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Experimental and numerical study on shear studs connecting steel girder and precast concrete deck

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Abstract. Shear studs are often used to connect steel girders and concrete deck to form a composite bridge system. The application of precast concrete deck to steel-concrete composite bridges can improve the strength of decks and reduce the shrinkage and creep effect on the long-term behavior of structures. How to ensure the connection between steel girders and concrete deck directly influences the composite behavior between steel girder and precast concrete deck as well as the behavior of the structure system. Compared with traditional multi-I girder systems, a twin-I girder composite bridge system is more simplified but may lead to additional requirements on the shear studs connecting steel girders and decks due to the larger girder spacing. Up to date, only very limited quantity of researches has been conducted regarding the behavior of shear studs on twin-I girder bridge systems. One convenient way for steel composite bridge system is to cast concrete deck in place with shear studs uniformly-distributed along the span direction. For steel composite bridge system using precast concrete deck, voids are included in the precast concrete deck segments, and they are casted with cast-in-place concrete after the concrete segments are erected. In this paper, several sets of push-out tests are conducted, which are used to investigate the heavier of shear studs within the voids in the precast concrete deck. The test data are analyzed and compared with those from finite element models. A simplified shear stud model is proposed using a beam element instead of solid elements. It is used in the finite element model analyses of the twin-I girder composite bridge system to relieve the computational efforts of the shear studs. Additionally, a parametric study is developed to find the effects of void size, void spacing, and shear stud diameter and spacing. Finally, the recommendations are given for the design of precast deck using void for twin I-girder bridge systems.

Keywords: shear stud; twin-I girder; finite element; load-slip; void

1. Introduction

Twin-I girder bridge systems utilizing full-width precast concrete deck segments both save the construction cost and time, and improve the deck behavior as compared with the systems using partial precast deck. The utilization of shear studs is the most common way to connect deck and steel girders. AASHTO (2012) gives the spacing requirements for the shear studs arrangement for steel-concrete composite bridges. The Chinese design code (2015) specifies the general requirements of diameter and spacing of shear studs along parallel and perpendicular to the traffic direction for shear studs connecting concrete deck and steel girders. All these design suggestions are given for general arrangement of shear studs, while no details for the use of precast concrete deck connected with prefabricated steel girders.

Push-out tests are often conducted by researchers to obtain the parameters for behavior modeling of the load-slip as well as shear resistance (Civjan, 2003, Han 2015, de Souza, 2017, Liu, 2013, Shim, 2014, Xue, 2008). Bonilla *et al*. (2015) proposed a modified formula for the shear resistance based on the finite element (FE) study and the experimental results of push-out tests. Huo *et al*. (2017) gave a prediction method to evaluate the shear capacity. Shim *et al*. (2014) proposed an empirical equation for evaluating the ultimate shear strength of shear studs. Xue *et al*. (2008) proposed an expression for the load-slip relationship and capacity of shear studs based on the push-out test results. Lee *et al*. (2014) developed put-out tests on investigate the behavior of shear studs used in high strength concrete, and they proposed a shear resistance equation was proposed based on the test results using linear regression analysis.

A precast concrete deck is connected to steel girders with shear studs in the voids or shear pockets. Huh *et al*. (2015) conducted some scale tests for single composite beam systems and shear push test to investigate the behavior of closely-spaced studs in shear pockets. Shim *et al*. (2001) used a bridge model test to investigate the behavior of shear studs for bridge systems using a precast deck, and developed the FE *analysis* and the experimental results to evaluate the shear and flexural stiffness of shear connections. Nguyen *et al*. (2011) conducted a parametric study including varying material and geometric parameters to investigate the behavior of shear connection distributed discontinuously. Xia *et al*. (2017) analyzed the behavior of

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steel girder bridge composite with precast deck using shear studs, and found the cracking can affect the behavior of shear studs and the composite system. Ranzi *et al*. (2007) proposed a model for the partial shear interaction in steel-concrete composite beams using the short- and long-term linear analysis. Zheng *et al*. (2014) proposed an analytical approach using a modification factor to investigate the composite effect using discrete shear connectors. Kaveh and Ghafari (2016) developed research on optimum design of floor beam based on the cost, and showed that the full composite action was depended on construction and installation of shear studs.

Finite Element Method (FEM) is an effective method used for numerical study for structures. Xing *et al*. (2016) developed experimental and numerical simulations on the behavior of partially connected elastic concrete-steel composite beams, and their research showed that the FE analysis results had good agreement with the experimental results, and exhibited good applicability of the elastic concrete in the composite beams. Han *et al*. (2016) developed the FE analysis on the behavior of shear stud through push-out test. The FE analysis was validated using previous experimental research, and obtained good agreement. Han *et al*. (2017) extended to the research on the fatigue analysis of shear studs in the composite beam using the FE analysis verified using the test results. The use of the FE analysis agreed with the test results as well as was extended to more parametric study. Ma *et al*. (2018) conducted experimental and numerical analysis on the behavior of steel composite girder bridge, and their research showed that the FE analysis obtained good agreement with the test data, and could be used to predict the behavior of the girder bridge. In the paper, the push-out test is conducted to investigate the load-slip behavior of shear studs, and a detailed FE model is developed to analyze and compare with the test data. Additionally, a simplified model with a modification coefficient is proposed for a composite bridge system analysis to simplify the simulation process and obtain the local deformation of shear studs. Finally the parameters including spacing of void (void spacing), stud diameter, and stud spacing are studied to investigate the effect to twin-I girder bridge systems with precast concrete deck.

2. Push-out Test

Figure 1 presents the assembly of a twin-I girder with a precast concrete deck. The shear studs in the voids are used to connect the steel girder and the precast concrete deck, thus shear studs are not distributed uniformly along the girder length. The push-out tests are designed based on shear studs within the void in the precast concrete deck.

