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Static behaviour of multi-row stud shear connectors in high- strength concrete

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Abstract. In regions of high shear forces in composite bridges, headed stud shear connectors need to be arranged with a small spacing in order to satisfy the design requirement of resisting the high interface shear force present at this location. Despite this, studies related to groups of headed studs are somewhat rare. This paper presents an investigation of the static behaviour of grouped stud shear connectors in high-strength concrete. Descriptions are given of five push-out test specimens with different arrangements of the studs that were fabricated and tested, and the failure modes, load-slip response, ultimate load capacities and related slip values that were obtained are reported. It is found that the load-slip equation given by some researchers based on a single stud shear connector in normal strength concrete do not apply to grouped stud shear connectors in high-strength concrete, and an algebraic load-slip expression is proposed based on the test results. Comparisons between the test results and the formulae provided by some national codes show that the equations for the ultimate capacity provided in these codes are conservative when used for connectors in high-strength concrete. A reduction coefficient is proposed to take into account the effect of the studs being in a group.

Keywords: composite beams; ductility; group; high-strength concrete; push-out tests; slip; stud shear connectors

1. Introduction

Headed stud shear connectors are the most widely adopted elements used to provide ductile and robust shear connection in steel-concrete composite structures (Oehlers and Bradford 1995, Johnson 2004). Other types of shear connectors have some inherent drawbacks, e.g., the shear stiffness of rebar connectors is low and can lead to significant deformations that reduce the composite behaviour of a beam, while channel connectors are not easy to install and are brittle (Slutter and Driscoll 1965). In bridge beams, which experience fatigue loading, ductile headed stud connectors lead to large fatigue endurances and are therefore used almost exclusively in this application.

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The structural behaviour of stud shear connectors has been investigated with much interest over many decades (e.g., Viest 1956, Chapman and Balakrishnan 1964, Davies 1967, Yam and Chapman 1968, Johnson *et al*. 1969, Ollgaard *et al*. 1971, Ansourian and Roderick 1978, Johnson and Molenstra 1991, Oehlers and Bradford 1995, Bradford *et al*. 2006, Lam 2007, Xue *et al*. 2008, Liu and Alkhatib 2013). Push-out testing is the most efficient means of physical testing to determine the behaviour of shear connectors, as full-scale beam testing is very costly. 12 push-out tests were conducted by Viest (1956) to determine the behaviour and load carrying capacity of stud shear connectors, and his tests showed that a steel stud was suitable for use as a shear connector in composite steel-concrete construction. Empirical equations were also presented for determining maximum load. Extensive push-out tests for stud shear connectors in lightweight and normal-weight concrete performed and reportedby Ollgaard *et al*. (1971) lead to the provisions in the American AASHTO (2004) standard, and elsewhere. Lee *et al*. (2005) investigated large stud shear connectors (up to 30 mm diameter), which are beyond the limitations imposed in current design codes, and found that the design shear provisions in the Eurocode 4 (BSI 2005a) and AASHTO (2004) give conservative strengths for large studs. Extensive research can also be found on effects of friction welding (e.g., Gilmour 1974), the effects of temperature (e.g., Van Dalen 1983), and the like.

Vehicle loading causes variable shear forces in bridge engineering, and considerable effort has been expended on research of the fatigue behaviour of stud connectors. Clarke (1972) investigated the shear connection in steel-concrete composite members that may be subjected, by the passage of wheel loads, to either uniaxial shear forces or shear forces which vary in direction as well as in magnitude. It was found that the endurance of a stud under the most severe form of rotating shear can be as little as one tenth of that of a stud subjected to the same load applied statically in uniaxial shear. Gattesco and Giuriani (1996) performed tests under reverse cyclic loading, and these tests gave useful information both on the shape of the load-slip curves and on the damage accumulation at the end of each cycle. Later, Gattesco *et al*. (1997) presented eight tests subjected to different values of slip amplitude and slip history. Johnson (2000) re-examined the test data obtained by some investigators (An and Cederwall 1996, Oehlers and Coughlan 1986, Oehlers and Foley 1985, Roberts and Dogan 1998, Slutter and Driscoll 1965), and drew some conclusions for the re-drafting of the relevant clauses in Eurocode 4 (BSI 2005b). Lee *et al*. (2005) studied the fatigue behaviour of large stud shear connectors up to 30mm in diameter, and found that the fatigue endurance obtained from the tests was slightly lower than the current design clauses in Eurocode 4.

