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Launch Load Experiment of Shear Connector

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Abstract

The S-PC (Steel Box-Prefabricated Concrete Deck) shear connector which combines the bridge deck with steel box girder by the way of watering concrete rear is proposed herein in allusion to the features of the construction of Steel Box-Prestressed Concrete composite large-span rigid frame bridge. Several specimens' push-out test are designed and accomplished. There is a research on the behavior under load conditions, regularity of loading-slipping, failure mode and damage phenomena of S-PC shear connector. The formula of the relationship overall the loading process between loading and slipping basing on the experiment date and regression theory is proposed. The calculation of cross section stress simulation is developed using the finite element software.

Keywords: Shear connector; S-PC shear connector; the relationship between loading and slipping; composite bridge.

1. Introduction

Steel-concrete composite structure is a new structure which flourished on the basis of steel structure and reinforced concrete structure. It combines steel and concrete through shear connector to resist sliding and separating under several of loads, which makes the two parts work together. With a wide application of composite structure, shear connector receives more attention. The feature of S-PC shear connector， mentioned in this article ,is that waters concrete rear to make the combination of shear connectors and steel box into work. It gives S-PC shear connector a plenty of advantages. It can use prefabricated bridge deck, separately prestress the bridge deck, and prevent cracking in negative moment region and so on. It is an applicable rigid shear connector for the fabricated steel box-prestressed concrete composite continuous rigid frame bridge. In the previous studies [1-4], researchers focused on shear connector itself and the strength of the concrete whether the flexible shear connector with stud or the rigid shear connector with channel section, and few people research its performance affected by watering concrete rear. In order to grasp and understand the working performance of S-PC shear connector of concrete deck and steel girder especially the influence of watering concrete rear, we need to test the deformation performance of S-PC shear connector and the regularity of loading-slipping in the whole loading process, realize the working performance of S-PC shear connector and watering concrete rear , and obtain the loading-slipping curve and failure mode, to provide reliable data for the design of SB-PC combined continuous rigid frame bridge. 5 specimens' push-out tests are designed and accomplished, and following experimental results to formula of relationship between loading and slipping. Finally, researchers make a calculation of cross section stress simulation using the finite element software, and analyze load-bearing and failure mode of S-PC hear connector based on the result.

2. Test situations

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The experimental design two kinds of a total of 5 specimens, The first class has three specimens, Each specimen design for the two shear connectors from both sides, Numbered is: N1, N2, N3. The each specimen of the second class is designed for two shear connectors, it is equivalent to half a model ,the first class of N1, N2 specimen, has the same dimension parameters with the corresponding parts of the N1, N2 specimen, the numbered is : N1A,N2A.The shear connector use the No. 5 channel steel, height of 5cm, considering that is the push-out test of vertical loading, So it simplifies the annular anchoring reinforced of the S-PC shear connector, used the straight bar of the diameter of Φ8 welding in the No. 5 channel steel to replace it. Hereinto, reverse the round of the channel steel shear connectors on the N2 and N2A specimens. All the steel among the middle of specimens are I-shaped members, the lower and upper of I-shaped member have a piece of steel plate terminated, The thickness of the steel plate are 6mm. All specimens concrete plates are prefabricated plate, obligate shear connector hole in prefabricating, pouring the concrete among shear connector hole after assembly. Introduce representative type structure of the experiment specimens such as Fig.1, the completion of the assembly and pouring as shown in Fig.2.

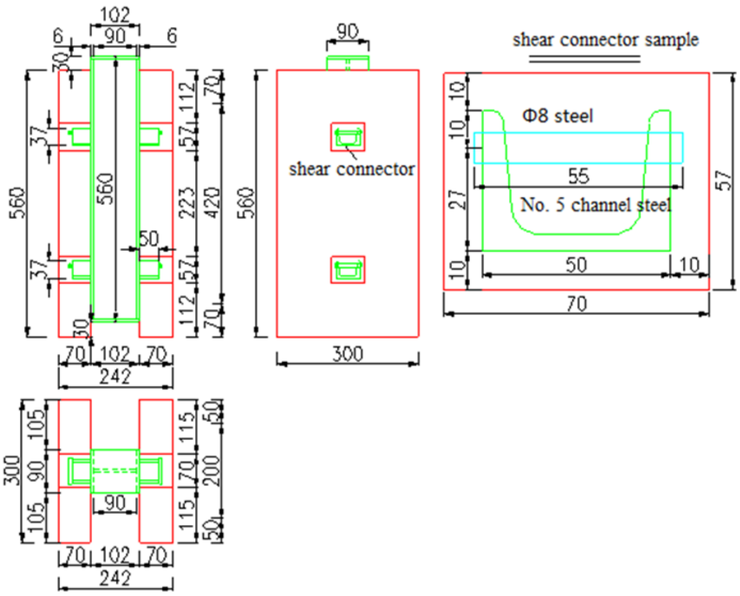


Fig.1 Specimen N1 and N1A form and structure

Fig.2 Pour the shear connector hole after assembled

By pre-estimating obtain in the each kind of shear connector nominal design capacity F before loading test, press the 0.2F pre-press 2 times, each holding charge 5min, to eliminate the effect of non-elastic deformation. Get into formal load testing condition after preload complete, the typical load conditions shown in Table 2.

