- Technical Paper -

EFFECTS OF CFRP-SHEET LAYERS ON PRETENSIONED PC BEAMS HAVING RUPTURED STRANDS STRENGTHENED IN FLEXURE

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ABSTRACT

This paper describes the experimental study on strengthening of pretensioned PC beams having 50% of strands ruptured using different amount of CFRP sheets. The flexural capacity was recovered up to 91.5% of that of the undamaged PC beam. However, the flexural capacity did not increase accompanied by increasing number of layers of CFRP sheets. The strength of the bonded sheets could not be fully utilized in the composite actions because of the premature failure. Besides, the debonding of CFRP sheets in the strengthened PC beams was affected by the amount of the sheets.

Keywords: externally bonded CFRP sheet, flexural capacity, prestressed concrete beam, strand rupture, debonding

1. INTRODUCTION

For more than 60 years, since it was invented in 1940s, the prestressed concrete (PC) has become an important technology for long span bridges. Especially, in the field of bridge construction, PC took an advantage over the ordinary reinforced concrete and steel because of high performance and ease of maintenance. Recently, there has been a concern in the degradation of PC girders. One of the most severe cases is the rupture of prestressing strands or tendons due to various factors such as corrosion and collision due to the crashes by vehicles. Besides, an increasing demand in the applied load has raised requirements in upgrading the capacity of the existing girders. It has created a challenge to develop a practically feasible strengthening method, which provides not only an effective enhancement in structural capacity in short time but also a safety for prolonged use.

The application of fiber reinforced polymer (FRP) materials in construction has been increased in the past 20 years [1]. Carbon fiber reinforced polymer (CFRP) is a type of FRPs, which is a polymer matrix composite material reinforced by carbon fibers. The major advantages of CFRP sheets are pointed out as high strength, corrosion resistance, ease to implement, and less impact to the original geometry. CFRP sheets are bonded to external faces of RC structures for multipurpose strengthening. This method can be carried out within short time, without using of heavy equipments compared to the other conventional methods (strand splices, external post-tensioning tendons or steel plate jackets). To the date, many studies have proven the effects of externally bonded CFRP sheets on the increase in flexural capacity of RC beams [2, 3]. Thus, the externally bonded CFRP sheet method has been adopted in strengthening of flexural RC members (slabs and beams) [1]. However, the research data have tended to focus on the strengthening of RC beams rather than PC beams. Especially, little attention has been paid to the effects of this strengthening method on PC beams having ruptured strands.

It has been shown that on the strengthening of the damaged PC beams by one layer of CFRP sheets, the capacity of strengthened PC beams increased about 11% compared to that of the damaged one [4]. However, it was still far less than the capacity of the undamaged PC beam. In this regard, the present study aims to improve the flexural capacity of the strengthened PC beams having ruptured strands by increasing the number of layers of CFRP sheets bonded to specimens. This paper discusses the effects of the amount of CFRP sheets based on the experimental outcomes.

2. EXPERIMENTAL PROGRAM

2.1 Test specimens

(1) Specimen details

The details of specimens are shown in Fig. 1. Two types of specimens were prepared including one undamaged beam (or control beam (CB)) and six damaged beams (DB2). The 3,300 mm long specimens have a rectangular section of 150 mm width by 300 mm height. Four prestressing strands of seven-wire type having 10.8 mm nominal diameter were used as tensile reinforcement. The initial prestressing stress of 1075 N/mm^2 was applied for each strand. In order to prevent shear failures, the stirrups of diameter 10 mm were provided at the spacing of 100 mm in the middle of span and 60 mm near the supports.

In order to simulate the rupture of strands in the damaged beams, 100 mm long cover concrete at the midspan of the beams was not cast at the beginning so

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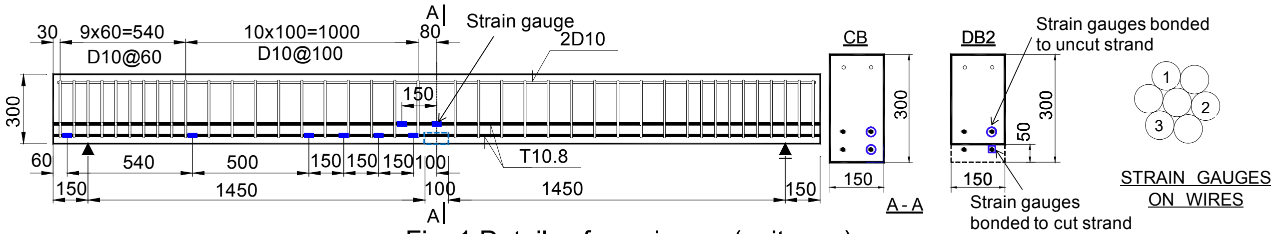

