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Numerical procedure for nonlinear behavior analysis of composite slim floor beams

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ABSTRACT

A design procedure is developed for composite slim floor beams. Based on cross-sectional analysis, the flexural properties of the slim floor beams are evaluated in terms of the plastic and yield moment resistances. The moment–curvature/deflection models are proposed and are verified by the available test results of composite slim floor beams. The nonlinearities of materials and the composite action at the interface of the steel and concrete components are considered in the prediction of the nonlinear behavior of the beams. Parametric studies are conducted to investigate the likely influences of material strengths and various geometric properties on the performance of the beams. The design procedures developed herein are validated by comparing the existing test results presented in literature. The computational results are found to agree well in both the elastic and plastic ranges, as compared with the test results.

1. Introduction

Composite slim floor system has been used successfully throughout the world and especially in Europe since it is able to provide floor systems with a minimum constructional depth. Composite slim floor is a generic term used to describe a type of floor construction where the key feature is that the steel beam is contained within the slab depth, resulting in a flat appearance (Fig. 1), and it offers important benefits in terms of cost (long spanning capabilities without or with fewer secondary beams, shallow floor depth, inherent fire resistance, etc.) [1,2], as well as the advantages offered by ordinary down stand composite beam construction. Since its unique appearance and merits, composite slim floor systems have been used in many modern building projects such as commercial and residential buildings, hospitals, schools, etc. However, compared to other conventional steel and composite constructions, application of the composite slim floor has been limited in many countries by the lack of design specifications and practical analysis procedures.

Good understanding of the overall behavior of a composite slim floor is essential in its design practice. Computer-based methods available for composite construction have been recently reported by researchers. Several numerical methods have been proposed to predict the behavior of multi-layered composite beams. Based on the principle of virtual work, Ranzi et al. [3–5] proposed an analytical formulation for the analysis of generic multi-layered composite beams which were formed by n layers and interconnected by flexible interface connections between the adjacent layers. This method based on strong form of integration was used to derive algebraically the displacements. Moreover a curvature locking in n-layered finite elements was set in evidence. Karama [6] also presented a multi-layer laminated composite structure model to predict the mechanical behavior of multi-layered laminated composite structures. Regarding the structure's moment–curvature behavior prediction, several methods were also reported by Lui and Chen [7], Poggi and Zandonini [8], Goto and Chen [9,10]. However, most methods involved either a complicated mathematical formulation or versatility for design purposes. Furthermore, some proposed methods would require cumbersome numerical calculations to ensure a convergence in the solution. Some studies regarding the prediction of moment–rotation curves for connection were experimentally and theoretically investigated and linear, bilinear and exponential models were proposed and used [11]. Uy and Bradford [12] proposed a straightforward method to predict the moment–curvature relation of profiled composite beams using the nonlinear stress–strain relation of materials. However, the proposed moment–curvature relation was not expressed in a simple formula to trace the nonlinear load-deformation behavior of composite beams. Ge and Usami also presented simple formulas for the moment–thrust–curvature relationship of the composite columns and the method was later used in a study of concrete-filled steel box columns [13].

In this paper, a simple design procedure is developed to predict the flexural strength of a composite slim floor beam. Also, based on the moment–rotation formulas reported by Ge and Usami [13] for the composite box columns and that proposed by Kishi and Chen [14] for the moment–rotation prediction for a column-to-beam connection, a semi-analytical method is proposed to predict the nonlinear moment–curvature and moment–deflection curve of composite slim floor

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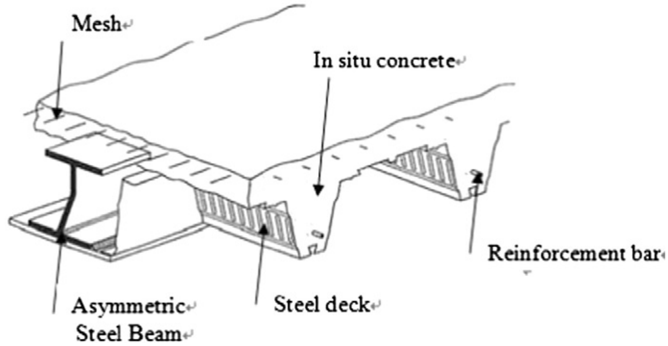

Fig. 1. Slim floor system configuration.

beams. The method developed in this paper is capable of performing the following: 1) analysis of a composite slim floor beam by estimating the flexural capacities of the beam taking into account the effect of composite action between the steel beam and concrete slab; 2) refined beam non-linear analysis to predict both the moment–curvature and moment–deflection of a composite slim floor beam.

