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Behaviour and design of composite beams subjected to negative bending and compression

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ABSTRACT

This paper investigates the behaviour of steel–concrete composite beams subjected to the combined effects of negative bending and axial compression. For this study, six full-scale tests were conducted on composite beams subjected to negative moment while compression was applied simultaneously. The level of the applied axial compression varied from low to high. Following the tests, a nonlinear finite element model was developed and calibrated against the experimental results. The model was found to be capable of predicting the nonlinear response and the ultimate failure modes of the tested beams. The developed finite element 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, when a compressive load acts in the composite section, the negative moment capacity of a composite beam is significantly reduced and local buckling in the steel beam is more pronounced, compromising the ductility of the section. Rigid plastic analysis based on sectional equilibrium can reasonably predict the combined strength of a composite section and, thus, can be used conservatively in the design practice. Detailing with longitudinal stiffeners in the web of the steel beam in the regions of negative bending eliminate web buckling and increase the rotational capacity of the composite section. Based on the experimental outcomes and the finite element analyses a simplified design model is proposed for use in engineering practice.

1. Introduction

Composite construction of steel and concrete is a popular structural method due to its numerous advantages against conventional solutions. The optimal combination of the properties of the two most popular construction materials, i.e. steel and concrete, results in structures that are both safe and economic. Composite action between the steel beam and the reinforced concrete slab, which is commonly achieved through the welding of shear studs to the top flange of the beam, results in significant reduction of beam deflections, enabling the use of smaller steel sections compared with bare steel systems.

Continuous composite beams represent an efficient structural method in many structural systems, such as buildings and bridges, due to additional advantages associated with the favourable redistribution of internal forces across the member and the easier satisfaction of serviceability checks. However, the design and analysis of continuous composite beams is rather complicated due to their different behaviour in positive (or sagging) and negative (or hogging) moment regions. Moreover, in regions of hogging moments, e.g. at the internal support regions of continuous members, a large part of the steel beam section is subjected to compressive stresses, thus the bottom flange and the web are susceptible to local instabilities.

In engineering practice, there are situations where composite beams are subjected to combined actions, e.g. simultaneous action of positive or negative bending and axial tension or compression. Such examples include: a) in floor beams where the axial force can either be as part of a specific bracing system or where the beam acts as part of a diaphragm [1]; b) high-rise frames where the effects of wind loading become significant and can impose large axial forces on the beams of the building; c) structures where inclined members are used, e.g. stadia beams or inclined parking ramp approaches; and d) bridges, where inclination and traffic loads may introduce large axial forces on the supporting beams.

Current structural codes, e.g. [2–4], do not provide specific rules for the design of composite beams under combined axial forces and bending moments; they rather refer to rules established for bare steel sections. Since the behaviour of a composite beam differs substantially from that of a bare steel section, the moment–axial load interaction of composite beams still deserves further investigation. Despite the large amount of available experimental data on the flexural behaviour of composite beams [5–7], experimental data on the behaviour of composite beams under combined loading is rather limited. The effects of axial tension on the sagging and hogging moment regions of composite beams were studied in previous research by the authors [8,9]. In this work, the ultimate strength of composite beams subjected to combined actions was investigated by a large experimental programme, rigid plastic sectional analyses and extensive finite element simulations. Interaction curves were established and simple design rules were proposed for

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use in practice. The effect of pre-stressing on composite beams under positive bending was studied by Uy and Bradford [10] and Uy [11]. The performance of composite beams under combined bending and torsion was reported by Nie et al. [12] by studying experimentally and theoretically 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 composite beams with both full and partial shear connection. Based on the tests, design equations for ultimate limit analysis of composite beams were proposed. Baskar and Shanmugan [15] tested a number of steel–concrete composite girders under bending and shear loading. They found that the ultimate load carrying capacity is increased significantly compared to bare steel girders. Elghazouli and Treadway [16] presented results from a series of tests on partially-encased composite steel–concrete beam-columns. The experimental inelastic behaviour of the specimens under lateral loading and axial gravity loads was examined. The specimens in their study, however, were symmetrical through both their x and y axes and thus more appropriate for use as columns. Uy and Tuem [17] were the first to consider the effect of tension in composite beams. An analytical study on combined axial load and bending was performed through a cross-sectional analysis and a rigid plastic analysis.