Table 2 Loading condition of N1 specimen

loading	Sequence and maximum load (kN)	Load increment (kN)	Loading method
1~3(elastic)	0→150→0	10	Loop three times
4 ~ 5 times (craze)	0→190→0	10	Loop three times
The 6th (damage)	0→620	20	Monotonic loading

Shear connector specimens loading through universal testing machine in Chongqing Jiaotong University Structure Laboratory Center, displacement measuring device was arranged at shear connector and between two pairs of shear connector, shared 6 dial indicator to measure, specimens for N1A and N2A, displacement measuring points are arranged at the shear connector, total 2 dial indicator measuring points, as shown in Fig.3

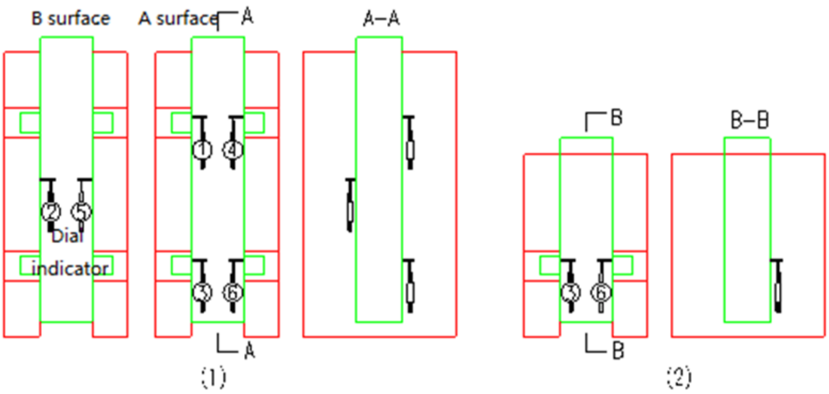


Fig.3 Specimen measuring points arrangement

3. Analysis of test results

3.1 Actual measurements load-slip curve

The typical load - slip curve of S-PC shear connector specimens under cyclic loading is shown in Fig.4. Dial indicator testing slip value is the amount of relative slip between steel structures and concrete measuring points, curve represents the amount of slip is the average of test results, is amount of slip the whole process of recording that the shear connector specimen under external loads. In the load - slip curve, abscissa is the amount of slip, the vertical axis is the whole external load that specimen withstood.

Fig.4 shows the middle (the middle of upper and lower shear connector)of test piece N1’s load-slip curve, the load slip curve, as we can see, when the load is less than $0.33Q_U$, the relationship of loading and slipping showed a linear correlation. The linear properties under cyclic loading can indicate that S-PC shear connector do have strong rigidity, after unloading, only small amount of residual slipping lasted, so shear connectors have a idea flexible working condition. The load-slip curve under the first cyclic loading cannot overlap with the following ones that are mainly due to the friction and clearance of interface.

Fig.5 below shows the average value of the load-skip curves of the central parts of specimen N1 ~ N3 (i.e., the measuring points 2 and 5 in Fig.3). The curves of the central specimen parts reflect the average slip better. It is clear that the curve is linear and steep at the initial loading area and then the slope gradually decreases, which shows an obvious nonlinearities. With the loading continuing, the slope of the curve continues decreasing to a small constant value. According to the properties of the S-PC shear bond curve, the working session will be divided into elastic stage, elastic-plastic stage and plastic stage.

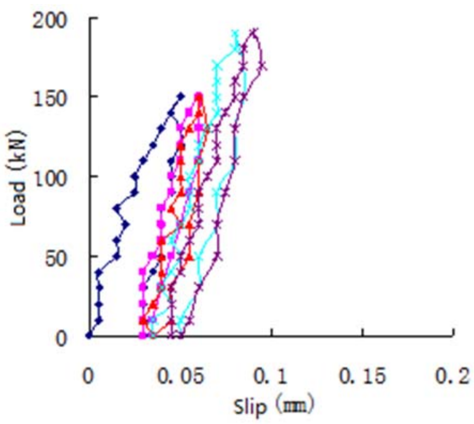


Fig.4 Load-slip curve of middle part in N1

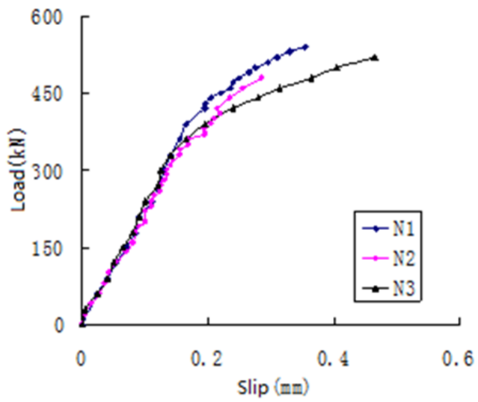


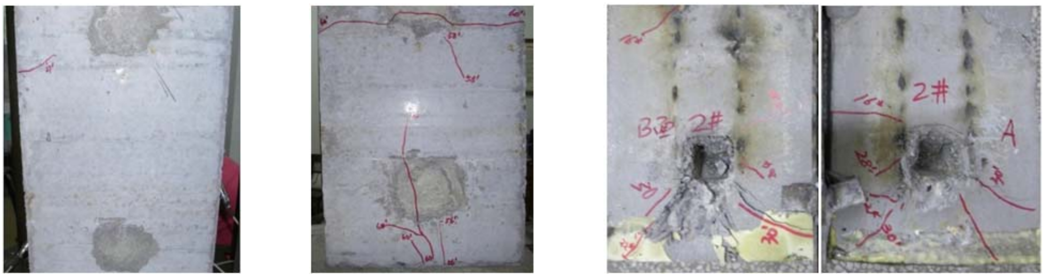
Fig.5 Load-slip curve of middle part in N1

