- *Technical Paper* -

SHEAR BEHAVIOR OF UFC-RC HYBRID BEAMS WITH PBO FIBER

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ABSTRACT

The UFC is a cementitious composite reinforced by fiber with excellent properties. And PBO has the highest tensile strength among the organic fibers. This study is aimed to use PBO fiber reinforced UFC to strengthen the RC beams. And it investigates the shear behavior of UFC-RC hybrid beams with the parameters of different kinds of fiber. In addition, the method for evaluating the shear capacity of UFC-RC hybrid beams was proposed. The calculated values showed good agreement with the experimental results.

Keywords: shear capacity, UFC, PBO, volume content of fiber, fiber length, bond stress, hybrid beam

1. INTRODUCTION

Ultra-high strength fiber reinforced concrete (UFC) has been highly developed and improved in the last few years. UFC is characterized by extremely high compressive strength and excellent ductility. Due to the high compressive strength and ductility, this material has been studied as strengthening material to improve the structural strength of the structures [1]. Unfortunately, little research in this field uses UFC as part of newly constructions. With the Recommendations for Design and Construction of Ultra-high Strength Fiber Reinforced Concrete Structures (draft) [2] (UFC guidelines, hereafter) published by Japan Society of Civil Engineers (JSCE) in 2006, the standard mixed proportions are given. The UFC guidelines suggest using steel fiber as the reinforcing fiber. Steel fibers could be considered as the most effective and suitable fiber. Even though using steel fibers provided high tensile strength and flexural strength, it still had certain potential risks such as the low resistance for corrosion and almost no resistance for heat. In order to overcome the potential risk of steel fiber, this study focused on organic fibers which have the advantages such as high resistance to corrosion, heat, chemical attack, light weight and high strength. A high tensile strength and high elastic modulus fiber is supposed to improve the post-cracking behavior of UFC [3]. On the other hand, in the current UFC guidelines, there is only the evaluation method for the shear capacity of linear UFC members. However, the evaluation method for calculating the shear carried by UFC in the composite structures was unclear yet.

As the background mentioned above, this study used the poly (p-phenylene-2,6-benzobisoxazole) (PBO) fibers which has the highest tensile strength and elastic modulus among the organic fibers. This study also proposed a new composite structure between UFC with PBO fiber and RC beam. Four UFC-RC hybrid beams with different lengths and types of fiber were examined in this study to investigate the shear behavior and shear carried by UFC. Finally, the test results were compared with the calculated values based on the evaluation method of UFC guidelines.

2. TEST PROGRAMS

2.1 Test Specimens and Materials

The details of the test beams are illustrated in Fig.1, including the dimension and reinforcing bar arrangement of the beams. Table 1 summarizes the material properties of the UFC panels and RC beams. In this study, four UFC-RC hybrid beams were tested to investigate the shear behavior. The UFC-RC hybrid beams were consisted of cast-in-place RC beams with strengthened UFC panels at both sides.

The designed compressive strength of concrete aimed to obtain 40 N/mm^2 at a seven-day age. High early strength cement and water with the water-to-cement ratio at 40%, fine aggregate, coarse aggregate and superplasticizer were used. The high-performance air-entraining water reducing agent was used in the amount of 0.35% to the weight of cement in each mixture.

Six longitudinal D25 tensile bars with the yield strength of 1008 N/mm^2 were used as tensile bars and compressive bars in all four specimens. The D6 reinforcing bars with the yield strength of 328 N/mm^2 bars were used as the stirrups in the non-test shear span.

