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# Performance of Pretensioning Prestressed Concrete Beams with Ruptured Strands Flexurally Strengthened by CFRP Sheets

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## ABSTRACT

This paper presents the effects of flexural strengthening method for PC beams having ruptured strands using CFRP sheets. CFRP sheets with different lengths and number of layers were externally bonded to the damaged PC beams. The flexural capacity of the strengthened beam was recovered up to 91.5% of that of the original one. The increase in the sheet lengths improved the member stiffness. The strains in the remaining prestressing strands were reduced and the openings of flexural cracks in the constant moment region were well restrained with the increase in number of layers. Moreover, amount of the bonded sheets affected the failure modes. The failure modes changed from debonding induced by flexural cracks to debonding from the sheet ends when number of layers was greater than two. The predicted flexural capacities based on ACI 440.2R-2008 tended to overestimate because the end debonding failure was not able to predict.

**Keywords.** Flexural strengthening, prestressed concrete beam, ruptured strands, externally bonded CFRP sheets

## INTRODUCTION

Prestressed concrete (PC) has been shown to be an advantageous concrete technology with high performance as high strength, durability, low cost and small section. Since the first introduction in 1950s, PC has been used widely in over the world, especially for long span bridge girders. Because of the structures' ages or new requirements in upgrading the service loads, many PC bridges are considered to be repaired and strengthened. Besides, there has been a concern for the deterioration of PC girders in many countries in recent years. One of the most severe cases is the rupture of strands or tendons because of chloride attacks or external impacts. The severe damages lead to the reduction of load bearing capacity and affect the beam behaviour. These damages required not only an emergency structural inspection but also a practical repair and strengthening. Many conventional methods may be adopted to address the problems including the replacement of girders, repairing and strengthening methods using internal splices, external post-tensioning tendons or steel plate jackets (Harries, 2009). Nevertheless, the implements of those methods consume much time, labours and on the other hand, the repairing and strengthening materials themselves may not be prevented from future corrosion.

In recent years, carbon fiber reinforced polymer (CFRP) sheets have taken the advantage of the conventional materials in retrofitting reinforced concrete (RC) structures. The benefits of CFRP sheets include high strength, light dead load added to the existing structures, high resistance to corrosion, easy implement without requirements of heavy equipments, large space and short construction time. For flexural strengthening, CFRP sheets are bonded to concrete surface at the tension side in order to enhance the load capacities, reduce the crack widths, deflections, and decrease the stress in internal steels. Many studies have focused on the application of CFRP sheets in flexural strengthening of RC structures. So far, however, there has been little discussion about the effects of flexural strengthening of pretensioning PC beams having ruptured strands using externally bonded CFRP sheets. Hence, this study aims to evaluate the effects of externally bonded CFRP sheets on flexural strengthening of pretensioned PC beams having ruptured strands. The experimental parameters were the lengths of CFRP sheet, the presence of U-shaped anchorages and the number of CFRP sheet layers. Furthermore, this study compared the experimental results with the predicted values based on ACI guidelines (ACI 440.2R-2008).

## OUTLINE OF THE EXPERIMENT

**Details of specimens.** The pretensioning PC beams having a rectangular cross-section of 150 mm wide by 300 mm height and 3300 mm long were prepared. First, the prestressing strands were set and an initial stress of 1075 N/mm$^2$ was provided. Then, high early strength concrete was cast. After the concrete hardening, the jacking pressure was released and the prestressing force transferred from the strands to concrete by the bond between them. The reinforcement arrangements of the specimens are shown in Fig. 1. Four of seven-wire prestressing strands of 10.8 mm diameter, whose cross-section area was 70.08 mm$^2$, were used as tensile reinforcement. The deformed bar stirrups of 10 mm nominal diameter were provided to prevent the shear failure. Specimens were classified into three types: a control beam (CB); beams with one cut strand (DB1) and beams with two cut strands (DB2). In order to simulate the damage status, in the damaged beams, the prestressing strands were cut at the middle of the span. The concrete sections, then, were restored to the original rectangular shape using a high strength polymer cementitious mortar. The 28-day compressive strength of mortar was 58.2 N/mm$^2$. In Fig. 1, the solid blue 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 wires. The strain at one location was taken as the average value obtained from these three measurements. The designed material properties of the specimens are given in Table 1.