The push-out tests were conducted to investigate the load-slip behavior of the shear studs and to estimate the capacity of shear studs. Four specimens (including S1, S2, S3 and S4) were designed. Three of them (S1, S2, and S3) use single-row shear studs containing 2 studs (4 studs totally), and S4 uses three-row shear studs containing 6 studs (12 studs totally) as shown in Figs. 1 through 3. For

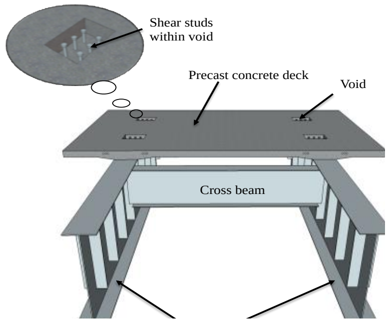


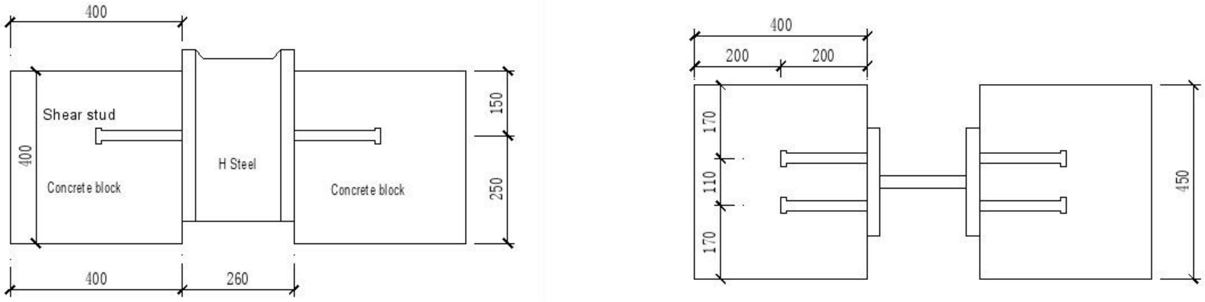
Fig. 1 Assembled twin-I girder with a precast concrete deck

Table 1 Loading plan

Phase	Load step	Force increment (kN)	Total applied force (kN)
I	1	40	40
	2	40	80
	3	40	120
	4	40	160
	5	40	200
	6	40	240
	7	40	280
	8	40	320
	9	40	360
	10	40	400
	11	40	440
	12	40	480
	13	40	520
	14	40	560
	15	40	600
	16	40	640
II	17	Displacement control (with an increment of 0.05mm)	
	18		
	19		
	20		

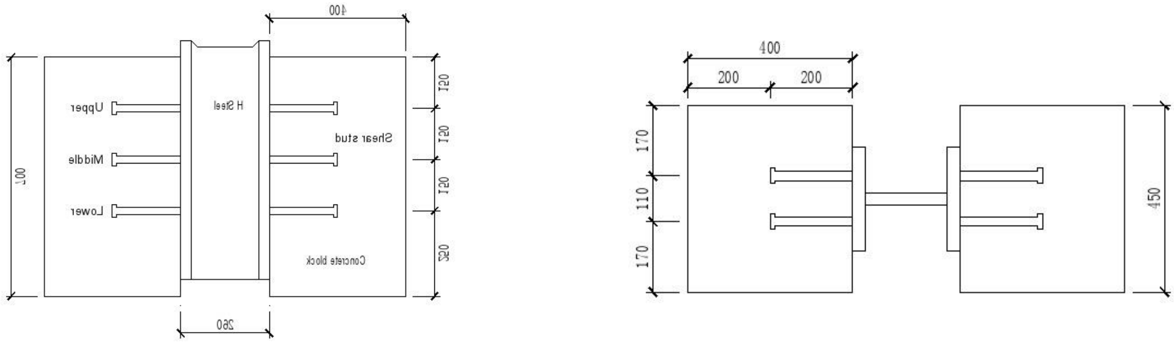
Specimen S1, the steel flange was oiled before concrete was casted to avoid the friction effect between steel and concrete. The specimens were loaded systematically. Both force and displacement controls were used as shown in Table 1. Force control is used for Phase I, and displacement control is used for Phase II. The designed maximum force applied to S1 through S3 was about 800kN, and the designed maximum force applied to S4 is about 2160kN. The loading setup is shown in Fig 4. For each test specimen, the displacement gages are attached to the steel flange where the shear studs are welded, and strain gauges are attached on each shear stud to measure the strain change during the testing (see Fig.5). Dial gauges are used to measure the relative slip between steel flange and concrete.

The load-slip curves of each shear stud for each test specimen were recorded and shown in Fig. 6 (which is the reference of the validation of FE model in the following section). Note that for S1 through S3, there are totally four



(a) Elevation view (b) Plane view

Fig. 2 View of test specimen S1 through S3 (unit: mm)



