- Technical Paper -

AN EXPERIMENTAL STUDY OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH INTERNAL PBO FIBER MESHES IN SHEAR

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ABSTRACT

This study aims to develop a new concrete structure by using the advanced PBO fiber meshes as a shear strengthening material inside concrete structural elements. The experimental parameters include the number of PBO fiber mesh layers and the width of PBO fiber meshes in the shear span. The results revealed that increasing the number of the PBO fiber mesh layers can increase the shear capacity of the RC beams, however, the shear capacity will be reduced if the strengthened width of the PBO fiber meshes is over than the effective width in the shear span.
Keywords: PBO fiber meshes, shear strengthening, internal strengthening system, shear capacity

1. INTRODUCTION

Since shear failure of concrete members is commonly known to be sudden and brittle, steel reinforcements for shear are usually provided into concrete structural elements to ensure the safety of the residents and the properties. However, the utilization of steel reinforcements has showed some drawbacks because of its electromagnetic property which can cause corrosion damages in the concrete structures. In order to avoid the corrosion damages, since the electromagnetic neutrality can be obtained from the application of FRP materials and the FRP itself generally exhibits an excellence in terms of tensile strength and lightweight. The idea of using Fiber Reinforced Polymer (FRP) materials as a substitute for stirrups inside the concrete structures is invented and this process may be called as the internal FRP strengthening system. Moreover, this internal strengthening system is expected to relieve of fire and UV light defects when compared with traditional FRP strengthening system, in which the FRP materials are bonded externally to a concrete surface and directly affected by fire and sunlight.

At the present time, the newly developed Polyparaphenylene Benzobis Oxazole (PBO) fiber meshes, as shown in Fig. 1, have been promoted as the new generation of strengthening materials with super fibers. Actually, the elastic modulus and the tensile strength of the PBO fibers are fairly higher than those of a high strength type of carbon fibers and they also have greater impact-tolerance and energy absorption capacity than other types of strengthening fibers. Moreover, the PBO fibers demonstrate high creep resistance and high fire/fuel resistance as well [1].

With an attempt to create a new development of a shear strengthening system of reinforced concrete (RC) members, the objective of this study is mainly focusing on the mechanical characteristic of RC beams strengthened with internal PBO fiber meshes. The elementary test of this study had already been conducted by the authors to ensure the strengthening performance of the PBO fiber meshes when they were used for strengthening concrete members inside the concrete cover, the result showed that the internal PBO fiber meshes in concrete members could bring their performance as the same level as the uniaxial tensile behavior and increasing the number of the PBO fiber mesh layers could increase the structural performance of the concrete members as well [2].

In this study, the RC beam test was carried out with total of six specimens, varied in number of PBO fiber mesh layers and width of PBO fiber meshes in the shear span. Shear capacities, failure mode, crack patterns and shear resisting mechanism were investigated and discussed in this paper.

2. EXPERIMENTAL PROGRAMS

2.1 Experimental cases and specimen details

The experimental program consisted of six RC specimens. One of them, called REF, was chosen to be the reference beam in which the beam had not been strengthened by any mesh or stirrup. Two parameters, listed in Table 1, were selected to investigate the

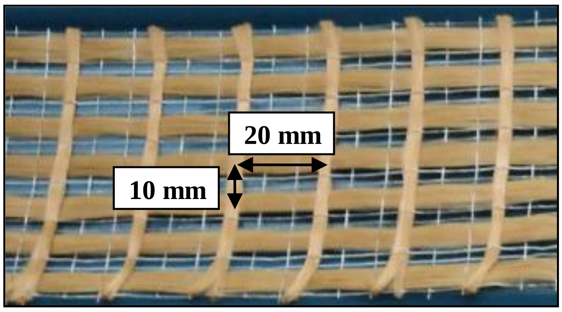

Fig. 1 PBO fiber meshes

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structural behavior of the RC beams strengthened with internal PBO fiber meshes.

In series I, four RC specimens consisted of REF, PBO1-700, PBO2-700 and PBO3-700, were considered. The difference of each specimen was the number of layers of the PBO fiber mesh which was increased from zero layer in REF to be one, two and three layers in PBO1-700, PBO2-700 and PBO3-700, respectively.

