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Study on uplift performance of stud connector in steel-concrete composite structures

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Abstract. The main role of studs, which act as connectors of the steel-concrete composite structures, is to ensure that the steel and the concrete work together as a whole. The studs in steel-concrete composite structures bear the shearing force in the majority of cases, but in certain locations, such as the mid-span of a simply supported composite beam, the studs bear axial uplift force. The previous studies mainly focused on the shearing performance of the stud by some experimental and theoretical effort. However, rare studies involved the uplift performance of studs. In this paper, the single stud uplift test on 10 composite specimens was performed. Meanwhile, based on the test, numerical analysis was introduced to simulate the concrete damage process due to the stud uplifted from concrete. The static ultimate bearing capacity, under which the stud connector was pulled out from the damaged reinforced concrete, is much larger than the cyclic ultimate bearing capacity, under which the weld joint between stud and steel plate fractured. According to the fatigue test results of 7 specimens, the fatigue *S*-*N* curve of the construction detail after minus 2 times standard deviation is $\log N = 24.011 - 9.171 \log \Delta\sigma$, the fatigue strength corresponding to 2×10^6 cycles is 85.33 MPa.

Keywords: uplift performance; stud connector; ultimate bearing capacity; fatigue strength

1. Introduction

Steel-concrete composite structures are those of combining steel and concrete, with different physical and mechanical properties, to work together through some connectors. As a flexible member, the stud is the most important one of the connector in steel-concrete composite structures. In order to make the steel and the concrete work together as a whole and not separate each other, the stud connectors was subjected to not only shearing force between the steel and the concrete, even the force making the stud uplift from concrete. For example, under the dead load and vertical external force, the studs of both ends of the simply-supported composite beam bear maximum horizontal shear force due to the relative tangential slip between steel plate and concrete, while the studs of the mid-span bear axial uplift force due to the normal separation between steel plate and concrete, as shown in Fig. 1.Many scholars (Lubliner and Oliver 1989, Lee *et al*. 1998, Nie and Fan 2004, Lee *et al*. 2005, Lam 2007, Xue *et al*. 2012, Xu and Sugiura 2014) have studied the

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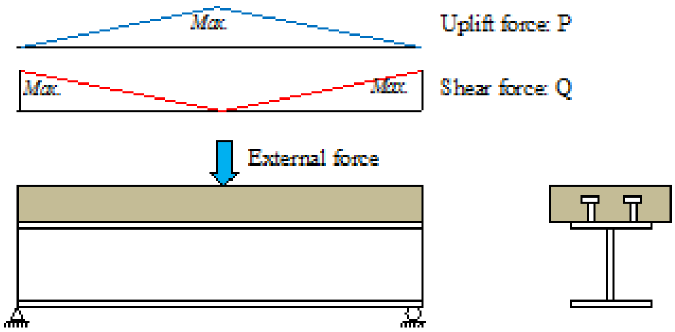


Fig. 1 Distribution diagram of the shearing force and the uplift force of the studs in the simply-supported composite beam

shearing ultimate bearing capacity and shearing fatigue properties of studs in steel-concrete composite structures, and the relevant achievements have been adopted in the design specifications. A series of stud push-out tests (Ollgaard *et al*. 1971, Jayas and Housain 1989, Slutter *et al*. 1992, Nie 2009, Xu *et al*. 2012) was carried out to deduce the calculation formulation of the shearing ultimate bearing capacity. Meanwhile, it was confirmed that the concrete tensile failure is the main failure form under ultimate loading. Besides, plenty of fatigue shearing tests (Gattesco and Giuriani 1996, Nguyen and Kim 2009, Qureshi *et al*. 2011, Wang *et al*. 2014) on stud connector were performed to obtain the fatigue strength and find that the fatigue fracture mainly initiates from the weld between steel plate and concrete. However, the studies (Hiragi *et al*. 1990) on axial uplift performance of stud are just limited in ultimate bearing capacity considering the effect of concrete compressive strength, length of stud and diameter of stud head.

In this paper, based on the experiment and numerical analysis, the uplift damage process and influence of the reinforced rate and concrete grade to uplift ultimate bearing capacity under static uplift load was obtained. Moreover, the fatigue strength and fatigue damage form of shear stud in steel-concrete composite structures was proposed by cyclic uplift load test.

