



# Axial behaviour of prestressed high strength steel tubular members



J. Wang<sup>a</sup>, S. Afshan<sup>b,\*</sup>, L. Gardner<sup>a</sup>

<sup>a</sup>Imperial College London, London, UK

<sup>b</sup>Brunel University London, London, UK

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## ABSTRACT

The axial behaviour and design of hot-finished high strength steel tubular elements with internal prestressing cables, representing the chord members in prestressed trusses, are examined in this paper. A comprehensive programme of experiments and numerical modelling was performed, the results of which were combined to develop resistance expressions for the design of prestressed high strength steel members. A total of 12 tensile and 10 compressive member tests were carried out, with the key variables examined being the steel grade (S460 and S690), the initial prestress level and the presence of grout. Numerical models were developed to replicate the structural response of the compressive member tests and subsequently used to generate parametric results, where the member slenderness, size of prestressing cable, applied prestress level, steel grade (S460 or S690), and grout condition (grouted and non-grouted), were varied. The presence of cables was shown to enhance the tensile capacity of the members, while the addition of prestress resulted in extended elastic range. In compression, the effect of prestress was detrimental, and a modified Perry-Robertson method, developed in [1], was extended to hot-finished high strength steel members.

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## 1. Introduction

Long-span steel trusses are commonly used in a broad range of modern structures, where there are demands for large column free spaces, such as in airport terminals, aircraft hangers, sports stadia and auditoriums. The overall economy of these long-span structures is governed by both their structural form as well as the materials chosen for their individual components. High strength steels (HSS), with yield strengths in excess of 460 N/mm<sup>2</sup>, offer the potential for light-weight design and savings in the cost of material. However, while the higher strength of the material enables smaller cross-sections to be used, thereby reducing the structural self-weight, the stiffness (controlled by the Young's modulus of the material), which governs the serviceability limit state design, remains unchanged. Prestressed steel trusses, consisting of cable-in-tube systems, whereby the steel cables are housed within hollow structural sections, have been used in previous engineering applications [2] as a method for increasing load-bearing capacity and controlling deflections. Cables and prestressing enable the self-weight of the structure to be reduced and dead load deflections can be counter-acted by suitable profiling of the cable and adjustment of the prestress level; under live load, the elastic range of the structural response can

be extended by prestressing, although the initial stiffness remains essentially unchanged. Combining the beneficial aspects of high strength steel and prestressing, prestressed HSS trusses can offer efficient solutions for long-span structures. An investigation into the structural behaviour and design of HSS prestressed cable-in-tube arched trusses has been carried out; the focus of the present paper is on the axial behaviour of HSS tubular elements with internal prestressing cables, representing the chord members in such trusses, while the wider research programme has included full scale tests and numerical modelling of prestressed arched trusses, which are reported in [3].

Previous studies of prestressed steel trusses have identified the enhanced structural performance brought about by the addition of prestressing cables and demonstrated the further improvements achieved through application of increased prestress levels. The influence of employing different prestressing cable profiles in Warren trusses was studied in [4], where it was shown that member forces and deflections decrease linearly with an increase in eccentricity of the cables. Studies investigating the use of different truss shapes and geometries, including straight truss girders [4–8], arched trusses [9–15] and space trusses [16,17] have also been carried out. The behaviour and design of prestressed steel beams [18–24], columns [25–29] and individual cable-in-tube truss elements [1,30] have also been examined, where the potential benefits of prestressing at the structural member level were highlighted. In their recent study, Gosaye et al. [1,30] carried out an investigation into the tensile

\* Corresponding author.

E-mail address: Sheida.Afshan@brunel.ac.uk (S. Afshan).

and compressive axial behaviour of ordinary strength steel tubular truss elements containing prestressing cables through a combination of analytical modelling, experiments and numerical modelling. The benefits of prestressing, in terms of increased member capacity and an extended elastic range, was demonstrated for the case of prestressed members subjected to axial tensile loading [30], while for prestressed members loaded in compression, the detrimental effects of prestressing were assessed and described through the development of a modified Perry–Robertson design method. With previous work on prestressed steel trusses focused mainly on tubular elements of ordinary strength steels, the objective of the present study is to extend the application of prestressing to high strength steels, thereby enabling the exploitation of the combined benefits of high strength steels and prestressing.

In the investigated structural system, the prestressed cables, housed within the bottom chord of tubular arched trusses, apply a compressive force to the chord members, which depending on the nature of the externally applied loads are subsequently subjected to either tensile (e.g. in the case of downward gravity loading) or compressive loading (e.g. in the case of wind uplift loading). The behaviour and design of prestressed chord elements subjected to both external tensile and compressive loading are the subject of this study, and includes a programme of laboratory testing and numerical modelling. Descriptions of the experimental investigation and the numerical modelling study, including the key results obtained and discussions thereof, leading to the establishment of design rules, are presented herein.