Fig. 1 Details of specimens (unit: mm)

Table 1 Experimental cases

Case	Name	CFRP				
		t_f (mm)	n_f	b_f (mm)	l_f (mm)	w_f (mm)
1	CB	-	-	-	-	-
2	DB2	-	-	-	-	-
3	DB2-100-1	0.111	1	125	1,000	-
4	DB2-100U-2b	0.333	2	125	1,000	180
5	DB2-100U-3b	0.333	3	125	1,000	180
6	DB2-100U-4b	0.333	4	125	1,000	180
7	DB2-100U-5b	0.333	5	125	1,000	180

t_f: thickness of one layer CFRP sheet; n_f: number of longitudinal CFRP sheet layers; b_f: width of CFRP sheet; l_f: length of CFRP sheet; w_f: width of U-shaped transverse sheet

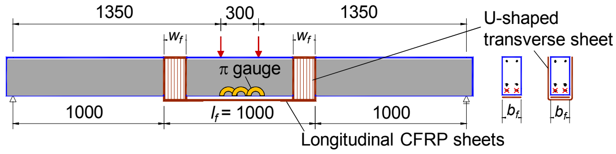

Fig. 2 Attaching layout of CFRP sheets (unit: mm)

Table 2 Material properties

Concrete	Prestressing strand		Steel rebar	Mortar
f'_c (N/mm^2)	f_{pu} (N/mm^2)	f_{py} (N/mm^2)	f_y (N/mm^2)	f'_m (N/mm^2)
55	1,894	1,722	370	50.2

f'_c: compressive strength of concrete; f_{pu}, f_y: ultimate and yield strengths of prestressing strand; f_y: yield strength of steel rebar; f'_m: compressive strength of mortar

that the two lower prestressing strands were exposed and cut after concrete get hardened. After cutting strands, the cover concrete was filled with a high strength polymer cementitous mortar to obtain the original rectangular shape.

(2) Strengthening schemes

The experimental cases are listed in Table 1. Fig. 2 illustrates the layout of strengthened beams with externally bonded CFRP sheets. The unidirectional CFRP sheets were bonded to the bottom side of the damaged PC beams for flexural strengthening. In the table, CB denotes the undamaged beam and DB2 denotes the reference-damaged beam, which were not strengthened with CFRP sheets. The number of the longitudinal sheet layers was varied from one to five layers in cases 3 to 7. Except case 3, in the other strengthened beams, one layer of the U-shaped transverse sheets wrapped the both ends of longitudinal sheets in order to prevent debonding of CFRP sheets. The longitudinal sheet lengths were a constant value of 1000 mm, which was assumed to cover the transfer length of the ruptured strands. The names of the strengthened PC beams, for example DB2-100U-2b, indicate the damaged PC beam (DB2); the length of the longitudinal CFRP sheets in centimeter unit (100); the presence of U-shaped anchorages (U); the number of layers in the longitudinal direction (2) and the type of CFRP sheet (b). CFRP sheets were bonded to concrete surface by epoxy resin with a wet-layup procedure. After the sheets were attached, the specimens were cured in room temperature for at least seven days before the loading tests.

(3) Material properties

The material properties of concrete, prestressing strand, steel rebar and mortar are given in Table 2. The concrete mix was designed such that a mean 28-day compressive strength of 55 N/mm^2 in standard cylinder tests could be obtained.

Seven-wire prestressing strands with the nominal diameter of 10.8 mm, class A, type SWPR 7AN (JIS G3536-2008) were used for tensile reinforcement. The nominal area of a prestressing strand was 70.08 mm^2. The tensile strength and yield strength of prestressing strand were 1,894 N/mm^2 and 1,722 N/mm^2, respectively. For compression reinforcement and stirrups, the deformed bars with the nominal diameter of 10 mm and the yield strength of 370 N/mm^2 were used.

