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Punching shear behavior of steel-concrete composite decks with different shear connectors

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ABSTRACT

The ultimate strength of composite deck is frequently governed by the punching shear capacity when subjected to severe conditions of loads concentrated in small areas. However, that was unfavorable brittle fracture behavior. The punching shear capacity may be increased by setting more reinforcement bars or using high strength concrete. In addition to these traditional methods, proper shear connector arrangement can be alternative to get higher shear punching resistance. In order to find the proper arrangement method, slabs with three types of shear connectors (headed studs, perfobond ribs and epoxy glue) were simulated through finite element model. The material nonlinearities of headed stud, epoxy glue and concrete were considered in the material model. The results show that punching shear strength and failure modes of those slabs are different. Flexural behavior is dominant for slab with perfobond ribs and its load capacity is the smallest. Slab with epoxy glue have the largest strength, while small energy absorption capacity is observed.

1. INTRODUCTION

Steel–concrete composite deck systems are widely used in highway bridges. The steel slab acts as a permanent formwork for erection. The composite action between steel slab and concrete slab can be obtained through shear connectors. Then the steel slab acts as a tensile reinforcement for the hardened concrete and reduces the cross-sectional area of the composite deck significantly. But, while the flexural strength of bridge deck will be improved, the increase in shear strength is relatively small. Therefore, strengthened decks may develop due to punching shear failure, which is unfavorable brittle fracture behavior.

On the other hand, the overall behavior of composite slab largely depends on the type of shear connector. But there are few advices on shear connector design when considering the punching shear strength. At present, the headed stud is the most widely used type of shear connector. However, the test results of (Sonada 1992) showed that slabs with close headed stud arrangements failed in a punching shear failure mode and the strength of the steel plate would not much contribute to enhance

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the fatigue strength of composite decks. The reason may be that these headed studs can induce the stress concentration and become the origin of the cracking of the composite slabs, which decreases the service life of the composite slabs (Zhao 2008). Perfobond shear connector was introduced for composite beams to overcome the fatigue problem of the studs under live load in (Zellner 1987). It consists of a steel plate with a number of uniformly spaced holes. The potential advantages of the perfobond rib shear connectors are: they are easy to customize and fabricate; there are smaller obstacles than the studs during erection; and a perfobond rib could replace a number of headed studs (Veldanda 1992). To date, few studies focused on composite deck with perfobond ribs and no design information has been provided (Kim 1992). Strong epoxy glue is another shear connection used in recent years, especially in field of upgrading structures. Basically it glues steel plates to the surface of the concrete. The plates then act compositely with the concrete and help to carry the loads. However the research work of shear punching resistance of composite slab using epoxy glue has seldom been reported. Such a work is important because of the different mechanical behaviors between epoxy glue and headed studs. The reliability of this new technique has to be ensured before its application.

In all, punching shear failure is unfavorable brittle fracture, and the punching shear behavior of the slabs was greatly affected by the shear connector type. In this paper, the effect of three shear connector types on the punching shear behavior was studied through finite element method.

2. FINITE ELEMENT MODLE

2.1 General

Numerical models for three slabs were established using finite element program ABAQUS. The dynamic explicit method was used. All the slabs measured 1.2 m square, which were composited by 150 mm thickness concrete slabs and 6 mm thickness steel slabs. They were simply supported in two sides and centrally loaded from the bottom through a 10 mm square steel plate, as shown in Fig. 1. The yield strength of the steel was 294 MPa. The mean concrete cylinder strength was f'_c = 36.7 MPa. Two lays of reinforcement bars were set in each orthogonal direction. The cover to the top and bottom reinforcement was 40 mm and 20 mm respectively. The reinforcement ratio in both direction of the slab was 3.4%. The yield strength of reinforcement bar was 335 MPa.

Headed stud

The numerical model S1 was validated for a slab with headed studs tested in punching by (Furuuchi 2000). Studs of 110 mm height and 13 mm diameter were placed on the steel slab with a space of 140mm, as showed Fig. 1(a).