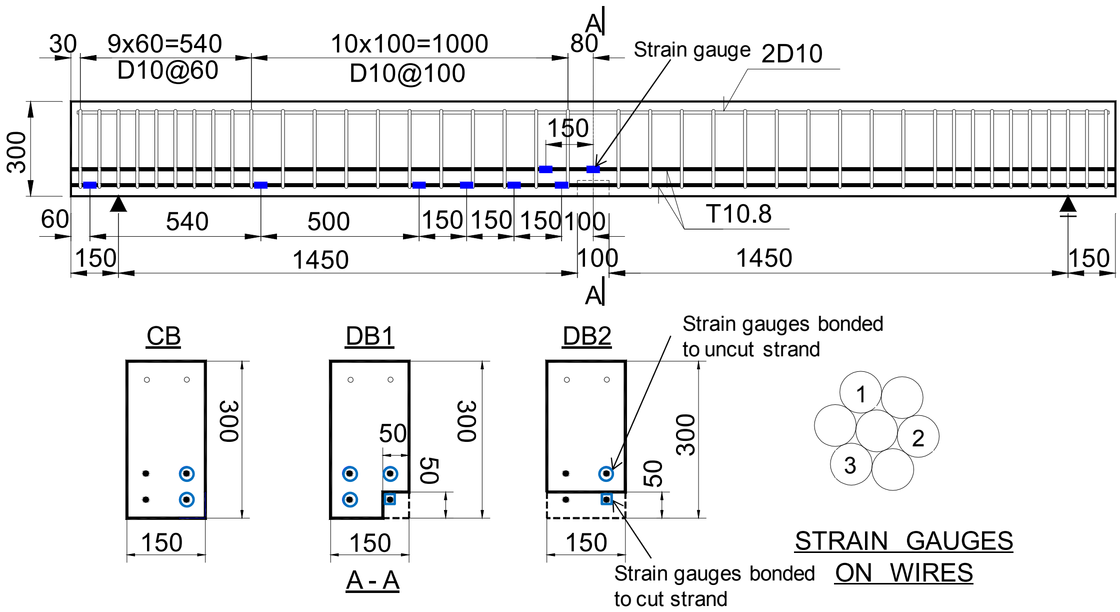


**Figure 1. Arrangement of reinforcing bars and internal strain gauges (Unit: mm)**

**Table 2. List of the experimental cases**

| No. | Name | CFRP $t_f$ (mm) | $n_f$ | $b_f$ (mm) | $l_f$ | $w_f$ |
|---|---|---|---|---|---|---|
| 1 | CB | - | - | - | - | - |
| 2 | DB1 | - | - | - | - | - |
| 3 | DB2 | - | - | - | - | - |
| 4 | DB1-100 | 0.111 | 1 | 125 | 1,000 | - |
| 5 | DB1-200 | 0.111 | 1 | 125 | 2,000 | - |
| 6 | DB1-284 | 0.111 | 1 | 125 | 2,840 | - |
| 7 | DB1-100U | 0.111 | 1 | 125 | 1,000 | 180 |
| 8 | DB2-100 | 0.111 | 1 | 125 | 1,000 | - |
| 9 | DB2-100U-2b | 0.333 | 2 | 125 | 1,000 | 180 |
| 10 | DB2-100U-3b | 0.333 | 3 | 125 | 1,000 | 180 |
| 11 | DB2-100U-4b | 0.333 | 4 | 125 | 1,000 | 180 |
| 12 | DB2-100U-5b | 0.333 | 5 | 125 | 1,000 | 180 |

*$t_f$: thickness of CFRP sheet; $n_f$: number of layers of longitudinal CFRP sheet; $b_f$: width of longitudinal CFRP sheet; $l_f$: length of longitudinal CFRP sheets; $w_f$: width of transverse CFRP sheet*

