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Comparative study on two kinds of finite element analysis of PBL shear connectors

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ABSTRACT
According to the different construction forms of PBL shear connectors in steel-concrete composite beam and steel-concrete joint section, eight finite element models in two groups of the two construction forms are conducted to study different mechanical properties of PBL shear connectors. Following conclusions can be drawn from the finite element method calculation results. The load-slip curve, mechanical properties of PBL shear connector are quite different in two construction forms. With the same construction parameter, the ultimate bearing capacity, shear stiffness and ductility factor of PBL shear connectors in steel-concrete joint section are better than that in steel-concrete composite beam. In addition, concrete strength, perforated diameter, thickness of the perforated plate, diameter of the perforated rebar and construction form are the influencing factors of the bearing capacity, shear stiffness and ductility factor of PBL shear connectors.
Keywords : PBL, finite element analysis, push-out test, construction form, parametric studies.

I. INTRODUCTION

With the rapid development of steel-concrete composite structure in China, PBL shear connectors attract more and more attention in the past two decades, PBL consists of perforated plate, perforated plate welded on the steel components, concrete dowels formed in perforated be used to resist horizontal shear forces and vertical lift after pouring concrete, adding perforated rebar in perforated can increase its bearing capacity significantly. PBL shear connectors are used widely in the realm of engineering because of its superior behavior in bearing capacity, shear stiffness and fatigue performance. PBL shear connectors were applied in steel-composite beam in bridge engineering originally, and later in steel-concrete joint section of long-span bridges such as Chongqing ChaoTianMen bridge, Nanjing Third Yangzi River Bridge, Edong Yangtze River Bridge and so on.

The use of PBL shear connector in steel-concrete composite structure is increasingly widespread, but the study of its mechanical properties lags far behind the practice. There is not a code about the relevant provisions of PBL shear connectors in any country, especially in bearing capacity, shear stiffness and fatigue performance is the lack of a clear definition. Due to the lack of quantitative indicators of PBL shear connectors in mechanical properties, leading to its application in steel-concrete composite constructions is inconvenient. Therefore, in order to ensure the structural safety, we have to use a high level of safety factor or take model tests to verify.

For these reasons, lots of in-depth work is taken by the researchers. There are three main methods to research the shear connectors in the current study: push-out tests, model tests and finite-element analysis.

Because model tests remain a costly and time consuming option, push-out tests have the disadvantages of can't be able to study the mechanical behavior with detailed and intuitive, analytical procedures that can predict the nonlinear response and the ultimate bearing capacity of the push-out test are developed in order to replace most of the experiments.

The domestic and foreign scholars take the bearing capacity of PBL shear connectors as the object of study have done a great deal of push-out tests on PBL shear connectors while there is still no consistent conclusion. Because there is no standard way to push-out tests of PBL shear connectors; Therefore, scholars around the world using diverse construction parameters (e.g., concrete strength, perforated diameter, thickness of the perforated plate, diameter of the perforated rebar, layout of connectors and the test structure) and unlike test methods (e.g., control parameters, load method and test content) when the push-out tests are conducted. During the push-out tests, since researchers consider different factors, they get the test results are discrete, hard to find the statistical law. According to the different stress states of PBL shear connectors in steel-concrete composite structures, 8 finite element models push-out tests of two construction forms are conducted to research the influences of different test structures and parameters on its mechanical properties. Parametric studies using these models were carried out to investigate the variations in concrete and so on.

II. DESIGN OF PUSH-OUT TEST

DESCRIPTION OF PUSH-OUT TEST SPECIMEN

Push-out test is an important method to study the properties of shear connectors and first applied to research the shear performances of the stud. At present, many countries have codes about push-out tests mainly applied to stud and other traditional shear connectors. Specimen's configuration and detail instructions of "Specific Push Test" of other shear connectors in Eurocode4 have become the main basis for push-out tests of PBL shear connectors in U.S., Europe, and Japan, the commonly used test structure as shown in Fig.1, we call it "Construction A" in this article. The push-out tests of many scholars are based on this test structure. The PBL shear connectors not only subject shear force between steel and concrete, but also bear separating force between steel and concrete, they have the same structural parameters and stress states with that in steel-concrete composite beam.