3.2 specimen failure modes

During the whole process of loading, a short crack appeared near the shear connector hole edge when the load reached $0.33Q_U$ for the 1st time (Q_U is the shear strength for the S-PC shear bond). As the load increases, a few short cracks showed on the surface of the concrete and the crack development process was slow and the amount was very few as shown in Figure 6a. Because they were assembled components, the peeling of steel and concrete was not observed during the loading process and there was almost no crashing. It is believed that when the load is less than $0.33Q_U$, the specimen can be considered as in an idea elastic working condition.

When the load increased to $0.4Q_U$, tiny cracks appear in the internal side of the shear connector holes. The crack width increase is not obvious when the loading repeats below $0.5Q_U$, and the specimen can be approximately considered as in an elastic working condition.

As shown in fig.6b, when the load is in the region of $0.5Q_U$ to $0.7Q_U$, especially when increasing from $0.7Q_U$ to Q_U, the crack width, the number of slips and the slips increased significantly. And horizontal cracks, diagonal cracks and vertical cracks showed on the concrete surface around the shear connectors and below, which meant the specimen turned into a failure stage. With the loading increasing, shear cracks beneath the keys developed rapidly with a slight noise, and finally the concrete lost its bearing capacity because of the damages of the shear connectors, which can be appreciated from Fig.6(c).



(a) Specimen after cracking (b) Specimen before failure (c) Specimen after failure

Fig.6 The whole destruction process of the specimen

3.3 S-PC Shear load-slip relationship

Main factors affecting S-PC Shear load - slip relationship are: shear strength of shear keys, shear connector external load *Q*, shear connector appearance characteristics and shear connector spacing. By regression analysis of the results with the test data, where slip value used in the analysis is the average of shear connectors at the slip value for each of the slip curve fitting, and establish a S-PC shear connector load - slip curve relationship:

$$\ln\left(1-\frac{Q}{Q_u}\right) = -\alpha\, S^{\beta} \qquad \alpha = 3.021 \quad \beta = 0.5883 \tag{1}$$

In the equation, S is the slip value at interface of the S-PC shear bond with the concrete, and the unit is mm; Q_U is the shear strength of S-PC, and *Q* is the load with the unit of KN. The comparison curve of the average value based on the test of specimen N3 and the calculation value is fig.7.

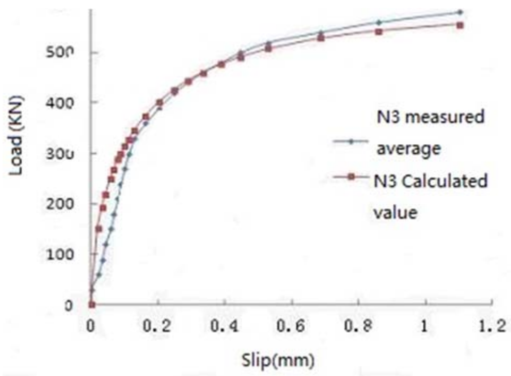


Fig. 7 Comparison between calculated value and measured value of N3

4. S-PC Performance Analysis of shear connector under load

4.1 FEM

For the further study of the features and working performance of S-PC shear bond, the model was established with the FEM software ABAQUS and shown in Figure 8. The model is formed by precast concrete panels, steel, steel structures and shear-shaped key respectively. The constitution is based on the stress-strain relationship of uniaxial tension and uniaxial compressive stress in <Code for design of concrete structures>. The constitution of H-shaped steel member, shear connector and steel reinforcement is the elastic-plastic enforced model of steel [5,6].

Concrete slabs, H-shaped member and shear connector were analyzed by finite element software with solid elements, steel with truss element. Shear connector is embedded with concrete slabs. The interface of shear connector and Concrete is analyzed by contacting analysis. Loading ways and boundary conditions are same as test conditions with the top-shaped steel member loaded, two lower bearing concrete slab.

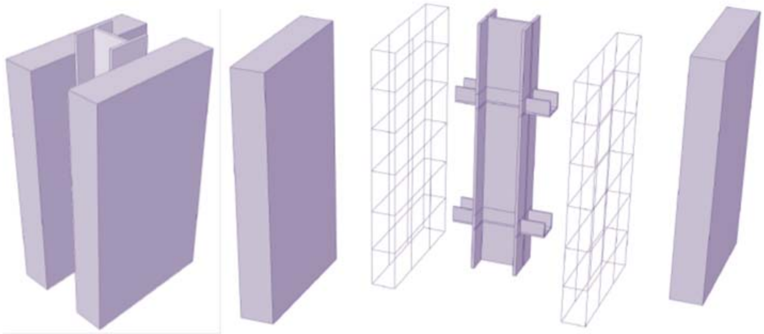


Fig.8 FEA model of the specimen

By the comparison of the measured value and FEM calculated results as in fig.9, we can see that they agree well in the elastic session and FEM has a relatively good precise and reliability in the elastic session. The difference in the post-crack and the post-processing session is mainly because of the difference of the constitutions of FEM and the real condition. It is indicated that the FEM analysis can reflect the real loading condition of shear connectors. In this identical essay, we will use FEM to start a local calculation model to further research loading properties of S-PC shear connector.

