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Three-Dimensional Simulation of the Shear Properties of Steel–Concrete Composite Beams using an Interface Slip Model

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Abstract: A three-dimensional finite element (FE) and analytical approach for the simulation of the shear properties of steel–concrete composite beams are presented in this paper. To simulate the interfacial behavior between steel girders and concrete slabs, we apply an interface slip model in the simulation. This model has been used in analyzing the flexural properties of composite beams. Both simply supported beam and continuous composite beam experiments reported in literature are simulated. The load deflection and slip rule between steel girders and concrete slabs, as well as the crack pattern and contour at the ultimate load, are analyzed. The results obtained from the FE analysis agree well with the corresponding experimental results, indicating that FE analysis can be used to effectively simulate the shear properties of steel–concrete composite beams.

Keywords: Steel-concrete composite beams, Finite element method (FEM), Shear property, Three dimensional, Interface-slip.

1 Introduction

A steel–concrete composite beam is a new type of structure that is based on steel and concrete structures. The top flange of the steel girder is effectively connected to the reinforced concrete deck by means of a sufficient number of shear connectors to ensure composite action and coordinate deformation. Over the past several decades, a number of analytical works have been done to examine steel–concrete composite beams under flexure (Nie and Fan, 2002; He, Li, and Shang, 2010). In the applications, composite beams under loads are often subjected to the combined actions of bending and vertical shear. For shear properties, however, further research is still necessary to gain a better understanding of shear properties under negative moments (Ansourian, 1982).

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Numerical analysis methods have been used to analyze the inelastic behavior of composite beams. Razaqpur and Nofal (1989) formulated a three-dimensional (3D) bar element to model the shear connectors in composite beams. The stiffness properties of the bar element were defined by a shear-slip relationship derived from experimental data. Qiu and Jiang (2005) proposed a "double-deck" model using Timoshenko beam elements for concrete slabs and steel girders, between which nonlinear Truss elements were applied to connect concrete and steel elements as the shear connectors. Nie and Tang (2008) developed a 3D finite element (FE) model using the general-purpose FE software ABAQUS to investigate the strength of composite beams with compact steel sections under combined hogging bending and shear. However, the interface slip law and transfer mechanism on the interface were not clearly elucidated in these analyses.

This paper aims to present a 3D finite element method for nonlinear behavioral simulation of the shear properties of steel–concrete composite beams. An interface element with no volume is numerically applied, separating the steel girder and concrete slab to account for the effect of shear connectors.

2 FE analytical approach

The 3D FE software COM3D, based on the computation code COM3, was developed in the concrete laboratory at the University of Tokyo (Okamura and Maekawa, 1991; Maekawa, Pimanmas, and Okamura, 2003). The authors conducted 3D simulations of the flexural properties of the composite beams using this software. In the current work, the same analytical approach and the interface slip model are used to simulate the shear properties of composite beams.

3D solid elements are used to simulate both steel girders and concrete slabs. The von Mises elastic-plastic model with hardening is employed for the steel girder elements. The 3D multi-directional smeared-fixed crack approach and spatial average constitutive models are used to simulate the mean response of reinforced concrete between cracks under tension, compression, and shear force. The diameter of reinforcing bars in concrete is implicitly considered smeared in the slab element.

The interfacial element with zero thickness, consisting of master and slave faces, is employed and modeled, as shown in Figure 1. The master face shares four nodes with the steel girder element, whereas the slave face shares the other four with the concrete slab element. Initially, each slave node has the same coordinates as the corresponding master node. During computation, the departure of the slave face against the master face at a normal direction represents the opening of the interface, whereas that in the tangential direction simulates the slip. Details about the constitutive model of the interfacial element can be found in the reference (He, Li, and Shang, 2010).