Some research has been focused on full-scale beam tests to investigate the behaviour of stud shear connectors. The ultimate strength and horizontal shear load redistribution of partial composite beams was obtained from tests by Lee *et al*. (2005), and it was found that the ultimate strength of the shear connection in the beam test was about 1·59 times that obtained from push-out tests. Similar results were obtained four decades earlier by Slutter and Driscoll (1965). This indicates that push-out tests can provide a conservative value for the strength of stud connectors, so the results of push-out tests are reliable for engineering design and are adopted in national codes of practice.

In recent years, much research has been devoted to the finite element analysis of stud connectors (e.g., Kim *et al*. 1999, Nguyen and Kim 2009). Lam and El-Lobody (2005) performed parametric studies that considered the concrete strength and shear stud diameter using finite element modelling, and it was found that the finite element model could provide a good understanding of the different modes of failure observed during experimental testing. Mirza and

Uy (2009a) developed a three-dimensional push test model with a two-dimensional temperature distribution field based using a finite element method, which could be applied to steel-concrete composite beams, and it was concluded that the stud shear connector strength under fire exposure was very sensitive and that profiled steel sheeting slabs exhibit greater fire resistance. In subsequent work, the effects of steel fibre reinforcement (Mirza and Uy 2009b), of strain regimes (Mirza and Uy 2010a), and of the combination of axial and shear loading (Mirza and Uy 2010b) on the behaviour of headed stud shear connectors in composite steel-concrete beams were investigated.

At the present time, most available research work has concentrated on the behaviour of single stud shear connectors, and few research papers are available in the open literature concerning group effects, despite the fact that studs are often grouped in regions of high interface shear such as at the ends of simply supported beams. Xu *et al*. (2012) performed parametric static analyses of stud groups (13 mm diameter and 80mm high) with typical push-out tests, while Spremic *et al*. (2013) conducted push-out experiments of headed shear studs (16 mm × 100 mm) in group arrangements. However, the studs and their arrangement were of the type used in building frame construction. Xue *et al*. (2012) also undertook push-out tests to investigate the behaviour differences between single-stud and multi-stud connectors (22 mm × 200 mm) in normal strength concrete. Currently, high-strength concrete (being defined herein as having a cylinder strength in excess of 50 MPa) is widely used in bridge engineering, and its behaviour is significantly different to normal strength concrete (Nawy 2001). To this end, the objective of this paper is to investigate the static behaviour of grouped stud shear connectors in high-strength concrete. Push-out tests of specimens with typical stud arrangements encountered in bridge engineering are reported, and the strength capacities are compared with those in design codes. Based on the test results, a load-slip relationship and a reduction coefficient to allow for group effect are proposed. The test results also provide benchmark solutions for computational modelling needed to undertake parametric studies of groups of headed stud shear connectors in high-strength concrete.

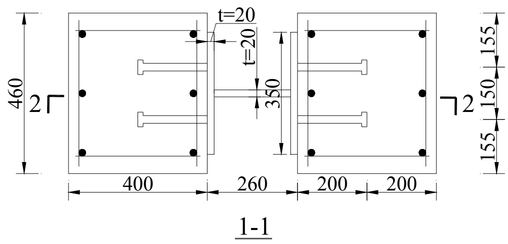
2. Experimental program

2.1 Test specimens

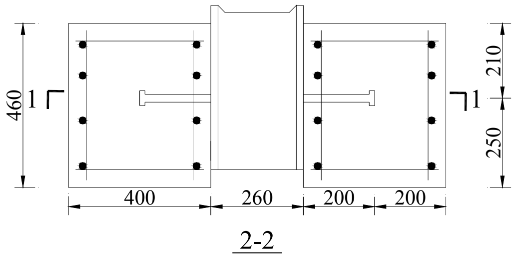
Stud shear connectors of 22 mm diameter and 200 mm in length as-welded were used, and five push-out specimens were designed and fabricated, as shown in Fig. 1. One of these specimens was a typical push-out specimen configured in accordance with Eurocode 4 (BSI 2005a), while the other four had multi-row stud shear connectors with a row spacing of 100 mm, which is the minimum spacing achievable with automatic welding. The stud configurations are given in Table 1. The headed studs were firstly welded to the flanges of the steel sections, following which the reinforcement was placed and the concrete then cast in the vertical direction, unlike the procedure of Eurocode 4 (BSI 2005a) but the casting was undertaken carefully to avoid voids behind the stud shear connectors. Lubricating oil was greased onto the surface of the steel flanges, in order to eliminate friction between the steel and concrete.

