



PERFORMANCE OF STUD CLUSTERS IN PRECAST BRIDGE DECKS

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Abstract. A new design approach to clustered stud shear connection in composite bridges with precast decks is required to accommodate highly concentrated shear force in small area. Shear connection of the prefabricated slab consists of stud connectors, mortar in a shear pocket and reinforcement around the pocket. More general design approach for the shear connection is provided by relative strength between shear strength of shear connectors, bearing strength of mortar in shear pockets, and the shear strength of precast deck. Considering the relatively high strength mortar in the bearing zone of the shear connection this paper deals with structural performance of stud clusters to simplify the connection details. In a shear pocket, closer stud spacing than the current pitch requirement was considered. Push-out tests were conducted to evaluate the ultimate strength according to expected failure modes. The main parameters of the test were stud spacing and confining details. In order to use group arrangement of stud connectors, it is necessary to prevent premature failure of bearing zone by strengthening the shear connection using confining reinforcements. An empirical equation of ultimate shear strength of the shear connection was proposed to consider the effect of stud spacing when the spacing is less than five times stud diameter. Fatigue tests showed that the fatigue endurance of clustered stud connectors with spacing of more than three times stud diameter can be evaluated using current design codes.

Keywords: shear connection, precast deck, stud cluster, stud spacing, ultimate shear strength, fatigue endurance.

1. Introduction

Full-depth precast decks for fast bridge construction are increasingly applied to composite bridges. Essentially, those bridges have many connections and their structural performance is crucial not only for structural efficiency but also for constructability. For those bridges, shear connections between precast slabs and steel girders typically draw a significant amount of attention from engineers. Shear connectors are embedded in filling material in a shear pocket and impart highly concentrated forces onto the bearing material. This concentrated force causes the concrete to fail in tension by embedment cracking, ripping, shear and splitting resulting in the decrease of ultimate strength of shear connection (Oehlers, Bradford 1995). Failure modes of the shear connection are guided according to the ratio of the shear strength of mechanical connectors and bearing material strength.

Stud connectors are the most common type of shear connectors used and need to be arranged according to the design provisions on minimum and maximum pitch requirements. Due to the constraints, rigid connection

such as perfobond connectors is frequently used for high shear regions with small area for the connectors. However, it is difficult to use the rigid connector for the shear connection in precast decks because reinforcement details have difficulty to be accommodated near the shear pocket area or in the narrow joint area (Shim *et al.* 2001; Shim, Kim 2010; Tsujimura *et al.* 2000). Further, the strength of the connection is governed by shear strength of the concrete slab in these cases. To resolve these limitations, group stud shear connection with rather large studs was proposed and details for the connection have been investigated (Badie *et al.* 2002; Okada *et al.* 2006; Shim *et al.* 2004, 2007). The effective shear stiffness of the connection was proposed for the analysis of composite members (Marčiukaitis *et al.* 2013; Shim *et al.* 2000).

For group stud shear connection in cast-in-place concrete slab, test results showed that the current design provisions are applicable for the ultimate strength and fatigue endurance when the minimum spacing was satisfied (Okada *et al.* 2006; Shim, Kim 2010). In their study, the effect of the group arrangement on static strength of stud

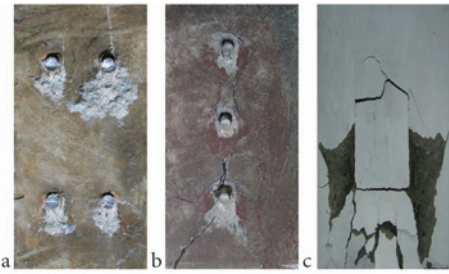


Fig. 1. Failure modes of shear connection: a – stud failure; b – stud failure after cracking; c – concrete failure

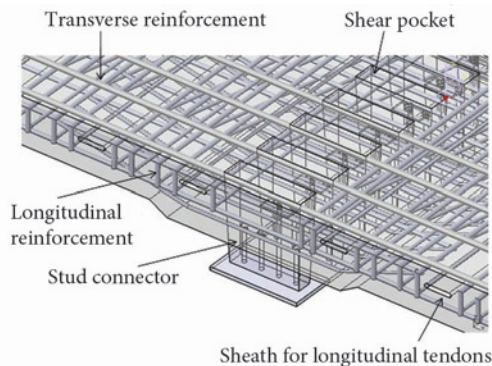


Fig. 2. Shear connection for precast deck

shear connection was not observed because of strong concrete slab. All the specimens showed stud shank failure with minor damage of concrete slab. They also did parametric analyses and proposed shear strength reduction equations. However, those results were not verified through the experiment.