A high strength polymer cementitous mortar composed of a premix of cement, fine aggregate, fibers and additives blended with a urethane-based polymer liquid was used as a patching material for section restoration. The design 28-day compressive strength of the mortar was 50.2 N/mm^2.

The CFRP sheet with 0.111 mm thickness was employed in DB2-100-1. In the other strengthened cases, the thickness of one CFRP sheet layer was 0.333 mm, so called type "b". The tensile strength and Young's modulus of CFRP sheets were 3,400 N/mm^2 and 2.3x10^5 N/mm^2, respectively.

2.2 Instrumentations and loading method

Before casting of concrete, the strain gauges were bonded to the prestressing strands in terms of measuring strains before, after cutting and during the loading test. In Fig. 1, the solid rectangles denote the locations where strain gauges were attached to prestressing strands. There were six locations where strain gauges were attached in cut strands and two locations in uncut strands. At each location, three strain gauges were attached on the three different wires. The strain at one location was taken the average value obtained from these three measurements.

Four linear variable differential transducers were set at the midspan and two supports to measure the beam deflection. In addition, the strain gauges were attached to top fiber of concrete at mid span and along CFRP sheets in order to obtain the compressive strain in concrete and tensile strains in CFRP sheet. Crack openings in the constant moment region were measured using π-gauges. The specimens were subjected to a static four-point bending using 1000 kN loading machine. All of the measurements were recorded through a data logger. Moreover, the crack propagations were marked with the applied load during the loading process.

3. RESULTS AND DISCUSSIONS

3.1 Flexural capacity and utilization of CFRP sheets

Table 3 summarizes the experimental outcomes including the ultimate loads, the failure modes, compressive strain in concrete and tensile strain in CFRP sheets at midspan at ultimate loads. First, the ultimate load was reduced from 142.6 kN in CB to 66.7 kN in DB2. In other words, in DB2, the rupture of two strands, which is equal to 50% of strand area in CB, resulted in a reduction of ultimate load by 53.2% compared to the undamaged one. Second, as can be seen from the figure, the ultimate load was restored up to 130.5 kN (91.5%) of that of CB when three layers of CFRP sheets were bonded to the damaged beam. Furthermore, up to three layers of CFRP sheets bonded, the increment of the ultimate loads was accompanied by the increase in number of layers. Nevertheless, the results of the beams strengthened by four and five layers did not follow the same tendency. The ultimate loads of those specimens exhibited a slight decrease from that of the beam strengthened with three layers.

Regarding the values of tensile strain of the bonded CFRP at midspan (Table 3), it is clear that in DB2-100-1, the only one layer of CFRP sheet utilized almost its strength to the beam capacity. The strain in CFRP sheet at midspan was 14,148x10^{-6}, about 96% of the rupture strain of the CFRP sheet (ε_{fu}=14,782x10^{-6}). However, the results implied that the bonded CFRP sheets were underutilized in the other strengthened PC beams. The strains in CFRP sheets at midspan section became smaller when the greater amount of CFRP sheets was provided.

3.2 Failure modes and deformation responses

Fig. 3 illustrates the relationship between the load and deflection responses of the PC beams strengthened by different number of layers in comparison to CB and DB2. As given in Table 3, the undamaged PC beam (CB) failed due to crushing of concrete in compression zone while the prestressing strand did not yield. This failure was of brittle nature as a sudden drop of the load carrying capacity. The damaged PC beam (DB2) failed in flexural tension, the strand yielded prior to concrete crushing. Thus, DB2 exhibited a ductile behavior.

Among the strengthened PC beams, DB2-100-1 showed the smallest deflection at the ultimate load. The load-deflection curve of this specimen represents a sudden failure with a substantial reduction of load capacity. At this point, the delamitation of CFRP sheet explosively occurred from the midspan towards the end of the bonded sheet. Since the internal prestressing strands yielded, the load carrying capacity was dropped to the same level as that of DB2 in which the strands yielded. Meanwhile, the compressive strain in the top fiber of concrete in DB2-100-1 was still far less than the ultimate strain of concrete (Table 3), which was assumed to be 3,000x10^{-6}. Similarly, in the beam strengthened by two layers of CFRP sheets (DB2-100U-2b), a drop in the load took place at the instant of the sheet debonding. It was noticed that the debonding of the bonded sheets was initiated from the flexural crack in the constant moment region and propagated toward the sheet end (Fig. 4). As the internal prestressing tensile strands were yielded before the debonding of CFRP sheets occurred in DB2-100U-2b, the member stiffness was reduced.

