FLEXURAL STRENGTHENING EFFECT OF PRE-TENSIONED UFC PANEL ON REINFORCED CONCRETE BEAMS

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Recently, various strengthening methods have been utilized to enhance the structural performance and extend the life cycle of RC structures. However, the existing strengthening methods still have some drawbacks especially in the durability aspect. In this study, with the outstanding properties of UFC (i.e., high strength, ductility, and durability), a new flexural strengthening method using precast UFC panels was used to strengthen the RC beams. However, to obtain greater strengthening effect and durability, PC strands were pre-tensioned to the panel and this panel was subjected to a heat curing procedure to supplement a hydration procedure and eliminate the effect of shrinkage. Using this novel technology, this research was conducted to investigate the flexural enhancement and corresponding behavior of RC beams strengthened by pre-tensioned UFC panel. Five pre-tensioned UFC panels and eight strengthened RC beams were prepared and investigated using the bending test. Two different experimental parameters, i.e., prestressing level and amount of PC strands, were used. The undercut anchor bolts were applied for sufficient bonding between interfaces. The bending results of panels were investigated to compute the exact prestressing level in order to determine the calculation of prestressing losses. The results of the strengthened beams revealed that the pre-tensioned UFC panel drastically enhanced the loading capacity of RC beams, and each variable parameter affected the different structural characteristics. To ensure compatibility along a cross-section of the strengthening system, the compatibility along panel specimens and strengthened RC beams was investigated. Finally, the strain compatibility was satisfied at the mid-span of beams where the calculation of load-carrying capacity in strengthened beams could be carried out by using conventional flexural section analysis.

Key Words: pre-tensioned UFC panel, amount of PC strand, prestressing levels, undercut anchor bolt system, flexural strengthening mechanism

1. INTRODUCTION

Reinforced concrete (RC) structures have been broadly utilized to handle high-capability resistance since the 19th century. Their resistant ability, however, tended to diminish in time. To increase the efficiency of RC structures along with optimizing construction time and cost, enhancing their structural
strength and extending their usability has become necessary. Many strengthening methods, such as attaching steel plate, bonding with fiber-reinforced polymer (FRP) and external post-tensioning, have been applied to infrastructures. The existing methods can highly enhance the strength performance, but some of them still cause problems on the structural durability especially under severe environments. Therefore, the new flexural strengthening method using pre-tensioned UFC panel is proposed to enhance the high flexural strength and improve better durability simultaneously.

UFC (Ultra high strength fiber reinforced concrete) is an advanced cementitious material reinforced with short steel fibers. It was originally developed from reactive powder concrete (RPC) in 1995 by Richard and Cheyrezy\(^1\)). Combining various fine materials (i.e., cement, silica fume, and silica sand) with special water-reducing agent, UFC can be mixed with very low water-cement ratio while the uniform distribution of steel fibers still exists inside the matrix because of high flowability property\(^2\)). Regarding to the recommendation for design and construction of UFC structures (draft) by JSCE\(^3\)), the compressive strength of UFC with 2% by volume of fiber content is in excess of 150 MPa and more than 5 MPa in compressive and tensile strength. UFC can perform high flexural toughness and ductility according to the effect of steel fibers. Moreover, the close-packed structure of UFC provides excellent durability against severe environments such as chloride attack and heavy abrasion\(^4\)). From the comparison of the beam sections made by prestressed UFC and H-shaped steel to resist the same moment capacity (150 kN-m), the size and self-weight between two sections are comparable (50 kg/m)\(^5\)); but, UFC has better durability against severe environment. Thus, UFC has been applied to various infrastructures, including thin-complex and aesthetic elements, as demonstrated by structural bridges worldwide\(^6\),\(^7\)).

