Engineering Structures 31 (2009) 432–443

Contents lists available at ScienceDirect

Engineering Structures

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

Numerical studies of interactive buckling in prestressed steel stayed columns

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ARTICLE INFO

Article history:
Received 25 January 2008
Received in revised form
10 July 2008
Accepted 1 September 2008
Available online 9 October 2008

Keywords:
Cable-supported structure
Nonlinear buckling
Interactive buckling
Finite element modelling
Prestressing

ABSTRACT

A steel column that is reinforced by prestressed stays generally has an increased strength in axial compression. In the past, greater emphasis was placed on obtaining its higher critical buckling load. However, detailed knowledge of the post-buckling behaviour is important to ensure the safety and the efficiency of the structure. Although a few studies into the post-buckling behaviour exist, interactive buckling behaviour has never been investigated. As interactive buckling can lead to more dangerous instabilities, the current work examines this for the most popular stayed column configuration using nonlinear finite element analysis. It is shown that interactive buckling becomes the worst case, with a commensurate decrease in the maximum load capacity, where a higher mode governs the critical buckling response.

1. Introduction

A prestressed steel stayed column (Fig. 1) is a structural component that is reinforced by either cable stays or rods such that its strength is increased in axial compression. Ordinary columns have a propensity to buckle under axial compression primarily due to their characteristic of being slender. To counter this, a prestressed steel stayed column is equipped with pre-tensioned stay systems; these restrain the column buckling displacement through horizontal crossarms placed at some intermediate distance from the column ends. Consequently, this additional system acts to prevent the principal movement during conventional buckling and potentially provides a considerable increase in axial strength. Therefore, knowledge of the critical and post-buckling behaviour of stayed columns is important to design the system safely and more efficiently.

An application of this column type can be found where slender supports or towers are required — for example, it was used as a temporary support during the erection phase of the main stage of the "Rock in Rio III" stadium in Rio de Janeiro, Brazil [1,2]. In addition to the literature describing its practical uses, a number of research works on stayed columns have existed since the 1960s, such as those evaluating critical buckling loads [3–8], imperfection sensitivity studies to the linearly evaluated critical load [9,10], and examining column's maximum axial strength [11–13].

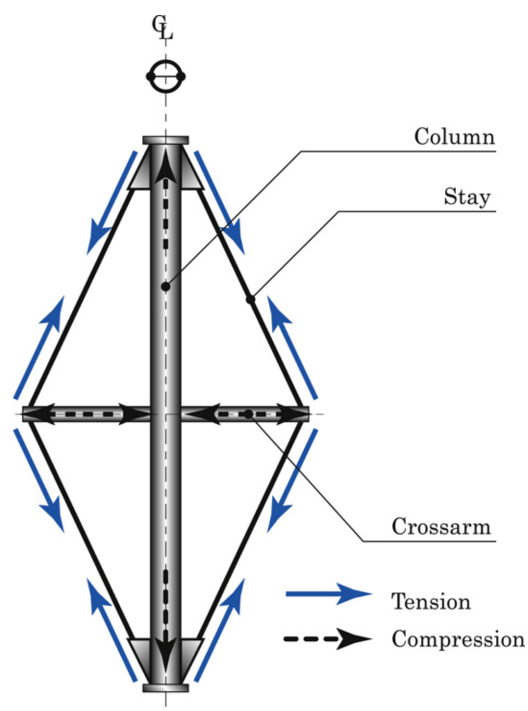

Fig. 1. Principle of the prestressed steel stayed column: stays are pretensioned to provide lateral restraint against overall buckling.

Although there are a few examples of post-buckling equilibrium paths for stayed columns in previous work [11–15], to the

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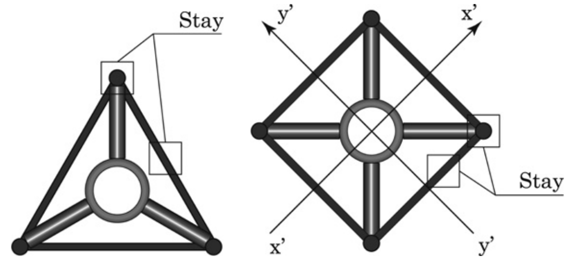
doi:10.1016/j.engstruct.2008.09.008



(a) 3 stay frames. (b) 4 stay frames.

Fig. 2. Example cross-section for prestressed stayed columns. Note that the assumption of circular hollow sections for the main column component reduces behavioural complexity in three-dimensions.

knowledge of the authors, investigations into interactive buckling have not been attempted at all. Interactive buckling is a phenomenon in which buckling modes with different wavelengths are triggered simultaneously. It has been reported as quite a notorious phenomenon for structural safety from previous work [16,17], particularly when global and local instabilities interact as seen in extensive studies on sandwich struts [18–20]. Indeed, interactive buckling in stayed columns could frequently occur because it is known that the critical loads of the lowest mode and higher modes are often close together. However it must be stressed that the interaction between local buckling modes within the column element itself, most frequently having a circular tube for the cross-section, from effects such as cross-section ovalization [21] and global modes is beyond the scope of the present discussion.

