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Static behavior of stud connectors in bi-direction push-off tests

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ABSTRACT

Headed stud shear connectors are commonly used to transfer longitudinal shear forces across the steel-concrete interface. In order to investigate the behavior of headed shear stud connectors, bi-direction push-off tests were conducted. Eighteen specimens, including six forward and twelve inverse push-off specimens, were tested to evaluate the failure modes, bearing capacity and load-displacement relationship of studs. An accurate numerical model was developed and validated against the experimental results, and based on which extensive parametric studies were performed to investigate the variation in concrete strength, stud yield strength, stud diameter and length-to-diameter ratio of stud on the structural performance. Based on the experimental and numerical results, new design equations of stud shear capacity and stud load-slip relationship were proposed and compared with the current code of practices GB 50017-2003, AISC, EN 1994-1-1, and relevant references. Comparing to the existing approaches, the proposed formulas have a better match with the experimental values.

1. Introduction

Steel-concrete composite structures have been widely applied in bridges and high-rise buildings. Meanwhile, headed stud shear connectors have been applied in some construction projects recently, and they are usually connected with steel beams or corrugated metal plates to transfer the longitudinal shear forces at the steel-concrete interface. Deformation of the shear connectors always causes the relative slippage at the steel and concrete interface, thereby possibly affecting the structural stiffness and load carrying capacity of the composite structures. Hence, it is necessary to study the performance of the shear connectors and it is commonly examined by push-off tests.

Wang et al. [1] investigated the fatigue behavior of steel-concrete composite beams and studs, and proposed an effective calculation method for the deflection of steel-concrete composite beam. It was found that the equation in AASHTO (American Association of State Highway and Transportation Officials) was the safest equation to predict the fatigue life of stud in practical design. Lee et al. [2] also studied the static and fatigue behavior of large stud shear connectors up to 30 mm diameter, which were beyond the limitation of current design codes. The results showed that the design strength and fatigue endurance in Eurcode-4 gave conservative values for large studs. Han et al. [3,4] conducted experimental and numerical analysis on shear studs in push-off test with crumb rubber concrete. It was found that the ductility of stud improves significantly with the increasing rubber content and the best ratio of rubber content was approximately 10%. It also showed that welding defect at the stud bottom was most adverse on the ultimate slip and ductility of studs. Lam et al. [5] developed an effective numerical model to simulate the behavior of studs in composite beam through push-off tests. Araújo et al. [6] studied the shear strength of headed shear connectors associated with precast concrete hollow-core slabs with a structural concrete topping through push-off test. Several code prescriptions were compared and a proposition to modify an existing design equation for the ultimate shear capacity of headed studs in composite precast hollow-core slab beams was presented by Araújo et al. [6], focusing on the influence of the structural concrete topping.

The mechanical property of the stud shear connector in inverse push-off test is also a key factor in evaluating the structural seismic performance. However, little research has been done to investigate the static behavior of stud shear connectors in inverse push-off tests. This paper will focus on this point. Eighteen specimens, including six push-off specimens and twelve inverse push-off specimens, were tested considering the influence of concrete strength and stud diameter. Detailed finite-element (FE) models of specimens were further established, and the numerical modeling results with experimental validation were presented. Subsequently, new practical equations of shear capacity of stud were proposed based on the experimental and numerical results. Modeling results from the proposed formulas showed satisfactory agreement with the experimental results obtained from the current studies and literatures.

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Nomenclature

A_s	cross-sectional area of a stud connector
E_c	elastic modulus of concrete
E_s	elastic modulus of steel
E_{st}	hardening modulus
h	length of stud
d	stud diameter
P_u	ultimate load
P_u^T	ultimate load in push-off test
P_u^L	ultimate load in inverse push-off test
f_{cu}	compressive cube strength of concrete
f_c	compressive strength of concrete
f_c'	compressive cylinder strength of concrete
f_s	yield strength of stud
f_y	yield strength of steel
f_u	ultimate tensile strength of stud
f_{us}	ultimate tensile strength of steel
γ	ratio of minimum tensile strength to yield strength of stud
γ_v	partial factor

2. Push-off test

2.1. Description of test specimens

To examine the behavior of headed stud shear connectors, eighteen specimens were designed and fabricated in accordance with the standard push-off test specimen in code EC4 [7]. The push-off specimens were divided into two groups. Six specimens denoted as FP1 to FP6 in group 1 were designed for push-off tests, and twelve specimens denoted as IP1-1 to IP6-1 in group 2 were designed for inverse push-off tests. There is a repeat specimen for each inverse push-off test (IP1-2 to IP6-2).

