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Effective shear connection for shallow cellular composite floor beams

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ABSTRACT

Shallow cellular composite floor beam is a new type of composite floor beam that usually consists of a structural steel beam with regularly spaced web openings and concrete slab casted above the steel decking. In this study, the shear transferring mechanisms of shallow cellular composite beams design with innovative shear connection systems are investigated. A detailed finite element analysis program was performed to investigate the force transferring mechanism, load bearing capacity and failure behavior of the shear connections under direct longitudinal shear forces by simulating the push-out tests. Four different configurations of shear connections (web opening configurations) were designed and an intensive parametric study was conducted to determine the material and geometric parameters that likely influence the behavior of the shear connection. Finally, the findings from this investigation are incorporated with the bending and push-out test results to develop design methods for this form of shear connection. The failure mechanisms of the shear connection were confirmed, and it was also revealed that this type of shear connection is effectively capable to provide the desired shear resistance and ductile behavior if designed properly.

1. Introduction

The increasing demand of long span beams and shallow floor depth had led to the development of various slim floor systems such as Slimflor, Slimdek, Asymmetric Slimflor Beam (ASB) and Ultra Shallow Floor Beam, being used in commercial and residential buildings, hospitals, schools, etc.… The slim floor system usually is composed of profiled steel decking, an embedded steel beam and the concrete slab, resulting in a flat appearance of the floor (Fig. 1) and it offers important benefits in terms of features such as long spanning without or with fewer secondary beams, shallow floor depth, inherent fire resistance, etc.… (Lawson et al. [1–3], Hicks et al. [4]), as well as others advantages offered by the conventional composite beams. The use of composite slim floor systems requires comprehension of the behavior of all structural components, among which the shear transfer between the steel beam and concrete slab that enables a composite action is one important aspect in design of the composite slim floor systems.

The composite slim floor systems have been studied in terms of the integrated composite beam (Lawson et al. [1–2]; Mullet et al. [5–7]; Wang et al. [8]) and several experimental studies were conducted in the last decades. However, the roles that shear connections and shear transfer mechanism play in the overall behavior of the composite slim floor system are not yet well understood. In ordinary slim floor beams such as Slimfloor, Slimdek and ASB, the shear transfer is only assumed providing by the bonding effect at the interface between the concrete and steel beam. This adhesion based bond strength is found very limited and is prone to shear failure under small load. To enable a ductile behavior, it is essential to increase and assure an effective interaction between the two elements. Therefore, an enhanced form of slim floor beam called the shallow cellular composite floor beam which consists of a row of regularly spaced web openings perforated in the encased steel web was proposed. Shallow Cellular composite floor beam (SCCFB) is a generic term used for this type of composite floor construction where the key feature is that the steel beam with regularly spaced web openings is contained within the concrete slab.

Two configurations of the shear connection are designed representing different web opening geometries: the "circular opening" and the "clothoidal opening". A series of push-out tests on the circular opening shear connection configuration were performed by Huo and D'Mello [9], while the circular and clothoidal openings shear connections configurations were also investigated through a series of flexural bending tests by Chen et al. [10]. Based on these previous investigations, an explicit finite element analysis was conducted to study the distinct behavior of the shear connection, and four different web opening configurations were designed and investigated by simulating the push-out test. The experimental and FE simulations results were all analyzed in terms of the load bearing capacity, failure behavior and longitudinal force transfer mechanism of the shear connections. It aims to develop the design procedure for the longitudinal shear resisting capacity of the shear connection configuration.

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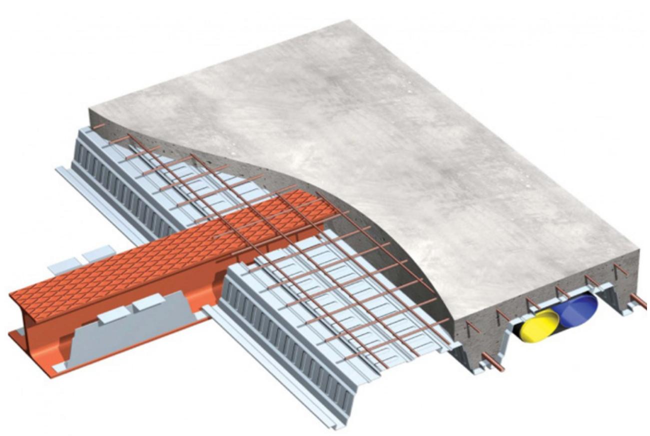

(a) Ordinary Slim Floor configuration

(b) SCCFB with decking configuration

Fig. 1. Configurations of different slim floor system construction.