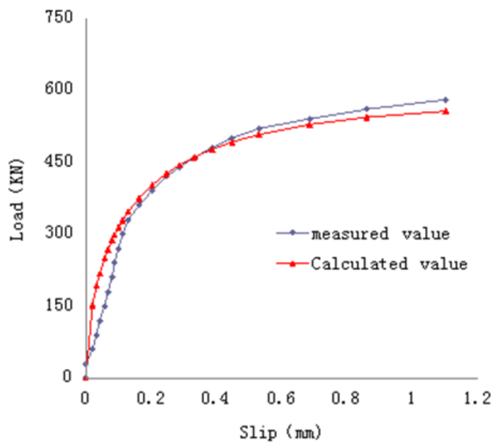


Fig.9 calculated value and measured value

4.2 Cross-section stress distribution of concrete plate

As is shown in Fig. 10, the stress distribution of cross section is determined by the xoy coordinate in cross section C that is 40mm to bearing surface of shear connector, in which x and y axes represent the width and thickness direction of concrete slab, respectively.

Fig.11 shows the maximum and minimum principal stress distribution of concrete plate in cross section C when loads are 205kN (0.33) and 435kN (0.7), respectively.

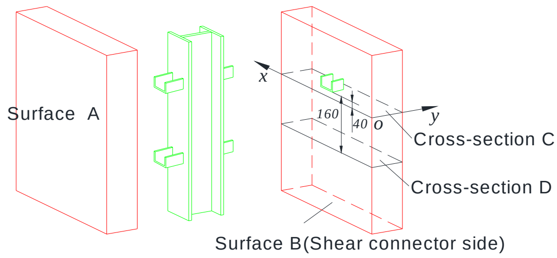


Fig. 10 Stress value position

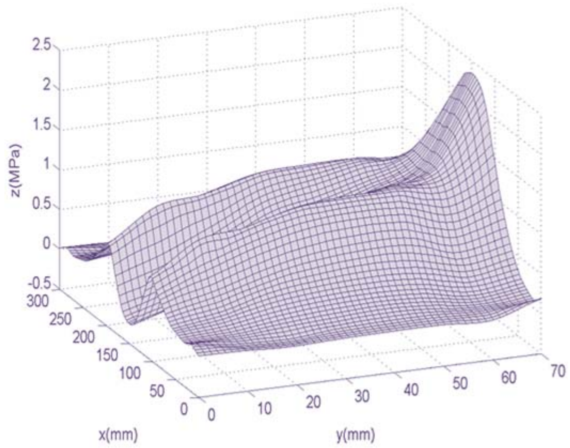


Fig.11 (a) The maximum principal stress of C cross-section (205kN)

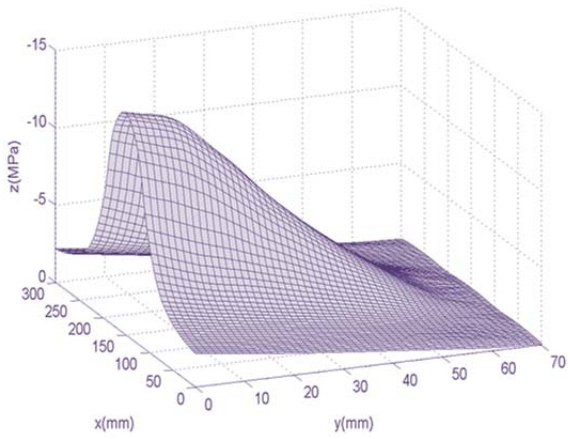


Fig.11 (b) The minimum principal stress of C cross-section (205kN)

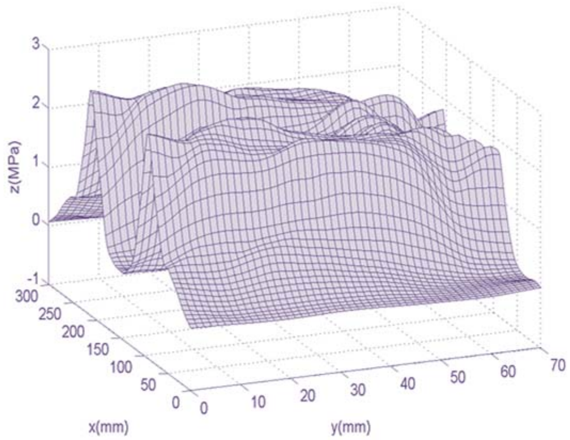


Fig.11(c) The maximum principal stress of C cross-section (435kN)

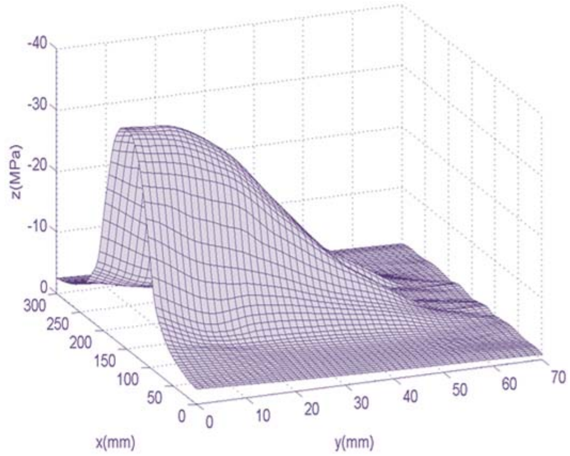


Fig.11 (d) The minimum principal stress of C cross-section (435kN)

It can be found that the minimum principal stress was mainly distributed in the core compression zone below shear connector, out of compression zone, compressive stress spread rapidly and became small. The position of maximum principal stress namely tensile stress was corresponding to the splayed inclined crack position on concrete slab.

