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Technical report

Study on Load-Slip Characteristic Curves of Perfobond Shear Connectors in Hybrid Structures

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Abstract

Load-slip characteristic of shear connectors is the basis of connectors' stiffness inputting in finite element analysis and load transfer study of shear connector groups. Based on three series and 24 groups large-scale experiments of perfobond strip shear connectors (PBL) and depended on the cutting-edge measurement techniques of distributed optical fiber sensors, mechanic characteristics and important influence factors were analyzed thoroughly, corresponding formula for ultimate bearing capacity of PBL connectors was suggested. Further load-slip characteristics under elastic limit and ultimate bearing state were induced, load-slip curve expression of PBL connectors under static complete loading was derived. The results show that the elastic limit load of PBL connectors in hybrid structures is about 0.35 times the ultimate bearing load, the yield load is about 0.7 times the ultimate bearing load. The complete load-slip curve of a PBL connector consists of a straight line branch in elastic phase and a curve branch following logarithmic distribution in nonlinear phase.

1. Introduction

Hybrid structure comprises steel girder members and concrete girder members among different spans or parts. The stress transfer of steel-concrete joint segments is achieved by shear connectors and relevant bearing facilities. Perfobond strip shear connectors (PBL) were used extensively in steel-concrete composite bridges in recent years for its convenient construction and excellent mechanical performance, in contrast to other types of shear connectors, such as studs and block connectors. The failure mode and mechanical characteristics of PBL connectors in hybrid structures considerably differ from those in superimposed beams because the perforated plates embedded in surrounding concrete as well as welded mother plates in hybrid structures has stronger interfacial restraints (Zhang *et al.* 2007). Load-slip relationship of PBL connectors represents their stiffness characteristic under static loads, it is the basis of finite element analysis on composite structures and the load transfer property of PBL connector groups as well. Present studies on PBL connectors have been concentrated in its ultimate bearing capacity and mechanical behavior. Medberry (2002) and Ahn (2008) investigated the ultimate bearing capacity and the mechanical performance, but their experiments are both based on the push-out test which applied to head studs in superimposed beams and the ultimate bearing capacity of specimens is far lower

than that of PBL connectors in hybrid girders. Based on the tests of PBL connectors, Wang (2011) preliminarily analyzed the load-slip relationship of PBL connectors, but less numbers of specimens and the limitation of testing conditions and means induced non-negligible errors, moreover, the test results gained were inconvenient for finite element analysis. Base on the concerns of the stiffness of PBL connectors and the study on PBL connector groups, an experimental and analytical research program was conducted. The study consists of three series of large-scale experiments on PBL connectors: a) the selection experiment of PBL connectors on steel-concrete joint segments of bridge pylons for the third Nanjing Yangtze River Bridge (hereafter referred to as the third bridge experiment); b) PBL experiment on the anchor system of distributed load-transfer for the fourth Nanjing Yangtze River Bridge (hereafter referred to as the fourth bridge experiment); c) the experiment of PBL connector groups supported by the national science foundation (hereafter referred to as the foundation experiment). Depending on the cutting-edge measurement method of distributed optical fiber, the mechanical characteristics and important influence factors on PBL connectors in hybrid structures were analyzed and the formula for calculating the ultimate bearing capacity of PBL connectors in hybrid structures was proposed. Furthermore, the characteristic load and corresponding characteristic slip in elastic limit state were summarized and the load-slip distribution curves of PBL connectors under static complete loading were presented.

2. Experimental program

2.1 Specimens design

As mentioned above, the ultimate bearing capacity of PBL connectors in superimposed beams is much less

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than it in hybrid structures, therefore the push-out test adopted in hybrid structures which is well applied to superimposed beams would bring in more conservative test results. The experimental methods of Tsurumi Fairway Bridge (Yamadera *et al.* 1993) in Japan were referred in this study. The vertical push loading was employed in the third bridge and the foundation experiment, while the horizontal pull loading was employed in the fourth bridge experiment. Following influence factors were considered: the hole diameter on perforated plates, the thickness of perforated plates, the concrete strength, the diameter of perforated rebar, the ratio of transverse steel reinforcements and the existence of perforated rebar, and so on. The mechanical behavior of specimens under complete loading was studied. The specimen size and experiment design of the third bridge experiment are described by Li (2005), and those of the fourth bridge experiment are provided by Wang (2013). A schematic representation of the foundation experiment is shown in **Fig. 1**, and detailed state-

ment of three series of experiment is shown in **Table 1**.

The Q345B low-alloy high-strength structural steel was used in all perforated plates. Circular opening with $\Phi 45$, $\Phi 60$ and $\Phi 80$ diameters were adopted in shear connectors respectively, in which the opening size of each shear connector is uniform in a specimen, moreover, the spacing between openings is more than 2.5 times the opening diameter. Perforated rebars with HRB335 ribbed steel bars were placed in the center of openings. Transverse steel reinforcement was set in surrounding concrete of specimens in the fourth bridge and the foundation experiments, while it was laid in the concrete base and the reserved holes located on both sides of PBL connectors in the third bridge experiment, in which polyethylene foam was filled up the reserved holes before concrete casting.