2. Test procedure

The cheese head studs for arc stud welding with 22 mm diameter and 105 mm height was used. The diameter was measured to calculate the actual stress of the stud. According to cheese head studs for arc stud welding (GB/T 10433-2002), the maximum diameter is 22 mm and the minimum one is 21.48 mm. But the actual measurements show that the minimum diameter is 21.39 mm, and the average diameter of 10 studs is 21.57 mm.

The stud was welded by arc stud welding torch in the middle of a steel plate with the dimensions of 703 mm × 400 mm × 24 mm. The stud was implanted in an 840 mm × 315 mm × 250 mm reinforced concrete block with 6Φ8 round rebar as main reinforcement bars in the cross-section, with reinforcement ratio 3.8%, and with 8Φ8 round rebar as the stirrups in the longitudinal direction. 10 specimens with concrete of grade C40 were produced, among which three ones were used for static load tests (No. ST1~ST3), and seven ones for fatigue tests (No. ST4 ~ST10).

A framework produced by 24 mm thick steel plates was designed for the benefit of loading.

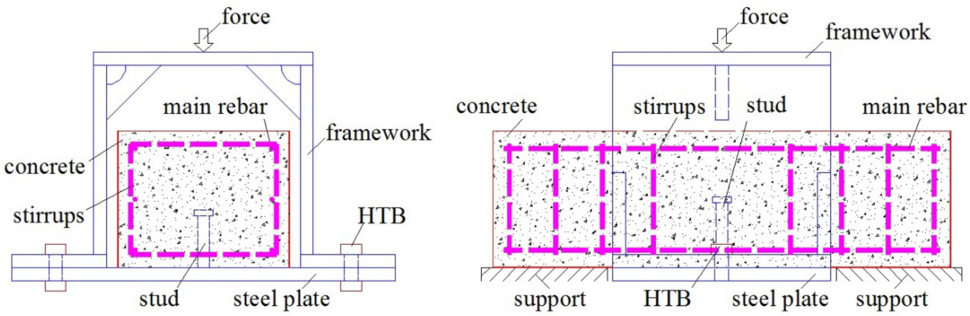


Fig. 2 Sketch of the test equipment

The specimen is connected to the framework by two high strength bolts. The force is transmitted to the steel plate through the framework in order to achieve the purpose of pulling out the stud, as shown in Fig. 2.

Before the test, four dial indicators were installed at the four corners to measure the deformation between the steel plate and the concrete under the external force. Before the static load test, the specimen is pre-loaded to 20 kN, repeated three times.

The load increments was controlled at about 1 kN while the specimen ST1 was loaded due to lack of experience of stud pull-out test. The load increments of the specimen ST2 and ST3 were controlled at about 10 kN. The framework's weight, which is 1.9 kN was considered in calculation of the actual test load.

Before the fatigue test, each of the 7 specimens was pre-loaded to 20 kN, repeated three times. The lower limit of the fatigue test load maintained at 5 kN, not including the framework's weight, and the maximum load changed from 35 kN to 50 kN, with loading frequency of 5 Hz~6 Hz.

3. Uplift ultimate bearing capacity

3.1 Test results and analysis

The specimens denoted by ST1, ST2 and ST3 were destroyed when the test static load reaches a certain value due to the sudden increase of relative deformation and separation between the steel plate and the concrete, as shown in Fig. 3. After the steel plates of the destructed specimens were removed, the three specimens were found to have the same failure modes exactly, and the studs were pulled out directly from the reinforced concrete with intact shape while the latter failed with the shape of an inverted cone due to the combined action for uplift force of the stud and out-of-plane bending of the beam, as shown in Fig. 4. The relationship between the actual test loads and the average deformations for the four corners of the framework is shown in Fig. 5. As can be seen, the actual test load and the average deformation substantially conform to the linear relationship before reaching bearing limit state, and the destruction of the specimen is concrete brittle failure, in which the stud is pulled out suddenly.