The proposed methods are validated by comparing the computational results with the available test results. A parametric study is conducted to investigate the likely influences of the various materials and geometric properties on the performance of this new form of composite construction.

2. Research significance

Important information are obtained from experimental investigations on composite slim floor beam systems; however, researchers and designers are still looking for simple and accurate analysis methods capable of evaluating the behavior of a full-scale composite beam. This need is more pronounced due to the high cost of structural tests and finite element analysis simulations. Extensive and accurate computational methods are presented in this paper to gain insight into the flexural behavior of a composite slim floor beam in order to overcome the problems encountered by researchers and designers.

3. Flexural capacity of composite slim floor beam

3.1. Fundamental assumptions

Consider a slim floor beam section shown in Fig. 2, which is composed of a steel beam section, a profiled steel decking, and concrete. The length of the perimeter of the interface between the concrete and steel beam section (the bond interface length) is denoted by C; while the effective length from the support to the design section, required to ensure the full bond strength is denoted by L_{eff}. Other geometric parameters are illustrated in Fig. 2.

The assumptions are made based on the rigid plastic analysis that at the ultimate state, the steel beam is fully yielded, and the concrete in compression develops its full compressive strength f_c, while the concrete in tension is not considered. The effects of profiled steel decking and the reinforcing bars above the steel beam are also not taken into account here. The longitudinal shear bond at the interface of the concrete and steel beam is assumed to be at its maximum value notated as τ_{yb}. Therefore, the maximum bond strength at the interface in the region of the effective length L_{eff} is obtained by:

$$P_b = \tau_{yb} C L_{eff}. \quad (1)$$

According to the previous research results and the international design recommendations (Eurocode 4 (ENV 1994-1-1) [15], BSI 5950 [16], Jeong et al. [17], Chen et al. [18]), the shear strength at the interface of concrete and steel beam ranges from 0.1 to 0.8 N/mm^2.

3.2. Partial and full shear connection analysis

Considering the section shown in Fig. 2, the flexural strength of the composite beam can be derived by equilibrium of the stress and force distributed over the composite section (concrete and steel). The general composite mechanism of a beam section is described in two main steps: the full shear connection (FSC) and the partial shear connection (PSC).

Initially, when a load is first applied on the beam, the same strain distribution occurs over the concrete slab section as well as over the steel section as shown in Fig. 3(c). At this stage the beam is said to behave as a full composite beam, and there is no slip across the steel beam-concrete slab interface. The available bond strength across the interface is sufficient to prevent slip occurring and ensures that the neutral axis in the concrete slab section (y_c) is coincident with the neutral axis in the steel beam section (y_s): $y = y_c = y_s$.

As the load exerted on the beam increases, the curvature as well as the shear stress at the interface will increase. If the beam is capable of developing the full plastic moment, the beam is a full composite beam. In this case, the beam should exhibit a full shear interaction, and the interface bond strength is sufficient to resist the interface bond force.

In the case when the resulting bond force at the interface exceeds the available interface bond strength, slip will occur at the interface between the concrete slab and steel beam, and there will appear two neutral axes in the strain distribution over the cross section as shown in Fig. 3(d). Then the composite section is said to exhibit partial interaction or partial shear connection. Although the neutral axis depth y_c for the concrete slab is different from the neutral axis depth y_s for the steel beam section, the curvature of the concrete element (φ_c) should be equal to that of the steel beam section (φ_s), since no uplift separation occurs in the beam. This concept will be used in predicting the moment–curvature in next section.

The equilibrium method is used to determine the depth of the plastic neutral axis (P.N.A.). It is assumed that the depth of the plastic neutral

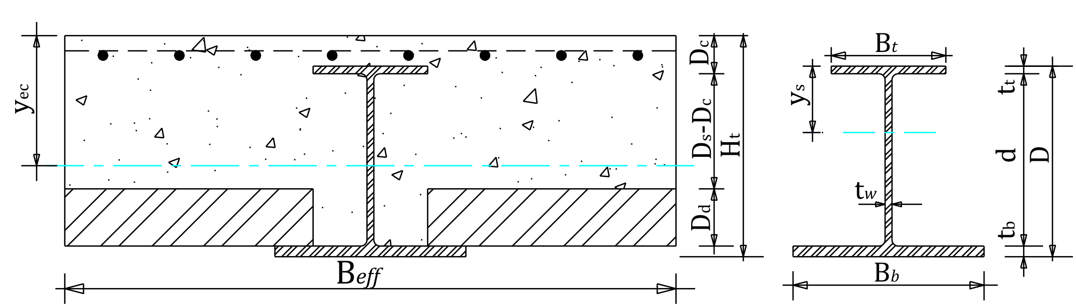

Fig. 2. Slim floor beam section.