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Cable-stayed columns and their applications in building structures

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ABSTRACT

Stayed columns have been used as architecturally expressive lightweight elements in buildings and tensioned-membrane structures. Their structural merits of reduced core size and enhanced compression strength even outweigh the architectural elegance. The main emphases of this paper, as such, is to reveal the structural benefits, the counter-intuitive structural behaviour, and to raise research interest in this special type of column through a series of case-studies. Structural behaviour of one and two-tier cross-arm cable-stayed columns are investigated for both symmetric and anti-symmetric modes. The use of prestressed tension elements (cables or rods as stays) along with a compression member (tube or solid core) and the pinching effect of cross-arms contribute to their anomalous structural behaviour. A *Strength Enhancement Ratio* (SER) is defined that evaluates the enhanced strength resulting from transforming a steel tube into a cable-stayed column. This provides a criteria for designers to determine when cable-stayed action should be considered as a useful and efficient means of providing the required strength to slender columns. The latter part of the paper presents various architectural applications of stayed columns through a series of case-studies.

1. Introduction

Masts in yachts and sail-boats are historic predecessors of modern day stayed columns, the latter being a strikingly innovative structural enhancement to conventional columns. Stayed columns demonstrate a successful way to enhance column stiffness while maintaining a light-weight core. Use of different materials (wood, concrete, and steel) and sections for the core have added delight to the innovative variations in the forms and details. Designers have found a way to harmoniously integrate stayed columns with roof cladding, glass façades, and other components of a building. Stayed columns are used in tensile membrane structures to equilibrate the high tension forces from membranes and cables in order to safely transfer the forces to the foundations. Other potential applications may include use as vertical struts in cable domes, as compression bracing in frames, and as deployable masts for outer-space applications. The first part of the paper describes the materials and typical geometries used for stayed columns. The structural behaviour of both single and double cross-arm columns are examined. Geometric and force parameters that affect column strength are considered in the analyses. A formula is given to calculate the additional column strength gained after transforming a given steel tube into a cable-stayed column. The second part is devoted to recent applications through a case-study approach that describes seven buildings that employ cable-stayed columns, both for their structural efficiency and iconic value.

2. Structural form

Stayed columns consist of a central core to which transverse cross-arms are welded at intermediate spacings in single or multiple tiers along the column height. The core is usually made of hollow steel tube tapered at the ends. Solid-sawn wood and bamboo may be other options. Steel cables or rods are attached between the tube ends and the ends of cross-arms. The stays are prestressed to provide initial stiffness. Different topological alternatives are possible with respect to the number of cross-arms along the height of a column and also the number of cross-arms in plan view, namely, cruciform (in two orthogonal directions) and triform (at 120° from each other) configurations.

Smith R.J. et al. [1], Hafez et al [2], Hathout et al. [3], Temple et al. [4,5], Smith E.A. [6], Serra et al [7], and Saito et al. [8] have dealt with understanding and predicting the structural behaviour and strength of stayed columns. In this paper, columns with pinned ends are examined for gravity loads only. It is assumed that lateral bracing to the structure would be provided by other elements such as shear walls or braced frames located elsewhere in the building structure.

3. Structural behaviour

Consider a simple column 5.90 m tall made of a hollow steel section 76.2 mm dia. x 3.17 mm thick. The buckling load for the tube alone

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without cable-stays is calculated using the Stiffness Probe Method (SPM) and verified with the Euler elastic buckling load $N_E = (\pi/L)^2\ E_c I = 27.5\,\text{kN}$, where $E_c = 200\,\text{kN/mm}^2$, $L = 5.90\,\text{m}$, $I = 4.7 \times 10^5\,\text{mm}^4$. Another limit state is the tube yield load which is calculated as $N_y = A_c F_y = 211\,\text{kN}$, where $A_c = 728.4\,\text{mm}^2$ and $F_y = 0.290\,\text{kN/mm}^2$.

Now, consider the tube section welded with cross-arms and with stays attached. Two types of stayed columns were examined, namely, a column with one tier of cross-arms at mid-height and another column with two tiers of cross-arms at one-third spans (Fig. 1a and b). Cables do not run continuous between the tube ends but are attached between the ends of the tube and cross-arms. The column is assumed as hinged at both ends.

When the stay cables are adequately pretensioned, they impose an initial compression force on the tube. An axial gravity load increases the compression in the central tube and reduces the initial tension in the stay cables. For design purposes, three distinct stages of loading are considered as shown in Fig. 2: at initial cable prestressing, during service and at ultimate. Referring to Fig. 2a, vertical equilibrium at the top node of a single cross-arm column calls for the following equation to hold at all times,