**Table 1. Material properties**

| Concrete | Prestressing strands | | Steel |
|---|---|---|---|
| $f'_c$ (N/mm$^2$) | $f_{pu}$ (N/mm$^2$) | $f_{py}$ (N/mm$^2$) | $f_y$ (N/mm$^2$) |
| 55 | 1,720 | 1,460 | 295 |

*$f'_c$: compressive strength of concrete; $f_{pu}$: ultimate tensile strength of prestressing strands; $f_{py}$: yield strength of prestressing strands; $f_y$: tensile strength of steel bar*

**Table 3. Properties of CFRP sheets**

| Type | $t_f$ (mm) | $f_{fu}$ (N/mm$^2$) | $\varepsilon_{fu}$ (mm/mm) |
|---|---|---|---|
| a | 0.111 | 3,400 | 0.0148 |
| b | 0.333 | 3,400 | 0.0148 |

*$f_{fu}$, $\varepsilon_{fu}$: ultimate tensile strength and rupture strain*

**Experimental cases.** A total of 12 specimens were tested, which were divided in three categories: reference beams (cases 1-3), series 1 (cases 4-7) and 2 (cases 8-12). The experimental cases are listed in Table 2. Figure 2 illustrates the layout of strengthened beams with the externally bonded CFRP sheets. In series 1, one layer of CFRP sheet with different lengths was attached to the bottom of the PC beams in which 25% of prestressing strands

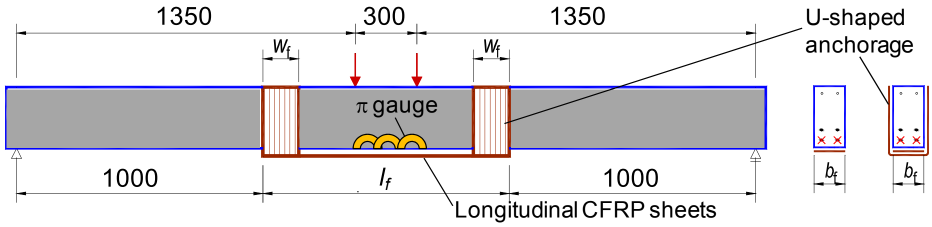


**Figure 2. Layout of externally bonded CFRP sheets (Unit: mm)**

were cut. Additionally, in case 7, one layer of the U transverse CFRP sheets were provided at both ends of the longitudinal CFRP sheet.

In the second series, the damaged beams having 50% of strands ruptured were strengthened with the different number layers of CFRP sheets. The number of layers was varied from one to five. The widths and lengths of CFRP sheets were constant values of 125 mm and 1000 mm, respectively. In addition, one layer of U-shaped anchorages were provided in all the cases of series 2.

The unidirectional CFRP sheets were bonded to the bottom of the beams by wet-layup method with fibers oriented along the longitudinal axis of the beams. The properties of CFRP sheets are given in Table 3. After 7-day curing time, the specimens were tested to failure.

## EXPERIMENTAL RESULTS

**Loss of capacity due to rupture of strands.** Figure 3 shows the load-deflection curves of the damaged beams in comparison to CB. As can be seen, loss strand areas of 25% in DB1 and 50% in DB2 led to the reduction of 25% and 53% of the ultimate loads, repectively. The cracking loads were also decreased from 62 kN in CB to 52 kN in DB1 and 25 kN in DB2. It is certain that the reduction of flexural capacity is associated with the loss of strand areas. Also, the significant changes in the slopes of the curves indicating the member stiffness in pre-cracking and post-cracking regions were decreased when the strands were ruptured.

