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Fatigue performance of stud shear connectors in steel-concrete composite beam with initial damage

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ABSTRACT

As a key component in composite beams, the studs are prone to fatigue failure under reciprocating load. Fatigue problem is more prominent especially under circumstances of concrete cracking, stud corrosion or with initial damage. Therefore, static and fatigue tests are carried out to study the fatigue properties of push-out specimens with initial defects, including stud damage and concrete cracking. The test results show that the damage of stud has a great influence on fatigue life, while the crack of concrete has a little influence on fatigue life. The damage of stud has a greater influence on fatigue performances compared to static properties. In addition, based on the dissipative energy theory and experimental phenomenon, the roles of stud and concrete in the process of stud fatigue failure and their interaction are summarized. The dissipative energy mainly includes the shear plastic strain energy of the stud, the plastic strain energy of concrete under compression after the stud, and the heat energy generated by the friction between the stud and concrete.

1. Introduction

Steel-concrete composite beams have become popular in recent years for use in bridge engineering [1,2]. Under the complicated environment and load, there may be some damage to the composite beam. There might be some damage, such as corrosion, fractures of weld leg and longitudinal or transverse cracks in the concrete deck. The static and fatigue behavior of stud connection is sophisticated and affects the design resistance and stiffness of composite beams [3,4]. The damage of the stud and concrete may have a great influence on the shear fatigue performance of the interface.

Welding defects significantly lower the shear capacity of studs, as is widely known. There are many types of welding defects that might appear, such as inadequate penetration, absence of fusion, and gas inclusion [5]. To determine how the damage location and degree affected the static behavior and shear capacity of stud shear connections, six specimens with identical geometrical dimensions were investigated by Qi et al [6]. The test findings showed that, in comparison to the shear capacity of normal specimen, a loss of up to 36.6 % and 62.9 % of the shank area might cause a falling shear capacity of 7.9 % and 57.2 %, respectively. The push-out test was simulated using mathematics, and the results of the test were used to validate the study. It was shown that even though the area of the stud had significantly decreased, the shear capacity was not affected by the severity of the damage when the damaged part was placed 0.5d (where d is the shank diameter) from the stud root, based on the numerical model.

Concrete cracks would lead to stud corrosion, resulting in a decline in shear capacity. As a result, the cracks of concrete slab in composite beam and the initial damage of studs may reduce the fatigue performance of studs. According to Hu et al. [7], the vertical cracks (longitudinal cracks) might cause the shear capacity stud to be reduced. Rong et al. [8] conducted a fatigue test on three push-out specimens with rusty studs, and the test results revealed that the fatigue life of studs after corrosion reduced dramatically, with the fatigue life decreasing by up to 40 % when the stud corrosion rate reached roughly 20 %. The upper surface of the concrete slab carries the most tensile stress and is prone to cracking in the negative bending moment zone.

In addition, many studies on stud fatigue in steel–concrete composite beams have been conducted. By performing fatigue testing on stud and channel connectors, Slutter et al. [9] found that fatigue failure occurred at the weld zone during tests, and that the stress amplitude had the most noticeable influence on the fatigue life of the connection. Fatigue life predictive formula was proposed by fitting test data. Through regression analysis of 179 static tests and 145 fatigue tests, Hirokazu et al. [10]

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found that the fatigue strength of the connector is not only related to the strength of concrete, but also related to the ratio of the height and diameter of the stud. Gattesco et al. [11] carried out low-cycle fatigue testing on eight composite beams, focusing on issues such as interface slips and shear connection degree. The results demonstrated that local concrete crushing around the studs and stud shearing were the primary causes of composite beam failure under low cycle fatigue loads. The traditional "load-fatigue life" method, according to Gattesco, is not suitable for composite beams with partial shear connections under low-cycle fatigue loads because large slippage between the concrete slab and the steel beam would result in plastic deformation of studs and redistribution of shear forces. By summarizing the previous test results and adopting the mode of Eurocode 4, Johnson et al. [12] proposed a formula for calculating the fatigue life of composite beams. Hanswille et al. [13,14] conducted fatigue tests on 71 push-out specimens of stud connectors designed according to Eurocode4. The static strength of the stud drops at the early fatigue life of 10 % to 15 % owing to the initial crack at the stud's root, according to the testing data. The results of fatigue testing with various loading sequences reveal that the P-M linear cumulative damage theory does not match the real stress state.

Previous researches on stud shear connectors mainly focused on non-damaged studs and concrete slabs, the research on the fatigue performance of the bolt caused by the cracks and the damage of the bolt is limited. The effects of the stud damage and two types of concrete cracks on the fatigue life, failure mechanism, and slip between concrete slab and steel beam were investigated using four static push-out tests and the corresponding four fatigue push-out specimens.