(a) Elevation view (b) Plane view

Fig. 3 View of test specimen S4

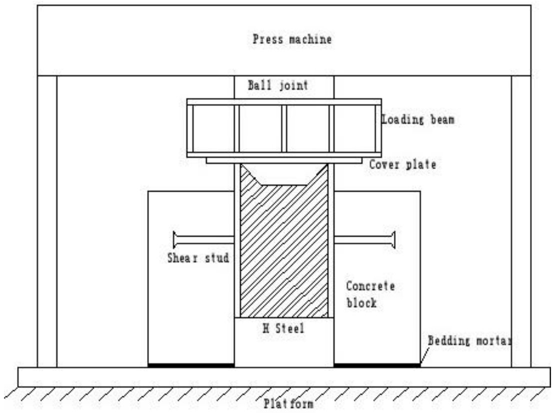
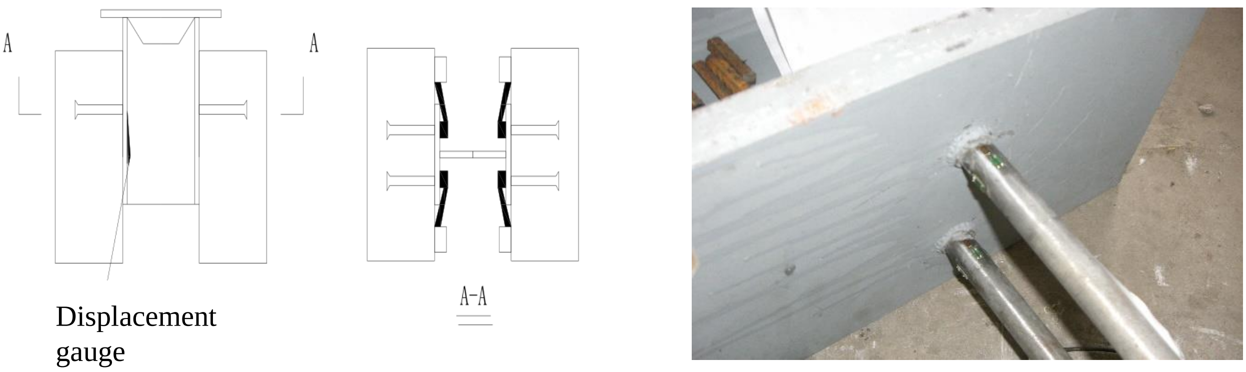
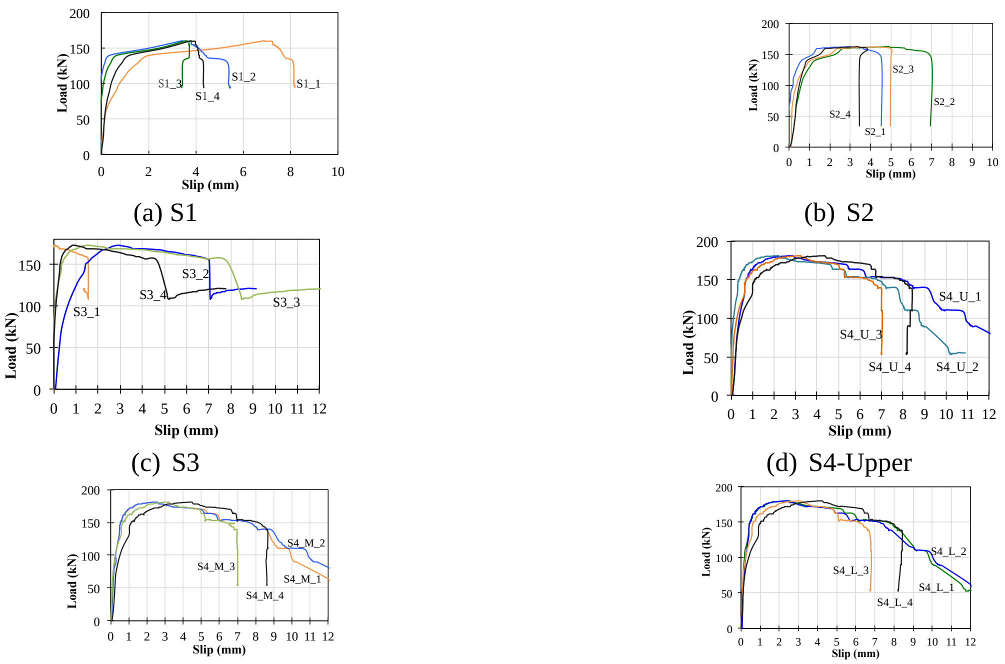


Fig. 4 Loading setup



(a) Displacement gauge (b) Strain gauge

Fig. 5 Instrumentation



(a) S1 (b) S2

(c) S3 (d) S4-Upper

(e) S4-Middle (f) S4-Lower

Fig. 6 Load-slip curves for all test specimens

Table 2 Test data summary for test specimens

		Qu（kN）	Aver.	Ks（kN·mm-1）	Aver.	Qy（kN）	Aver.
S1		160		425		110	
S2		163	167	354	431	123	119
S3		172		464		125	
	Upper	181		428		130	
S4	Middle	181	181	431	495	135	131
	Lower	180		627		128	

studs in the test specimen (denoted by S1_1, S1_2, S1_3, and S1_4 for S1, S2_1, S2_2, S2_3, and S2_4 for S2, and S3_1, S3_2, S3_3, and S3_4 for S3) For specimens S1 through S3, along with the applied force increase, the steel (shear studs) and concrete departed, and the relative slippage between steel and concrete increased slowly in the elastic range; in the elastic range, the relative slippage increased fast, and the shear studs had obvious shear deformation, and failed finally. The departure between steel and concrete occurred earlier for S1 than for S2 and S3 due to the oiled surface.

For specimen S4, the steel and concrete departed along with the applied force increase, and the relative slippage between steel and concrete increased slowly within elastic range; when the applied force was in the inelastic range, the slippage increased fast, and the shear studs failed but the lower ones failed firstly and the upper ones failed lastly.

Table 2 summarizes the test results for each test specimen. From the test data of the four test specimens, when the failure occurred, the concrete and shear studs departed at the top of the shear studs, and the concrete crashed at the bottom of the shear studs. The shear studs had shear deformation and bending deformation, and failed with shear failure mode. Fig. 7 presents this shear stud failure mechanism for the tests.

3. Finite Element Analysis

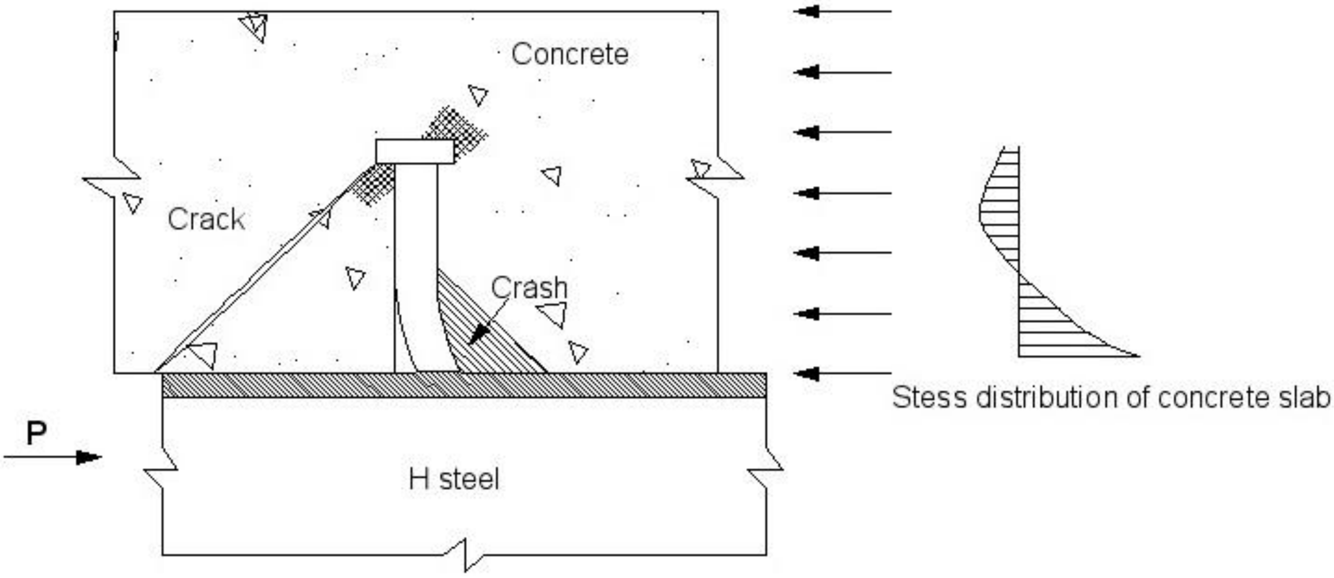
The ABAQUS software is used to develop three-dimensional nonlinear FE models to simulate the push-test specimen. Solid elements of C3D8R type are used to model a concrete deck, steel beam and shear studs. Truss elements (T3D2) are used to model reinforcing bars. Fig. 8 presents the FE model. The constraints between the steel web and flange, between the flange and shear studs adopt ties.

