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3D STABILITY OF PRESTRESSED STAYED COLUMNS

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Abstract: *A geometrically nonlinear analysis of the buckling and post-buckling behavior of the stayed columns is employed using FEM and ANSYS software. The buckling of these members depends on their geometrical and material properties, prestressing and boundary conditions. In the paper are discussed respective critical buckling loads and post-buckling paths with regards to 2D LBA (linear buckling analysis) and 3D GNIA (geometrically nonlinear analysis with imperfections). Former tests and recent detailed analyses of other authors are commented with respect to 3D analysis, level of imperfections and boundary conditions at the central crossarm.*

Keywords: Prestressed stayed columns; nonlinear buckling; finite element modelling; 3D analysis; sliding stays.

1. Introduction

The stayed columns in a practical layout are formed by a central steel tube of length *L*, a mid-span crossarm with 4 arms of length *a* in angle $\alpha = 90°$ and stays made of cables or rods, each with prestressing *T*. The basic setup shown in Fig. 1 was analyzed analytically by Smith et al. (1975) and Hafez et al. (1970), distinguishing 3 zones of behavior according to level of prestressing and resulting in principal formulas for buckling loads under arbitrary stay prestressing and „optimal" prestressing T_{opt} giving maximal buckling load $N_{cr,max}$. Influence of initial deflections was studied e.g. by Saito and Wadee (2009), showing predominant buckling modes with respect to ratio $2a/L$, stay area A_s, and shape of initial deflections (respective modes shown in Fig. 2). The stayed columns were also tested experimentally, e.g. by Araujo et al. (2008), Servitova & Machacek (2011), Osofero et al. (2012), the last one revealing post-buckling behavior of imperfect stayed columns depending on critical modes and level of prestressing.

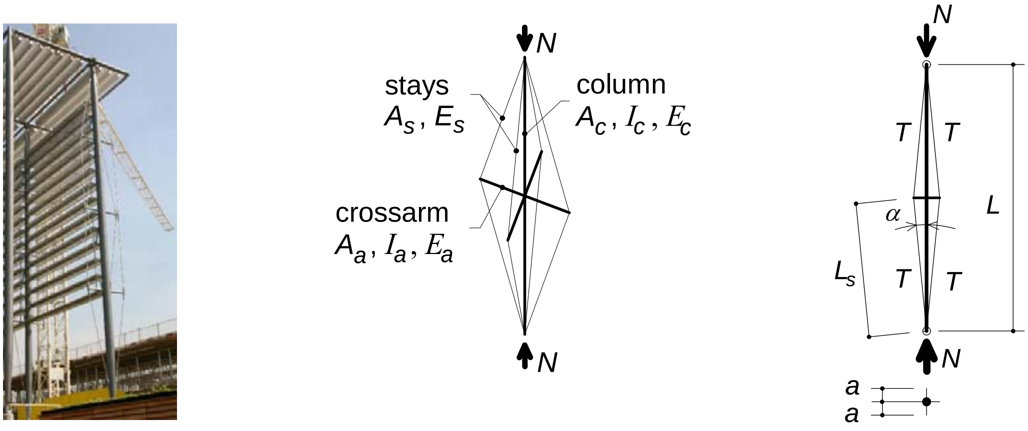

Fig. 1: Example (London site), space layout, geometry.

The buckling and post-buckling behaviour was studied using GNIA (geometrically nonlinear analysis with imperfections) by Saito and Wadee (2008, 2009). The results cleared up the stable or unstable paths of column behavior after buckling in symmetric, antisymmetric and interactive buckling modes (Fig. 2).

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Recent parametrical study by Wadee et al. (2013) introduced three levels of global column initial deflections (L/1000, L/400, L/200), various ratios $2a/L$ (to cover all possible buckling modes) and initial stay prestress up to $3T_{opt}$. The maximum load-carrying capacity N_{max} was then established by GNIA and respecting relevant test results (Fig. 2), within all three prestressing zones.

