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Effect of corrosion on the shear transfer behavior of stud shear connectors

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ABSTRACT

The effect of corrosion on the shear transfer behavior of stud shear connectors was investigated in this study. Experimental investigation was performed using an innovative test setup for single stud shear connector. Two series of specimens having different stud diameters were fabricated and tested. The test specimens were firstly corroded to different corrosion rates by electronic accelerating method. Loading test was then performed to obtain the load-slip curves and ultimate strengths of corroded test specimens. Corrosion rates were measured from the studs obtained from the failure test specimens. Test results were compared with standard push out test specimens having the similar corrosion rates. It is shown that the test results obtained from the single stud shear connectors are conservative compared with the corroded push test specimens, which proves the validation of single stud shear connector test method. The effect of corrosion on the shear transfer behavior of stud shear connectors is also presented.

Key words: Corrosion; Loading test; Push test specimen; Single stud shear connector; Test setup

1.0 INTRODUCTION

The economic loss caused by corrosion in concrete structures was tremendous. Therefore, effect of the corrosion is crucial to predict the behavior of concrete structures in use. Many researches have been conducted to evaluate the effect of corrosion of reinforcing bars on the concrete structures. (Bazant, 1979; Vassie, 1984; Asami and Kikuchi, 2003; Duffó, *et al.*, 2004; Caré, *et al.*, 2008). However, there is few research conducted on the effect of corrosion on the behavior of stud shear connectors used in steel-concrete composite beams. (Chen *et al.*, 2016; Wang *et al.*, 2016)

Steel-concrete composite beams are developed structures based on RC structures and steel structures, and nowadays widely used in buildings and bridge constructions due to the satisfying utilization of the two materials. However, the unfavorable condition may cause corrosion occur in the interface between the steel and concrete since there is lack of protection. Headed stud shear connectors are the most common type of shear connectors and are used in composite bridges. The behavior of the stud *connectors* has been broadly investigated by many researchers (Lam and Ellobody, 2005; Nie, *et al.* 2008; Xue, *et al.*, 2008**;** Smith and Couchman, 2010; Mirza and Uy, 2010; Kim, *et al.*, 2011). The deterioration in strength of stud connectors due to fatigue damage has also been reported (Coughlan, 1987; Oehlers, 1990; Johnson, 2000; Dai and Liew, 2010; Dogan and Roberts,2012; Lin et *al*, 2013; Wang *et al.*, 2014). Chen *et al.* (2016) has investigated the behavior of corroded shear stud connectors based on push out test specimens. But the corrosion rates of four stud shear connectors of push out test specimens were different. In order to accurately evaluate the effect of corrosion, an innovative test setup for single stud shear connectors was proposed in this study.

2.0 EXPERIMENTAL INVESTIGATION

2.1. Test Specimens

The proposed test device is shown in Fig. 1(a). Both the horizontal force and vertical force on the test specimen was measured. The horizontal force was applied by a hand jack. Fig. 1(b) shows details of the test specimens.

The test specimens were labeled that the corrosion state, nominal stud diameter and excepted corrosion rate and could be identified from the label.

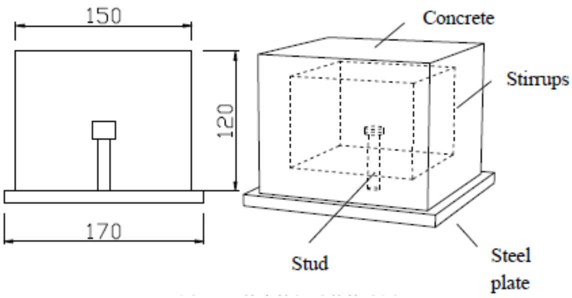

Fig. 1 Test setup of single stud shear connector
(a) Test device (b) Test specimen

For example, the labels "W10.0-5" and "B16.0-10" define the specimens as follows:

- The first letter indicates that the designed corrosion state, where the prefix letter "W" refers to corrosion along whole stud shank while the letter "B" refer to corrosion only at the bottom of stud shank.
- The following three digits (10.0 and 13.0) indicate the nominal diameter of the studs in mm.
- The following one (5) or two digits (10) are the expected corrosion rates of stud in percentage.

