Engineering Structures 100 (2015) 490–510

Contents lists available at ScienceDirect

Engineering Structures

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

A full scale experimental study of prestressed stayed columns

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ARTICLE INFO

Article history:
Received 30 August 2014
Revised 15 June 2015
Accepted 16 June 2015
Available online 2 July 2015

Keywords:
Long columns
Prestressed stayed columns
Steel columns
High strength steel
Cabled columns
Full scale tests
Buckling
Load carrying capacity
Design

ABSTRACT

This paper presents the results of an experimental study on 12 m prestressed stayed columns. In total, 44 tests were carried out to investigate the compressive strength and behaviour of such systems by varying column cross-section geometry, diameter of cables, initial pretension level of stays and steel grade. The details of material testing for both steel and cable, and the compressive strength of each specimen including a detailed analysis of results for further numerical and analytical investigations are presented. The applicability of available analytical and design methods for determining the elastic buckling load and the load carrying capacity of stayed columns was assessed. The results provide detailed data on the behaviour of realistic PSSC and highlight the importance of the imperfections and the benefits of such systems.

1. Introduction

Using slender columns helps structural engineers to design long span structures whereby self-weight is not the dominant load case. However, global buckling becomes a crucial issue in the design of the columns. For slender columns, using high strength steel has little or no effect on the load carrying capacity of slender columns so that the usual solution is to increase the cross-section dimensions. Stayed-columns are known to improve the load carrying capacity of slender columns whenever elastic buckling in compression is the critical failure mode. In fact, adding stays and cross-arms to slender columns can improve both the elastic buckling load and the load carrying capacity as they provide translational and rotational restraint along the length. Fig. 1 illustrates a typical prestressed stayed column (PSSC), comprising a slender column (also known as core or main column), cross-arm members and pretensioned stays (i.e. cables or bars). Commonly, stayed columns have up to three cross-arms along the length (see Fig. 2). Cross-arms have two (plane or planar) or four (spatial or 3D) arms depending on the application. PSSCs have a wide range of applications and Fig. 3 provides one example. These structural typologies have been investigated experimentally, numerically and analytically by researchers since the 1960s. Table 1 summarises most of the research studies found in the literature between 1963 and 2013.

In general, researchers reported symmetric and antisymmetric global buckling eigenmodes (Fig. 4a and b) and an asymmetric post-buckling mode (see Fig. 4c). Wadee et al. [24] reported that buckling mode 3 is the non-linear combination of modes 1 and 2 that develops only in the post-buckling range.

It is the objective of this paper to report on an experimental investigation of long columns that attempts to contribute towards the development of a practical design method for PSSC. It is further noted that in practice, many of the PSSC found in real structures take very conservative assumptions when assessing the benefits of the stayed system even if it is claimed that the compressive resistance of PSSC with a single cross arm may increase by 2–5 times.

Based on a review of the literature (Table 1), the experimental specimens in this paper were designed to investigate different parameters such as the effect of the stayed system, column cross-section, steel grade, cable diameter, and prestress force levels. Then, available analytical methods are used to determine the elastic buckling load and the load carrying capacity of the

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http://dx.doi.org/10.1016/j.engstruct.2015.06.033
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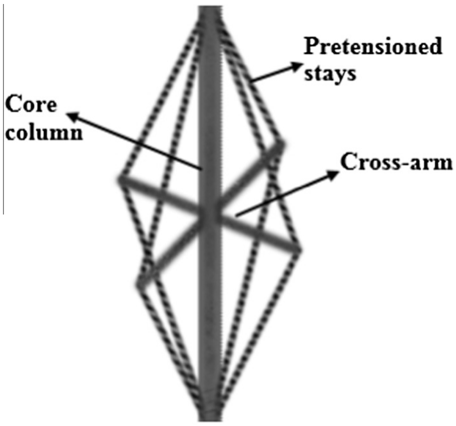

Fig. 1. Prestressed stayed column.

tested stayed columns and the results are compared to verify their accuracy and applicability.

The structure of the paper is the following: the details of material testing of steel and stayed systems are described in Section 2, while test setup, configuration and the experimental specimens are presented in Section 3. Section 4 reports on the test observations and the analysis of the results. In Section 5, a brief review of the methodologies for determining the elastic critical buckling and the load carrying capacity of stayed columns is presented and compared with experimental results. Finally, general conclusions are drawn in Section 6.

2. Material testing of steel and stayed system

The material testing of specimens is always necessary for experimental investigations, for quality control, analysis of experimental results and, finally, further numerical and analytical investigations. In this research, material testing for both steel profiles and stayed systems was performed. The following section presents the material testing procedure and its results.