The construction parameters and stress states of PBL shear connectors in steel-concrete joint section different from that in steel-concrete composite beam. Therefore, in order to ensure the structural safety and effectively transfer forces between the steel and concrete, the concrete strength, height and thickness of the perforated plate in steel-concrete joint section are bigger than that in steel-concrete composite beam. Because of these reasons, test structure of specimen is different from "Construction A", some scholars designed another structure for push-out tests as shown in Fig.1, we call it "Construction B".

A parametric study was conducted using the finite element method for concrete strength of 30 and 50 N/mm2 with various perforated diameter, thickness of the perforated plate, diameter of the perforated rebar and layout of connectors shown in Table 1, the eight finite element models of two construction forms ("Construction A, B") are designed in the thesis according to priority, the influence of performance of concrete and perforated rebar, perforated diameter, thickness of the perforated plate and diameter of the perforated rebar are considered in the parametric studies.

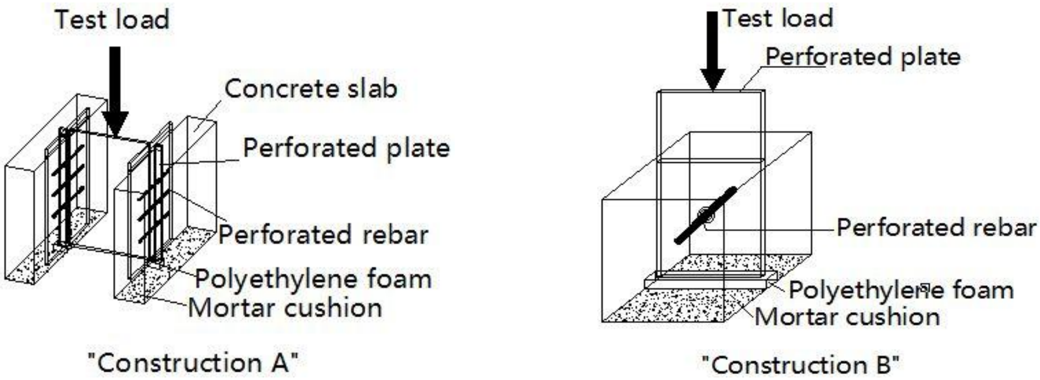
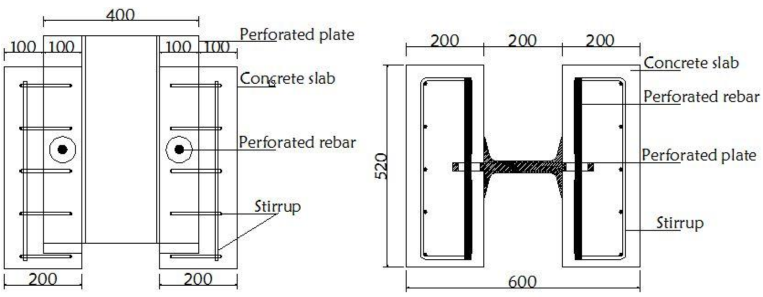


Fig.1 Push-out test layouts of PBL shear connector

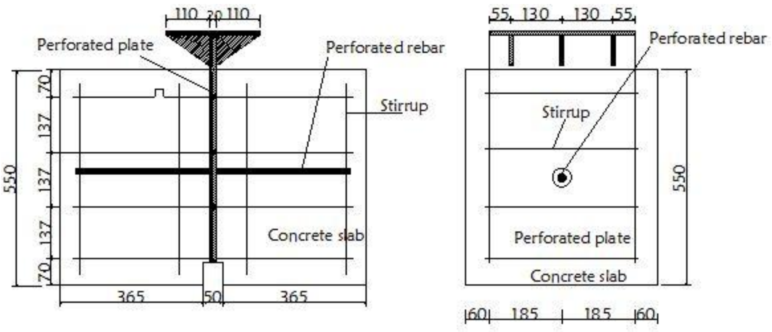
Table 1 Details of push-out specimens

Specimen Type	Specimen No.	Diameter of the perforated rebar(mm)	Concrete strength	Thickness of the perforated plate (mm)	Perforated diameter (mm)	The number of shear connectors
A	A1	16	C50	20	60	2
	A2	16	C30	20	60	2
	A3	16	C30	8	40	2
B	B1	16	C50	20	60	1
	B2	16	C30	20	60	1
	B3	16	C50	8	40	1
	B4	25	C50	20	60	1
	B5	25	C50	8	60	1

The configuration of "Construction A" as shown in Fig.2. "Construction B" with single shear connector as shown in Fig.2.