2.2. Material Properties and Measurements

Three concrete cubic specimens were prepared at the time of push test specimen casting, to determine the concrete strength of the push test specimens. Table 1 summarizes the material properties of concrete at 28 days. Two kinds of studs with the nominal diameter of 10.0 and 13.0 mm are used in this study. Tensile tests for the stud material were conducted. The yield stress from the tensile tests was determined by 0.2% strain because the steel for studs generally does not show clear yielding point. Table 2 summarizes the material properties of stud material. Quality control of welding process is a very important factor since the effect of welding quality may cover the effect of corrosion. Therefore, welding trials were carried out to obtain proper and reliable welding quality.

Table 1. Material properties of concrete

Specimen	E_c(MPa)	f_{cu} (MPa)
1	3.32×10^4	45.4
2	3.38×10^4	45.8
3	3.40×10^4	46.7
Average	3.37×10^4	46.0

Table 2. Material properties of stud material

Specimen	Elastic modulus (MPa)	Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)
10.0 mm	1.94×10^5	462.7	512.0	26.4
13.0 mm	1.98×10^5	431.2	490.6	24.9

2.3 Accelerating Corrosion Process

All specimens, except the uncorroded one (control specimen), were immersed in a 5% NaCl solution for three days after cured for 28 days, then the direction of current about 0.2 μA/cm^2 was arranged for accelerating stud corrosion, studs worked as the anodes, while a piece of stainless steel positioned in the solution served as cathode, as shown in Fig. 2. The corrosion time of each specimen was determined based on the expected corrosion rate. The faraday's theory is used to calculate the corrosion time. The calculated results are shown in Table 3 and Table 4 for series 10.0 mm and series 13.0 mm, respectively. It should be noted that the actual corrosion rates of test specimens may differ from those expected corrosion rates.

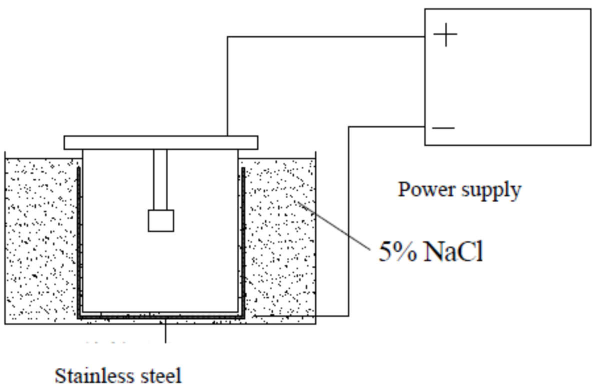

Fig.2. Set-up of Electronic accelerating corrosion

Table 3. Excepted stud corrosion rate and actual corrosion time of 10.0 mm series

Specimen	Excepted corrosion rate (%)	Corrosion time (days)	Measured corrosion rate (%)
W13.0-0	0	0	0
B13.0-0			0
W13.0-5	5	599	2.77
B13.0-5			9.56
W13.0-10	10	1199	9.09
B13.0-10			16.67
W13.0-15	15	1798	12.15
B13.0-15			19.08
W13.0-20	20	2398	15.35
B13.0-20			23.81
W13.0-25	25	2997	21.46
B13.0-25			29.22
W13.0-30	30	3596	24.35
B13.0-30			36.74
W13.0-35	35	4196	29.13
B13.0-35			40.62
W13.0-40	40	4795	36.78
B13.0-40			44.78
W13.0-45	45	5394	39.07
B13.0-45			50.04
W13.0-50	50	5994	46.44
B13.0-50			----

