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Optimal prestressing of triple-bay prestressed stayed columns

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A B S T R A C T

A nonlinear finite element model of a triple-bay prestressed stayed column is developed within the commercial package ABAQUS. A linearly obtained 'optimal prestressing force' that maximizes the critical buckling load is investigated since this quantity has been demonstrated in previous work on single-bay prestressed columns to provide a lower bound to the actual maximum load carrying capacity when compared to experimental results and nonlinear modelling. The ratio of the crossarm to the overall column length, the diameter of the cable stays, the relative lengths of the individual crossarms and the ratio of the initial prestressing force to the aforementioned linear optimal prestress are varied. Measures for the relative efficiency of the main column and the stays are defined and the objective of the optimization study is for the efficiency to be maximized. It is found that the true optimal prestress is generally higher than the equivalent, linearly obtained, quantity but by a significantly reduced factor when compared to an equivalent study for single-bay prestressed stayed columns.

1. Introduction

Prestressed stayed columns, which are usually made from tubular steel elements that are reinforced by external cable stays, as represented in Fig. 1, are being increasingly used in the construction industry. With the introduction of the crossarms and prestressed cables, stayed columns possess significant extra axial strength when compared with conventional columns without necessarily a commensurate increase in self-weight. This type of structure offers an innovative, aesthetic and practical solution to the problem of low critical buckling load capacities in highly slender columns. For example, during the construction of the Rock in Rio III stadium in Brazil [1,2], such columns were used as a lightweight solution to prop the incomplete stadium roof while the construction was completed. The columns were constructed and prestressed on site such that they eliminated the need for using expensive shoring systems that would have increased the time and cost of construction significantly. Fig. 2 shows some other real-world applications of prestressed stayed columns with multiple bays.

Research on such structural components can be dated from the 1960s. The initial research focus mainly concerned the evaluation of the critical buckling load [3–9]. Effects of different levels of prestress [10] and initial imperfections were then studied [11,12]. The nonlinear behaviour of prestressed stayed columns has only been studied extensively relatively recently [13,14]. This more recent work has demonstrated that although for each configuration of crossarm length, main column length and stay diameter there exists a so-called 'optimal prestressing force' that maximizes the critical buckling load [10], the behaviour of the columns in the post-buckling range is considerably more complex and affects the ultimate load carrying capacity [15–19]. The work has resulted in recommendations for the actual optimal initial prestress accounting for the post-buckling behaviour and the development of a detailed procedure for the design of such single-bay column systems [20,21].

Most existing studies have been focused on single-bay stayed columns while multiple crossarm cases have only been recently investigated in terms of nonlinear behaviour [19]. It has been shown that there is a great deal of advantage to be gained from the introduction of crossarms. However, the benefits can be outweighed by the increased cost by demanding higher structural strengths from the individual elements of the system. Saito and Wadee presented a study of the optimal prestress in terms of the ultimate strength and cost effectiveness for the single-bay column [20] and determined the recommended prestress values. Unlike earlier research on the magnitude of the prestress [22], the maximum load carrying capacity is not necessarily the only indicator for choosing the preferred level of prestress. The required resistances of the column and the stays need also to be taken into consideration. This allows the designer to choose the appropriate prestress level more wisely when designing the stayed column, since the strength of the materials and their relative costs are also important factors. A similar approach is also used in the current study to investigate the actual optimal prestress for the triple-bay prestressed stayed column. Recommendations for the actual optimal prestress are provided for the structures with different geometric arrangements.

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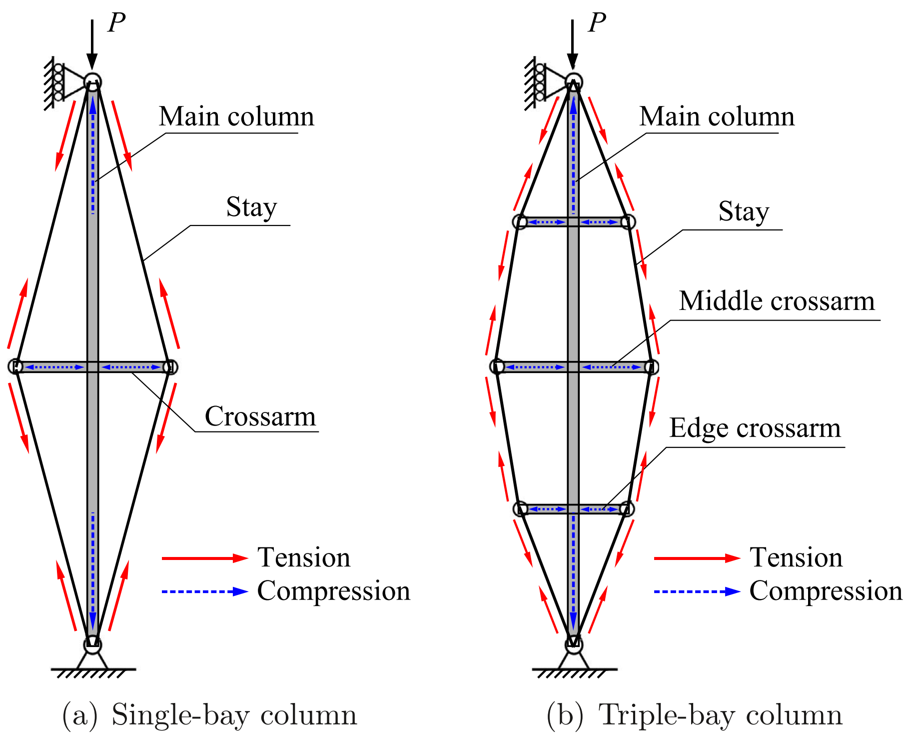