2. Experimental program

2.1. Specimen design and material properties

Eight push-out test specimens, including four static and four fatigue specimens were tested in this study. The specific dimensions of the test specimen are shown in Fig. 1. The parameters of the test, including stud damage, concrete transverse crack and concrete longitudinal crack, are listed in Table 1. The concrete slab had a thickness of 150 mm, a width of 400 mm, and a height of 500 mm. Q345 hot rolled H steel was utilized as the steel beam with a length of 550 mm. The pressure load, the vertical displacement of concrete, the vertical displacement of steel beam, and the strain of studs were measured in the static and fatigue test by LTR-1 load sensor, digital display dial indicator, and DH3816 strain testing system, respectively. The stud has a diameter of 19 mm and an overall length of 80 mm, and it is made of ML15 steel. The rebars were HPB300 type with diameters 10 mm and 8 mm. The longitudinal and transverse reinforcement ratios of specimens were 0.785 % and 0.670 %, respectively. The material property of the stud connector was obtained by metal tensile test with a 20 T universal testing machine and the yield strength and ultimate tensile strength were 400.6 MPa and 480.5 MPa (Fig. 2). The yield strength, ultimate tensile strength, and young's modulus of rebar with a diameter of 8 mm and 10 mm are 312.5 MPa, 471.8 MPa, 195 GPa, and 390.2 MPa, 458.5 MPa, 195GPa. Three standard cube specimens were used to measure the compressive strength and elastic modulus of concrete, and the average results were 57.54 MPa and 35.7 GPa, respectively.

Concrete and steel are the two major materials damaged in the composite beam under load. Overall, it can be said that there were three different types of steel fatigue failure modes (shown in Fig. 3 (a)) [15]:

Table 1
Testing variables.

Group	Specimen	Damage type	P_{max}/P_{min} (kN)
Static	S-P-N	none	
	S-P-S	stud damage	
	S-P-T	transverse crack	
	S-P-L	longitudinal crack	
Fatigue	F-P-N0	none	220/40
	F-P-N	weld damage	220/40
	F-P-S	stud damage	140/40
	F-P-T	transverse crack	220/40
	F-P-L	longitudinal crack	220/40

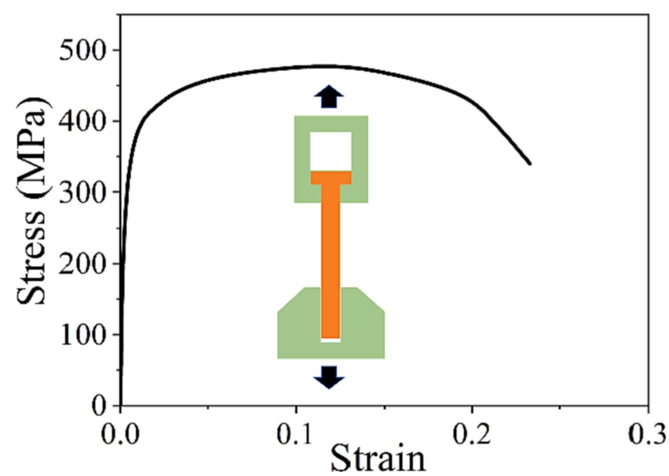

Fig. 2. Stress–strain curve for the stud steel material.

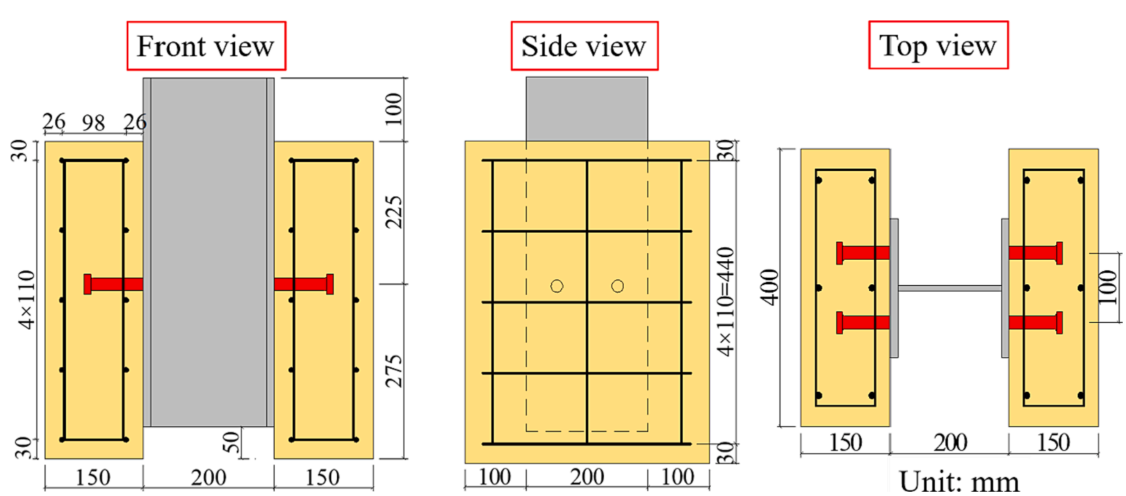

Fig. 1. Specific dimensions of push-out specimen.

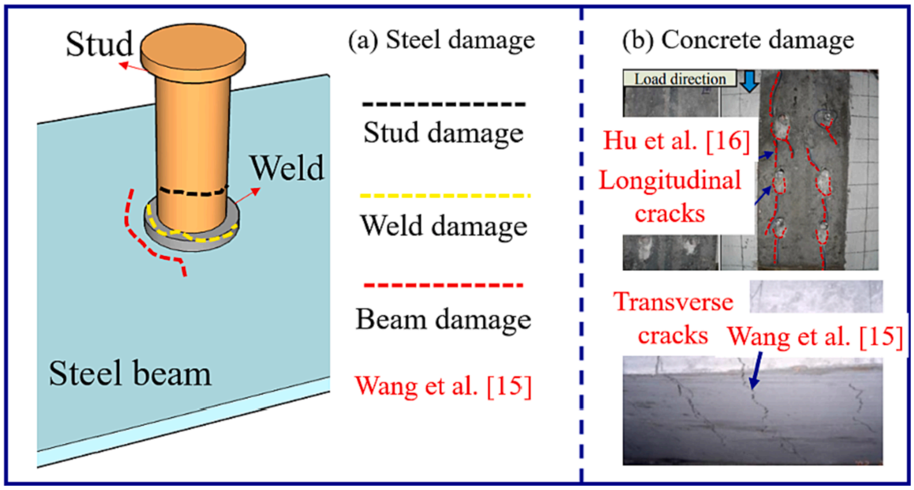

Fig. 3. Locations of steel and concrete damage.