4.3 Shear stress distribution

Mises stress distribution along both the x and y directions (shown in Fig. 12, x and y are the center line and edge of bearing surface respectively) are shown in Fig.13.

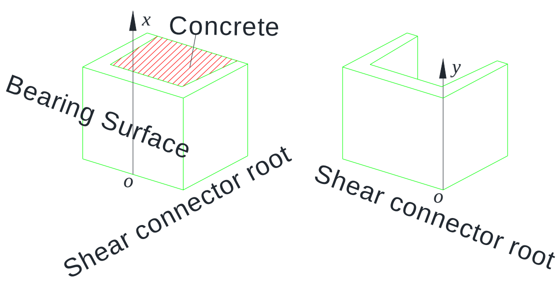


Fig.12 The position of stress value

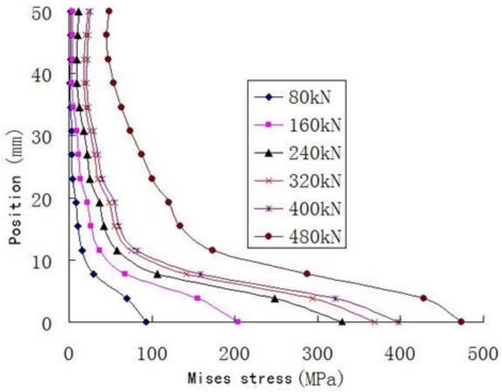


Fig.13(a) The mises stress in the center of bearing surface

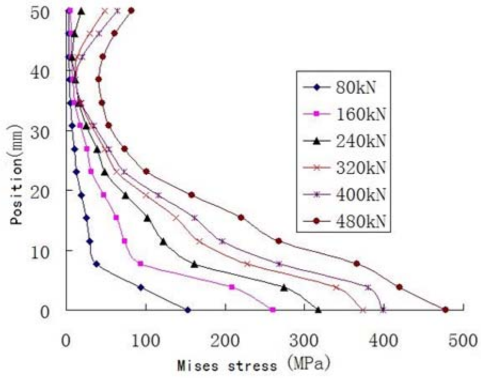


Fig.13(b) The mises stress on the edge of bearing surface

It can be seen from Fig.13, the S-PC shear connector is a rigid shear connector, stress distribution along center line and edge of bearing surface is slightly different, stress in the root is large and it decreased sharply with the increase of distance to root, so that the shear stress is mainly concentrated in root position of shear connector. As the load increases, the shear stress increases, the integral curve moves to the right. It can be found that an inflection is in the upper edge stress curve, when load is small, the shear connector is acting like cantilever beam that stress is large in the root and small in the end and results in no inflection. However, when load is large, shear connector rotates a litter compared with welded steel members, results in a reduction of constraints to inside concrete in the end of shear connector, thus increases the force of shear connector end, forms a shear and bending interaction and results the inflection of stress curve.

Mises stress distribution along both the x and y directions (shown in Fig. 14, x and y are the root of bearing surface and the root of side surface, respectively) are shown in Fig.15.

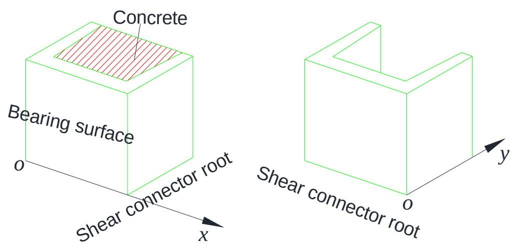


Fig.14The taking value position of stress

It can be seen from the Fig.15 and Fig.16, when load is small, stress that close to shear connector edges is large because that edge are the interface of concrete and steel, besides, concrete inside of shear connector has little influence on this region. With the increase of load, root of shear connector begins to yield, and stress in the root eventually becomes the same.

There are three main failure models of the S-PC shear connector, (1) Concrete failure, (2) Shear failure in the root of shear connector, (3) Shear connector failure by bending.