The contact between steel flange and concrete can affect the slippage between steel and concrete, and its effect depends on the normal compressive force. Su (2016) conducted an experimental study to obtain the relationship between the shear strength and normal compressive force. The contact between shear studs and concrete adopts Penalty contact. The dynamic friction coefficient usually ranges between 0.5 and 0.7, and it is taken as 0.5 in the paper.

Concrete Damage Plastic model is used to modify the concrete material property. The stress-strain curve proposed by Ding (2014) is applied in the model, and the equation is as follows:

$$y = \begin{cases} \dfrac{A_1 x + (B_1 - 1)x^2}{1 + (A_1 - 2)x + B_1 x^2} (x \le 1) \\ \dfrac{x}{\alpha_1 (x-1)^2 + x} (x > 1) \end{cases} \quad (1)$$

(a) Failure of shear studs



(b) Failure mechanisms between steel and concrete

Fig. 7 Failure mechanisms of shear studs

(a) S1 through S3 (b) S4

Fig. 8 FE models

where, y is the ratio of stress σ to the concrete uniaxial compressive strength f_c, x is the ratio the concrete compressive strain ε to the peak compressive strain, A_1 and B_1 are the coefficients correlated to the concrete cube compressive strength f_{cu}.

$$A_1 = 9.1\, f_{cu}^{-4/9}$$
$$B_1 = 1.6(A_1 - 1)^2 \quad (2)$$
$$\alpha_1 = 0.15$$

The steel material is modeled using an elastic isotropic material in the elastic range with an elastic modulus of 200 GPa and Poisson's ratio of 0.3, and a bilinear kinematic hardening plastic material in the inelastic range. The ABAQUS classical plasticity material model is used for steel in the inelastic range. The yield strength of the steel material is 345MPa.

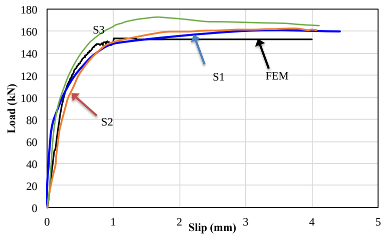


Fig. 9 Load-slip curve for test data and FE analysis results for S1 through S3

Table 3 Comparisons between test data and FE analysis results for one-row shear studs

Test specimen	Ultimate capacity Qu (kN))	Aver.	Shear strength Ks (kN·mm-1)	Aver.	Yield capacity Qy (kN)	Aver.
S1	160		425		110	
S2	163	167	354	431	123	119
S3	172		464		125	
FE		153		441		112

3.1 Boundary conditions and load

A symmetric boundary condition is applied to the symmetric plane for the half FE model to restrain the lateral displacement. At the bottom of concrete deck, the vertical displacements are restrained. The displacement load method is used with an increment of 4 mm to apply force to the steel girder.

3.2 Detailed FE analysis for push-out test

3.2.1 Test of one-row shear studs

Previous research often uses the way to average the test data to obtain the shear strength and yield capacity to be used in the analyses (Su *et al*., 2010, Lee *et al*., 2014). Fig.9 presents the load-slip curves for test data and FE analysis results. When the slip is within 1mm, a good agreement is achieved between the test data (S2, and S3) and FE analysis results. The FE analysis curve is similar to that of the test data. After the slip up to 2 mm, the FE analysis results have the maximum capacity to be smaller than the test data, but the difference is not big. Therefore, the FE analysis can be used to conservatively predict the behavior of the shear studs.

3.2.2 Test of three-row shear studs

Figure 10 presents the load-slip curves for test data and FE analysis results for three-row shear studs (S4). When the slip is within 0.2mm, a good agreement is achieved between the test data and FE analysis results. The curve of FE results fits the curves of the test data and demonstrates a smaller maximum capacity than the test data. Within the elastic range, the FE results have a good agreement with the test data; the forces in the bottom-row shear studs are the largest, and the forces in the middle-row are the smallest. In the inelastic range, there are some differences between the FE

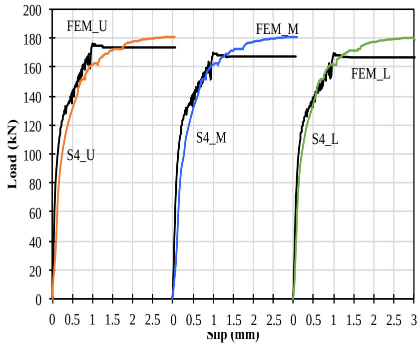


Fig. 10 Load-slip curve for test data and FE analysis results for S4

Table 4 Shear distribution coefficients for three-row shear studs

Test specimen	Upper row	Middle row	Lower row
S4	0.324	0.314	0.362
FE	0.324	0.316	0.360