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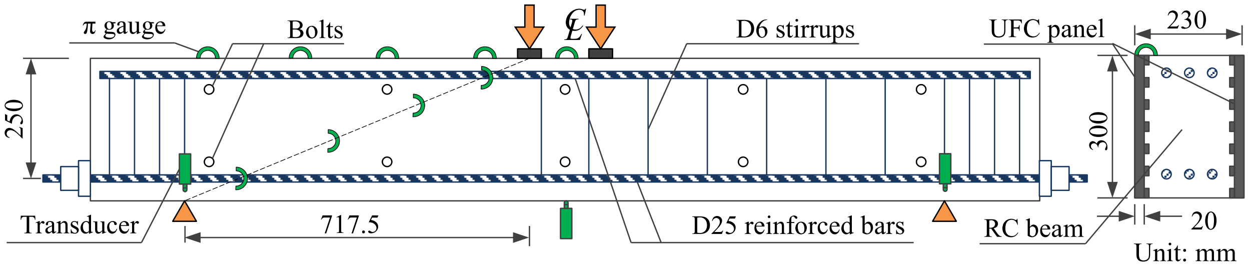

Fig. 1 Layouts of specimens

Table 1 Specimens details and material properties

Name	Fiber		UFC panel				Reinforced concrete beam	
	Type	Length (mm)	f'_c (N/mm^2)	E_c (kN/mm^2)	G_F (N/mm)	Thickness (mm)	f'_c (N/mm^2)	E_c (kN/mm^2)
P8	PBO	8	158.9	42.8	7.6	20	43.4	31.0
P15	PBO	15	156.1	44.4	8.2		44.4	30.3
P22	PBO	22	155.6	44.9	10.1		38.8	29.3
SF	Steel	15,22 (mix)	170.3	46.6	11		45.7	31.4

Table 2 Mix proportion of UFC panels

Name	Unit weight (kg/m^3)						Flow value (mm)
	Fiber	W	C	S	Admixture		
					SP	D	
P8	27.0	159.3	1287	908.3	38.7	6.3	280×270
P15	27.0	156.3	1287	911.3	38.7	6.3	250×230
P22	27.0	159.3	1287	908.3	38.7	6.3	200×200
SF	137.5	168.3	1287	899.8	38.5	6.5	275×275

W: Water, C: Premix binder, S: Sand, SP: Superplasticizer, D: Defoaming agent

The UFC panels were fabricated in advance using PBO fibers with three different lengths (8mm, 15mm and 22mm) and steel fibers (mixed 15 and 22 mm). The mix proportion of UFC panels is shown in Table 2. In order to ensure the beam and panels not being separated, the shear keys distributed throughout the panels. According to the manufacture, when the shear keys area is 30% of the panel area and the shear keys height is 25% to the panel thickness, shear keys could provide sufficient bond strength. Based on the tests, the shear keys were designed as 25mm in diameter and protruded 5mm from the surface. Also, ten bolts were provided to fix the panels onto the RC beam as shown in Fig. 1.

2.2 Loading Test and Instrumentation

The specimens were subjected to a four-point bending test with a simply-supported condition. The shear span to effective depth ratio is 2.87. The steel plates with 50mm in width were placed at the supporting points. In order to decrease the horizontal friction, the Teflon sheets and grease were inserted between the specimens and supporting steel plates. The other steel plates with 65mm in width were placed at the loading points. Anchor plates and anchor nuts were provided at both ends of the longitudinal tensile reinforcements to provide sufficient anchorage.

Four displacement transducers were set at the mid-span and supporting points to measure the deflection. Five strain gauges were attached on the longitudinal tensile reinforcements to measure the distribution of steel bars strain. Four π-gauges were attached along the line where the diagonal crack was expected to occur in order to measure the crack opening displacement. Five π-gauges were attached along the interface between the UFC panels and the RC beam at the test span to measure the separation displacement.

3 MECHANICAL PROPERTIES OF UFC WITH PBO FIBER

In this study, in order to obtain the necessary mechanical properties of the UFC, compressive strength test was carried out. The specimens are cylinder specimens with 50mm in diameter and 100mm in height. The results of compressive strength were shown in Table 1. Fracture energy test was also carried out by three-point bending using notched beams according to JCI-S-002-2003 "Method of test for load-displacement curve of fiber reinforced concrete by use of notched beam" [5], the results were shown in Table 1 as well. Also, the tension softening curves were estimated from the P-LPD (load-loading point displacement) curves. The P-LPD curves obtained from fracture energy test by following the procedures specified in JCI-S-001-2003 "Method of test for fracture energy of concrete by use of notched beam" [4].

