

Study on mechanical behavior of rubber-sleeved studs for steel and concrete composite structures



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HIGHLIGHTS

- Headed stud wrapped with rubber sleeve, “rubber-sleeved stud”, was proposed.
- Eighteen push-out specimens of stud connectors were prepared and tested.
- Failure process of the shear connectors was simulated through 3D finite element models.
- Advice for rubber-sleeved stud design was given.

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ABSTRACT

The stiffness of headed stud is sometimes so large that it causes non-uniform distribution of shear forces at interface between steel and concrete members in composite structures. To solve this problem, headed stud wrapped with rubber sleeve, named “rubber-sleeved stud”, was proposed. Eighteen push-out specimens were performed. Furthermore, numerical simulation on nonlinear behavior of the shear connectors was conducted. The results show that, compared with ordinary stud, the variation of shear strength for rubber-sleeved stud is negligible, but the stiffness markedly decreases and the shear mechanism changes. Based on these results, advice in designing rubber-sleeved stud was given.

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1. Introduction

Steel and concrete composite structures utilizing the advantages of both steel and concrete are widespread in the built environment, in particular for buildings and bridges. The overall behavior of these structures largely depends on the type of shear connector used to transfer shear forces at the interface between steel and concrete. At present, the headed stud is commonly used type of shear connector in steel and concrete composite structures [1,2].

Headed stud is a flexible shear connector because it has to undergo some deformation before it can supply any force. When headed stud is applied, the interaction between steel and concrete is considered to be incomplete referred to as partial interaction, partial composite action or incomplete interaction [3]. However, when a large number of headed studs are applied, the stiffness at

the interface becomes so large that it causes the non-uniform distribution of shear forces for the headed studs. As a result, some headed studs suffer high shear forces, which affects the mechanical behavior of the structure. The study by Xue et al. [4] on the mechanical properties of headed studs for composite truss joint shows that the stiffness of headed stud, the layout of headed studs, and the steel backing plate are the main influencing factors on shear forces of headed studs. And the shear forces in the first few rows of headed studs are greater than others on the gusset plate. Machacek and Cudejko [5,6] studied more than 30 variants of shear connectors of a simple truss with Vierendeel panel at mid-span. The nonlinear distribution of the longitudinal shear forces depends on stiffness of the shear connector and the layout of the shear connectors above truss nodes. These studies show that to ease the non-uniformity of shear forces, one of the reasonable ways is to reduce the stiffness of the shear connector.

The behavior of the studs including stiffness has been extensively investigated since the 1950s through experimental tests, mainly push-out tests. Viest [7] made one of the earliest studies,

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in 1956, in which 12 push-out tests of round steel studs were conducted. Three types of failure modes were observed from the tests and empirical equations were presented for determining critical load. Johnson and Oehlers [8] attempted to find a rational basis for existing knowledge and practice for push tests of studs in composite T-beams. Oehlers and Coughlan [9] proposed the stiffness of stud shear connectors in composite beams. Push-out tests were also carried out to evaluate the effect of concrete on the behavior of the stud connectors by many researchers [10–13]. Xue et al. [2] conducted push-out tests to investigate the different behavior between single-stud and multi-stud connectors. The results show that the ultimate strength of single-stud connectors is about 10% larger than that of multi-stud connectors.

On the other hand, push-out tests are often costly and time consuming. Finite element modeling of shear connector can provide an efficient alternative to push-out tests. Moreover, the numerical model also presents details of failure process which are difficult to observe during testing. Many researchers investigated the behavior of head stud connectors using models based on Finite Element Method (FEM). Lam and El-Lobody [14] developed an accurate nonlinear finite element model to investigate the behavior of headed stud connectors in solid slabs. The results obtained from the finite element analysis agreed well with those from experiments. Nguyen and Kim [15] included the damage and failure in the material model for headed stud to accurately obtain the shear strength of stud connector. Mirza and Uy [16] developed a three dimensional nonlinear finite element model to study the behavior of steel anchors for both solid and profiled steel sheeting slabs. It was observed that the proposed nonlinear model can predict the shear strength of the steel anchors to an acceptable accuracy. Guezouli and Lachal [17] developed an accurate and efficient 2D nonlinear finite element model to investigate the mechanical behavior of the shear connector between prefabricated concrete slab and steel girder in composite structures for bridges.

Although the behavior of headed stud connectors has been studied extensively, few studies related to the method of reducing the stiffness of shear connector for decreasing the non-uniform distribution degree of shear forces. Hiragi et al. [18] proposed a new type of shear connector, which was an ordinary headed stud wrapped urethane at the root. Push-out test and beam test were carried out. The proposed shear connector shows flexible behavior more remarkably. Inspired by the work of Hiragi et al. [18], a new kind of shear connector compositing ordinary stud and rubber sleeve was proposed as shown in Fig. 1 (hereafter, it is abbreviated to “rubber-sleeved stud”). Rubber-sleeved stud is easy to fabricate, and it can be convenient to control the stiffness of the shear connector by changing the dimension of rubber sleeve.