In series II, the width of the PBO fiber meshes (l_f) used for strengthening RC beams in the shear span was reduced from 700 mm in PBO1-700 to be 560 mm and 420 mm in PBO1-560 and PBO1-420, respectively.

Figure 2 shows the outline of the strengthened specimens in the test. The test span of all specimens was designed to fail in shear with shear span effective depth ratio, effective depth, specimen width, specimen height equal to a/d=2.80, d=250 mm, b=200 mm and h=300 mm, respectively.

2.2 Materials

(1) Concrete

In the experiments, self-compacting concrete (SCC) was mixed and cast into the formwork for allowing concrete infiltrating into the holes of PBO fiber meshes, leading to a good bond between concrete and the meshes. Mix proportion of the self-compacting concrete, given in Table 2, was composed of high-early strength cement, lime stone powder, fine aggregates, coarse aggregates, viscosity improver and superplasticizer. The designed compressive strength of 7-days curing concrete was 35 N/mm^2.

Table 1 Experimental cases

Series	Specimen designation	Number of PBO fiber mesh layers	l_f (mm)	Number of PBO fiber mesh strips	A_f (mm^2)
REF	REF	-	-	-	-
I	PBO3-700	3	700	225	51.19
	PBO2-700	2	700	150	34.13
I, II	PBO1-700	1	700	75	17.06
II	PBO1-560	1	560	60	13.65
	PBO1-420	1	420	45	10.24

l_f: width of the internal PBO fiber meshes in shear span
A_f: total cross-sectional area of the PBO fiber meshes

(2) Steel reinforcements

High strength reinforcing bars with 25.4 mm in diameter were selected to be tensile reinforcements in all specimens. The yield strength was 1181 N/mm^2. The compression bars were 9.53 mm in diameter with yield strength 388 N/mm^2. The stirrups with 12.7 mm in diameter were arranged in one side of the specimen, to control the side of failure happening at the test span, with 100 mm in spacing. The yield strength of stirrups was 388 N/mm^2. In addition, the 6.35 mm diameter round bars were provided for preventing stress concentration at the point load as shown in Fig. 2.

(3) PBO fiber meshes

The anisotropic orthogonal PBO fiber meshes were produced by roving 5 mm PBO fibers with the nominal thickness equal to 0.0455 mm in each strip of the main direction and 2.5 mm PBO fibers with 0.0224 mm nominal thickness in each strip of the other direction [3]. The tensile strength and modulus of elasticity of the PBO fibers were 5800 N/mm^2 and 270 kN/mm^2, respectively.

The total length of the wrapped PBO fiber meshes used in PBO1-700, PBO1-560 and PBO1-420 was about 0.90 m each while the total length in the wrapped PBO fiber meshes used in PBO2-700 and PBO3-700 were about 1.60 m and 2.30 m, respectively.

(4) Epoxy resin

Since the results from the elementary test done by the authors exhibited that coating the PBO fiber meshes with epoxy resin could uniformly gather PBO fibers in the meshes leading to the higher performance of the strengthening effect [2], all the PBO fiber meshes in this experiment were coated by epoxy resin (570 g/m^2) around two hours before casting. The tensile strength of the epoxy resin is higher than 30 N/mm^2.

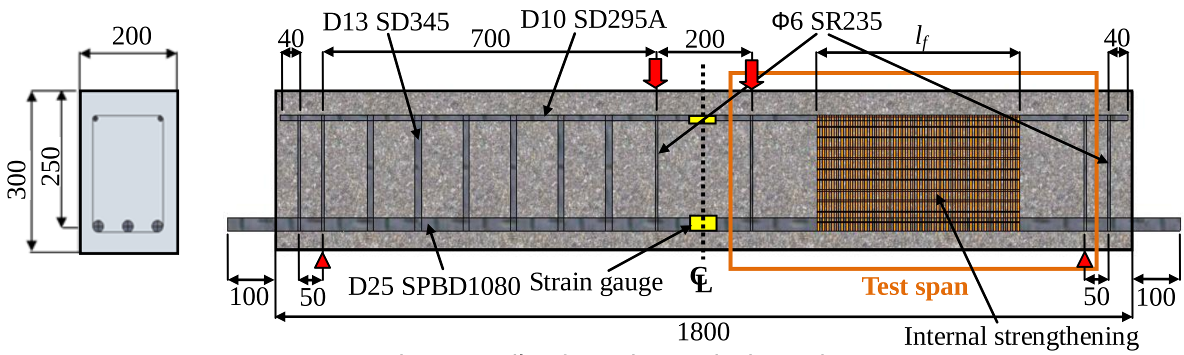


Fig. 2 Details of specimens (unit: mm)