## 2. Experimental investigation

### 2.1. Overview

An experimental study was carried out in the Structures Laboratory at Imperial College London to assess the structural response of prestressed high strength steel cable-in-tube systems under tensile and compressive loading. In total 12 tensile (6 grouted and 6 non-grouted) and 10 compressive (6 grouted and 4 non-grouted) cable-in-tube member tests were conducted with a view to 1) assess the influence of prestress level and presence of grout on the response and 2) provide the necessary information to develop and validate numerical models. The tests carried out to characterise the material properties of the high strength steel tubes and grout are firstly described, followed by a description of the prestressing and grouting operations and an account of the tensile and compressive member tests. The high strength steel tubes were hot-finished grades S460 and S690 SHS 50×50×5, which encased 7 wire strand Y1860S7 prestressing steel cables. Fig. 1 depicts a typical test specimen, with the main components labelled.

The key variables of the cable-in-tube specimens were the steel grade (S460 and S690), the presence of cable and initial prestress level (No cable,  $P_{nom}$ ,  $0.5P_{opt}$  and  $P_{opt}$ ) and the presence of grout,

**Table 1**  
Design parameters of prestressed specimens.

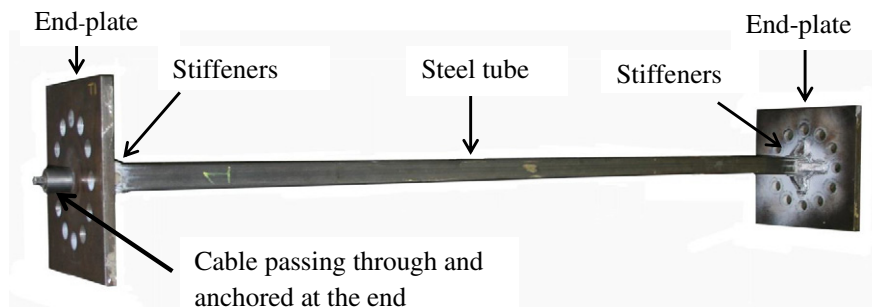
Specimen	Nominal length (m)	No. of cables	Grouted (Y/N)	Target prestress (kN)
T460NGN	2	0	N	N/A
T460NG0	2	1	N	5 ( $P_{nom}$ )
T460NG1	2	1	N	95 ( $0.5P_{opt}$ )
T460NG2	2	1	N	189 ( $P_{opt}$ )
T460G1	2	1	Y	95 ( $0.5P_{opt}$ )
T460G2	2	1	Y	189 ( $P_{opt}$ )
C460NG0	1	1	N	5 ( $P_{nom}$ )
C460NG2	1	1	N	189 ( $P_{opt}$ )
C460G0	1	1	Y	5 ( $P_{nom}$ )
C460G1	1	1	Y	95 ( $0.5P_{opt}$ )
C460G2	1	1	Y	189 ( $P_{opt}$ )
T690NGN	2	0	N	N/A
T690NG0	2	1	N	5 ( $P_{nom}$ )
T690NG1	2	1	N	84 ( $0.5P_{opt}$ )
T690NG2	2	1	N	167 ( $P_{opt}$ )
T690G1	2	1	Y	84 ( $0.5P_{opt}$ )
T690G2	2	1	Y	167 ( $P_{opt}$ )
C690NG0	1	1	N	5 ( $P_{nom}$ )
C690NG2	1	1	N	167 ( $P_{opt}$ )
C690G0	1	1	Y	5 ( $P_{nom}$ )
C690G1	1	1	Y	84 ( $0.5P_{opt}$ )
C690G2	1	1	Y	167 ( $P_{opt}$ )

as shown in Table 1, where a list of the tested specimens is provided. Fig. 2 shows the labelling system employed throughout the paper. The prestress level  $P_{nom}$  is a nominal prestress level of 5 kN to ensure that the cables were taut during grouting and testing. The prestress level  $P_{opt}$ , as defined in [30], is the optimum prestress force that causes the cable and the tube to yield simultaneously when the system is under tension, which maximises the extent of the elastic range. The unfactored value of  $P_{opt}$  depends on the material and geometric properties of the tube and cable, and can be calculated from Eq. (1) [30], where  $A$ ,  $E$  and  $f_y$  are the cross-sectional area, Young's modulus and yield stress, respectively, of the cable (denoted with a subscript c) and the tube (denoted with a subscript t). From the measured properties reported in Table 2, it was determined that  $P_{opt} = 189$  kN for the S460 members and 167 kN for the S690 members. Note that the actual levels of prestress achieved in the experiments differed slightly from these target values and are reported in the following sections.

$$P_{opt} = \frac{A_t A_c}{A_t E_t + A_c E_c} (f_{cy} E_t - f_{ty} E_c) \quad (1)$$

### 2.2. Material tests

Material tests on the individual components of the cable-in-tube specimens, namely the steel tube, cable and grout, were first carried out, details of which are described in this section. The resulting material properties were used in the subsequent analysis of the member



**Fig. 1.** Typical configuration of tested specimens.

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