Stud shear connection in precast slab bridges, material properties of mortar in shear pockets and bedding layer should be considered for the evaluation of structural performance of stud shear connection (Shim *et al.* 2000). The thickness of the bedding layer generally varies along the bridge because of the section change and girder connection details. From the experiments on stud shear connection with those conditions, the ultimate strength of the shear connection in a precast deck was 75–101% of the tensile strength of the stud due to weaker bedding layer, and an empirical equation only for the stud shank failure was proposed. When the filling mortar has 1.5 times greater compressive strength than concrete for precast decks of minimum 35 MPa, the effect of compressive strength on the ultimate strength of the shear connection is negligible (Shim *et al.* 2001).

In order to accommodate new design trends of steel-concrete composite bridges with prefabricated concrete decks, large studs up to 31.8 mm diameter were experimentally investigated and availability of the current design provisions for stud shear connectors was verified based on the test results (Badie *et al.* 2002; Shim *et al.* 2004). Larose (2006) conducted experiments on stud clusters within a circular grout pocket. He reported that the confinement

by a steel tube enhanced the shear strength of the grouped stud shear connection.

The failure modes of shear connection are categorized as shown in Fig. 1. Mode 1 is defined as stud failure without considerable concrete damage. Mode 3 means the concrete failure without stud failure. When the connectors are failed after considerable concrete damage, it is defined as Mode 2. When the post-cracking strength of the concrete slab is enough to resist shear strength of stud connectors, Mode 2 is expected. Therefore, it is necessary to increase shear strength of concrete slab to utilize the shear strength of stud clusters.

Recently, the full-depth precast decks have been increasingly applied to twin-girder bridges and open-box girder bridges. It reduces the construction cost by about 15–20% but several difficulties need to be solved. In order to satisfy the design requirements for composite action, it is necessary to place 6–8 shear pockets in each precast slab even when 25 mm studs are used. In a precast deck these pockets reduce the flexural stiffness resulting in cracking during delivery and erection process. The precast decks need longitudinal post-tensioning essentially and transverse pre-tensioning for wider decks (Shim, Chang 2003). Therefore, clustered stud arrangement of stud connectors is essential to solve the complex details. The previous empirical equation did not consider this case (Shim, Kim 2010).

Fig. 2 shows the typical examples of the shear connection detail dealt in this paper. Details of the deck are very complicated and need to be simplified by reducing the number of the shear pockets. One of the critical constraints for the simplification is the minimum pitch requirement of stud connectors in a shear pocket. The current minimum stud spacing is for shear connection in cast-in-place concrete slab. Maximum aggregate size and weld ability of the connectors using a welding gun are considered in this requirement. However, the shear connection for precast decks has high strength mortar around stud connectors. The minimum spacing is reduced only if the reduction of shear strength of the shear connection is considered. In order to reduce the number of shear pockets for the simpler details of precast slabs, it necessary to verify fatigue endurance of the connection for the reduced spacing. The reduction of static strength of the shear connection considering the reduced spacing does not significantly increase number of connectors because the fatigue endurance governs the design of shear connection.

In this paper the effects of the stud spacing on the static and fatigue performance were investigated. The group arrangement of stud connectors for prefabricated concrete slab was considered, including confining internal and external reinforcing bars to increase bearing strength and shear strength of the concrete slab, respectively. A new empirical equation for the clustered stud shear connection considering the reduced stud spacing was proposed. Fatigue tests were also conducted to verify the fatigue strength of group stud shear connection.

2. Experimental program

2.1. Static tests of shear connection

The experimental program consists of three series (G, GCIP, and S). G specimens deal with grouped stud shear connection for precast decks and GCIP for cast-in-place concrete decks (Shim, Kim 2010). The effect of stud spacing need to be estimated when concrete slab has a significant damage in bearing zone or splitting cracks in the direction of shear force, which is shown in Fig. 1b. S specimens had larger stud spacing in order to neglect effects of the group arrangement on static strength of shear connection. Table 1 summarizes the push-out specimens to investigate static behaviour of shear connection. In addition, previous test results (Shim *et al.* 2001) were used to evaluate the effects of the design parameters on static and fatigue strength of the shear connection.

Push-out specimens were fabricated to execute static tests for the evaluation of shear strength of shear connection with clustered stud arrangement. Fig. 3 shows the push-out specimen for precast decks. Precast decks with 250 mm thickness were prefabricated and were combined

with steel beam by filling non-shrink mortar in shear pockets. Nine clustered studs with 25 mm and 22 mm diameter were welded on flanges and stud pitch was varied to have $5d_s$, $4d_s$ and $3d_s$ (d_s is stud diameter in mm). Even though the mortar fills the shear pocket with narrow space, it is impossible to allow the stud spacing less than $3d_s$ due to the limitation on welding by a welding gun.

As mentioned before, it is necessary to prevent premature failure of bearing zone and concrete slab. In order to increase the strength of mortar and the shear strength of the concrete slab, constraining reinforcements were arranged inside and outside the shear pockets, as presented in Fig. 4. External reinforcements were placed before casting concrete of the precast slabs. Internal reinforcements were put in the shear pockets after placing the slab on a steel beam. Dimensions of the shear pocket were the same for all the specimens.