Table 2 Mix proportion of concrete

Maximum size of coarse aggregate [mm]	Water Cement Ratio w/c [%]	Fine to Aggregate Ratio s/a [%]	Unit weight (kg/m^3)						
			Water W	Cement C	Lime stone powder L	Fine aggregate S	Coarse aggregate G	Super plasticizer SP	Viscosity improver V
15	60	45	175	292	249	718	857	(C+L)×1.5%	W×0.2%

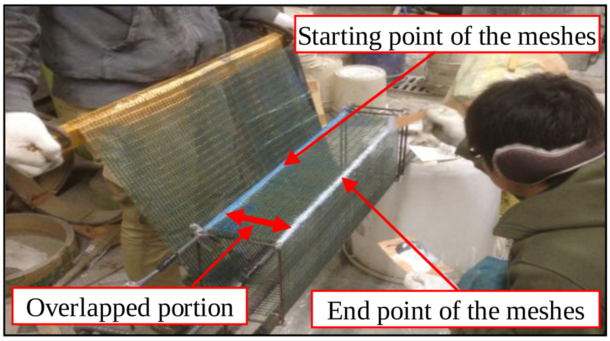


Fig. 3 Fabrication of PBO fiber meshes

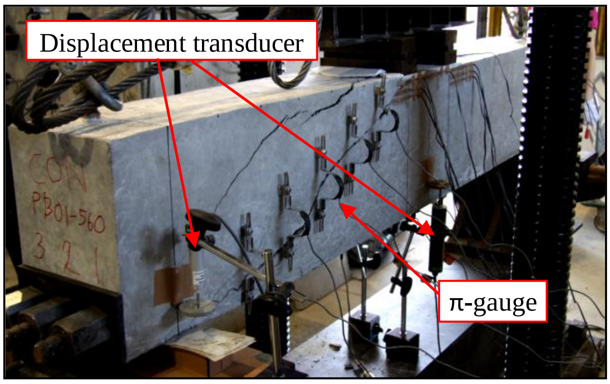


Fig. 4 Measurement items

2.3 Specimen fabrication

After the steel reinforcements were arranged and the steel strain gauges were attached to the center of both longitudinal reinforcing bars and compression bars, the PBO fiber meshes were attached to the compression bars as a starting point by using glue epoxy resin. Then, the PBO fiber meshes were coated by the epoxy resin, as mentioned in section 2.2, to unify the PBO fibers in the meshes. After that, the meshes were wrapped around the compression bars and the tensile reinforcing bars of the specimen until they reached their end designed point, then, using the glue epoxy resin again. Therefore, there was an overlapped portion of the PBO fiber meshes of 145 mm as shown in Fig. 3. While setting up, the PBO fiber meshes were kept tensioned by hand in order to ensure the maximum effectiveness of the strengthening.

2.4 Loading method

The specimens were placed on the roller supports with Teflon sheets and grease inserted between the connection of them for preventing horizontal friction. As shown in Fig. 2, the specimens were subjected to a four-point bending in which the load was generated from a 200-ton loading machine. To reduce stress concentration, steel plates were placed on the top surface of the specimens and also at their supports. In addition, anchorage plates and nuts were tightened at the tips of longitudinal bars for preventing the anchorage failure during the test.