### Effects of the CFRP sheet lengths and U-shaped anchorages

***Capacities and stiffness.*** Figure 4 demonstrates the load-deflection curves of the PC beams having one cut strand (DB1) strengthened by CFRP sheets with different lengths and providing U-shaped anchorages. As can be seen from the figure, the specimens showed linear elastic behaviors up to the cracking points. These points illustrate the loads when the first crack initiated in the constant moment region. After the cracking points, the curves became nonlinear as numerous flexural cracks formed in shear spans. From experimental data given in Table 4, the initial stiffness was improved with increasing the sheet lengths. Particularly, when the full length of span was bonded with CFRP sheet the initial stiffness went up to 110% (DB1-284) of that in CB. The load capacities of the damaged PC beams strengthened by one layer of CFRP sheet were enhanced as far as 13% compared to DB1. Nevertheless, increasing the sheet lengths did not show a noticeble effect on the ultimate loads.

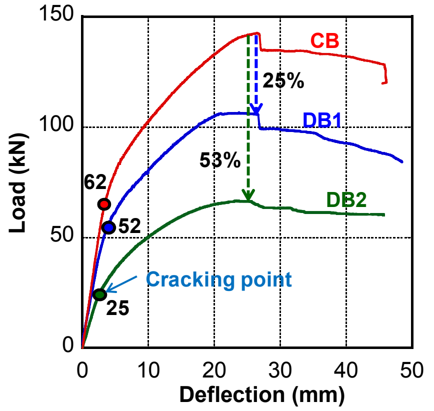


**Figure 3. Load-deflection curves of reference beams**

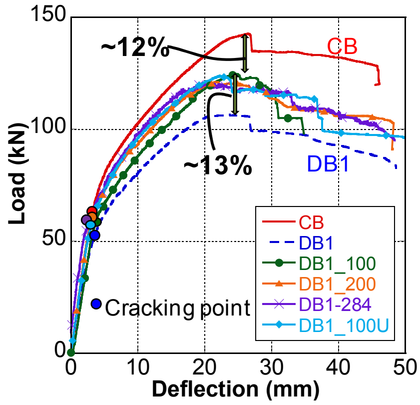


**Figure 4. Load-deflection curves of beams strengthend with different sheet lengths**

***Tensile strains in the remaining prestressing strands.*** Figure 5 provides the relationship between the applied load and the increment of tensile strains in remaining prestressing strands, which was circled in red color. The location of strain gauges was at middle of the beam span. This graph reveals the effect of the bonded CFRP sheets on reducing the tensile strains in the remaining prestressing strands. Since the bonded CFRP sheets participated in carrying the tensile stress with the internal prestressing strands in the strengthened beams, the increment of tensile strains of the remaining prestressing strands was declined at the same load level.

## Effects of the number of layers of bonded CFRP sheets

***Capacities and stiffness.*** Table 5 summarized the load carrying capacities and the stiffness of the strengthened PC beams in series 2. There was a recognizable effect of the number of layers on the cracking loads of strengthened beams. The cracking load significantly reduced from 62.3 kN in CB to 25.0 kN in the damaged beam (DB2). With larger number of layers, the strengthened beams performed higher cracking loads and initial stiffness. As can be seen, in the beam strengthened with five layers of CFRP sheets, the cracking load was restored to

**Table 4. Effect of sheet lengths and U-shaped anchorages**

| Name | $P_{cr}$ (kN) | $P_u$ (kN) | $P_u/P_u^{CB}$ | Initial stiffness (kN/mm) |
|---|---|---|---|---|
| CB | 62.3 | 142.6 | - | 20.36 |
| DB1 | 52.0 | 106.5 | 0.75 | 16.49 |
| DB1-100 | 59.0 | 124.7 | 0.87 | 19.10 |
| DB1-200 | 60.8 | 121.1 | 0.85 | 20.95 |
| DB1-284 | 59.6 | 120.2 | 0.84 | 22.31 |
| DB1-100U | 57.9 | 123.8 | 0.87 | 20.31 |