(1) The bottom portion of the studs had a failure due to fatigue shear, (2) The steel beam near the stud developed a fatigue crack, (3) weld failure in steel beam. Additionally, Qi et al. [6] investigated the influence of the damage degree on the static shear strength of the stud (stud damage depths were 3 mm, 7 mm, and 11 mm, respectively). They discovered that while the shear strength of the stud was not significantly impacted when the shank area was reduced by 36.6 %, it was significantly impacted when the shank area was reduced by 62.9 %. Therefore, the initial damages of the steel in this study included the weld damage caused by poor welding and the stud damage. The stud area was reduced about 62.9 % by cutting directly 15 mm away from the root of the stud at a cutting depth of 11 mm. A distance of 15 mm is reserved to avoid the influence of welding on the damage of the stud.

According to the research that is currently available, the major cause of concrete damage is the presence of cracks. Around the stud, longitudinal and transverse cracks would appear [15,16]. Consequently, there are two types cracks including longitudinal and transverse cracks that were preset in the concrete deck. The specific position is shown in the Fig. 4. The preset length and depth of the cracks were set at 100 mm and 80 mm, respectively, since the distance between the studs and the length of the studs are 100 mm and 80 mm, respectively. This allows the preset damage cracks to completely cover the studs. The concrete slab crack of composite beam widens to its maximum size under negative bending moment. The maximum width of the crack, according to earlier study [17], is around 5 mm. As a result, the width of the preset crack was determined to be 5 mm according to the most unfavorable principle.

Fatigue test was designed according to the results of static tests. The purpose of the fatigue test is to determine how different types of damage affect fatigue life. Thus, a single load amplitude was used to conduct the fatigue test. The upper limit of load in general fatigue test would be taken as the percentage of the static ultimate load. In order to obtain more data in this study, the upper limit of the fatigue test load was taken as 40 % of the static ultimate load, so that the fatigue failure of the specimen could not be too fast. According to static testing results, the ultimate bearing capacity of concrete damage and non-destructive specimens was similar, and the total bearing capacity of four studs varied between 569.2 kN and 590 kN. Therefore, a conservative upper limit of 220kn (40 % of 550 kN) was chosen. Since the specimens with stud damage have a bearing capacity of 369.9 kN, the upper limit was conservatively set at 140 kN (40 % of 350 kN). The lower limit was established at 40 kN to ensure that each stud would be subjected to a load of 10 kN in.

order to conduct the fatigue test stably.

2.2. Test setup and procedures

The push-out test setup and procedures were determined in accordance with the requirements of Japan Society of Steel Construction (JSSC) [18]. The test loading system is depicted in Fig. 5, which includes platform, dial indicator, fixing device, steel plate, force transducer, and

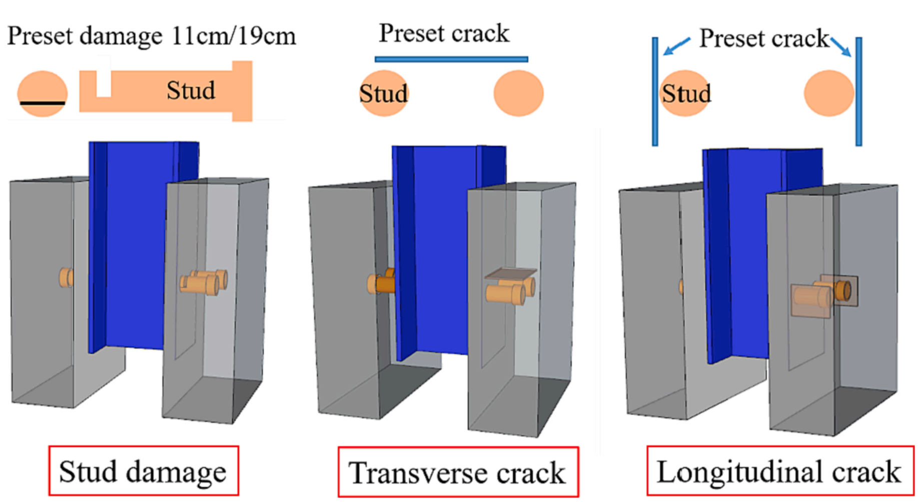

Fig. 4. Push-out specimens with different damage types.

