

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

W. Xue, J. Chen¹, A-Y Jiang and W-L Jin

Institute of Structural Engineering, Zhejiang University, China

¹Department of Civil Engineering, Zhejiang University of Science and Technology, China

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.

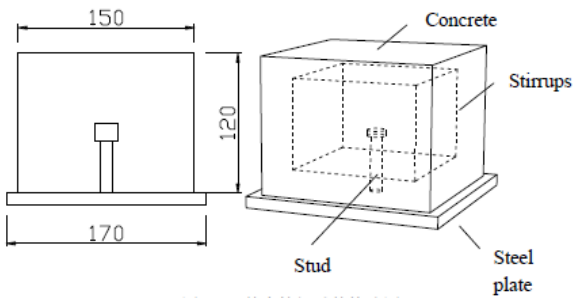


Fig. 1 Test setup of single stud shear connector
 (a) Test device (b) Test specimen

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 $0.2 \mu A/cm^2$ 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.

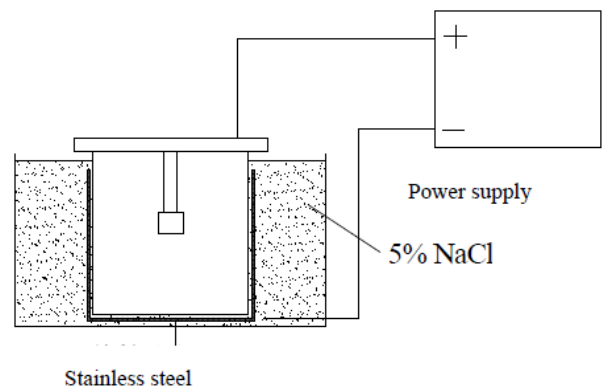


Fig.2. Set-up of Electronic accelerating corrosion

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

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

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.

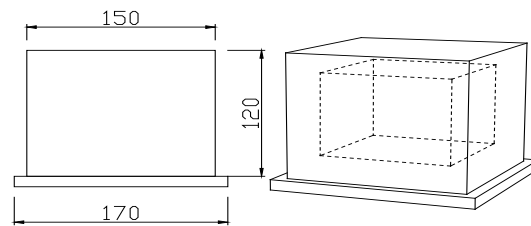


Fig.3. Test specimens for friction test

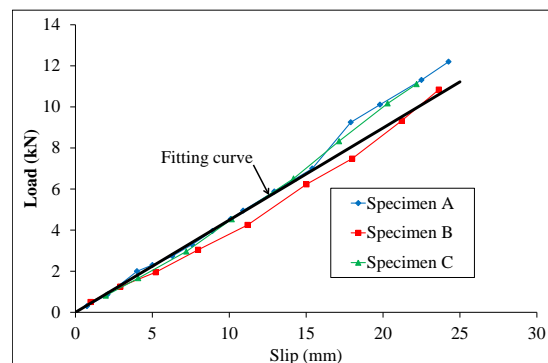


Fig. 4. Load-slip curves of specimens without studs

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

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

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)).

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: $\psi = (A - \Delta A) / A\%$. 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.

