Journal of Constructional Steel Research 65 (2009) 1063–1074

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Two-dimensional FE model for evaluation of composite beams, II: Parametric study

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ARTICLE INFO

Article history:
Received 4 June 2008
Accepted 23 January 2009

Keywords:
Semi-continuous composite beams
Finite element method
Levels of shear connection
Parametric analysis
Degree of moment redistribution
Required and available rotations
ANSYS

ABSTRACT

In the present paper, the 2D finite element (FE) model presented and validated in the companion paper "Two-dimensional FE model for evaluation of composite beams, I: Formulation and Validation" is used to undertake a parametric study focused on both the required and available rotations and the moment redistribution capacity of semi-continuous composite beams. The investigation has shown that some tendencies already established in the literature regarding beams with full shear connection are not applicable to cases with partial shear connection.

1. Introduction

The use of systems based on the combined behaviour of steel and concrete materials have been of interest for decades. Composite action enhances structural efficiency by combining the structural elements to create a single composite section [1]. One of the most common composite systems is the composite beam, in which a steel beam interacts with the concrete slab it supports by means of shear connectors. This system is well recognised in terms of the stiffness and strength improvements that can be achieved when compared with non-composite solutions.

In the last years, the use of composite beams with a certain degree of continuity has become more common. Nevertheless, composite beams behave very differently in this situation when compared to the simply-supported case and can almost never provide the same strength or stiffness in the positive moment regions as in the negative moment regions, which results in a more complex design process.

The composite system in the sagging moment region is structurally ideal, as the steel beam is in tension and the concrete slab in compression. Nevertheless, in the hogging moment region (e.g., supports) the concrete slab is in tension (reinforcement is therefore necessary) and the steel beam in compression, resulting in a much lower resistance moment. Both the hogging and sagging moment resistances should be efficiently utilised in order to obtain a more economical beam design. This leads to the necessity for moment redistribution from the support to the span in order to use the larger sagging resistance [2].

The use of partial connection provides the opportunity to achieve a better match of applied and resisting moment and some economy in the provision of connectors [3]. However, there is a lack of information on the use of partial shear connection in regions of hogging moment [4,5]. Increased confidence in the performance of composite beams with partial shear connection should lead to improvements in design guidelines and, consequently, better economy in design.

Over the last decades, with the advance in computing facilities, realistic numerical studies and full-scale experimental tests have been complementing each other in more comprehensive structural assessments and have been providing design engineers with a wide range of information that can assist them to develop safer and more efficient designs [6–8]. According to Abdollahi [9], the more complex the geometry of the structure, the more a computer-based numerical approach becomes necessary in order to obtain the desired solution.

In this paper, the two-dimensional finite element model, which has been presented and had its accuracy and reliability demonstrated in the companion paper, is used to undertake a parametric study of the effects of several structural parameters (e.g. amount of reinforcement, degree of shear connection and

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doi:10.1016/j.jcsr.2009.01.005

load–slip characteristic of studs) on the behaviour of composite beams. In particular, attention is focused on the required and available rotations and the effect of partial shear connection in semi-continuous arrangements. In the present paper, the case of composite structures under dynamic – seismic – loadings characterised by sagging moments at beam ends is not dealt with.

2. Partial shear connection and partial interaction

Any investigation of the influence of partial shear connection on the behaviour of semi-continuous composite beams should first define the concepts of level of shear connection, in both the hogging and sagging moment regions.

Generally, for the sagging moment region, the term full shear connection is used when the capacity of the shear connectors $(\Sigma q_n)_{(+)}$, between the sections of zero and maximum bending moments, is equal to or greater than the lowest capacity value (resistance), V_h, of the following components: steel beam section in tension and concrete slab in compression.

Conversely, the situation in which the connection fails in shear before either the concrete slab or the steel beam reach their maximum capacities is known as partial shear connection. Therefore, partial shear connection is present when $(\Sigma q_n)_{(+)} < V_h$, with the level of shear connection being defined as $\eta^+ = (\Sigma q_n)_{(+)}/V_h$.

Depending on the deformability of the studs, the connection may deform resulting in relative movement along the boundary (interface slip) and thus greater shear deformation of the beam as a whole. This is the concept of partial interaction, and it occurs to some extent in all beams. Unsurprisingly, this effect is found to be more significant for beams with partial shear connection.