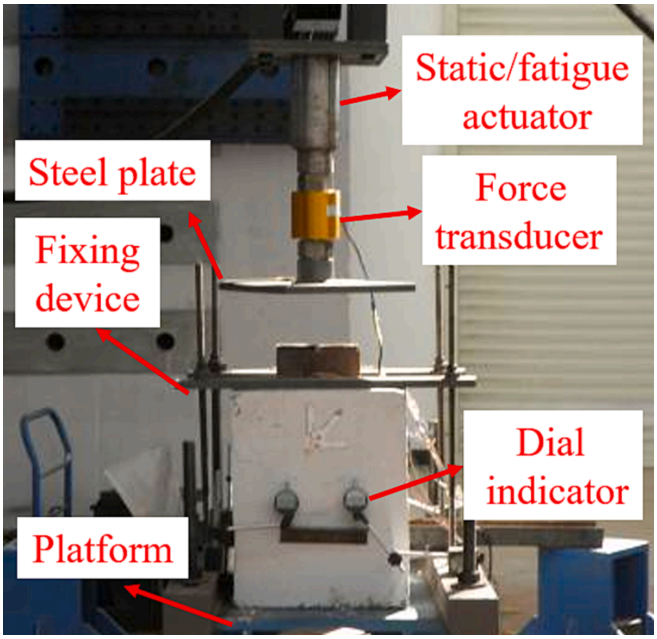

Fig. 5. Instruments of test.

actuator. The fixing device is used to secure the specimen in fatigue test prevent the specimen from moving during fatigue loading. For static tests, the specimens were preloaded before the formal test to ensure that each equipment functioned properly. Load control with an increment of 5 kN was utilized initially in formal loading. Data of load sensors and strain gauges were collected after loading of each level of load, and the readings of displacement were recorded. Meanwhile, crack development of concrete slab was observed. Displacement control was used to replace force control when the relative slip between steel and concrete reached 1 mm. According to this control mode, the displacement loading rate was 0.01 mm/s, and every time the displacement rose by 0.2 mm, all data was gathered and loaded until the specimen failed. Same as static test, fatigue tests were also preloaded to test whether the instrument was in normal condition. In the fatigue test of undamaged and pre-damaged specimens (concrete crack), the upper limit of fatigue load is 220kN, about 42 % of the ultimate load of the corresponding static test, and the lower limit of fatigue load is 40kN. For stud damaged specimens, the upper limit of fatigue load is 140kN, about 42 % of the ultimate load of the corresponding static test, and the lower limit of fatigue load is 30kN. As shown in Fig. 6, the fatigue loading procedures were mainly divided into two parts: static preloading and fatigue loading. In static preloading stage, 20 % of the upper limit load was used as one level until it was loading to the upper limit, and the load is unloaded to the median value of load by grading during unloading. The fatigue loading procedure is as follows: switch the software to dynamic loading → keep the median load → set the load amplitude → adjust the loading frequency. During the fatigue test, the stability of the load should be maintained to ensure that the error does not exceed 3 % of the maximum load.

3. Experimental results and discussion

3.1. Static experimental results

The load-slip relationship for the push-out test is shown in Fig. 7, where the load is the force of a single stud, which is equal to the machine load divided by four. The failure processes of static push-out specimens are similar. Take S-P-N specimen for example, the load was sustained mostly by the interface adhesion and friction between the steel beam and the concrete slab on both sides at the early stage of test loading. When the load of single stud progressively increased to 41.3 kN, it exceeded the adhesion and friction forces between the steel beam and the concrete plate, causing the steel beam and concrete plate to slip. When the load was increased to around 50kN, along with the sound of concrete crushing. Finally, two studs on the steel beam were shear damaged, and the concrete slab was totally removed from the steel beam. For S-P-S, two studs were shear damaged on one side, and the breakdown occurred suddenly. The shear capacity and stiffness were reduced by 36.6 % and 40.5 % when the damage degree of the stud is 62.9 % and transverse and longitudinal cracks have little effect on these.

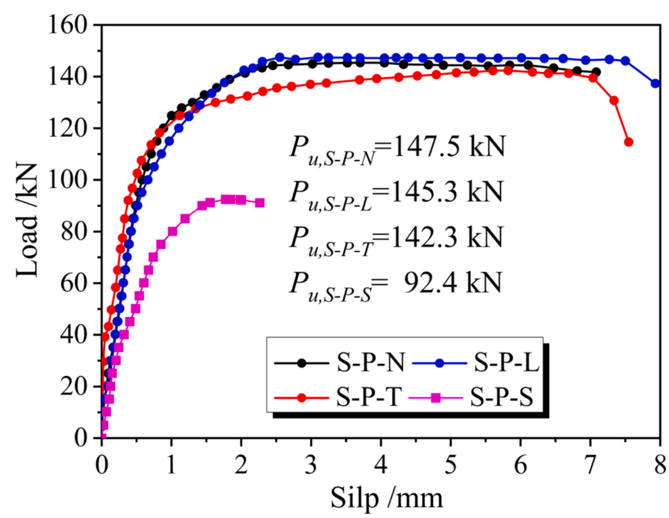

Fig. 7. Load-slip relationship of single stud at static load.

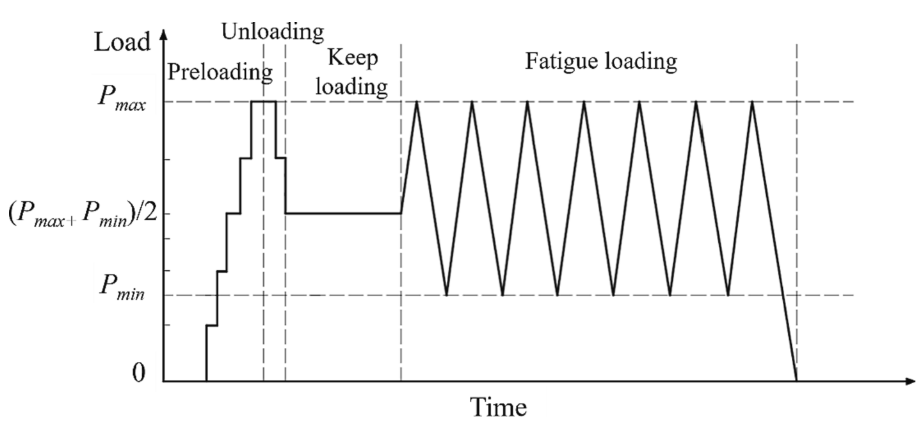

Fig. 6. Fatigue loading procedures.