For the grouped stud shear connection in cast-in-place deck (GCIP specimens in Table 1) nine 25 mm studs are arranged to satisfy the minimum pitch requirements. Longitudinal and transverse spacing is 125 mm and 62.5 mm, respectively. To prevent severe damage of the concrete slab,

Table 1. Static test specimen for precast decks

Specimen	d_s , mm	f_{cm} , N/mm ²	f'_c , N/mm ²	B_H , mm	Q_w , kN	δ_w , mm	S , mm	Details	Failure modes
G25NS	25	49.5	32.6	20	115.1	5.00		No*	Mode 3
G25OS	25	49.5	32.6	20	135.6	3.60	$5d_s$	Ext**(D16)	Mode 2
G25IS	25	49.5	32.6	20	126.5	10.73		Int*** (D10)	Mode 2
G25OS-1	25	49.5	32.6	20	105.1	3.52	$4d_s$	Ext(D16)	Mode 1
G25NS-2	25	49.5	32.6	20	107.0	4.11		No	Mode 2
G25OS-2	25	49.5	32.6	20	131.6	3.61	$3d_s$	Ext (D16)	Mode 2
G25IS-2	25	49.5	32.6	20	120.9	9.30		Int (D10)	Mode 2
G22OS	22	49.5	32.6	20	119.9	6.67		Ext (D16)	Mode 1
G22IS	22	49.5	32.6	20	119.4	5.65	$4d_s$	Int (D10)	Mode 1
G22OS-1	22	49.5	32.6	20	110.9	7.56		Ext (D16)	Mode 1
G22IS-1	22	49.5	32.6	20	112.2	28.75	$3d_s$	Int (D10)	Mode 1
GCIP1-1	25	–	57.6	–	220.0	14.50		No	Mode 1
GCIP1-2	25	–	57.6	–	227.8	11.21		No	Mode 1
GCIP2-1	25	–	57.6	–	233.4	17.45		Ext (D16)	Mode 1
GCIP2-2	25	–	57.6	–	206.8	14.55	$5d_s$	Ext (D16)	Mode 1
GCIP3-1	25	–	57.6	–	203.0	14.00		Ext (D16×2)	Mode 1
GCIP3-2	25	–	57.6	–	241.5	12.06		Ext (D16×2)	Mode 1
S22A	22	61.09	35.8	20	141.6	7.26		No	Mode 1
S22B	22	61.09	35.8	20	154.7	8.14	$13d_s$	No	Mode 1

Notes: *No – no additional reinforcement; **Ext – external reinforcements added; ***Int – internal reinforcement added.

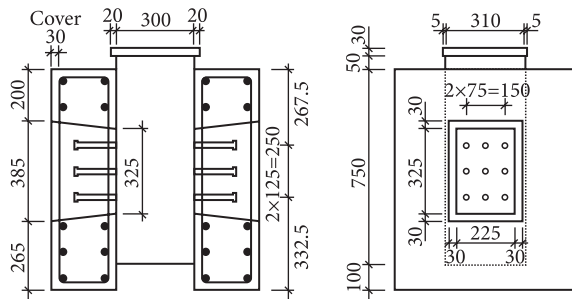


Fig. 3. Push-out specimens

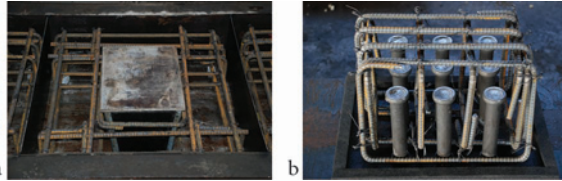


Fig. 4. Details of confining reinforcement: a – external reinforcements; b – internal reinforcement

16 mm reinforcing bars are placed at the top and bottom concrete slab. The slab has 400 mm thickness and the design compressive strength of concrete is 40 MPa. Average compressive strength of concrete was 57.6 MPa resulting in minor damage in concrete slab. S22A and B specimens are for the single arrangement in precast decks. Stud spacing was thirteen times greater than stud shank diameter.

In order to ensure quality of cast-in-place mortar and enough strength for the bearing zone of studs, filling mortar had 1.5 times greater than the compressive strength of concrete for precast decks. From previous research (Shim *et al.* 2000), higher strength of mortar do not increase the shear strength of shear connection if the failure mode is stud shank failure. Yield strength of the reinforcement for all specimens is 450 MPa and tensile strength of stud connectors was 426 MPa.

Static tests of push-out specimens were performed in a hydraulic testing machine with a 10 000 kN capacity. Subsequent load increments were imposed such that failure does not occur in less than 15 min according to

EN 1994-1:2004 Eurocode 4: Design of Composite Steel and Concrete Structures – Part 1: General Rules and Rules for Buildings. Longitudinal slips between each concrete slab and steel section were measured continually during loading or at each load increment using four 1/1000 mm LVDTs. The slip was measured at least until the load had dropped to 20% below the maximum load.