The main objective of this paper is to study the mechanical behavior of the proposed rubber-sleeved stud. Eighteen push-out test specimens were fabricated and tested, including shear connectors with different dimension of the rubber sleeves. And nonlinear finite element models have been developed to simulate the failure process of shear connectors under shear loading. Additionally, the

numerical results were verified by the experimental ones, and revealed further mechanical characteristics of the rubber-sleeved stud. All the findings of experimental and analytical works at present study may provide reference for applying rubber-sleeved stud in steel and concrete composite structures.

2. Experiment program

2.1. Test specimens

Experimental investigation of shear connector behavior is usually carried out by push-out tests. In this paper, the experiment included 18 push-out test specimens that were fabricated according to Eurocode 4 [19], 15 of which utilized rubber-sleeved studs and the remaining used ordinary studs. The varied parameters of test specimens were: rubber sleeve height, h_r ; rubber sleeve thickness, t_r . Rubber sleeve height (ranged from 25 mm to 75 mm), and rubber sleeve thickness (ranged from 2.5 mm to 7.5 mm) were considered to study the effects on behavior of the connectors when subjected to shear forces. Monotonic loading and uniaxial cyclic loading were used to check the difference of the shear connectors' behavior under the two loading types. The details of test specimens are summarized in Table 1, in which “S” and “RS” are identified for ordinary shear stud and rubber-sleeved stud respectively, “M” and “U” for monotonic loading and uniaxial cyclic loading respectively. The details of the specimens that were produced to perform the push-out tests are shown in Fig. 2. The dimension of the concrete slab was $500 \times 460 \times 150$ mm. In the concrete slab, two layers steel bars ($\varnothing 10$ mm) at a spacing of 100 mm were placed in longitudinal and transverse directions. And the thickness of the steel plates was 20 mm.

Fabrication process is shown in Fig. 3. The rubber sleeves were cut, opened and fixed on the studs by steel wires after the studs were welded automatically onto the steel plates. Taking the effect of concrete casting direction into account, the specimens were cast upward to ensure the quality of the concrete slabs and the right position of the rubber sleeves. The steel component of the specimen was divided into two T-shaped beams which were connected by bolts.

2.2. Material properties

The uniaxial compressive strength of concrete was tested by 150-mm cubic specimens. Table 2 presents the average values of compressive and tensile strength of concrete and the average value of the modulus of elasticity. In all groups, headed studs and reinforcing bars used in the tests were from the same batch. Based on the tensile tests, the mean yield strength f_y , and the ultimate tensile strength f_u of headed stud were determined as 410 MPa and 450 MPa, respectively. Steel used as reinforcement for the concrete members show yield strength and ultimate strength equivalent to 369 MPa and 462 MPa, respectively. The rubber sleeves were made of NR45° natural rubber, since they have low hardness and very good resistance to abrasions and acids. Table 3 shows the material property of rubber sleeves.

2.3. Test setup and loading procedure

The test setup used in the experiments is shown in Fig. 4. The specimens were tested using a servo hydraulic testing machine with a capacity of 4000 kN. The specimens were laid on supporting deck of the test machine, with sand spread on the surface of deck to reduce friction. During the monotonic tests, the displacement control was used. The time taken to reach the ultimate load was controlled not to be less than 15 min. During the uniaxial cyclic loading, force control was used. Ten loading cycles were applied with an increment of 8 kN. After ten loading cycles, monotonic load was applied until complete failure. The time and the load from the machine load cell, the corresponding longitudinal slip between the concrete slab and the steel plate were measured. Two LVDTs (Linear Variable Differential Transformer) were placed on each steel flange to measure the slip continuously. All the data was collected by a data acquisition system.

3. Experiment results

3.1. Failure modes

In all specimens, the failure occurred in the stud shank. The studs yielded and fractured in the root, and no concrete crack happened in the surface of the specimens. Fig. 5 shows the surface of concrete slab. Cavities were observed vertically below the studs. For rubber-sleeved studs, the studs pressed all the roots of rubber sleeves into failure.

To inspect the deformation of the studs and the state of the concrete and rubber sleeves, six concrete slabs from six different groups were sawed through the position of studs longitudinally.

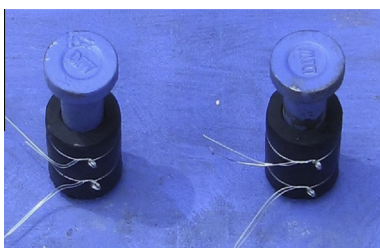


Fig. 1. Rubber-sleeved studs.

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