2.4 Loading Test Setup And Procedure

Corroded push test specimens were loaded in the test device shown in Fig. 1. The horizontal and vertical forces were measured. The measured ultimate strengths of specimens are shown in Tables 5 and 6. Slip between the steel member and the two slabs is measured using LVDTs. In this study, the expected failure load of corroded specimens is difficult to estimate and so the load is first applied in increments up to 10% of the failure load of the previous specimen. Subsequent load increments were then be imposed such that failure does not occur in less than 15 minutes and the approximate loading rate is 0.5 mm/min. The longitudinal slip between each concrete slab and the steel section was measured at each load increment. The friction between the concrete block and steel plate was obtained by specimen without studs, as shown in Fig. 3. The test results of three test specimens were shown in Fig. 4. The friction coefficient obtained by fitting curve is 0.58.

Table 4. Excepted stud corrosion rate and actual corrosion time of 13.0 mm series

Specimen	Excepted corrosion rate (%)	Corrosion time (days)	Measured corrosion rate (%)
W13.0-0	0	0	0
B13.0-0			0
W13.0-5	5	599	2.77
B13.0-5			9.56
W13.0-10	10	1199	9.09
B13.0-10			16.67
W13.0-15	15	1798	12.15
B13.0-15			19.08
W13.0-20	20	2398	15.35
B13.0-20			23.81
W13.0-25	25	2997	21.46
B13.0-25			29.22
W13.0-30	30	3596	24.35
B13.0-30			36.74
W13.0-35	35	4196	29.13
B13.0-35			40.62
W13.0-40	40	4795	36.78
B13.0-40			44.78
W13.0-45	45	5394	39.07
B13.0-45			50.04
W13.0-50	50	5994	46.44
B13.0-50			----

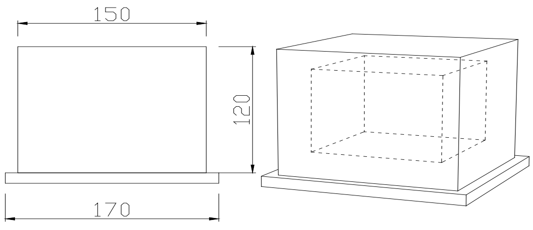

Fig.3. Test specimens for friction test

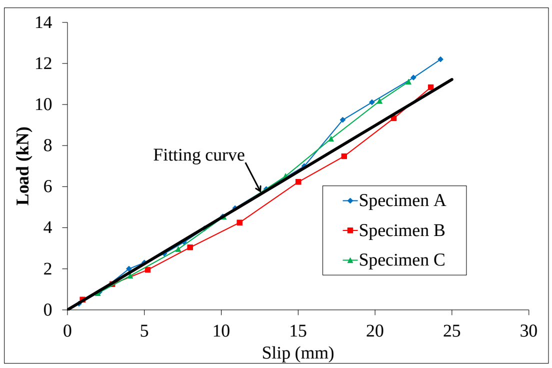

Fig. 4. Load-slip curves of specimens without studs

Table 5. Ultimate strengths of single stud specimens 10.0 mm series

Specimen	Measured corrosion rate (%)	Ultimate Strength (kN)
W10.0-0	0	43.37
B10.0-0	0	43.37
W10.0-5	2.97	38.67
B10.0-5	8.23	37.6
W10.0-10	8.93	36.11
B10.0-10	12.68	31.62
W10.0-15	12.01	30.62
B10.0-15	17.38	31.62
W10.0-20	17.65	29.53
B10.0-20	25.71	30.16
W10.0-25	20.06	27.68
B10.0-25	32.23	28.34
W10.0-30	25.55	24.59
B10.0-30	39.19	27.89
W10.0-35	---	---
B10.0-35	44.78	22.86
W10.0-40	38.15	21.38
B10.0-40	49.09	18.54
W10.0-45	42.41	18.75
B10.0-45	53.43	14.09
W10.0-50	54.14	14.38
B10.0-50	68.09	8.61