2.2 Loading and measurements

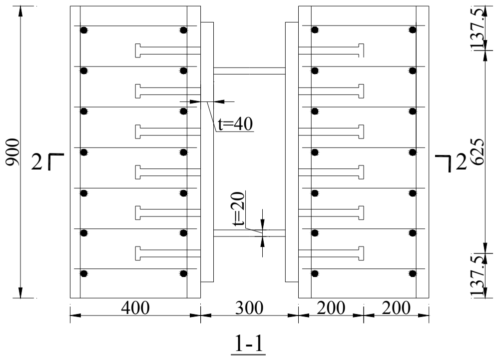
The specimens were tested using a FCS hydraulic loading system which had a load capacity of



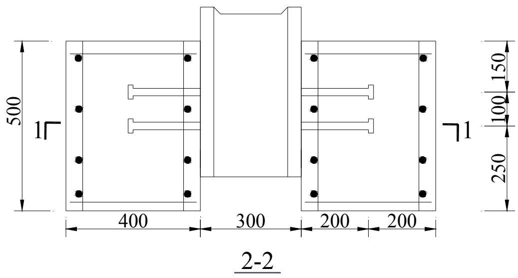
(a) Specimen SS-2 (top view)



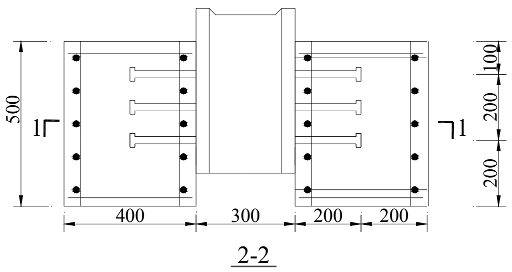
(b) Specimen SS-2 (front view)



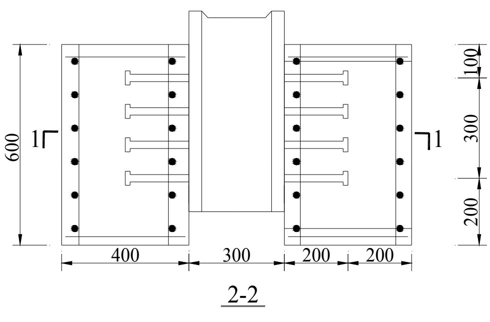
(c) Specimens GS-12, GS-18, GS-24, GS-36 (top view)



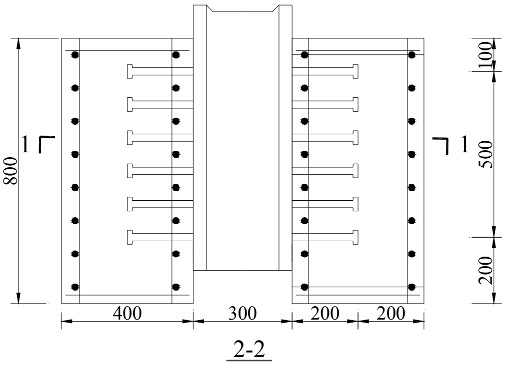
(d) Specimen GS-12 (front view)



(e) Specimen GS-18 (front view)



(f) Specimen GS-24 (front view)



(g) Specimen GS-36 (front view)

Fig. 1 Configuration of test specimens

Table 1 Studs on each specimen

Specimen	Number of rows	Number of studs in each row	Number of studs on each flange	Number of studs on one specimen
SS-2	1	2	2	4
GS-12	2	6	12	24
GS-18	3	6	18	36
GS-24	4	6	24	48
GS-36	6	6	36	72