2.2. Fatigue tests of shear connection

Two sets of test specimens were fabricated to estimate the effect of stud spacing on the fatigue endurance of grouped stud shear connection, as presented in Table 2. Dimensions and material properties of the fatigue specimens were the same as those of static test specimens.

To assess the effect of grouped arrangement with reduced stud spacing, the previous experimental results on fatigue strength of shear connection were utilized (Lee *et al.* 2005; Shim *et al.* 2000, 2001). Among the test results, 25 mm stud connectors were selected for the comparison with current test results. FG25OS specimens had external reinforcements to strengthen the shear capacity of concrete slab.

3. Test results

3.1. Static behaviour of grouped stud shear connection

Two series of test specimens showed different failure modes according to relative strength ratio between concrete slab and stud connectors. Fig. 5 shows typical three failure modes of the shear connection from the static tests of G series.

Table 1 summarizes the test results in terms of shear strength, slip capacity and failure mode. Shear connection in a shear pocket showed behaviour of a block connector due to high strength mortar and internal reinforcements as shown in Figs 5c–5d. Mode 2 in Table 1 means that there was stud shank failure with severe cracking of concrete slab. Grouped stud shear connection with precast slabs had severe concrete cracking. Average shear strength of Push-out specimens with cast-in-place slab was 1.7 times greater than G25 specimens with the same stud spacing.

Table 2. Fatigue test specimens

Specimen	Compressive strength of mortar, MPa	Compressive strength of concrete, MPa	Stud spacing	Concrete slab	Reinforcement detail	Stress range, MPa
FG25OS-1	49.5	32.8	$4d_s$	Precast	Ext.	130
FG25OS-2	49.5	32.8	$4d_s$	Precast	Ext.	150
FG25OS-3	49.5	32.8	$3d_s$	Precast	Ext.	130
FG25OS-4	49.5	32.8	$3d_s$	Precast	Ext.	150
FGCIP-1	–	57.6	$5d_s$	Cast-in-place	No	140
FGCIP-2	–	57.6	$5d_s$	Cast-in-place	No	150
FGCIP-3	–	57.6	$5d_s$	Cast-in-place	No	160

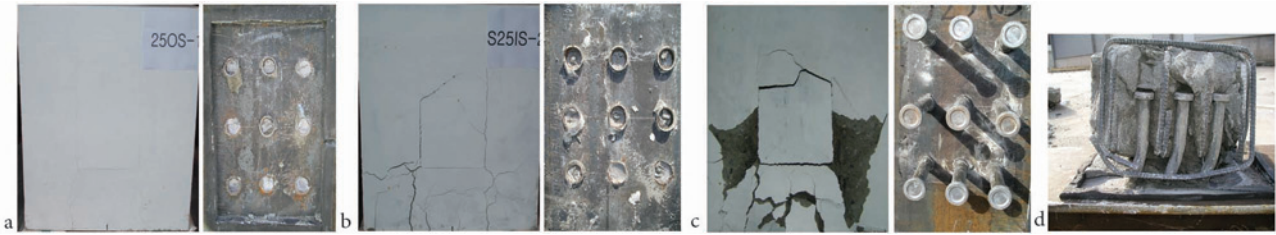


Fig. 5. Failure patterns of group stud shear connection in precast deck: a – G25OS-1 (Mode 1); b – GS25IS-2 (Mode 2); c – G25NS (Mode 3); d – effect of internal reinforcement

Therefore, Eq (1) needs to be changed to consider concrete strength by using a common parameter of $\sqrt{f_{cm}E_{cm}}$ as specified in the design code *EN 1994-1:2004*. Instead of strength of concrete slab, the compressive strength of mortar (f_{cm} , N/mm²) should be included for the shear connection of precast decks.

For group stud connection of precast decks, closer pitch reduced the shear strength up to 30% when the failure mode is stud failure after concrete cracking of the slab. External reinforcements increased post-cracking strength of the concrete slab while internal reinforcement increased bearing strength a little. Therefore, it is important to strengthen the concrete slab when group stud connectors are used. When the failure mode is splitting failure of the concrete slab without stud failure, current design provisions on shear strength of concrete slab according to *EN 1994-1:2004* are appropriate to evaluate the strength of the connection.

Fig. 6 represents the load-slip curves of the static test specimens. From the curves of 25 mm studs with stud spacing of $5d_s$, external and internal reinforcements showed 17.9% and 10% increase of the static strength respectively comparing to the specimens without additional reinforcement. The confining reinforcements increased the shear strength of concrete slab and bearing strength of mortar resulting in the change of failure mode from Mode 3 to Mode 2. For 25 mm studs with stud spacing of $3d_s$, external and internal reinforcements showed 23% and 13% increase of the static strength, respectively. Shear connection with internal reinforcement showed stable behaviour after peak load. However, specimens with 22 mm studs showed negligible increase of shear strength by additional

reinforcement. These specimens showed stud shank failure with minor damage in concrete slab.