Table 6. Ultimate strengths of single stud specimens 13.0 mm series

Specimen	Measured corrosion rate (%)	Ultimate Strength (kN)
W13.0-0	0	65.28
B13.0-0	0	65.28
W13.0-5	2.77	61.76
B13.0-5	9.56	60.68
W13.0-10	9.09	55.95
B13.0-10	16.67	54.2
W13.0-15	12.15	54.42
B13.0-15	19.08	45.51
W13.0-20	15.35	51.16
B13.0-20	23.81	45.1
W13.0-25	21.46	45.5
B13.0-25	29.22	42.14
W13.0-30	24.35	43.5
B13.0-30	36.74	35.25
W13.0-35	29.13	37.01
B13.0-35	40.62	31.44
W13.0-40	36.78	34.95
B13.0-40	44.78	29.35
W13.0-45	39.07	32.34
B13.0-45	50.04	16.21
W13.0-50	46.44	27.6
B13.0-50	----	65.28

Table 7. Ultimate strengths for push out test specimens D10.0series

Specimen	Measured corrosion rate (%)	Ultimate strength (kN) Test (P_{test})
D10.0-0A	0	42.9
D10.0-10	4.93	40.5
D10.0-20	16.44	38
D10.0-30	23.61	34.8
D10.0-40	34.66	30.1
D10.0-50	44.33	25.8

2.5 Corroded Push Out Test

Two series of corroded push out test specimens were also tested for comparison. The test specimens were corroded and tested as the same procedure described in Chen *et al.* (2016). The materials used in push out test specimens were the same as these used in single stud test specimens (different from test specimens in Chen et al (2016)).

Table 8. Ultimate strengths for push out test specimens D13.0series

Specimen	Measured corrosion rate (%)	Ultimate strength (kN) Test (P_{test})
D13.0-0A	0	69.3
D13.0-10	6.78	66.3
D13.0-20	15.41	62.1
D13.0-30	22.43	57.3
D13.0-40	34.99	45.8
D13.0-50	42.12	41.9

The measured corrosion rates of studs and ultimate strengths were shown in Tables 7 and 8. The test specimens were labeled that the nominal stud diameter and excepted corrosion rate could be identified from the label. The first letter indicate that the nominal diameter of the stud, where the prefix letter “D” refers to diameter.

3.0 TEST RESULTS

3.1 Measurement of Stud Corrosion Rate

The corroded studs were retrieved from the failed specimens (shown in Fig. 5.) and the corrosion product was cleaned using a corrosion-inhibited HCl solution (Bertoa, *et al.*, 2008). The corroded studs having different corrosion rates are shown in Fig. 6 The area loss of the steel rebar (ΔA) was estimated afterwards by subtracting the post-corrosion area from the measured pre-corrosion area.

The post-corrosion area of stud was calculated using the measured diameter of the shank of the stud. The measured diameter of the shank was used to calculate the corrosion rate of each stud (ψ) as: ψ = (A-ΔA)/A%. For push out test specimens, the average corrosion rate of eight studs is taken as the corrosion rate of each push test specimen. It is shown that the measured corrosion rates of both single stud test specimen and push test specimens are different from those expected corrosion rates. There is no corrosion occurs between the interface of concrete slab and steel plate.

(a) Specimen W10.0-5

(b) Specimen W13.0-10

Fig. 5. Typical failure mode of single stud shear connector specimen

(a) 10-30

(b) 10-50

(c) 13-30

(d) 13-50

Fig. 6. Corroded stud shear connectors

3.2 Static Behaviour

The static behaviour of stud connectors can be described using load–slip curve and ultimate strength. In this study, the effect of corrosion on static behaviour of stud was investigated.

