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Behaviour and design of composite beams subjected to sagging bending and axial compression

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ABSTRACT

This paper presents an experimental and numerical study on the ultimate strength of steel–concrete composite beams subjected to the combined effects of sagging (or positive) bending and axial compression. Six full-scale composite beams were tested experimentally under sagging bending and increasing levels of axial compression. A nonlinear finite element model was also developed and found to be capable of accurately predicting the nonlinear response and the combined strength of the tested composite beams. The numerical model was then used to carry out a series of parametric analyses on a range of composite sections commonly used in practice. It was found that the sagging moment resistance of a composite beam is not reduced under low-to-moderate axial compression, while it significantly deteriorates under high axial compression. Sectional rigid plastic analyses confirmed the experimental results. The moment–axial force interaction does not change significantly between full and partial shear connection. Based on the experimental and numerical results, a sagging moment–axial compression interaction law is proposed which will allow for a more efficient design of composite beams.

1. Introduction

Steel–concrete composite construction is a very efficient structural method for framed buildings, bridges, and stadia, due to several well-established advantages that it provides compared to other structural types. The optimal combination of the individual properties of structural steel and concrete, results in structures that are safe, robust, and economic. Steel–concrete composite beams are an ideal solution for building floors or bridge decks due to the increased speed of construction and flexibility that they offer. Moreover, the restraining effect of the concrete slab provides increased resistance to global (out-of-plane) instability failure modes, which are common in non-restrained steel beams.

Steel–concrete composite beams are increasingly being used in situations where they can be subjected to the simultaneous actions of flexure (sagging or hogging bending moments) and axial forces (tensile or compressive). Some representative examples include: a) diaphragmatic forces due to lateral (wind or seismic) loading on composite floor beams; b) high-rise frames where the effects of wind or seismic loading may impose large axial forces to the beams of the building; c) structures where inclined members are used, e.g. stadia beams or inclined parking ramp approaches; and d) cable stayed bridges, where the inclined cables and traffic loads may introduce large axial forces to the supporting composite deck [1].

The current structural provisions for composite construction, e.g. AISC 360-10 [2], AS2327.1 [3] and Eurocode 4 [4], do not provide a unified method for the design of composite beams under combined actions; instead, they refer the designer to rules established for bare steel sections. However, the behaviour of a composite beam differs substantially from that of a bare steel section; therefore, the moment–axial load interaction in composite beams deserves further investigation. Despite the large amount of available experimental data on the flexural behaviour of composite beams (see for example [5–7]), experimental data on the behaviour of composite beams under combined loading is limited. The combined effects of bending and shear force in composite beams were studied experimentally by Nie et al. [8], and numerically, using the finite element method (FEM), by Liang et al. [9,10]. The authors recently studied the shear strength and moment–shear interaction in compact composite beams using experimental tests supplemented by parametric numerical analyses [11]. In that study, the high degree of conservatism in current structural codes is highlighted, and design models for the shear strength and moment–shear interaction are proposed. The performance of composite beams under combined bending and torsion was studied by Nie et al. [12] through experiments on eleven steel–concrete composite beams. The effect of torsion on straight and curved beams was also studied by Tan and Uy [13,14]. Their research provided experimental data for the effects of torsion on

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composite beams with both full and partial shear connection. Based on the tests, design equations for ultimate limit analysis of composite beams are proposed.

This paper presents an experimental and numerical study on the ultimate strength of steel–concrete composite beams subjected to the simultaneous actions of sagging bending and axial compression. This study is the last part of a larger research project aiming to evaluate the axial force–moment interaction response of composite beams under all combinations of axial compression or tension and sagging or hogging bending moments. Previous studies by the authors investigated the behaviour and design of composite beams under tension and hogging bending [15], tension and sagging bending [16], and compression and hogging bending [17]. The experimental interaction curves resulting from those studies are summarised in Fig. 1 along with the interaction curves obtained by numerical analyses using the FEM. The quadrant that is studied in this paper is specified in the same figure.

The results of six full-scale tests on composite beams under sagging bending and various levels of axial compression are presented first. Details of a nonlinear FEM model that was developed and validated against the experimental results are given next. The model was found to be capable of predicting the nonlinear response and the ultimate failure modes of the tested beams with reasonable accuracy. The developed numerical model was further used to carry out a series of parametric analyses on a range of composite sections commonly used in practice. It was found that the sagging moment resistance of a composite beam is not reduced when a low-to-moderate axial compression acts on the section, while it significantly deteriorates when the axial compression is high. The sagging moment–axial compression interaction diagram does not change when the minimum, according to EC4, partial shear connection is used. Based on the experimental and numerical results a simple design model is proposed for use in practice.

