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Modeling composite beams with partial interaction

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ABSTRACT

This paper presents a finite element model for the analysis of composite beams with partial interaction. In this model, the elements of the composite beams are modeled by six different types of frame elements. Compared with other methods presented in the literature, the main advantages of the proposed method are as follows: (1) intuitiveness, as the different elements of the model present a close and easy to understand relation with the structural behavior of the composite beam; (2) applicability as the method directly provides useful information for the design work; (3) versatility and generalization in dealing with any combination of loading and boundary conditions (Furthermore, the proposed model enables the analysis of statically indeterminate structures, tapered beams as well as structures with non-uniform shear connector distributions.); (4) easy elaboration of models; and (5) possible widespread use of the model, as the proposed method can be implemented in any structural software. To validate the accuracy and the efficiency of the proposed model, a set of FEMs are verified against those results obtained by analytical equations available in the literature for different boundary and loading conditions. Furthermore, a set of parametric studies are performed to investigate the effects of the size of the FEMs along with the influence of the connection stiffness on the behavior of composite beams with different I beams.

1. Introduction

In the last decades, the use of concrete and steel composite beam structural systems has received significant attention both numerically (e.g. [15], [35], [12], [5]) and experimentally (e.g. [1], [28], [10], [11], [6] and [13]). This popularity is due to their construction speed together with structural and cost advantages. In a steel–concrete composite beam the tensile strength of the steel and the compressive strength and mass of the concrete slab are exploited. These two materials are connected with shear struts so that they act compositely. For a composite beam with rigid shear connection, there is full interaction between the steel and the concrete members. In this case, there is no relative slip at the interface of both materials and Navier hypothesis is fully applicable. This approach is followed by most codes (e.g. the rigid-ideal plastic method in [8,9]). Nevertheless, all shear connections are flexible to some extent and therefore, full interaction is rarely achieved in practice. For this reason, partial interaction (see e.g. [34], [18], [25] and [3]), with a relative slip at the interface, commonly appears in actual structures. The simulation of this relative slip is of primary importance because it affects both the deflections and the stresses in both the concrete and steel members. Therefore, partial interaction occurs to some extent in all beams weather fully connected or not. However, according to Queiroz et al. [22], any flexibility in the connection may be ignored for beams designed for full connection.

A number of studies have been carried out to simulate the behavior of composite beams with partial shear interaction. According to many authors (see e.g. [29]), the first analytical model including partial shear interaction for beams is attributed to Newmark et al. [17]. In this method, the equilibrium and compatibility equations for an element of the composite beam are reduced to second order differential equations. This model assumes distributed bonds at the concrete–steel interface. These bounds enforce contact between components and allow longitudinal interlayer slip. The differential equation approach of this method was also followed by Martínez and Ortiz [2], who defined the analytical solutions for elastic simply supported composite beams under simple loading cases. This procedure assumes that the deflections of the centroids of steel and concrete cross-sections are the same and continuous connection at the concrete–steel interface. The main inconveniences of these analytical methods are as follows: (1) obtaining the analytical equation of any simple load case requires many efforts. (2) The analysis is complex and costly to apply and is limited to some particular load cases and their combinations. (3) The effects of the actual non-continuous shear struts cannot be studied. For all these reasons, the analytical approach is far from being suitable for practical design [33]. Alternatively, numerical methods have propitiated the development

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of approximated analysis procedures that are more suitable for practical design than analytical equations. Examples of approximated methods can be found in the literature (see e.g. [21], [30], [19], [26]). Among these procedures, it is to highlight the finite element model simulation. This issue has received considerable attention in the last years.

A major concern of the simulation of composite beams by finite element model (FEM) analysis lays on the model dimensionality. Many researches (such as [7], [27] or [4]) have proved that one-dimensional finite element models can be used to simulate satisfactorily the global behavior of composite beams. Nevertheless, these are not adequate to simulate the local responses, such as the distribution of stresses in concrete and steel components and in their interface. This limitation made research focus on 2D and 3D models to simulate the behavior of composite beams (see e.g. [16]). On the one hand, 3D models are especially adequate for accurate simulation of local aspects of composite structures. An example of their application is to define an accurate distribution of stresses at discontinuity sections. Nevertheless, according to Queiroz et al. [23,24] the numerical convergence problem and the large computation times of these models discourage its use for complex structural systems. Although the recent development of adequate software, such as ABAQUS/explicit (see e.g. [20,31]), has improved considerably the convergence, and therefore, the applicability of the 3D models, many authors agree that 2D models might still be preferred for practical design work. A detailed review of some of the main 2D and 3D models presented since the eighties is presented by Titoum et al. [32]. Many authors (see e.g. [22]), have presented shell element models using springs to simulate the behavior of the connection. These models might be very accurate. In fact, they are able to simulate local effects, such as patch loading or web buckling, including shear deformation. Nevertheless, the accuracy of the shell element models is associated with two problems: (1) the results of these models cannot be directly used in design, as integration of stresses is required; and (2) especially in large scale structures, shell element models might result more computationally challenging than beam element models. Because of these problems, beam element models might be preferred as they provide relatively accurate results to be used in design with lower computational effort. Furthermore, shear deformation can be included. One of the methods based on 2D simulation by linear frame elements is presented in [23,24]. In this method, the concrete–steel interface is simulated by discrete nonlinear springs located at the concrete centroid.