The performance and behavior of UFC had been studied for various structural applications. For instance, Oesterlee\(^8\)) used a cast-in-place UHPFRC, an ultra-high strength concrete with 3% fiber content, in the rehabilitation of concrete bridge slabs. A flexural test of composite RC beams overlaid by UHPFRC and steel-reinforced UHPFRC (R-UHPFRC) was conducted. The results revealed that the load carrying-capacity of RC beams reinforced by UHPFRC and R-UHPFRC could be increased by 12% and up to 165%, respectively. Even though the steel reinforcement in R-UHPFRC can highly strengthen RC beams, the durability of steel reinforcement should be considered because the internal constraints between UFC and conventional steel may induce the occurrence of shrinkage cracks or creep cracks\(^3\)). As for the application of UFC in strengthening, the UFC panels were used to strengthen the shear behavior of RC beams in many configurations. In the research conducted by Shibata et al.\(^9\)), the UFC panels were attached on both sides of RC beams, which drastically enhanced the shear capacity by 100%. However, the shear strength of the RC beam attached by UFC panel on the bottom side could be increased by only 38% due to the weaker resistance of the UFC in tension. Moreover, the bonding between concrete and UFC panel also essentially affected the strengthening performance. Thus, the new pre-cast UFC panel prestressed by PC strands was proposed to strengthen the flexural performance of RC beams as shown in Fig. 1. The applied PC strands and prestressing force enhance the tensile resistance of the UFC material and reduce the number of cracks. This concept of the pre-tensioned UFC panel is believed to improve the safety and durability of the RC structure. Moreover, to obtain bonding between the RC beam and the pre-tensioned UFC panel, the undercut anchor bolts were anchored to distribute the load between the interfaces.

To investigate the flexural performance and failure mechanism of RC beams strengthened by pre-tensioned UFC panels, two parameters were used in this research: the amount of PC strands and the prestressing level in UFC panels. Bending tests for five pre-tensioned UFC panels and eight strengthened beams were carried out to verify the actual prestressing level and examine the flexural performance of pre-tensioned UFC panel on RC beams, respectively. The strain compatibility along section of the panel and strengthened beam was confirmed by calculation. Finally, the calculation method for the loading capacity has been proposed.

2. THE FABRICATION PROCEDURE FOR PRE-TENSIONED UFC PANEL

(1) Fabrication of pre-tensioned UFC panel

First, a formwork of panel with the dimension of 150x1500x50 mm (width x length x thickness) is es-
established in a prestressing bed. PC strands are set up and tensioned through an anchorage abutment as shown in Fig. 2(a). In Fig. 2(b), PC strands are fixed before casting the UFC. Due to the high flowability of UFC around 260 mm in diameter, the casting can be achieved even in the thin-complex shape of the panel as displayed in Fig. 2(c). Afterward, primary curing is carried out; then, PC strands are cut after hardening of the UFC panel as shown in Fig. 2(d). At this stage, the transferring of initial prestressing force to the UFC panel has been completed. All pre-tensioned UFC panels are treated to secondary heat curing, which is steam curing at 90°C for 48 hours, according to the standard recommended by JSCE 3) as shown in Fig. 3. With the standardized curing method, the UFC becomes dense and provides greater strength.

Each pre-tensioned UFC panel shown in Fig. 4 has approximately 30 kg of self-weight. The effect of self-weight is insignificant to be concerned with the workability and the increase of structural weight. Due to the comparative self-weights of the UFC and steel, the means of steel plate installation can be replaced by pre-tensioned UFC panel. Moreover, the high flexural strengthening by the UFC panel is predominant as discussed in Chapter 5.