"Construction A"



"Construction B"

Fig.2 Configuration of finite element model of PBL shear connector

III. Finite Element Model

For a numerical model of the shear connector, all different components associated with the connection must be properly represented, such as the concrete slab, concrete dowels, steel plate, perforated plate and perforated rebar. ABAQUS has the capable of conducting finite element analyses considering both geometric and material nonlinearity and includes interface elements and constraint conditions, was selected for this purpose.

Finite Element Mesh

Combinations of three-dimensional solid elements, which are available in the ABAQUS element library, are used to model the push- out test specimen. There is a three-dimensional eight-node element (C3D8) as shown in Fig.3. In the modeling of the concrete, perforated rebar, perforated plate and in the rest of the model, C3D8 is used elsewhere. Considering the symmetry of the physical structure, quarter of a complete model is established to calculate to save time. Fig.4 shows the finite element mesh used to represent a push-out test specimen.

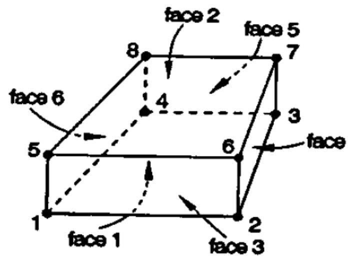


Fig.3 Three-dimensional eight-node element (C3D8)

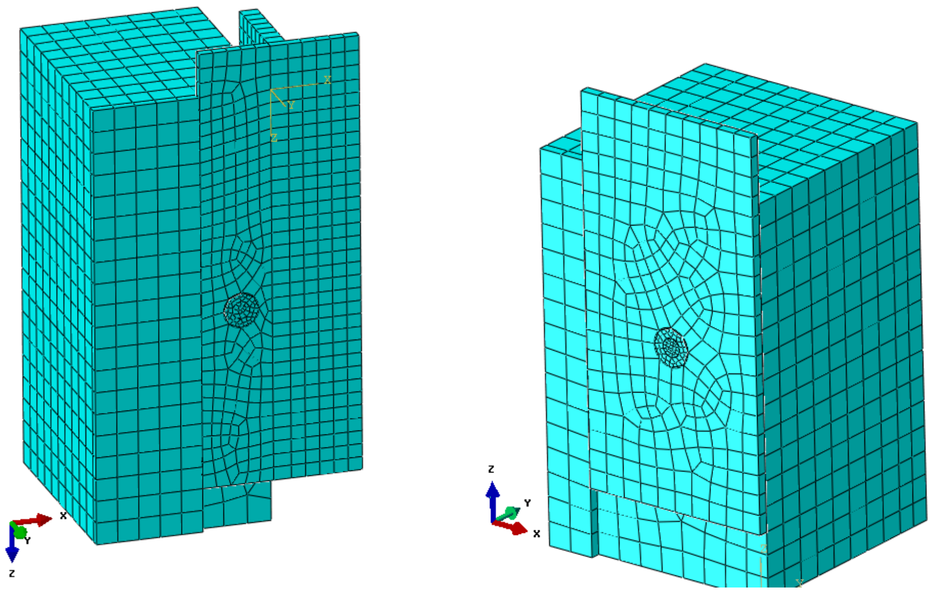


Fig.4 Finite element mesh of the model

Application of Load

A vertical displacement is applied at the coupling point on the steel beam as shown in Fig.4. Displacement is applied using the ABAQUS/Explicit available in the ABAQUS software. Because of the models have complex contact problems that there is difficult to calculate. Obviously, with this approach, we can get the convergence of the calculated results easily.