Load-slip curves

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

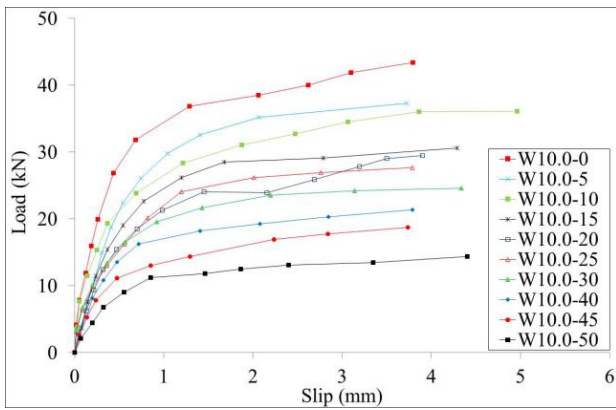


Fig. 7. Load-slip curves of W10.0 series specimens

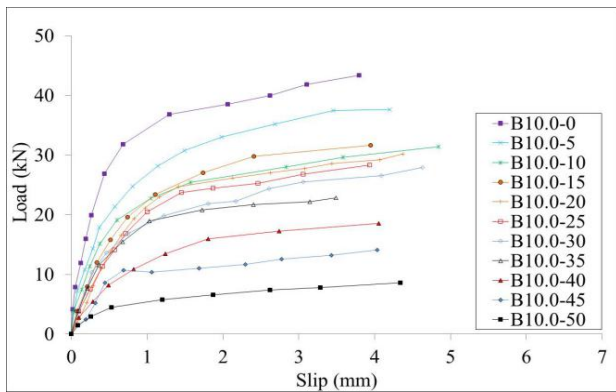


Fig. 8. Load-slip curves of B10.0 series specimens

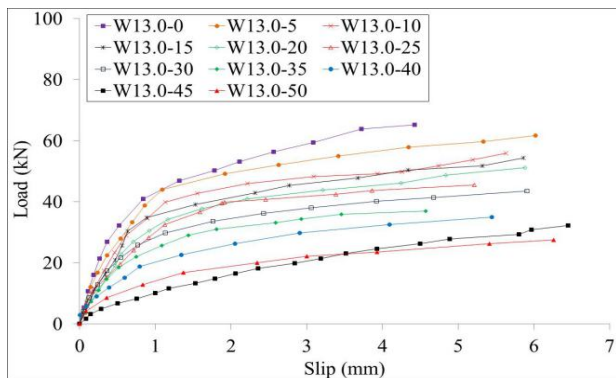


Fig. 9. Load-slip curves of W13.0 series specimens

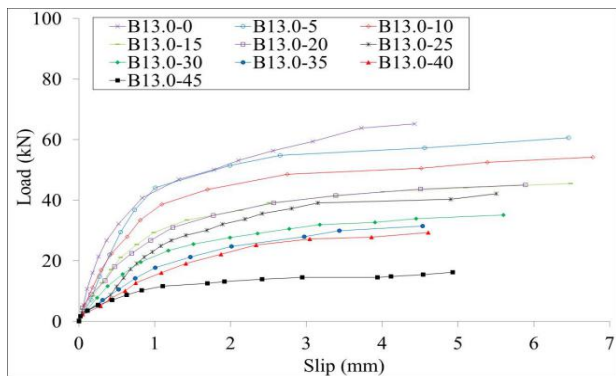


Fig. 10. Load-slip curves of B13.0 series specimens

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.

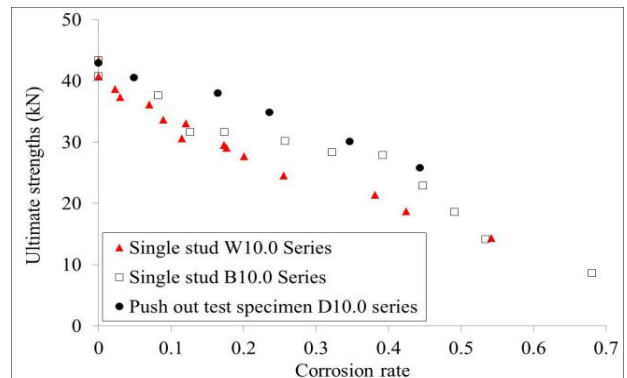


Fig. 11. Comparison of ultimate strengths of W10.0, B10.0 and D10.0 series specimens

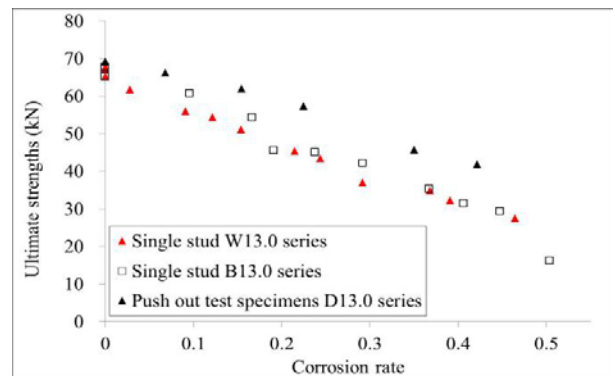


Fig. 12. Comparison of ultimate strengths of W13.0, B13.0 and D13.0 series specimens

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

The research work was also supported by the National Natural Science Foundation of China (51608484).

References

Asami, K. and Kikuchi, M. (2003), "In-depth distribution of rusts on a plain carbon steel and weathering steels exposed to coastal-industrial atmosphere for 17 years", *Corros. Sci.*, (45), 2671–2688.

