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Prestressed cold-formed steel beams: Concept and mechanical behaviour

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ABSTRACT

An innovative concept, whereby the load-carrying capacity and serviceability performance of cold-formed steel beams are enhanced by utilising prestressing techniques, is presented. The prestressing force is applied by means of a high-strength steel cable, which is housed at a location eccentric to the strong geometric axis within the bottom hollow flange of the cold-formed steel beam, inducing initial stresses in the beam that are opposite in sign to those introduced during the subsequent loading stage. As a consequence, the development of local instabilities during loading is delayed and thus the capacity of the beam is enhanced. Furthermore, the pre-camber induced during prestressing, as well as the contribution of the cable to the bending stiffness of the system, decrease the overall vertical deflections of the beam. The conceptual development of prestressed cold-formed steel beams and a study investigating the potential benefits are presented. The mechanical behaviour of the proposed beams in both the prestressing and imposed loading stages is described in terms of analytical expressions, while failure criteria for the design of the cold-formed steel beam and the cable are also developed by employing interaction equations in conjunction with the Direct Strength Method. Geometrically and materially nonlinear finite element analysis with imperfections is employed to simulate the behaviour of the proposed beams. Sample numerical results are presented and compared with the developed analytical expressions and failure criteria, demonstrating the substantial enhancement in moment capacity and serviceability performance offered by these beams.

1. Introduction

Sustainable structural solutions are needed more than ever in the construction industry to decrease the carbon-footprint of the built environment. Prestressing techniques are often employed in structural engineering to offer such solutions by enhancing the load-carrying capacity and serviceability performance of structural members and systems.

Although prestressing is typically employed in concrete structures, its application in steel structures can also offer benefits [1]. The underlying principle in both cases is essentially the same, where the application of prestress results in the partial or even full cancellation of the stresses that arise at specific regions within the members under loading. However, while in the case of concrete structures the aim is to impose compressive stresses on parts of the cross-section to overcome the intrinsically weak tensile performance and thus prevent cracking, in the proposed prestressed cold-formed steel beams, the purpose is to enhance the performance of the members by applying tensile stresses on parts of the cross-section that are prone to instability. Previous research studies on prestressed steel structures focused on the application of prestress to hot-rolled steel elements, including bare steel beams [2–5], composite beams [6–12], steel trusses [1,13,14], tubular members [15–17], stayed columns [18–22] and steel arches [23,24]; considerable enhancements in load-carrying capacities and reductions in deflections of these members and systems have been reported.

Cold-formed steel members offer lightweight and efficient solutions in a range of structural applications because of their intrinsic high strength-to-weight ratio and optimised geometries. However, owing to their thin-walled geometry, cold-formed steel members are highly vulnerable to local instability phenomena that complicate the prediction of their behaviour. Local, distortional and global buckling together with their interactions may occur at stress levels lower than the material yield strength and hence prevent the full utilisation of the cross-sectional capacity of the members. The concept proposed herein is to delay these instabilities and thus enhance the load-carrying capacity of cold-formed steel beams through the application of prestressing. This is achieved by housing a high-strength steel cable within the cross-section profile, at a location eccentric to the strong geometric axis, and using it to apply initial stresses that are opposite in sign to the stresses from the applied loading. Furthermore, as a consequence of introducing an initial pre-camber during prestressing and the contribution of the cable to the bending stiffness of the system, the overall deflections of the

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member can be significantly reduced, thus improving the serviceability performance.

Owing to the enhanced performance of prestressed cold-formed steel beams, a smaller steel section is required for a given demand in capacity and span length, resulting in material and therefore self-weight savings relative to conventional non-prestressed beams. Potentially, as a result of their increased moment capacity, the proposed beams may be employed more widely as primary structural elements in the construction of buildings and other structures. The use of prestressing in conjunction with cold-formed steel has been previously explored in practice when proprietary LiteSteel Beams [25,26] were used to form long-span shell structures [14], with important economies in the erection process and significant savings in material reported.

The objectives of the present paper are to introduce the concept of prestressed cold-formed steel beams, to study their structural behaviour and to evaluate the benefits they may offer. Firstly, simple analytical expressions are developed to examine the mechanical response of the prestressed steel members. Subsequently, failure criteria for the design of prestressed cold-formed steel beams are proposed by analysing the prestressed beams as beam-column members. For this purpose, interaction equations, alongside the Direct Strength Method (DSM), are employed to determine the capacity of the members under the combination of axial loads and bending moments. Finite element (FE) models, which idealise the material response, the beam–cable connection alongside the boundary and loading conditions, are then created to compare the mechanical behaviour of the proposed beams in the prestressing and imposed loading stages with the developed analytical expressions and capacity predictions. Finally, sample FE results are analysed in detail and the potential benefits of prestressed cold-formed steel beams are discussed. Conclusions are then drawn.