Material Model of Concrete

Based on past research work, the writers realized that no FE model could handle unloading cycles with concrete due to cracking, and that the objective of this paper is to compare two kinds of finite element models of PBL shear connectors, concrete is treated as a material as shown in Fig.5. In this way, we'll get the descending segment of load-slip curves. Following the BS 8110, Young's modulus of the concrete, and the yield stress can be calculated from the following relations:

$$\varepsilon_{yc} = 0.00024\sqrt{f_{cu}}$$
$$f_{yc} = 0.8 f_{cu} \qquad (1)$$
$$E_c = f_{yc} / \varepsilon_{yc}$$

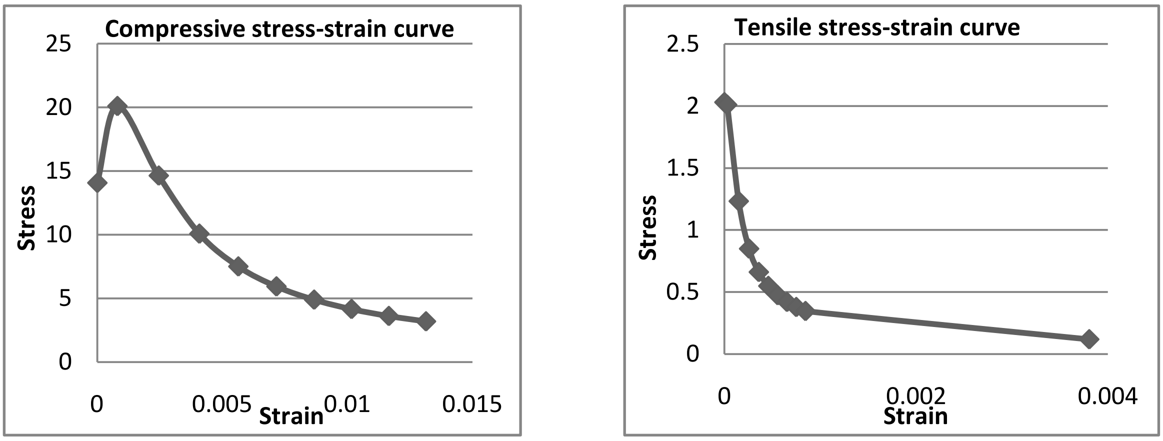


Fig.5 The stress strain curve of concrete (C30)

Material Model of Steel

The steel used in perforated rebar, perforated plate and steel beam is modeled with the yield stress of 345N/mm^2 in this study using the bilinear shown in Fig.6. The steel material model behaved as linear elastic material with Young's modulus E_s up to the yield stress of steel, f_{ys}. After this stage, it becomes fully plastic. In this paper, the following values are used for the steel material: E_s:200,000 N/mm^2 and f_{ys} 345N/mm^2.

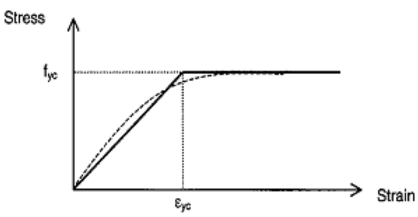


Fig.6 Bilinear stress strain curve for steel model

IV. RESULTS AND DISCUSSION

In this paper, the writer got the Load-slip curves of finite element models based on finite element analysis as shown in Fig.7. Previous studies have found that the mechanical properties of PBL shear connectors are complex and controlled and restricted by many factors. The primary mechanisms contributing to the shear capacity of the perfobond rib are (1) the concrete dowels formed through the holes of the plate, (2) the perforated rebar, (3) the concrete end bearing resistance in the slab, and (4) the chemical bond between the concrete and the steel beam. The effect of the chemical bond on the shear capacity is relatively small, so its contribution can be ignored in finite element model analysis. Comparison the Load-slip curves of different models, we can get the following conclusions.

(1) The Load-slip curves of "Construction A" different from the Load-slip curves of "Construction B" obviously (Fig.7). All the Load-slip curves of "Construction A" have two stages of rise and decline, according to changes in slope of the curves, the rising stage can be divided into two parts, "linear" and "nonlinear". Whereas, the Load-slip curves of "Construction B" have rising stage without declining stage. The rising stage has similar properties with "Construction A".

(2) The ultimate load of the two kinds of PBL shear connectors has large difference. Comparison the Load-slip curves of "Construction A" and "Construction B" as shown in Fig.8, we can known that with the same concrete strength, perforated diameter, thickness of the perforated plate and diameter of the perforated rebar, the ultimate load of the latter is much larger than the former.

(3) The slippage of the two kinds of PBL shear connectors is difference. Fig.8 indicated that, if finite element models "A1" and "B1" have the same concrete strength, perforated diameter, thickness of the perforated plate and diameter of the perforated rebar, the slippage corresponding to ultimate load of the latter is five times more than the former, include the finite element models of other two groups ("A2" and "B2", "A3" and "B3"). In addition, the ultimate slippage of "Construction B" is much larger than "Construction A".

