Journal of Constructional Steel Research 122 (2016) 274–291

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Stability of prestressed stayed steel columns with a three branch crossarm system

Pengcheng Li [a,b], M. Ahmer Wadee [a,*], Jialiang Yu [a], Nathan G. Christie [a], Minger Wu [b]

[a] Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK
[b] Department of Structural Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form 3 March 2016
Accepted 9 March 2016

Keywords:
Prestressed stayed columns
Analytical modelling
Finite element modelling
Nonlinear buckling
Imperfection sensitivity

ABSTRACT

Analytical and numerical investigations of the stability of prestressed stayed columns with three crossarms branching laterally and symmetrically are presented. It is shown that modal symmetry is broken automatically if the critical mode is antisymmetric, which distinguishes it from the stayed columns studied hitherto. The governing imperfection distribution that should be adopted within finite element analysis to capture the actual load-carrying capacity is also obtained. The findings suggest that when the critical buckling mode is symmetric, the governing imperfection distribution should also be symmetric. Conversely, if the critical buckling mode is antisymmetric, a symmetric imperfection distribution or an asymmetric imperfection distribution may be adopted as the most severe imperfection distribution depending on the system characteristics. This would enable designers to determine an accurate prediction of the actual strength through nonlinear finite element analysis.

1. Introduction

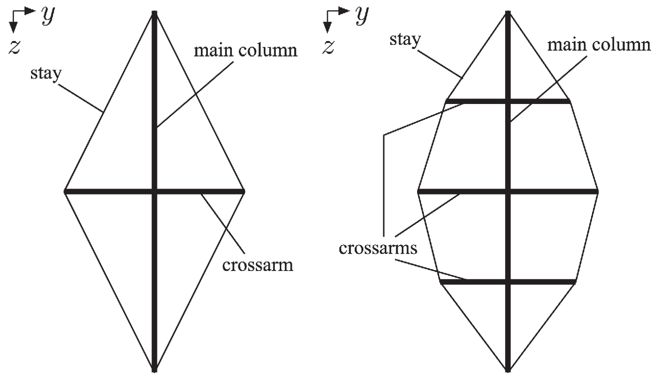
Prestressed stayed columns, which usually comprise a slender column and an external cable-stay system that is pre-tensioned [1], have been increasingly used as an efficient and aesthetic solution for improving the buckling strength of an ordinary column member [2–4]. Prestressed cable stay systems, two of which are represented in Fig. 1, have been shown to provide effective lateral elastic supports to the column that can restrain it against buckling and potentially improve the axial strength considerably [5]. The stayed column can be classified into a single-bay stayed column or a multi-bay stayed column, shown in Fig. 1, according to the number of crossarm systems that are present in the *z*-direction of the main column element. Moreover, different layouts of crossarms in the *xy*-plane may be used, as shown in Fig. 2 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 *xy*-plane to 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.

A discussion of the practical uses of this system in the civil engineering construction sector may be found in [6]. Temple [7] and Smith [8] found that the introduction of the crossarms and stays could improve the buckling load of an ordinary column significantly; Hafez et al. [9] derived the relationship between the initial pretension and the buckling load for an ideally straight stayed column. Chan et al. [10] analysed the imperfection sensitivity of the prestressed stayed columns numerically. Saito and Wadee were the first to investigate the perfect post-buckling [11], imperfection sensitivity [12] and interactive buckling behaviour [13] of the stayed column systematically. Further research included experimental studies [14] that led to the formulation of design equations and recommendations [15]. Prestressed stayed columns are by their very nature constructed from highly slender elements. Hence, geometrically nonlinear elastic analyses have been demonstrated to be sufficiently accurate given that yielding tends to occur significantly after the ultimate load capacity is reached [16,17]. Hence, in the current work, only geometrically nonlinear elastic analyses are conducted and the consideration of more stocky main column elements is left for the future.

However, all the previous research works [4,13,16,18] were primarily focused on the stayed columns with two or four branch crossarms, as represented in Fig. 2(a) and (c). As far as the authors are aware, investigations into the stayed columns with a three branch system, as shown in Fig. 2(b), have hitherto not been attempted. A recent analytical study [19] investigated a tetrahedron-shaped unit cell within a lattice material that may be considered to be similar to a discrete version of a three crossarm stayed column system. However, the current work presents both geometric and finite element (FE) analyses specifically for prestressed columns, the latter using the commercial code ABAQUS [20]. An initial study determines the axis about which buckling initially occurs. The load carrying capacity of the stayed column with different

* Corresponding author.
E-mail addresses: 1110113@tongji.edu.cn (P. Li), a.wadee@imperial.ac.uk (M.A. Wadee), j.yu12@imperial.ac.uk (J. Yu), nathan.christie10@imperial.ac.uk (N.G. Christie), wuminger@tongji.edu.cn (M. Wu).

http://dx.doi.org/10.1016/j.jcsr.2016.03.007
0143-974X/



(a) Single-bay stayed column (b) Triple-bay stayed column

Fig. 1. Single and multi-bay prestressed stayed column.

imperfection combinations about the governing axis is then analysed using nonlinear FE analysis, the aim of which is to determine the most severe imperfection profiles, the sensitivity to those and to the initial prestress level. It is indeed found that the three crossarm problem is sensitive to specific imperfection profiles and that a fairly high prestress would lead to a safe and efficient design configuration.

