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Research Article

Study on Bearing Capacity Formula and Influence Factors of PBH Shear Connectors

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Abstract: Based on structure principle of shear connector, a new type of perfobond hoop has been proposed. The mechanical advantage of PBH has been compared to traditional shear connector by mechanical analysis. According to the measurement and reinforcement requirement suggested by ECSS, the finite element model has been established. The important design parameters which have influence on carrying capacity of PBH shear connector have been analyzed, such as concrete strength, hole numbers, bore diameter, bar diameter and the thickness of steel plate with hole. Carrying capacity calculation expression of PBH shear connector was put forward by regression analysis. The calculation expression has been verified by four groups of shear resistance experiments and the test results agree well with the calculated value by the expression.

Keywords: Bearing capacity, calculation formula, influence factors, PBH shear connector, regression analysis

INTRODUCTION

The steel with high tensile strength and the concrete with high compression strength are reasonably used in tensile zone and the compression zone and high performance, economical efficiency are pursuited to a great limit, which are the design principles of composite steel and concrete structure. Mechanical properties of steel concrete composite structure are affected not only by its own material properties, but also connection form of shear connectors on the junction surface (Liu, 2005).

At present, there are so many types of shear connectors and Perfobond Leiste (PBL) is the most widely used. More researches about PBL are studied by relevant scholars in recent years, Lei (1999) pointed out adhesive strength of concrete to steel plate is the main reason of shear bond strength. Zong and Che (1999) first considered the effects of parameters such as concrete grade and transverse reinforcement and put forward the formula of linear regression. Zhang *et al*. (2007) analyzed the ultimate bearing capacity quantitatively according to the test results and established the unified calculating formula of all kinds of shear connectors. Hu *et al*. (2007) and Hu *et al*. (2006) proposed the bearing capacity formula of PBL shear connectors by experiment and obtained the conclusion that penetrating reinforcement and the transverse structure reinforcement; concrete tenon shared bearing capacity together in resistance to shear force. Xiao *et al*. (2010) considered PBL shear connectors test by dividing it into two stages, the force mainly depends on the concrete with holes in elastic stage and relies on the cross-cutting reinforce in plastic stage. In addition, Xia *et al*. (2009) and some foreign scholars (Oguejiofor and Hosain, 1997; Valente *et al*., 2004; Vianna and Neves, 2009; Ahn *et al*., 2010) put forward their own bearing capacity formula for PBL shear connectors.

Fig. 1: Local construction of PBH shear connectors

METHODOLOGY

The structure principle and of transmission mechanism PBH shear connector: In this study, we want to seek for one kind of Perfobond Hoop (PBH) according to the theory of structure fundamentals. The PBH shear connector is developed on the basis of PBL, consisting of penetrating stirrups and stiffened steel plate ribs with openings. Penetrating stirrups and longitudinal reinforcement form the whole reinforced skeleton together. The local main structure is shown in Fig. 1.

The shear stiffness of PBH shear connectors is mainly provided by the concrete tenon and reinforced concrete columns formed by penetrating rebar. Due to the ferrule effect of Stirrup, the compressive and shear properties of concrete tenons can be effectively improved. Penetrating reinforcement is portion of the stirrup and also part of the steel skeleton. The deformation is restrained and the internal force

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distribution is more uniform. Different from PBL shear key which only makes use of reinforced concrete tenon force to resist interface shear stress, PBH shear key makes stirrup forming reinforcement skeleton with longitudinal reinforcement as penetrating reinforcement. The stirrup will resist shear with reinforced concrete tenon.

