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Experimental investigation on hysteretic behavior of simply supported steel-concrete composite beam

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ABSTRACT

This study aimed to investigate the seismic behavior of simply supported steel–concrete composite I beam and box beam through a quasi-static experimental study. A total of 22 composite beams included in the experiments, and parameters including shear connection degree, transverse reinforcement ratio, longitudinal reinforcement ratio, section type, diameter of stud, and web thickness were investigated. Based on the test, hysteretic response, skeleton curves, failure mode, stiffness degradation, ductility, and energy dissipation were discussed. Results show the following: (1) Composite beams have favorable seismic performance, the displacement ductility ratio ranged from 2.5 to 8.75, whereas the maximum equivalent viscous damping ratio ranged from 0.219 to 0.470. (2) The higher the degree of shear connection, longitudinal reinforcement, and transverse reinforcement, the plumper the hysteretic curve and the greater the bearing and energy dissipation capacity. The ductility of composite beam increased as the longitudinal reinforcement ratio increased. The stiffness degradation and residual deformation were less effected by other parameters. (3) Findings suggest that the transverse reinforcement ratio ranged from 0.4% to 0.8%, the positive shear connection degree should be greater than 1, and the spacing of stud in the negative moment region should not be larger than that in the positive moment region. To ensure welding quality and convenient construction, a large diameter of stud should be applied in practical engineering. Moreover, when the girder is welded by a thin web, transverse diaphragm plate and vertical reinforced rib should be added in the steel girder if these areas are heavily loaded.

1. Introduction

Steel–concrete composite beams have been widely applied in engineering due to their small size, light weight, high bearing capacity, favorable seismic performance, and convenient construction [1–6]. Scholars from various countries have consistently studied composite beams and frames through experiments. Nie et al. [7] completed six low-cycle loading tests of steel–concrete composite beams to simulate their seismic performance in a negative moment region by considering the longitudinal reinforcement ratio and shear connection degree. Experimental index, such as ductility and stiffness reduction factor, was also discussed. Tappli et al. [8] conducted an experiment on the monotonic and repetitive loading of steel–concrete composite beams, and the results showed that the slip between steel girder and concrete slab increased considerably under repeated load than bear monotonic load. Xue et al. [9] studied the seismic performance of ordinary and pre-stressed composite beams and analyzed failure pattern, hysteresis curve, seismic ductility, energy dissipation, stiffness degradation, and displacement restoring capacity. The results manifested that pre-stressed steel–concrete composite beams also have good seismic performance.

In addition, Nie et al. [10] conducted 14 connections composed of concrete-filled square steel tubular columns and steel–concrete composite beams under low reversed cycle loading. In this study, node stress process, failure pattern, hysteresis curves, skeleton curves, displacement restoring capacity, ductility, rigidity degeneration, and energy dissipation on seismic performance were investigated. Vasdravellis et al. [11] completed four full-scale semi-rigid partial-strength steel–concrete composite beam-to-column joints in a pseudo-static experimental study. The results showed that the specimens have good energy dissipation capacity and ductility, but the stiffness and strength degradation situation were not evident. Bursi et al. [12,13] conducted six different degrees of shear connection of steel–concrete composite frame tests under static and quasi-static loads. The authors discussed the mechanical properties of the specimens including bearing capacity, ductility, and yield criterion under seismic loading. Their analyses revealed that composite frames with a low shear connection degree of approximately 0.4 have similar performance with frames that have full shear connection under severe seismic loads. Nonetheless, the shear connection degree should be sufficiently high to protect shear connectors in the central part of beams from failure.

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Test research on the hysteresis performance of composite beams mainly considered the effect of shear connection degree and longitudinal reinforcement ratio, but parameters including transverse reinforcement ratio, cross-section form, and web thickness are rarely studied. In addition, excessive studs used in engineering increased the difficulties of pouring concrete because of the adoption of a small-diameter stud in bridge engineering. Hence, conditions with the same shear connection degree of different stud diameters for construction conducive should be researched.

Therefore, this study aims to thoroughly investigate the seismic behavior of steel–concrete composite beams, based on the theoretical, numerical, and experimental research of our team [14–16]. Moreover, three objectives were included in this study:

(1) To investigate the seismic performance of 22 simply supported steel–concrete composite I and box beams through a pseudo-static experimental study;
(2) To analyze the effects of shear connection degree, transverse reinforcement ratio and longitudinal reinforcement ratio, stud diameter, cross-section form, and web thickness on the seismic performance of composite beams. The target performance included hysteresis curve, skeleton curve, stiffness degradation, ductility and bearing capacity, and energy dissipation of the composite beams;
(3) To recommend reasonable scopes of transverse reinforcement ratio and degree of shear connection for composite beams were recommended based on the test results.