This paper aims to provide a structured approach to the simulation of the partial interaction behavior using simple finite element software. To do so, a model uniquely composed of beam elements is proposed. This model directly provides useful information for the design work without the need of stress integration. To do so, it proposes a two-dimensional finite element model to analyze the behavior of composite beams with partial interaction and arbitrary boundary and loading conditions. In this model, the different elements of the composite beams are modeled by six different types of frame elements (concrete slab, steel beam, vertical struts, spring shear connector elements and elements representing concrete thickness and steel thickness). Compared with the analytical equations presented in the literature, the main advantages of the proposed model are as follows: (1) intuitiveness, as each of the elements of the model presents a close and easy to understand relation with the structural behavior of composite beams; (2) applicability, as the method directly provides useful information (such as forces in steel beam and concrete slab, shear connector forces or beam deflections) for the design work; (3) versatility and generalization in dealing with any combination of loading and boundary conditions. The proposed model enables the analysis of statically indeterminate structures, tapered beams, frames as well as structures with non-uniform shear connector distributions. Furthermore, this model might be easily modified to deal with 3D structures and nonlinear behavior of concrete slab, steel beam and shear connectors. (4) As the models include sequences of repetitive elements, they can be easily elaborated by simple preprocessing algorithms. And (5) as the model only includes frame elements, the model behavior can be easily reproduced by simple structural software.

The paper is organized as follows. In Section 2, the analytical equations presented in the literature to define the behavior of simply supported composite beams under different loading cases are reviewed. In Section 3, the main characteristics of each of the elements of the proposed frame model are described in detail. In Section 4, the numerical application of the model to two different examples (a simply supported and a continuous composite beam) is presented. To validate the accuracy and the efficiency of the proposed model, this section includes different FEMs verified against the results of the analytical equations. In this analysis, the effects of the connection stiffness and the geometrical and mechanical properties of the beam elements are also studied. Finally, some conclusions are drawn in Section 5.

2. Composite beams with partial shear interaction: analytical approach

The analytical equations of composite constant depth simply supported beams with partial interaction under simple load cases can be found in [2] (Eqs. (1)–(4)). In this procedure, the equilibrium equations of the composite beam are reduced to second order differential equations from which analytical results can be obtained. These equations are based on the following assumptions: (1) the shear connectors, as well as concrete and steel, behave linearly. (2) Concrete slab and steel beam have the same curvature (and same rotation) throughout the length of the composite beam. (3) Frictional effects and uplift at the concrete–steel interface are neglected. And (4) the discrete shear connectors at the concrete–steel interface are uniform throughout the length composite beam. With k_q being the connector stiffness under shear force, s_q being the shear connector longitudinal spacing and n_q being the number of shear struts in every row separated s_q, the distributed constant stiffness of the shear connections throughout the beam is assumed as $K_q = (n_q \cdot k_q) / s_q$. These parameters are illustrated in Fig. 1.A.

As an example of the results of the analytical approach, the analytical equations for concrete slab axial forces at cross section x, $N_c(x)$, for different loading cases are presented as follows:

$$N_{c,Q}(x) = \frac{-M(x)}{a_{cr}} \cdot \psi_Q = \frac{-M(x)}{a_{cr}} \times \left(1 - \frac{ch\left(\frac{l}{2 \cdot x_q}\right) - ch\left(\frac{l}{2 \cdot x_q} - \frac{x}{x_q}\right)}{\frac{x}{x_q} \cdot \frac{(l-x)}{x_q} \cdot ch\left(\frac{l}{2 \cdot x_q}\right)}\right) \tag{1}$$

$$N_{c,q}(x) = \frac{-M(x)}{a_{cr}} \cdot \psi_q = \frac{-M(x)}{a_{cr}} \cdot \left(1 - \frac{x}{x_q} \cdot \frac{sh\left(\frac{x}{x_q}\right)}{ch\left(\frac{l}{x_q}\right)}\right) \tag{2}$$

$$N_{c,M}(x) = \frac{-Mext \cdot x}{L \cdot a_{cr}} \cdot \psi_M = \frac{-Mext \cdot x}{L \cdot a_{cr}} \cdot \left(1 - \frac{sh\left(\frac{x}{x_q}\right)}{\frac{x}{l} \cdot sh\left(\frac{l}{x_q}\right)}\right) \tag{3}$$

$$N_{c,P}(x) = -\zeta_C \cdot P - \zeta_S \cdot P \cdot \xi_S = -\left(1 + \frac{A_s^2 \cdot h_{sc}^2}{A_R \cdot I_R}\right) \cdot \frac{A_{cR} \cdot P}{A_R} - \left(1 - \left(1 + \frac{A_s^2 \cdot h_{sc}^2}{A_R \cdot I_R}\right) \cdot \frac{A_{cR}}{A_R}\right) \cdot P \cdot \frac{ch\left(\frac{x}{x_q} - \frac{l}{2 \cdot x_q}\right)}{ch\left(\frac{l}{2 \cdot x_q}\right)} \tag{4}$$

in which $N_{C,Q}(x)$ is the axial force when a concentrated load Q is applied at mid-span, $N_{C,q}(x)$ is the axial force when a constant distributed