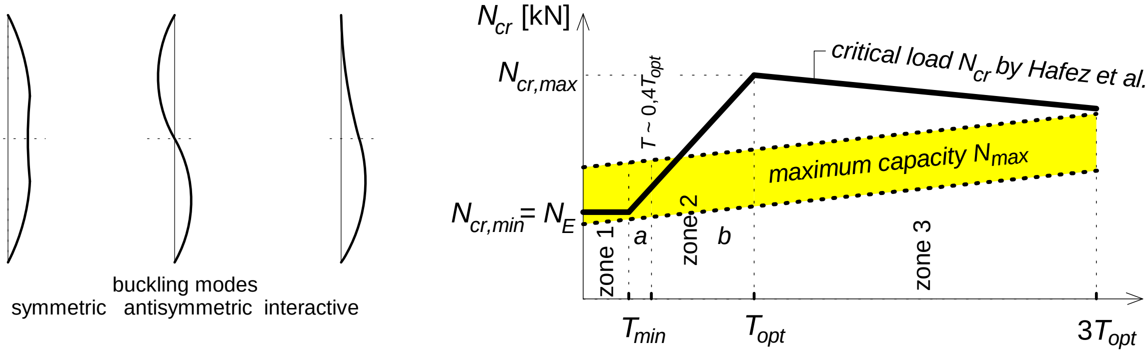

Fig. 2: Buckling modes, critical loads and load-carrying capacity.

All former analytical and numerical studies concerned elastic nonlinear 2D analysis, possibly extended for an influence of 4 space arms/stays of the space perpendicular crossarm but with buckling in the direction of the arms. The connections between the stays, columns and the crossarm were assumed to be fixed as ideal hinges.

The present paper deals with 3D behavior of the stayed columns using GNIA (geometrically nonlinear analysis with imperfections) with respect to dissimilarity of 2D and 3D behavior. Moreover, an arrangement with stays sliding on the crossarm which may be advantageous from assembly point of view is analyzed.

2. Nonlinear 3D analysis

Numerical GNIA ANSYS modeling used the following finite elements:

- column and crossarm tubes: BEAM188 (3D, 2x6 = 12DOF, large deflections, material nonlinearity),
- cable stays: LINK180 (3D, 2x3 = 6DOF, large deflections, material nonlinearity, introduced tension only),
- saddle at crossarm (in case of sliding stays): SHELL281 (3D, 8x6 = 48DOF, large deflections, material nonlinearity).

The prestressing was introduced by the stay's thermal change and external loading by axial column displacement. The respective prestressing loads and external column loading values were recalculated from the column reactions. Numerical procedure employed arc-length method to follow unloading path.

The column under investigation has following parameters (span L, cross-section area A, second moment of area I, Young's modulus E):

- tube column Ø 50x2 [mm]: L = 5000 mm, A_c = 301.59 mm^2, I_c = 87009,6 mm^4, E_c = 200000 MPa,
- crossarm tube Ø 25x1.5 [mm]: a = 250 mm, A_a = 110.74 mm^2, I_a = 7675.7 mm^4, E_a = 200000 MPa,
- cable Macalloy stay Ø 4 mm: L_s = 2513 mm, A_s = 12.57 mm^2, E_s = 200000 MPa.

2.1. Stayed columns with stays fixed to the crossarm

Analytical buckling analysis of this perfect stayed column in 2D according to formulas given by Hafez et al. (1970) provides the following results:

- Euler's critical buckling load of the column without stays N_{cr} = 6.87 kN,
- maximal critical load of the stayed column with symmetrical buckling $N_{cr,max,sym}$ = 39.78 kN,
- maximal critical load of the stayed column with antisymmetrical buckling $N_{cr,max,anti}$ = 36.79 kN,
- optimal prestressing T_{opt} = 1.302 kN.

