ΣΥΜΠΕΡΙΦΟΡΑ ΚΑΙ ΣΧΕΔΙΑΣΜΟΣ ΣΥΜΜΙΚΤΩΝ ΔΟΚΩΝ ΥΠΟ ΣΥΝΔΥΑΣΜΕΝΗ ΚΑΤΑΠΟΝΗΣΗ

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ΠΕΡΙΛΗΨΗ

Συχνά σύμμικτες δοκοί από χάλυβα και σκυρόδεμα καταπονούνται υπό συνδυασμένη ροπή κάμψης και αξονικές δυνάμεις. Ωστόσο, οι ισχύοντες κανονισμοί δεν καλύπτουν το σχεδιασμό και τη συμπεριφορά σύμμικτων δοκών υποκείμενων στην ταυτόχρονη δράση κάμψης και σημαντικών αξονικών φορτίων. Ένα εκτεταμένο ερευνητικό πρόγραμμα που περιλαμβάνει είκοσι οχτώ δοκιμές διεξήχθη πρόσφατα στο Πανεπιστήμιο του Δυτικού Σύδνεϋ (Αυστραλία), με στόχο τη διερεύνηση της συμπεριφοράς σύμμικτων δοκών υπό αρνητική ή θετική κάμψη και θλιπτική ή εφελκυστική αξονική δύναμη. Η έρευνα αυτή συνοδεύεται από θεωρητικές αναλύσεις, καθώς και λεπτομερείς προσομοιώσεις με τη μέθοδο πεπερασμένων στοιχείων και παραμετρικών μελετών. Διαπιστώθηκε ότι η καμπτική ροπή αντίστασης μιας σύμμικτης δοκού μειώνεται στις περισσότερες περιπτώσεις υπό ταυτόχρονη αξονική φόρτιση. Η χρήση μερικής διατμητικής σύνδεσης δεν μεταβάλλει σημαντικά το σχήμα της καμπύλης αλληλεπίδρασης. Με βάση τα πειραματικά και αριθμητικά

αποτελέσματα, προτείνονται απλοί κανόνες σχεδιασμού για τον πιο ακριβή σχεδιασμό σύμμικτων δοκών.

BEHAVIOUR AND DESIGN OF COMPOSITE BEAMS UNDER GENERALISED ACTIONS

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1. ABSTRACT

Steel-concrete composite beams can be subjected to combined bending and axial forces; however, the behaviour of composite beams under combined loading is not covered by the current design standards. An extensive experimental investigation comprising twenty-four full-scale tests was conducted recently in the University of Western Sydney, aiming to investigate the behaviour and ultimate strength of compact composite beams under sagging or hogging bending and compressive or tensile axial forces. The research was accompanied by theoretical analyses, including detailed finite element simulations and parametric studies. This paper gives a summary of the research outcome on this topic. It was found that the moment capacity of a composite beam is reduced in most situations under simultaneous axial loading. Partial shear connection does not alter the shape of the interaction curve, but it affects the ductility of the beam and the amount of axial load transferred to the slab. Based on the

experimental and numerical results, simplified design rules are proposed to account for the effect of axial loads on the bending capacity of composite beams.

2. INTRODUCTION

Composite beams often can be 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; 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) cable bridges, where inclination and traffic loads may introduce large axial forces on the supporting beams. Current structural codes, e.g. Eurocode 4, AISC 360-10 and AS2327-1, do not provide a unified approach for the design of composite beams under combined axial force and bending moment; they 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, experimental data on the behaviour of composite beams under combined loading is rather limited. Recent studies on the effects of other combined actions (e.g. shear and torsion) include those by Nie et al. [4], Liang et al. [5], Tan and Uy [6], and Vasdravellis and Uy [7].

This paper presents the results of a research program carried out at the University of Western Sydney (Australia) aiming at investigating the moment-axial force interaction in steel-concrete composite beams. The research consisted of twenty-eight tests on full scale composite beams subjected to bending (sagging or hogging) and axial force (compressive or tensile). The experiments were complemented by detailed finite element analyses (FEM) and parametric studies and the experimental findings were confirmed and reliably generalised. It is shown that it is important to account for the effects of axial force in the design of composite beams, and that slightly different interaction laws exist for each combination of sagging or hogging bending and compressive or tensile axial force. Based on the experimental and numerical results, design models are proposed for the more efficient design of composite beams in situations where axial force is present.