This paper studies the behaviour of composite beams under the combined effects of negative bending and axial compression and is part of a large research project which aims to establish the complete interaction diagram for composite beams subjected to combined axial forces and bending moments. In this context, six full-scale tests were conducted on composite beams subjected to combined actions, while the level of the applied axial compression varied from low to high. Following the tests, a detailed nonlinear finite element model was developed and validated against the experimental results. The model was found to be capable of predicting the nonlinear response and the ultimate failure modes of the tested beams. The developed finite element 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, when a compressive load acts in the composite section, the negative moment capacity of a composite beam is significantly reduced and local buckling in the steel beam is more pronounced, compromising the ductility of the section. Rigid plastic analysis based on sectional equilibrium can reasonably predict the combined strength of a composite section and, thus, can be used conservatively in design practice. Detailing with longitudinal stiffeners in the web of the steel beam in the regions of negative bending eliminate web buckling and increase the rotational capacity of the composite section. Based on the experimental outcome and the finite element analyses a simplified design model is proposed for use in engineering practice.

2. Experimental programme

2.1. Details of test specimens

Six full-scale composite beams were designed and tested as part of the experimental programme. The tested beams are denoted throughout this paper as CB1 to CB6. Specimens CB1 and CB6 were tested under pure negative moment and pure axial compression, respectively, while specimens CB2 to CB5 were tested under combined negative bending and an increasing level of applied axial compression. The relevant geometry and details of the reinforcement and shear studs are shown in Fig. 1. All specimens were constructed with a 600 mm-wide and 120 mm-deep concrete slab connected to a UB203 × 133 × 30 universal beam section. The beam-to-slab connection was achieved through 19 mm-diameter, 100 mm-long headed shear studs welded in a single line along the centre of the top flange of the steel beam. The provided number of shear studs was calculated to ensure full shear connection between the slab and the beam. The degree of shear connection in hogging moment regions of composite beams is defined as the ratio of the shear connection strength provided by the studs to the strength of the weakest component (steel reinforcement or steel beam), while the tensile strength of the slab is neglected [18]. That is:

$$\beta = \frac{N_{ss} F_{stud}}{min\{F_r, F_{beam}\}} \tag{1}$$

where β is the degree of shear connection, N_{ss} is the number of studs in the shear span (half span), F_{stud} is the strength of an individual stud, F_r is the axial strength of the reinforcement in the slab, and F_{beam} is the axial strength of the steel beam. In the experimental beams $N_{ss} = 8$, $F_{stud} = 110$ kN from the pushout tests (described later), and $min\{F_r, F_{beam}\} = F_r = 250$ kN, thus $\beta = 3.5 > 1$; therefore, a full shear connection was ensured. A group of three studs was welded to the ends of each of the beams to reduce slip and ensure full utilization of the reinforcing bars. Longitudinal and transverse reinforcement was placed in the concrete slab in the arrangement shown in Fig. 1.

Two 10 mm-thick web stiffeners were welded between the beam flanges at the point of the vertical load application to prevent premature web buckling due to the concentrated midspan load. In addition, specimens CB5 and CB6 were reinforced by using a series of web and flange stiffeners at the two ends of the beam (see Fig. 1). This configuration aimed to avoid local failure due to large stress concentration at the points of the axial load application and allowed for the high compressive loads to be partly transferred to the composite cross-section at the midspan, as will be discussed later. Due to an unexpected failure of specimen CB2 due to lateral buckling, lateral bracing was placed along the length of the beams CB3 to CB6 to eliminate the possibility of lateral–torsional buckling failure mode. The lateral bracing consisted of steel rectangular members anchored on the edges of the concrete slab and welded on the bottom (compressive) flange of the steel beam, as shown in Fig. 2.

2.2. Material property tests

Both 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 at determining the 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 × 100 × 400 mm specimens. The results are summarised in Table 1. Tensile tests were also conducted on coupons cut out from the flange and web of the steel beams as well as the reinforcing bars. The values obtained from the tests for the yield stresses, the ultimate stresses at fracture, and the modules of elasticity are reported in Table 2.

The load-slip characteristics of the shear studs were evaluated by conducting three push-out tests. The push-out specimens were constructed using shear studs and concrete from the same batches as those used to form the steel–concrete composite beams in the main experimental series. Each of the push-out specimens were tested following the testing procedure described in Eurocode 4 [2]. The resulting load–slip curves showed that the average capacity of one shear stud is about 110 kN, while the maximum slip achieved during the tests varied from 8 to 14 mm, as demonstrated in Table 3. Table 3 also reports the slip values at the maximum load during the tests. These values are 5.8, 6.9, and 8 mm, demonstrating good ductility of the shear studs.

2.3. Experimental setup

A combination of load actuators was used to produce simultaneous axial compressive loads and bending moments in the composite beam specimens. The vertical load was applied with the use of a 1000 kN-capacity hydraulic actuator with a usable stroke of 250 mm. The axial compressive load was applied using four 800 kN-capacity hydraulic actuators placed in parallel. Therefore, this system was capable of applying a maximum 3200 kN axial load with a 200 mm usable