2. The innovative shear connection system

2.1. Structural configuration

Shear connection in steel-concrete composite construction is defined as an interconnecting element set between the steel and concrete of a composite structural member. To enable effective composite action, the shear connection should have sufficient strength and stiffness. In this study, the shear connection is formed by combining the cast-in-place concrete (the infill concrete element) passing through the openings with a reinforcing bar (tie-bar element). The generic form of the shear connection system is depicted in Fig. 2. Two configurations of the shear connections are designed representing different web opening geometries namely the "circular opening" shear connection and the "clothoidal opening" shear connection. The circular opening shear connection is set for an "asymmetric I section" steel beam, while the clothoidal opening shear connection is set for an "inverted T section" steel beam. The schematic configuration of the two shear connections is shown in Fig. 3.

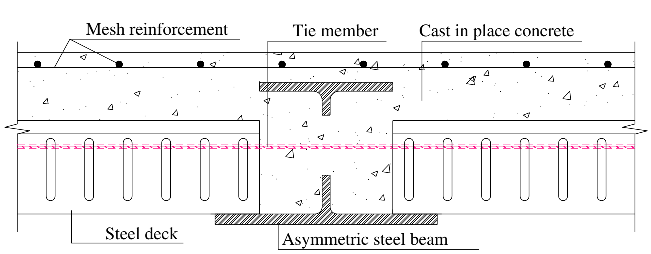

Fig. 2. Typical arrangement of shear connection with circular opening in shallow cellular composite floor beam.

2.2. Shear transfer mechanism

Different from the conventional shear connections in down-stand composite beams, in this SCCFB shear connection, the concrete completely fills the steel web openings and the force flow interacts between the steel web and the infill concrete. As the steel element is embedded within the concrete, the major part of the shear connection is activated by a combination of the infill concrete and the steel tie-bars. The shear bond at the interface between the steel beam and the concrete slab also contributes to the shear transfer mechanism within the SCCFB. The force transfer between different components and the mechanism of the composite action can be interpreted as: at the initial loading, the adhesion, the friction and the local compression are all activated at the contact zone of the connection system. The encased steel beam is subject to a longitudinal shear inducing bending and shear stresses in the section. With the load increasing, the shear resistance capacity of the concrete element passing through the opening will be reached, and large amount of slip would occur at the interface between the steel beam and the concrete slab, accompanying with initiation of cracks within the infill concrete. At this stage, the reinforcing tie-bars embedded in the infill concrete will contribute to improve the post-cracking behavior of the shear connection. As the load continues increasing meanwhile the concrete crushing continues, the tensile forces provided by the tie-bar elements will penetrate the cracks and increase the bearing capacity of the shear connection. When the load further continues increasing, cracks will also spread out in the infill concrete as well as in the concrete slab and redistribution of the internal forces will occur among the steel section member, the confined concrete and the steel reinforcing tie-bar (Fig. 4). To enable the desired bearing capacity and the ductile behavior of the shear connection, the presence of the tie-bar element would be very critical, and it enables the infill concrete element to carry the resulting tensile forces within the shear connection. Without the tie-bar elements, the shear connection would exhibit a brittle failure. Compared to headed shear studs, this type of shear connection is also an integral part of the composite beam, and it results in a complex superposition of the internal forces and shear bond stress in the system.

3. Finite element modeling

3.1. Geometric modeling

The finite element analysis study presented herein is based on the push-out test presented by Huo and D'Mello [9] and the bending test presented by Chen et al. [10]. The purpose is to develop accurate and reliable FE models in simulation of the push-out performance of the "concrete plug with tie-bar" shear connection in a composite slim floor beam. The FE models were established using ANSYS, considering all aspects that would likely influence the accuracy of the investigation (material properties; appropriate selection of element type and mesh size; appropriate set of boundary conditions and load; rational setting of analysis procedures; etc.). The generated FE models were first validated against the reference test results. The push-out test specimens [9] all consist of a steel section element and a concrete slab. The steel section element is a short universal column (254 × 254 × 73 UC) with three circular opening of 150 mm in diameter, spacing at 75 mm as shown in Fig. 5. The width of the concrete slab is 1000 mm and the two parts of the concrete slab on both sides of the steel section are connected by the infill concrete passing through the openings.

As the specimen has symmetric planes, only a half of the specimen is numerically modeled in this study with appropriate symmetry boundary conditions. Also, to save the computing time and cost, only one