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Finite element modelling of steel–concrete composite beams with high-strength friction-grip bolt shear connectors

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A B S T R A C T

High-strength friction-grip bolts (HSFGBs), that can be easily unbolted during deconstruction and structural modification, are proposed as shear connectors between the steel beam and concrete slab of composite beams in lieu of conventional headed shear studs for which deconstruction is problematic. These beams are potential sustainable and recyclable element for modern construction, but research contributions on composite beams with HSFGB shear connectors are very limited. This paper develops a three-dimensional finite element model to investigate the structural behaviour of steel–concrete composite beams with HSFGB shear connectors. Material non-linearities and the interaction of structural components are included in the model. Quasi-static finite element analysis using the dynamic explicit procedure is adopted for the analysis. The accuracy and reliability of the proposed finite element model are validated by comparing their results with available experimental results. An example is contrived to elucidate the typical mechanical performance of the composite beam, which the finite element study shows is different to that normally encountered in composite beams with headed stud connectors. Parametric studies are presented to quantify the effects of the change in the bolt spacing, diameter of hole, bolt pretension and the longitudinal reinforcement on the behaviour of the beam, so that usable design rules may be crafted.

1. Introduction

Many new medium-sized office building structures in urban environments have a somewhat short structural lifespan, because of changes of land use, increases in land value and the like. With composite steel–concrete structural systems being popular in constructing such medium-sized office buildings, deconstruction and re-use in deference to demolition is very difficult because the headed stud shear connectors welded to the top flange of the steel beam and embedded in the cast *in situ* concrete slab in the composite flooring system cannot be detached easily, rendering their reuse virtually impossible [1]. As an alternative, high-strength friction-grip bolts (HSFGBs) as shown in Fig. 1 are proposed as shear connectors between the steel beam and concrete slab of a composite beam to replace conventional headed shear studs. The advantages of HSFGB shear connectors are that they can be used to connect precast concrete slabs and steel girders during construction and they can be unbolted to deconstruct the building at the end of its service life and to recycle or reuse its components in preference to expensive and environmentally-disagreeable demolition [2,3]. The use of this type of shear connector can also be an effective approach for the rehabilitation and strengthening of existing non-composite structures such as bridges [4]. Despite its attractiveness, little research can be found in the open literature on the behaviour of steel–concrete composite beams with HSFGB shear connectors.

In the early 1970s, Marshall et al. [5] conducted an experimental study of the use of the HSFGBs as shear connectors in steel–concrete composite construction. More recently, Kwon et al. [4] investigated the behaviour of non-composite bridge beams strengthened by the use of post-installed shear connectors, while Liu et al. [6] presented numerical and experimental results that addressed the ultimate strength and the load-slip characteristics of HSFGB shear connectors in a proposed new sustainable composite beam. Pavlović et al. [7] also reported recent tests and analyses of push-out specimens using bolted shear connectors.

To avoid the significant monetary expense and testing time required for conducting full-scale experiments, computational

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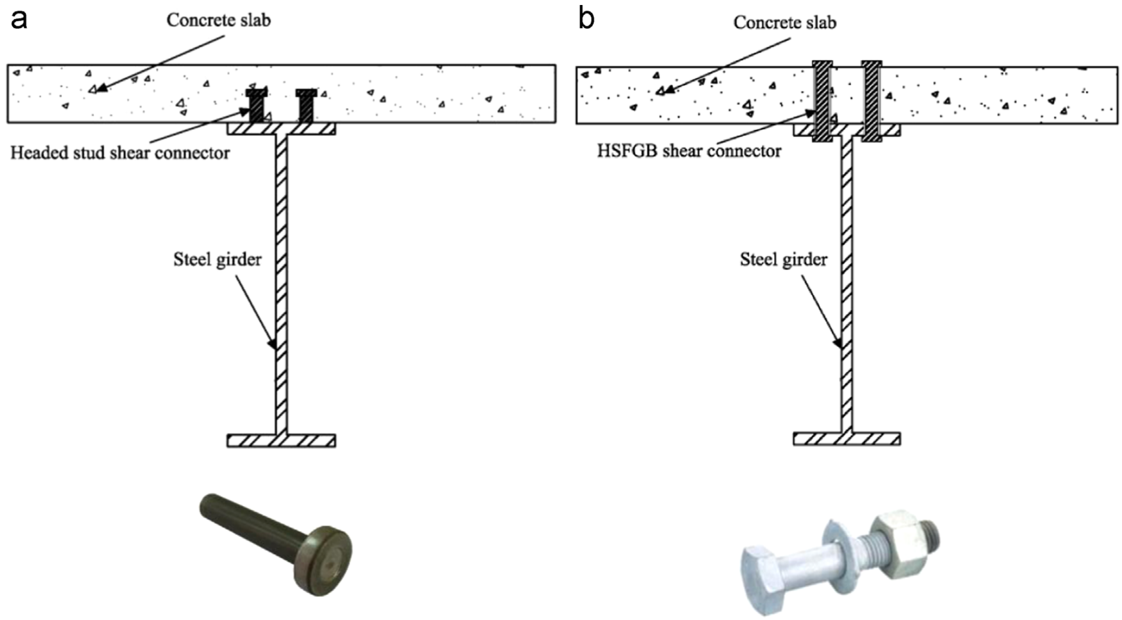

