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Moment–shear–axial force interaction in composite beams

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ABSTRACT

Composite steel–concrete beams are frequently used in situations where axial forces are introduced. Some examples include the use in cable-stayed bridges or inclined members in stadia and bridge approach spans. In these situations, the beam may be subjected to any combination of flexure, shear and axial loads. However, modern steel and composite construction codes currently do not address the effects of these combined actions. This study presents an analysis of composite beams subjected to combined loading. A finite element model (FEM) has been developed and the results derived from the model show excellent agreement with existing FEM and experimental results. The effect of compression and tension loads on a member subjected to flexure and shear is also explored. Design models are proposed for estimating the flexure and shear interaction of an axially loaded member.

1. Introduction

Composite steel–concrete composite beams are one of the most widely used methods of construction for steel-framed buildings, bridges and stadia. These beams are ubiquitous structural elements in which a steel beam and a solid or composite slab are interconnected by shear connection. These elements act together to resist action effects as a single structural member [25]. Generally, this connection is achieved through headed shear connectors welded to the top flange of the steel beam. The studs resist longitudinal slip and the vertical separation between the two elements. In continuous or semi-continuous structures, members are subjected to either positive (sagging) or negative (hogging) bending moments. The most efficient use of the materials' strengths occurs when the beam is subjected to positive bending at the mid-span. In this case, the steel component is subjected to tensile forces and the concrete component primarily in compression, thus utilising the favourable attributes of each material. A simple rigid plastic analysis (RPA) of a section can show that the positive moment capacity of a member can be increased by as much as 120% over the plain steel beam through composite action. Baskar and Shanmugam [3] found that composite action increased the positive moment capacity of a girder by 132%. While under positive bending, the concrete slab also provides buckling resistance to the top flange should it be subjected to compression and the ductility of the steel allows for the achievement of high curvatures.

At support locations, where negative bending moments are introduced, the force distribution is the opposite. The concrete component is treated as being cracked under the tensile load and contributes little to the ultimate strength. The concrete still aids in the transfer of the large tensile loads from the reinforcement through developing interaction with the shear connection. The vulnerability of the steel section to buckling under the compressive load and the relatively low tensile strength of the concrete combine to significantly reduce the ultimate moment capacity of the cross-section compared with the positive bending capacity.

For composite beams that are horizontal and free from any restraints, the design of such members simply requires addressing the interaction of flexure, M and vertical shear force, V. Distinct requirements for the design of beams subjected to flexure and shear are set by the modern steel and composite construction codes including AS2327.1 [25] and Eurocode 4 [4]. However, despite experimental and analytical evidence, the design ultimate shear strength of a composite beam is assumed to be that of the steel web only. The shear strength of the concrete is neglected unless it can be shown that it contributes to the ultimate shear strength of the beam. Liang et al. [13,14] showed that disregarding the contribution of the concrete in assessing the ultimate vertical shear strength results in conservative and inefficient designs. Design models for the strength interaction of both sagging and hogging bending in continuous beams and for sagging bending in simply supported beams were proposed. Their research showed that the ultimate

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vertical shear strength of a beam may be increased by approximately 85% compared with current design models by including the shear strength of the concrete slab. These results were later verified and revised through experimental and numerical studies carried out by Vasdravellis and Uy [31]. The design models previously proposed by Vasdravellis and Uy [31] and Liang et al. [13] for sagging and hogging bending respectively are:

$$\left(\frac{M}{M_{uo}}\right)^3 + \left(\frac{V}{V_{uo}}\right)^6 \leq 1 \quad \text{(Sagging bending)} \tag{1}$$

$$\left(\frac{M}{M_{uo}}\right)^{0.6} + \left(\frac{V}{V_{uo}}\right)^6 \leq 1 \quad \text{(Hogging bending)} \tag{2}$$

where M_{uo} and V_{uo} are the flexural and shear capacity of a member respectively. Vasdravellis and Uy [31] also proposed an equation for the shear capacity of a member which includes the contribution by the concrete slab:

$$V_{uo} = V_{pl.Rd} + V_{slab} \tag{3}$$

where $V_{pl.Rd}$ is the shear capacity of the steel web as determined by AS 4100 [24] and V_{slab} is given by:

$$V_{slab} = \varphi_s f(\lambda_{sd})(b_f D_{slab})^{0.7}\sqrt{f'_c}. \tag{4}$$

Further information on the equations proposed can be found in the relevant paper.

Composite beams often can be used in situations in which an axial load may be introduced into the member. Some examples include the use in cable-stayed bridges or inclined members in stadia and bridge approach spans. The necessity to transfer diaphragm forces due to wind and seismic loads will introduce an axial load into beams used in floor systems for braced multi-storey buildings. Continuous members may also incur axial loads due to thermal expansion or contraction of materials and the restriction of their longitudinal displacement at the supports. In these situations, the beam may be subjected to any combination of flexure, shear force and axial load, N (Fig. 1). However, modern steel and composite construction codes currently do not address the effects of these combined actions.