Therefore, the concepts of level of shear connection and level of interaction are different, since the former is governed by the strength of the studs in a composite beam and the latter is related to the stiffness of the shear connectors and their ductility. Nevertheless, if the number of connectors in a beam is increased, both the shear strength and the shear stiffness of the shear connection will increase (Oehlers and Bradford [10]).

In the hogging moment region, the term full shear connection is generally used when the shear connectors are able to develop the full capacity in tension of the reinforcing bars which are used to provide continuity for the composite beam.

The usual concept found in the literature, including the current design codes, is to consider that only the connectors located in the hogging moment region are responsible for the mobilisation of the reinforcement. Consequently, taking T as the tension capacity of the reinforcement and $(\Sigma q_n)_{(-)}$ the connection capacity of the studs in the hogging region, the level of shear connection is given by $\eta^- = (\Sigma q_n)_{(-)}/T$, where $\eta^- \leq 1$. However, shear connectors located in the sagging moment region can also assist in mobilising the reinforcing bars (Queiroz [11]).

In the present study, the usual concept is used to define the basic level of shear connection for this zone (η^-). The ratio α of moment capacity at the support (Msupp) to moment capacity in the span (Mspan — which takes into account the effect of the level of shear connection in the sagging moment region η^+), is given by (in the absence of a moment steel connection):

$$\alpha = \frac{[(\text{reinforcement yield strength})(\text{reinforcement area})(\eta^-)(\text{lever arm})]}{\text{Mspan}}. \tag{1}$$

After the analysis of each case, values for the level of shear connection in both sagging and hogging regions have been recalculated based on the stresses obtained in the reinforcing bars. These new values are termed "real values" of the parameters (η^-_{real} and η^+_{real}). A new value for the parameter α was also calculated (α_{real}).

3. Definition of the structural system

3.1. Key input parameters

The present parametric analysis was undertaken based on a symmetric 2-span propped composite beam subjected to a uniformly distributed load (Fig. 1(a)).

The composite connection was considered as being composed of two main parts: (a) reinforcing bars and, (b) a boundary condition (in the axial direction), representing the connection between the bottom steel beam flange and the column (Fig. 1(b)). This connection was assumed to be horizontally rigid, for simplicity.

Both the steel connection and the reinforcement can affect the level of continuity present. As the primary focus of this parametric study is composite beam behaviour, the steel connection was not explicitly modelled. Different degrees of continuity (different values of hogging moment) were obtained by varying the amount of reinforcement. The continuity of moments was guaranteed by both the reinforcement and the connection of the bottom steel beam flange.

Thus key input parameters are:

- Basic level of shear connection in the negative moment region (η^-): resistance of the shear connectors divided by the reinforcement strength;
- Basic level of shear connection in the positive moment region (η^+): number of connectors in this zone divided by the number of studs which would be needed to develop the plastic moment of resistance of the composite beam (Mp);
- Moment ratio α defined by Eq. (1).

3.2. Key output parameters

3.2.1. At the ultimate limit state (ULS)

The available rotation capacity ($\theta_{\text{available}}$) is defined as the rotation associated with the first reading of the ultimate limit state for the components: shear connectors or reinforcing bars. Depending on the component that fails first (reinforcement or stud), the available rotation capacity is defined as

- (ultimate elongation of the reinforcement + stud slip in the adjacent negative moment region) divided by the corresponding lever arm
  or
- (elongation of the reinforcement + ultimate stud slip in the adjacent negative moment region) divided by the corresponding lever arm.

It is possible, though extremely unlikely, that available rotation capacity could be limited by failure of the steel beam or the concrete slab (due to excessive deformations).

The required rotation (θ_{required}) is defined as the rotation needed to reach a specific positive moment, usually between 85% and 95% of the plastic moment of resistance of the composite beam, taking into account the level of shear connection in the sagging moment region (β Mspan). It is measured between the two adjacent beams (half the relative rotation), for the degree of redistribution desired. In cases where the target degree of redistribution is not obtained before failure of the composite system, the available rotation is considered insufficient.

The degree of moment redistribution, β, is given by:

$$\beta = M^+_{\max}/\text{Mspan} \tag{2}$$

in which $M^+_{\max}$ is the maximum positive moment in the span. $\beta_{\max}$ is the maximum possible value of the parameter β, corresponding to the situation in which the required rotation is equal to the available rotation ($\theta_{\text{required}} = \theta_{\text{available}}$).