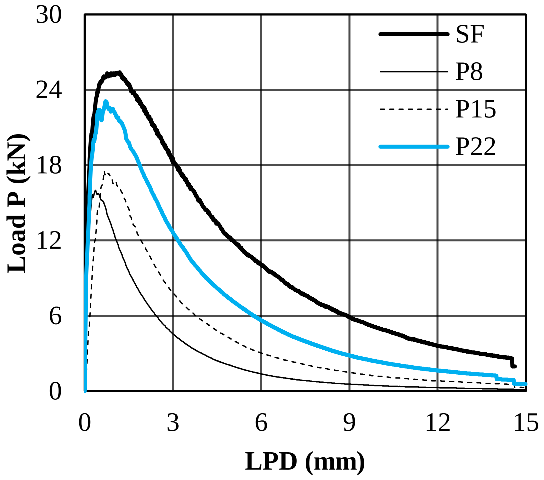

Fig. 2 P-LPD curves

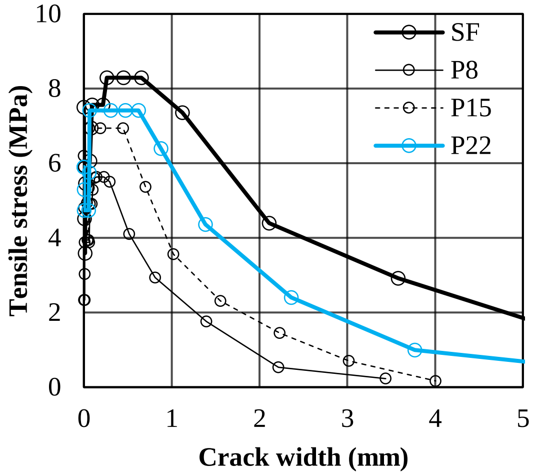

Fig. 3 Tension softening curves

The tension softening curves were estimated by using the published program proposed by Japan Concrete Institute. JCI standard specifies a method to estimate the tension softening curve by poly-linear approximation using the data of P-LPD curves. This method is a data fitting method which the tension softening curve was determined to agree on the analytical P-LPD curve with the experimental data. This method is effective for the fiber reinforced concrete of which softening diagram has a different shape. Fig. 2 shows the P-LPD curves and Fig. 3 shows the tension softening curves determined by the poly-linear approximation method.

According to the test results, the UFC tension softening curves could be modeled by the initial softening part, the plastic part and the final softening part. These three parts depended on the characteristics of the UFC matrix, the bridging effect of fibers and pull-out of the fibers, respectively. The tensile strength of each specimen can be obtained from the plastic part of the tension softening curves. It could be found that no matter in the P-LPD curves or in the tension softening curves, the performance of the UFC using PBO fiber are similar with the one using steel fiber. Due to the performance was not too much different between PBO and steel fibers, the evaluation methods of UFC using steel fibers were applied to evaluate the shear capacity of UFC using PBO fibers.

4 SHEAR BEHAVIOR OF UFC-RC HYBRID BEAM

4.1 Crack Patterns

Fig. 4 shows the crack patterns of four specimens after the loading tests. In each test specimen, the flexural cracks occurred on the RC beam and UFC panels at the same time. Thereafter, some of the flexural cracks developed into diagonal cracks. Then, more and more new diagonal cracks occurred and the cracks width expanded. The critical cracks are represented with red line.

