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Experimental study on shear behavior of studs under monotonic and cyclic loadings

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ABSTRACT

In steel–concrete composite structures, studs are critical in the shear transfer between steel and concrete. A series of push-out tests were performed to investigate the shear behavior of studs in high-strength concrete subjected to monotonic and cyclic loadings. All studs were attached to steel flanges by groove fillet welding. The primary parameters analyzed in this study included the stud diameter, stud tensile strength, and load type. The failure modes, load-slip curves, shear capacities, shear slips, shear stiffness, ductility, and energy dissipation capacities of the studs were studied. The experimental results indicate that the shear capacities, shear stiffness, and shear slips increased significantly with the increase in stud diameter. The studs subjected to cyclic loading exhibited lower shear capacities and shear slips than those under monotonic loading. The reductions in shear capacity and shear slip increased approximately with the increase in stud diameter, i.e., 25%–58% and 56%–81%, respectively. From the results of this test and those of previous works, it is deduced that groove fillet welding increased the shear capacities of 16-mm-diameter studs under cyclic loading by approximately 65% with respect to the stud welding. Finally, two empirical formulas were proposed to estimate the ultimate shear capacities and equivalent shear stiffness of studs under cyclic loading to design the studs in steel–concrete composite structures during seismic events.

1. Introduction

The seismic capacity and ductility of the steel–concrete composite structural system rely on the shear transfer between steel and concrete, and studs are critical in the shear transfer between steel and concrete. Early studies investigated the shear capacities of the studs under monotonic loading through standard push-out tests and beam tests [1]. In bridge structures, steel–concrete composite beams were generally subjected to repeated loading and had attracted extensive attention from researchers regarding the high-cycle fatigue resistances of studs [2–5]. It was generally of specific interest to the number of load cycles up to the fatigue failure of a stud subjected to a certain percentage of the monotonic ultimate shear capacity with a certain load range, while the number of load cycles of a stud varied from thousands to millions in high-cycle fatigue life. The low-cycle fatigue resistance of a stud concerned the load approaching or exceeding the monotonic yield shear capacity, and the number of load cycles was <1000. A novel type of push-out test was employed to examine the shear behavior of studs subjected to low-cycle fatigue loading [6]. The experimental results indicated that the residual monotonic shear capacities and shear slips of the studs decreased by almost 10% and 30%, respectively, after a certain number of load cycles.

Natural cyclic loads such as earthquakes, sea ice, and sea waves can vary the bending moment signs in the steel–concrete composite structural sections. Thus, the studs at the interface between the steel and concrete would be subjected to fully reversed cyclic loading. Currently, results from the existing literatures on the shear behavior of studs indicated that the studs subjected to fully reversed cyclic loading exhibited lower shear capacities and ductility than those under monotonic loading. Bursi and Gramola [7] performed push-out tests of 16-mm-diameter studs with different boundary conditions and different load histories. The shear capacities of the studs under cyclic loading were significantly lower than those calculated by Eurocode 4 by 36% [8]. Zandonini and Bursi [9] subsequently investigated the shear behavior of 22-mm-diameter studs subjected to cyclic loading. Compared with 16-mm-diameter studs, the 22-mm-diameter studs exhibited a lower reduction (17%) in shear capacity under cyclic loading. Civjan and Singh [10] performed ten push-out tests of 13-mm-diameter studs under monotonic and cyclic loadings. The shear capacities under cyclic loading were compared with those calculated by the Load and Resistance Factor Design Specification for Structural Steel Building [11], and the reductions were above 40%. The authors conjectured that the

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low-cycle fatigues of the stud and the weld joint, as well as the accumulated damage of concrete during cyclic loading reduced the shear capacity of a stud. Saari et al. [12] investigated the shear behavior of 19-mm-diameter studs under monotonic and cyclic loadings with an axial tension in a specimen modeling an infill wall. The shear capacity of the stud under cyclic loading was 20% below that calculated by the aforementioned specification. Their results also indicated that axial tensile loading would further decrease the shear capacity of the stud under cyclic loading. Adrian and Ciutina [13] investigated the seismic performances of four types of shear connectors: stud (including 16-mm-diameter stud and 22-mm-diameter stud), angle profile, pre-perforated steel plate, and reinforcement anchor hook. Except the reinforcement anchor hook, the decreased magnitudes of shear capacities and shear slips for other shear connector types were significant. For the 16-mm-diameter stud and 22-mm-diameter stud, the reductions were 21.2% and 40.8%, respectively. Meanwhile, the maximum shear slips of the shear studs under cyclic loading in the aforementioned researches [7, 9, 10, 12, 13] were far below the ductility criterion of the 6 mm stipulated in Eurocode 4 [8]. Pallare and Hajjar [14] reviewed many push-out tests from past literatures on the shear capacities of studs and proposed a 25% reduction in the monotonic shear capacity to account for cyclic loading. These experimental results showed that the reduction in the shear capacities of studs was significant and varied, and it would be affected by some parameters, including the stud diameter, stud ultimate tensile strength, concrete strength, load procedure, weld procedure, and tensile force.