Decrease of stud spacing from $5d_s$ to $3d_s$ reduced the shear strength of the shear connection by 7% for a standard specimen, 4.4% for internal reinforcing and 3.0% for external reinforcing. For the shear connection with 22 mm studs, the shear strength was reduced by 6.5% by decreasing the stud spacing from $4d_s$ to $3d_s$. This reduction is considered to propose the empirical equation. Filling material in shear pockets for stud connectors is required to have greater compressive strength than that of concrete for precast decks (Shim *et al.* 2001). From the observation of the static tests, grouped stud shear connection including mortar in the pocket showed similar behaviour to a block connector. Therefore, it is more effective to strengthen the connection by placing confining reinforcement around the shear pocket.

Ultimate slip capacity of the shear connection is defined as the slip when the shear load is reduced by 10% from its peak (Oehlers, Bradford 1995). According to *EN 1994-1:2004* a ductile connection is defined by the ultimate slip capacity greater than 6.0 mm. All the specimens which had Mode 1 failure showed enough slip capacity to ensure ductility of the connection, as summarized in Table 1.

3.2. Empirical equation for group stud shear connection in precast decks

In order to allow the particular design situation of closer stud spacing than the current design requirement, it is necessary to provide an empirical equation for static strength of the shear connection in precast decks. Previous

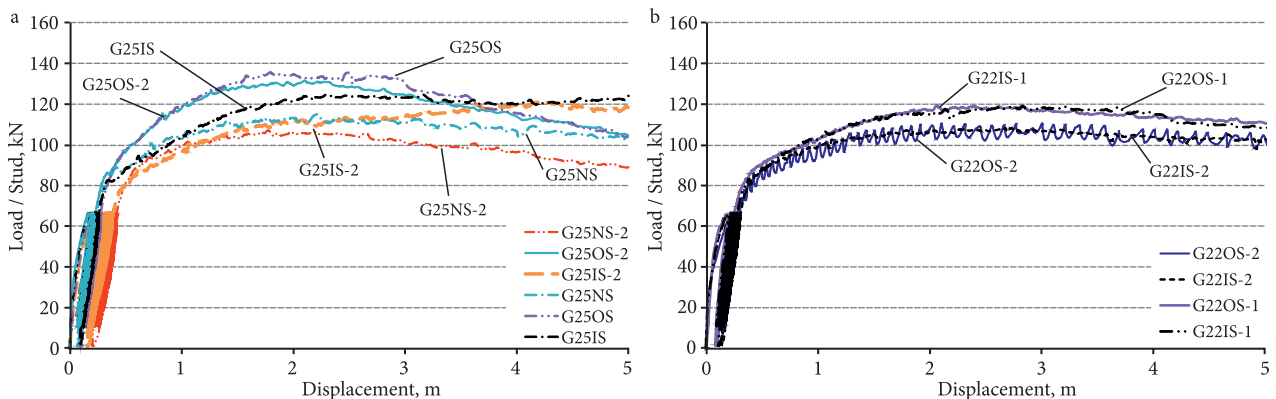


Fig. 6. Load-slip curves according to strengthening details: a – 25 mm stud – $3d_s$, $5d_s$; b – 22 mm stud – $3d_s$, $4d_s$

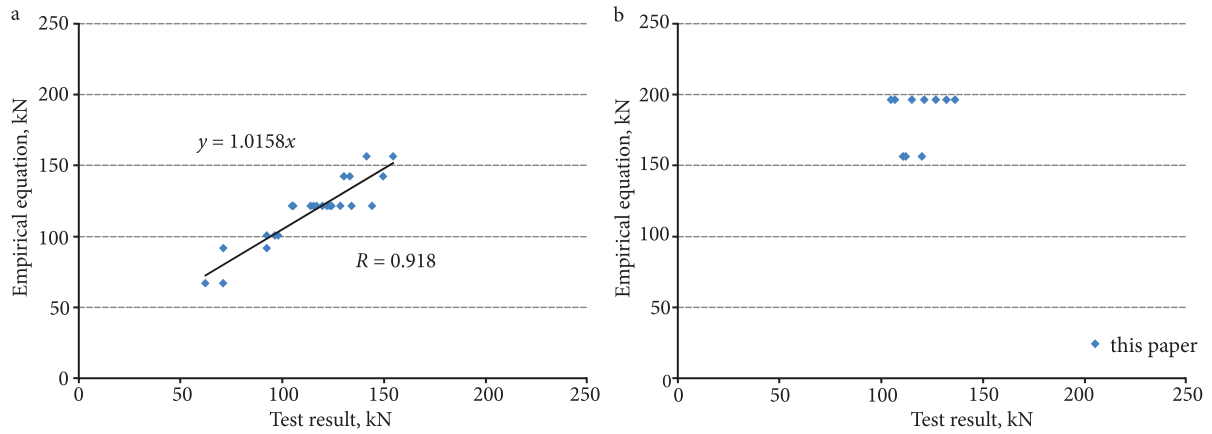


Fig. 7. Comparison of test results with previous empirical equation by Shim (2000): a – single arrangement of studs; b – group arrangement of studs

