Thin-Walled Structures 132 (2018) 58–68

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Buckling and collapse capacity of prestressed steel tube stayed columns with one and two crossarms

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ARTICLE INFO

Keywords:
Stayed columns
Two crossarms
Stainless steel
Buckling
Collapse load
Critical load

ABSTRACT

Prestressed tube stayed columns with one and two crossarms are investigated. The analyses are performed using SCIA Engineer software and ANSYS package and validated by tests of four stayed columns. First, the investigations concern the ideal (perfect) columns and cover linear buckling analyses (LBA) and geometrically nonlinear analyses (GNIA) to obtain critical loads and buckling modes under various prestressing levels. Second, the collapse loadings of the imperfect columns with initial deflections required by Eurocode EN 1993-1-1 are analysed with respect to relevant initial deflection modes and material behaviour (elastic for mild steel, nonlinear for stainless steel). All the analyses are performed for geometrical characteristics of the tested columns and the results concerning both the column with one or two crossarms are set against each other to assess the respective effectivity. In addition, the geometrical analysis of the prestressed ideal column with two crossarms and respective formulas concerning optimal prestressing and maximal critical loading are presented. Finally some recommendations for practical use are suggested.

1. Introduction

Slender compression columns may be designed as prestressed steel stayed elements to accomplish both structural and architectural requirements. Nowadays, there are a lot of marvellous and unique structures using prestressed elements, mostly thanks to the novel structural components (especially Macalloy/Detan rods/cables). For example the horizontal support of Grande Arche lift in Paris (Fig. 1) employed a central steel tube with one central crossarm and four stays to achieve pleasant and a trendy structural element.

Already in the mid 1950s the multiple crossarms were used by Vojevodin [1], to increase the strength capacity of even more slender compression elements as shown in Fig. 2. The stayed elements are usually formed by a central steel tube of the length L, crossarms with 4 arms of length a arranged in an angle $\alpha = 90^\circ$ and stays made of cables or rods, each with prestress T. However, common are also stayed elements with the crossarms in a planar arrangement (2 arms in the angle of $\alpha = 180^\circ$, with flexible or fixed support for out-of-plane buckling, see Fig. 2 mid) or a triple set-up (3 arms in the angle of $\alpha = 120^\circ$, see Fig. 2 right), shown in the case of just one central crossarm in Fig. 3.

In the last decades prestressed compression stayed elements with one central crossarm according to Fig. 3 were investigated in a detail analytically, numerically and experimentally. The milestones were accomplished by Smith et al. [2] and Hafez et al. [3], who discovered the three zones of buckling behaviour of ideal columns depending on the prestressing level of stays as shown in Fig. 4. The "zones" may be explained as follows: 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 the buckling. Higher prestressing than T_{opt} increases the column loading and, therefore, decreases the critical column load N_{cr}.

Another substantial progress was achieved by Wadee et al. [4], who investigated maximal load capacity of imperfect columns under various buckling mode shapes (symmetric, antisymmetric, interactive), which is roughly for an orientation also outlined in Fig. 4. Detailed investigations covering critical values, initial imperfections or maximal capacity of the stayed columns with just one crossarm were provided by Wong and Temple [5], Chan et al. [6], Saito and Wadee [7,8]. The background testing with principal results concerning buckling and collapse loadings were presented by Araujo et al. [9], Servitova and Machacek [10], Lima et al. [11], Osofero et al. [12], Ribeiro et al. [13], Serra et al. [14] and were also commented in full by the Authors in [15,18].

Simultaneously, the prestressed stayed compression elements with

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https://doi.org/10.1016/j.tws.2018.07.045
Received 22 April 2018; Received in revised form 23 July 2018; Accepted 23 July 2018
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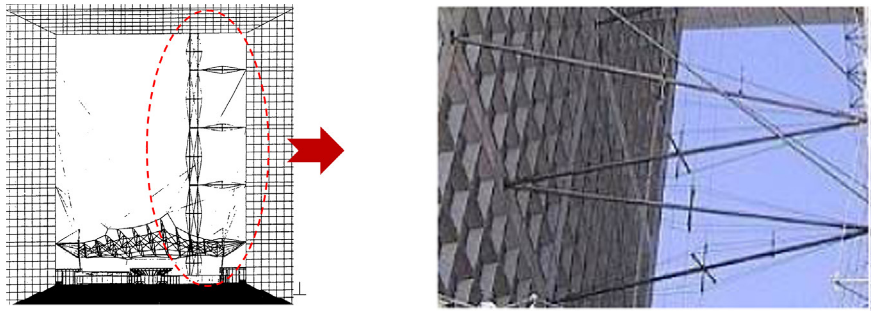

Fig. 1. Lift of the Grande Arche, Paris (left) and a detail of the stayed element with one central crossarm.