Some experimental and numerical investigations have been performed to improve the shear behavior of studs. Han et al. [15–17] investigated the shear behavior of studs in concrete with different rubber contents. The experimental results indicated that the ductility of studs increased with the increase in the rubber contents in steel–concrete composite beams [18]. However, none have reported the improvement in the shear capacity of a stud under cyclic loading. The reduction in shear capacity and shear slip of a stud causes resource wastage. An effective method to increase the shear capacity of a stud under cyclic loading is to improve the welded joint structural type. For studs, it had been determined that different weld procedures could vary their resistances to fracture [19, 20]. Civjan and Singh [10] compared the shear capacities of 13-mm-diameter studs using stud welding and shielded metal arc welding (SMAW)-fillet welding. The experimental results showed that the SMAW-fillet welding improved the ultimate shear capacities of studs under monotonic loading. They also indicated that placing the weld at the perimeter of the stud could increase the moment capacity at the stud base, thereby increasing the shear capacity. Therefore, fillet welding could be better than stud welding for studs. Studies on welded joint structural types indicated that groove fillet welding could be better than fillet welding in some cases [21–23]. Zhai et al. [24] investigated the effect of welded joint structural type on the shear behavior of tie-bars under cyclic loading. The experimental results showed that the shear capacity of a tie-bar using groove fillet welding was significantly higher than that using fillet welding. Thus, groove fillet welding is adopted in this test to investigate the ultimate shear capacities of studs under cyclic loading.

As an extensive application of high-strength concrete (HSC), the performance of steel–concrete composite structures in HSC has been studied [25], as well as the shear behavior of other types of shear connectors [26–28]. However, studies regarding the influence of HSC on the shear behavior of studs have not been reported.

In addition, the shear capacity of a stud had been stipulated in many design codes [29–32]; however, these design provisions overrated the shear capacities of studs in cyclic loading. Because the studs under cyclic loading were brittle while the relationship between the shear capacity and shear slip was approximately linear, the equivalent shear stiffness was approximately constant. The shear stiffness significantly affected the shear distribution of studs in steel–concrete composite structures during seismic events. However, a formula estimating the equivalent shear stiffness of a stud under cyclic loading does not exist.

This study aims to obtain additional data and an understanding of the shear behavior of studs under monotonic and cyclic loadings in HSC. The effects of load type, stud diameter, and stud tensile strength on the shear behavior of studs are investigated herein. Meanwhile, the results on the ultimate shear capacities and equivalent shear stiffness of the studs under cyclic loading from previous studies and this test are reviewed, to propose the design formulas of ultimate shear capacity, and the equivalent shear stiffness of a stud under cyclic loading.

2. Experimental program

2.1. Test specimen

In this test, six push-out specimens were fabricated according to Eurocode 4, three of which were subjected to cyclic loading and the remaining were subjected to monotonic loading. The other varied parameters of the specimens included the stud diameter and ultimate tensile strength. The details of the specimens are shown in Figs. 1 and 2. Every specimen consisted of an H-shaped steel beam with a cross-section of H 250 mm × 250 mm × 9 mm × 14 mm, two 300 mm × 600 mm × 600 mm HSC concrete blocks embedding 10-mm-diameter stirrups, and eight studs attached to the two H-beam flanges by welding. Beyond these, each specimen under cyclic loading had a 1450-mm long H-beam, and each specimen under monotonic loading had an 800-mm long H-beam. This difference was due to the concave locking device in the cyclic loading condition. All the specimens are summarized in Table 1.

2.2. Material property

The properties of the concrete and studs in the six push-out specimens are summarized in Columns 2, 3, and 4 of Table 1. Standard concrete prisms of size of 150 mm × 150 mm × 300 mm were used to determine the concrete axial compressive strength (f_c). The ultimate tensile strength (f_u) of the studs was obtained from standard tensile tests. The Chinese strength grades of the H-beams and stirrups were Q345B and HRB335, respectively.

2.3. Welded joint structural type

The typical weld procedure for studs is stud welding, which was primarily used in the previous experiments. Fillet welding was used to weld the 13-mm-diameter studs, and it significantly improved the ultimate shear capacities of the studs under monotonic loading, but it did not improve those under cyclic loading [10]. Groove fillet welding is also a typical welded joint structural type in welded structures, while some researches indicated that groove fillet welding was better than fillet welding in some cases, and thus groove fillet welding would improve the resistance to failure for studs under cyclic loading. The three welded joint structural types formed by the three weld procedures are shown in Fig. 3. The shaded area expresses the ideal deposited metal in a welded joint. In fillet welding, a clearance between the stud and the H-beam flange exists. It is obvious that the three welded joint structural types are significantly different. In this test, the groove fillet welding adopted CO_2 gas metal arc welding (CO_2 GMAW). All the weld procedures in the six push-out specimens were accomplished by professional welders according to the Chinese industry criteria.

2.4. Test setup and load procedure

The push-out specimens under monotonic loading were loaded using a pressure tester with a capacity of 2500 kN, as shown in Fig. 4(a). The monotonic push-out specimens were laid on the supporting deck of the test machine. A force sensor was placed on the