test results on stud shear connection in precast slabs (Hanswille *et al.* 2007; Shim *et al.* 2000, 2001) were included in the analysis. As shown in Fig. 7, the empirical equation from the previous research (Shim *et al.* 2000) showed good agreement with test results of shear connection with wider stud spacing but overestimated the shear strength of the shear connection with clustered stud arrangement as presented in Fig. 7b. Therefore, an additional modification factor is needed to evaluate the effect of closer stud spacing.

In order to investigate the effect of stud spacing, the reference values were collected from the previous tests (Shim *et al.* 2000, 2001). The modification factor (β_s) for stud spacing is assumed to be 1.0 when the pitch is wider than five times of stud shank diameter. An empirical Eq (1) for the reduction factor of stud spacing is proposed by linear regression analysis as shown in Fig. 8. When the stud pitch is smaller than 5 times of stud diameter, strength reduction of the shear connection is evaluated using the proposed equation. The equation only considers stud failure after concrete cracking. Therefore, it is necessary to check shear strength of concrete slab to utilize this equation.

$$\left\{ \begin{array}{l} \beta_s = 0.093 \left(\frac{s}{d_s} \right) + 0.516 \quad \text{for } 3 \leq \frac{s}{d_s} < 5 \\ \beta_s = 1 \quad \text{for } \frac{s}{d_s} \geq 5 \end{array} \right. \quad (1)$$

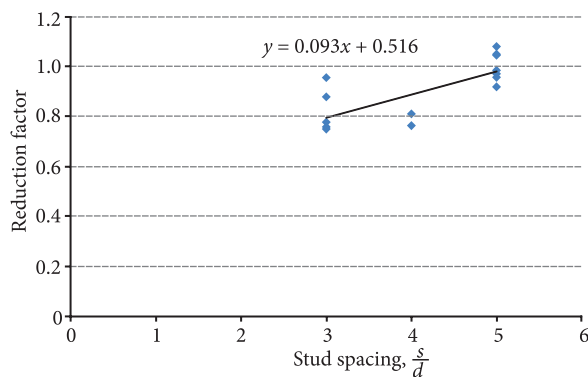


Fig. 8. Results of the statistical analysis

where s – pitch of stud connectors, mm; d_s – the stud shank diameter, mm.

From the observation of static tests it is preferable to strengthen the concrete slab for group stud shear connection to ensure ductile behaviour and greater shear strength. Compressive strength of mortar should be 1.5 times greater than that of concrete slab in order to provide enough bearing strength. In actual precast decks, transverse reinforcements around shear pockets need to be checked to have enough shear strength to resist the grouped stud shear connection according to the design codes *EN 1994-1:2004*. Based on these two requirements, a new empirical equation for Mode 1 and Mode 2 failure is needed to consider structural characteristics of shear connection in precast decks. Even though the strengthening of concrete slab increases the shear strength of the shear connection, it is necessary to be considered as a detail requirement and a safety margin which is similar to the design codes.

Combining two empirical equations for the stud shear connection in precast decks an empirical model (4) was proposed to evaluate the shear strength considering filling material in shears pockets, bedding height and stud spacing. The equation assumes the failure Mode 2 and non-shrink mortar as a filling material in shear pockets. As specified in current design codes *EN 1994-1:2004* the upper limit of the shear strength is:

$$P_{Rd} = \frac{0.8 f_u \pi d_s^2}{\gamma_v} \quad (2)$$

where γ_v – partial safety factor; d_s – diameter of the shank of the stud; f_u – specified ultimate tensile strength of the material of the stud.

Instead of material properties of concrete, compressive strength and elastic modulus of mortar are used.

$$P_e = k_c P_t = k_c \alpha_b \beta_s d_s^2 \sqrt{f_{cm} E_{cm}} \quad (3)$$

where $\alpha_b = 1 - 0.0086(B_h - 20)$ – for bedding thickness effect; β_s – for stud spacing effect as shown in Eq (1);

f_{cm} – compressive strength of mortar using a 50 mm cubic mould, MPa; $E_{cm} = 3.26 \cdot 10^3 \sqrt{f_{cm}}$ – elastic modulus of mortar, MPa (Shim *et al.* 2000).