2.5 Measurement items

As shown in Fig. 4, the mid-span deflection was measured by four displacement transducers set up at mid-spans and two side supports of the specimen at the same level. Electrical strain gauges with 2 mm gauge length were attached to the reinforcements in both compression bars and tensile reinforcing bars to measure actual strain of the steel reinforcements. Three 50 mm π-gauges were used to measure the width of the flexure cracks at the bottom of the specimen and the crack propagation on the side surface of the test-span was measured by five 100 mm π-gauges. In addition, cracks on the side surface were recorded by taking pictures during the test.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Increase of shear capacities

(1) Calculation method for shear carried by internal PBO fiber meshes

The shear capacity of RC beams strengthened with internal PBO fiber meshes is a combination of the shear carried by concrete and the shear carried by internal PBO fiber meshes as shown in Eq. (1). The shear carried by concrete can be calculated by considering the effect of compressive strength of concrete (f_c') in N/mm^2, reinforcement ratio (p_w) in percentage, effective depth (d) in mm and shear span effective depth ratio (a/d), as written in Eq. (2) [4].

$$V_{exp} = V_c + V_f \tag{1}$$

$$V_c = 0.2(f'_c)^{1/3}(p_w)^{1/3}\left(\frac{1000}{d}\right)^{1/4}\left(0.75+\frac{1.4}{a/d}\right)b_w d \tag{2}$$

where, V_{exp} is experimental value of shear capacity (kN), V_c is shear carried by concrete (kN), V_f is shear carried by internal PBO fiber meshes (kN) and b_w is the width of specimens (mm).

Therefore, the experimental value of shear carried by internal PBO fiber meshes (V_{fexp}) can be investigated by subtracting shear carried by concrete from V_{exp} as shown in Eq. (3).

$$V_{fexp} = V_{exp} - V_c \tag{3}$$

(2) Effect of number of PBO fiber mesh layers

Table 3 lists the summary of the experimental results in series I and series II. Among the specimens in series I, the shear capacity of PBO3-700 in which three layers of PBO fiber meshes were provided showed the highest value, while the shear capacities of PBO2-700, PBO1-700 and REF were gradually reduced as a reduction of number of PBO fiber mesh layers.

Figure 5 clarifies the increase in the shear capacities of tested beams in series I. By increasing the number of internal PBO fiber mesh layers from zero layer in REF to be one, two and three layers in PBO1-700, PBO2-700 and PBO3-700, the experimental shear capacities (V_{exp}) compared with REF beam increased by 48.74%, 72.51% and 113.71%, respectively. Moreover, the experimental values of shear carried by internal PBO fiber meshes (V_{fexp}) of PBO3-700 and PBO2-700 were higher than the value of

Table 3 Summary of experimental results

Specimen designation	Mechanical properties of concrete		V_{exp} (kN)	V_c (kN)	V_{fexp} (kN)
	f_c' (N/mm^2)	E_c (kN/mm^2)			
REF	41.2	30.0	77.8	77.8	-
PBO3-700	39.1	29.4	166.4	86.9	79.4
PBO2-700	33.7	28.3	134.3	82.7	51.6
PBO1-700	40.2	31.5	115.8	87.7	28.1
PBO1-560	39.1	30.5	130.5	86.9	43.6
PBO1-420	37.7	29.5	130.7	85.9	44.8

f_c': compressive strength, E_c: Young's modulus, V_{exp}: experimental value of shear capacity, V_c: shear carried by concrete, V_{fexp}: experimental values of shear carried by internal PBO fiber meshes

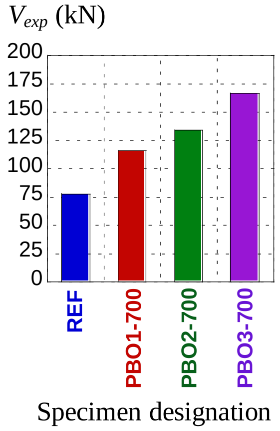


Fig. 5 Effect of number of the mesh layers

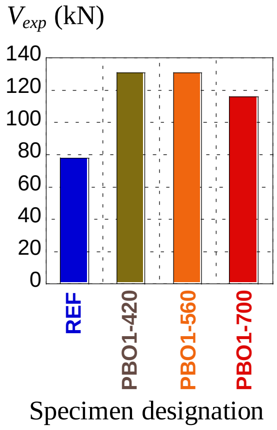


Fig. 6 Effect of width of the meshes in shear span

PBO1-700 by 83.68% and 182.97%, respectively.

(3) Effect of width of PBO fiber meshes in shear span

The effect of the width of PBO fiber meshes in the shear span on shear capacity is shown in Fig. 6. The results implied that the shear capacity of the strengthened beams decreased for wider range of fiber meshes in the shear span. The RC beams strengthened with the appropriate width of internal PBO fiber meshes may obtain the highest efficiency of the strengthening system.