3.2. Fatigue experimental results and discussion

3.2.1. Fatigue experimental results

The results of the fatigue test are summarized in Table 2. As Fig. 8 show, for F-P-N specimen in this fatigue test, the fatigue failure was mainly due to the poor welding quality and the initial crack during the welding of the stud, which leaded to the gradual development and diffusion of the crack under the fatigue load and the failure of the stud. Therefore, the fatigue test of a nondestructive specimen (F-P-N0) was supplemented, and only the fatigue life of this specimen was obtained, which was 122.86×10^4. Standard stud shear fatigue failure occurred in F-P-S, F-P-T, and F-P-L specimens, with F-P-T and F-P-L happening near the weld toe and F-P-S occurring at the pre-damaged location.

Under fatigue load, the tensile and shear composite stress was considerable at the damage point for pre-damaged specimen (F-P-S). As a result of the damage, a crack appeared at the stud's damage location under fatigue load, eventually leading to failure. Two studs were simultaneously damaged, and the concrete slab and steel beam were totally separated. For the specimens with concrete cracks preset, typical fatigue failure occurred on the studs, and obvious gray and bright surfaces could be seen. The gray surface was the fatigue crack propagation zone, and the bright surface is the static shear zone. With the increased of the number of cycles, the fatigue cracks gradually expanded, leading to the decrease of the net cross section area at the root of the stud. When the net cross section area at the root of the stud was not enough to continue to bear the fatigue load amplitude limit, the weak section was suddenly shear damaged. In this test, the fatigue life of the stud with good welding quality could reach 1.16 million times, while the fatigue life of the stud with poor welding quality is only 54×10^4, reducing by more than 50 %. The fatigue life of the specimen is only 12×10^4, which is reduced by about 90 %, which is more serious than the static performance reduction.

According to Fig. 8, the concrete wedge block area behind the stud was also damaged, which was similar to the static result, indicating that the concrete wedge block also contributed to the fatigue performance. The fatigue life of stud in specimen with longitudinal cracks is about 22 % longer than that with transverse cracks. According to the stress state of the stud [16], it can be found from Fig. 9 that the transverse crack was located in the stress area on the front of the stud, while the longitudinal crack does not affect the concrete wedge block area. Therefore, the transverse crack has a greater impact on the shear resistance of the stud than the longitudinal crack, which leads to the decline of fatigue life.

3.2.2. Residual slip growth due to fatigue

Under fatigue load, with the increase of the number of cycles, slip between concrete slab and steel beam gradually increases [19], which leads to the reduction of the sectional stiffness of composite beams. According to the relationship between residual slip and cycles in Fig. 10, it can be found that for F-P-S specimen, the crack germination stage is about 0–10,000 cycles, and it develops steadily to 10–100,000 cycles. For the F-P-N specimen, which had a toe injury, the buildup of residual slip was similar to that of nondestructive specimen (F-P-N0) until 40,000 cycles. But after 50,000 fatigue cycles, it continued to quickly grow until fatigue failure due to the initial damage. The relationship between residual slip and cycle numbers for F-P-L specimen was similar to that of the nondestructive specimen (F-P-N0), and the absolute value of residual slip is somewhat bigger. The typical three-stage rule of fatigue development is observed in these specimens obviously. The complete residual slip data of F-P-T specimen was not obtained because the dial indicators were out of power during the experiment. According to the fatigue test results, it could be found that damage of weld toe and stud would lead to rapid accumulation of damage in the stable fatigue development stage, which may be caused by local stress concentration of weld toe and the notch in stud.

Meanwhile, cracks in concrete would lead to large deformation of concrete in the early stage, and increase the slip between concrete slab and steel beam, which has less influence on the fatigue performance of the stud than welding defects. As shown in Fig. 10, the growth rate of residual slip is about twice that of nondestructive component before 20,000 cycles.

Oehlers [20] conducted fatigue tests on 116 push-out specimens, using unidirectional cyclic loading and reverse cyclic loading. According to the Paris formula commonly used to calculate fatigue strength and fatigue life in fracture mechanics and the results of push-out test, the relationship between slip δ between steel beam and concrete plate and the number of fatigue load cycles n is proposed, c and m were constants:

$$d\delta/dn = c(\Delta\tau/P_u)^m \tag{1}$$

According to the fatigue test results, Hanswille G et al. [13,14] obtained the calculation formula of residual slip δ_r between steel beam and concrete slab after n cycles:

$$\delta_r = C_1 - C_2 \ln\left(\frac{N-n}{n}\right) \geqslant 0 \tag{2}$$

$$C_1 = 0.104 \cdot e^{3.95 \cdot \frac{P_{\max}}{P_u}} \tag{3}$$

$$C_2 = 0.664 \cdot \frac{P_{\min}}{P_u} + 0.029 \tag{4}$$

Fatigue damage process is a microscopic damage accumulation process, which can also be characterized from the macroscopic deformation. In this study, the accumulation of residual slip is used to characterize the accumulation of damage. The test results are compared with the calculation results of Equation. (2) in Fig. 11. The complete residual slip data of F-P-T specimen was not obtained because the dial indicators were out of power during the experiment. In addition to the test results of F-P-S specimen can be consistent with the results calculation, the test results of the F-P-N specimen in the stage of stable development grow faster than the calculation results, the slope is about 2 times. In reality, the calculation result of F-P-N specimen is incorrect because the static ultimate bearing capacity of a damaged specimen is lower than that of a nondestructive specimen, resulting in overly high C_1 and C_2 values. The residual slips of F-P-L and F-P-N0 specimens in the first stage is higher than the calculation results, and the development rate in the second stage is close to the calculated result, but the duration of the second stage is lower than the calculated result.

In general, the fatigue test results are relatively discrete. Four fatigue tests were undertaken in this study, therefore, there are not enough

Table 2
Results of fatigue tests.

Specimen	Fatigue load /kN			Shear stress of single stud /MPa			Cycles /10^4	Failure mode
	$P_{\max}$	$P_{\min}$	ΔP	$\tau_{\max}$	$\tau_{\min}$	$\Delta\tau$		
F-P-N	220	40	180	194.08	35.29	158.79	54.31	c
F-P-N0	220	40	180	194.08	35.29	158.79	122.86	a
F-P-S	140	40	100	123.51	35.29	88.22	12.32	a
F-P-T	220	40	180	194.08	35.29	158.79	95.84	a
F-P-C	220	40	180	194.08	35.29	158.79	116.62	a

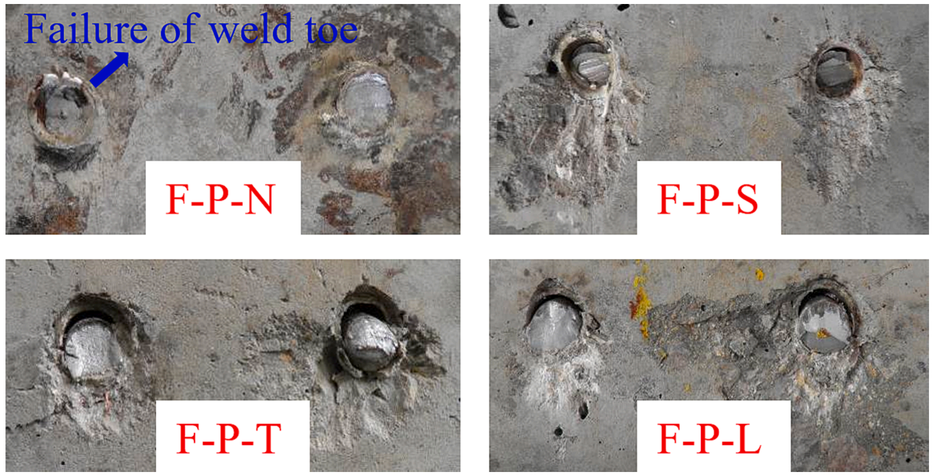

Fig. 8. Failure modes of fatigue specimens.

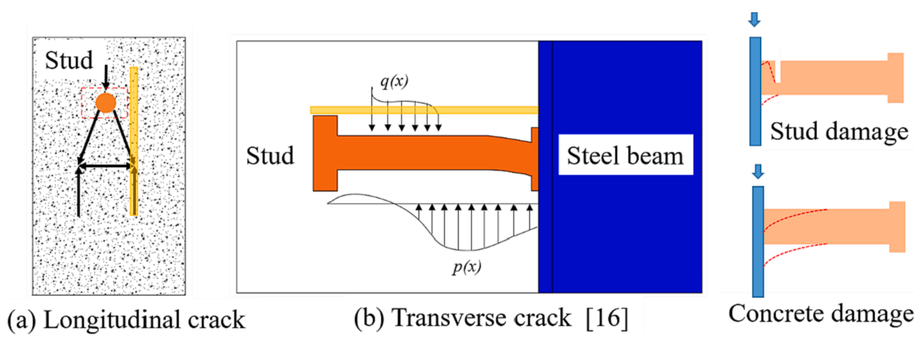

Fig. 9. Stress state of stud.

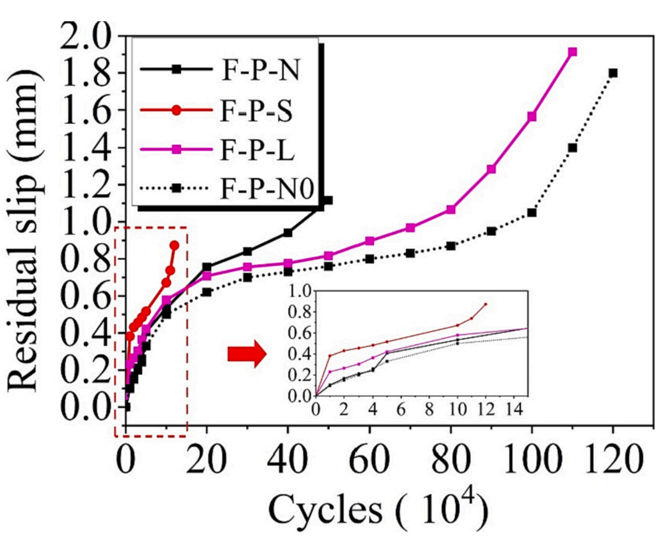

Fig. 10. Residual slip of fatigue specimens.

samples to provide an adjusted method for calculating C1 and C2 values. Only qualitative analysis of the parameter changes and associated affecting variables is possible. The slope of the fatigue stability development section in Fig. 11 is fitted as K_1. Equation. (2) shows that C1, where n = N/2, equals the slip value, and C2, which is the damage accumulation rate as indicated by the linear fitting slope K_1 of the fatigue stability development stage, equals the damage accumulation rate. As a result, C1 and C2 could be determined and their respective values entered into Equation. (2). Fig. 11 displays the fitting results.