Numerical FE analysis of such stayed column by LBA (linear buckling analysis) with medium prestressing (zone 2 in Fig. 2) is not possible as revealed by Saito and Wadee (2008), due to sudden slackening of the stays on the concave side at the instant of buckling. Therefore, introduction of initial deflections and GNIA is necessary. To determine 3D critical loads symmetric and antisymmetric initial deflection of very small values were introduced (see Fig. 2), with amplitudes in both cross-section directions $w_0 = 0.01$ (i.e. L/500 000), giving space amplitude of $w_0\sqrt{2}$. External load-axial deflection path for optimal prestressing under symmetric initial deflection (T_{opt} = 1.51 kN) is demonstrated in Fig. 3, showing bifurcation point with critical loading $N_{cr,max,sym}$ = 39.73 kN.

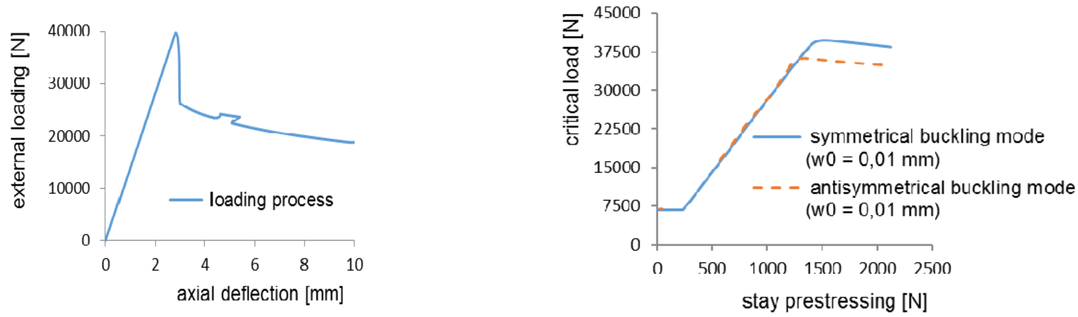

Fig. 3: Load-deflection path for the optimal prestressing (left), critical loads vs. pretensions (right).

The stayed column in its basic arrangement employs fixed hinged connections of the stays to the crossarm. The 3D GNIA was performed for 31 values of prestressing with both symmetrical and antisymmetrical initial deflections. Results are shown in Fig. 3, demonstrating zones 1, 2, 3 in accord with analytical solution. Sensitivity to amplitude of the initial deflection w_0 for the symmetrical buckling mode and comparison of the 3D GNIA maximal critical values with analytical 2D (Hafez et al., 1979) solution is presented in the Table 1. The 3D GNIA with the small initial deflections gives nearly identical critical loads $N_{cr,max}$ as the 2D analytical analysis. Negligible differences may arise due to imperfections, non-rigid crossarm and space buckling; the influence of the last one therefore seems to be rather unimportant.

Tab. 1: Maximal critical loads and optimal pretensions.

Initial deflection w_0 [mm]	Symmetrical mode		Antisymmetrical mode		Decisive $N_{cr,max}$ [kN]
	Optimal pretension T_{opt} [kN]	Maximal critical load $N_{cr,max,sym}$ [kN]	Optimal pretension T_{opt} [kN]	Maximal critical load $N_{cr,max,anti}$ [kN]	
0 (Hafez et al.)	1.41	39.79	1.30	36.79	36.79
0.01	1.51	39.73	1.35	36.18	36.18
0.05	1.58	39.25	-	-	-
0.10	1.61	38.62	-	-	-

Nevertheless, the space buckling is the fact confirmed by the tests and in the 3D GNIA demonstrated in Fig. 4, showing a stayed column with a predominant symmetrical initial deflection in the direction of the column cross section plane *x-z* (w_{0x} = 0.01 mm; w_{0z} = 5 mm). The column midspan deflection with increase of loading follows direction of the greater initial one and later traverse into space deflection (i.e. direction of the minimum rigidity), up to the buckling load value. The instant of change of the direction depends on value of prestressing: the greater prestressing, the higher value of the instant of change. Loss of prestressing in the stays is also shown in Fig. 4.