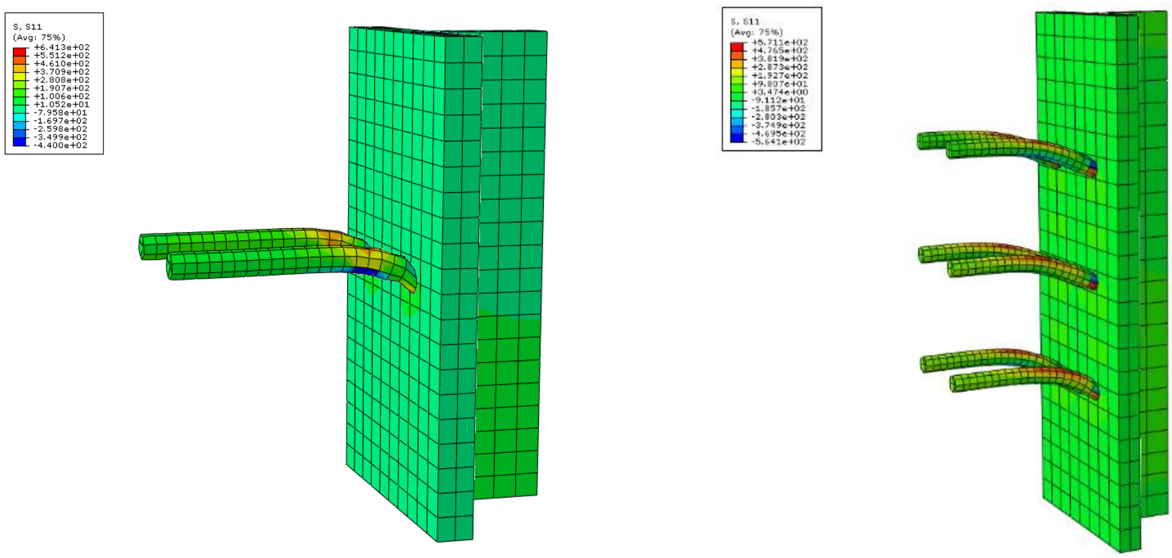
results and the test data, but they are not large. Table 4 summarizes the shear force distribution coefficients for test data and FE analysis results. The shear force distribution coefficient is used to denote the ratio between the force carried by each-row shear studs and the total applied force. The results in Table 4 show a good agreement between the FE analysis and the test data. Therefore, the FE model can be used to predict the behavior of shear studs.

3.2.3 Failure Mechanism

Figure 11 presents the normal stress distribution and deformation during the loading. The shear studs deformation is larger within the bottom including shear deformation and bending deformation. The deformation decreases from the shear stud bottom to the top. The stresses decrease from the shear stud bottom (where the studs are attached to the steel flange) to the top, and they are not high within the range away from the bottom. Both the bending moment and shear forces are induced at the bottom of the shear studs. The FE results above show that the test data have a good agreement with the test results. For the maximum load capacity, the FE results are relatively conservative compared with the test data. Fig.12 presents the failure of the shear studs from the test and the FE analysis. The shear studs fail with shear mode in both the FE analysis and the test. The FE analysis obtains similar failure to the test. Nonetheless, the comparisons show that the FE model is reasonably accurate and reliable to predict the behavior of the shear studs.

3.3 Simplified beam elements model for bridge systems

The FE analyses using solid elements (detailed model) for shear studs illustrated in the previous section have good agreements with the test data. But for a bridge system including steel girders, precast concrete deck and diaphragms, the volume of elements is large. The same



(a) S1 through S3 (b) S4

Fig. 11 Stresses and deformation distribution

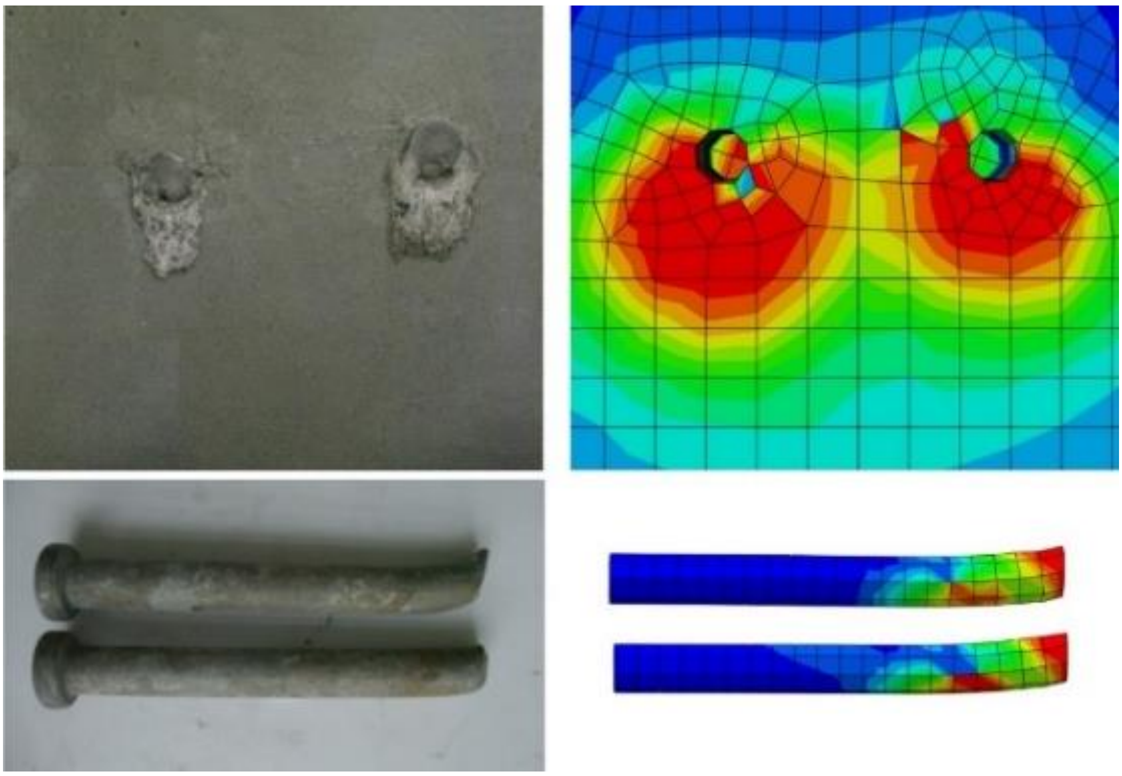
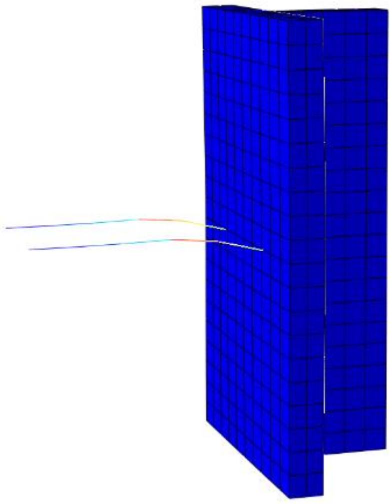