By using internal PBO fiber meshes with the width equal to 420 mm in PBO1-420 and 560 mm in PBO1-560, the shear capacity of the experimental value (V_{exp}) was higher than REF by 67.91% and 67.60%, respectively. However, when the mesh width was increased to 700 mm in PBO1-700, the reduction of V_{exp} was exhibited and the V_{exp} of PBO1-700 was higher than V_{exp} of REF only about 48.74% as shown in Table 3. In the same way, experimental value of shear carried by internal PBO fiber meshes (V_{fexp}) of PBO1-420 and PBO1-560 was higher than V_{fexp} of PBO1-700 by 59.74% and 55.15%, respectively.

3.2 Load-displacement relationships and crack development

The load-displacement curves of the tested specimens in series I are illustrated in Fig. 7 and in case of series II are illustrated in Fig. 8. The difference in displacement at the peak load of each specimen was revealed in series I. However, the difference in displacements of the strengthened specimens at the peak load in series II was much smaller than series I as the number of layer of the strengthened PBO fiber meshes was same.

For the REF beam shown in a blue line in Figs. 7 and 8, the beam exhibited a linear behavior prior to the presence of the first flexural crack when the load reached about 30 kN. After that, several small flexural cracks appeared close to the mid span of the concrete surface leading to a small inclination of the curve. The load continually increased until it reached the peak load at 155.68 kN and a clear big diagonal crack was observed around the middle height of the specimen at this state. The failure mode of this reference beam can be distinctly explained as a diagonal tension failure.

In case of the strengthened beams, both in series I and series II, all specimens exhibited a similar development of failure which was presented by

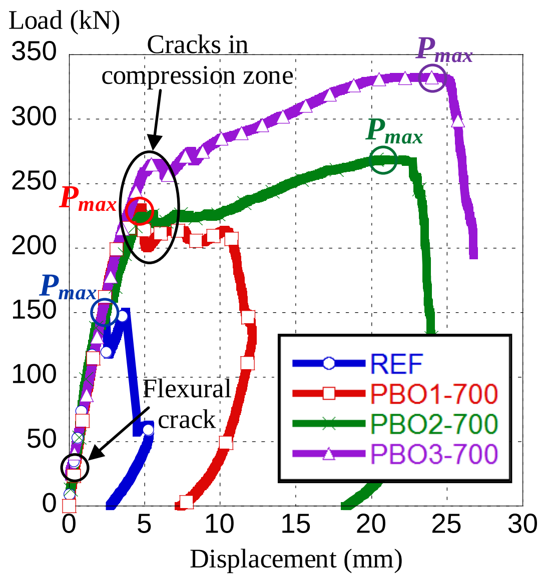


Fig. 7 Load-displacement curves in series I

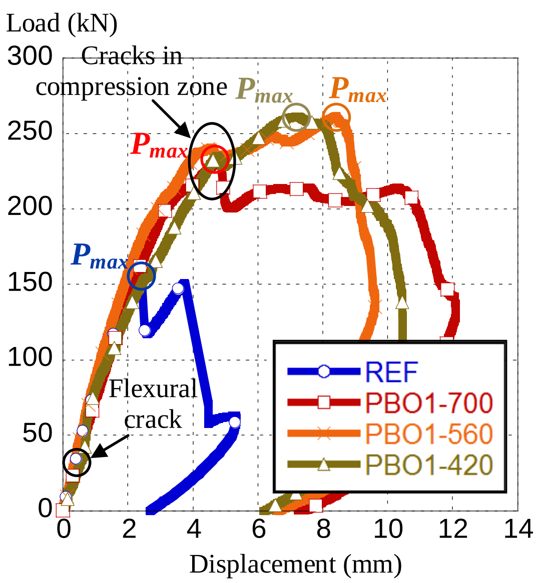


Fig. 8 Load-displacement curves in series II

showing PBO2-700 in Fig. 9 as a representative for all strengthened specimens. First, the specimens behaved in elastic behavior until the first flexural crack was observed at approximately the same level as the REF specimen. Then, flexural cracks propagated near the mid-span portion until the diagonal crack happened at middle height of the shear span as shown in Fig. 9(a). Figure 10 illustrates the relationship between the load and opening width at the middle height of the shear span of PBO2-700. It can be seen that the onset of diagonal crack started at the load around 150-160 kN, corresponded to the peak load of the REF specimen which was equal to 155.68 kN. This means that the shear resistance from the internal PBO fiber meshes initiated their performance after the diagonal crack had already occurred and this fact was same as the assumption in the utilization of conventional stirrup.

