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Tensile performance of prestressed steel elements

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ABSTRACT

Prestressed steel trusses can offer efficient structural solutions for long span applications such as aircraft hangars, stadia and warehouses. In the current study, the tensile behaviour of prestressed steel elements, which comprise tubular steel members with internal prestressing cables, is investigated. The stability of the elements under prestress and the load–deformation response of the prestressed elements to the subsequent application of tensile loading are examined analytically, numerically and experimentally, with good correlation achieved between the three approaches. The benefits of prestressing, in terms of increased member strength and stiffness, are demonstrated, and optimal prestress levels are investigated.

1. Introduction

For long-span structural systems, where self-weight becomes an increasingly dominant component of the design loading, significant material savings can be achieved through the use of high strength tensile steel cables in conjunction with conventional steelwork. Additional benefits can be gained by prestressing the cables, inducing internal forces in the structure that can counteract the applied external loads and control self-weight deflections.

Cable-in-tube systems, whereby the steel cables are housed within hollow structural sections, offer a practical means of realising the aforementioned concept, and bring further advantages such as ensuring the stability of the tube under the prestressing forces due to the stabilizing action of the internal tensioned cable. Examples of recent applications of prestressed cable-in-tube systems include the reconfiguration of the Sydney Olympic stadium and the Five Star Aviation hangar at Brisbane Airport, both in Australia [1].

Early work on the prestressing of steel structures was described by Magnel [2] in 1950, where it was shown experimentally that improved economy can be achieved by prestressing truss girders. More recent studies have explored the behaviour and design of prestressed steel beams [3,4], columns [5–9], trusses [10,11] and space trusses [12,13]. Studies of the structural response of sub-assemblies and the overall response of prestressed frames with sliding joints have also been carried out [14–17], as has a numerical investigation into the stress-erection process of such systems [18]. Each of the above described studies identified potential economies and enhanced performance through the use of prestressing.

In the system currently being investigated, developed by the company S^2 Space Solutions [19], the prestressed cables, housed within the bottom chord of the tubular arched trusses, apply a compressive force to the chord members, which is opposite in nature to the resultant forces arising from the externally applied gravity loads. The behaviour of trussed elements in the scenario described above, i.e. pre-compressed chord elements subsequently subjected to external tensile loading, is the subject of investigation in the present paper. The case of wind uplift, which would result in additional compressive loading of the prestressed element, will be examined in a companion paper.

Analytical and numerical models that predict the tensile behaviour of the cable-in-tube system, including the axial response during prestressing and under the application of tensile loading, and the stability of the system under prestressing are developed

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in Section 2. Experimental studies are described in Section 3, while comparisons between the test and analytical results and discussions thereof, are made in Section 4. Note that although previous research provides an insight into the possible influence of long-term effects, such as creep and shrinkage, on the response of structures [20,21], these have not been addressed in the present study. Further research is required on this topic.

2. Analytical modelling and numerical verification

In this section, the key behavioural aspects of prestressed steel elements are described, including their response to prestressing and under the subsequent application of tensile load. The stability of prestressed elements during the prestressing stage, the optimal level of prestress and tensile capacity are also investigated.

2.1. Axial response under prestress

During the prestressing stage of cable-in-tube systems, a tensile force, P, is applied to the cable and a compression force of equal magnitude is induced in the tube, as depicted in Fig. 1, where L_o is the original length of the cable and tube, x_c is the extension of the cable and x_t is the shortening of the tube.

When the prestressing process is complete the cable and the tube are locked in position at both ends such that there is no relative movement between the two components, as shown in Fig. 1(c). Since the prestressing force, P, of the same magnitude, but opposite in direction, is applied to the cable and the tube, the prestressed element is self-equilibrated when the tube and cable are attached at both ends. Therefore, provided no out of plane displacements (i.e. no buckling) are induced during prestressing the equilibrium condition for the prestressed system can be stated as in Eq. (1).

$$[P]_{\mathrm{cable}} - [P]_{\mathrm{tube}} = K_c x_c - K_t x_t = 0, \tag{1}$$

where K_c and K_t are the axial stiffnesses of the cable and the tube respectively. The respective stiffnesses are given by the following expressions:

$$K_c = \frac{E_c A_c}{L_o}, \quad K_t = \frac{E_t A_t}{L_o}, \tag{2}$$

where E_c and E_t are the Young's moduli of the cable and the tube respectively with A_c and A_t being the cross-sectional areas of the cable and the tube respectively.