As mentioned before, shear strength of grouped stud shear connection in precast decks is lower than that of normal shear connection with cast-in-place concrete slab. Statistical analysis for the empirical equation was executed in accordance with Annex D of EN 1990:2002 Basis of Structural Design. Thirty eight test results of shear connection in precast decks including previous test results (Hanswille *et al.* 2007; Shim *et al.* 2000) were used for the analysis. As shown in Fig. 9, the factor k_c of Eq (3) results to 0.22, while the current value in EN 1994-1:2004 is 0.29. The mean shear strength of the shear connection for precast decks was suggested as Eq (4) in the range of test parameters in this paper. The factor k_c is determined according to test results used for the statistical analysis. Therefore, it is necessary to have more experimental data to propose a design equation based on Eq (4):

$$P_e = 0.22\alpha_b\beta_s d_s^2 \sqrt{f_{cm} E_{cm}}, \quad (4)$$

where $\alpha_b = 1 - 0.0086(B_h - 20)$ – for bedding thickness effect; β_s – for stud spacing effect as shown in Eq (1); d_s – diameter of the shank of the stud; f_{cm} – compressive strength of mortar using a 50 mm cubic mould, MPa; $E_{cm} = 3.26 \cdot 10^3 \sqrt{f_{cm}}$ – elastic modulus of mortar, MPa (Shim *et al.* 2000).

The empirical equation for the clustered shear studs in precast decks will give 24% lower strength than the value from EN 1994-1:2004. It is necessary to design concrete slab to have enough shear strength to resist the ultimate shear strength of the clustered connectors by constraining reinforcements. The shear strength of the shear connection was increased through the use of higher strength mortar and confining reinforcing bars around shear pockets (Nguyen *et al.* 2009).

According to the test results by Larose (2006), stud clusters with steel tube confinement showed significant increase in shear strength of stud shear connection. A steel tube with 200 mm diameter and 1.6 mm thickness was used for the confinement of 16 mm stud connectors. 6 to 10 stud connectors were arranged in a shear pocket. Average cylinder strengths for the grout in shear pockets ranged from 48.7 MPa to 68.9 MPa. Fig. 10 shows the comparisons of test results and calculated values by Eq (3) according to different confinement methods. The results showed the extreme confinement increased the shear strength. Therefore, failure mode and its shear strength of grouped stud shear connection are effectively controlled by adding confinement as presented in Fig. 11 as an example design of a prefabricated prestressed concrete slab.

3.3. Fatigue endurance

Normally, the stud pitch is determined from the fatigue design. Minimum requirement for welding of studs using a stud gun is around $3d_s$. When the static failure mode of

the shear connection is stud failure with negligible damage of concrete slab, fatigue endurance of the shear connection with group arrangement is expected to be similar to that of normal arrangement. Push-out specimens with cast-in-place concrete slab showed much higher fatigue strength than the current design codes (Shim, Kim 2010). As shown in Fig. 12a, the concrete damage was not overlapped and remained in a sound state after fatigue failure of stud connectors. Therefore, the current design provisions on fatigue strength of stud connectors are applicable to the design of the group stud shear connection when the minimum spacing is satisfied and concrete slab has enough strength to resist the shear load.