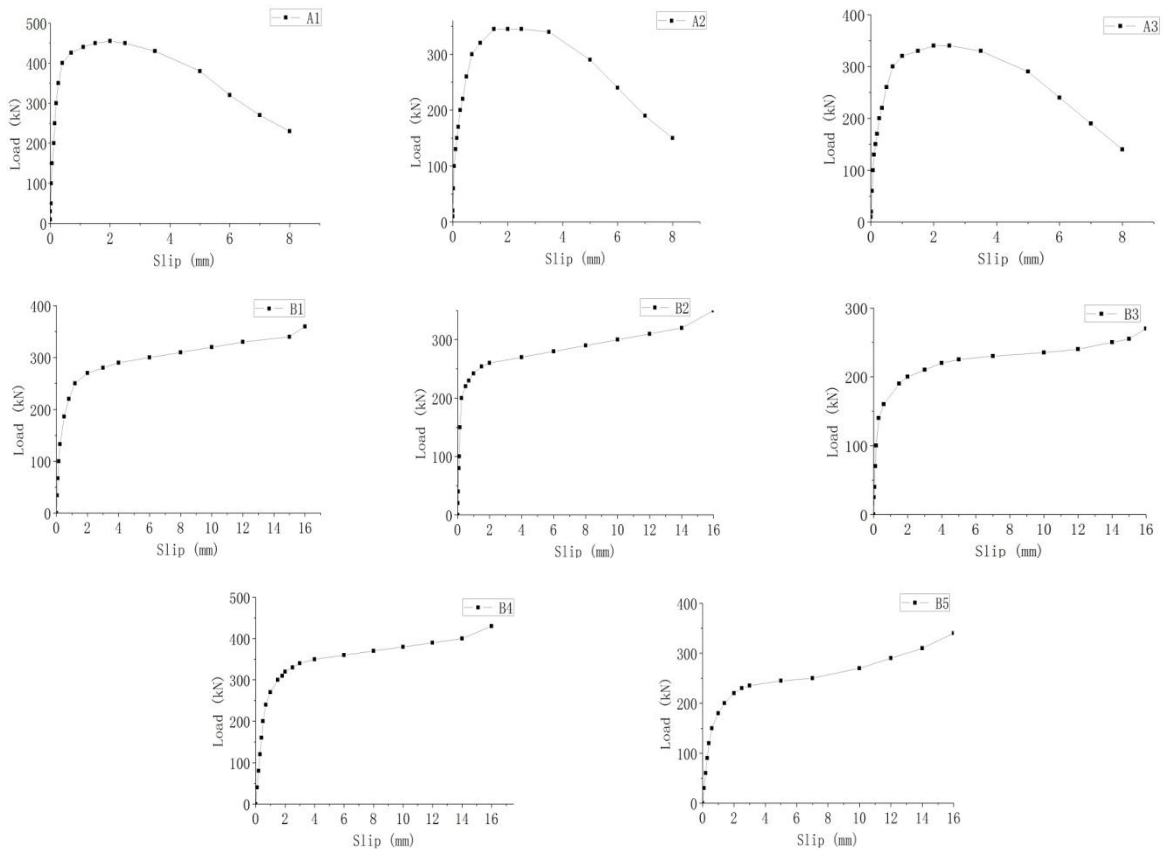


Fig.7 Load-slip curves of finite element models

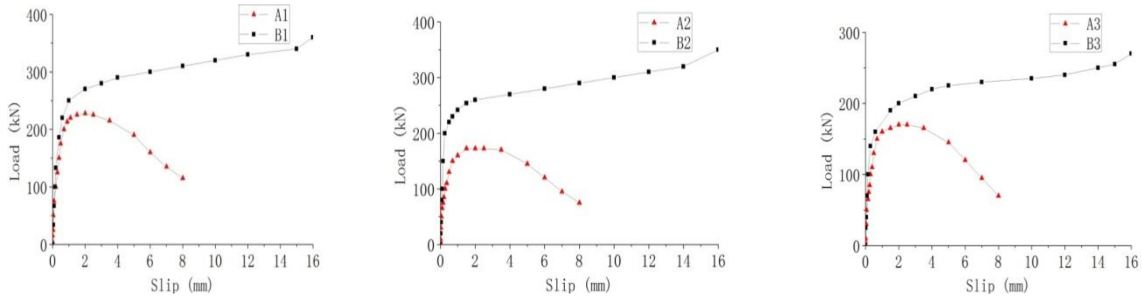


Fig.8 Comparison of two kinds of models' load-slip curves

Static performance indicators of PBL shear connectors

In this paper, the symbols of mechanical performance index definition of PBL shear connectors are as follows (Fig.9):