2. Mechanical behaviour and design concept

The mechanical behaviour and design of simply-supported prestressed cold-formed steel beams are explored in this section. Two stages of behaviour are considered. In Stage I, the transfer of the prestressing force into the cold-formed steel beam is assessed. In Stage II, the application of uniformly distributed imposed loading is investigated. Analytical expressions are employed to describe the elastic behaviour of the beams during the two stages, in terms of the stress levels at the critical cross-section of the beam, which is located at midspan, and the load–deflection response of the member.

The ultimate response of cold-formed steel members is highly dependent on the applied stress distribution which, especially in the case of cold-formed steel members subjected to combinations of axial load and bending moments, can be considered to be the key controlling parameter [27,28]. Hence, the stress distributions at different stages of loading are carefully assessed herein. A similar approach has been followed in previous research on prestressed steel beams [29,3] and prestressed composite steel beams [6,9,7].

2.1. Cross-sectional geometry and member restraints

In comparison with hot-rolled steel, the fabrication process of cold-formed steel is more rapid and less energy-intensive, while the flexibility offered by the rolling or pressing process allows the fabrication of members with complex and tailored cross-sectional geometries. This is exploited in the proposed concept, where a tubular region is formed within the cross-section profile of the cold-formed steel beam to house the prestressing cable.

The reference cross-section shown in Fig. 1 is used as an example throughout the present paper, the dimensions of which are listed in Table 1, where r_c is the radius of the cable. Note that the prestressing cable is eccentric to the strong geometric axis but not to the weak axis of the section. The cross-sectional geometry is essentially that of a lipped channel section with two longitudinal stiffeners in the web and

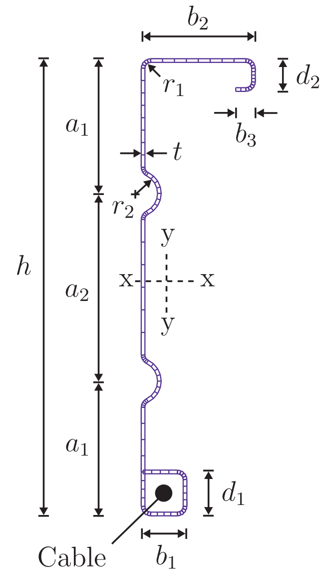

Fig. 1. Reference cross-section profile of the studied prestressed cold-formed steel beam. External dimensions are shown; r_1 and r_2 are the internal radii of the corners and web stiffeners respectively. Note that the x–x and y–y axes shown are the strong and weak geometric axes of the cross-section respectively, and that in-plane bending about the x–x axis is studied herein.

Table 1
Dimensions of the reference cross-section profile, where symbols are defined in Fig. 1.

h = 280.0 mm	b_1 = 28.0 mm	t = 2.25 mm	r_1 = 3.5 mm
d_1 = 28.0 mm	b_2 = 70.0 mm	a_1 = 82.5 mm	r_2 = 12.0 mm
d_2 = 20.0 mm	b_3 = 12.0 mm	a_2 = 115.0 mm	r_c = 5.25 mm

with the bottom flange being bent back towards the web to form the tubular region of the section. The bottom stiffener is required to increase the resistance of the cross-section to local buckling during the prestressing stage while the bottom part of the section is under compression. Similarly, the top stiffener increases the local buckling resistance of the cross-section during the imposed loading stage.

The means of connection between the bottom hollow flange and the web of the section is not explicitly considered herein, but it could be achieved by means of welding or screws, both of which have been evaluated during the development of the LiteSteel Beam [25,30]. Similarly, the anchorage system for the prestressing cable and the effect of the presence of any sheeting on the top flange are not explicitly examined.

Along the member, the prestressing cable is kept concentric to the bottom hollow flange by means of connecting collars, which are dimensioned to an outer diameter matching the internal dimensions of the hollow flange and are fitted to the cable at regular intervals. As discussed in [16,17], where the behaviour of prestressed steel tubular members was studied analytically, numerically and experimentally, the presence of the connecting collars reduces the effective length of the member and thus increases significantly its global flexural buckling strength when subjected to an internal compressive prestressing force. Therefore, in the present study, it is assumed that global flexural buckling under the internal prestressing force is restrained during both loading stages. Moreover, the proposed beams are assumed to be fully braced against lateral-torsional buckling (during both loading stages), owing to the presence of sheeting and sag bars at regular intervals at the top and bottom parts of the beam respectively. Similarly, distortional buckling due to negative bending (during the prestressing stage) is restrained by both the presence of the cable and by the bottom lateral restraints. Finally, note that the lateral restraints confine bending about