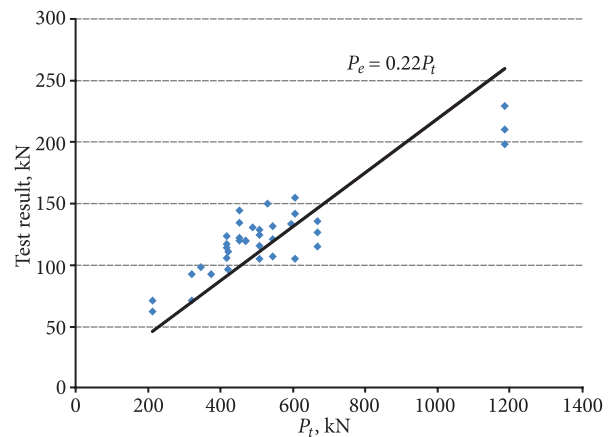


Fig. 9. Shear strength of group stud shear connection

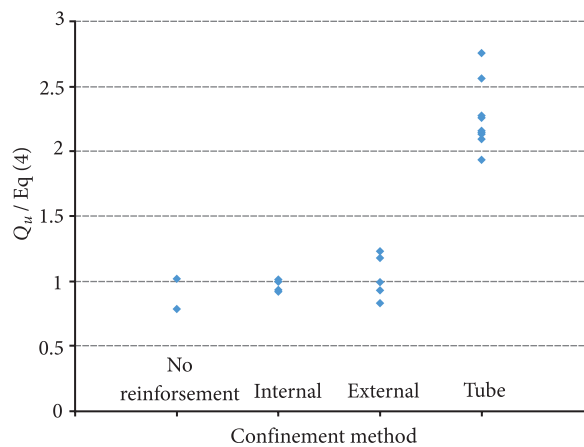


Fig. 10. Comparisons of shear strength according to confinement methods

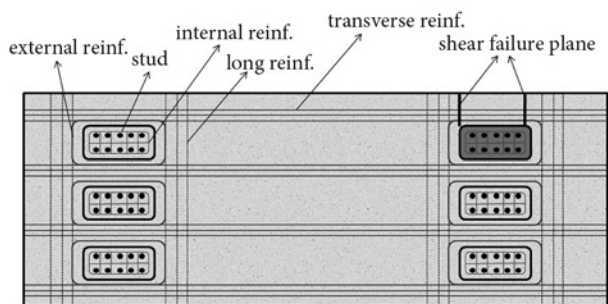


Fig. 11. Detail recommendation for shear connection in precast decks

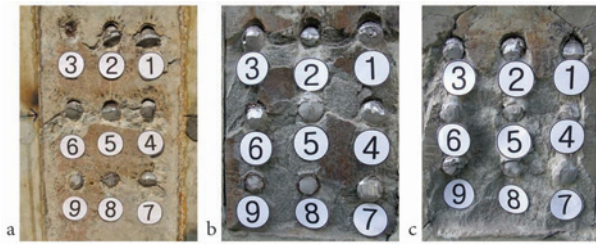


Fig. 12. Fatigue failure pattern of group stud shear connection: a – FGCIP-3; b – FG25OS-1; c – FG25OS-4

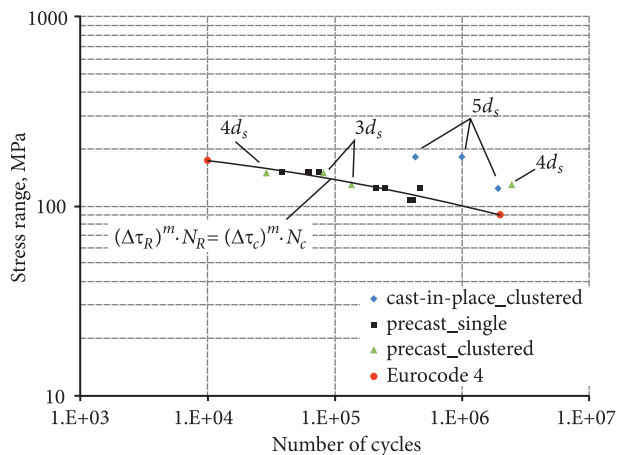


Fig. 13. Fatigue test results of clustered shear studs in precast decks

Damage overlapping of bearing zone was observed for the group stud shear connection in precast decks as presented in Figs 12b–12c. All the specimens had no shear failure of concrete slab. As stud spacing is closer, damage overlapping was significant and resulted in lower fatigue strength than the previous test results for normal arrangement (Shim *et al.* 2000). Damage in bearing zone of shear connection induces the higher stress concentration in weld collar of stud connectors.

Fig. 13 shows S-N curves of clustered stud shear connectors with closer spacing. Comparing with previous test results for single arrangement in a precast deck (Shim *et al.* 2001), clustered shear studs with closer spacing showed lower fatigue strength. However, the fatigue strength of the clustered studs in precast decks gave similar results from *EN 1994-1:2004*. However, it is essential to have careful considerations for the design of clustered shear studs in prefabricated slabs because the safety margin of fatigue endurance is decreased significantly judging from the test results. Without significant reduction of fatigue strength, it is possible to utilize the clustered shear studs for precast deck bridges when stud pitch is greater than $3d_s$.

4. Conclusions

1. For the design of full-depth prefabricated concrete slabs, simplification of details in precast decks is crucial for the constructability. Considering filling material in shear pockets for clustered shear studs, it is possible to use closer stud spacing than the current design provisions. The effects

of the stud spacing on the static and fatigue performance of shear connection in precast decks were investigated through tests and previous data. For the shear connection of precast deck bridges, the effects of the stud spacing and confining reinforcements were clearly observed. Decreasing the stud spacing resulted in a lower ultimate strength of the shear connection. For clustered stud connection of precast decks, closer spacing reduced the shear strength by up to 30% when the failure mode is stud failure after concrete cracking of the slab. The confining reinforcements inside and outside of the shear pocket enhanced the shear strength of the shear connection. It is more effective to strengthen the connection by placing confining reinforcement around the shear pocket.

2. The requirement of the minimum pitch for the stud connectors needs to be revised for precast decks. However, the shear connection with smaller spacing should have adequate reinforcement details to resist shear strength of group stud shear connectors. Considering filling material in shear pockets, bedding height and stud spacing, empirical equations for the evaluation of static performance of shear connection in precast decks were proposed.

3. Fatigue tests showed that the connectors in precast decks gave relatively lower fatigue strength than normal shear connection in cast-in-place concrete slab. In the range of test parameters of this paper, current S-N curves for the fatigue design of common stud connectors are applicable to the design of shear connection in precast decks.

4. Design recommendations on details were suggested to enhance the structural performance of shear connection in precast slabs. Reasonable safety margin is essential for the design of modular structures considering difficulties of quality control of connections in a construction field. Further experiments are needed to derive a design equation considering strengthening details such as high strength filling material and extreme confinement by a steel tube.

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