According to the formula (Hiragi *et al*. 1990), the uplift ultimate bearing capacity of the shear stud in test is 77.2 kN. However, the actual experimental values are smaller than the calculated value due to the limited beam width, etc. The uplift ultimate bearing capacity of the three specimens are 68.8 kN, 65.9 kN and 60.9 kN, respectively, with the mean value 65.2 kN; accordingly, the axial stress of the studs is 190.6 MPa, 179.0 MPa and 169.5 MPa with the mean value 179.7 MPa. The ultimate damage of the three specimens all happened due to the concrete damage, not the fracture of weld between stud and steel plate. However, for obtaining the uplift ultimate bearing capacity of the stud weld joint, a uplift test was conducted using the specimens

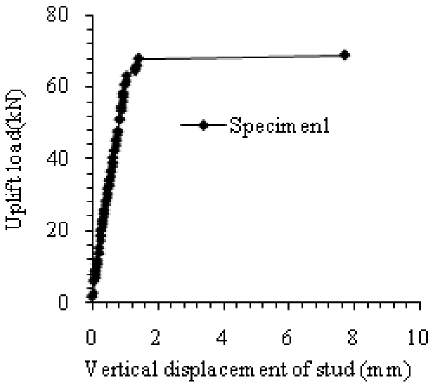
Fig. 3 Steel plate leave from the concrete

(a) Main body of damaged beam

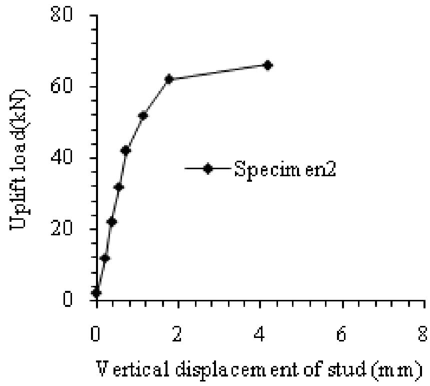
(b) Dropped concrete from damaged beam

(c) Intact stud connector

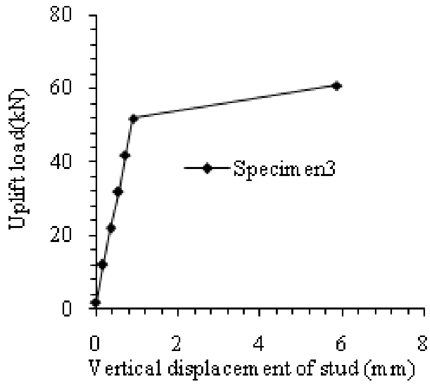
Fig. 4 Failure modes of the specimen ST3



(a) Specimen ST1



(b) Specimen ST2



(c) Specimen ST3

Fig. 5 Relationship between the static test load and the average deformation

without pouring concrete. The result shows that the ultimate bearing capacity exceeds 173.6 kN when the stud weld joint naked down and fractured, and the stress of the stud welded joint is about 483.1 MPa. Besides, according to Cheese head studs for arc stud welding (GB/T10433-2002), the ultimate stress of the stud material $\sigma_b \geq 400$ MPa, thereby the ultimate strength of the stud welded joints is 159.6 kN, which coincided well with the experimental value. On the other hand, based on the ultimate stress of the stud material and the mean value of the uplift ultimate bearing capacity of three specimens, so long as diameter of the stud is more than 7.2 mm, concrete damage is prior to stud weld damage.

3.2 Numerical results and analysis

Based on the test, the uplift ultimate bearing capacity and the final failure mode can be obtained, however, the process of the concrete damage was difficult to observe in details due to damage initiation coming from the inner of the concrete. Therefore, the numerical analysis on the uplift damage was performed by utilizing concrete plastic damage theory established by (Lubliner and Oliver 1989, Lee and Fenves 1998). As shown in Fig. 6, the damage parameter was calculated by the energy damage mode, as follow

$$D = 1 - \frac{W_s}{W_0} \tag{1}$$

W_s is the dash area, W_0 is the area of triangle OAB.