*$P_{cr}$, $P_u$: cracking and ultimate load*

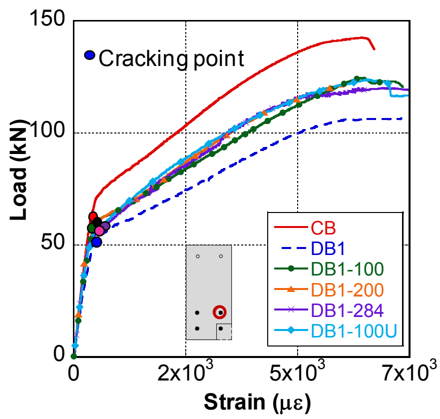


**Figure 5. Load-strain increment in remaining strands**

**Table 5. Effect of number of sheet layers on capacities and stiffness**

| Name | $P_{cr}$ (kN) | $P_u$ (kN) | $P_u/P_u^{CB}$ | Initial stiffness (kN/mm) |
|---|---|---|---|---|
| CB | 62.3 | 142.6 | - | 20.36 |
| DB2 | 25.0 | 66.7 | 46.8% | 10.92 |
| DB2-100 | 36.2 | 82.4 | 57.6% | 11.42 |
| DB2-100U-2b | 38.5 | 122.6 | 86.0% | 13.40 |
| DB2-100U-3b | 46.0 | 130.5 | 91.5% | 13.97 |
| DB2-100U-4b | 49.0 | 129.0 | 90.5% | 14.59 |
| DB2-100U-5b | 55.0 | 119.1 | 83.6% | 16.71 |

$P_{cr}$, $P_u$: cracking and ultimate load;

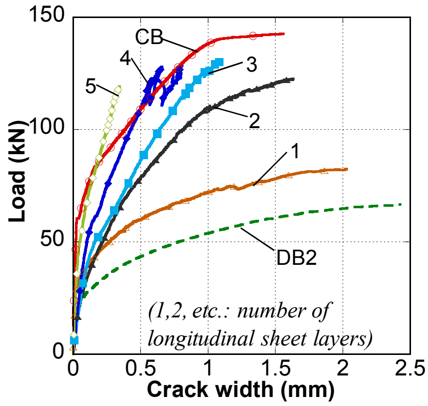


**Figure 6. Effect of number of layers on flexural crack widths**

55.0 kN equivalent to 88% of that of CB beam. Also, the initial stiffness of the strengthened beams was enhanced associated with the  increase in number of layers.

Despite of this, the strengthened beams did not provide the higher ultimate load when greater than three layers of CFRP sheets bonded. From the data in Table 5, the ultimate loads increased with increasing number of layers up to three layers. With three layers bonded, the ultimate load was recovered up to around 91.5% of CB. Nevertheless, this trend of increase in flexural capacity did not continue when the number of layers went into four and five. Evenly, the ultimate load of the beam strengthened by five layers indicated a noticeable reduction compared to that of the beam strengthened with three layers. It is likely that debonding of CFRP sheets occurred earlier in this specimen. Hence, the CFRP sheets did not effectively utilize higher strength to the flexural capacity of the beams.

***Crack widths and tensile strains in the remaining prestressing strands.*** Figure 6 illustrates the relationship between the applied load and the widths of the flexural cracks in the constant moment regions measured by π-gauges. It was certain that the openings of the cracks at midspan were well restrained and became smaller with the greater number of CFRP sheet layers.

The relationship of the applied load and the increment of the tensile strains at midspan of the remaining prestressing strands (red circle) is shown in Fig. 7. In the figure, there is a clear trend of decreasing in tensile strains of the prestressing strands when the number of CFRP layers was increased. The findings show that with greater amount of CFRP sheets participating in carrying the tensile stress, the proportion of tensile stress carried by prestressing strands became smaller at the same load level. Likely, the yielding loads of the internal prestressing strands are profited from the attaching of the larger amount of CFRP sheets. Figure 8 provides an evidence of the increasing the yielding loads. This figure compares the tensile strain (with consideration of pretensioning stress) at midspan of the remaining strands in the beams strengthened by two and three layers of CFRP sheets. It can be seen clearly, while the strain in DB2-100U-2b reached the yielding strain ($\varepsilon_y$) of prestressing strand, the strain in DB2-100U-3b was still far from this value.