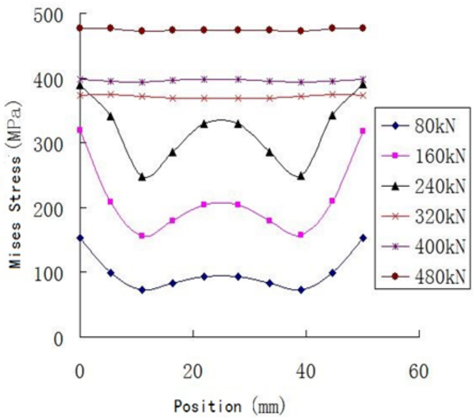


Fig.15 The mises stress in the root of bearing surface

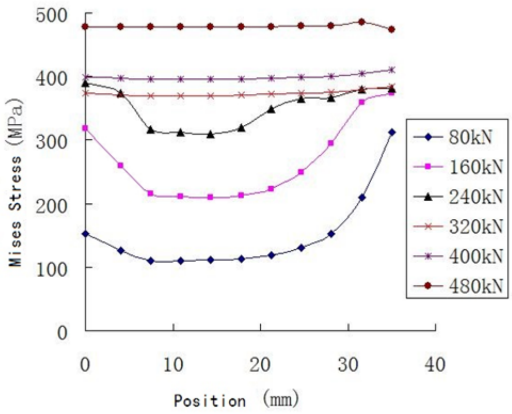


Fig.16 The mises stress in the root of side face

Rigid shear connector discussed in this thesis has enough stiffness. Therefore, in the concrete crushed, shear connector deformed seriously and set aside or cut, thus destroyed (showed in figure 17), this situation should be avoided. For the thickness of the steel plate is similar to S-PC rigid shear connector in actual bridge shall not less than 16mm,according to the finite element calculation is also the case, so regulations for the thickness of the steel plate S-PC rigid shear connector shall be not less than 16mm.

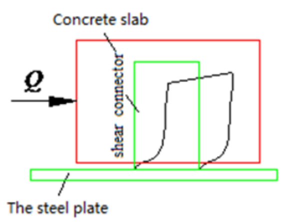


Fig.17 Deformation map of shear connector

The thickness of the wing plate of Welding shear connector steel beam is too small, which caused large deformation or damage.

The following finite element analysis is about the influence of displacement of shear connector and around the steel plate around shear connector, using two different size parameters analytical model, model A: the size is based on shear connector test model in this thesis while model B' shear connector size is based on the actual bridge (showed in figure 18), the size in model B is refer to the design Code for the Steel Structures. The loading mode in figure19 (1) is used in each model, the displacement of shear connector is taking its displacement of edge vertex, and the displacement of top flange plate is taking its maximum displacement of the plate around the root of shear connector as showed in Fig. 19(2).

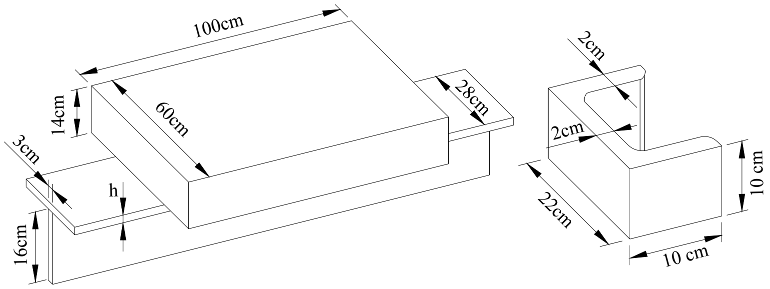


Fig.18 Dimension parameters of model B

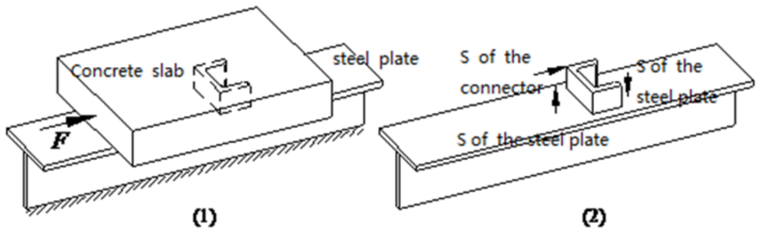


Fig.19Loading method and displacement measure points

The load-displacement of model A is showed in Figure 20 and 21,as the model B is showed in Figure 22 and 23legend in the chart is show to the steel plate thickness), It can be seen that the change of Shear Connector bearing Capacity caused great different effects to the deformation of steel plate.