Ultimate bearing capacity Vu: the maximum load is calculated by the FE model;

Bearing capacity in the use state V0: the load corresponding to slippage of 0.2mm;

Shear stiffness Ks: the stiffness corresponding to slippage of 0.2mm;

The limit slippage δυ: the slip corresponding to ultimate bearing capacity;

Ductility factor Dc: the ratio of limit slippage and 0.2 mm; that is Dc=δυ/0.2, the higher the value, the better ductility factor of PBL shear connectors. The main static characteristics of each PBL shear connector as shown in Table 2.

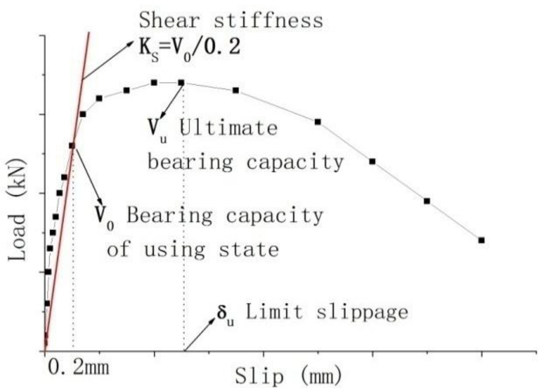


Fig.9 The definition of the static mechanical properties of PBL shear connectors

Table2 The main static mechanical properties of each PBL shear connectors

Specimen Type	Specimen No.	Ks(kN /mm)	V0(kN)	Vu(kN)	δυ(mm)	Dc	The number of shear connectors
A	A1	519.6	161.2	221.8	9.4	47	2
	A2	157.9	115.4	158.9	11.4	57	2
	A3	296.2	114.5	157.9	8.4	42	2
B	B1	806.6	163.7	396.5	25	125	1
	B2	388.7	123.4	327.9	20.4	102	1
	B3	324.9	101.4	245.8	29.7	148.5	1
	B4	440.5	250.1	544.7	33.2	166	1
	B5	437.0	104.3	398.4	45	225	1

Static mechanical property indexes and its influencing factors of PBL shear connector.

Finite element method (FEM) calculation results are given in Table 2 for each group of PBL shear connectors' mechanical property indexes. The ultimate bearing capacity, limit slippage, shear stiffness and ductility factor of "Construction B" are better than "Construction A" with the equivalent configuration parameters as shown in Table 2. However, the two kinds of PBL shear connectors have the roughly equal bearing capacity in the use state. According to the above analysis, construction form has a little effect on bearing capacity in the use state. The following analysis of the influencing factors of the main static mechanical properties of the PBL shear connectors.

(1) Ultimate bearing capacity

As we can see from table 2, the largest average ultimate bearing capacity of a single hole by FEM calculation is model "B4" and the least is model "A3". In addition, the ultimate bearing capacity of "Construction A" is less than "Construction B". It is the construction form that has a great effect on ultimate bearing capacity of PBL shear connectors.

For "Construction A", the ultimate bearing capacity of both model "A2" and "A3" are less than model "A1"; "Construction A" is the same, the ultimate bearing capacity of both model "B2" and "B3" are less than model "B1". The ultimate bearing capacity of PBL shear connectors will be weakened with the decrease of concrete strength or thickness of the perforated plate.

The ultimate bearing capacity of model "B4" is 1.38 larger than model "B1", the ultimate bearing capacity of model "B5" is 1.64 times as large as model "B3". However, the cross-sectional area of perforated rebar of the former is 2.44 times the size of the latter. From the above we can come to the conclusion that perforated rebar has a major impact on the ultimate bearing capacity of PBL shear connectors. But it is not a linear relationship; it suggests diameter of the perforated rebar is not the only factor affect the ultimate bearing capacity of PBL shear connectors. The thinner the perforated plate, the lower the ultimate bearing capacity, can be derived from Table 2, The ultimate bearing capacity of model "B1" is greater than "B3",and the ultimate bearing capacity of model "B4" is greater than "B5".