3. EXPERIMENTAL PROGRAM

The relevant geometry of the specimens, the test setup, and details of the reinforcement and shear studs are shown in Fig. 1. All specimens were constructed with a 600mm-wide and 120mm-deep concrete slab connected to a UB203x133x30 (equivalent to IPE 330) beam section. The beam-to-slab connection was achieved through 19mm-diameter, 100mm-long headed shear studs. A combination of load actuators was used to produce simultaneous bending and axial forces in the composite beam specimens, as shown in Fig .1. A combination of LVDTs and strain gauges was deployed to record the relevant parameters and to obtain the experimental behaviour of the beams. The vertical load was applied in incremental steps in the order of 10% of the theoretical design strength of the composite section. To obtain different levels of axial force, the increments of applied axial load were varied. Both loads were increased until either material failure occurred or the maximum stroke of either of the load actuators was reached. The resulting moment in each tested beam was calculated taking into account the equilibrium of the external forces acting on it.

4. EXPERIMENTAL RESULTS

A detailed description of the experimental results can be found in [8], [9], [10], and [11]. A brief summary of the complete moment – axial force interaction is provided herein. Fig. 2 presents the complete moment –axial force interaction diagram resulting from the four series of tests, i.e. positive bending and tension, positive bending and compression, negative bending and tension, and negative bending and compression. The results of the FEM analyses, described in the next section, are superimposed to the experimental data points. In all combinations the moment is reduced with increasing the applied axial load. Typical experimental failures of the specimens included slab compressive failure under positive bending, steel beam flange local buckling under negative bending, steel global buckling under axial compression, and shear connection failure under high axial compression/tension in the specimens designed with partial interaction. An important outcome of the experiments concerning compressive axial force is that a large amount of compression can be transferred from the steel beam to the concrete slab through the shear connection system if adequate reinforcement is provided at the ends of the steel beam. A set of plates welded to the beam flange and web, as shown in Fig. 1, can provide this capability.