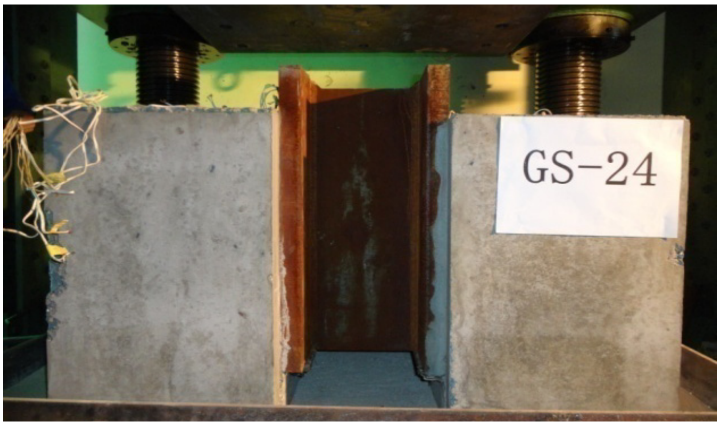


Fig. 2 Test set-up

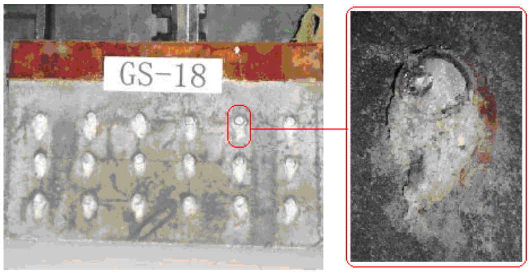
20 MN, as shown in Fig. 2. A sand cushion was deployed between the specimen and the loading base so as to eliminate the friction between the concrete slabs and the steel loading base and to ensure that the reaction force on the concrete slabs was distributed uniformly. Four linear variable differential transducers (LVDTs) with an accuracy of 0.001 mm were used to measure the interface slip, being placed on the two sides of each flange.

Nine 150 mm × 150 mm concrete specimens were cast from the same batch as the push-test slabs, and were air cured alongside the slabs. At testing, the average compressive cube strength was measured to be 72 MPa. The yield stress of the studs was measured to be 367 MPa, their ultimate tensile strength 480 MPa and fracture strain 28.8%.

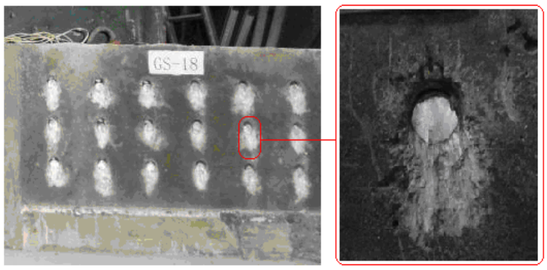
3. Test results

3.1 Failure modes

Fig. 3 shows the failure modes of the specimens, which was similar for each. At failure, the studs sheared off with significant plastic deformation being observed and, unlike in normal-strength concrete, little obvious failure was observed in the concrete slabs, except for some localized spalling around the studs. It can be seen in Fig. 3(b) that the localized spalling extended to the next row of studs.