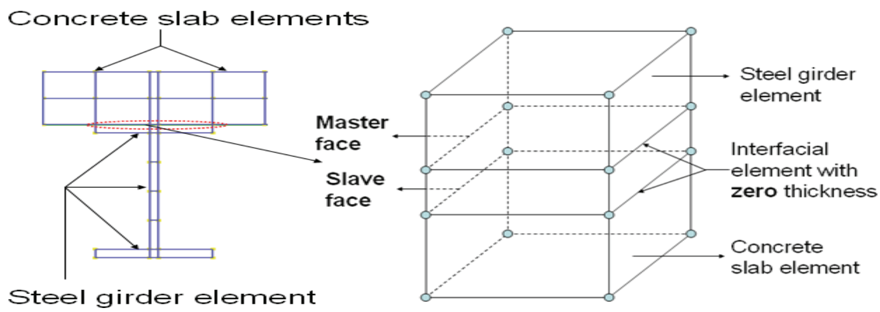

Figure 1: Interfacial elements

3 Simulation of the shear properties of composite beams under a positive moment zone

Four simply supported composite beams (CBS-9, CBS-10, CBS-11, CBS-12) with different shear–span ratios were tested for failure (Nie Xiao and Chen, 2004). The fracture morphology of this series of beams includes bending and shear failures, which respond better to the bending–shear properties. Four beams were chosen for the analysis using the proposed FE method.

The yield strengths of the flange, web, and steel bar are 273, 340, and 320 MPa. The concrete slab has a thickness of 100 mm and was reinforced with 8 mm (diameter) transverse steel. A 1/2 symmetrical FE model was constructed for the analysis. Figure 2 shows the mesh discretization and features of the composite beam. The parameters of the specimen are shown in Table 2.

Table 1: Material properties used in the analysis

Composite beam	Shear-span ratio	a(mm)	L(mm)
CBS-9	1	320	2000
CBS-10	2	640	2000
CBS-11	3	960	3000
CBS-12	4	1280	3000

Figure 3 shows the comparison of the computed nonlinear load–deflection relationship and the experimental data. The proposed analytical approach well corresponds

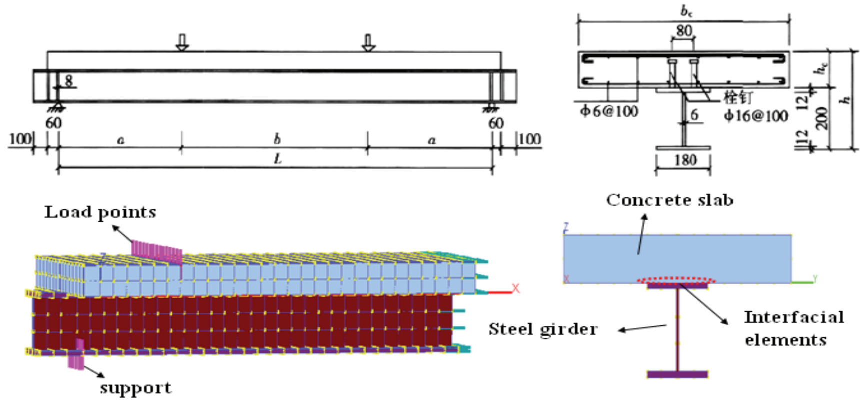

Figure 2: Features of the continuous beam and the 1/2 FE model

to the experimental data.

The crack pattern, displacement, and contour of beams CBS-9 and CBS-12 at the ultimate load are shown in Figure 4. For beam CBS-9, whose shear–span ratio is 1, the steel girder exhibits a yield strength in the principal tensile stress direction first, coupled with obvious shear deformation. The overlarge shear deformation of the steel girder causes the shear failure of the concrete slab. However, for beam CBS-12, whose shear–span ratio is 4, the concrete slab fails in the bend. The flange exhibits its yield strength under bending stress with no obvious shear deformation, whereas part of the web exhibits its yield strength.