According the Code for design of concrete structure (GB 50010-2002), the stress-strain relationship curve of concrete C40 was drawn from the recommended formulations, and the damage parameter was calculated by the computer programmer based on Eq. (1). In order to make a comparison between the stress and the damage parameter, the stress was normalized (σ_c/σ_{cu} and σ_t/σ_{tu}, here, σ_c is compressive stress, σ_{cu} is the peak value of compressive stress; σ_t is tensile stress, σ_{tu} is the peak value of tensile stress), and was put in same figures with damage parameter. As shown in Fig. 7, when the compressive stress approaches to the peak value, the corresponding compressive damage parameter is 0.3. When the compressive damage parameter is less than 0.3, the concrete do not reach the ultimate bearing capacity, and keeps in no damage state. As shown in Fig. 8, when tensile strain is close to 0.00025, the tensile strength decrease to 50% of the peak tensile stress, and the corresponding tensile damage parameter is about 0.6, which is judged as the lower limit of tensile damage. The FE model with same main rebar and stirrup reinforced rate to specimen was established as shown in Fig. 9. Contact was defined in the interface between stud and concrete without considering friction. The material property was set as the code for design of

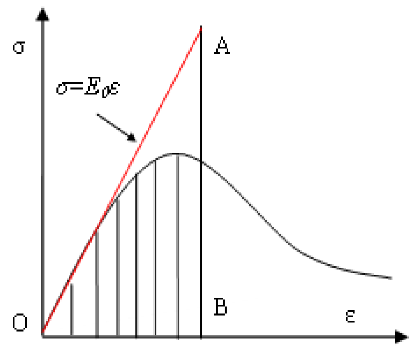


Fig. 6 Energy damage mode

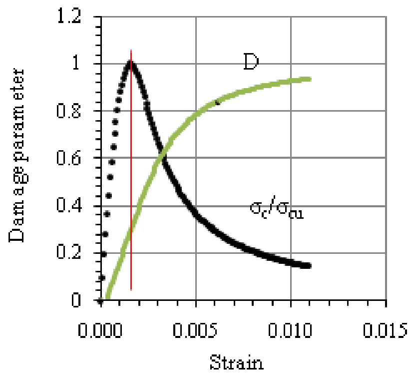


Fig. 7 Compressive damage parameter

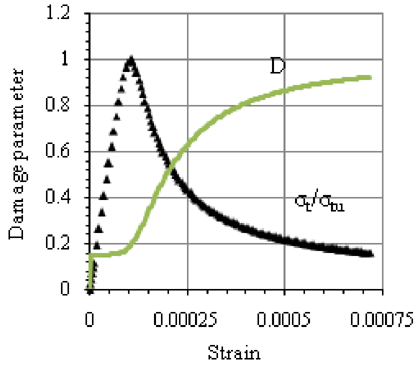


Fig. 8 Tensile damage parameter

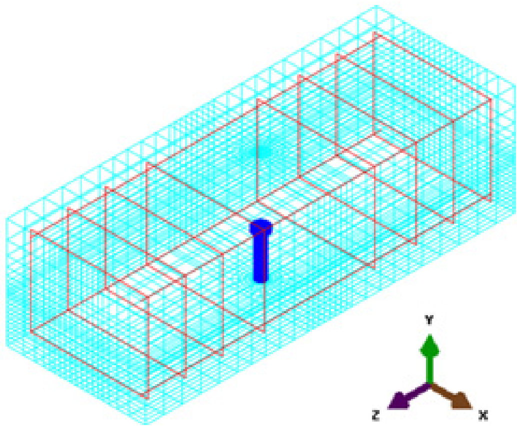


Fig. 9 FE model

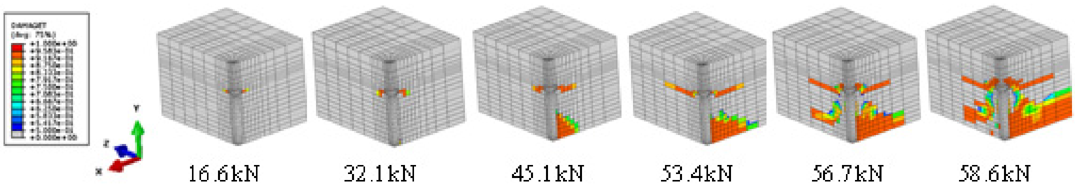


Fig. 10 Process of tensile damage

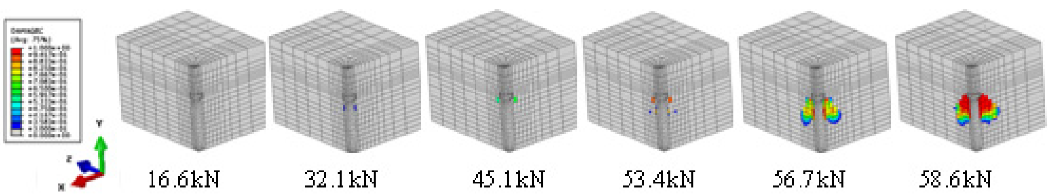


Fig. 11 Process of compressive damage

concrete structure (GB 50010-2002), and the damage parameters and corresponding different nonlinear strain was set as Fig. 8. Fine finite element analysis on concrete damage was carried out. The running time for one damage process by the computer with 32.0 GB of RAM is about 24 H.