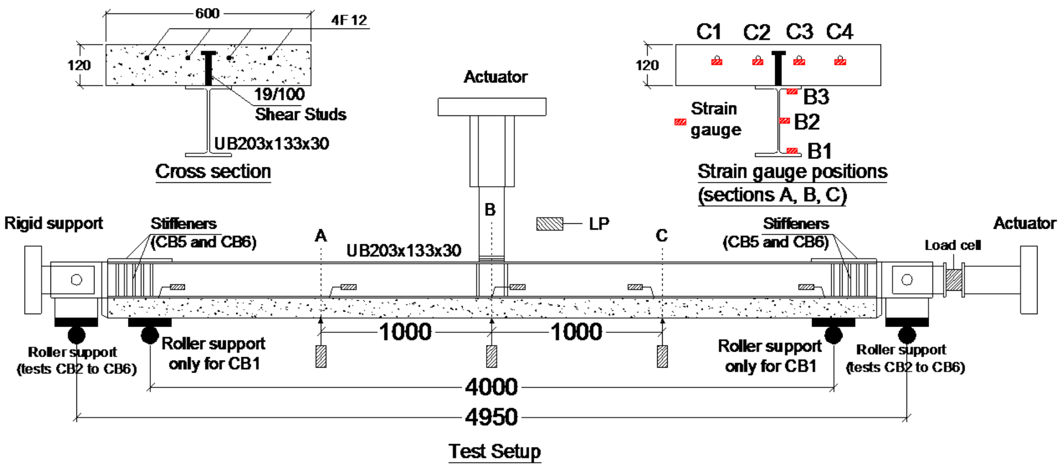

Figure 1 – The tests setup for negative bending moment

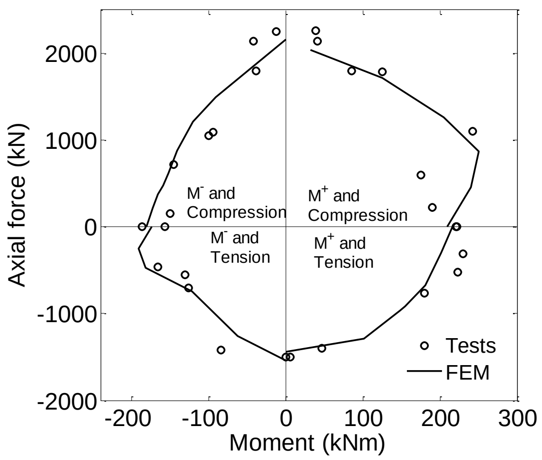

Figure 2 – Complete moment – axial force interaction curve from tests and FEM analyses

5. NUMERICAL ANALYSES

A nonlinear three-dimensional finite element model was developed to simulate the tests on the composite beams. An overview of the mesh and a schematic representation of the various modelling assumptions are depicted in Fig. 3. More details on the modelling assumptions and features can be found in [9]. The experimental tests were reproduced using the developed FEM model. The FEM model was able to predict the combined strength of the composite beams with good accuracy. The model was assessed by comparing the structural behaviour of the tested beams with that of the model in terms of force – deflection curves, slip evolution in the slab - beam interface, axial force – displacement response, and strain evolution in the steel beam. Fig. 4 shows typical comparisons which demonstrate good agreement between the experimental and numerical responses.

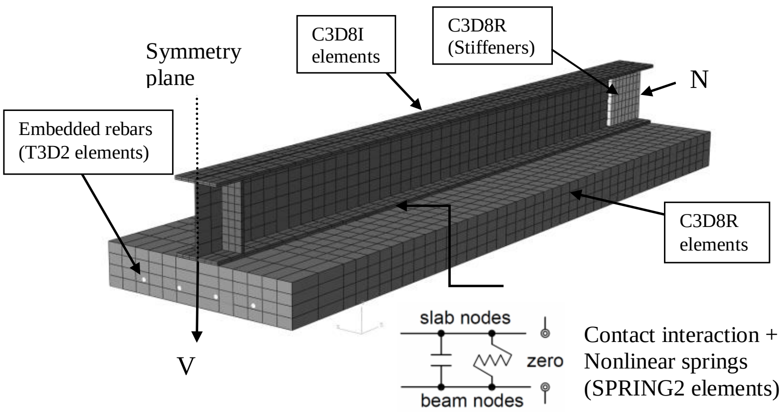

Figure 3 - The developed finite element model

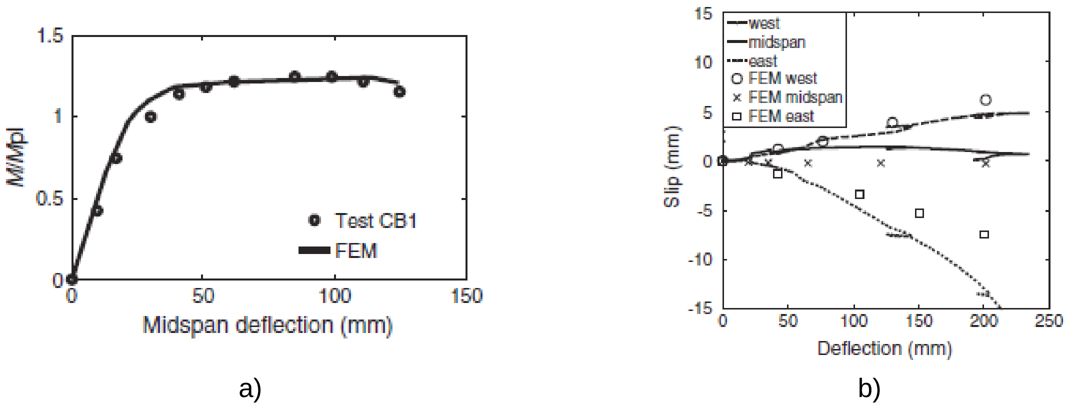

Figure 4 – Experimental versus numerical response comparison: a) negative moment – midspan deflection; and b) slip evolution under positive bending.