Perfobond rib

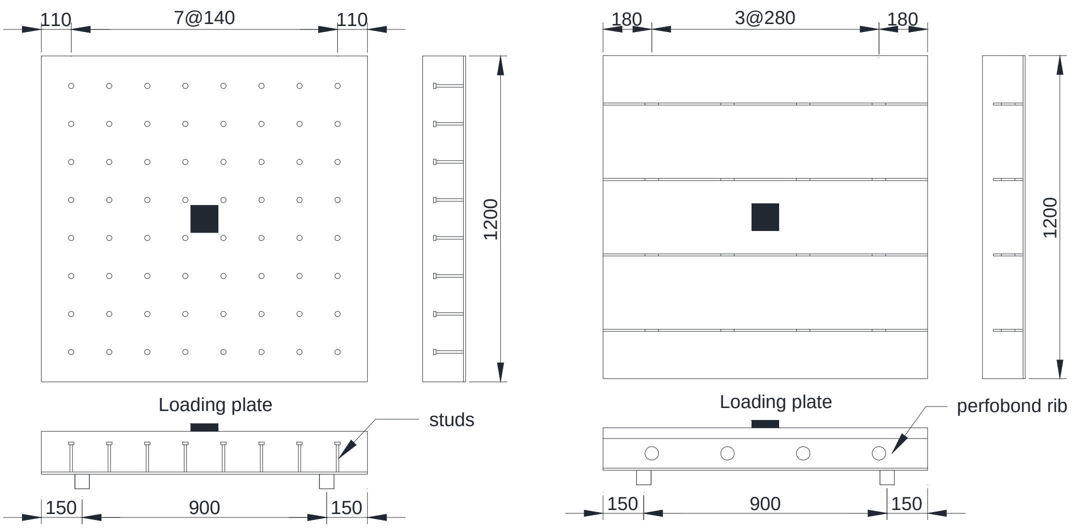
Fig. 1(b) shows the profile of model S2. The thickness of the perfobond rib was 8 mm. And the height was taken as 110 mm, the same as stud height. The diameter and center-to-center spacing of holes for the perfobond rib were chosen as 50 mm and 280 mm, respectively. This arrangement can supply sufficient shear strength in the interface between concrete slab and steel slab. Moreover, shear stiffness in the interface similar to that in S1 can be attained. Eq. (1) was calculation for the shear stiffness of perfobond shear connector proposed by (Zhao 2012)

$$k_s = 6.35d\sqrt{f_c^{'}E_c} \tag{1}$$

According to Eq. (1), the shear stiffness is 349 kN/mm in this study. For headed stud, since few experiments were taken on 13 mm diameter headed stud, approximate values of the shear stiffness may be assumed as 100 kN/mm according to (CEN 2004). Therefore, shear stiffness of four headed stud is approximately equal to one hole of the perfobond shear connector, and shear stiffness in the interface is similar to that in S1.

Epoxy glue

The numerical model S3 simulated composite slab using epoxy glue to connect concrete slab and steel slab. The thickness of the glue was taken as 1 mm.



(a) S1 (headed stud) (b) S2 (perfobond rib)

Fig. 1 Details of models

2.2 Material constitutive models

Concrete

In this study, plastic-damage model in ABAQUS was used. The nonlinear behavior of the concrete material is presented by an equivalent uniaxial stress-strain curve of concrete referred to the work by (Nguyen 2009).

Headed stud and perfobond rib

For simplicity, a bi-linear stress–strain model was used to model the stress-strain relationship of stud and perfobond rib with initial Young's modulus of 200 GPa. The mechanical behavior for both tension and compression is assumed to be similar.

Epoxy glue

The traction-separation model in ABAQUS was used, which assumes an initially linear elastic behavior followed by initiation and evolution of damage. Fig. 2 shows a graphic interpretation of a simple bilinear traction–separation law written in terms of the effective traction τ and effective opening displacement δ . K_0 and $\tau_{\max}$ are the initial stiffness and local strength of the material respectively. δ_y is a characteristic opening displacement at fracture, and G_{cr} the energy needed for opening the crack. In this study, the parameter values were referred to the study by (Obaidat 2010).

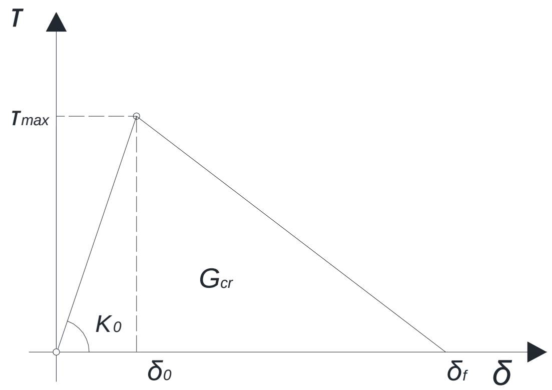


Fig. 2 Bilinear traction–separation law

2.3 Element type

Solid element C3D8R was used for concrete slab, steel slab and perfobond ribs. 8-Node 3-D cohesive elements were used to model the interface layer, which are composed of two surfaces separated by a thickness. As the diameter of the stud is too small to be simulated by solid element, the studs were modeled by beam element B32. All the studs were tied to steel slab in the bottom and embedded in concrete slab. The rebar was modeled by the truss element T3D2 and embedded in the concrete slab.

