling of a single-crossarm stayed column,” Journal of the Structural Division ASCE, 11071 ST1, pp. 249-268, January 1975.

[3] H. H. Hafez, M. C. Temple, and J. S. Ellis, “Pretensioning of single-crossarm stayed columns,” Journal of the Structural Division ASCE, 14362 ST2, pp. 359-375, February 1979.

[4] K. C. Wong and M. C. Temple, “Stayed columns with initial imperfections,” Journal of the Structural Division ASCE, 108 ST7, pp. 1623-1640, 1982.

[5] S. L. Chan, G. Shu, and Z. Lü, “Stability analysis and parametric study of pre-stressed stayed columns,” Engineering Structures, vol. 24, no. 1, pp. 115-124, January 2002.

[6] D. Saito and M. A. Wadee, “Post-buckling behaviour of prestressed steel stayed columns,” Engineering Structures, vol. 30, no. 5, pp. 1224-1239, May 2008.

[7] D. Saito and M. A. Wadee, “Numerical studies of interactive buckling in prestressed steel stayed columns,” Engineering Structures, vol. 31, no. 2, pp. 432-443, February 2009.

[8] R. R. Araujo, S. A. L. Andrade, P. C. G. S. Vellasco, J. G. S. Silva, and L. R. O. Lima, “Experimental and numerical assessment of stayed steel columns,” Journal of Constructional Steel Research, vol. 64, no. 9, pp. 1020-1029, September 2008.

[9] K. Servitova and J. Machacek, “Analysis of stainless steel stayed columns,” Proceedings 6th Intern. Symp. Steel Structures, Korean Society of Steel Construction, Seoul, pp. 874-881, 2011.

[10] L. R. O. Lima, P. C. G. Vellasco, and J. G. S. Silva, “Numerical modelling of prestressed stayed stainless steel columns,” Tubular Structures XIV, Taylor and Francis, London, pp. 377-382, 2012.

[11] A. I. Osofero, M. A. Wadee, and L. Gardner, “Experimental study of critical and post-buckling behaviour of prestressed stayed steel columns,” Journal of Constructional Steel Research, vol. 79, pp. 226-241, December 2012.

[12] M. A. Wadee, L. Gardner, and A. I. Osofero, “Design of prestressed stayed columns,” Journal of Constructional Steel Research, vol. 80, pp. 287-298, January 2013.

[13] R. Pichal and J. Machacek, “3D stability of prestressed stayed columns,” Proceedings 22nd Intern. Conf. Engineering Mechanics, Inst. of Thermomechanics, Academy of Sciences of the Czech Republic, Svratka, pp. 462-465, 2016.

[14] R. Pichal and J. Machacek, “Buckling and post-buckling of prestressed stainless steel stayed columns,” Procedia Engineering, vol. 172, pp. 875-882, 2017.