Fig. 1. Cross-sections of composite beams with different shear connectors: (a) headed stud shear connectors and (b) HSFGB shear connectors.

techniques have proven to be a highly effective alternative to study the structural response of composite beams. A comprehensive state of the art review on analytical and numerical formulations for the analysis of composite beams was presented ten years ago by Spacone and El-Tawil [8]. In the last decade, as a result of the enhancement in computer and software technology that allows complicated computational models to run faster and to post-process more easily than in the past, three-dimensional finite element models have attracted an increasing amount of attention from researchers. These three-dimensional finite element models are able to provide specific insight into the behaviour of composite beams, such as the stress and strain states under the composite action and the relative movement at the steel–concrete interface, some of which are difficult or even impossible to be completely observed in physical experiments, with this information being needed to contrive more efficient structural yet safe design guidance. Some of the initial work on three-dimensional finite element modelling of steel–concrete composite beams was reported by Thevendran et al. [9], Baskar et al. [10], El-Lobody and Lam [11] and Liang et al. [12], which discussed the modelling considerations involved in this kind of approach. Queiroz et al. [13] proposed a finite element model on the evaluation of full and partial shear connection in composite beams, while Vasdravellis et al. [14,15] simulated the non-linear response of a composite beam to investigate the effects of axial tension and compression on the flexural behaviour of the beam. Recently, for further improvement, more specific three-dimensional finite element models were presented by Tan and Uy [16] and Tahmasebinia et al. [17] to investigate the behaviour of a composite beam subjected to torsion and of a composite beam with steel trapezoidal decking, respectively. Such models tend to represent the shear connectors with three dimensional solid elements based on their material and geometric properties, thus the experimental results obtained from the push-out tests were not required [18].

The main objective of this paper is to propose an accurate three-dimensional finite element model to investigate the behaviour of a simply supported composite beam with HSFGB shear connectors, which can lead to contriving specific design guidance for this application. The geometric and material non-linear behaviour of all the components are taken into consideration in the modelling. The finite element model is verified by comparing its results with experimental results available in the literature. The validated procedure is then used to study the typical full-range load–deflection response, failure mode, relative slip between the concrete slab and the steel beam and the strain distribution in a composite beam subjected to either uniformly distributed or concentrated loads. Parametric studies are then performed to investigate the effects of the variation in the bolt spacing, diameter of the clearance hole, bolt pretension and the configuration of the longitudinal reinforcement on the behaviour of the beam.

2. Finite element model

A three-dimensional finite element model was developed using the commercial software ABAQUS [19], in order to simulate the behaviour of a steel–concrete composite beam with HSFGB shear connectors. The pertinent components include the concrete slab, steel beam, steel reinforcement and HSFGB shear connectors with washers. Both geometric and material non-linearity was considered in the finite element analysis. Formulations of the model geometry, element types, material behaviour and the solution technique are challenging, and detailed descriptions are outlined in the following sub-sections.

2.1. Finite element mesh

Overviews of the finite element model developed in this study are provided in Fig. 2(a) and (b), together with the relevant coordinate system in which the *X* and *Z* axes define the cross-sectional plane and the longitudinal beam axis is denoted as the *Y*-axis. Because of the symmetry of the specimens and the loading condition, only one quarter of the composite beam was modelled. For the concrete slab, the steel beam and a shear connector, a three dimensional eight node element (C3D8R) with a linear approximation of displacement, reduced integration with hourglass control, eight nodes and three translational degrees of freedom was used. The stresses at various points throughout the thickness of the element are provided at each integration node. For the steel reinforcement, a three dimensional truss element (T3D2) with a linear approximation of displacement, two nodes and three translational degrees of freedom was adopted. No moments or