Table 3 Ultimate loads and failure modes

Name	$P_u^{(exp)}$ (kN)	ε_u' (x10^{-6})	ε_{CFRP} (x10^{-6})	Failure modes
CB	142.6	2,733	-	CC
DB2	66.7	2,828	-	SY/CC
DB2-100-1	82.4	2,276	14,148	IC
DB2-100U-2b	122.6	2,886	7,037	IC
DB2-100U-3b	130.5	2,137	5,056	ED
DB2-100U-4b	129.0	3,148	3,658	ED
DB2-100U-5b	119.14	1,735	2,680	ED

$P_u^{(exp)}$: ultimate load in experiments; ε_u': compressive strain in top fiber of concrete at midspan at ultimate load; ε_{CFRP}: tensile strain in the bonded CFRP sheets at midspan at ultimate load; CC: concrete crushing; SY: strand yielding; IC: intermediate crack induced debonding; ED: debonding from the end of bonded sheets.

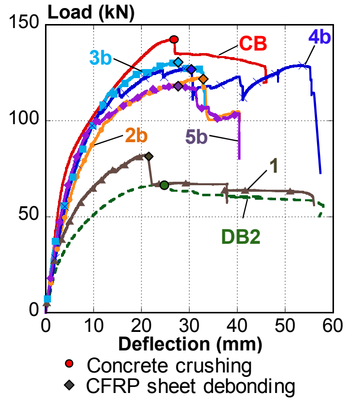

Fig. 3 Load-deflection curves

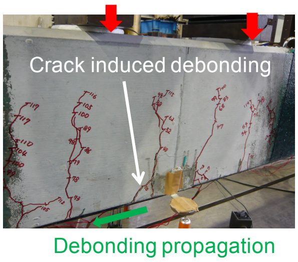

Fig. 4 Debonding in DB2-100-2b

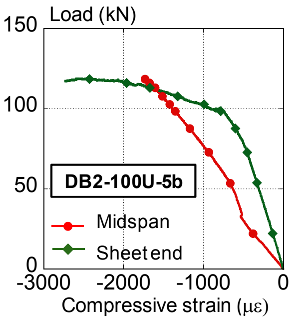

Fig. 5 Compressive strain in top concrete

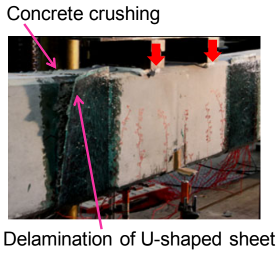

Fig. 6 Post-peak behavior in DB2-100U-5b

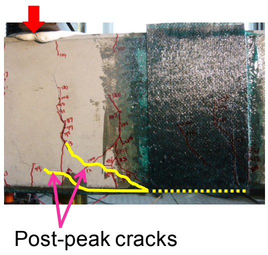

Fig. 7 Debonding crack in DB2-100U-4b

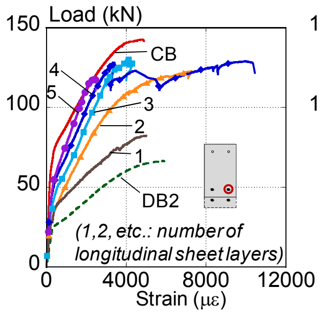

Fig. 8 Load-strain increment in uncut strand at midspan

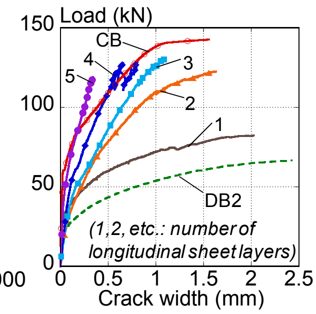

Fig. 9 Load-crack width responses

Hence, the deflection in DB2-100U-2b was much larger than that of DB2-100-1. Besides, the yielding of tensile strands led to the rapid increase in compressive stress in the top fiber, even though the increment of the load carrying capacity was small.