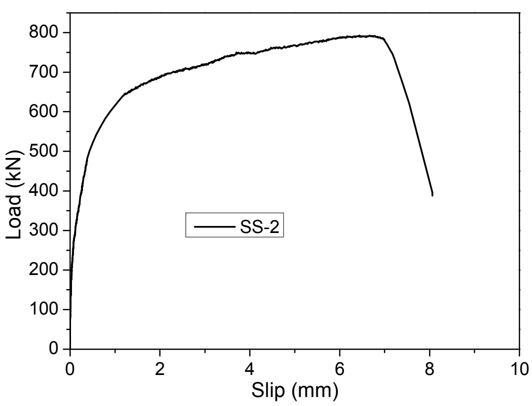


(a) Failure surface of steel flange

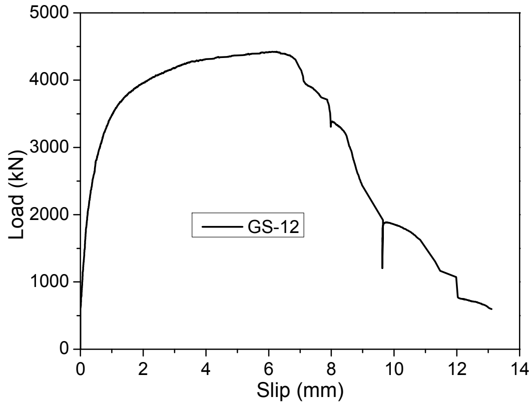


(b) Failure surface of concrete block

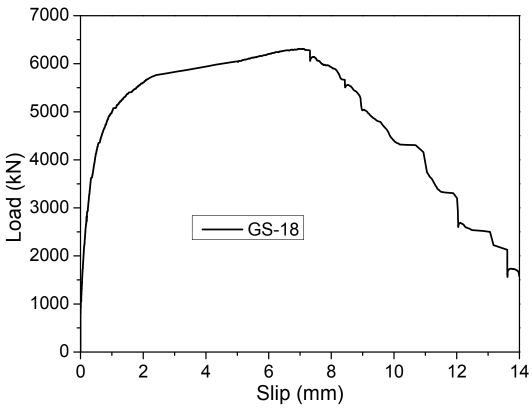
Fig. 3 Failure mode



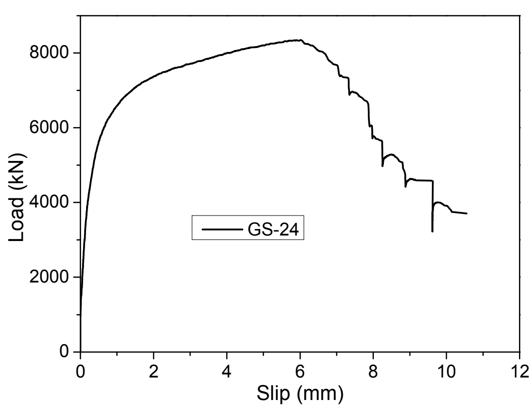
(a) Specimen SS-2



(b) Specimen GS-12

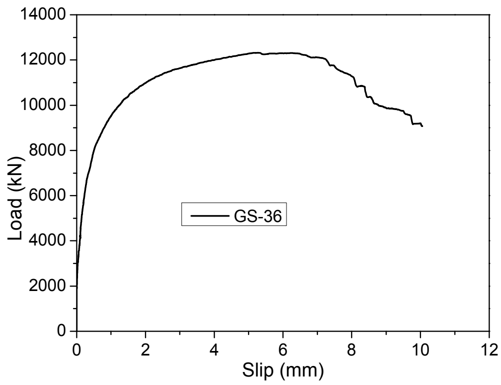


(c) Specimen GS-18

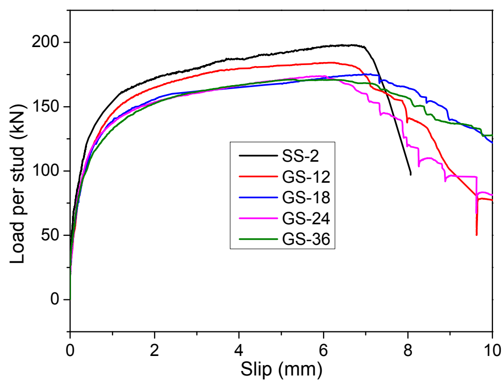


(d) Specimen GS-24

Fig. 4 Load-slip curves



(e) Specimen GS-36



(f) All specimens, per stud

Fig. 4 Continued

Table 2 Ultimate capacity and slip

Specimen	Ultimate capacity (kN)	Ultimate capacity per stud P_u (kN)	s_u (mm)	$s_{\max}$ (mm)
SS-2	792	198.1	6.66	8.06
GS-12	4423	184.3	6.25	13.1
GS-18	6310	175.3	6.96	14.1
GS-24	8347	173.9	6.02	10.6
GS-36	12,320	171.1	5.27	10.1

3.2 Load-slip response

The averaged load-slip response measured from the four LVDTs on each specimen is given in Figs. 4(a) to (e). Under monotonic deformation control, three distinct stages are represented, *viz*. an elastic stage, an elasto-plastic ascending range and a descending range. By comparison with typical push-test configurations using normal strength concrete, the stiffness of the shear connection is large and the limit of proportionality is around 40% to 50% of the ultimate strength of the specimen, at which the slip is around 0.2 mm. Following this, the ductile deformation (with a relatively small load increment) is indicative of yielding of the stud shear connectors, and beyond attaining the ultimate strength, the load decreases rapidly. The testing was terminated when all studs had sheared off. The maximum slips differed for each specimen, that with a single row of connectors (SS2) being smaller than the grouped connectors. The progressive failures of the studs by shearing are evident on the descending branch of the load-slip curves, indicating that all studs do not shear off at the same time.