2. Experimental study

2.1. Test introduction

A total of 22 simply supported steel–concrete composite I and box beams were included in the experimental study. The cross section of girder is shown in Fig. 1. Detailed geometric properties and characteristics of the specimens are presented in Table 1. l is the length of the specimen, w_c is the width of the concrete slab, h_c is the depth of the concrete, w_s is the width of the steel beam, h_s is the height of the steel beam, t_f is the thickness of the flange, t_w is the thickness of the web, d is the diameter of the stud, ρ_{st} is the ratio of the transverse reinforcement of concrete slab, ρ_{sl} is the ratio of the longitudinal reinforcement of concrete slab, $\eta+$ is the degree of shear connection in positive moment region, and $\eta-$ is the degree of shear connection in negative moment region (GB 50017-2003 [17]).

The calculation method of the degree of shear connection in the positive or negative moment region is defined, and the degree of shear connection in the positive moment region $\eta+$ is as follows:

$$\eta+ = n_+/n_{f+} \tag{1}$$

where n_+ is the actual number of shear connectors between intermediate point and the adjacent support and n_{f+} is the number of connectors for full shear connection. $n_{f+} = V_{s+} / V_{u+}$. V_{s+} is the entire horizontal shear at the interface between the steel beam and the concrete slab, which was taken as the lowest value according to the limit states of concrete crushing and tensile yielding of the steel section, that is, V_{s+} is the smaller of A_sf_s and A_cf_c. V_{u+} is the nominal strength of one stud shear connector. A_c is the area of concrete cross section, and A_s is the area of steel cross section. Stud shear bearing capacity can be determined by

$$V_u = 0.43A_{sd}(f_cE_c)^{0.5} \le 0.7A_{sd}f_u \tag{2}$$

where A_{sd} is the area of stud shear connector cross section, f_u is the ultimate strength of stud, f_c is the compressive strength of concrete, and E_c is the Young's modulus of concrete.

The degree of shear connection in the negative moment region $\eta-$ is defined as follows:

$$\eta_- = n_-/n_{f-} \tag{3}$$

where n_- is the actual number of shear connectors between the intermediate point and the adjacent support and n_{f-} is the number of

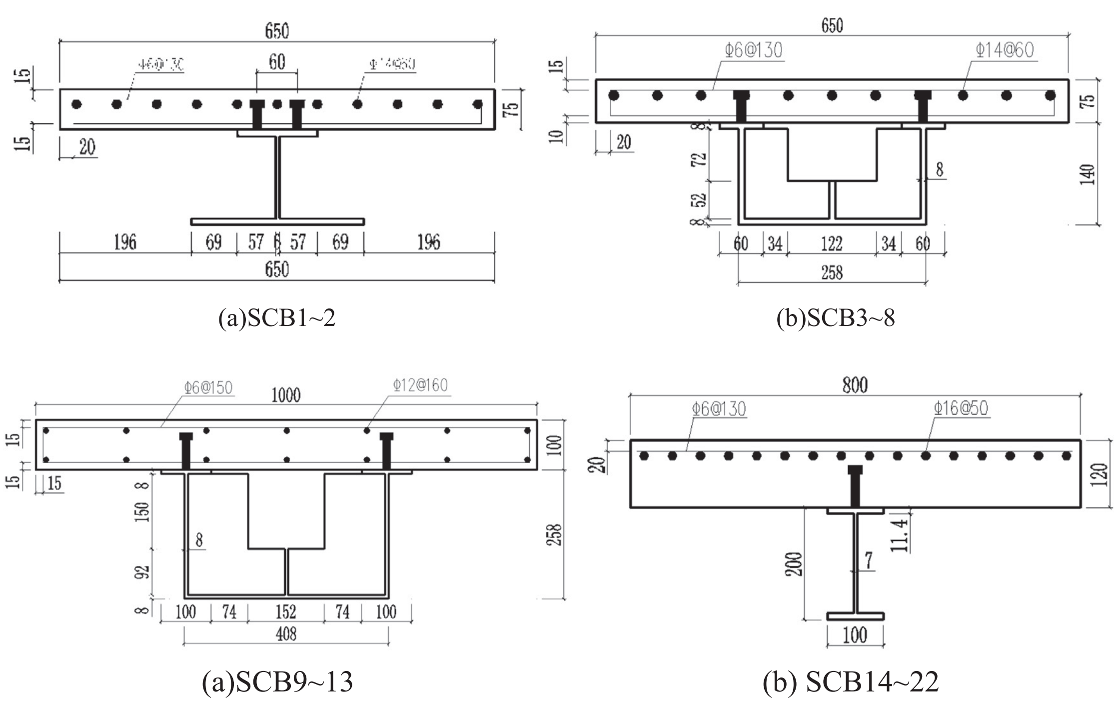

Fig. 1. Cross section details of the girder.