Under the action of interface shear, only when middle of the reinforced concrete tenon in PBL shear key is restricted by stiffening rib, the structure is amount to simply supported beam with cantilever beam. The cantilever will have a large deformation. PBH shear key is equivalent to continuous beam structure. At the ends of the reinforced concrete tenon, the constraints of the join forces is resisted by framework of steel reinforcement consisting of longitudinal bar and stirrup, which is similar to frame structure with multi-terminal constraints and internal force distribution is more reasonable.
The conclusions can be obtained as follows:

- When aperture of the steel plate is the same as penetrating bar diameter, the stirrup concrete tenon strength of PBH was larger than that of PBL. The shear bearing capacity of, PBH is larger than that of PBL.
- According to the mechanical characteristics of continuous beam and simply supported beam, the deformation of PBH is smaller than that of PBL under the same interface shear stress. So pressure of compressive zone of PBH reinforced concrete tenon is smaller than that of PBL.
- PBH makes interface shear distribution more even and potentiation between restraining concrete strengthen shearing resistance action.

Therefore, it is proved that the stress of the PBH is more reasonable, the shear bearing capacity is better than that of PBL.

Finite element simulation analysis:
Dimension selection of finite element model: The model is made and calculated according to the provision of Shear specimen size and reinforcement requirements of the European structures and Association (Eurocode 4, 1994), the specific size is shown in Fig. 2.

Establishment of finite element model: ANSYS finite element software is used to simulate and make analysis. Concrete was simulated by the Solid65 entity unit with eight nodes. Steel plate was simulated by Solid45 solid element. Virtual connection spring was set between the steel and concrete contact surface. Spring was simulated by selecting nonlinear functional spring element COMBIN39. The finite element model is shown in Fig. 3.

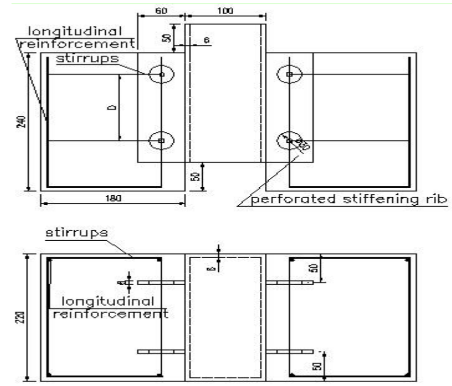

Fig. 2: Structure of shear connectors

Fig. 3: Mesh division of FEM

Calculation results of finite element model analysis: According to the results of finite element calculation, calculation of steel box and concrete stress distribution under the ultimate load are shown in Fig. 4 to 6.

The whole model of PBH shears connectors, the Von. Mises stress distribution of perforated steel plate; steel box and concrete are given in Fig. 4 to 6. As is shown from the graph:

- In the steel box and perforated steel plate parts, larger stress appeared and the part of concrete is relatively small.
- Stress concentration phenomenon appears on the steel box and perforated steel plate, especially in the connection between steel box and perforated plate and four corners at the top of the steel box. Its maximum value is 210 MPa, approximating steel yield strength.
- Stress concentrates at concrete symmetrical wedge block region; the concrete stress reaches the maximum value at the bottom of perforated steel plate. Two symmetric stress concentration belts occur at the top of the concrete.