3. RESULT AND DISCUSSION

The displacement of load plate was plotted versus the load to study the deflection behavior of the slabs as shown in Fig. 3. All the load-displacement curves show a linear part, which correspond to un-cracked behavior, followed by a part that the slab stiffness reduces. For model S1 and S3, the load reaches the peak in small displacement, and the peak values are 359.2 kN and 409.4 kN respectively. Model S2 with perfobond ribs shows smallest initial stiffness and load capacity. The stiffness of this slab decreases rapidly after the load reached 150 kN. The load capacity of S2 is 311.0 kN, and the corresponding displacement is about 1.5 times as those of the other two slabs. Energy absorption capacity of slabs was calculated as the size of the area under the load-displacement curve. Higher energy absorption capacity of S2 was observed.

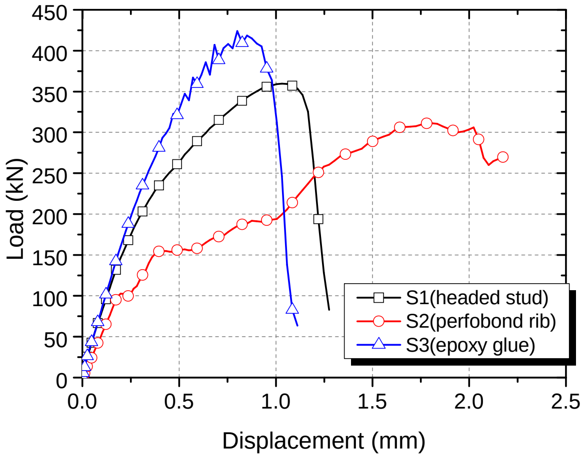
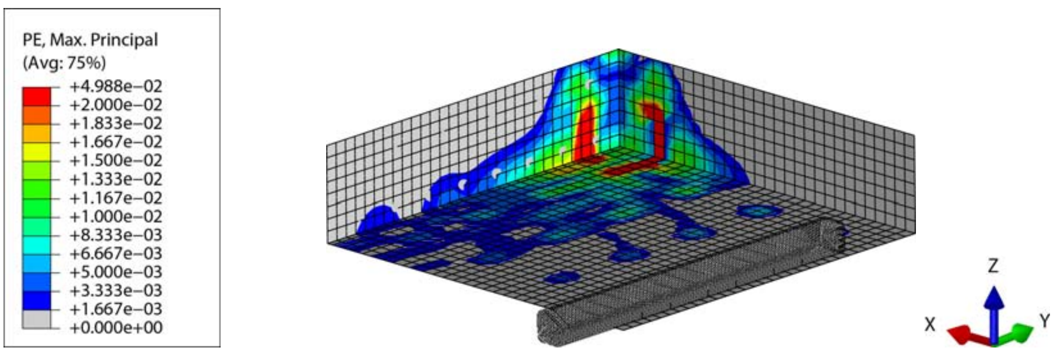
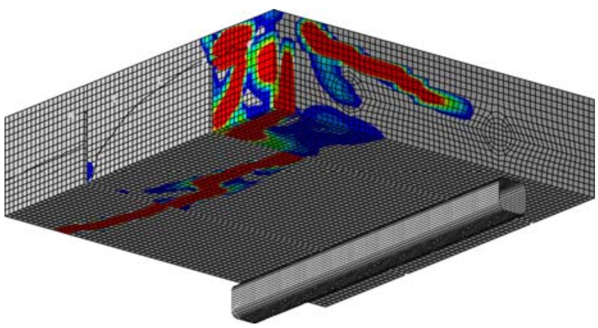


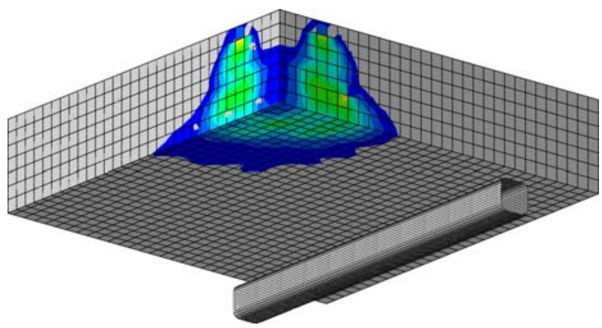
Fig. 3 Load-displacement curves



(a) S1 (headed stud)



