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Investigation of composite action on seismic performance of weak-axis column bending connections

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ABSTRACT

This paper presents a developed beam-to-column connection which is suitable for weak axis of I-section column and H-shaped beam. Ten cruciform joint specimens, including five bare steel joint specimens (SJ) and five composite joint specimens (CJ) reinforced with partial shear connection, were tested under reversal of loads to evaluate the effect of composite action on the developed weak-axis connections. The beam ends were designed with standard, RBS, cover-plate, taper flange, and welded haunch respectively. The experimental results are analyzed and the composite action is discussed based on the test data. Overall, most joints failed due to welding fracture at the conjunction of diaphragm, skin plate and beam-end flange. But relatively speaking, the composite specimens performed well and achieved the story drift ratios of 0.04 rad before experiencing 20% strength degradation because only slight strength degradation occurred in the composite joints compared to bare steel joints, thus the composite joints have a more stable bearing capacity. The test data clearly illustrate that the neutral axis shifted upward significantly under positive bending, resulting in larger strains on beam bottom flange. The reinforcing bars in concrete slab did not work well, but remained in elastic state. The slab slippage was negligible even in 50% degree partial shear connection. The welding quality is an important guarantee to avoid the brittle failure of the connections, and lamellar tearing resistant steel is suggested to be used in skin plate.

1. Introduction

In composite structures, different materials are expected to be arranged in an optimal geometric configuration in order to exploit the higher strength and stiffness of each material. Therefore, the composite structure widespread worldwide, in particular the high-rise buildings and long-span structures. In steel–concrete composite beams, steel beams work together with concrete slabs through shear connectors, in which composite floor slab acts as diaphragm and shear studs are provided to help transfer diaphragm loads to the steel moment frame, to laterally support the beams and to increase overall structural continuity. However, one of the reasons of premature failure in the Northridge earthquake is the presence of the composite slabs, leading to the upward shift of neutral axis then raising the strain demand on the beam bottom flange under the positive bending [1]. After the earthquake, the composite action on cyclic performance of steel moment connections was investigated by many researchers, but different findings, results and conclusions were made among different studies of different researchers. Relevant experimental studies conducted are briefly reviewed in the below.

Early research by Lee et al. [2] on the composite joint subassemblages revealed that the presence of a floor slab could increase the stiffness and strengths of the connection under positive bending, but this would diminish somewhat under the repeated loading. Then, Leon et al. [3] and Hajjar et al. [4] conducted experiments, including one bare steel and two composite full-scale exterior specimens, to study the composite action. The test results indicate that brittle failure occurred in all the bottom flanges of the tested connections, and the strains near the bottom flange of the specimens with the presence of a slab were several times larger than those near the top flange. Afterwards, Uang et al. [5] investigated the slab effect with only 12% of the full composite action on seismic performance through cyclic testing in order to study the effectiveness of using the reduced beam section (RBS) or welded triangular haunch for seismic rehabilitation of PN type connections. Test results showed that the composite slab only increased the beam positive flexural strength by about 10% and no strength increased for negative bending, and no negative effect of composite action was observed in this testing program. At the same period, Civjan et al. [6] conducted an experimental study using RBS or welded triangular haunch with approximately 25% fully composite action for seismic rehabilitation, which is parallel to the study by Uang et al. The test results indicated that with the presence of a composite slab, the strains of top flange were significantly reduced compared to the bare counterpart, while the strains of bottom flange were similar, and shear stud failures were observed in their testing program. Chen and Chao [7] studied the effect of composite action on seismic performance of steel moment connections with reduced beam section. It was reported that all the fractures occurred in

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the bottom flange due to the much larger strain demand on the bottom flange. This study indicated that the slab effect can be very detrimental to the bottom flange even in RBS connections when a composite action is very strong. Jones et al. [8] conducted an experimental study to investigate the effect of a slab on seismic performance of RBS moment connections. Notably, there were no studs welded within the reduced sections of the beams. In their testing program, there was no negative effect of composite action on the seismic performance, but a positive effect of stabilizing the beam against lateral torsional buckling was observed. Liew et al. [9] experimentally studied flush end plate connections with composite slabs. Crushing of concrete slab was the dominant failure mode that governed the ultimate moment capacities of the joints, and the joints were found to perform better when they are subjected to negative moment. Kim et al. [10] carried out a testing program to emphasize the influence of the composite slab with 100% composite action on connection behavior. The test results indicated that the slabs effect was detrimental to the seismic performance of moment connections. They reported that fracture in the beam bottom flange was notable in all composite specimens as the bottom flange strain of composite specimen was 4.4 times higher than that of bare steel counterpart under positive bending. Bursi et al. [11] focused their attention on the behavior of composite beams with full and partial shear connection. The study revealed that composite frames with a low shear connection degree of about 0.4 performed as well as their counterpart with full shear connection through experimental and numerical analysis. Nakashima et al. [12] presented an experimental study on a steel frame to examine the composite action. There was only a row of studs spacing 300 mm on the top flange of the beams. This study indicated that fracture occurred in the beam bottom flange, and pointed out that the effective width approximately equaled to the column width, similar to the conclusion of [9]. More recently, research by Lee et al. [13] exhibited that a significant upward shift of the neutral axis when subjected to positive bending using the pre-Northridge type connection with only 15% fully composite action. And the seismic performance was significantly improved when the joint specimen utilized the RBS and with details to minimize the composite action.