As a contrast, the perforated plates of specimens US60-20-30P were smeared lime paste followed by greasing on the surfaces to lessen the bond and friction effect between the steel plate and surrounding concrete,

Fig. 1 Schematic of PBL specimens (4 connectors shown).

Table 1 Types and parameters of PBL connector specimens.

Specimens	Numbers	f_c (MPa)	A_p (cm ²)	r (%)	P_u (kN)	P_y (kN)	Specimens	Numbers	f_c (MPa)	A_p (cm ²)	r (%)	P_u (kN)	P_y (kN)
HT60-25-46	4	49.7	3150	1.20	792	478	OS60-20-28-1	5	44.0	1832	0.48	587	409
HT60-20-46	4	36.9	3150	1.20	645	433	OS60-20-28-2	5	51.7	1832	0.48	506	396
HT60-16-46	4	49.3	3150	1.20	507	356	OS60-20-28-3	5	34.2	1832	0.48	516	384
HT60-00-46N	4	49.3	3150	1.20	397	211	US60-20-12	3	51.2	900	0.89	486	274
OD60-22-32*	3	51.8	3600	0.48	598	361	US60-20-30	3	51.2	900	0.89	621	461
OD60-16-32*	3	43.4	3600	0.48	453	391	US60-20-20	3	51.2	900	0.89	537	354
OD45-16-32*	3	43.4	3600	0.48	443	319	US75-20-20	3	51.2	900	0.89	618	417
OD45-12-32	3	51.8	3600	0.48	330	286	US60-20-30X	3	51.2	900	1.56	622	502
OD60-20-32	3	29.6	2990	0.48	465	295	US60-20-30P	3	51.2	900	0.89	325	203
OS60-20-32	3	29.6	1590	0.48	485	324	UF60-20-25-1	2	42.2	4750	0.58	525	399
OD45-16-32	2	28.4	2990	0.48	315	217	UF60-20-25-4	2	60.4	4750	0.58	728	600
OS45-16-32	3	29.6	1590	0.48	383	240	UF60-20-22-8L	2	42.3	4750	0.26	386	301

Note: in the specimen's identification, initial H, O and U denote the third bridge experiment, the fourth bridge experiment and the foundation experiment, respectively. The second letter S, D, T and F denote the numbers 1 ~ 4 of PBL connectors in specimens, respectively. In the following numbers, the fore number denotes the opening diameter of perforated plates, while the middle number denotes the diameter of perforated rebars, and the hind number denotes the thickness of perforated plates. All above units are taken as mm. The number of the fourth item denotes the specimen's batch. The suffix N, X, P and L denote the specimens without perforated rebars, the specimens with a high reinforced ratio, the unbonded specimens and the specimens with a lower reinforced ratio, respectively.

whereas other specimens keep nature interface to simulate the common construction condition. The concrete strength in **Table 1** is shown as average cubic compressive strength in one group of specimens and the ratio of transverse steel reinforcement is defined as the total sectional areas of transverse reinforcement divided by the area of perforated plate.

2.2 Experimental arrangement

Stress distribution on the perforated plates was investigated because the bond and friction between the surrounding concrete and perforated plates significantly affected the ultimate bearing capacity of PBL connectors (Wayne *et al.* 1995). Thus, multiple distributed optical fibers were setup on both sides of perforated plate (shown in **Fig. 2**). Meanwhile, strain gauges were arranged in key points to precisely position and adjust the fiber sensors.

Perforated rebars in opening holes enhanced the load-carrying capacity of shear connectors and improved the ductility of shear connectors as well. In order to real-timely monitor the stress change of reinforced concrete dowels, grooves were engraved into right above and right below the perforated rebars (shown in **Fig. 3**), and distributed optical fibers were placed into the grooves to collect strain data of the perforated rebars under each load step. The polished grooves were cleaned before setup of strain gauges and optical fibers, and then optical fibers were pasted into the grooves with adhesive

(shown in **Fig. 4**). Considering that the perforated plates were compressive under all load steps, optical fibers should be pre-stretched before their layout. Epoxy resin was poured into the grooves following the arrangement of optical fibers and strain gauges, and then liquid silicon was poured into the grooves after epoxy resin solidified.

As well as the strain measurement, it is important to gauge the relative slip of each rows of PBL connector. The observation holes in surrounding concrete were reserved at both sides of connectors, in which lateral stub rebars were welded at the perforated plates in order to place dial indicators for slip measurement (shown in **Fig. 5**).