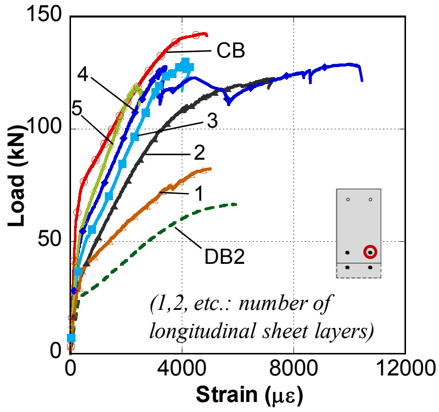


**Figure 7. Effect of number of layers on increment of strains in remaining strands**

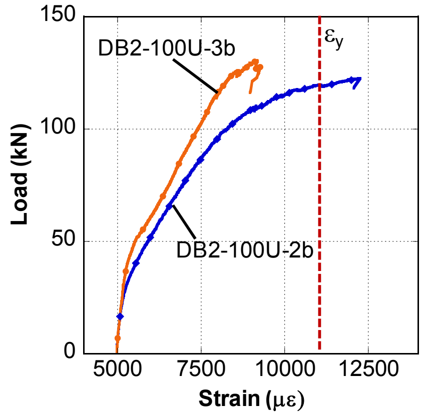


**Figure 8. Comparison of tensile strains in remaining strands**

***Failures of composite actions.*** The critical sections in the strengthened PC beams were shifted from the constant moment region to the portion near the sheet ends when the amount of the bonded sheets was increased. When the PC beam was strengthened with two layers of CFRP sheets, debonding was initiated by the flexural cracks and propagated from midspan towards the end of the longitudinal sheets as shown in Fig. 9. The behaviors, however, were different when the beams were bonded with more than two layers. Figure 10 detailed the general behaviors in the beams strengthened by more than two layers of CFRP sheets. First, the flexural cracks were generated in the constant moment region. After that, as the load gradually increased, the cracks were formed in the shear span, from the loading points to the end of the bonded CFRP sheets. After the cracks at the ends of the bonded sheets opened (Fig. 10(a)), the beam stiffness was reduced and the increase in the load became slow. Figure 10(b) shows the debonding of the longitudinal sheets initiated from the sheet end in DB2-100U-4b, in which the solid yellow lines represent the cracks observed after the peak load. Since the debonding occurred at the end of the CFRP sheets, the sections near the end of the sheets became critical. The debonding between the bonded CFRP sheets and concrete, then, was followed by the crushing of concrete at the top fiber of the section near the sheet end as shown in Fig. 10(c). Finally, the U-shaped anchorages were delaminated from the top of section. Generally, the failures due to debonding of CFRP sheets are brittle because the CFRP sheets abruptly terminated carrying the tensile stress.