Figs. 10 and 11 show the process of tensile and compressive damage, respectively. In order to make a more visible effect to observe the damage propagation process, a 1/4 model near the shearing stud was displayed in these two figures, which can show the damage propagation in three directions, *X*, *Y* and *Z*. Tensile damage initiates earlier than compressive damage, and plays a more leading role in the whole damage process. Tensile damage firstly initiates from the concrete near the stud top and expands around it in horizontal direction. With the load increasing, the damage also starts from the lower surface of the concrete beam due to the beam bending. Compared with tensile damage, the compressive damage occurs in a relatively small region near the stud top.

In the analysis, it was assumed that the stud was uplifted from concrete 2mm was regarded as the limit state. The effect of concrete grade and the reinforcement ratio, etc. on ultimate bearing capacity of the stud connector was studied. The vertical displacement variation of stud end with the load increase was illustrated in Figs. 12 and 13. The variation trend is similar to the average deformations for the four corners of the framework observed from the test in Fig. 5, The vertical displacement keeps almost linear relationship with load before the bearing limit state is reached.

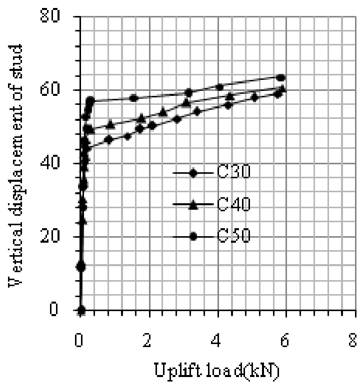


Fig. 12 Relationship between load and stud vertical displacement with different concrete grade

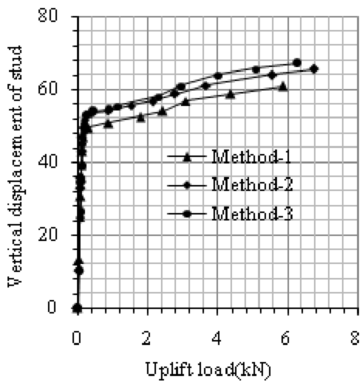
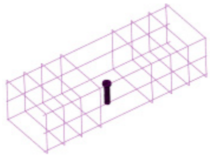
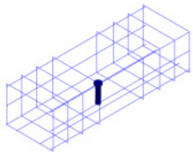
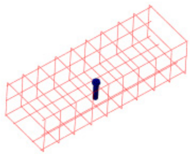


Fig. 13 Relationship between load and stud vertical displacement with different reinforced rate

Table 1 Ultimate bearing capacity with different reinforced rate

Reinforced method number	Illustration	Ultimate bearing capacity (kN)
Method-1 (Specimen)		53.1 kN
Method-2 (Add main rebar)		56.6 kN
Method-3 (Add main rebar and stirrup)		57.2 kN

Once the concrete comes into a failure state, the stud pulls out suddenly. As Fig. 12 shown, enhancing concrete grade can make the initial linear increasing stage become long, and increase the ultimate bearing capacity. C30, C40 and C50 concrete were used in this analysis. The tensile strength are 2.01 MPa, 2.39 MPa, 2.64 MPa, respectively, and compressive strength are 20.1 MPa, 26.8 MPa, 32.4 MPa, respectively. According to the analysis results, the ultimate bearing capacity of the concrete C30, C40 and C50 are 50.2 kN, 53.1 kN and 58.2 kN, respectively. As Fig. 13 and Table 1 shown, ultimate bearing capacity can be increased through increasing a certain reinforced rate. Moreover, it also can be found that increase of the reinforced rate of main rebar was more effective to improve ultimate bearing capacity than increase of the reinforced rate of stirrup.