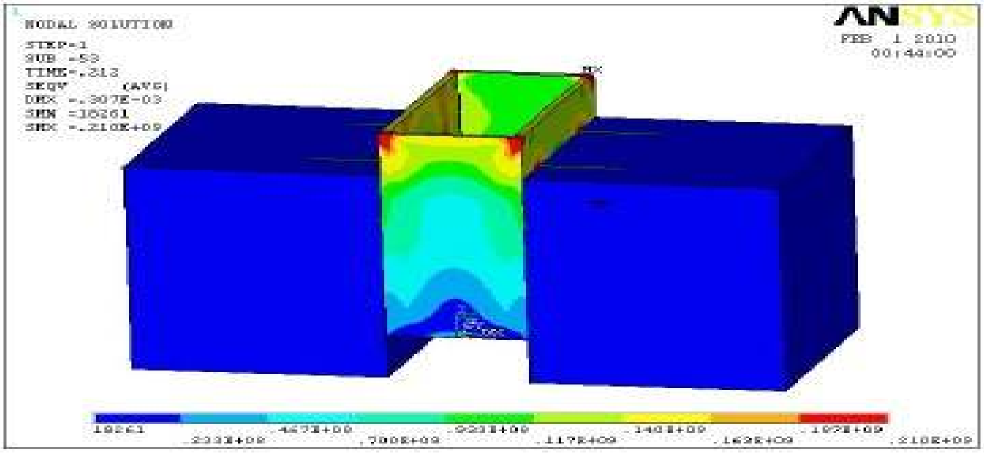

Fig. 4: Mises stress of PBH

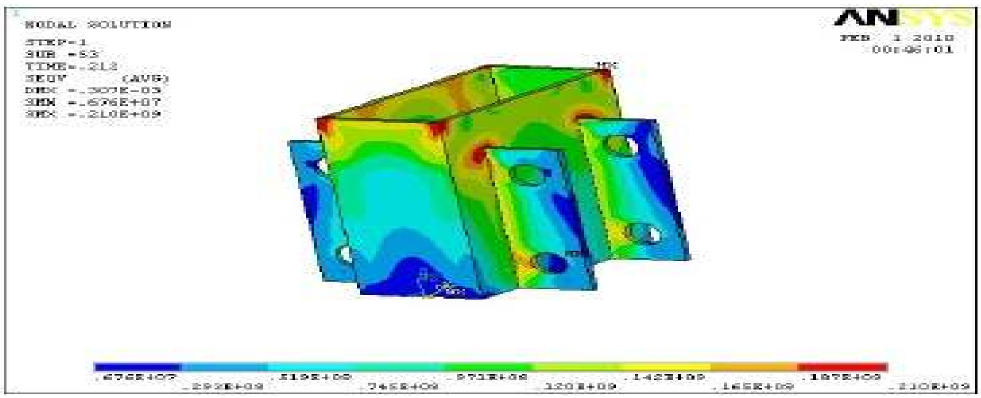

Fig. 5: Mises stress of PBH opening plate and steel box

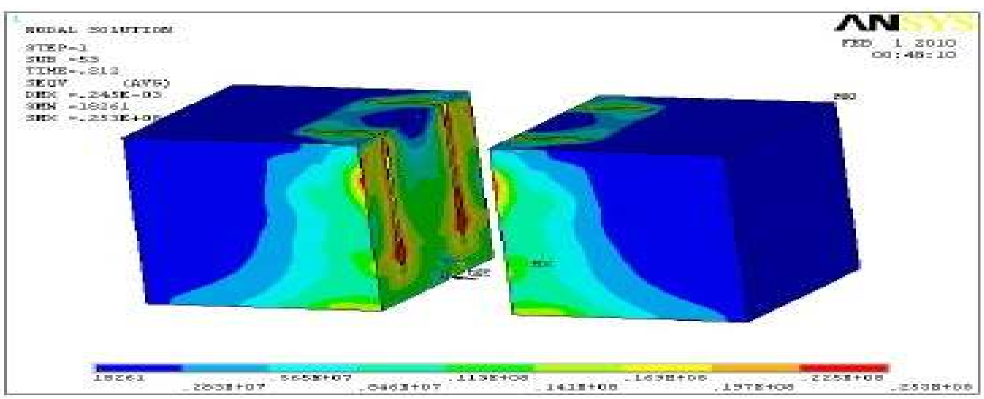

Fig. 6: Mises stress of PBH concrete

Analysis of the influence factors of PBH shear connector:

Influencing parameters analysis of bearing capacity: Based on the finite element simulation, the design parameters including strength grade of concrete, reinforcement, steel plate hole spacing and hole diameter were analyzed, the effect of parameters on the bearing capacity of the curve are shown in Fig. 7 to 10.