Interestingly, in the PC beams strengthened with more than two layers, the critical sections were shifted to the portions near the sheet ends because the debonding initiated from the end of the bonded sheets. The beams strengthened by three and five layers exhibited a nearly similar behavior and failure mode, except the ultimate load was higher in DB2-100U-3b than that in DB2-100U-5b. In these strengthened PC beams, the loads gradually increased accompanied by the formations of cracks spreading from constant moment region to shear spans. On further loading, the flexural cracks formed and opened at the ends of the bonded sheets led to the decrease in the flexural rigidity. Consequently, the beams exhibited a large deformation while the load rose slowly. Since the bonded sheets were debonded from the end portions, the CFRP sheets stopped carrying tensile stress at the sections near the sheet ends. Thus, it was supposed that the tensile stress at this portion was resisted by only the internal prestressing strands. The strengthened beams, then, failed when the concrete at the top fiber of the section near the sheet ends crushed. Fig. 5 gives evidence that the concrete strain in the top fiber of concrete was greater at the portion near the sheet end than that at the midspan. The crushing of concrete occurred within the portion where the sheets were bonded and the U-shaped anchorage sheets were delaminated in the post-peak loading (Fig. 6). Hence, the load significantly declined in the post-peak region of load-deflection curves of the specimens DB2-100U-3b and DB2-100U-5b.

Apart from the previous two cases, the performance of the beam bonded with four layers of CFRP sheets was more complicated (Fig. 3). Until the first drop in the load-deflection curve, which was owing to the debonding of CFRP sheets from the sheet ends, the behavior of DB2-100U-4b was similar to the PC beams strengthened by three and five layers. Immediately after the drop, the internal prestressing strands accelerated to grow in the response to a sudden increase of tensile stress. Subsequently, the load again went up slowly. The crack initiated from the sheet end propagated towards the nearest loading point and linked to the flexural crack as shown in Fig. 7. The occurrence of these cracks not only reduced the flexural stiffness of the section near the loading point but also discontinued the effectiveness of the bonded sheets at this portion. As a consequence, the section near the loading point became critical followed by the increase in both tensile strain in prestressing strands and compressive strain in concrete at the top fiber. Finally, the specimen failed when the concrete was crushed in the constant moment region, near the loading point. The compressive strain in top fiber of concrete at midspan approximately reached the ultimate strain of concrete in DB2-100U-4b, whereas those of DB2-100U-3b and 5b were still far less than this value as shown in Table 3.

From the above discussion, although the ultimate loads were enhanced in the strengthened PC beams, the premature bond failures restricted the full utilization of CFRP sheets to the flexural capacity of the strengthened beams. More importantly, the debonding of CFRP sheets tended to change from the debonding induced by cracks in the constant moment region to the debonding initiated from the ends of the bonded sheets when the amount of CFRP sheets was increased. Therefore, to maintain the composite action in case of a great amount of CFRP sheets bonded, the prevention of debonding from the end of CFRP sheets is necessary.

3.3 Effects of number of CFRP sheet layers on tensile strain in uncut prestressing strands and crack widths in constant moment region

Fig. 8 provides the relationship between the applied load and the increment of tensile strains which were measured at the midspan of the uncut prestressing strand. The increase in the amount of CFRP led to the decrease in the tensile strains of the prestressing strands. The development of tensile strains exhibited a significant improvement in case the beams strengthened by two layers of CFRP sheets compared to the one bonded with one layer due to the difference of the thickness of the CFRP sheet layers. When the thicker CFRP sheet was used, the total thickness of CFRP sheets in case of two layers was 6 times greater than the thickness of the sheet in case of one layer of CFRP sheet was bonded to the damaged beam.

Fig. 9 compares the opening of the flexural cracks in constant moment region in corresponding to the applied load. There is a clear trend of deceasing in the widths of the cracks at certain load levels. Owing to the effect on reducing the tensile stress in the prestressing strands, the widths of the cracks were well restrained and became smaller when the larger amounts of CFRP sheets were bonded.