In the specimen P8 (PBO fiber with 8mm), the diagonal crack occurred at 261.4kN, but the crack did not extend from the loading point to the supporting point. The critical crack angle of P8 was much larger than other specimens. It could also explain that the bond length between the fibers with 8 mm and concrete is not enough to provide the sufficient bridging effect. So that the crack expanded immediately after the flexural crack developed into the diagonal crack.

In the specimens P15 (PBO fiber with 15mm), P22 (PBO fiber with 22mm) and SF (steel fiber), the diagonal cracks occurred around 245kN to 265kN. After the flexural cracks developed into the diagonal cracks, the cracks extended to the loading point and supporting point. Then the load reached to the maximum and the crack width expanded quickly. Finally, most of the fibers were pulled out after the peak load. The critical crack angles of these three specimens were around 30 degree as shown in Fig. 4.

4.2 Load-displacement Curves

The load-displacement curves and the loading test results of four beams are shown in Fig. 5 and Table 3. The load-displacement curves could be divided into certain stages. First, the flexural crack could be observed at the mid-span of the beam and the strain of longitudinal bar at the mid-span also increased at this time. Second, since the RC beam was attached by the UFC, the diagonal crack was difficult to observe directly. But it is still possible to infer that the diagonal crack has occurred from the reduced stiffness. Next, the diagonal crack could be observed on the UFC panels, at the same time, the stiffness reduced again. After the diagonal crack occurred on the UFC panels, the shear force was transferred from the UFC matrix to the reinforcing fibers. At this stage, the load still increased due to the bridging effect of reinforcing fibers. While the crack width expanded and the load reached to the peak, fibers started to be pulled out from the matrix. Finally, with the fibers being pulled out, the load dropped slowly till the end of the loading test.

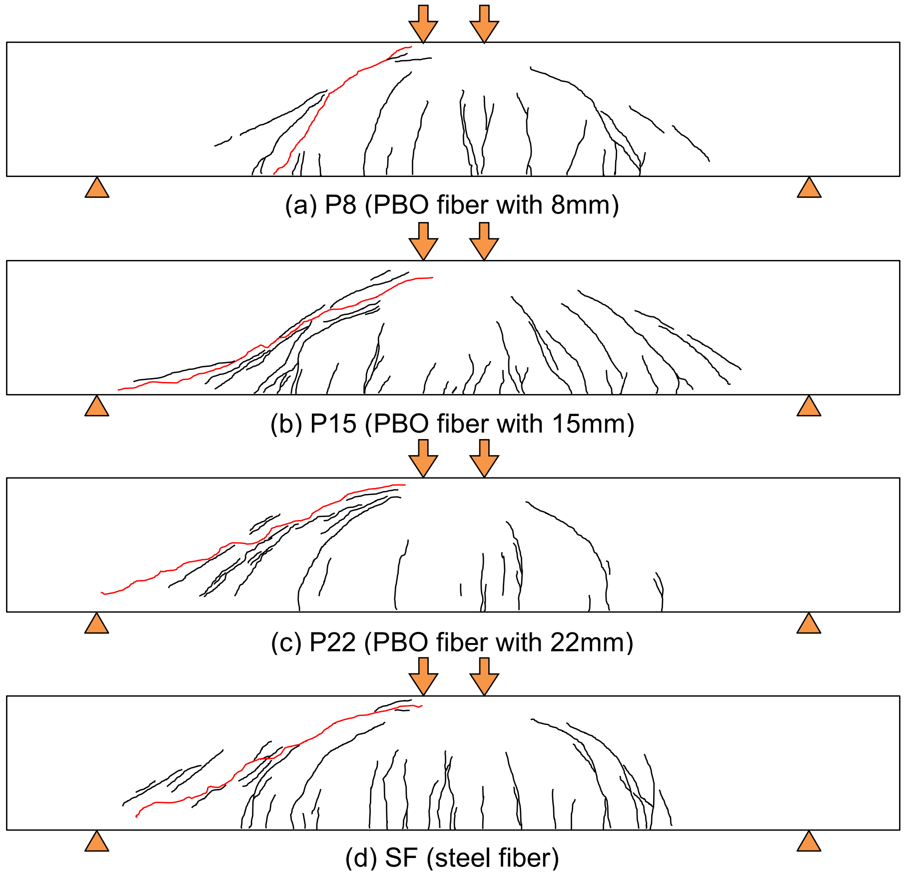

Fig. 4 Crack patterns (critical crack in red)