RESULTS AND DISCUSSION

According to the finite element analysis, the strength of concrete, number of hole, diameter, diameter and hole through the thickness of the steel plate and other design parameters have a significant effect on the bearing capacity of PBH shear connector:

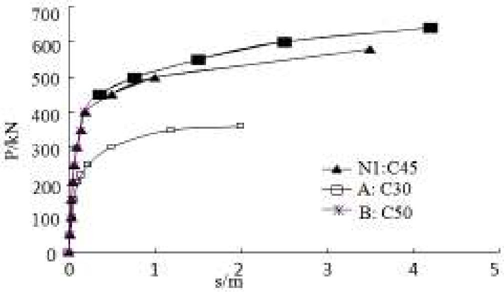

Fig. 7: Influence of concrete strength on carrying capacity

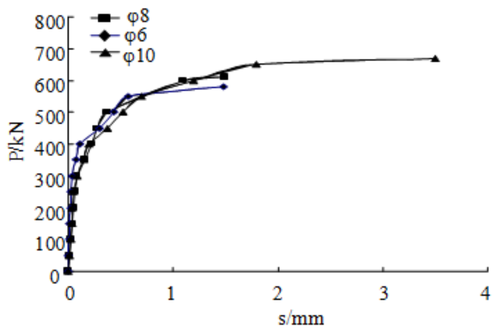

Fig. 8: Influence of reinforce bar diameter on carrying capacity

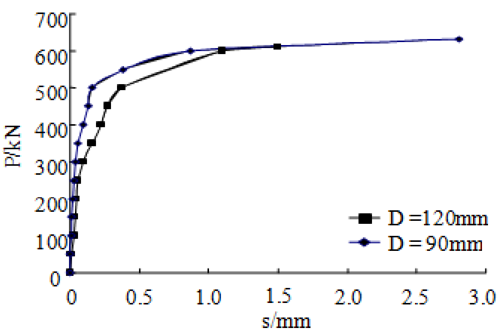

Fig. 9: Influence of hole distances to carrying capacity

- Figure 7 shows that Concrete strength has a great influence on the bearing capacity and ductility of PBH shears connector. As for specimen of C30concrete, ultimate bearing capacity and displacement are respectively 352 kN, 2.05 mm. As for specimen of C50 concrete, ultimate bearing capacity and displacement are respectively 639 kN, 4.23 mm. The bearing capacity has improved 81.5% and the ductility has improved 106.3%.
- Figure 8 shows steel during the penetration process has a significant contribution on ductility. When the diameter increases from 6 to 10 mm, limit displacement increased from 1.48 to 3.51 mm.
- Figure 9 shows reducing the hole spacing can improve bearing capacity and ductility of PBH shear connector.

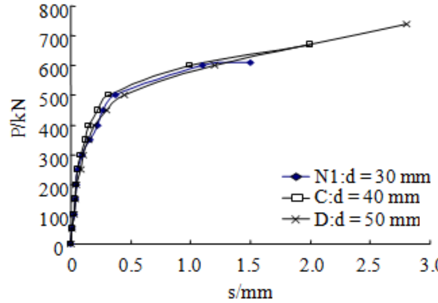

Fig. 10: Influence of plate hole diameter to carrying capacity

Fig. 11: Structure of steel box

Fig. 12: Loading mode

- Figure 10 shows that Plate hole diameter enlargement also improves the ultimate bearing capacity and ductility. It proves that increase of plate hole area can help penetrating rebar and concrete tenon joint have a better resisting shear effect, improving the bearing capacity further.

Taking all the calculations into consideration, various factors have an obvious effect on the ductility of shear connector, while the influence on the ultimate bearing capacity is not the same. The influence of concrete strength is the maximum and the others are relatively small.