3.3 Ultimate capacity

The ultimate strength of each specimen, that of one stud (P_u), the slip corresponding to the ultimate strength (s_u) and the maximum slip ($s_{\max}$) are given in Table 2. It can be seen that the number of rows of studs has a significant effect on the ultimate strength, with the stud strengths in Specimens GS-12, GS-18, GS-24 and GS-36 decreasing by 7.0%, 11.5%, 12.2% and 13.6%

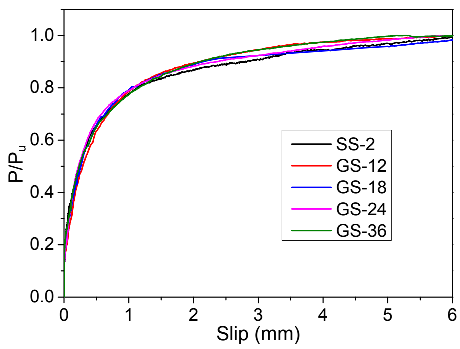


Fig. 5 Relationship between non-dimensional load and slip

respectively when compared with a single row, and indicating that the effects of the studs in groups needs to be taken into account in structural engineering design. However, it can be seen in Table 2 that the differences in the maximum slips is not large, while the slips at ultimate strength are almost the same, being indicative of the group effect having no obvious influence on the ductility of the shear connection.

4. Discussions and proposed formulae

4.1 Expression for load-slip relationship

The minimum slip requirements of Eurocode 4 (BSI 2005b) for ductile shear connectors is 6 mm, and so the slips within the range 0 to 6 mm are plotted against the non-dimensional load P/P_u in Fig. 5. It can be seen that there is a good agreement between each of the experimental curves, which indicates a prescriptive relationship could be introduced to depict the load-slip response.

Typical push-out tests for single stud shear connectors in normal and high strength concrete were conducted by An and Cederwall (1996), and they proposed the use of the empirical relationship

$$\frac{P}{P_u} = \frac{2.24(s-0.058)}{1+1.98(s-0.058)} \tag{1}$$

for shear connection with normal strength concrete, and

$$\frac{P}{P_u} = \frac{4.44(s-0.031)}{1+4.24(s-0.031)} \tag{2}$$

for shear connection high strength concrete, in which P is the shear force, P_u the ultimate strength of the stud connector and s the slip in units of mm.

Thirty push-out tests on headed stud shear connectors whose shrank diameters were in the range 13 mm to 19 mm and whose length was in the range 55 mm to 95 mm were conducted by Xue *et al*. (2008) to investigate the effects of stud diameter and height, concrete strength, stud welding technique, transverse reinforcement and steel beam type on the load-slip response, and the proposed the load-slip response as

$$\frac{P}{P_u} = \frac{s}{0.5 + 0.97s} \tag{3}$$

Lorenc and Kubica (2006) have proposed

$$\frac{P}{P_u} = \left(1 - e^{-0.55s}\right)^{0.3} \tag{4}$$

while push-out tests were conducted by Xue *et al*. (2012) to investigate the different behaviour between single-stud and multi-stud connectors in normal strength concrete, with the proposed load-slip relationship being

$$\frac{P}{P_u} = \left(1 - e^{-0.5s}\right)^{1/3} \tag{5}$$

for single-stud shear connectors, and

$$\frac{P}{P_u} = \left(1 - e^{-0.7s}\right)^{1/3} \tag{6}$$

for multi-stud shear connectors.

Based on the test results in the current paper, the load-slip response of grouped stud connectors in high strength concrete given by

$$\frac{P}{P_u} = \left(1 - e^{-0.61s}\right)^{0.34} \tag{7}$$

is proposed based on regression analysis, and it was found that this expression falls between the two equations proposed by Xue *et al*. (2012).