According to the Equation. (2), C1 stands for the slip value at n = N/2, which is the curve's slope turning point in the stable portion, $\delta_r'' = 0$. From this perspective, the effective area of the stud, particularly C1 generated from the fitting of experimental data, has an impact on the key accumulation rate as well. It has been shown that the damage area has the biggest impact. The upper and lower limits of fatigue should both have an impact on C2, which influences the slope of the fitted curve and the pace of fatigue development.

$$\delta'_{r,n=\frac{N}{2}} = \frac{C_2 N}{N\left(\frac{N}{2}\right) - \left(\frac{N}{2}\right)^2} = K_1 \tag{5}$$

$$\delta_{r,n=\frac{N}{2}} = C_1 - C_2 \ln\left(\frac{N - \left(\frac{N}{2}\right)}{\frac{N}{2}}\right) = C_1 \tag{6}$$

All the other specimens had shear fatigue at the root of the stud, with the exception of the F-P-S specimen, which failed at the predetermined damage point under fatigue pressure. The stud was in the composite stress state of bending and shear for the specimens with stud damage, and there was a significant stress concentration at the incision, which was also the cause of the short fatigue life. The studs were essentially subjected to direct shear force in the case of the other damaged specimens, and finally they were destroyed at the root. The slip buildup was somewhat hastened by the concrete cracking, and the fatigue life was somewhat decreased. The fatigue life of the specimens with transverse crack (F-P-T) and longitudinal crack (F-P-L) was reduced by roughly 22 % and 5 % correspondingly in comparison to the non-destructive specimens (F-P-N0). The fatigue life also dropped dramatically, by around

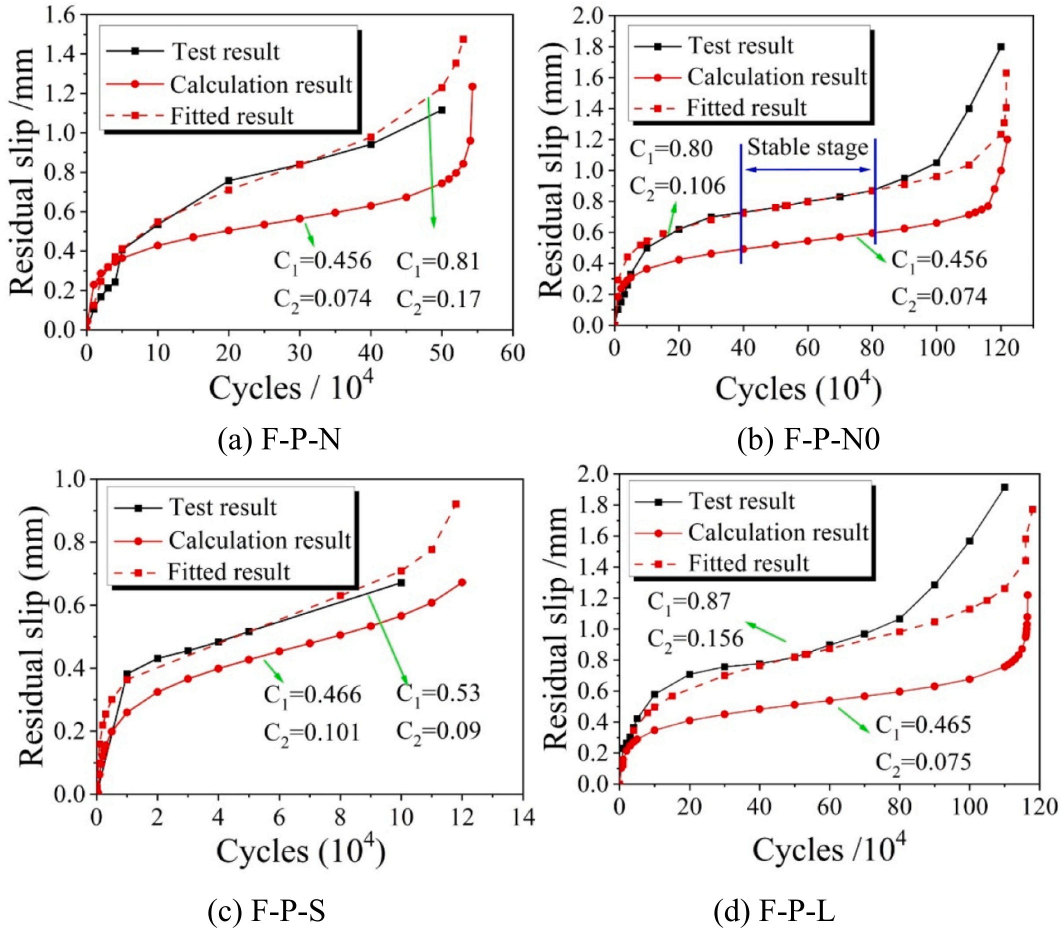

Fig. 11. Residual slip of calculation results.