Fig. 12 Failure mechanisms of shear studs

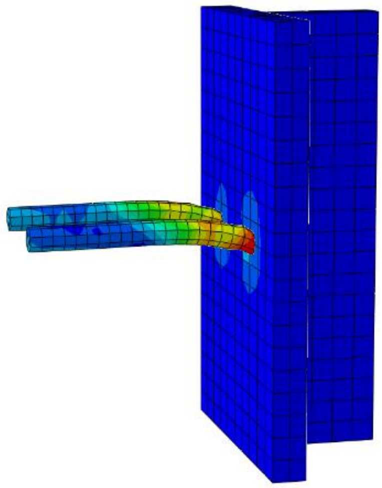
simulation method usage for a bridge system is highly time-consuming and software demanding, so it is not a better way to design or predict the behavior of the bridge. Some studies assume rigid connection between deck and steel girders, which cannot better investigate the behavior of shear studs in the system.

To save the computation time and cost, a simplified model is proposed as follows (Beam model). Solid elements are used to model a precast concrete deck and steel girders. Truss elements are used to model reinforcing bars. The sweep method is used to mesh the model. Tie constraints are used for contact surfaces between steel web and flange, between steel flanges and shear studs. The contact surface between steel girders and concrete deck adapts frictionless surface-to-surface contact. The shear studs are embedded into a concrete deck. The boundary condition is the same as that in previous section. Beam elements are used to model the shear studs, and the modulus is factored by a coefficient to represent the load-slip behavior of the shear studs (i.e., modification coefficient). Fig.13 presents a solid model and a beam model.

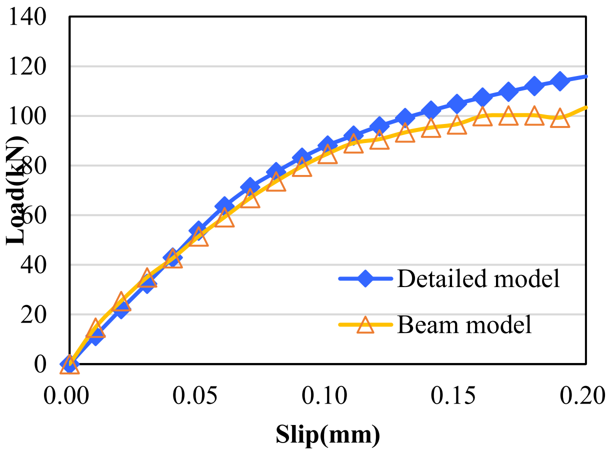
The results are compared with the FE results from the



(a) Beam model



(b) Detailed model



(c) Load-slip curves

Fig. 13 Stresses and deformation distribution for different models

Table 5 Shear capacities for three-row shear studs

Shear stud diameter (mm)	Beam	Solid
16	234	282
22	441	448
28	489	518

previous solid element model. Different coefficients are used to obtain an approximate coefficient. The behavior of the system within the slippage of 0.2mm is focused on finding an approximate modification coefficient. Fig.13 shows the stress distribution comparisons between the beam element model and solid element model. The bending and shear deformation occur during loading, and the stresses at the bottom of shear studs are the maximum. Additionally, three sets of models with different diameters of shear studs are compared to obtain the approximate coefficient. Table 5 gives the ultimate capacity using a modification coefficient of 0.25, and the load-slip curves are similar. Therefore, the modification coefficient of 0.25 is adapted in the paper.

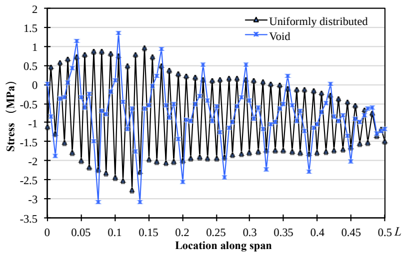
4. Parametric study on behaviour of shear studs

In the section, the parameters including void spacing, diameter of shears studs, and spacing of shear studs are studied to investigate the behaviour of a steel bridge connected with the precast deck using shear studs within voids.

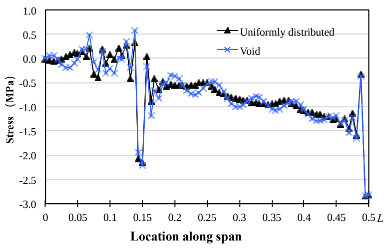
4.1 Comparions between using void and using uniformly-distributed shear studs

Uniformly-distributed shear stud arrangement is a general way to connect steel girders and cast-in-place concrete deck (or cast-in-place joints for a partially precast concrete deck), which can guarantee the binding between concrete and steel. For a full-width precast concrete deck, void is a way to connect steel girders and deck.