2.3 Data collection and loading

Strain data was collected by UCAM strain measuring instrument, in which the temperature compensation of strain chips detached by the adoption of independent temperature compensation chips. Strain collection of optical fibers was acquired by the NBX-7000 optical instrument (shown in **Fig. 6**), in which the sampling interval is 1cm and the spatial resolution is 5 cm. Slip data of PBL connectors was gained by the real-time reading of dial indicators which setup at corresponding position of PBL connectors.

10000kN compression testing machine was used to subject loads to the third bridge specimens, while specimens of the fourth bridge and foundation experiments were loaded by 1000kN and 2500kN elec-

Fig. 2 Layout of optical fibers and strain chips.

Fig. 3 Indenting of Perforated rebar.

Fig. 4 Setup of fiber sensors.

Fig. 5 Slip measurement of PBL.

Fig. 6 Data collection of optical fibers.

Fig. 7 Loading of foundation specimens.

tro-hydraulic servo controlled testing machines, respectively. Loading of the foundation specimens is shown in Fig. 7. Monotonic loading mode was employed in the third bridge experiment. As to the fourth bridge specimens, one specimen in each of the first three groups of them (marked with asteroids in Table 1) adopted the monotonic loading mode, and other two specimens of this groups used two-unloading and reloading mode. Moreover, the latter eleven groups of specimens in the fourth bridge experiment were taken monotonic loading method as well. Testing programs were determined by mechanical analysis of specimens prior to loading and given as following: preloading firstly, constant force loading secondly, displacement loading in the end, in which the loading mode was changed from constant force loading to displacement-controlled loading as the yielding of PBL connectors occurred. The loading speed is 5kN/s and the load holding duration is about 5-10mins for each load step under the force-controlled loading mode, additionally, the loading speed is 0.05mm/s and the load holding duration is about 10~20mins for each load step under the displacement-controlled mode.

3. Experimental result

3.1 Mechanical behavior under complete loading

As for PBL shear connector specimens in rational configuration, failure mode of specimens showed shearing rupture of perforated rebars when the thickness of the perforated plates is not less than 20mm. Large stiffness and excellent ductility performance were observed in tests (except specimens with plain concrete dowels). The relative slip of shear connectors was tiny in preliminary loading, in which the slip was generally less than 0.1mm

(a) the third bridge specimens

(b) the fourth bridge specimens

(c) the foundation specimens

Fig. 8 Load-slip relationship curves of three series specimens.

in elastic stage. The slip of PBL connectors increased gradually with increasing load and cracks occurred firstly in the middle or bottom of surrounding concrete, while the corresponding cracking load was still relatively small. With further increase of load, yielding of PBL connectors occurred as the slip approached in the order of 1.2mm, followed by quickly growth of the slip. The load born by PBL connectors with perforated rebars continued to increase in the displacement loading mode. Some of the load-slip curves in three series of the experiment specimens were shown in Fig. 8, in which the load-slip curve

of the specimen HT60-0-46N was shifted to the right 10mm.

As shown in **Fig. 8**, the working characteristic of PBL connectors during the complete loading process could be divided to three stages (Lou *et al.* 2012): the pseudo-elastic stage, the elasto-plastic stage, and the yield-strengthen stage. The load-slip characteristic of PBL connectors generally varied linearly in the pseudo-elastic stage, in which the deformation of reinforced concrete dowels was tiny, thus the load-slip curves seemed very steep in this stage. Subsequently, serious damage of reinforced concrete dowels occurred in the elasto-plastic stage, it showed that the gradual decrease of the slopes of load-slip curves with the degradation of the stiffness of PBL connectors. The yielding load of PBL connectors directly corresponded to the extreme points of curvature in load-slip curves, meanwhile, the perforated rebars yielded and the fractured concrete dowels slide each other under the yielding load. Then the PBL connectors approached the yield-strengthen stage, in which the load-slip curves showed apparently ascendant branch and it was the obvious difference that the test results of PBL connectors in hybrid structures distinguish from the push-out test results of PBL connectors in superimposed beams.

The ultimate load and the yielding load of a single PBL connector for all specimens were listed in **Table 1**. The statistics on the testing data showed that the yield load of a PBL connector was about 0.695 times its ultimate load (the standard deviation was 0.079) and the slip corresponding to the yield load was in the order of 1.2mm.

3.2 Mechanical characteristic of perforated rebars

Comparing to the load-slip curves of PBL connectors with perforated rebars, the ductility performance of specimens HT60-0-46N (shown in **Fig. 8(a)**) without perforated rebars was poor and their failure mode of the specimens is in a brittle manner since no obvious omens were observed before failure. The ultimate slip of all four specimens in the group of specimens HT60-0-46N were less than 2mm, and their ultimate bearing capacities were obviously less than the capacities of the same size specimen with perforated rebars too, thus the perforated rebars played an important role on the load-slip characteristic of PBL connectors.

