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Compressive behaviour and design of prestressed steel elements

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ABSTRACT

The tensile performance of the chords of steel trusses can be considerably enhanced through the addition of prestressed cables. However, under compression, which may arise due to wind uplift, the prestressing may have a detrimental effect. The behaviour and design of prestressed steel elements in compression is examined presently. Eight experiments on prestressed elements were carried out, where the key variables examined were the initial prestress level, the presence of grout and the member slenderness. Cross-sectional behaviour and member buckling behaviour are examined analytically, numerically and experimentally, with good correlation achieved between the three approaches. The benefit of adding grout to bond the prestressing steel to the encasing tube is also investigated and design approaches for both non-grouted and grouted prestressed elements are proposed.

1. Introduction

The addition of high tensile cables to conventional steel components can lead to significant material savings, particularly for long span structural systems. Further benefits can be achieved by prestressing the cables to induce internal forces in the structure that can counteract the applied external loads and control self-weight deflections. Prestressing of steel structures has been the subject of a number of investigations. Early work by Magnel [1] in 1950 experimentally demonstrated the improved economy that can be achieved by prestressing truss girders. More recent studies have explored the behaviour and design of prestressed steel beams [2,3], columns [4–6], trusses and space trusses. The behaviour of prestressed frames with sliding joints has also been examined both during the stress-erection process and under external loading. The above studies have highlighted the potential economies and enhanced performance that can be achieved through the use of prestressing.

The present paper focuses on cable-in-tube systems, in which the prestressing cables are encased within structural hollow sections, with the advantages that the tensile force in the cable will stabilize the surrounding tube against buckling during prestressing and enable the addition of grout, which bonds the two components together to reduce reliance on the end anchorage, as well as increasing compressive strength. Examples of recent applications of such prestressed systems include the reconfiguration of the Sydney Olympic stadium and the Five Star Aviation hangar at Brisbane Airport, both in Australia [7].

In the context of trusses, the tensile performance of the bottom chord can be considerably enhanced through the addition of prestressed cable [8]. However, in instances of load reversal (e.g. due to wind uplift) in trusses without horizontal end anchorage that would allow catenary forces to develop, the presence of prestress could be detrimental. The behaviour and design of prestressed elements subjected to external compression is the subject of the present paper.

Analytical and numerical models that predict the compressive behaviour of the cable-in-tube system are developed in Section 2. Experimental studies are described in Section 3, while comparisons between the test, numerical and analytical results and discussions thereof, are presented in Section 4, followed by design proposals.

2. Analytical modelling and numerical verification

In this section, the key behavioural aspects of prestressed elements under compression are described. Firstly, the axial response of the element during the prestressing stage is analysed. The compressive behaviour at the cross-sectional level, considering purely axial deformations, is then examined. Subsequently, member buckling behaviour is introduced with the effect of the addition of grout after prestressing being discussed.

2.1. Axial response under prestress

To prestress the cable-in-tube system, a tensile force, P_i, is applied to the cable and a compression force of equal magnitude is induced in the tube and the components are locked in position at both ends. Provided the tensioned cable is in contact with the surrounding tube at sufficiently regular intervals with the compressed tube, overall buckling is prevented

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[8,9] and the equilibrium condition for the prestressed system during the prestressing stage can be stated as:

$$[P_\mathrm{i}]_\mathrm{cable} - [P_\mathrm{i}]_\mathrm{tube} = K_\mathrm{c} x_\mathrm{c} - K_\mathrm{t} x_\mathrm{t} = 0, \tag{1}$$

Where x_c and x_t are the axial displacements during prestress while 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:

$$K_\mathrm{c} = \frac{E_\mathrm{c} A_\mathrm{c}}{L_\mathrm{o}}, \quad K_\mathrm{t} = \frac{E_\mathrm{t} A_\mathrm{t}}{L_\mathrm{o}}, \tag{2}$$

Where L_o is the original length of the system; 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.

2.2. Cross-sectional behaviour of prestressed elements under compression

The cross-section behaviour of prestressed elements in compression, where member buckling effects are ignored, is first considered. For non-grouted stocky elements in compression, three cases are considered in the following sub-sections: Case I refers to the scenario where the cable slackens before yielding of the tube in compression; Case II refers to the case where the tube yields prior to the slackening of the cable; and Case III considers the simultaneous yielding of the tube and slackening of the cable. The case which actually arises depends on the geometric and material properties of the tube and cable, as well as the level of prestress:

$$\text{Case}\begin{cases} \text{I}, & \text{if } \dfrac{P_\mathrm{i}}{A_\mathrm{c}E_\mathrm{c}} < \dfrac{f_\mathrm{ty}}{E_t} - \dfrac{P_\mathrm{i}}{A_\mathrm{t}E_\mathrm{t}}, \qquad (3a) \\ \text{II}, & \text{if } \dfrac{P_\mathrm{i}}{A_\mathrm{c}E_\mathrm{c}} > \dfrac{f_\mathrm{ty}}{E_t} - \dfrac{P_\mathrm{i}}{A_\mathrm{t}E_\mathrm{t}}, \qquad (3b) \\ \text{III}, & \text{if } \dfrac{P_\mathrm{i}}{A_\mathrm{c}E_\mathrm{c}} = \dfrac{f_\mathrm{ty}}{E_t} - \dfrac{P_\mathrm{i}}{A_\mathrm{t}E_\mathrm{t}}, \qquad (3c) \end{cases}$$

Where f_cy and f_ty are the yield stresses of the cable and the tube respectively.