55 %, when welding damage occurred. It has been discovered that when concrete was damaged, the fatigue performance as still well even if the crack measured 5 mm. However, following damage to the stud rod or the welding site, the fatigue life cannot be totally assured, and treatment is urgently required.

4. Conclusions

Static and fatigue tests were carried out on studs in steel–concrete composite study the effects of initial damage in stud and concrete on fatigue performance. The following conclusions are drawn:

1. Compared with nondestructive specimens, the fatigue life of transverse crack and longitudinal crack specimens were reduced by 22 % and 4.9 %, respectively, which is determined by the stress characteristics of the stud. Transverse crack makes the stud easily in a state of bending and shear composite, while longitudinal crack does not.
2. Compared with the preset cracks of concrete, the damage of stud and weld collar had more influence on fatigue performance, in which the loss of stud section of 62.9 % leaded to only about 10 % of fatigue life. The initial damage of stud accelerates the damage accumulation in the stable fatigue development stage, while the concrete cracking leads to the increase of residual slip in the early stage.
3. The existing calculation methods of residual slip are not completely applicable to the test results of different stresses, and most of the calculation results are too small, which requires some modification of their coefficients.

CRediT authorship contribution statement

Kaiwei Lu: Conceptualization, Methodology, Writing – original draft. **Linpu Du:** . **Qizhi Xu:** . **Yiming Yao:** Writing – review & editing, Data curation. **Jingquan Wang:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

[1] Nie J, Cai CS. Steel-Concrete Composite Beams Considering Shear Slip Effects[J]. J Struct Eng 2003;129(4):495–506.

[2] Xue WC, Ding M, Wang H, Luo ZW. Static behavior and theoretical model of stud shear connectors. J Bridge Eng 2008;13(6):623–34.
[3] Bonilla J, Bezerra LM, Mirambell E, Massicotte B. Review of stud shear resistance prediction in steel-concrete composite beams. Steel Compos Struct 2018;27(3): 355–70.
[4] Rambo-Roddenberry, M.D. Behavior and Strength of Welded Stud Shear Connectors, 2002, Ph.D. Dissertation, University of Blacksburg, VA, USA.
[5] Han Q, Wang Y, et al. Numerical analysis on shear stud in push-out test with crumb rubber concrete[J]. J Constr Steel Res 2017;130:148–58.
[6] Jianan Qi, Jingquan W, Ming Li, et al. Shear capacity of stud shear connectors with initial damage: Experiment, FEM model and theoretical formulation[J]. Steel Compos Struct 2017;25(1):79–92.
[7] Hu Y, Zhong R, Meloni M, et al. A Novel Shear Strength Prediction Approach for Headed Shear Studs Embedded in Ultrahigh-Performance Concrete[J]. J Struct Eng 2021;147(11):04021181.
[8] Rong X. Experimental study on static and fatigue behaviors of stud connectors for composite beams after corrosion[J]. Chin Civil Eng J 2013;46(2):10–8.
[9] Slutter RG, Fisher JW. Fatigue strength of shear connectors[R]. Highw Res Rec No.147 1966.
[10] Hiragi H, Matsui S, Fukumoto Y. Static and fatigue strength of studs [J]. Iabse Symposium Brussels 1990;60:197–202.
[11] Gattesco N, Giuriani E, Gubana A. Low-cycle Fatigue Test on Stud Shear Connectors[J]. J Struct Eng 1997;123(2):145–50.
[12] Johnson RP. Resistance of Stud Shear Connectors to Fatigue[J]. J Constr Steel Res 2000;56(2):101–16.
[13] Hanswille G, Porsch M, Ustundag C. Resistance of Headed Studs Subjected to Fatigue Loading: Part I: Experimental Study[J]. J Constr Steel Res 2007;63(4): 475–84.
[14] Hanswille G, Porsch M, Ustundag C. Resistance of Headed Studs Subjected to Fatigue Loading, Part II: Analytical Study[J]. Journal of Constructional Steel Research, 2007, 63(4): 485-49.
[15] Wang Y, Nie J. Fatigue behavior of studs in a composite beam based on fracture mechanics[J]. China J. Tsinghua Univ. (Science and Technology) 2009;49(9): 1467–70.
[16] Hu Y, Qiu M, Chen L, et al. Experimental and analytical study of the shear strength and stiffness of studs embedded in high strength concrete[J]. Eng Struct 2021;236.
[17] Qi J, Cheng Z, Wang J, Tang Y. Flexural behavior of steel-UHPFRC compositebeams under negative moment. Structures 2020;24:640–9.
[18] Japan Society of Steel Construction. Push-out test method and relevant research status of cylindrical head stud. Technical Report of JSSC: 35, 1996.
[19] Nie JG, Wang YH. RESEARCH STATUS ON FATIGUE BEHAVIOR OF STEEL-CONCRETE COMPOSITE BEAMS[J]. Eng Mech 2012;29(6):1–11.
[20] Oehlers DJ, Coughlan CG. The Shear Stiffness of Stud Shear Connections in Composite Beams [J]. J Construct Steel Res 1986;6(4):273–84.