Figure 14 presents the stress distribution in the top and bottom of the concrete deck. For the bottom of the concrete deck shown in Fig. 14 (a), the bottom of concrete deck is mostly in compression within the voids, while the tensile stress is available between voids. The maximum stress of



(a) Top



(b) Bottom

Fig. 14 Stresses distribution of concrete deck (half span)

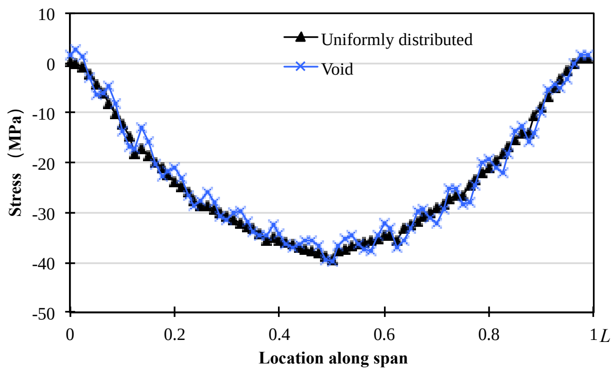


Fig. 15 Stresses distribution at top flange in steel girder

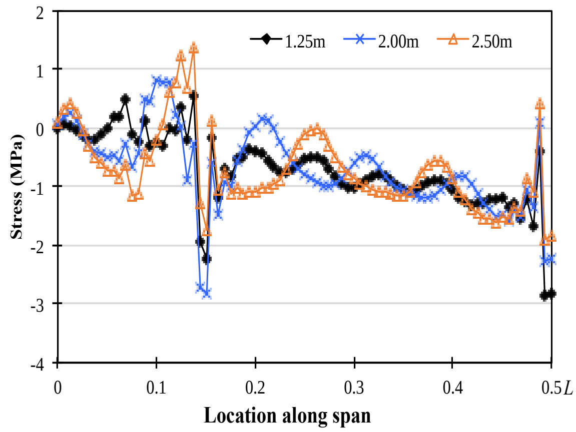
the concrete in the voids is larger than that of uniform-distributed shear studs. For the top of the concrete deck shown in Fig. 14 (b), the concrete deck is mostly in compression at both sides, and the stress distribution is similar for both types. Therefore, the crack may occur for the concrete in the voids (e.g., the tensile stress is bigger than 1.4 Mpa), and the cast-in-place concrete in the voids can use the concrete material with higher tension strength.

Fig.15 presents the top flange stress distribution. The results show that the distribution curve is smooth for uniformly-distributed shear studs, but there is a shift for the shear studs in the voids. The stresses are slightly bigger than uniformly-distributed shear studs.

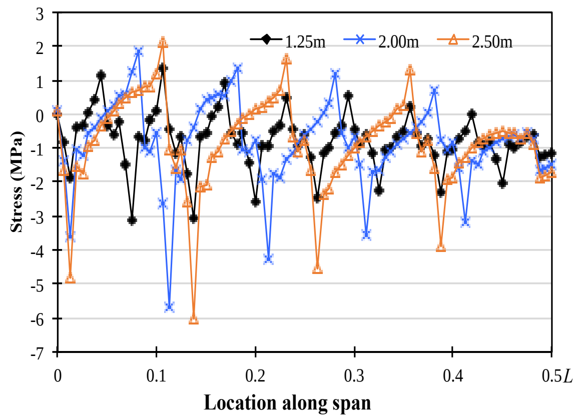
The results above show that there are some differences between the two types. The tensile stress in the concrete in the voids should be paid attention to. The stresses in the steel girders are similar for the two types.

4.2 Void spacing

For twin-I girder systems, void spacing depends on the precast deck length and void size. The precast deck length is determined on the basis of the lifting capacity, and the length is usually within 2.5m and 4.0m. The void size is a rectangle with width and length varying from 0.5m to 0.8m.



(a) Top surface



(b) Bottom surface

Fig. 16 Stress distribution in concrete deck

When the void spacing increases, the amount of the voids can be reduced in the precast concrete deck and cast-in-place work. But large void spacing can induce some changes to the stress distribution in steel and concrete. Three sets of models are developed to investigate the effect of void spacing based on the same shear stud spacing and number.

Figure 16 presents the stress distribution in the concrete deck for different void spacing. For the top surface of the deck shown in Fig. 16(a), the stresses vary a lot with void spacing increase, and the tensile stresses are induced within the voids. For the bottom surface shown in Fig. 16 (b), the void spacing increase causes the amplitude of tension and compression stress to increase. Compressive stresses are induced within the voids, but the tensile stresses are induced between the adjacent voids. Under vertical loading, the concrete deck between the adjacent voids is not connected to steel girders, and it behaves as a continuous girder to make the concrete deck within the voids carry the negative moment, and the concrete deck between voids carry the positive moment. With the increase of void spacing, the behavior of continuous girder is more significant, because it reduces the composite effect between steel and concrete and strengthens the local effect on the concrete deck. While, for smaller void spacing, it is small.

Figure 17 gives the top flange stress distribution of steel girders for different void spacing. The stresses vary a lot along with the increase of void spacing. Therefore, the void

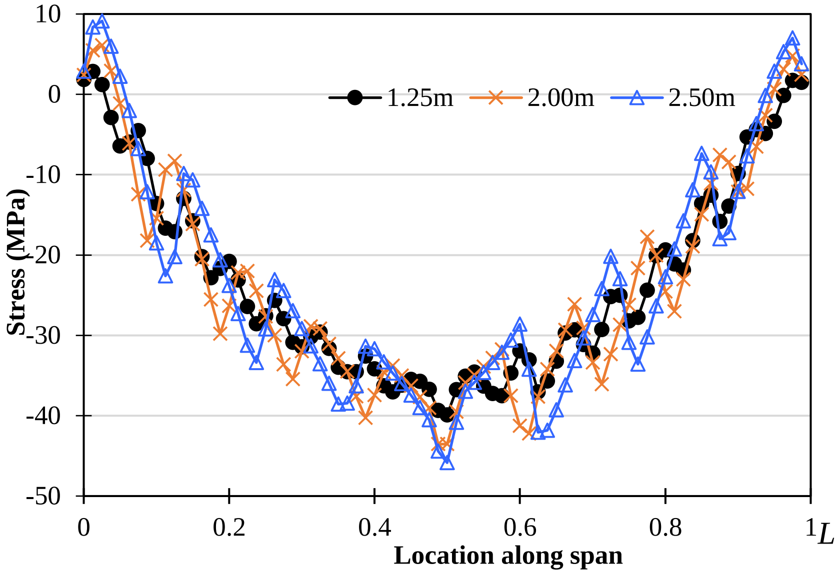


Fig. 17 Bottom flange stress in steel girders

Table 6 Analysis results for different shear stud diameters

Results	Diameter (mm) 16	22	28
Steel top flange (MPa)	-41.69	-41.67	-41.62
Steel bottom flange (MPa)	38.35	38.34	38.33
Concrete top flange (MPa)	-2.37	-2.38	-2.39
Concrete bottom flange (MPa)	-1.11	-1.12	-1.13
Vertical deflection (mm)	7.971	7.970	7.969