$$N = P + \sum T(P)\cos\alpha \tag{1}$$

where $\Sigma T(P)$ is the sum of the tension of all four individual cables at any given load P, and α is the angle between each cable and the axis of the tube. The variation of the angle α between the initial and ultimate loadings caused by column shortening is considered. Note that $N(P) > P$ at all times, i.e., the axial compression force in the tube is always larger than the applied load by the amount equal to the residual tension in the cables. The difference $N(P) - P$ is greatest at cable prestressing ($P = 0$) and least at ultimate ($P = P_{cr}$) when the cables are subjected only to a residual tension, $T_{res} > 0$. Only for the objectionable case when cables fully slacken as P increases would $\sum T = 0$ and $N(P) = P$. The quantity T_{res} depends mostly on the amount of initial cable prestressing, T_o. As the column shortens by a strain $\Delta\varepsilon$, the inclined cables shorten as well, but by a smaller strain equal to $\Delta\varepsilon\ cos^2\alpha$. For the double cross-arm stayed column shown in Fig. 2b, vertical equilibrium of the two end segments of this column is also given by Eq. (1). For the central segment, the same equation holds true with $\alpha = 0$. The previous discussion on the difference between forces N and P is applicable here as well. However, note that the change in strain imposed on the central segment by a change ΔP in

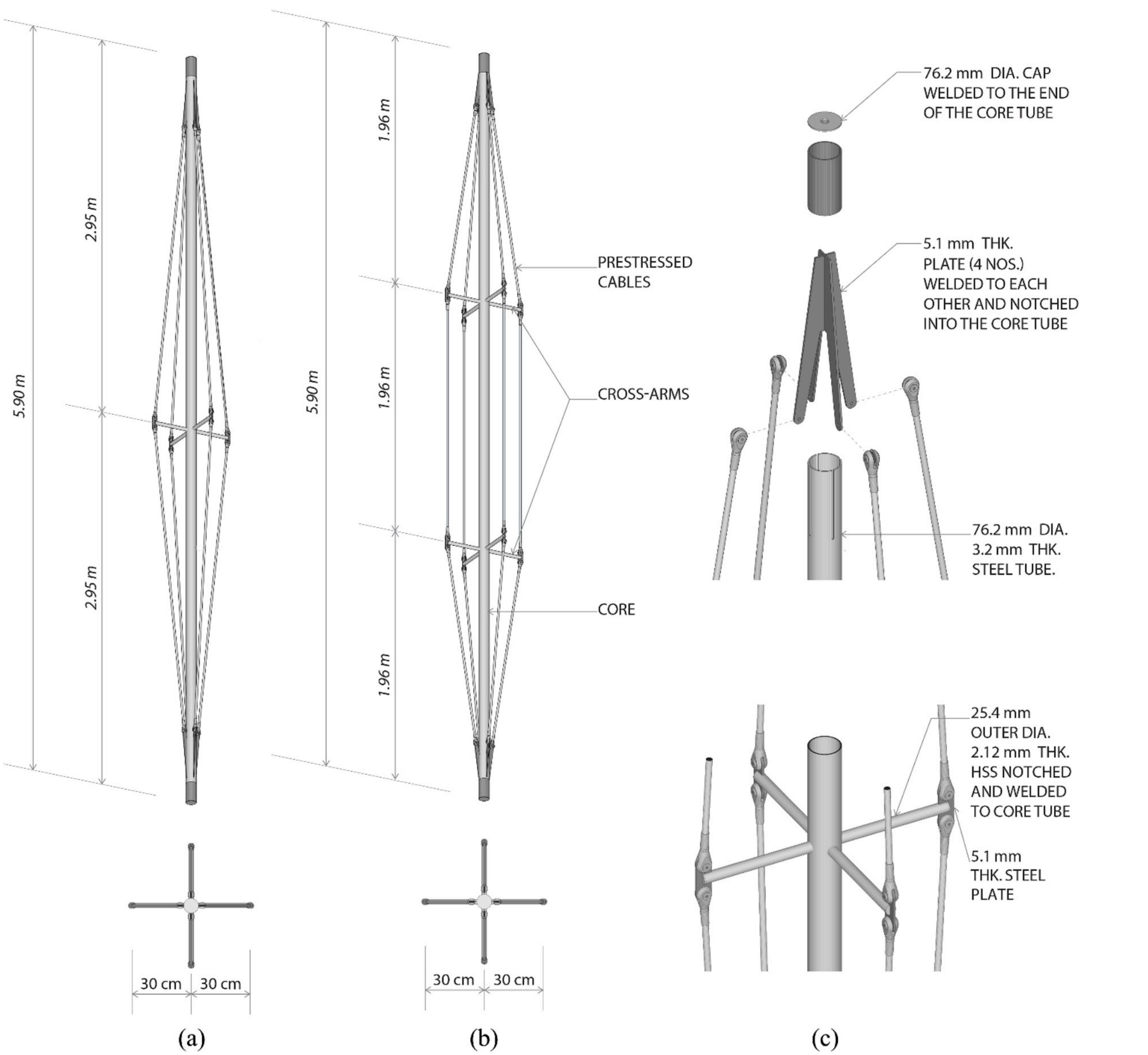

Fig. 1. (a) Single cross-arm column, (b) Double cross-arm column, and (c) typical connection details between the tube and cross-arms.