This current work describes the interactive buckling response of a single-crossarm stayed column, which was investigated using the finite element (FE) code Abaqus [22].

2. Methodology

2.1. Imperfection

The current investigation involves FE analysis; Riks analysis was conducted using the FE code Abaqus to reveal equilibrium paths for interactive buckling. Firstly, using this finite element method (FEM), buckling analysis was conducted to obtain values of the critical load for distinct mode buckling, which led to the evaluation of the benchmark prestress T_{opt}; subsequently, the interactive buckling behaviour was explored with this prestress forming the basis of the investigation.

Following the previous study [14], a single-crossarm stayed column, which was the simplest type, shown in Fig. 1, was modelled. It is worth noting that the majority of the literature deals with this single-crossarm type. It should also be noted that although the paper deals with a two-dimensional system, in reality the system is three-dimensional. The column must therefore be supported by more than three stay frames, as shown in Fig. 2(a), to benefit from an elevated buckling load. Another noteworthy point is that struts with a circular hollow section for the main column element and four stay frames, as shown in Fig. 2(b), would have identical and invariant second moments of area $I_{x'x'}$ and $I_{y'y'}$ regardless of the axes of bending ($x'x'$ or $y'y'$), which define the direction of overall buckling.

For this type of stayed column, the levels of the buckling loads for Modes 1 and 2 are often close together; therefore, interactive buckling would potentially occur as the combination of Modes 1 and 2 (see Fig. 3). Therefore, it would be necessary to take into account this type of buckling behaviour in order to achieve structural safety in design.

Table 1
Selected combinations of μ_1 and μ_2 for the imperfection

Case	Coefficients	
	μ_1	μ_2
Mode 1	1.000	0.000
Case 1	0.750	0.3307
Case 2	0.500	0.4330
Case 3	0.250	0.4841
Mode 2	0.000	0.5000

Formulation of the FE model follows the same process as in the previous study [14]. The column and the crossarm were modelled as beam elements and the stays were modelled as truss elements. The "No compression option", which prevents any compression force entering the truss elements, was also adopted to simulate any slackening in the stays.

A more complicated shape of initial out-of-straightness is needed to induce interactive buckling, rather than a simple shape based on sinusoidal waves, which were adopted in previous works [11–14]. In this study, imperfection shapes were created by combining a half sine wave and a full sine wave, ensuring that the interaction between Modes 1 and 2 behaviour would be induced. Thus, the shape function for the imperfection is expressed as follows:

$$W_\delta(x) = \delta L\left[\mu_1 \sin\frac{\pi x}{L} + \mu_2 \sin\frac{2\pi x}{L}\right], \quad (1)$$

where δ represents the relative amplitude of the basic imperfection to the column element of length L; μ_1 and μ_2 are coefficients for the components of the imperfection, expressing a proportion of each wave in the imperfection. For the definitions of the geometric properties of the prestressed stayed strut, see Fig. 4.

In order to investigate the transition from Modes 1 to 2 buckling through interactive buckling, different combinations of amplitudes of a half sine wave and a full sine wave were selected. The amplitude of the imperfection were selected in order that the end-shortening caused by the initial out-of-straightness would be the same [23,24], thus

$$\int_0^L \frac{1}{2}\left[W_{1\delta}'^2(x) + W_{2\delta}'^2(x)\right] dx = \mathcal{E}_0, \quad (2)$$

where

$$W_{1\delta}(x) = \delta L\mu_1 \sin\frac{\pi x}{L}, \qquad W_{2\delta}(x) = \delta L\mu_2 \sin\frac{2\pi x}{L}, \quad (3)$$

and $\mathcal{E}_0$ is the first order approximation of the end-shortening caused by the initial out-of-straightness, which yields the following equation:

$$\mu_1^2 + 4\mu_2^2 = 1. \quad (4)$$

From the above equation, the combinations given in Table 1 were obtained, which have the transition of the imperfection profile for the column element as shown in Fig. 5.

As for δ, 1/300 was generally selected to obtain the actual level of the design load from the equilibrium path. This value represents the recommended level of an initial local bow imperfection in the global analysis of frames for hot finished sections in Eurocode 3 [25], accounting for the effects of all types of imperfection, including residual stress and geometrical imperfections, such as lack of straightness and any minor eccentricities present in joints.

It should be noted that the imperfection discussed in this section is the global imperfection for the column element prior to the introduction of the prestress. Hence, the actual imperfection for the prestressed structure is different from the profile obtained from Eq. (1); this profile varies depending on the dimension and properties of the structure as well as the applied prestress.