4.3 Shear Capacity of UFC Panels

Shibata et al. introduced a shear capacity evaluation method of RC beam strengthened by UFC panels and showed that it is possible to determine the shear capacity as the accumulation of UFC panels and RC beam [6]. Therefore, in this study, the shear carried by UFC-RC hybrid beam was assumed to divide into two parts as shown in Fig. 6. The shear carried by the UFC panels can be calculated by the following equations:

$$V_{UFC} = V_u - V_c \quad (1)$$

$$V_c = 0.20 f_c'^{1/3} p_w^{1/3} \left(\frac{1000}{d}\right)^{1/4} \left(0.75 + \frac{1.4}{a/d}\right) b_w d \quad (2)$$

where,

V_u : ultimate shear capacity

V_c : shear capacity of RC beam

V_{UFC} : shear capacity of UFC panels

For the evaluation method of V_c, it was calculated using the equations proposed by Niwa et al. [7].

By calculating the V_{UFC} using above evaluation method as summarized in Table 3, it was confirmed that the UFC panels can increase the shear capacity of UFC-RC hybrid beams. However, compared the P8 specimen with others, the shear carried by UFC was around 42% lower. This is because when the load of P8 reached to the first peak load at 261.4kN, the diagonal crack occurred on the UFC panels. Then the load suddenly dropped and the stiffness of the beam slowly declined. Thereafter, the load increased again, and dropped after the new diagonal crack occurred on the UFC panels again. Finally, the loading stopped because the load abruptly dropped at the displacement of 6.16mm and the sound of fibers being pulled out could be clearly heard.

From Fig.5 and Table 3, it is found that for the specimens P15, P22 and SF, the ultimate shear capacities were obviously increased almost twice by the UFC panels. The ultimate shear capacities of P15 and P22 are only about 7% lower than that of the SF specimen. From the test results, though the shears carried by the UFC panels of P15 and P22 are nearly the same, the behavior after the diagonal crack occurred on the panels and the post-peak behavior are fairly different. It can be noticed that compared with P22, the stiffness of P15 declined slightly more after the diagonal crack occurred. This could be considered that the longer fibers show a better bridging effect while the cracks occurred. Moreover, the load of P22 dropped slowly after reached to the peak since the longer fibers are supposed to have longer bond length and provide higher bond strength between fibers and concrete matrix. On the other hand, the load of P15 dropped quickly after the peak, because the bond length was insufficient when the crack width was expanding so that the fibers could be pulled out easier than P22. Finally, taking the practical application and safety into account, the loading stopped when the mid-span

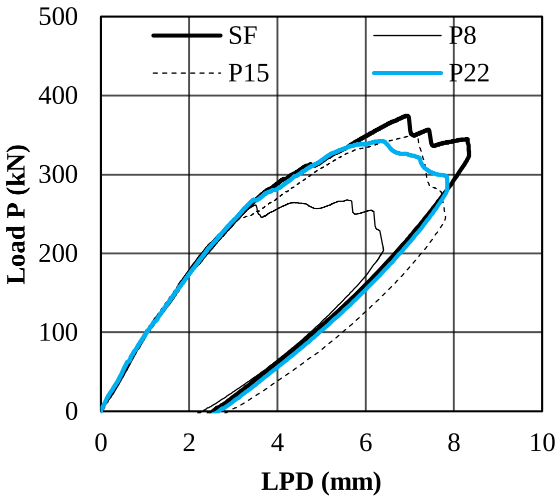

Fig. 5 Load-displacement curves

Table 3 Test results

Name	V_u (kN)	V_c (kN)	V_{UFC} (kN)	δ_u (mm)
P8	135.6	85.3	50.3	5.60
P15	176.9	85.8	91.1	7.08
P22	172.9	82.1	90.8	6.37
SF	187.4	84.9	102.5	6.94