2.1. Tensile coupon tests on steels

Tensile coupon tests were carried out to obtain the mechanical properties of the core and cross-arms to provide more information for further analysis. These experiments were performed in accordance with EN ISO 6892-1:2009 [25]. The tests were performed on a 20 tonne Servosis hydraulic testing machine with estimated rate of 6 MPa s^{-1}. Tensile coupon specimens were extracted from the four hot-rolled CHS steel profiles that were used in the experiments (two profiles per steel grade). Owing to the nature of CHS profiles, coupons were machined along the gauge length to obtain a reduced section followed by the grip length flattening (see Fig. 5). The flattening was executed by compression using a 500 ton hydraulic press, without disturbing the reduced section. Finally, coupon specimens were finished with a second machining process to obtain the required dimensions. Table 2 summarises the measured Young's modulus, yield and ultimate stresses, and strain results of the specimens.

2.2. Material testing of the stays

Table 3 presents the geometrical and nominal mechanical properties of the cables used in the experiments. Tensile testing of the cable systems was performed to determine the axial stiffness of the stays. Eight specimens were tested for each cable diameter (10 and 13 mm). The tensile force that was applied during the cable tests was set to exceed the maximum tension that was expected during the column tests but much lower than its minimum breaking load. Fig. 6 depicts the tensile test longitudinal layout. The specimens included the anchors, cables and load cells to be able to reproduce the true behaviour realistically, as both the threaded steel rods (anchors) and load cells contribute to the axial stiffness of each stay. The tension force was applied by a 60 ton hydraulic jack and both forces and displacements were recorded by a pair of custom made load cells and linear transducers (see Fig. 6). Fig. 7 shows force versus displacement of the stayed system.

Fig. 7 clearly shows that the behaviour of stays is nonlinear especially for the low tension range ($\Delta \leqslant 20$ mm) and becomes approximately linear for the higher tension range. Therefore, for low loading levels, the modulus of elasticity is not constant and it depends on the tensile stress [26]. This is explained by the production process of wire ropes (by twisting strands around a core wire), as the rope twists as it is stretched. The resulting changes of stiffness become less important as the tension increases and the rope becomes more compact. However, stiffness and modulus of elasticity should be determined from the linear zone by performing cyclic test as reported by [26]. A study should be performed to check the effect of using nonlinear stiffness for stay systems by numerical simulations which is outside the scope of

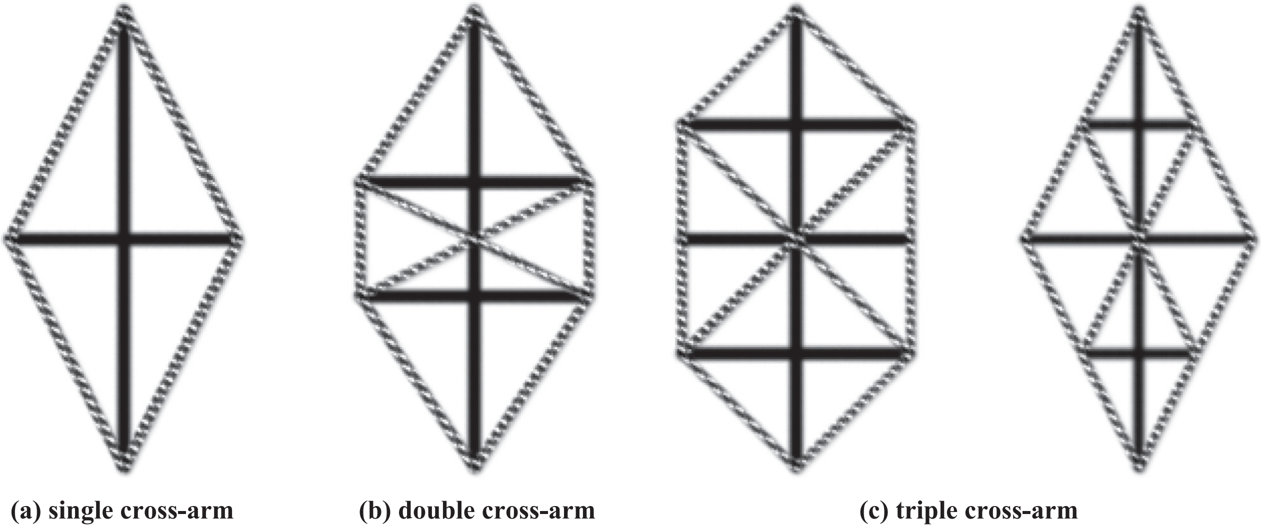

Fig. 2. Common types of prestressed stayed columns.