Depending on the distributed optical fibers setup at the upper and lower edges of the perforated rebars, the strain distribution of the perforated rebar on specimens UF60-20-25-1 under some load cases was shown in **Fig. 9**, in which the origin on the abscissa axis corresponded to the location of the perforated rebar being at the center of the perforated plate. As shown in **Fig. 9**, strains of the perforated rebar in elastic stage were small, so that slip along loading direction were small as well. In this stage, the concrete dowel of the PBL connector had no cracks, so its relative slip consisted of the difference between the

perforated plate and the surrounding concrete and the elastic compression of the concrete dowel. With the load increasing, the concrete dowel cracked and the relative slip occurred along cracking contact planes, moreover, a tendency of relative separation was yielded in both the crack sliding planes of the concrete dowel. The effect of concrete aggregate interlock (Sagasetta *et al.* 2011) induced a large axial tensile force to the perforated rebar, which in turn imposed a clamping force on both sides of surrounding concrete by the perforated rebar. Furthermore, the reinforced concrete dowel transferred shear force as a strut (Walraven *et al.* 1981). According to the shear-friction theory (Kahn *et al.* 2002; Harries *et al.* 2012), the transverse steel reinforcement in surrounding concrete and the perforated rebars were two sources of the interfacial friction on the perforated plate. In the later loading stage, strains of the perforated rebar near the perforated plate quickly increased in a tension-shear state, and the perforated rebar would be sheared off as the load approached the ultimate bearing capacity. Thus the perforated rebar significantly affected the load-slip curves of PBL connectors and its deformation directly related to the relative slips of connectors.

The perforated rebar under loading could be analogized to a beam model on foundation (El-Ariss *et al.* 2007), the strain diagram of the perforated rebar at the

(a) strain distribution in upper edge

(b) strain distribution in lower edge

Fig. 9 Strain characteristic of perforated rebar in PBL connector.

lower edges (shown in Fig. 9(b)) was similar to the bending moment distribution diagram of an infinite length beam on foundation carried a concentrated force at origin. Meanwhile, the perforated rebar carried longitudinal tensile force yielded by above mentioned counteractive clamping force, so their sectional strain was produced by dowel effect and tension effect together. The dowel effect was superior in the strain of the perforated rebar at initial loading (load cases “1700kN” and before in Fig. 9), while the tension effect was dominate at later loading stage (load cases of displacement loading in Fig. 9, e.g. dis1mm, dis3mm).

According to the theory of elastic foundation beams, opposite stress of certain magnitudes should emerged on the lower edge of the perforated rebar about $\pi/4\lambda$ length off the loading location (herein λ denoted the coefficient of foundation deformation). So the load-carrying capacity and the deformation of the perforated rebar were related to the bearing stiffness, EI , that is the product of the concrete elastic modules and the second moment of the cross section area of the perforated rebars.

3.3 Effect of interface friction on perforated plate

The concrete dowel all kept in a compression-shear stress state during complete loading process, while the perforated rebar kept in a tension-shear stress state, and if they were taken as two independent mechanical members, the bearing capacity of each member was small, thus the

Fig. 10 Strain distribution of perforated plate.

(a) scraps in perforated plate (b) scraps in concrete dowel

Fig. 11 Friction image in PBL interface.

interaction between the reinforced concrete dowel and the perforated plate formed a major portion for the load-carrying capacity of PBL connectors. The strain distribution of the perforated plate on specimen UF60-20-25-1 at different load steps was shown in Fig. 10, in which the origin of the abscissa axis corresponded to the top of the surrounding concrete at the loading end. As shown in Fig. 10, strains of the perforated plate continuously increased with the load increasing. Meanwhile, the slopes of the strain curves (strain gradient) grew as well. According to the relationship between strain gradient and bond stress (Kwak *et al.* 2001), bond and friction stress around the perforated plate also continuously increased with load increasing, in which the interface shear of friction between the perforated plate and the surrounding concrete could be gained by the integral of the strain gradient along the whole height of the perforated plate in the loading direction. The interface shear of friction accounted for a considerable proportion for the bearing capacity of PBL connectors as a large slip occurred in the later loading stage.

In order to observe the failure mode of PBL connectors, specimens were disassembled along the interface of perforated plate after loading. The appearance of the perforated plate and the concrete dowel in specimen UF60-20-25-1 was shown in Fig. 11, in which obvious scraps were observed on the face of fracturing concrete dowel and on the edge of the circular opening of the perforated plate. It showed that strong friction effect occurred in the location of PBL connectors, meanwhile it demonstrated that the aggregate interlock effect apparently existed on both adjacent contact sliding planes, and the perforated plate was strongly confined by the perforated rebars and the transverse steel reinforcement in surrounding concrete.