(2) Bearing capacity of using state

The bearing capacity of using state of model "A2" account for 71 percent of model "A1", as do "Construction B", The bearing capacity of using state of model "B2" account for 75 percent of model "B1". The other parameters of two FEM are alike except different concrete strength. The above conclusion shows that the concrete strength has an important effect on the bearing capacity of using state.

The bearing capacity of using state of model "A3" is far less than model "A1", FEM calculation result of model "B3" is far less than model "B1", The bearing capacity of using state of model "B2" account for 75 percent of model "B1". As is also the model "B5" and model "B4", the bearing capacity of using state of model "B5" only account for 40 percent of model "B4", the other parameters of two FEM are alike except different thickness of the perforated plate. The above conclusion shows that the thickness of the perforated plate has a significant effect on the bearing capacity of using state.

The diameter of the perforated rebar also plays a role in PBL shear connector's bearing capacity of using state. Compared with the FEM with perforated rebar are 25mm and 16mm in diameter in "Construction B". If the perforated plate is thick enough, and in this context, the bigger diameter of the perforated rebar is, the higher the bearing capacity of PBL shear connectors in using state is also.

Compared with the FEM calculation results of "A1"&"B1", "A2"&"B2", "A3"&"B3".The FEM calculation results showed that the bearing capacity of using state of "Construction A" and "Construction B" is roughly the same. The Load-slip curves of the two constructions' FEM come close in the using stage in Fig.9. Arguably, the differences in construction forms have a little effect on the bearing capacity of using state of PBL shear connectors.

(3) Shear stiffness

Shear stiffness is the ability of a structure to resist shear force. Shear stiffness of model “A1” is greater than model “A2”, Shear stiffness of model “B1” is greater than model “B2”. Difference between the form model and the latter model is concrete strength. So, it is concrete strength, which has an important effect on the shear stiffness of PBL shear connectors. In the use-phase, shear capacity of PBL shear connectors are provided by the concrete dowels formed through the holes of the plate and the perforated rebar. Consequently, the concrete strength significant influence shear stiffness of PBL shear connectors.

The shear stiffness of model “A1”,”A2” is about two times that of model “A3”,”B3”. So the conclusion that thickness of the perforated plate has an important influence on PBL shear connectors’ shear stiffness. The shear stiffness of PBL shear connector with heavy plate is better than that of PBL shear connector with sheet steel.

The shear stiffness of model “B1” is greater than that of model “B4”. It shows that the shear stiffness of PBL shear connectors is also concerned with the diameter of perforated rebar, in fact, it is concerned with the perforated diameter. If FEM with the same perforated diameter, the smaller the diameter of perforated rebar, the more likely concrete aggregate will get into the hole of perforated plate, therefore, the shear stiffness is as well improved.

(4) Ductility factor

As you can see from Table 2, the ductility factor of “Construction B” is higher than that of “Construction A”, and the ductility factor of model “A1”,”A2” are higher than that of model “B1”,”B2”. We can raise its ductility factor by increasing the strength of concrete when PBL shear connector application in combined structures.

V. CONCLUSIONS

Eight finite element models’ push-out calculations of two construction forms were carried out and the calculation results obtained allow the following conclusions to be drawn:

(1) The load-slip curves of FEM of “Construction A” and “Construction B” have major differences, but they all consisted of elastic and plastic parts. The two construction forms correspond to PBL shear connectors of steel-composite beam and steel-concrete joint section respectively.

(2) If the two construction forms’ PBL shear connectors with the same parameters, the ultimate bearing capacity and the limit slippage are obtained by “Construction A” are about 50 percent that obtained by “Construction B”, the shear stiffness and ductility factor of “Construction A” are far less than that of “Construction B”, however, bearing capacity of using state of PBL shear connectors in the two construction forms almost the same.

(3) The FEM calculation results showed the influencing factors of PBL shear connector’s bearing capacity, shear stiffness and ductility factor are concrete strength, perforated diameter, thickness of the perforated plate, diameter of the perforated rebar and construction form.

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