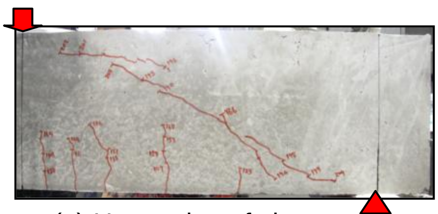
After the appearance of the diagonal crack, being different from the REF beam, the load still continually increased although the diagonal crack became clearer and bigger. After that, as shown in Fig. 9(b), cracks in the compression zone suddenly occurred causing a little drop of the load-displacement curves of the strengthened specimens and the obvious change of the stiffness was also observed. These cracks in the compression zone had played an important role in the peak load control of PBO1-700 because PBO1-700 was the only one of all strengthened beams which failed after the occurrence of the cracks in compression zone. In addition, the stage when the cracks in compression zone had occurred can be considered as a serviceability limit state of the reinforced concrete beams strengthened with internal PBO fiber meshes because the beams still had an ability to carry the shear force even the big cracks in compression zone were clearly observed. Therefore, the people had enough time to repair the beams before the beams reached their ultimate stage at the peak load.

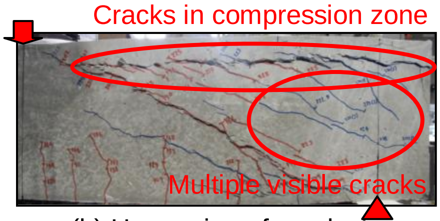
After the cracks in the compression zone happened, multiple visible cracks were observed in the shear span and the progression of the load was significantly slow with a much extension of the deflection especially in PBO2-700 and PBO3-700, which can be seen explicitly in Fig. 7. Finally, the diagonal crack and cracks in the compression zone became dangerously wider and the sound of rupture of the meshes could be heard before the load reached their peak load as displayed in Fig. 9(c).

3.3 Shear resisting mechanism and crack patterns

As mentioned before, all the strengthened beams behaved linear manner during the initial state of the loading. After the diagonal crack occurred at the middle height of the shear span, the load kept increasing mainly because of the tensile force from the internal PBO fiber meshes which was embracing the inner portion of the beams. After that, because of the extension of the meshes, the expansion of the main diagonal crack became wider in the next state prior to the presence of cracks in the compression zone.

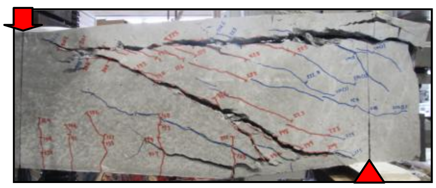
It was anticipated that cracks in the compression zone had occurred because of the weak bond between the outer upper portion of the concrete and the internally strengthened PBO fiber meshes at the area where these two materials were attaching. The reason of the weak bond was that the filling concrete was not completely penetrated into the holes of the meshes, therefore, the bond between concrete and the meshes was sensitive to be separated. The occurrence of cracks in the compression zone was the key that the peak load of PBO1-700 became lower than peak loads of PBO1-560 and PBO1-420, even the amount of mesh was fairly higher. From this phenomenon, it means that the highest efficiency of this internal strengthening system can be obtained by using the appropriate width of the meshes, not the longest width of the meshes.