4. Load-slip characteristic

As mentioned above, the working stages of PBL connectors can be divided into the pseudo-elastic stage, the elasto-plastic stage and the yield-strengthen stage. According to the mentioned load-carrying mechanism, on the basis of the experimental data of 78 specimens which being sorted three series and 24 groups (shown in Table 1), the load-slip characteristic of PBL connectors in each stage was investigated. As shown in Fig. 8, there was quite evident difference in the load-slip distribution and ultimate load-carrying capacity among different types of connectors, because of complicated load-carrying mechanism of PBL connectors and many factors which affected their bearing capacity (Medberry *et al.* 2002). Nondimensionalization of the load bearing capacity for PBL connectors was conducted to facilitate discussion and the ultimate bearing capacity P_u was calculated firstly.

4.1 Ultimate bearing capacity

The ultimate bearing capacity of a PBL shear connector

in hybrid structures refers to its peak load in the load-slip curve. The bearing capacity will descend dramatically after that. As for the PBL shear connector with the perforated rebar, the ultimate bearing capacity is corresponding to the load when the perforated rebar is just sheared off, while for that without the perforated rebar, aggregate interlock of the plain concrete dowel is almost failed when the ultimate bearing capacity is approached. According to above analysis, the ultimate bearing capacity P_u of a PBL connector comprises three components as follows: the adhesion force from the aggregate interlock of a concrete dowel, the dowel action of a perforated rebar and the interface friction induced by the clamping force resulting from both the perforated rebar and the transverse steel reinforcement. The adhesion force from the aggregate interlock is relevant to the root of the concrete strength, $\sqrt{f_c}$ (Bentz *et al.* 2006). The dowel action of the perforated rebar under shear failure is relevant to $f_y/\sqrt{3}$ (Jelic *et al.* 1999). When subjected to the limit load, the perforated rebar is already yielded but the transverse reinforcement remain elastic. Therefore shear contribution from the transverse reinforcement can be gained by regression analysis, and P_u is given by

$$P_u = 2\alpha A_c \sqrt{f_c} + 2A_d f_y / \sqrt{3} + (2\mu A_d f_y + \beta A_{tr} f_s) \quad (1)$$

where μ denotes the shear-friction coefficient between the perforated plate and the surrounding concrete, it can be taken as 0.7 (Robbat *et al.* 1985). α denotes the influence coefficient of the cohesive force from the concrete dowel, and β denotes the influence coefficient of shear offering from the transverse steel reinforcement. They are determined by regression analysis.

Based on the testing data of the mentioned 78 specimens, regression analysis was conducted followed by the result arrangement. The ultimate bearing capacity P_u of a single PBL connector was given as follows:

$$P_u = 0.498 A_c \sqrt{f_c} + 0.255 A_d f_y + 0.065 A_{tr} f_s \quad (2)$$

where above units are taken as kN-cm-MPa. As for the specimen without the perforated rebar, the section area of

the perforate rebar is taken as zero.

Equation (2) is the calculation expression of the ultimate bearing capacity of a PBL connector in natural interface (perforated plate being in bonded state). As to the unbounded specimens (US60-20-30P), the coefficient in the final item is taken as zero since the interface friction weakens and the load-carrying capacity obviously decreases.

The ultimate load-bearing capacities of all specimens calculated according to Eq. (2) are listed in **Table 2**. For comparison, the tested ultimate loads are shown in the table as well, herein Eq. (2) presents nice consistency with the test results.

Ultimate slip under the ultimate loads appears more discrete, since perforated rebars at a tensile-shear stress state have already been necking while PBL connectors are subjected to ultimate loads and approaching to failure. The fracture of perforated rebars not only relates to the failure mode of PBL connectors, but also closely relates to the ductility index of perforated rebars, loading history and loading method. Due to space limitations, not to proceed with this description.

4.2 Elastic limit load

As shown in **Fig. 8**, the load-slip curves of PBL connectors have steep branches in early loading for large elastic stiffness. The relative slip is tiny under small loading, even no slip occurs in early loading stage as the bonded effect on the interface between the perforated plate and surrounding concrete. The relative slip of a PBL connector in pseudo-elastic stage consists mostly of three parts: the displacement difference between the perforated plate and the surrounding concrete, the elastic compression of the concrete dowel, and the elastic deformation of the perforated rebar as a beam on elastic foundation.

The displacement difference between the perforated plate and the surrounding concrete relates to the strength of the perforated plate and the concrete strength. In elastic stage, the concrete dowel has no cracks or micro-cracks, and no slip occurs in the potential cracking plane, thus the elastic deformation of the concrete dowel mainly results from the elastic compression of cement

Table 2 Comparison of load-slip characteristics for all specimens.