δ_u: displacement at the maximum load

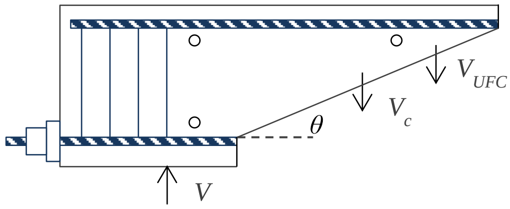

Fig. 6 Forces model in UFC-RC hybrid beam

displacement reached to 8mm. It is also worth mentioning that the UFC panels did not separate from the RC beams and showed good structural integrity for all of the test specimens.

4.4 Relationships between Crack Width and Fiber Length

Fig. 7 shows the relationships between the maximum width of critical crack and the PBO fibers length. The critical crack width of P8, P15 and P22 are 6.1mm, 5.4mm and 4.4mm, respectively. It is clear to see that with the increase in PBO fiber length, the crack width reduced. This is because the fiber with 8mm is so short that it could not increase the shear capacity at the early stage of the diagonal crack occurred. On the other hand, longer fibers as 15mm and 22mm have longer bond length so that they can resist the expanding of cracks and provide higher shear capacity.

Based on the above results, it was confirmed that the UFC5 panels can increase the shear capacity of UFC-RC hybrid beams, and the fiber length is one of the most important factors to affect the shear behavior and the crack patterns. It could be assumed that the UFC panels can have a higher shear capacity while using longer PBO fibers, but there is an effective length of PBO fiber. When the length of PBO fiber is shorter than the effective length, the shear capacity can be strengthened effectively. However, when the length is longer than the effective length, it would only affect the bridging effect and the post-peak behavior but not the shear capacity.

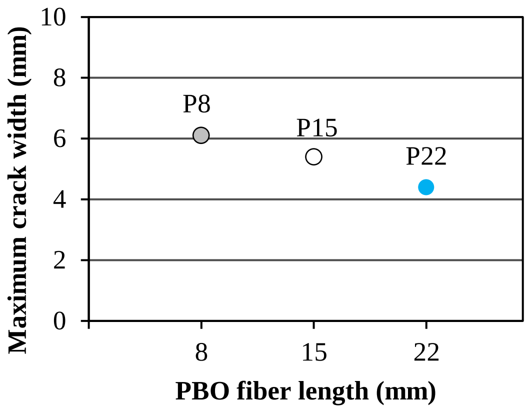

Fig. 7 Relationships of maximum crack width and PBO fiber length

5. EVALUATION METHOD OF SHEAR CAPACITY

In the UFC guidelines [2], only the calculation method of shear capacity of linear members has been mentioned. The evaluation methods for composite structures and UFC using PBO fibers are not clear. So it has to be clarified whether the shear capacity of UFC-RC hybrid beam can be evaluated by the existing method or not.

According to the UFC guidelines, the shear capacity of UFC can be obtained by the following equations:

$$V_y = V_{rpc} + V_f \quad (3)$$

$$V_{rpc} = 0.18 f'^{1/2}_c \cdot b_w d \quad (4)$$

$$V_f = (f_v / \tan \beta_u) b_w z \quad (5)$$

where,

- V_y : shear capacity of UFC (kN)
- V_{rpc} : shear capacity provided by matrix (kN)
- V_f : shear capacity provided by reinforcing fibers (kN)
- f'_c : compressive strength of UFC, (N/mm^2)
- f_v : average tensile strength perpendicular to diagonal cracks of UFC (N/mm^2)
- b_w : width of web (mm)
- d : effective depth (mm)
- β_u : an angle between member axis and a diagonal crack (°)
- z : distance from the location of compressive stress resultant to the centroid of the tension steel (mm)