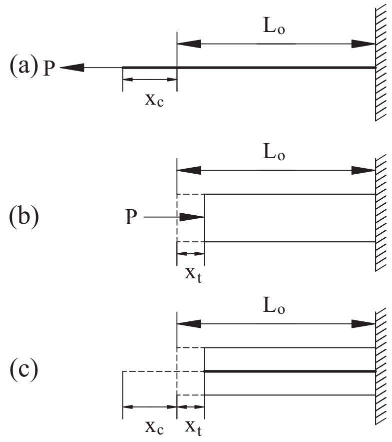

Fig. 1. (a) Force diagram of cable during prestress; (b) force diagram of tube during prestress; (c) tube and cable locked in position after prestress.

2.2. Stability under prestress

Previous analytical studies [22,23] have shown prestressing elements (i.e. the cables, in the context of the present study) can stabilize their compressed counterparts (i.e. the steel tubes housing the cables) provided that there are sufficient connection points between the two elements. The connection points have been shown to offer effective lateral restraint and thus reduce the buckling length of the compressed element. If the cable is in constant contact with the tube, cable-in-tube systems have infinite connection points, which implies an infinite elastic buckling load [23]. Buckling under prestress would not therefore be anticipated in these systems.

To verify the above analytical findings, a finite element model was implemented using the commercial finite element (FE) analysis software, ABAQUS [24]. The tube to cable cross-sectional area ratio (A_t/A_c) and Young's modulus ratio (E_t/E_c) were 8.96 and 1.58, respectively. Prestress was introduced through thermal loading and the coefficient of linear expansion of the cable, α_c, was set as $12 \times 10^{-6}\ \mathrm{K}^{-1}$.

In the numerical simulation, truss elements were used to model the cables since they can only resist axial forces while beam elements, which possess both axial and flexural stiffness, were used to model the tube. The cable and the tube were attached using tie constraints at the ends and constraint equations were applied at various connection points along the length of the tube and cable to prevent relative out of plane motion between the two components.

The number of connection points was varied between one (at mid-length) and three (at quarter points). Finite intervals were chosen since in the experimental investigation of Section 3, the cable was significantly smaller in diameter than the steel tube and connections between the cable and the tube were made by means of collars spaced regularly along the member length. This is described in Section 3.

The numerical modelling was conducted in two stages. In the first stage, an elastic buckling analysis of the tubular element under the prestressing action of the cable was carried out and the buckling mode shapes were obtained. In the next stage, a geometrically nonlinear analysis utilising the Riks arc-length solution technique [25], was performed with the first eigenmode from the elastic buckling analysis as an initial imperfection with an amplitude of $L_o/100000$. An incremental prestress was applied to the cable through thermal loading. As illustrated in Fig. 2, the FE results are in close agreement with the analytical results and show that the buckling load N_{cr} with respect to that of the unsupported member N_E, increases in proportion to $1/L_{cr}^2$, where L_{cr} is the spacing between the connection points (or collars).

2.3. Behaviour of prestressed system under tension

Analytical expressions for the axial load-displacement equilibrium paths of prestressed elements under tensile loading are derived in this section. Three cases are considered in the following sub-sections: Case I refers to the scenario where the tube yields prior to the cable; Case II refers to where the cable yielding prior to the tube; and Case III considers the two elements yielding simultaneously. The case which actually arises depends on the geometric and material properties of the tube and cable, and the level of prestress, as described in the following sub-sections.

2.3.1. Case I: Tube yields prior to cable

The three stages of behaviour that occur for Case I are illustrated in Fig. 3, where the adopted notation is defined. The ratios of geometric and material properties between the tube and cable, as well as the level of applied prestress determine whether the