2. Experimental programme

2.1. Test specimens

Six full-scale composite beams were designed and tested. The tested beams are denoted as CB1 to CB6. Specimens CB1 and CB6 were tested under pure sagging bending and pure axial compression, respectively, while specimens CB2 to CB5 were tested under combined sagging bending and progressively increasing levels of axial compression. The relevant geometry and details of the specimens are shown in Fig. 2. All specimens were constructed with a 600 mm wide and 120 mm deep concrete slab connected to an UB203x133x30 steel beam section (equivalent to an IPE270 or W40 profile). The composite action was achieved by welding 19 mm-diameter, 100 mm-long headed shear

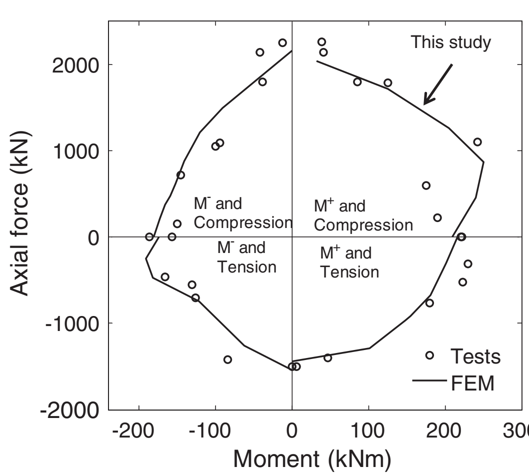

Fig. 1. Complete moment–axial force interaction diagram resulting from tests and FEM analyses.

stud connectors in a single line along the centre of the top flange of the steel beam. The number of shear studs was calculated in order to achieve partial shear connection between the slab and the beam. The degree of shear connection (β) achieved is 0.5 if the nominal value of the strength of a shear stud is used, and 0.6 if the actual strength resulting from the pushout tests (described later) is used. A group of three studs was welded near the supports to transfer the longitudinal shear without premature shear failure in the cases where high axial compression was applied. Longitudinal and transverse reinforcement was also placed in the concrete slab in the arrangement shown in Fig. 2. Two 10 mm-thick web stiffeners were welded to the beam web at the point of the axial load application to prevent premature buckling due to the concentrated load.

2.2. Material property tests

Concrete and steel material property tests were performed to obtain the actual strength of the materials. Concrete tests consisted of standard cylinder compressive tests and flexural splitting tests. The latter aimed to determine the flexural tensile strength of the concrete. The cylinders were 200 mm high with a diameter of 100 mm, while the flexural tests were performed on $100 \times 100 \times 400$ mm specimens. The results are summarised in Tables 1 and 2. Tensile tests were conducted on coupons cut out from the flanges and web of the steel beams as well as the reinforcing bars. The values obtained from the tests for the 0.2% proof stress, tensile stress (i.e. maximum nominal stress), and Young's modulus are reported in Table 3.

The load–slip behaviour of the shear studs was evaluated by conducting three push-out tests according to the Eurocode 4 procedure [4]. The push-out specimens were constructed using concrete from the same batches as the one used to form the steel–concrete composite beams in the main experimental programme. The resulting load–slip curves showed that the average strength of one shear stud is about 108 kN, the average maximum slip is 14.1 mm, and the average slip at maximum load is 10.1 mm.

2.3. Experimental setup

The experimental setup is shown in Fig. 2. The composite beams were simply supported at the two ends and a combination of hydraulic actuators was used to apply simultaneous sagging bending and axial compression to the composite beam specimens. The free span of the beams was 4000 mm for CB1 and 4950 mm for the rest of the tests, as indicated in Fig. 2. The vertical load was applied at the midspan using a 1000 kN — capacity hydraulic actuator with a stroke of 250 mm. The axial compression was applied using four 800 kN — capacity hydraulic actuators placed horizontally and in parallel, imposing a controlled displacement at the one end of the beam, while the other end was restrained in the horizontal direction. This system was capable of applying a maximum 3200 kN axial load, and the stroke was 200 mm. In specimens CB2 and CB3, the axial load was applied to the beam through a plate welded to the steel beam section. Thus, the load was transferred to the composite section via the shear connectors. However, this setup resulted in premature failure of the (already weak) shear connection, and, therefore, in beams CB4, CB5, and CB6 the axial compression was transferred to the composite beam section using a triangular spreader plate of height equal to the composite section, as schematically shown in Fig. 2. In this way, the loaded area was the area of the steel beam plus a portion of the slab area equal to the width of the spreader plate times the depth of the slab.

2.4. Instrumentation

A set of linear variable differential transformers (LVDTs), load cells, and strain gauges was used to monitor the experimental behaviour of the beams, as shown in Fig. 2. LVDTs were placed at the midspan and