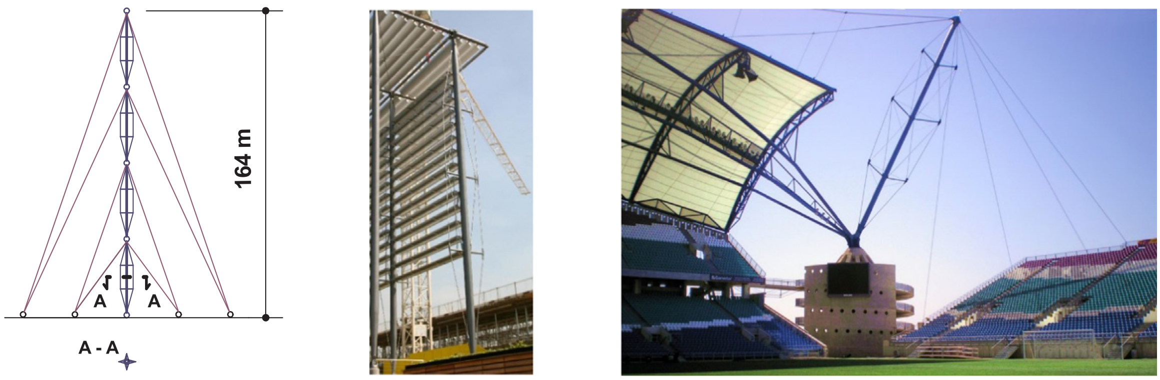

Fig. 2. Compression elements with multiple crossarms: Mast in Russia built in 1955 (left), London Chiswick Park (mid), Estádio Algarve in Faro (right).

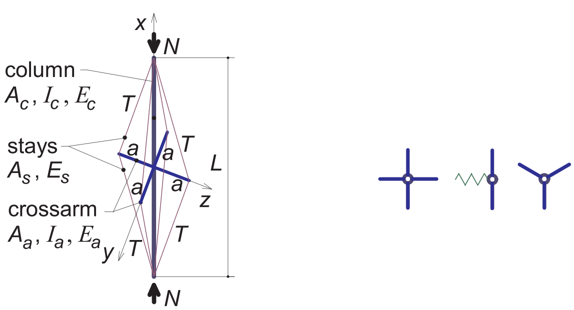

Fig. 3. Prestressed stayed column with a central crossarm and possible layout of the crossarms (4 arms, 2 arms with a support for out-of-plane buckling, 3 arms).

multiple crossarms were analysed both numerically and experimentally (e.g. Khosla [19], Jemah and Williams [20]). Nevertheless, more deep investigation into this area was published in the last years only. Martins et al. [21] tested stayed tube columns with two crossarms of the total length 18 m, two different column diameters and various prestressing. The tests provided valuable experimental data concerning the axial shortening and lateral deflections under loading. Yu and Wadee [22] investigated stayed columns with three crossarms using ABAQUS software. The investigation covered various column to crossarm ratios, varied diameters of cable stays and values of prestressing. The “efficiency indicators” were used to optimize the total design and an optimal prestressing. These authors [23] further developed a nonlinear analytical model verified by ABAQUS nonlinear analysis, studied parametrically buckling modes and drew attention to possibility of a buckling mode jumping. Lapira et al. [24] analysed prestressed stayed columns with three crossarms in a detail. They provided an analytical investigation of the systems in 3D and furthermore with an additional stay system located in the middle quarters of the column. The resulting formulas cover maximal critical values corresponding to the optimal and any other prestressing, which were verified by FEM using ABAQUS software.

This article comes out of 4 tests conducted on prestressed stainless steel stayed columns with total length of 5 m, which were performed at the laboratory of the Czech Technical University in Prague. The tests are briefly discussed and used for validation of the proposed numerical GMNIA using ANSYS software. Afterwards, prestressed stayed columns of the same characteristics as the tested ones with one central crossarm and relevant initial deflections are investigated for various boundary conditions. Finally, the prestressed stayed columns of the same length of 5 m, but with two crossarms located at the thirds of the column length are analysed in-depth. Effectivity of adding the second crossarm is evaluated in the article conclusions. Appendix embraces the analytical formulation of the prestressed stayed elements with two crossarms, leading to the approximate formulas for optimal prestressing and maximal collapse loading under arbitrary prestressing.

2. Tests and numerical analyses

Owing to a sudden change of the internal energy in a specific buckling of prestressed structures and the following restoring of the equilibrium concerning a formation of another structural configuration the use of linear buckling analysis (LBA) is not sufficient (see also [7,25,26]). Therefore, the geometrically nonlinear analysis with imperfections (GNIA) is a necessity. Nevertheless, the LBA is useful to find critical loadings and modes of buckling for a preview and an approximate analytical formulation is provided in Appendix A.

2.1. Tests

The 4 laboratory tests on the stainless steel prestressed stayed columns with one central crossarm were performed with the arrangement having the same characteristics as follows (see Fig. 5):

- Central tube Ø 50 × 2 [mm], stainless steel 1.4301 (L = 5000 mm, A_c = 302 mm^2, I_c = 87,009 mm^4, $E_{c,ini}$ = 184 GPa).
- Crossarm tubes Ø 25 × 1.5 [mm], stainless steel 1.4301 (a = 250 mm, A_a = 111 mm^2, I_a = 7676 mm^4, $E_{a,ini}$ = 184 GPa).