Although different findings, results, conclusions and suggestions were made from different studies depending on the details of beam-to-column connections and composite slabs, the following statements can be made from the above literature review. On one hand, it was consistently observed that when a composite action is very strong, composite effect is quite detrimental to seismic performance, causing a significant upward shift of the neutral axis under positive bending moments and leading to bottom flange strains several times larger than that of the top flange, and eventually resulting in premature fracture of the beam bottom flange [3,4,7,10]. On the other hand, when a composite action is not strong and connection modification of RBS, cover-plate, tapered beam flange, haunch or other scheme were used, little negative effects were observed due to composite action. Instead, the composite slab was beneficial to some extent for decreasing the lateral instability of the beams [5,6,8,11,13]. Based on all consider studies, it is possible to concluded that although composite slab effects on seismic performance depend on the details of beam-to-column connections and the composite action still remains hard to discern, the degree of composite action should be given the most careful consideration.

In China, it is usual practice to design them as fully composite. In this case, extensive shear studs must be provided to accomplish a full composite action according to a well-established design procedure [14–16], just like the past design and construction practice in Korea [13]. As the adoption of partial composite action in a practical seismic design is largely hampered by the paucity of experimental data, this paper aimed to experimentally evaluate the composite effect of the steel beam and floor slab with partial shear connection.

While substantially all the previous researches deal with steel moment connections for the strong-column axis, thus the other objective of this study was to evaluate the seismic behavior of weak axis column bending connections used in steel moment resisting frames. A monotonic experimental study was presented in the companion paper [17]. This paper presents an experimental study on weak-axis moment connections with reinforced concrete (RC) floor slab that was subjected to horizontal cyclic loading leading to very large deformations.

2. Experimental program

2.1. Test specimens

An experimental program was conducted to clarify the cyclic behavior of weak-axis moment connections with RC slabs in the Construction Structure & Earthquake Resistance Lab of Chang'an University. In this program, ten interior beam-to-column weak-axis connections were subjected to horizontal cyclic loading with reversal displacements. All specimens were designed and fabricated in pairs, where one specimen was bare steel joint and the other involved a concrete slab. For each pair of specimens, the detailing and experimental apparatus were exactly the same, with the only difference of the presence of a concrete slab. Therefore, half of the specimens had a concrete slab, denoted as CJ-1 to CJ-5 (where "CJ" refers to composite joints), and the other half are bare steel specimens, denoted as SJ-1 to SJ-5 (where "SJ" refers to steel joints). There were two parameters varied in the connections: the presence of a composite slab and the type of beam flange, as shown in Table 1.

Fig. 1 shows a configuration of the developed weak-axis connection specifics. The main feature of this connection is that there are two skin plates between the tips of I-section column flanges, parallel to the column web, thus forming a box-strengthened panel zone, similar to the additional plates of [18]. The extra cost for the developed weak-axis connection for I-shaped column is significantly minor compared to that of box column, but they have similar panel zone.

The characteristics of each specimen are as follows, and the details of the moment connection for each specimen are depicted in Fig. 2 based on the suggestion of [19]. Specimens SJ-1 and CJ-1 were standard joints, used as benchmarks for comparison with other joint specimens (see

Table 1
Summary of test specimens.

Specimen designation	Beam and column	Beam to column connection	The presence of RC floor slab
SJ-1	Beam: HN350 × 175 × 7 × 11	Standard	No
SJ-2	Column: HW350 × 350 × 12 × 19	RBS	No
SJ-3		Cover-plate ($t = 6$)	No
SJ-4		Taper flange ($t = 12$)	No
SJ-5		Welded haunch ($t = 12$)	No
CJ-1		Standard	Yes
CJ-2		RBS	Yes
CJ-3		Cover-plate ($t = 6$)	Yes
CJ-4		Taper flange ($t = 12$)	Yes
CJ-5		Welded haunch ($t = 12$)	Yes