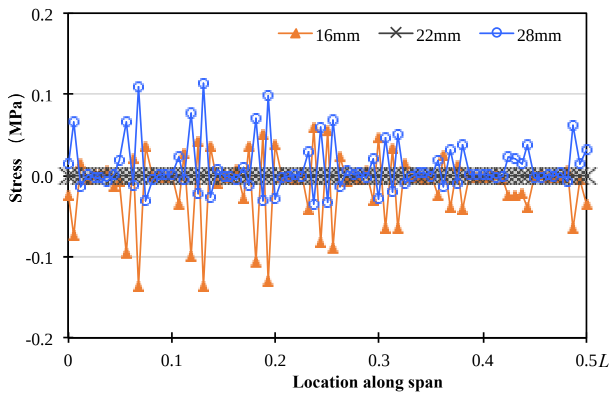


Fig. 18 Stress amplitude in bottom of concrete deck

spacing has a big effect on the behavior of bridge system, and to the void spacing should be determined with consideration of the concrete tensile strength to guarantee the composite behavior between steel and concrete.

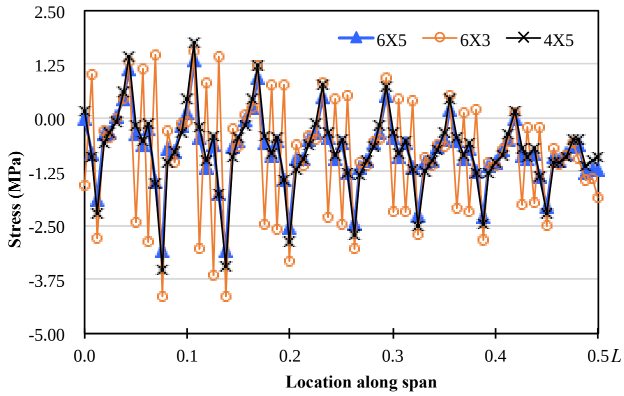


Fig. 19 Stress in concrete bottom surface for different longitudinal stud spacing

4.3 Shear stud diameters

Three sets of shear stud diameters are analyzed to investigate the behavior of steel girders and concrete deck.

Figure 18 presents the stress amplitude in the bottom surface of concrete deck for different shear stud diameters. The stress amplitude changes slightly with the increase of shear stud diameter. Table 6 summarizes the results. The variations of steel stress, concrete stress and vertical deflection are small. Therefore, the shear stud diameter has little effect on the behavior of composite twin-I girder systems.

4.4 Shear stud spacing

Figure 19 presents the concrete bottom flange stress distribution for different longitudinal shear stud spacing (e.g., the spacing of shear studs along the girder length). The stress increases with the spacing increase. For the steel bottom flange stress shown in Fig.19, the steel stress increases slightly with the increase of stud spacing. Therefore, the shear stud spacing has a small effect on the behavior of the bridge system.

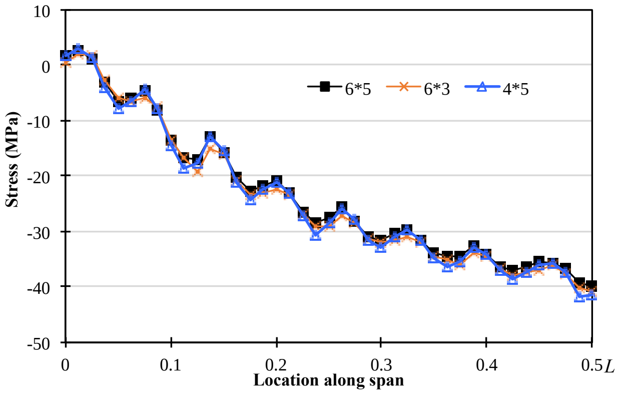


Fig. 20 Steel top flange stresses for different longitudinal stud spacing

Table7 Analysis results for different shear stud spacing

Results	Void		
	6X5	6X3	4X5
Transverse distance (mm)	12.0	12.0	15.0
Longitudinal distance (mm)	12.5	25	12.5
Steel top flange (MPa)	-41.69	-42.45	-43.49
Steel bottom flange (MPa)	38.35	38.62	38.15
Concrete top flange (MPa)	-2.37	-2.16	-2.33
Concrete bottom flange (MPa)	-1.11	-1.90	-1.54
Vertical deflection (mm)	7.971	8.042	7.991

Table 7 summarizes the analysis results for different shear stud spacing. With the increase of the longitudinal and transverse spacing of the shear studs, the stress in the steel girder is increased, the concrete stress is decreased, and the deflection is increased. Therefore, the composite behavior of steel and concrete is reduced. Although the increase of stud spacing can supply more inconvenience for construction, the spacing cannot be too big to reduce the composite behavior.

5. Conclusions

This paper analyzed the push-out test specimen, and contains the FE model validation and simplification, and parametric study on connection between steel and precast concrete deck. The conclusions and remarks are made as follows:

- For both of one-row shear studs and three-row shear studs, the shear strength is stable within the slip of 0.2 mm, but it decreases when the slippage exceeds 0.2 mm. It can be treated in practice that the shear strength is linear within the slippage of 0.2 mm.
- When a failure occurs during push-out test, shear stud top (away from where the shear stud is welded to the steel flange) depart with concrete, and the concrete crashes at the bottom of shear studs (where the shear stud is welded to the steel flange). Both bending and shear deformations occur for shear studs, and the shear studs fail in the shear mode.
- The detailed FE model using solid elements can simulate the detailed behavior of the shear studs generating similar failure mode to the test, and it has a good agreement with the push-out test results demonstrating a similar load-slip curve to the test data as well. The FE analysis can be used to improve the analysis process with the modification coefficient of 0.25 with saving the volume of model and computation time.
- The behavior of twin-I girder systems using void is similar to that using uniformly-distributed studs. The parameters of void spacing and shear stud spacing have some effects on the behavior of the composite systems, especially for the concrete deck. The tensile stress in concrete deck within the voids are kind of sensitive to the large void spacing and shear stud spacing, which should be paid extra attention to during the design and maintenance of the bridge.

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