6. PARAMETRIC ANALYSES

The validated FEM model was used to conduct an extensive parametric study on composite beams subjected to combined bending and axial force. A wide range of composite beam section commonly used in buildings was studied. The results of the parametric analyses generally confirmed the experimentally derived interactions. Both full and various degrees of partial interaction were studied. The shape of the interaction was not affected in most situations when the composite beam had partial shear connection. More details of the parametric analyses are provided in [8], [9], [10], [11]. Regression analysis of the numerical results allowed the derivation of simplified design equations for use in practice.

7. PROPOSED DESIGN MODELS FOR COMPOSITE BEAMS UNDER BENDING AND AXIAL FORCES

Based on the experimental and numerical results simplified equations are proposed for the design of composite beams subjected to any combination of positive or negative bending moment and axial tension or compression. In the following equations, M_{u} and N_{u} represent the bending and axial resistances of a composite section, respectively, calculated according to the current structural codes (e.g. Eurocode 4):

a) Composite beams under negative bending and compression (Fig. 5a):

$$\frac{M}{M_{\mathrm{u}}} + \frac{N}{N_{\mathrm{u}}} \leq 1.0 \qquad (3)$$

According to this formula, the hogging moment resistance of a composite beam is reduced with the presence of compression forces following a linear relationship. Although the interaction diagrams from the parametric analyses indicated that in some cases the reduction in moment capacity is delayed [10], a linear reduction is proposed for a reasonably conservative design, which also agrees the experimental output. The proposed design formula assumes that adequate lateral restrain is provided to the compression flange so that flexural or distortional buckling is excluded as failure mode. In addition, longitudinal stiffeners according to the design details proposed in Vasdravellis et al. [10] is recommended to be welded to the steel beam web at the internal support regions of continuous composite beams to ensure that web local buckling is delayed and adequate rotation capacity for plastic structural analysis is available.

b) Composite beams under negative bending and tension (Fig. 5c):

$$\frac{N}{N_{\mathrm{U}}} + 0.8\frac{M}{M_{\mathrm{U}}} = 1, \quad \text{for N} > 0.20\mathrm{N_U} \tag{4}$$

$$M = M_{\mathrm{U}}, \qquad \text{for N} \leq 0.20\mathrm{N_U} \tag{5}$$

According to this formula, the bending capacity at the hogging moment regions of composite beams is not reduced when an axial tensile force up to 20% of the axial strength is applied in the beam, and it reduces linearly to zero when larger values of axial force are present.

c) Composite beams under positive bending and tension (Fig. 5d)

$$\frac{M}{M_{\mathrm{U}}} + 0.6\frac{N}{N_{\mathrm{U}}} = 1.0 \tag{6}$$

According to this equation, the moment capacity of a composite section is reduced linearly until the 40% of the M_u by increasing the axial tensile force acting on the steel section. It has to be pointed out, however, that in practice it is very rare for a beam to be subjected to tensile axial forces greater than the 30%-40% of its axial capacity; however, it was judged as necessary to study the whole range of axial force percentages in order to complete the interaction diagram and have a full picture on the behaviour of composite beams under combined actions.

d) Composite beams under positive bending and axial compression (Fig. 5b):

$$M = M_U \text{ , for } N < \gamma N_{\mathrm{U}} \tag{3}$$

$$(1-\gamma)\frac{M}{M_{\mathrm{U}}} + \frac{N}{N_{\mathrm{U}}} = 1.0 \text{ , for N} > \gamma N_{\mathrm{U}} \tag{4}$$

γ=0.3 , if N applied to steel section only

γ=0.4 , if N applied to both the steel section and the concrete slab (i.e. a column type loading).

The proposed design model assumes that the sagging moment capacity of a composite section is not reduced when a predefined level of axial compression acts simultaneously. The level of axial compression is 30 % when the axial force is applied to the steel section and 40 % when the axial force is applied to both the steel section and part of the concrete slab. For greater values of axial compression, the moment capacity is linearly reduced until N_{U}.