Verification of bearing capacity test:

Test component design and loading: To prove that the finite element analysis results are correct, 4 groups of specimens were built to make entity test. Two holes with the diameter of 30 mm were on each rib of PBH shear connector. The steel bar and penetrating stirrup are R 235 reinforcement and the diameters are 8 and

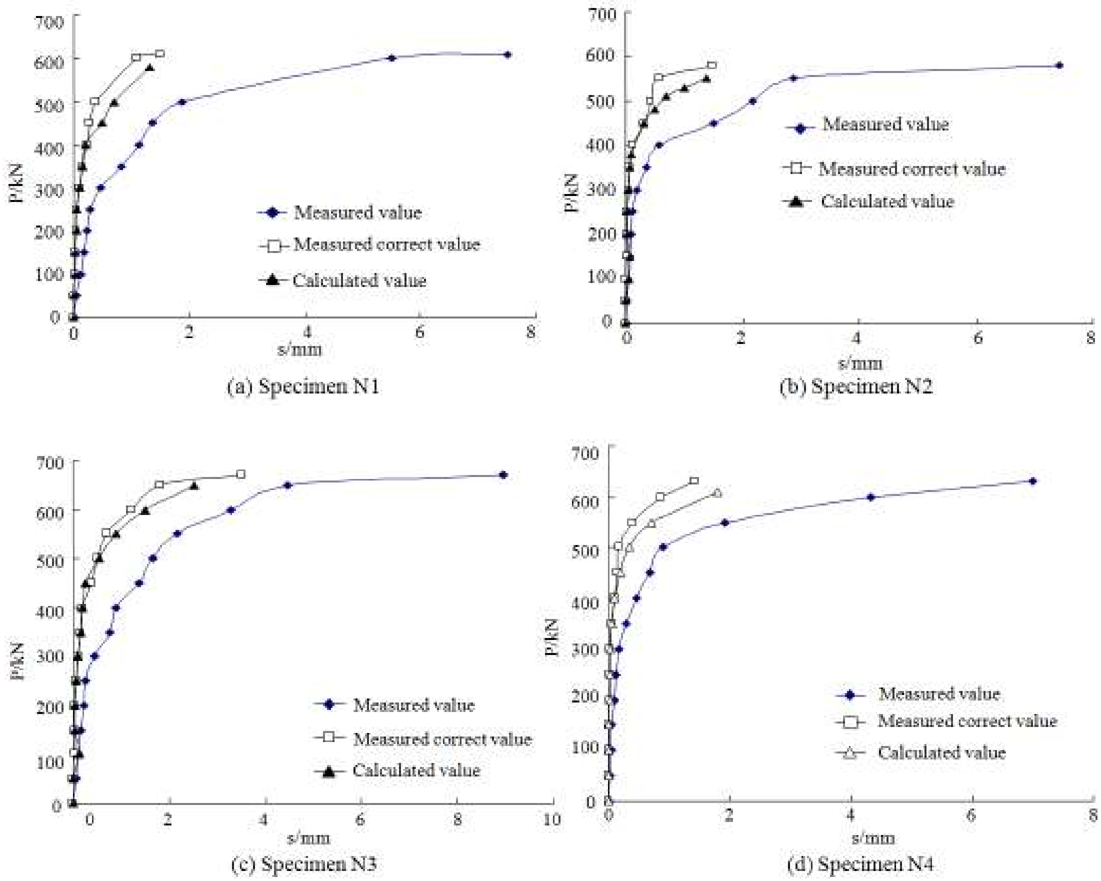

Fig. 13: Load-displacement curve

6 mm, respectively. The specimen model was shown in Fig. 11.

Test specimens were loaded by a universal testing machine in Chongqing jiaotong University laboratory of Structural Engineering. A dial indicator test was used to test the relative displacement and deformation between steel box and concrete. The loading regime was shown in Fig. 12.

Finite element analysis and comparison of test: Figure 13 is the finite element analysis of PBH shear load slip curve and experimental comparison.

Since the test condition is limited, relative magnitude of real slip between neighbor places on both sides cannot be measured. There is certain distance between box measuring point (located in the middle of steel box) and concrete measuring point (located 1cm outside of the interface concrete). The measured values need to be modified to obtain slippage on the interface between steel box and concrete.