Specimens	Test value		Calculated value		$K_{0.35}$ kN/mm	Specimens	Test value		Calculated value		$K_{0.35}$ kN/mm
	P_u /kN	$S_{0.35}$ /mm	P_u /kN	$S_{0.35}$ /mm			P_u /kN	$S_{0.35}$ /mm	P_u /kN	$S_{0.35}$ /mm	
HT60-25-46	797	0.175	792	0.200	1386	OS60-20-28-1	587	0.116	558	0.112	1741
HT60-20-46	645	0.116	628	0.110	1995	OS60-20-28-2	506	0.085	566	0.110	1808
HT60-16-46	507	0.069	544	0.047	4079	OS60-20-28-3	516	0.094	547	0.119	1611
HT60-00-46N	397	0.092	372	--	--	US60-20-12	486	0.107	543	0.094	2030
OD60-22-32*	598	0.108	614	0.152	1415	US60-20-30	621	0.054	543	0.038	5074
OD60-16-32*	453	0.049	452	0.038	4156	US60-20-20	537	0.069	543	0.056	3383
OD45-16-32*	443	0.023	412	0.033	4336	US75-20-20	618	0.096	600	0.097	2160
OD45-12-32	330	0.019	342	0.026	4662	US60-20-30X	622	0.171	674	0.214	1104
OD60-20-32	465	0.085	508	0.060	2941	US60-20-30P	325	0.055	369	0.037	5074
OS60-20-32	485	0.095	524	0.081	2265	UF60-20-25-1	525	0.058	510	0.046	3849
OD45-16-32	315	0.037	377	0.027	4801	UF80-25-25-4	728	0.153	764	0.200	1337
OS45-16-32	383	0.034	394	0.036	3846	UF60-20-22-8L	386	0.041	427	0.028	5435

pastes that can be calculated with an elastic contact model (Boresi *et al.* 2011) on the perforated plate and the concrete dowel. The elastic deformation is relevant to the concrete area, the magnitude of contact inner force and the material properties of two elastic contact bodies. Furthermore, the magnitude of contact inner force relates to the thickness h of the perforated plate and the square of opening diameter, D^2 . Moreover the thickness h not only relates to the failure mode of the concrete dowel, but also affects the sectional stress distribution of the perforated plate (Xiao *et al.* 2012). The material property of the concrete dowel is represented by the concrete compressive strength f_c , and the deformation of the perforate rebar is relevant to the foundation stiffness EI which is relevant to the concrete compressive strength f_c and the fourth power of the diameter of the perforate rebar, d^4 . Lastly, the bearing capacity of a PBL connector increases as the lateral pressure induced by the restraints of transverse reinforcement increases on the perforated plate.

Thus five effect factors as mentioned above, f_c , D^2 , d^4 , h and ρ (the ratio of transverse reinforcements) are selected to conduct a regression analysis on the basis of the testing data of 23 groups of specimens (excluding the specimens without perforated rebars) in Table 1, the load-slip relationship in elastic stage by the regression analysis is given as follows:

$$P_e = A \ln(S_e \cdot f_c D^2 d^4 h \rho) + B \quad (3)$$

where P_e and S_e denote the elastic load and the corre-

Fig. 12 Regression analysis of load-slip relation in elastic stage.

sponding elastic slip of a PBL connector, in which their units are kN and mm, respectively. The other units are taken as MPa-cm, the unit of ρ is taken as % and A , B are the regression coefficients.

Equation (3) can be rearranged to the following form:

$$S_e \cdot f_c D^2 d^4 h \rho = \exp(P_e / A - B / A) \quad (4)$$

where the right item in the equality is denoted as the generalized load, then the product $f_c D^2 d^4 h \rho$ is the generalized elastic stiffness of a PBL connector.

The linear relationship between $0.35P_u$ and corresponding slip $S_{0.35}$ in Eq.(3) is shown in Fig. 12 by regression analysis, in which the Pearson correlation coefficient is 0.842. As shown in the figure, there is a stronger linear relationship between the relative slip and the generalized load in elastic stage. In order to acquire the elastic limit load and corresponding elastic limit slip of a PBL connector, being in a range of $0.2P_u$ - $0.5P_u$ and on the basis of the testing data of 23 groups of specimens in Table 1, regression analysis and data processing were conducted according to Eq.(3). Comparisons of the regression analysis on the elastic limit load of a PBL connector under static loading are shown in Table 3.

According to the principle of standard deviation estimation on big sample population (Sha *et al.* 1993), being a 95% confidence level, the variation of the standard deviations σ_i on the slip sample is investigated in a range of $0.2P_u$ - $0.5P_u$. It is clear from the comparisons shown in Table 3 that the standard deviations σ_i of the slip samples in the range of $0.2P_u$ - $0.35P_u$ have no significant changes at a $0.05P_u$ load increase, but the standard deviations σ_i of the slip samples increase obviously from the load $0.4P_u$ and corresponding Pearson correlation coefficients present a decrease tendency. This phenomenon suggests that the significant change of the slips has occurred, thus the elastic ultimate load of a PBL connector can be taken as $0.35P_u$, and its corresponding slip $S_{0.35}$ can be regarded as the elastic limit slip. Specimens enter the elasto-plastic working stage while the loads go beyond $0.35P_u$.