The test specimen (see Fig. 1) consists of a steel beam ($h_w \times b_f \times t_f \times t_w = 250 \times 116 \times 13 \times 8$ mm, I25a for short), two concrete slabs attached to the flanges of the steel beam with dimensions of 460 mm in length, 300 mm in width, and 150 mm in thickness for each slab, and two headed stud shear connectors attached to each flange with shank diameter of 16 mm (80 mm in length) or 19 mm (80 mm in length) or 22 mm (110 mm in length) respectively, as shown in Fig. 1d. The studs were welded with the steel beam by completely penetration butt weld. A summary of specimen information is listed in Table 1.

2.2. Materials

Q235 steel with nominal strength of 235 MPa was used for I25a steel beam. Hot-rolled ribbed bars (HRB) with nominal diameter of 10 mm and nominal strength of 235 MPa were used as reinforcing bars spaced by 150 mm. Three types of headed stud shear connectors with different diameters were used to transfer the shear force between steel beam and concrete slab. The type of studs was grade 4.6. Tensile coupling tests were carried out for the structural steel and reinforcing bars according to GB/T 228-2010 [8] before the test and the results are presented in Table 2.

Two types of concrete with nominal strength of 30 MPa and 50 MPa were used in this study. Silica based sand and crushed carbonate stone were used as fine aggregate and coarse aggregate, respectively. The mix proportion is summarized in Table 3. The material properties of the concrete were obtained by standard cubes (150 × 150 × 150 mm) after 28 days of curing according to the standard GB/T 50081-2002 [9], as shown in Table 2.

2.3. Experimental setup and loading procedure

The schematic view of the test setup is shown in Fig. 2. The

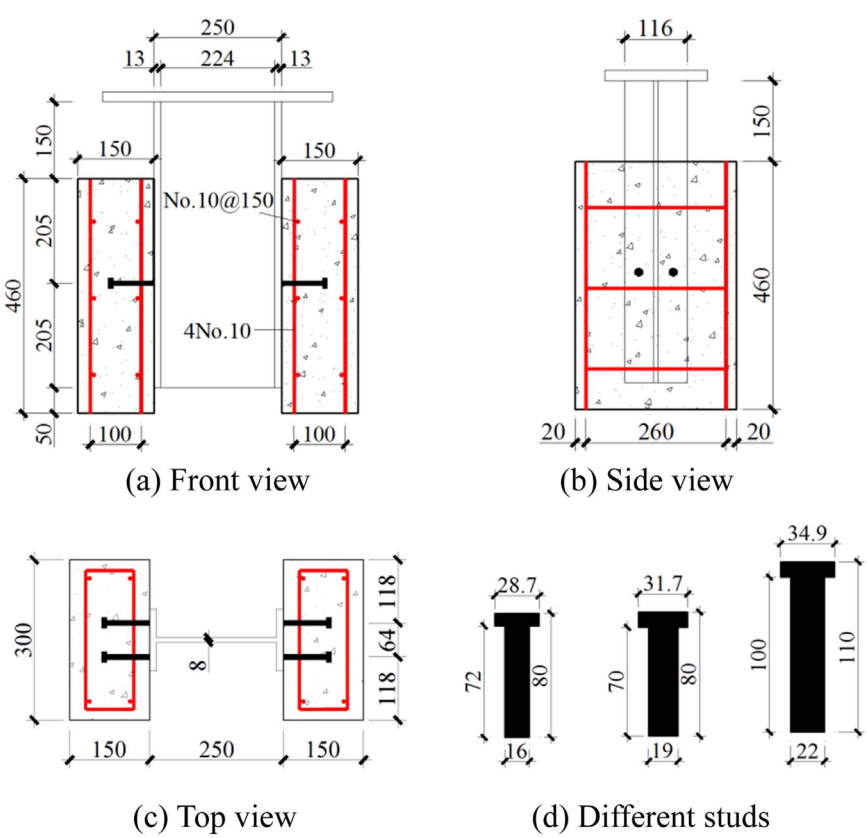

Fig. 1. Detail of the specimens; units: mm.

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