4. Uplift fatigue strength

Under repeated fatigue loads, the failure of six specimens have the same characteristic of joint fracture between the stud and the steel plate, as shown in Fig. 14, except the specimen ST10 in which stud was pulled out directly from reinforced concrete due to the increased spacing of stirrups caused by wrong positions. And the initiation of fatigue cracks was located in the heel of the weld. Furthermore, the base metal of the steel plate could be tore if the stud was not vertical to the plate.

The fatigue test results were summarized in Table 2 and the specimen ST10 is not taken into account in the analysis of the uplift fatigue strength.

In general, the fatigue *S*-*N* curve of engineering structures was indicated in the double logarithmic coordinates, and its expression is as follows

$$\log N = A + m \log \Delta\sigma \pm C \quad (2)$$

Where, N is the number of cycles of fatigue failure, $\Delta\sigma$ is the applied stress amplitude, A is the

(a)

(b)

Fig. 14 Failure modes of the specimen ST4

Table 2 Uplift fatigue test results

No.	Dia. of the stud (mm)	Lower load (kN)	Upper load (kN)	Cycles	Failure mode
ST4	21.65	5	50	90,469	The joint fractured between stud and steel plate
ST5	21.39	5	40	1,392,451	
ST6	21.52	5	35	2,206,462	
ST7	21.56	5	45	365,095	
ST8	21.69	5	38	1,674,619	
ST9	21.58	5	42	1,116,484	
ST10	21.90	5	47	190,492	Stud was pulled out from the concrete

intercept of the *S*-*N* curve, m is the slope of the *S*-*N* curve, C is the statistical error of N, $C = K \cdot m_N \sqrt{1-r^2}$, m_N is the mean log squared error of N, r is the correlation coefficient which should be negative, and the *S*-*N* curve represents the different guaranteed probability when K is equal to different values, as $K = 2$ is often adopted in China.

Linear regression analysis was done on the logarithmic test data of specimen ST4~ST9, and the result is shown in Fig. 15.

The corresponding equation of the regression curve is as follows

$$\log N = 24.203 - 9.171 \log \Delta\sigma \tag{3}$$

Where $r = -0.938$, $m_N = 0.277$, $C = 0.192$.

The following equation can be obtained after subtracting two times standard deviation from Eq. (3)

$$\log N = 24.011 - 9.171 \log \Delta\sigma \tag{4}$$

According to Eq. (4) the uplift fatigue strength is 85.33 MPa when the number of cycles is 2×10^6. If the stud diameter is 22 mm, then the calculated fatigue limit capacity is 32.4 kN, which is about half of the static load bearing capacity.

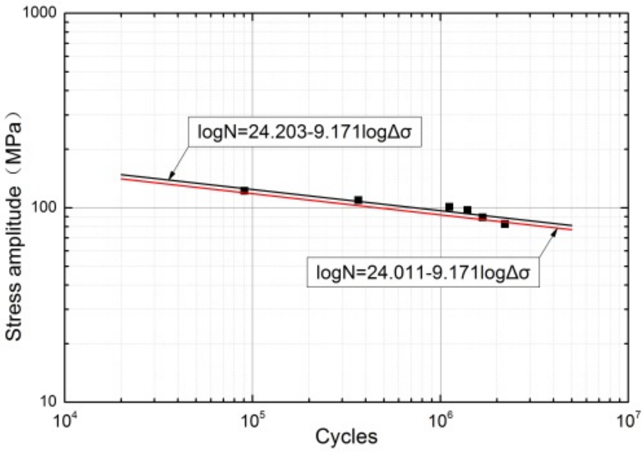


Fig. 15 Uplift fatigue test data and the logarithmic linear regression curves

5. Conclusions

The main conclusions were drawn from the test and numerical analysis results, as follow:

- The static test results of three specimens show that the ultimate bearing capacity of a single stud pulled out from reinforced concrete is 65.2 kN when the stud diameter is 22 mm and the concrete grade is C40, less than the ultimate bearing capacity of the stud welded joint.
- Tensile damage of the concrete is the main failure mode in static limit state, and increasing concrete grade and reinforced rate can improve the static ultimate bearing capacity in a certain extent.
- The uplift fatigue test results of seven specimens show that the main fatigue failure mode is the fracture of the stud welded joint, and the fatigue *S*-*N* curve of the construction detail is $logN = 24.011 - 9.171 log\Delta\sigma$ after minus two times standard deviation, and the fatigue strength corresponding to 2×10^6 cycles is 85.3 MPa.

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