<u>Load-slip curves</u>
The load-slips curves of test specimens W10.0 series and B10.0 series are shown in Fig. 7 and Fig. 8, respectively. The load-slips curves of test specimens W13.0 series and B13.0 series are shown in Fig. 9 and Fig. 10, respectively. Since the failure mode of all specimens is stud failure, the load-slip curves only could be measured up to the point of ultimate strength. Studs having corrosion along whole length and studs having bottom corrosion showed similar load-slip curves. It is shown that the initial stiffness of

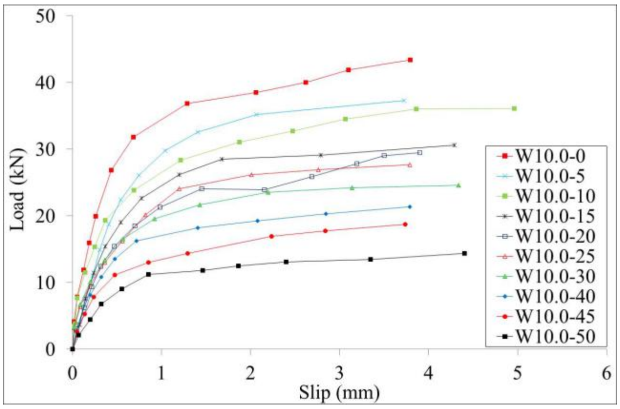

Fig. 7. Load-slip curves of W10.0 series specimens

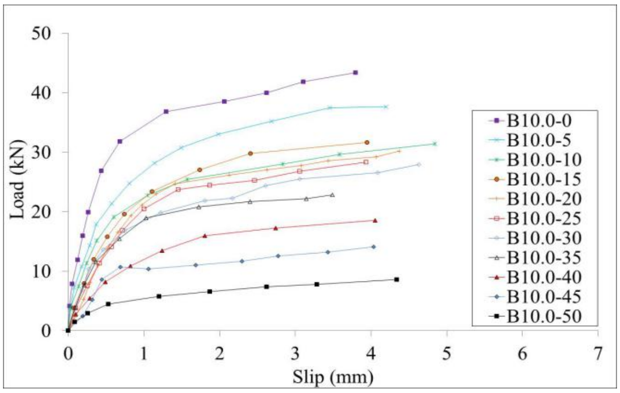

Fig. 8. Load-slip curves of B10.0 series specimens

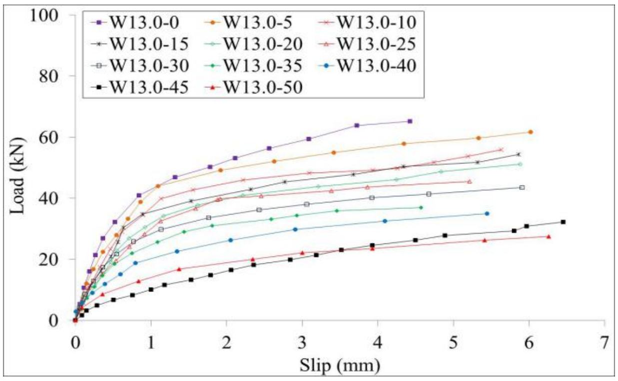

Fig. 9. Load-slip curves of W13.0 series specimens

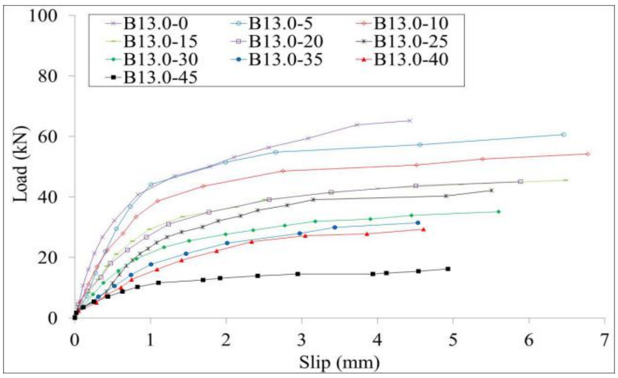

Fig. 10. Load-slip curves of B13.0 series specimens

specimens decrease with the increment of corrosion rate for both two series specimens. The ductility of specimens showed no obvious relation with corrosion rates.

Ultimate strength

In this study, the failure mode of all push test specimens is stud failure. Fig. 4 shows typical stud failure of the test specimens. The ultimate strengths of test specimen series 10.0mm diameter series and 13.0 mm diameter series are shown in Table 5 and Table 6, respectively. It is shown that the ultimate strengths of test specimens decrease when the corrosion rate increases. It means that the corrosion has significant effect on the ultimate strengths of test specimens.