From the above equations, it was found that it is necessary to define f_v to calculate the capacity provided

Table 4 Comparison of calculated values and experimental values

Name	f'_c (N/mm²)	f_v (N/mm²)	V_{rpc} (kN)	V_f (kN)	V_y (kN)	V_{UFC} (kN)	V_y / V_{UFC}
P8	158.9	4.3	27.2	27.8	55.0	50.1	1.10
P15	156.1	5.3	27.0	63.6	90.6	91.1	0.99
P22	155.6	5.7	26.9	67.8	94.8	90.8	1.04
SF	170.2	6.4	28.2	74.8	103.0	102.5	1.00

f'_c: compressive strength of UFC, f_v: average tensile strength of UFC, V_{rpc}: shear capacity provided by matrix, V_f: shear capacity provided by reinforced fibers, V_y: calculated shear capacity of UFC, V_{UFC}: experimental shear capacity of UFC

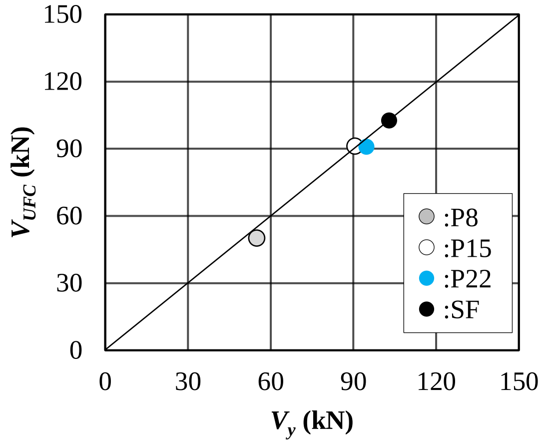

Fig. 8 Comparison of calculated values and experimental values

by fiber reinforcement. The UFC guidelines assumed that there is a close relationship between average tensile strength perpendicular to diagonal cracks f_v and characteristic values of tension softening.

In Eq. (3), the shear capacity of UFC consists of two components, one that is resisted by the matrix and another by fiber reinforcement. Then, the total strength is expressed as the sum of the two components. The shear capacity of UFC matrix is determined by the Eq. (4). It is a linear member that has no shear reinforcing bar. And the shear capacity provided by fiber reinforcement is determined by the Eq. (5).

Table 4 shows the calculation results of shear carried by the UFC based on UFC guidelines and the comparison with experimental values. It can be seen from Fig. 8, the calculation values V_y of all the specimens show good agreement with the experimental values V_{UFC}. According to the calculation results it was found that the shear capacity of UFC is highly related to the tensile strength itself which is determined by the length of fibers. In P8, the compressive strength is higher than P15 and P22, the shear provided by the matrix is slightly higher as well, but the tensile strength of P8 is much lower than others. On the other hand, the shear capacity of P22 is similar with P15 because these two specimens had similar tensile strength values. As the result, the fiber length plays a key role in the PBO specimens. However, since the experimental data is not sufficient, more researches are needed to find out the appropriate length of PBO fiber.

6. CONCLUSIONS

(1) The shear capacity of UFC-RC hybrid beams can be improved by attaching the UFC panels to the both sides of a RC beam. And the shear capacity of UFC using appropriate length of PBO fibers has the close capacity with UFC using steel fiber.

(2) The UFC panels have higher shear capacity when longer PBO fibers are used. However, there is an effective length of PBO fiber. When the length of PBO fiber is longer than this effective length, it would only affect the bridging effect and the post-peak behavior but not the shear capacity.

(3) The shear capacity of UFC-RC hybrid beams using PBO fibers can be evaluated by the evaluation method based on the UFC guidelines. The calculated values show good agreement with the experimental results.

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