(b) S2 (perfobond rib)

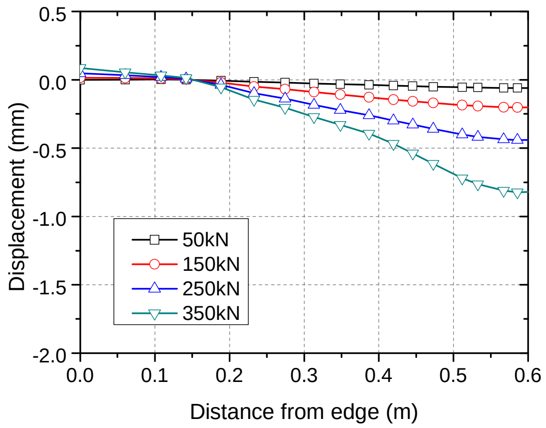


(c) S3 (epoxy glue)

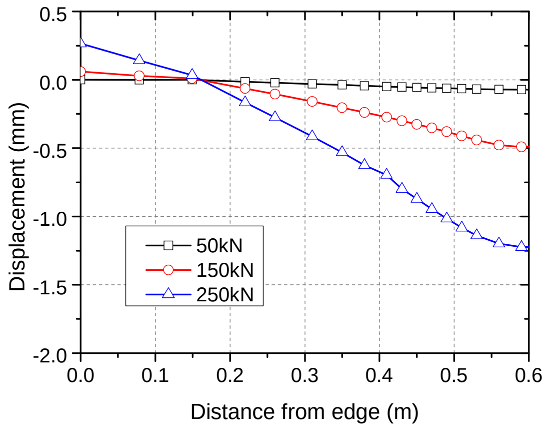
Fig. 4 Failure modes of the slabs

The failure modes of slabs are illustrated in Fig. 4. The contour plot of maximum principal plastic strain is depicted. The punching shear area can be seen easily in all slabs, while differences can be recognized. For S1 and S3, the distance between the perimeter of the failure cone and the load plate was approximately 150 mm. It corresponds to an angle of 45° of the punching failure surface. For S2, the obtained distance was 40 mm and punching shear area was retrained between two perfobond ribs as shown in Fig. 4(b). Moreover, it can be clearly seen that plastic region of S2 developed more fully. That may be the reason of larger ultimate displacement.

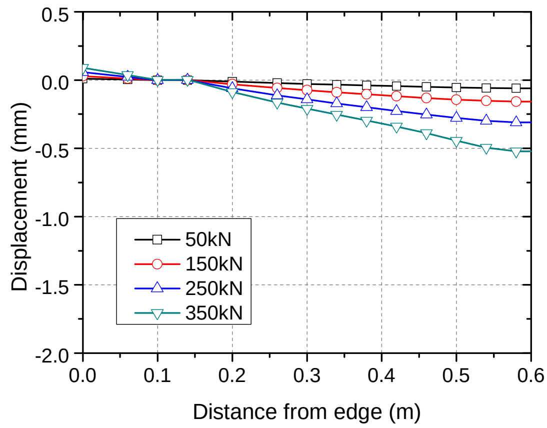
Miyamoto (1991) predicted the punching shear failure mode using deformed shape of the slab. The mix bending and shear failure modes in the slab can be identified with gradual transition from smooth parabolic shape to severely affected center of the slab with formation of inflection point. Fig. 5 shows the deflected profile of middle cross-section. The smooth parabolic profile of displacement is obtained and during the later stage the central portion of the slab is not affected significantly, especially for model S2. It indicated that flexural behavior of slab is found to be dominant for S2.



(a) S1 (headed stud)



(b) S2 (perfobond rib)



(c) S3 (epoxy glue)

Fig. 5 Deflected profile of middle cross-section in different load stages

4. CONCLUSIONS

Numerical models for three composite slabs were established to investigate the effect of different types of shear connectors (head studs, perfobond ribs and epoxy glue)on the punching shear behavior. The results show that flexural behavior is dominant for slab with perfobond ribs. Its load capacity is the smallest, while it has higher energy absorption capacity. Slab with epoxy glue have the largest strength, but it is more brittle. All the slabs show elastic initially, and the slab stiffness reduces as the load increases.

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