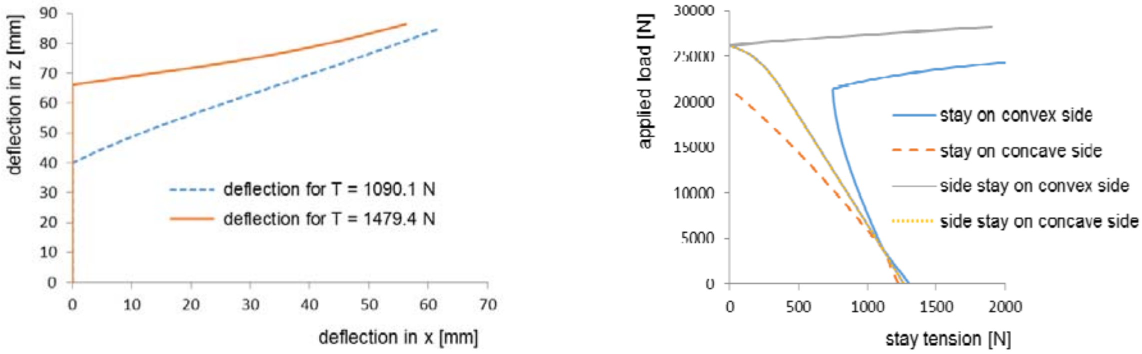

Fig. 4: The space buckling of initially symmetrically deflected column with w_{0x} = 0.01 mm; w_{0z} = 5 mm (left) and loss of prestressing in the stays (right).

2.2. Stayed columns with stays sliding at the crossarm

Modelling requires use of shell elements and introduction of friction (coefficient ν) at the saddle-stay interface. Comparison of results for symmetrical buckling mode with $\nu = 0.1$ is given in Fig. 5.

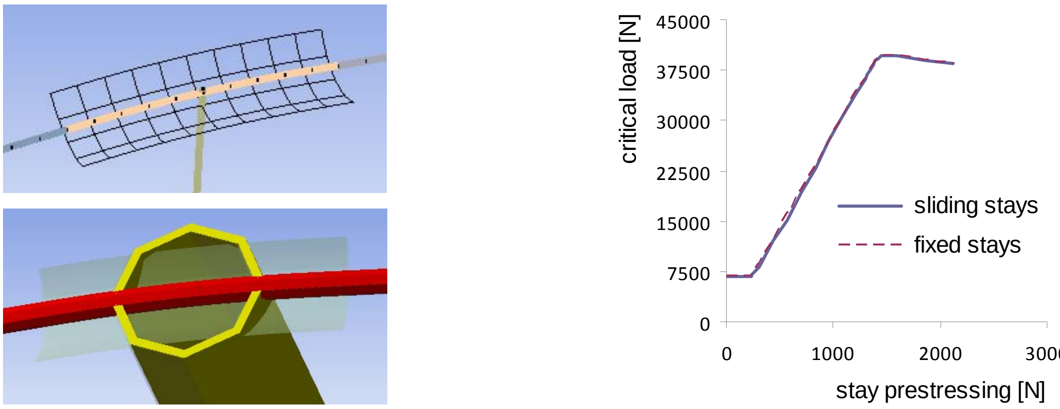

Fig. 5: Sliding saddle FE modeling (left), behavior and $N_{cr,max,sym}$ for fixed and sliding stays (right)

3. Conclusions

- Geometrically nonlinear analysis with imperfections (GNIA) in 3D proved buckling of the prestressed stayed columns in the space (in the direction between the arms of the central crossarm). Nevertheless, the critical loads received using 2D analysis and buckling in the direction of the arms gives nearly identical values.
- Amplitudes of initial deflections (w_0) using 3D GNIA affect substantially the buckling behavior and value of the respective critical load N_{cr}. In the investigated column the value of $w_0 \leq L/50000$ lowered the value $N_{cr,max}$ of less then 3 %. From the sensitivity study the values $w_0 \leq L/500000$ may be recommended for calculation of bifurcation load corresponding to LBA.
- Stays sliding on the crossarm with friction $\nu = 0.1$ and symmetrical buckling mode give nearly identical critical loads as for the fixed stays for various prestressing in all zones 1, 2, 3 including $N_{cr,max}$. Other modes of buckling and frictions are currently under detailed investigation.

Acknowledgement

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