The three stages of behaviour that occur for Case I and Case II are illustrated in Fig. 1, where the adopted notation is defined. The corresponding analytical expressions for the load–displacement equilibrium path of the system, summarised in Table 1, were derived by following a similar approach as in [8]. In the sign convention adopted, positive values denote compression and shortening whilst negative values denote tension and elongation, with the axial displacement x_1, x_2 and x_3 being measured from the state of the system at the beginning of each loading stage.

For Case III, initial prestress is applied such that the tube yields and the cable slackens simultaneously under compressive loading. This may be defined as the optimal prestress level since this provides the most extensive elastic range and hence the stiffest response.

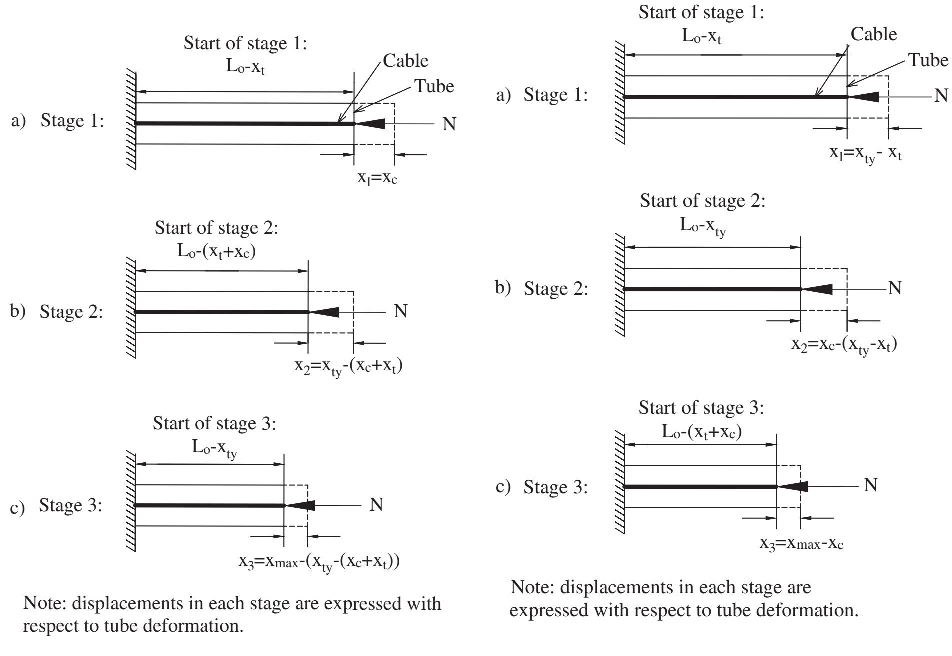
The optimal prestress level under applied compressive load, $P_\mathrm{opt,c}$, can be derived by equating the expressions for the strain required to slacken the pretensioned cable to that required to yield the precompressed tube, as shown in Eq. (4):

$$\frac{P_\mathrm{opt,c}}{A_\mathrm{c}E_\mathrm{c}} = \frac{f_\mathrm{ty}}{E_\mathrm{t}} - \frac{P_\mathrm{opt,c}}{A_\mathrm{t}E_\mathrm{t}}, \tag{4}$$

rearranging in terms of $P_\mathrm{opt,c}$ gives

$$P_\mathrm{opt,c} = \frac{A_\mathrm{t}A_\mathrm{c}f_\mathrm{ty}E_\mathrm{c}}{A_\mathrm{t}E_\mathrm{t} + A_\mathrm{c}E_\mathrm{c}}. \tag{5}$$

The formulations of Table 1 can be used to generate axial load–deformation graphs for prestressed elements. Sample analytical results are presented and comparisons are made with corresponding numerical results generated using the FE software ABAQUS [10]. Truss and beam elements with the *elastic–perfectly–plastic* material properties defined in Table 2 were used to model the tube and prestressing cable, respectively. A tie constraint was applied between the two components for all degrees of freedom except longitudinal displacement along the member length. Initial prestress was applied to the cable in the first step of the numerical analysis by means of thermal loading. External compressive load was then applied in the following step through displacement control.



Note: displacements in each stage are expressed with respect to tube deformation.

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(a) Case I.

(b) Case II.

Fig. 1. Generalised coordinate definitions for non-grouted stocky elements in compression.