4 Simulation of the shear properties of composite beams under a negative moment zone

The proposed FE model was used to analyze the shear properties under a negative moment zone (SCB-7), following the simulation of a simply supported composite beam conducted by Xue, Cheng, Zhao, and Fu (2008). The concrete slab has a thickness of 100 mm, reinforced with 10 mm (diameter) longitudinal bars and a 6.5 mm (diameter) stirrup with 100 mm special distance. The modulus of elasticity and compressive strength of concrete are 33.52 GPa and 44.3 MPa, respectively. The yield strength of reinforcement is 335 MPa. The features of the composite beam and the 1/2 FE model of the beam are shown in Figure 5.

Figure 6 shows the comparison of the computed nonlinear shear force-deflection relationship with the experimental data. The FEM results show good agreement with the experimental findings.

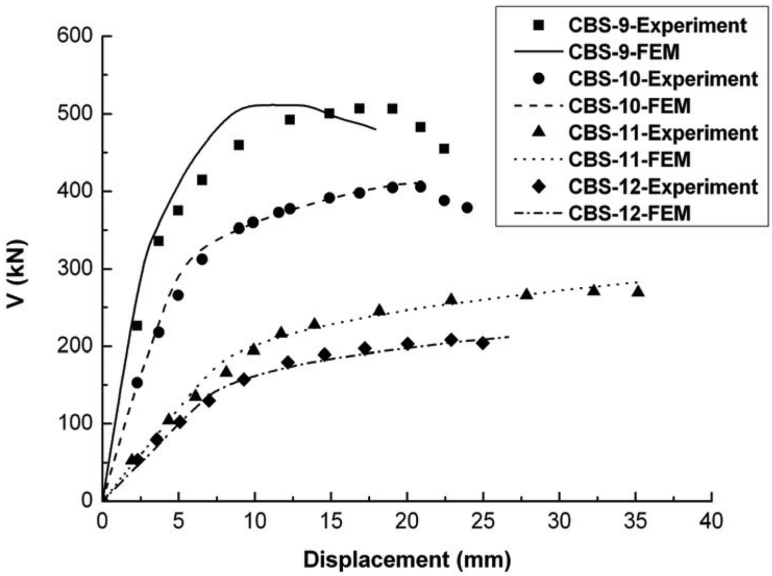

Figure 3: Load-deflection curve

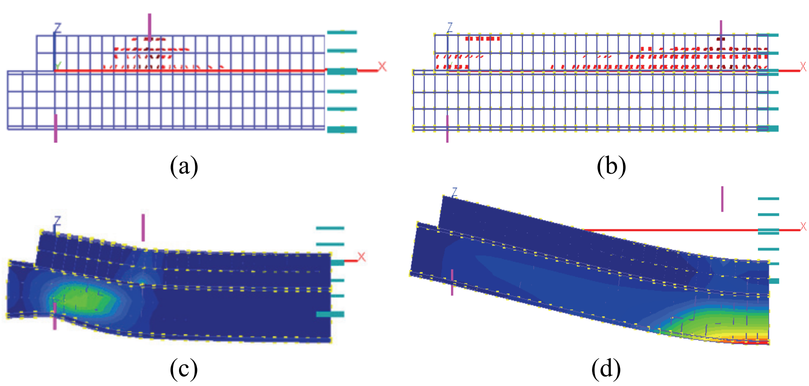

Figure 4: Crack pattern at the ultimate load (a): CBS-9 (b): CBS-12 displacement and contour at the ultimate load (c) : CBS-9 (d): CBS-12