The calculation of elastic slip of a PBL connector can be gained from the generalized load of a PBL connector in the right item of Eq. (4) dividing by the generalized stiffness. Being at 95% confidence level, the average elastic limit slip corresponding to the elastic ultimate

Table 3 Regression comparisons of elastic load of a PBL connector

Load	A	B	Pearson's r	average of slip	Standard deviation of slip
P_i (kN)				S_i (mm)	s_i (mm)
$0.20P_u$	8.425	49.766	0.8034	0.0267	0.0250
$0.25P_u$	11.663	49.307	0.8055	0.0451	0.0320
$0.30P_u$	16.169	39.659	0.8035	0.0590	0.0407
$0.35P_u$	19.332	34.802	0.8418	0.0923	0.0490
$0.40P_u$	22.283	27.771	0.8146	0.1375	0.0741
$0.45P_u$	25.091	20.290	0.8108	0.2069	0.1208
$0.50P_u$	28.635	4.878	0.8011	0.3061	0.1925

Note: A and B are corresponding to the regression coefficients in Eq.(3).

load $0.35P_u$ is about 0.0923mm and the standard deviation of the slip is 0.049mm in **Table 3**, Furthermore considering the discreteness of the statistics data, maximum elastic limit slip approximates 0.2mm. The calculated values and experimental values of the elastic limit slip for all specimens under the elastic ultimate loads $0.35P_u$ are listed in **Table 2**, and it shows that the elastic slips by testing and calculating from Eq. (3) are closely consistent.

5. Complete load-slip curve

A complete load-slip curve of a PBL connector reflects its mechanical property during the complete loading process and it is a basis of simplified finite element analysis on PBL connectors as well as the study on the shear transfer and shear distribution of shear connector groups in hybrid structures. The load-slip curve of a PBL connector in hybrid structures differs from that in composite or superimposed structures. The latter load-slip curve has a more obvious descending branch since there is adverse uplift effect on the connectors and weaker restraints from transverse reinforcement. Meanwhile, the former load-slip curve under the shear failure mode of concrete dowels has a more obvious strengthened ascendant branch because of the stronger restraints from transverse reinforcements in surrounding concrete.

The complete load-slip curve of a PBL connector in hybrid structures consists of two branches: a linear branch and a nonlinear branch. The linear branch corresponds to the elastic behavior of a PBL connector, in which the load-slip relationship appears linear characteristic, and the nonlinear branch corresponds to a procedure of stiffness degradation of a PBL connector, in which the shear stiffness gradually reduces with load increasing, but the softening phenomenon doesn't occur even after failure of the shear connector. According to above mentioned division on the working stages of a PBL connector, the linear branch refers to the pseudo-elastic working stage, in which the elastic limit load of a PBL connector is about $0.35P_u$, and the nonlinear branch refers to the elasto-plastic stage and the yield strengthened stage. Regression analysis was conducted on the basis of the tested data of 23 groups of specimens in **Table 1**. Then a complete load-slip curve is gained, in which the linear branch is denoted by a straight line and non-linear branch follows logarithmic distribution. Herein the complete curve P_δ - S is given as follows:

(1) $P_\delta = P/P_u \leq 0.35$:

$$P_\delta = kS = 0.35 / S_{0.35} \cdot S \quad (5)$$

where $P_\delta = P/P_u$, the units of above variables in right item are taken as kN; k denotes the slope of the straight line, thus the elastic stiffness of a PBL connector is the product of k and the ultimate load P_u ; S and $S_{0.35}$ denote the slip of a PBL connector and the elastic ultimate slip corresponding to $0.35P_u$ respectively, their units are taken as mm. The elastic stiffness of all PBL connector

specimens is listed in the last column of **Table 2**.

The elastic ultimate slip $S_{0.35}$ is calculated as follows:

$$S_{0.35} = \exp(0.05P_{0.35} - 1.543) / (f_c D^2 d^4 h \rho) \quad (6)$$

where $P_{0.35}$ denotes 0.35 times the ultimate load and its unit is kN; the other denotations and corresponding units are the same as above.

(2) $P_\delta = P/P_u > 0.35$:

$$P_\delta = a - b \ln(S + c) \quad (7)$$

where a , b and c are all regression coefficients, the other denotations and corresponding units are the same as above. Based on the regression analysis, a , b and c can be expressed as follows:

$$a = 0.09858 \ln(f_c^2 \rho^2 h / D^2 / d^2) + 0.31921 \quad (8)$$

$$b = 0.03563 \ln(f_c^2 \rho^2 h / D / d) - 0.32317 \quad (9)$$

$$c = 0.01 \exp(5.5555 - f_c^2 \rho^2 h / D^2 / d^2 / 147.93677) - 2 \quad (10)$$

where all denotations in Eq.(8)-Eq.(10) are the same as above, the unit of f_c is taken as MPa, the unit of ρ is taken as % and the other units are all taken as cm.