Comparisons between the test results and the empirical expressions given in Eqs. (2) to (7) are shown in Fig. 6, and it can be seen the formula proposed in this paper agrees well with the test results of grouped stud shear connectors and that the equations proposed by other researchers do not apply to grouped stud shear connectors in high strength concrete.

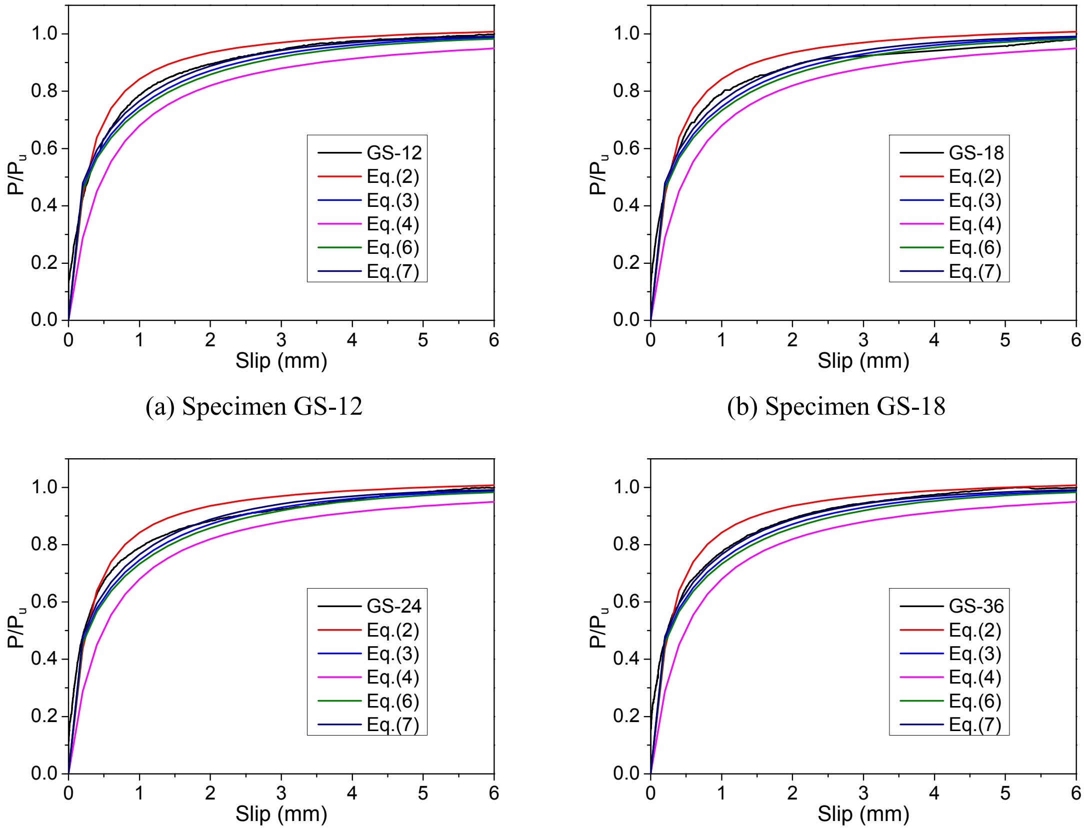
4.2 Ultimate capacity

Calculation methods of the ultimate capacity of headed stud shear connectors are given in several national codes, such as Eurocode 4 (BSI 2005a), AASHTO (2004) and the Chinese code (Ministry of Construction of China 2003), but all the equations are obtained based on the test results of single stud shear connectors in normal-strength concrete slabs.

The strength of stud shear connectors that are welded automatically is given in Eurocode 4 (BSI 2005a, b) by

$$Q_u = \min\left\{0.8 f_u A_{sv},\quad 0.29\alpha d^2 \sqrt{f_{ck} E_c}\right\}$$

$$\alpha = \begin{cases} 0.2\left(\dfrac{h_{sc}}{d} + 1\right) & \text{for} \quad \dfrac{3 \le h_{sc}}{d \le 4} \\ 1 & \text{for} \quad \dfrac{h_{sc}}{d > 4} \end{cases} \tag{8}$$