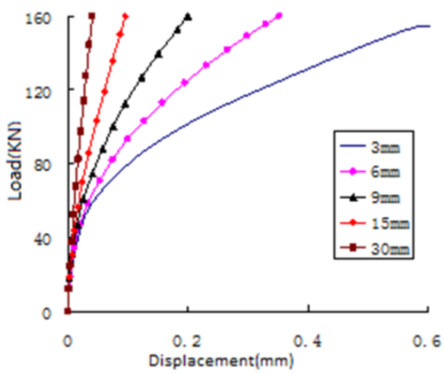


Fig.20 Load-displacement curve of steel plate

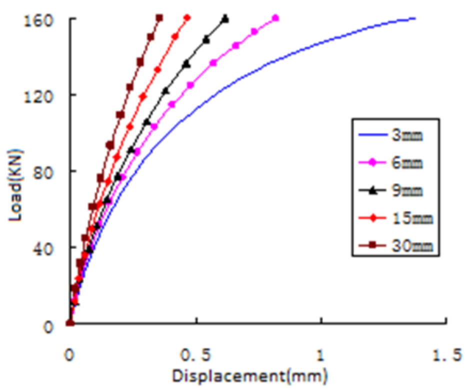


Fig.21 Load-displacement curve of shear connector

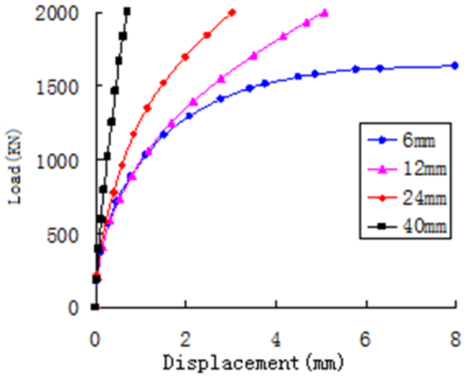


Fig.22 Load-displacement curve of steel plate

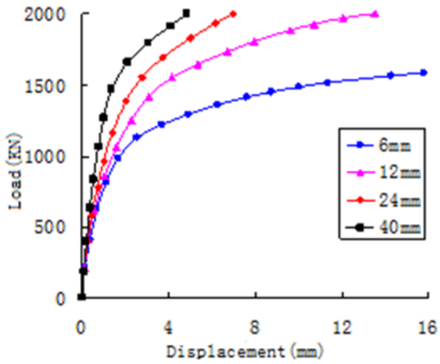


Fig.23 Load-displacement curve of shear connector

Because of a single shear connector is not fully reflect the restriction in the flange of steel beam and concrete plate, the single shear connector in Figure 18 is change to double with the vertical shear connector interval of 50cm and the corresponding model of steel beam and concrete plate extend to 20cm. Deformation Curve of the double shear connector model is showed in Figure 24 and Figure 25, whose ordinate is total loading. It is well-known that the shear carried by the shear connector is half of its ultimate load according to the literature. When the load carried by the rigid shear connector is half of its ultimate load, the displacement of plate (equivalent to deformation) is 0.03mm with almost in straight state and the displacement of shear connector is 0.066mm due to its own deformation. The results show that when the thickness of the wing plate is more than 15mm, it has little influence on shear connector so it can avoid the failure of wing plate lead to the failure of shear connector.

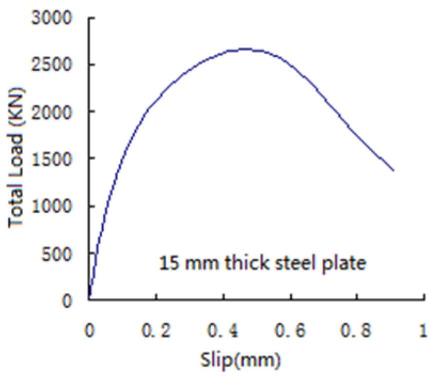


Fig.24 Load-slip curve of steel plate

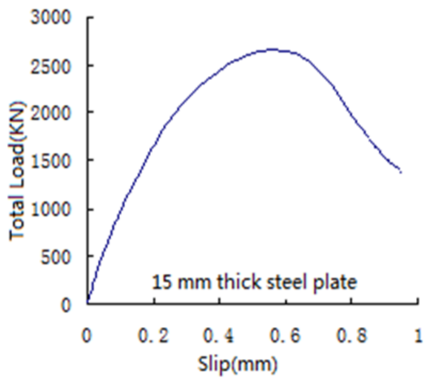


Fig.25 Load-displacement curve of shear connector

Shear capacity based on crushing of concrete

Because of the confinement of stirrups carried by the concrete under shear connector and the concrete underside is in the core compression, an improvement coefficient of concrete strength must be multiplied when calculating the ultimate load of shear connector, not just use the bearing area of shear connector multiplied by concrete strength. The following calculation of improvement coefficient divided into two with one improvement coefficient k1 is represented by concrete slab width and another improvement coefficient k2 is represented by concrete thickness, the whole improvement coefficient k is represented by k1 multiply k2. So the calculation formula for ultimate load of shear connector expressed as follows:

$$Q_{u1} = A\ f_{ck}k = bh\ f_{ck}k_1k_2 \tag{2}$$

Where:

A=bh (shown in Fig. 26) ; where f_{ck} is the axial compressive strength of concrete ; k as the Coefficient of strength increase of concrete ; k_1 as the Coefficient of strength increase of the shear connector along the width ; k_2 as the Coefficient of strength increase of the shear connector along height direction .

The determination of k_1 and k_2 :

The determination of the coefficient k_1 along slab width direction. When the load to the limit load , according to the result of finite element calculation , take the stress distribution near the pressure-bearing surface of shear connector directly below the center , namely, compressive stress distribution along the concrete slab width direction , its stress distribution curve is Symmetrical hat , as shown in fig. 26 . Area surrounded by the actual stress distribution curve, according to the principle of equal area equivalent to a rectangle, the height of the rectangle for the axial compressive strength of concrete is f_{ck} , k_1b as the rectangle's width. In this way, we get k_1 as the coefficient of strength increase of shear connector along the width.

Similarly, the S-PC shear connector along height direction namely k_2 can be obtained, the coefficient of strength increase of concrete slab along thickness direction, take the stress distribution of shear connector directly below the center. Area surrounded by the actual stress distribution curve, according to the principle of equal area equivalent to a rectangle, the height of the rectangle for the axial compressive strength of concrete is f_{ck} , k_2h as the width of rectangle . So we got k_2 as the coefficient of strength increase of shear connector along the width.