The effect of axial load introduced through the installation of prestressing cables was researched by Troitsky et al. [26], Saadatmanesh et al. [21,22] and Ayyub et al. [1,2]. Similarly, Uy and Craine [28] and

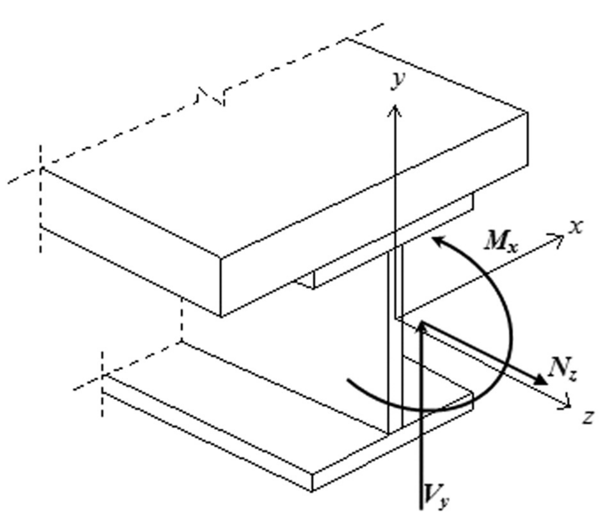

Fig. 1. Member subjected to flexure, shear and axial loads.

Lorenc and Kubica [18] compared conventional steel–concrete composite beams with beams post-tensioned using steel prestressing cables. Their studies noted a 15% and 25% increase in sagging flexural strength due to the combined action of axial compression respectively. Chen and Gu [7] studied prestressed beams subjected to positive moment and observed an increase in the sagging flexural strength of 84% with a further increase of 7% observed by using a draped tendon. Chen [6] tested prestressed composite beams subjected to hogging moments. It was found that the addition of the external tendons significantly increased the cracking moment resistance of the beams while only slightly lowering its yield moment. Chen et al. [8] later tested two-span and three-span continuous beams with post-tensioning tendons finding an 18% increase in the sagging moment capacity and a 262% increase in the cracking moment at the supports. However, in all of these studies utilising post-tensioning cables, the specimens were subjected to no more than approximately 15% of the axial compressive strength.

Uy and Bradford [27] employed a cross sectional analysis method (CSA) for their prestressed composite beam model. This extended upon previous research by including a longitudinal discontinuity at the beam–slab interface to represent the effects of partial shear connection (PSC). Loh et al. [16,17] also performed experimental and analytical studies on the effect of PSC in hogging moment regions of composite beams. It was found that, for beams using lower degrees of shear connection, a significant increase in rotational capacity was achieved, with only a slight reduction in peak moment resistance. Later studies also confirmed the results that the ductility of the beam is considerably increased when partial shear connection is used [19,29].

Shanmugam and Lakshmi [23] completed a thorough review of over 70 papers on steel–concrete composite columns covering both concrete-encased and infilled sections. This showed the extensive research that had been undertaken on axially loaded members. The composite columns in these papers, however, like many recent studies including Elghazouli and Treadway [10] and Dundar et al. [9] were doubly symmetric as opposed to a typical composite beam, such as the cross-section used in this study, which is only symmetrical about its y-axis.

Uy and Tuem [30] were the first to address the effect of tension and provide a full moment–axial load interaction diagram for composite beams. A detailed analytical study of composite beams under combined flexure and axial force was performed by two methods: a CSA and an RPA. The CSA calculates the moment–curvature response of the composite beam subjected to any combination of sagging or hogging bending and axial compression or tension. The RPA and CSA in this study show almost identical results for most cases. The only variation occurred for the sagging bending and axial compression combination where the RPA results were greater than those of the CSA. This was caused by the fact that part of the cross-section was not yielded at the ultimate case, which is contrary to the RPA's fully yielded assumption. Their model was limited to specimens with FSC and also placed the axial load at the level of the plastic neutral axis. Thus it does not include the additional moment induced by an eccentrically placed axial load or its effect on the load carrying capacity.

The authors recently studied the behaviour and design of composite beams under the four combinations of flexure and axial loads [32–35] namely: tension and negative bending, tension and positive bending, compression and negative bending and compression and positive bending respectively. Each of these studies contains an experimental series, a finite element analysis and design recommendations for the M–N interaction of each respective loading combination. Kirkland and Uy [12] performed a CSA and extended previous research with revised design models for all four combinations of flexure and axial loads as well as the influence of partial interaction. The proposed design models are given below.

Quadrant I Sagging bending and compression:

$$M \leq M_{uo}, \quad \text{for } N \leq 0.6\,N_{uo} \tag{5}$$