Bazant, Z.P. (1979), "Physical model for steel corrosion in sea structures-applications", *J.Struct. Div.*, (105), 1137–1153.

Bertoa, L., Simionib, B. and Saettab, B. (2008), "Numerical modelling of bond behaviour in RC structures affected by reinforcement corrosion", *Engineering Structures*, **30**(7), 1375–1385.

Caré, S., Nguyen, Q.T., L'Hostis, V. and Berthaud, Y. (2008), "Mechanical properties of the rust layer induced by impressed current method in reinforced mortar", *Cement and Concrete Research*, (38), 1079–1091.

Chen, J., Zhao Y.X., Wu L. and Jin W.L. (2016) "Experimental investigation and design of corroded stud shear connectors", *Advances in Structural Engineering*. 19(2), 218-226.

Coughlan, C. G. (1987), *The stiffness of stud shear connections in composite beams subjected to static and fatigue loading*, Thesis presented to the National University of Ireland, at Cork, Ireland, in partial fulfillment of the requirements for the degree of Master of Engineering Science.

Dai, X.X. and Richard Liew JY. (2010), "Fatigue performance of lightweight steel–concrete–steel sandwich systems", *Journal of Constructional Steel Research*, **66**(2), 256–276.

Dogan, O. and Roberts, T.M. (2012), "Fatigue performance and stiffness variation of stud connectors in steel–concrete–steel sandwich systems", *Journal of Constructional Steel Research*, **70**(3), 86–92.

Duffó, G.S., Morris, W., Raspini, I., and Saragovi, C. (2004), "A study of steel rebars embedded in concrete during 65 years", *Corros. Sci.*, (46), 2143–2157.

EN 1994-1-1: 2004. Eurocode 4: *Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings*.

Johnson, R.P. (2000), "Resistance of stud shear connectors to fatigue", *Journal of Constructional Steel Research*, **56**(2), 101–116.

Johnson, R.P. (2004) *Composite Structures of Steel and Concrete: beams, slabs, columns and frames for buildings*, Third Edition, Blackwell Publishing Inc.

Kim, S., Jung, C. and Ahn, J. (2011), "Ultimate strength of composite structure with different degrees of shear connection", *Steel and composite structures*, **11**(5), 375-390.

Lam, D. and Ellobody, E. (2005), "Behavior of Headed Stud Shear Connectors in Composite Beam", *Journal of Structural Engineering-ASCE*, **131**(1), 96-107.

Lin, W., Yoda, T. and Taniguchi, N. (2013), "Fatigue tests on straight steel–concrete composite beams subjected to hogging moment", *Journal of Constructional Steel Research*, **80**(1):42–56.

Mirza, O. and Uy, B. (2010), "Finite element model for the long-term behaviour of composite steel–concrete push tests", *Steel and composite structures*, **10**(1), 45-67.

Nie, J.G., Fan J.S. and Cai, C.S. (2008), "Experimental study of partially shear-connected composite beams with profiled sheeting", *Engineering Structures*, **30**(1), 1–12.

Oehlers D.J. (1990), "Deterioration in strength of stud connectors in composite bridge beams", *Journal of Structural Engineering-ASCE*, **116**(12), 3417-3431.

Smith, A.L. and Couchman G.H. (2010), "Strength and ductility of headed stud shear connectors in profiled steel sheeting", *Journal of Constructional Steel Research*, **66**(6), 748–754.

- Vassie, P. (1984), "Reinforcement corrosion and the durability of concrete bridges", *Proceeding of Institution of Civil Engineers*, (76), 713–723.
- Wang, Y.H., Nie, J.G. and Li, J.J. (2014). "Study on fatigue property of steel–concrete composite beams and studs", *Journal of Constructional Steel Research*, **94**(1), 1–10.
- Wang, W.L., Chen, J. and Jin, W.L. (2016) "Experimental Investigation of Corroded Stud Shear Connectors Subjected to Fatigue Loading", *Journal of materials in civil engineering*, DOI: 10.1061/(ASCE)MT.1943-5533.0001688.
- Xue, W., Ding, M., Wang, H. and Luo, Z. (2008), "Static Behavior and Theoretical Model of Stud Shear Connectors", *Journal of Bridge Engineering-ASCE*, **13**(6), 623-634.

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;