4.0 COMPARISON

The ultimate strengths of single stud test specimen series 10.0mm diameter series and 13.0mm diameter series are compared with test results of push out test specimens, as shown in Figs. 11 and 12, respectively. It is shown that the ultimate strengths of push out test specimens are relatively high than those of single stud test specimens having the same corrosion rate.

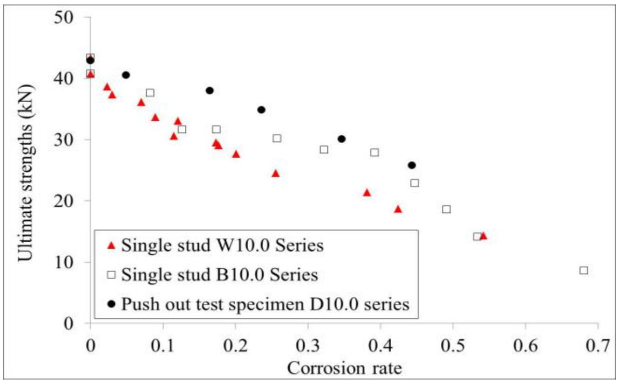

Fig. 11. Comparison of ultimate strengths of W10.0, B10.0 and D10.0 series specimens

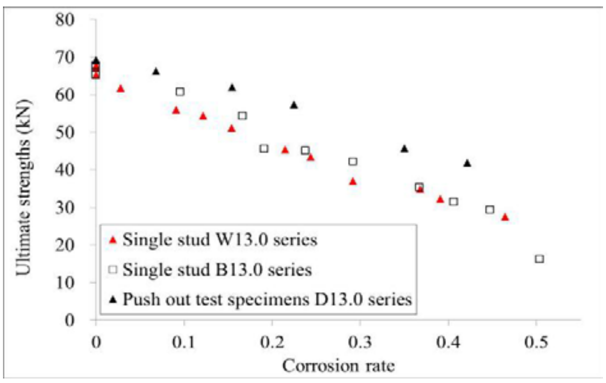

Fig. 12. Comparison of ultimate strengths of W13.0, B13.0 and D13.0 series specimens

For specimens having 10.0mm diameter, studs having corrosion along the whole length showed lower ultimate strengths compared with those studs having bottom corrosion. While for specimens having 13.0 mm diameter, studs having corrosion along the whole length showed similar ultimate strengths as those studs having bottom corrosion. Generally, ultimate strengths obtained from corroded single stud test specimens are conservative compared with those obtained from corroded push out test specimens.

5.0 CONCLUSIONS

Experimental investigation of steel and concrete composite push test specimens with corrosion deterioration were conducted in this study. Two series of e push test specimens having different stud diameters were tested. The test specimens were firstly electronic accelerating corroded then loaded to failure. Based on the test results, the effect of corrosion on the load-slip curves and ultimate strength were studied. It is shown that the corrosion of stud has significant effect on the ultimate strengths of test specimens. Test results obtained from the loading tests were compared with design strength predicted by current Eurocode 4. It is shown that the design strength was unconservative for corroded specimens. New design equation with reasonably accuracy was proposed which enables the designer to consider the effect of corrosion.

Acknowledgment

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Nomenclature

A = cross section area of stud;
ΔA= cross section area loss of stud;
d = the diameter of the shank of the stud;
d_c = the diameter of the shank of the corroded stud;
E_c = the elastic modulus of the concrete at 28 days;
E_{cm} = the elastic modulus of the concrete slab;
f_{ck} = the characteristic cylinder compressive strength of the concrete at the age considered;
f_{cu} = the compressive strength of the concrete at 28 Days;
f_u = specified ultimate tensile strength of the material of the stud;
P_{test} = ultimate strength obtained from test results;
Ψ = corrosion rate of stud;