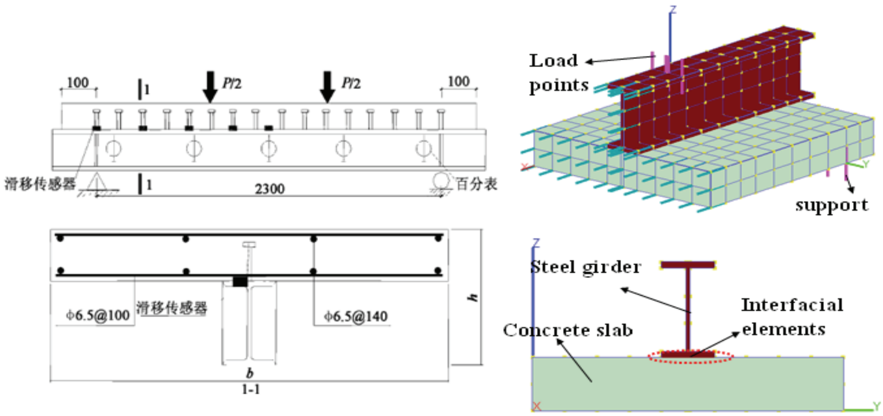

Figure 5: Features of the composite beam and the 1/2 FE model

The shear force–slip curve of the composite beam predicted using the FE model is compared with the corresponding experimental data in Figure 7. The interface slip distribution law of the composite beams under the negative moment zone differs from that under the positive moment zone. The non-uniform stiffness and low tensile strength of concrete may cause a change in the interfacial slip direction. Good prediction can be achieved using the proposed FE analysis. Figure 8 shows the crack pattern at the ultimate load of the composite beam. The comparison between the FE analysis using the interface slip model and the experiment shows good agreement.

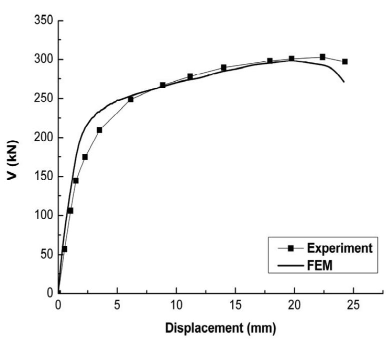

Figure 6: Shear force-displacement curve

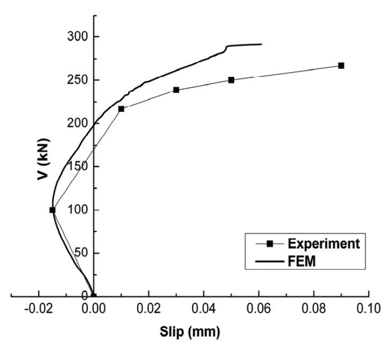

Figure 7: Shear force-slip curve

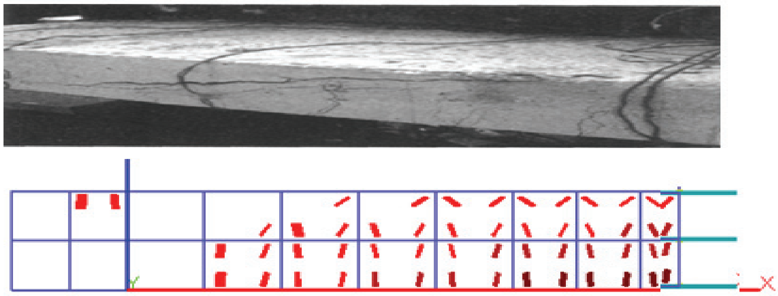

Figure 8: Crack pattern compared with the experimental results

5 Conclusions

The proposed FE method can better simulate the contribution of concrete slabs to the shear strength of steel–concrete composite beams. The model shows significant contribution from the slabs. The comparison of the load deflection curves obtained by FE analysis using the interface slip model and the experiment shows good agreement.

The results of the FE analysis, as well as the test conducted in the corresponding experiment, show that the shear–span ratio imposes a decisive influence on the failure mode of the testing beams. The transformation of the fracture morphology can be simulated using the proposed FE model.

The interface slip distribution law differ for the composite beams under positive and negative moment zones. Interfacial behavior can be simulated using the interface slip model. The load–slip curve obtained by FEM shows good agreement with the experimental data.

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