Fig. 1. Columns reinforced by cable stays with different crossarm systems.

2. Model formulation

The model of the triple-bay prestressed stayed column is formulated by using the commercial finite element (FE) software ABAQUS [23]. It comprises a main column element, three pairs of crossarms and a series of prestressed cable stays. Since the main column element is very slender, it is modelled using 'B23' cubic Euler–Bernoulli beam elements, whereas the generally shorter crossarms are modelled using the 'B22' quadratic Timoshenko beam elements such that the effects of flexural shear may be captured. The stays are modelled with the 'T2D2' truss elements with the 'no compression' option enabled to ensure the stays only resist tension [24]. Moreover, the stay components are modelled as separate finite elements to enable each component to carry different forces, which has been demonstrated to simulate the mechanical problem accurately [14,25]. As shown in Fig. 3 (a), the stayed column is simply-supported and loaded axially. Three pairs of crossarms are rigidly connected to the one-quarter, one-half and three quarter length points of the main column. Prestressed cable stays are assumed to be pinned to the ends of the column and the tips of the crossarms. The length ratio of the edge crossarm to the middle crossarm is defined as $\gamma = a_e/a_m$ and is one of the key parameters varied in the current study since it has been shown to have a significant impact on the effectiveness of the system [26].

Different arrangements of crossarms along the length in the *yz*-plane may be used, as shown in Fig. 4 with (a) showing the simplest one-dimensional system with both (b) and (c) showing two-dimensional systems. Note that the column in practice should be supported by at least three crossarms in the *yz*-plane. This would ensure that it would benefit from the increased load carrying capacity by avoiding an obviously weaker buckling axis, assuming that the main column element is either a circular or square hollow section. The single-bay case with a three crossarm rosette, as represented in Fig. 4 (b), was studied recently

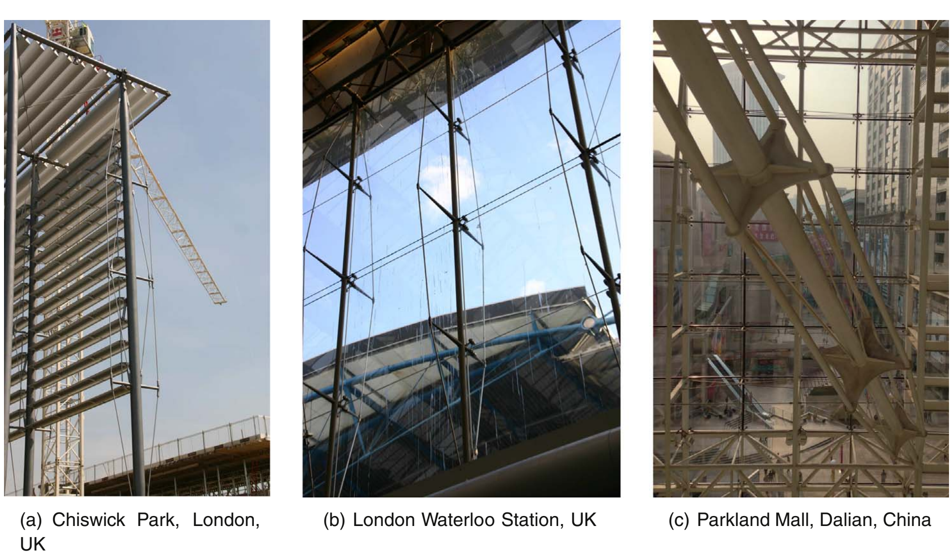

Fig. 2. Applications of prestressed stayed columns in the construction industry; photographs (a) and (b) were taken by Daisuke Saito; photograph (c) was taken by the lead author.