(a) Specimen GS-12

(b) Specimen GS-18

(c) Specimen GS-24

(d) Specimen GS-36

Fig. 6 Test results and regression curves

in which d is the diameter of the shank of the stud in the range 16 mm ≤ d ≤ 25 mm, f_u the specified ultimate tensile strength of the stud steel but not greater than 500 MPa, f_{ck} the characteristic cylinder compressive strength of the concrete at the age considered whose density is not less than 1750 kg/m^3, h_{sc} the overall nominal height of the stud and E_c the secant modulus of elasticity of the concrete determined from

$$E_c = 22\left[\frac{(f_{ck}+8)}{10}\right]^{0.3} \quad \text{(GPa)}, \tag{9}$$

with f_{ck} being in units of MPa.

The expression is provided by AASHTO (2004) to calculate the shear strength of one stud shear connector embedded in a concrete bridge is

$$Q_u = 0.5 A_{sc}\sqrt{f_{ck}E_c} \le 0.85 A_{sc} f_u \tag{10}$$

where A_{sc} is the cross-sectional area of a stud shear connector (mm^2).

The formula for the strength of stud shear connectors provided by the Chinese code (Ministry

Table 3 Test results and calculated values

Specimen	Test	Eq. (8)	Eq. (9)	Eq. (10)	Test / Eq. (8)	Test / Eq. (9)	Test / Eq. (10)
SS-2	198.1	146	155.1	127.7	1.36	1.28	1.55
GS-12	184.3	146	155.1	127.7	1.26	1.19	1.44
GS-18	175.3	146	155.1	127.7	1.20	1.13	1.37
GS-24	173.9	146	155.1	127.7	1.19	1.12	1.36
GS-36	171.1	146	155.1	127.7	1.17	1.10	1.34

of Construction of China 2003) is

$$Q_u = 0.43 A_{sc}\sqrt{f_c E_c} \le 0.7 A_{sc} f_u \tag{11}$$

in which f_c is the compressive cube strength of the concrete at the age considered, and which is similar to that given by AASHTO (2004).

Comparisons between the test results and the values obtained from the prescriptive equations are listed in Table 3, and it can be seen that both the test results for a single stud shear connector and for grouped stud shear connectors are larger than the values calculated from the codes, due to the contribution of the high strength concrete in the tests.

4.3 Reduction coefficient

Shear studs with a diameter of 22 mm and a height of 200 mm are widely used in bridge engineering. When the spacing is 100 mm, the reduction coefficient β for the group effect can be obtained by curve fitting of the results of the tests as

$$\beta = -0.0786\ln(n) + 0.9895, \quad n \ge 2 \tag{12}$$

in which n is the number of rows, and the coefficient of regression is 0.9433, which indicates quite accurate curve fitting, as shown in Fig. 7.

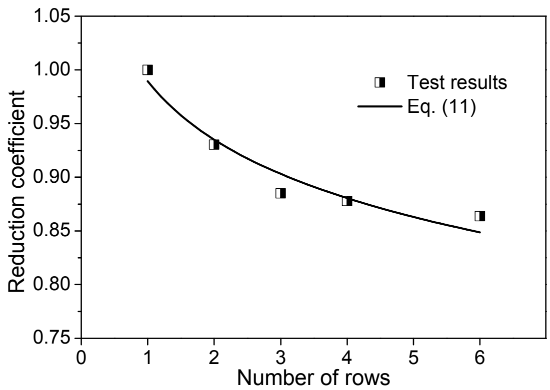


Fig. 7 Test results and proposed reduction coefficient β

5. Conclusions

This paper has investigated the static behaviour of grouped stud shear connectors in high strength concrete as used in bridge beam design, for which the following conclusions can be drawn:

(1) The push-out tests for grouped stud shear connectors in high strength concrete that were conducted found that group effect has a significant influence on the ultimate capacity and the maximum slip, while the effects on the failure mode and the relative slip corresponding to the ultimate capacity were not as profound.
(2) An expression for load-slip response for grouped stud shear connectors with typical arrangements was proposed based on test results.
(3) Comparisons between the test results and prescriptive formulae provided by national codes shows that the ultimate capacity of stud shear connectors embedded in high strength concrete is larger than the values calculated from the formulae.
(4) Based on the push-out test results, a reduction coefficient for grouped stud shear connectors has been proposed.

Acknowledgments

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