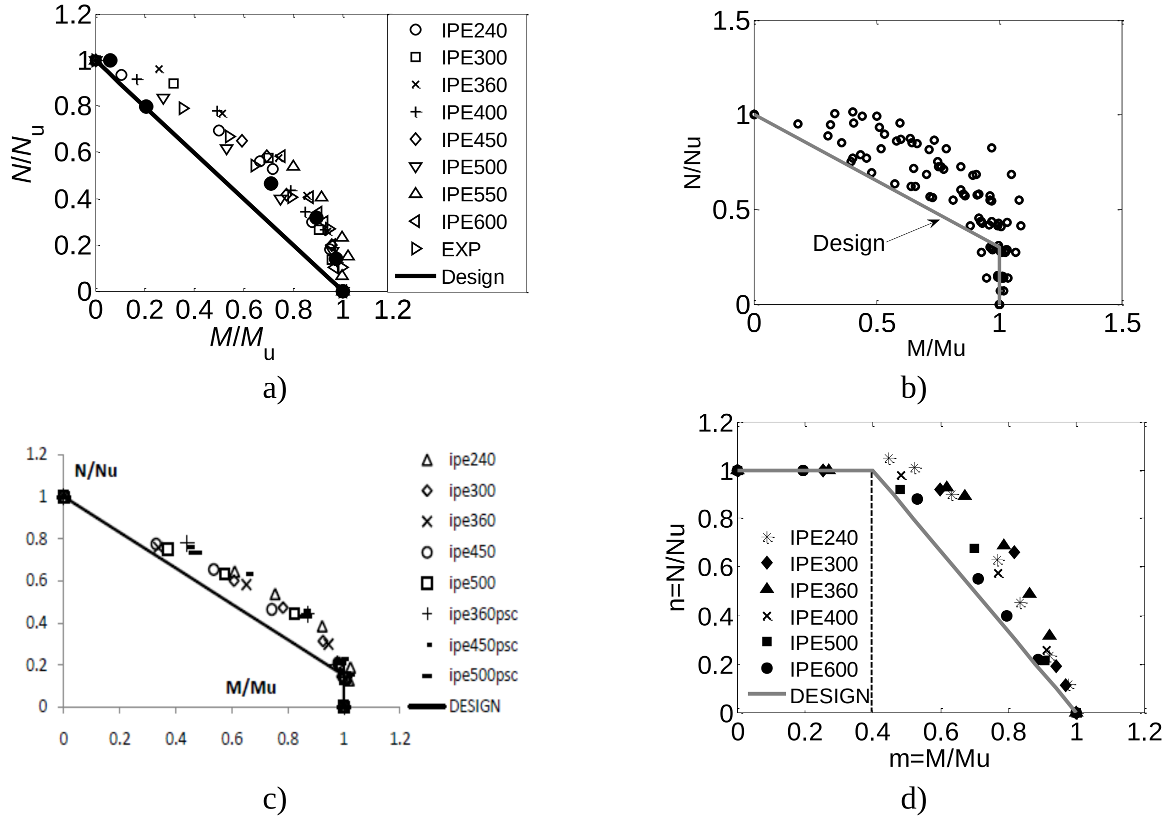

Figure 5 – Results of parametric analyses and proposed design equations for composite beams under combined bending and axial force.

8. CONCLUSIONS

The main conclusions from this research are:

- The experiments and the numerical simulations demonstrated that it is important to account for the axial force in the design of composite beams and that slightly different moment-axial force interaction laws correspond to each of the four quadrants of the complete interaction.
- The bending moment capacity of a composite beam deteriorates under the simultaneous action of a relatively high axial compressive or tensile force. However, the reduction is less or negligible under a low to moderate axial force in most of the cases.
- In order to transfer substantial compressive forces in a composite beam without experiencing premature buckling of the steel section, reinforcing the flanges and the web with additional steel plates locally at the edges is recommended.
- The developed three-dimensional nonlinear finite element model can be used as a tool for the assessment of the nonlinear behaviour and the ultimate failure modes of composite beams under combined negative or positive bending and axial compression or tension.
- Simplified design models for the moment – axial force interaction in composite beams are proposed for use in practice.

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