The fitting diagrams on the parameters a , b and c are shown in **Fig. 13** by linear regression analysis, respectively. As shown in **Fig. 13**, the fitting parameters have strong linear correlation with the relevant variables.

The comparison of the fitted data by Eq. (5) ~ Eq.(10) and the tested load-slip curves of partial PBL connectors is shown in **Fig. 14**. It shows that the fitting curves have a nice consistency with the tested curves in general, especially for the curve regions in the elastic stage and nearly ultimate load stage. However, the fitting curves of specimens HT60-25-46T have a small deviation from the tested curves during the yield and strengthened stages because the specimens contained the relatively thick perforated rebars lead to coarse aggregate uneasy to enter into the opening holes on perforated plates. So the concrete dowels show bearing deficiency under normal pressure, and the specimens have relatively lower bearing capacity during the yield and strengthened stages. The complete load-slip curve takes full consideration main factors affected the load and slip of PBL connectors, so it is in well agreement with the tested curve. Thus it can be taken as a basic input of simplified finite element analysis on PBL connectors. Meanwhile, it sets a foundation for the analysis of PBL connector groups.

6. Conclusions

Based on the tested data of 78 specimens presented in the third bridge experiment, the fourth bridge experiment and the foundation experiment, depended on the cutting-edge technique of optical fiber measurement, the load-slip characteristics and calculation equations on PBL connectors at the elastic limit state and the ultimate

(a) linear fitting of parameter a (b) linear fitting of parameter b (c) linear fitting of parameter c

Fig. 13 Parameter regression of complete curves.

bearing state were deduced, respectively. Then an expression of the complete load-slip curve on the PBL connector was proposed. According to above analysis, useful conclusions can be drawn as follows:

- (1) The bearing capacities of PBL connectors in hybrid structures are enhanced and their ductility performance is improved because the normal clamping force from perforated rebars effectively apply to both slide planes of concrete dowels, meanwhile the reinforced concrete dowels directly transfer shear force as the compressive struts.

(a) specimens HT60-25-46T

(b) specimens OD45-16-32

(c) specimens UF60-20-25

Fig. 14 Fitting comparisons of slip-load complete curves for PBL connectors.

- (2) As for the PBL connectors in hybrid structures, since there are stronger restraints on the perforated plate resulted from perforated rebars and transverse steel reinforcements in surrounding concrete, the interface friction between the perforated plate and surrounding concrete substantially increases. It constitutes an important part of the load-bearing capacities of PBL connectors in hybrid structures.
- (3) The mechanical behavior of PBL connectors in hybrid structures under complete loading process can be divided into three working stages:

pseudo-elastic stage, elasto-plastic stage and yield-strengthen stage. The elastic limit load is about 0.35 times the ultimate bearing capacity and the yield load is about 0.7 times the ultimate bearing capacity.

- (4) The complete load-slip curve of a PBL connector in hybrid structures consists of linear and nonlinear two branches, in which the slope of the linear branch refers to the elastic stiffness of a PBL connector and the nonlinear branch follows algorithmic distribution. The complete load-slip curve proposed above can be taken as an input stiffness of nonlinear finite element analysis on hybrid structures.
- (5) There are many factors that affected the load-slip relationship of PBL connectors, moreover, the average slip of PBL connectors under the elastic limit load is less than 0.1mm and more discrete, thus further study on the stiffness of PBL connectors is still required.

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Notation

a	regression constant on complete curve	$K_{0.35}$	elastic stiffness under 0.35 times the ultimate load
A	regression constant on elastic load	P	load of a PBL shear connector
A_c	area of concrete dowel	P_e	elastic limit load
A_d	area of perforated rebar	P_y	yield load
A_p	area of perforated plate	P_u	ultimate bearing load
A_{tr}	area of transverse reinforcement steels	P_δ	nondimensionalized load
b	regression constant on complete curve	r	Pearson correlation coefficient
B	regression constant on elastic load	ρ	ratio of transverse reinforcement steels
c	regression constant on complete curve	S	relative slip of a PBL connector
d	diameter of perforated rebar	$S_{0.35}$	elastic limit slip
D	Opening diameter of perforated plate	S_e	elastic relative slip
E	the Young's modulus of concrete	S_u	ultimate slip
f_c	concrete cubic compressive strength	α	regression coefficient of the cohesive force
f_s	yield strength of transverse reinforcement steels		Concrete dowel
f_y	yield strength of perforated rebar	β	regression coefficient of shear offering from the transverse reinforcement steels
h	thickness of perforated plate		
I	moment inertia of perforated rebar	μ	Shear-friction coefficient