(a) Happening of shear crack



(b) Happening of cracks in compression zone


(f) Yielding of compression bar


(c) Peak load


(d) Rupture of internal PBO fiber meshes


(e) The specimen after loading test

Fig. 9 Crack development of PBO2-700

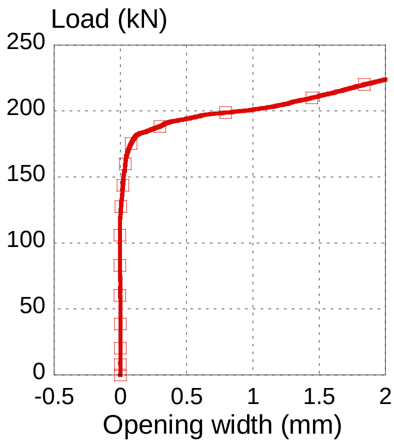
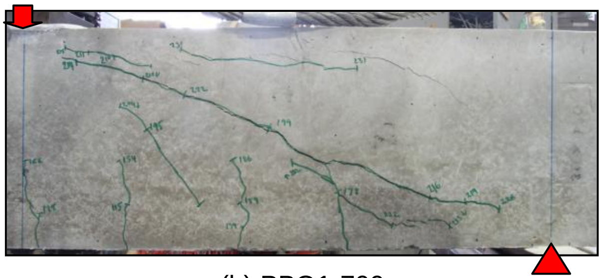
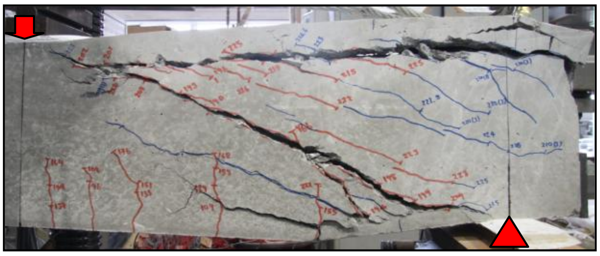


Fig. 10 Load-opening width at the middle height of shear span of PBO2-700

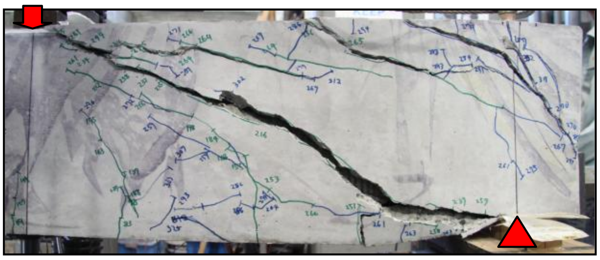
(a) REF



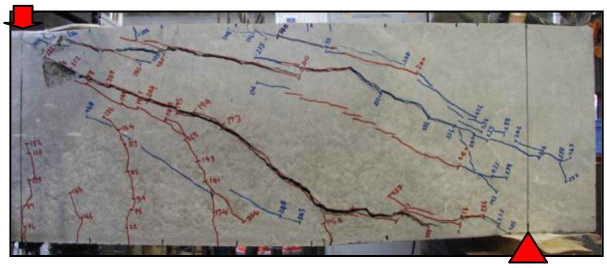
(b) PBO1-700



(c) PBO2-700



(d) PBO3-700



(e) PBO1-560

(f) PBO1-420

Fig. 11 Crack patterns (at peak load)

After the occurrence of cracks in the compression zone, the shear force was still increasing with a very small inclination of the load-displacement curve. During this state, only the internal PBO fiber meshes and the core concrete were expected to carry the shear force until the load reached the peak. The picture of the PBO2-700 after loading test can be seen as shown in Fig. 9(e). Figure 11 shows the crack patterns for all tested specimens at the peak load. It can be seen that the effect of cracks in the compression zone had occurred in all strengthened specimens.

Just before the peak load, the sound of the rupture of the strengthened PBO fiber meshes was heard often and the rupture of the PBO fiber meshes was examined again by opening the outer portion of the concrete and investigating the inside PBO fiber meshes, after finishing the test as presented in Fig. 9(d). It is noted that only some parts of the strengthened PBO fiber meshes were ruptured and the region of rupture frequently happened where the yielding of compression bar occurred as seen in Fig. 9(f).

4. CONCLUSIONS

(1) The internal strengthening system by using the PBO fiber meshes is effective for improving the performance of RC beams. The PBO fiber meshes can carry the tensile stress after the occurrence of the diagonal cracks.

(2) The shear capacity of RC beams (V) and the shear carried by internal PBO fiber meshes (V_f) can be increased with the increasing of the number of internal PBO fiber mesh layers.

(3) The highest efficiency of the RC beams strengthened with internal PBO fiber meshes can be obtained by using the appropriate width of the internal meshes. By using the proper width, the loss in bond between concrete and the meshes was reduced, leading to the higher shear performance of the beams.

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