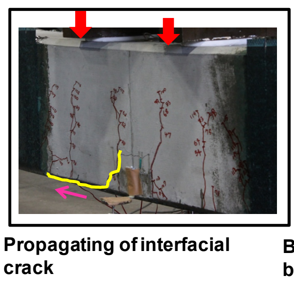


**Figure 9. Debonding in DB2-100U-2b**

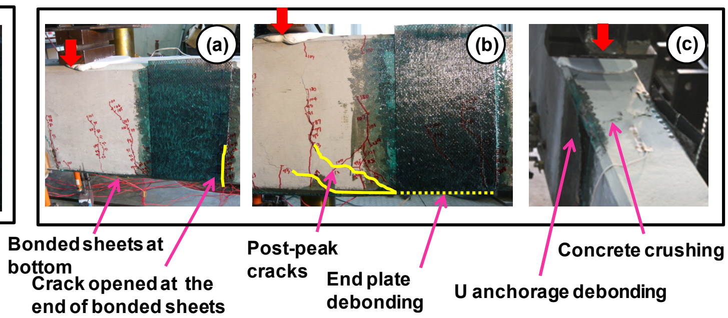


**Figure 10. General behaviour of beams strengthened with greater than two layers**

The differences in the failures of the strengthened beams can be explained by an interfacial stress model as shown in Fig. 11. Figure 11(a) introduces the stresses acting in a concrete element near the interface between concrete and bonded sheets. The element is subjected to interfacial shear stress ($\tau$), interfacial normal stress ($\sigma_y$), and the tensile stress ($\sigma_x$). When the tensile stress at the bottom of concrete section is due to a bending moment at a considered section, the typical distribution of interfacial stresses is given in Fig. 11(b). The interfacial stresses shows the high concentration 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 (Sayed-Ahmed et al., 2009 and Smith et al., 2001). Once the combination of three stress components exceeds the strength of the weakest element the debonding occurs.

Turning now to the experimental evidences on the failure modes, they were accompanied by the behaviors of the remaining prestressing strands previously given in Fig. 8. As can be seen, when small amount of CFRP sheets bonded (e.g. two layers), the strands yielded at the middle of the span leading to the widening of flexural cracks in constant 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. In a different manner, when larger amount of CFRP sheets was bonded (e.g. three layers), the tensile strain in the remaining strands did not reach yielding strain. Hence, the width of flexural cracks in the constant moment region remained small and interfacial stresses did not rise at the middle of the span. However, debonding was generated from the end of the bonded sheets because of high concentration of the interfacial stresses. 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. On the other hand, it is certain that the behaviors of

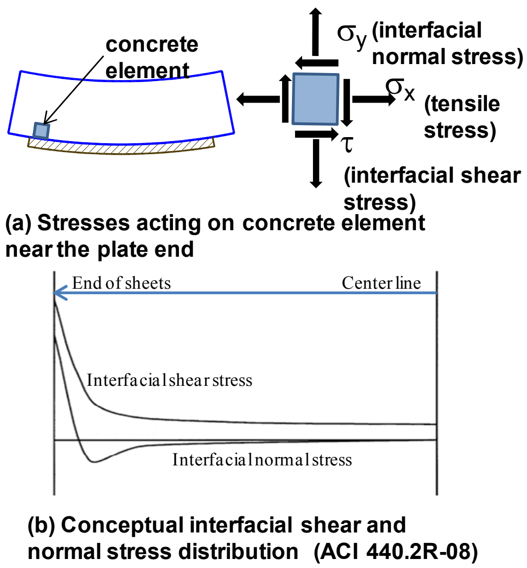


**Figure 11. Stresses in concrete element near the sheet end**

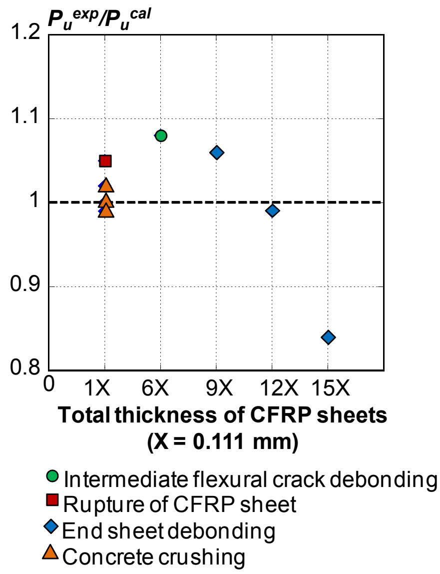


**Figure 12. Validation on the predicted capacities based on ACI guideline**

prestressing strands are highly related to the effective stress in the strands. Therefore, the effects of prestressing stress level to debonding behavior in PC beams need to be further taken into account.