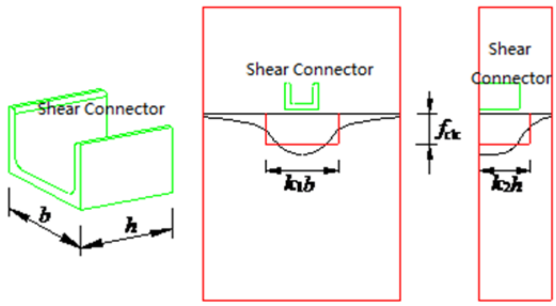


Fig.26 Equivalent figure of dimensions

According to the calculation of shear connector test-piece in this paper , get $k = k_1 k_2 = 2.0$, the width of the shear connector b=50mm ， the height of shear connector h = 50 mm , the axial compressive strength of concrete $f_{ck} = 32.4MPa$, The ultimate bearing capacity of single shear connector is : $Q_{u1} = bh\ f_{ck} k = 163kN$

Equations (2) serve as a measure of ensuring rigid shear connector not only has enough stiffness but also the concrete can be crushed.

Table 2 provides a calculation of the ultimate bearing capacity of single shear connector values and test averages, which is compared with the calculated values of Euro code.

Table 2 Calculation result comparison

	Ultimate bearing capacity(kN)	Ratio of calculation results with the Eq(4.5)
Calculation result of Eq(2)	163	
Average of Specimen N1 - N3	155	0.95
Average of Specimen N1A-N2A	160	0.98
Eurocode calculation result	120	0.74

Based on the shear bearing capacity calculation of shear failure when it reaches the limit load, the shear connector may be cut in welds, or it is possible that itself was cut and destroyed. From the analysis of the stress of the shear connector specimen in previous chapter 3 , shear connector roots of maximum stress, therefore, shear connector parts bear the greatest shear .Under the effect of shear , when shear connector is absolutely rigid , and shear stress can be regarded as a uniformly distributed load (Fig. 27(2) below) , but actually it is not completely rigid, therefore, the stress of the shear connector is approximately the lower large , the upper small non-uniform load (Fig. 27(3) below).

The finite element analysis under two kinds of situations in Fig.27(1) and (2) , shear force is equal to the resultant force of uniformly distributed load , which is about $0.7Q_u$, get the shear force and bending moment of the roots of shear connector and Fig. 28 (1) (2) as shown in . We can find that under the constraint of a concrete shear connector root bending moment is small , its value is 4.423 , not under the constraint of a concrete shear connector moment to 2.36x103, It can be seen that when the shear stiffness , mutual constraints made by concrete slab and steel beam result in shear connector nearly completely shear state.

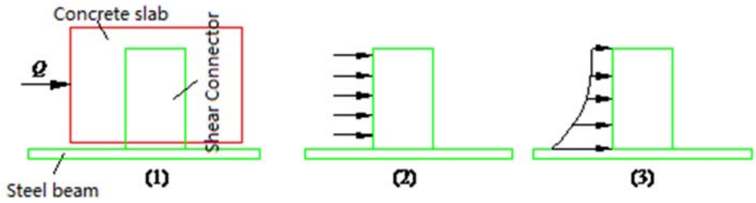
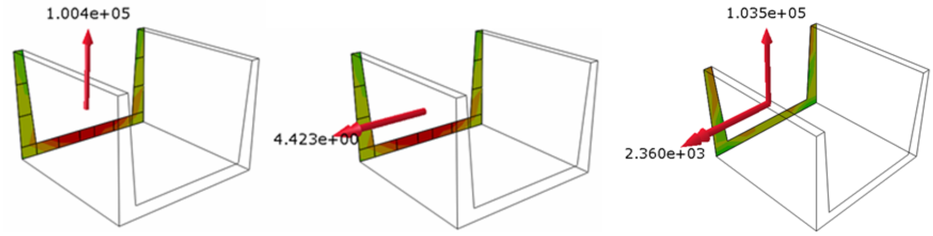


Fig.27 Force diagram of shear connector



(1) (2)

Fig.28 Shear force and bending moment without constraints

As a result, because shear dominant the stress of shear connector with small stiffness, therefore , in the preliminary design, the shear strength of steel τ_b and the shear area S as the product of bearing capacity , that is :

$$Q_{u2} = \tau_b \bullet S \tag{3}$$

Accordingly, comprehensive analysis of type (2) and type (3), get the bearing capacity of the shear connector is:

$$Q_u = \min\{Q_{u1}, Q_{u2}\} \tag{4}$$

5. Conclusions

This paper has done the S - PC shear connector launch test showed that when the load is less than $0.33Q_u$ the specimen approximate work for ideal elastic stage, and residual slip approximate to zero after unloading ; When the loads within the cyclic loading of $0.5Q_u$, the specimen work for approximate elastic stage , the width of crack and increase of residual slip is not obviously ; When the load reaches $0.5Q_u$ to $0.7Q_u$, the specimen into the elastic-plastic phase of work ; When the load increased from $0.7Q_u$ to Q_u , the specimen into the damage stage, the width of crack , the number of cracks and slippage were significantly increased until the specimen destruction .

According to the experimental data and regression analysis, we get the relationship of load—slippage of S-PC shear connector, and the calculated values and measured values coincide well. The S-PC shear connector specimen through solid finite element modeling, using general finite element software ABAQUS analysis results coincide well with the test results, based on the finite element analysis results, which reveals the transfer mechanism of the S - PC shear connector and the stress distribution of different position and direction, and laid the foundation of research and application for this after pouring concrete

S-PC shear connector.

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