It can be seen from Fig. 13 that PBH shear bond finite element simulation calculation and correction values are in good agreement with experiment data, showing PBH shear bond finite element simulation analysis has certain accuracy. Finite element analysis of shear stress characteristics of PBH is reliable. Calculation of the PBH shear stiffness is a bit small than the actual value, which may be because there are some differences between the true constitutive relation and uniaxial constitutive relation for concrete in finite element analysis. As is shown in the concrete performance of later stage, constitutive relation in later stage is larger than earlier stage. The deviation between the yield load calculated value and the measured value is 2.5~7%. The deviation between ultimate bearing capacity calculation value and the actual value is 3~9%. It indicates that this calculation result is correct and reliable.

PBH SHEAR CONNECTORS BEARING CAPACITY CALCULATION FORMULA

Bearing capacity calculation formula: There were no specification on PBL shear bond form, size and bearing capacity of the provisions, the existing PBL shear bearing capacity calculation formula is proposed based on test basically empirical formula (Hu and Pu, 2007; Hu *et al*., 2006; Xiao *et al*., 2010; Xia *et al*., 2009).

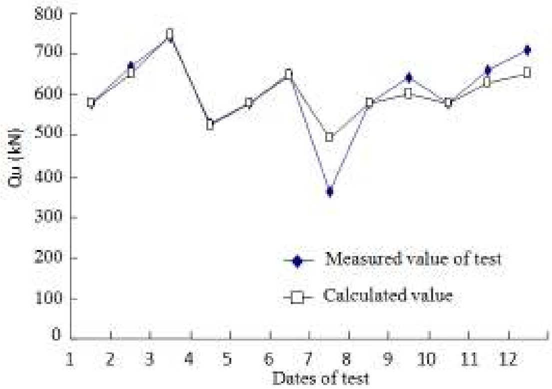

Fig. 14: Comparison of experimental result and expression result

The current formula is in various forms, but its main forms are constituted by addition of main parts of carrying capacity, that is concrete part outside hole + hole concrete part + through reinforced portion = shear bearing capacity. The bearing capacity is related with corresponding strength of materials, size and structure. Therefore, referencing PBL shear bearing capacity calculation formulas and finite element analysis results, PBH shear bearing capacity calculation formula is formula 1 as follows:

$$Q_u = b_1 A_c \sqrt{f_c'} + b_2 d^2 \sqrt{f_c'} + b_3 A_{tr} f_s \quad (1)$$

The multivariate regression analysis method was used in MATLAB preparation procedures for regression analysis, With reference to the related finite element analysis data; undetermined parameters for type1 were solved respectively:

$$b_1 = 2.3645 \quad b_2 = 5.7944 \quad b_3 = 2.5794$$

The bearing capacity calculation formula for PBH shear connector is as follows:

$$Q_u = 2.3645 A_c \sqrt{f_c'} + 5.7944 d^2 \sqrt{f_c'} + 2.5794 A_{tr} f_s \quad (2)$$

In the equation above,

A_c = Tenon area through the perforated steel plate concrete
F'_c = Compressive strength of concrete
d = Stiffener plate hole diameter
A_{tr} = The total area through the stirrup
f_s = Through the hoop tensile yield strength

Formula correctness verification: Through the comparison between regression formula and test data, Fig. 14 can be drawn as follows:

Figure 14 shows that test values are in good agreement with the calculated values, which validated the correctness of the formula.

CONCLUSION

- Aufbau principle of PBH is more scientific and the stress distribution is more reasonable. Carrying capacity of PBH shear connectors is better than that of PBL shear connector.
- Analyzing ultimate bearing capacity of PBH by the finite element method is reasonable. The strength of concrete, diameter of bar diameter, pitch of holes for the steel plate, open hole caliber and other factors have a great influence on the bearing capacity and the ductility of the PBH.
- The computational formula of bearing capacity for PBH obtained by regression analysis is of medium precision, which can offer reference for the design of similar combined members.

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