## VALIDATION OF THE EQUATIONS IN THE GUIDELINES OF ACI

The recent guideline of ACI (ACI 440.2R-08) suggests computing the flexural capacities of the beams with externally bonded FRP sheets based on stress and strain equilibrium in a flexural section. The equation given for the flexural capacity of PC beams strengthened with externally bonded FRP sheets consists of two components: capacities carried by prestressing strands and fiber sheets:

$$M_n = A_p f_{ps}(d_p - \frac{\beta_1 c}{2}) + \psi A_f f_{fe}(h - \frac{\beta_1 c}{2}) \quad (1)$$

Where:
*$A_p$: area of prestressing steel*
*$f_{ps}$: stress in prestressing steel at beam failure*
*$d_p$: effective depth to centroid of prestressing steel*
*$f_{fe}$: stress in fiber sheet at beam failure*
*$A_f$: area of FRP sheets*
*$\beta_1$: ratio of depth of equivalent rectangular stress block to depth of the neutral axis*
*$\psi$: partial reduction factor, $\Psi$ =0.85*

In Eq. (1), the stress in fiber sheets at the beam failure ($f_{fe}$) is determined from the maximum strain in the FRP sheets at the sections where concrete crushes, FRP sheets are debonded or FRP sheets rupture. The effective strain of the bonded sheets in case an immediate crack-induced debonding ($\varepsilon_{fd}$) is predicted based on the empirical equation (2). In this equation, the debonding strain of the bonded sheets depends on compressive strength of concrete and properties of bonded sheets.

$$\varepsilon_{fd} = 0.418\sqrt{\frac{f_c'}{n_f E_f t_f}} \leq 0.9\varepsilon_{fu} \quad (2)$$

Where:
*$f'_c$: compressive strength of concrete (MPa)*
*$n_f$: number of FRP layers*
*$E_f$: Elastic modulus of FRP sheet (MPa)*
*$t_f$: thickness of FRP sheet (mm)*
*$\varepsilon_{fu}$: ultimate strain of FRP sheet*

Figure 12 represents the validation on flexural capacities of the strengthened PC beams between experimental data and the calculations based on ACI guidelines. The reduction factor $\psi$ = 0.85 was employed in the calculations. Even so, the calculated values were overestimated when the total thickness of CFRP sheets provided was increased, for example, in the case of four (12X) and five layers (15X) were bonded. A possible explanation for this is the differences of failure modes from the predictions. The debonding from the sheet ends occurred in the experiments; however, the recent guideline has been unable to predict the flexural capacity of the strengthened beams failed in end sheet debonding. Besides, as discussed previously, the dependence of the failure behaviours of composite actions and both the bonded sheet lengths and amount needs to be taken into account.

## CONCLUSIONS

First, the externally bonded CFRP sheets show the effective performance in improvement of the flexural capacities and the recovery of the stiffness of PC beams having ruptured strands. Moreover, since CFRP sheets participate in carrying the tensile stress with the internal prestressing strands, the crack widths are well restrained as well as the tensile strains in the prestressing strands are reduced at the same load level. When small amount of CFRP sheets are bonded, the increase in the length of CFRP sheets or providing U-shaped anchorages at the ends of the longitudinal sheets do not result in the increment of flexural capacities because the debonding induced by flexural crack is a prior failure. In spite of this, the member stiffness is enhanced associated with increasing the sheet length.

Second, the increase in the cracking loads and decrease of tensile stress carried by remaining strands are accompanied by increasing number of layers of the CFRP sheets. The ultimate load is enhanced up to 91.5% of the original beam by bonding three layers of CFRP sheets. Furthermore, the failure modes tend to change from debonding induced by flexural cracks to debonding from the sheet ends when the damaged PC beams are strengthened with greater amount of CFRP sheets. The debonding from the ends of the longitudinal CFRP sheets is caused by high stress concentration near the sheet ends which is due to (i) great amount of CFRP sheets bonded; and (ii) high shear and moment at the curtailment of CFRP sheets. Therefore, to employ the strength of CFRP sheets with a large amount of CFRP sheets effectively, sufficient lengths of CFRP sheets with increasing the number of layers need to be further studied. In addition, the existing equations in the guidelines of ACI are insufficient to predict the debonding from the ends of bonded sheets. Thus, the calculated flexural capacities of the PC beams strengthened by externally bonded CFRP sheets tend to overestimate when this failure occurs.

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