3.4 Loss of stress in cut prestressing strands

Concerning the ruptured strands, it is important to determine the response of the strands after rupture. Fig. 10 illustrates the behavior of the prestressing strands before, after the cutting of prestressing strands and at the ultimate loads. The vertical axis indicates the strain, while the horizontal axis shows the location of the gauges from the middle of span. "Zero" corresponds to the midspan. Clearly, the prestressing strains were dropped in a certain length after cutting. This length was assumed to be similar to the required length to transfer the effective stress to concrete when the bonded prestressing strands were pre-tensioned with the starting point at the edge of concrete portion. Thus, the length in which the prestressing stress was lost due to rupture of strand can be predicted based on the equation given by ACI-318 [5]:

$$l_{tr} = 0.0476 f_{pe} d_b \quad (1)$$

Where,
l_{tr}: transfer length (mm)
f_{pe}: effective stress in prestressing strand (N/mm^2)
d_b: diameter of prestressing strand (mm)

The calculated values of the transfer lengths are shown in Table 4. The blue dashed lines in Fig. 10 illustrate the calculated values and the horizontal arrows indicate the length of the bonded CFRP sheets. In comparison to the actual behavior of the strands, except DB2-100U-5b in which the effective stress was obtained within the calculated length; in the other cases, the reduction of the prestressing stress was likely taken place further than the calculated transfer length. Possibly, the other factors affecting the transfer lengths like compressive strength of concrete, concrete cover have not been reflected in Eq. (1). Hence, determination of the length, which the prestressing stress is lost when the strand is ruptured, has been still conservative.

Importantly, the tensile strains in the cut strands did not increase noticeably at the ultimate load in the beams strengthened with two to four layers. It is apparent that even in the high moment region, the contribution of the ruptured strands in carrying the tensile stress was very slight. Furthermore, in DB2-100U-5b, at the ultimate load, the strains show significant reductions from the values at the level after cutting, especially at the location near the end of the bonded sheets. There was a possibility that in this specimen, under bending, the slip of the cut strands reduced the bond strength between the prestressing strands and concrete, hence, decreased stress in the strands.

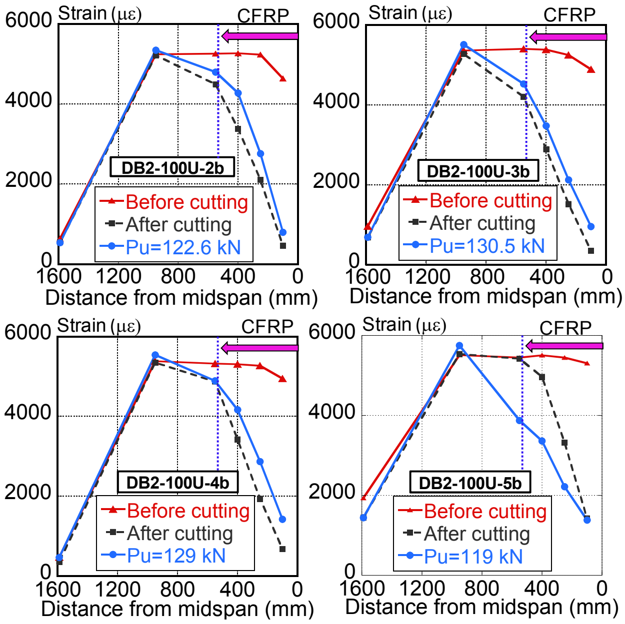

Fig. 10 Loss of stress in the cut strands

Table 4 Assumed transfer length

Name	f_c' (N/mm^2)	d_b (mm)	f_{pe} (N/mm^2)	$l_{tr}^{(ACI)}$ (mm)
DB2-100U-2b	54.4	10.8	997	513
DB2-100U-3b	54.4	10.8	1007	518
DB2-100U-4b	54.4	10.8	1025	527
DB2-100U-5b	59.5	10.8	1034	532

3.5 Failure mechanism

The differences in the debonding failures of the strengthened beams, as discussed in the section 3.3, can be explained by an interfacial stress model shown in Fig. 11. This figure shows the stresses acting in a concrete element near the interface between concrete and bonded sheets. The element is subjected to interfacial shear stress (τ), interfacial normal stress (σ_y), and the tensile stress (σ_x). When the tensile stress at the bottom of concrete section is computed from a bending moment at a considered section, the interfacial stresses are typically high at the end of the bonded sheets. According to previous studies, the interfacial stresses are highly related to the distance between a support and the sheet end, elastic modulus and thickness of the bonded plate, elastic modulus of the adhesive layers and concrete compressive strength [6, 7]. Once the principal stress, that is the combination of three stress components, exceeds the strength of the weakest element, the debonding occurs.