2. Problem definition

The current work focuses on a single-bay prestressed stayed column with a three branch crossarm system in the *xy*-plane, the geometry of which is shown in Fig. 3. In this model, the angles between the individual crossarms are 120°, such that the configuration is rotationally symmetric. Apart from the crossarm length a and the stay diameter ϕ_s, the same dimensions and properties are used as in [9], as shown in Table 1, with the main column and the crossarm elements being assumed to be circular hollow sections. In the current work, the length of the column is fixed; the stay diameter, however, is varied from 1.6 mm to 13 mm with seven separate cases being considered, as presented in Table 2. Moreover, the crossarm lengths are varied from 152.5 mm to 762.5 mm with five separate cases being considered, as presented in Table 3. The following assumptions are made in the current study:

1. The main column element is a circular hollow steel cross-section and is loaded concentrically.
2. The column is simply-supported. The connections between the stays and the main column element, and between the stays and the crossarms, are ideal pins. The connections between the crossarms and the main column element are completely rigid. Moreover, the cable stay goes slack at the instant it goes into compression.

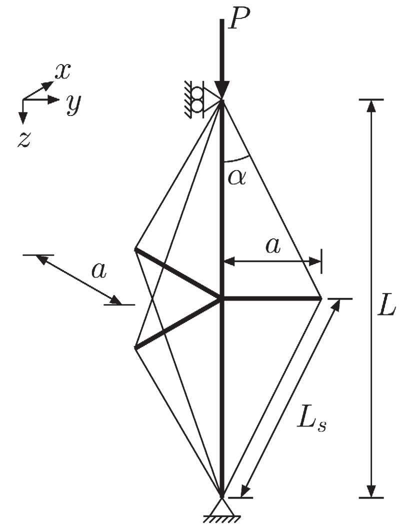


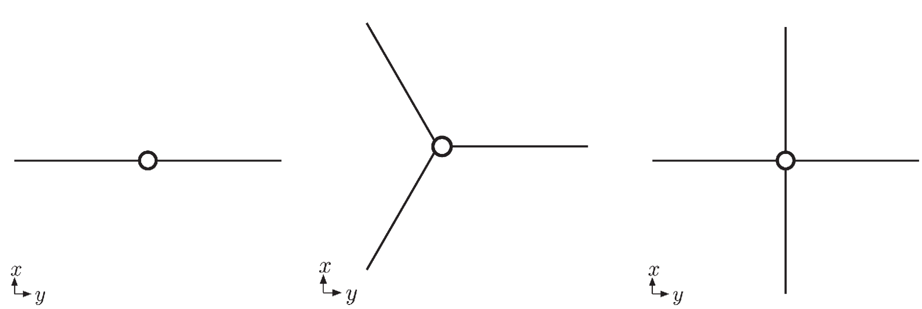
Fig. 3. Geometry of stayed column with overall length L, three crossarms in the *xy*-plane of length a and six stays with length L_s.

3. The column is assumed to be made of highly slender elements and so the analysis conducted is purely elastic.

The final assumption relies on the main column element being very slender, which means that elastic buckling dominates the behaviour with yielding and plasticity being of negligible importance. From EC3 [21], the normalized slenderness $\overline{\lambda}$ is given by the expression:

$$\overline{\lambda} = \sqrt{\frac{N_y}{N^C}}, \tag{1}$$

where N_y is the yield load and N^C is the critical buckling load respectively of a column element. Taking a realistic value for the steel yield stress as 355 N/mm^2 for the main column element and the properties detailed in Table 1, the normalized slenderness can be evaluated as $\overline{\lambda} = 3.56$. This implies that the critical buckling load is less than 8% of the yield load. Moreover, in actual experimental studies of stayed columns, even though the buckling load of the column system is considerably enhanced due to the prestressed stay system, it has been demonstrated quite conclusively for practical arrangements [16,14,17,4] that elastic behaviour is (almost) exclusively observed. Even if material yielding is detected, it is only observed at deformation levels that are well beyond those at the ultimate load. This is primarily owing to the fact that such slender elements are employed in stayed columns and provides the current justification for the final stated assumption.



(a) 2 branches (b) 3 branches (c) 4 branches

Fig. 2. Different numbers of branches in the crossarm system. Case (a) only works if the buckling displacements are constrained to be only in the *y*-direction; cases (b) and (c) would work if the column displaces anywhere in the *xy*-plane.