As shown in Fig. 12, when the small amount of CFRP sheets was bonded in the specimens (e.g. two layers), the strands yielded at the middle of the span leading to the widening of flexural cracks in constant

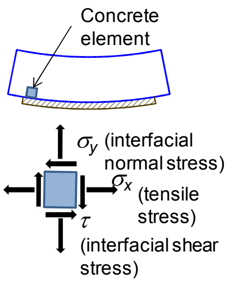

Fig. 11 Stresses on a concrete element

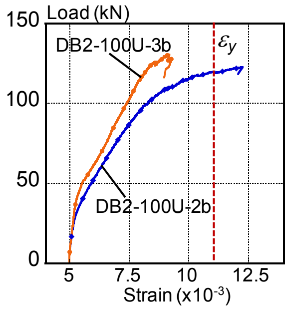

Fig. 12 Comparison of tensile strains in strands

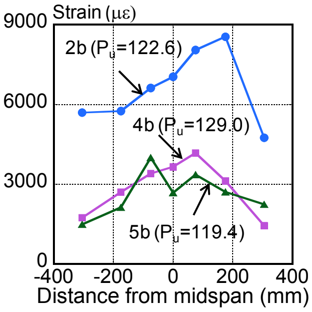

Fig. 13 Distributions of strains along CFRP sheets

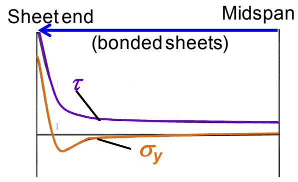

Fig. 14 Typical distribution of interfacial stresses

moment region. The widening of the cracks accelerated a rise in shear and normal stresses at the interface between concrete and the bonded sheets, then induced the debonding from the crack mouth towards the support. As shown in Fig. 13, the tensile strains in the bonded sheets reached the maximum values at the location near crack mouths. The strains in case of two layers were bonded were much higher compared to the others. Also, the shear stress which was caused by the gradient in the tensile strains raised as the crack opened. In contrary, when the larger amount of CFRP sheets was bonded (e.g. three layers), the tensile strain in the remaining strands did not reach the yield strain, hence, the interfacial stresses did not rise at the middle of the span. However, the debonding was initiated from the end of the bonded sheets because of high concentration of the interfacial stresses (Fig. 14 [8]). Moreover, in the experiments, the curtailments of the bonded sheets were located within the length in which of prestressing stresses were reduced due to the strands ruptures. From this point of view, the debonding from the end of the bonded sheets in this study can be explained by the concentration of the stresses near the sheet ends, which referred to the total thickness of the bonded CFRP sheets and the curtailments of the bonded sheets located in high shear and moment regions.

4. CONCLUSIONS

The externally bonded CFRP sheets show an effective performance in the recovery of the flexural capacity of the PC beams having ruptured strands. The ultimate load was recovered up to 91.5% of that of the undamaged PC beam. Since the bonded CFRP sheet participated in carrying the tensile stress, the crack widths in the constant moment region are controlled and the tensile strains in the remaining prestressing strands become smaller at the same loads associated with the increase in the number of layers of the sheets. However, when a large amount of CFRP sheets was bonded, the premature debonding failure occurred resulting in the underutilization of CFRP sheets.

The failure modes tended to change from the debonding induced by flexural cracks to the debonding from the sheet ends when the PC beams having ruptured strands were strengthened with larger amount of CFRP sheets. The debonding from the ends of the longitudinal CFRP sheets was caused by high stress concentration near the sheet ends, which was due to large amount of the bonded CFRP sheets and high shear and moment at the curtailments of CFRP sheets. Therefore, to employ the strength of CFRP sheets with a large amount of CFRP sheets effectively, when increasing the number of layers, a sufficient sheet length needs to be taken into account.

In addition, in the ruptured strands, the prestress is lost within a certain length from the edge of concrete. Furthermore, the contribution of the ruptured strands in resisting tensile stress during the loading is slightly small. Hence, the loss of prestressing stress in the ruptured strands is an important key to consider the sufficient lengths of the provided sheets that needs to be further investigated.

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