(2) Prestressing losses

Since the applied prestressing may not be constant with time and can induce prestressing loss in the UFC panel, the estimation of loss is important for obtaining the target prestressing level in the panel. Two kinds of loss were considered in this study: a shrinkage loss and an elastic shortening loss for considering the time-dependent and the immediate loss. However, for future actual construction, other kinds of long-term prestressing losses should be considered to be applied in the pre-tensioned UFC panel, such as the loss caused by the relaxation in PC strands. The details of estimated loss in this study are described as follows:

a) Loss caused by shrinkage

Autogenous shrinkage is an important phenomenon that can arise during the fabrication of the UFC. Thus, shrinkage loss is a significant factor for loss calculation, which can be calculated by Eq. (1). In this study, the applied shrinkage strain of the UFC was assumed to be 850×10⁻⁶, which was the shrinkage strain during the primary and secondary curing of the UFC conducted by Kono et al.¹⁰; the same mix proportion of the UFC and curing condition as applied in this study.

\[ \Delta f_{SH} = E_{pc} \varepsilon_{SH} \]  

where \( \Delta f_{SH} \) and \( \varepsilon_{SH} \) are the shrinkage loss and strain, respectively.

b) Loss caused by elastic shortening

This is an immediate loss affected by the transferring of initial prestress and the shrinkage stress in the UFC panel.
Table 1 Experimental cases and the applied initial prestress of pre-tensioned UFC panel.

| Name     | Series | $A_{PC}$ (mm$^2$) | $f_{UFC}$ (MPa) | $f_{PC}$ | $f_0$ | $f_{SH}$ | $f_{ES}$ | $f_{total}$ | $f_{app,PC}$ | $f_{app,UFC}$ |
|----------|--------|-------------------|-----------------|-------|------|---------|---------|-----------|-------------|-------------|
| 40PS-5   | P-I    | 40                | 5               | 950   | 5.02 | 170     | 0.90    | 23.68     | 193.68      | 1,143.68    | 6.04        |
| 103PS-5  | P-I, II| 103               | 3               | 360   | 4.95 | 170     | 2.34    | 29.16     | 199.16      | 559.16      | 7.70        |
| 139PS-3  | P-II   | 139               | 2               | 270   | 5.02 | 170     | 3.16    | 32.72     | 202.72      | 472.72      | 8.73        |
| 103PS-3  | P-II   | 103               | 7               | 3     | 220  | 0.30    | 170     | 2.34      | 21.48       | 191.48      | 411.48      | 5.66        |

$A_{PC}$: Total cross-section of PC strands, $f_{UFC}$: Target prestressing level in UFC panel, $f_{PC}$: Required prestress for each PC strand, $f_{app,PC}$: Applied prestress for each PC strand, $f_{app,UFC}$: Applied prestressing level in UFC panel computed by the transferring force from two PC strands to UFC panel, $E_{PC}$: the elastic modulus of PC strand (200×10$^3$ MPa) and $E_{UFC}$: the elastic modulus of UFC (50×10$^3$ MPa).

Based on the strain compatibility at the same level of UFC and PC strands, the varied strain in the UFC panel directly affects the changing strain in the PC strands, which also results in the elastic shortening loss in the PC strands. Therefore, the calculation of elastic shortening loss can be computed as Eq. (2)$^{11}$.

$$
\Delta f_{ES} = E_{PC} \left( \frac{f_0 + f_{SH}}{E_{UFC}} \right)
$$

where $\Delta f_{ES}$ is the stress of elastic shortening loss, $f_0$ is total initial prestress in the UFC after transfer, and $f_{SH}$ is prestress in the UFC from shrinkage, $E_{PC}$ and $E_{UFC}$ are the elastic modulus of PC strand and UFC, respectively.

### 3. BENDING TEST OF PRE-TENSIONED UFC PANELS

#### (1) Experimental parameters and specimens

Five pre-tensioned UFC panels had 50 mm of thickness and 150x150 mm of dimension as shown in Fig. 4. Three target prestressing levels were 3, 5, and 7 MPa, which were applied through three different amounts of PC strands. The experimental cases and the applied initial prestress including the losses are described in Table 1. Moreover, Fig. 5 shows the details and bolt locations of the panels.

#### (2) Materials

**a) UFC**

UFC is a cementitious material composed of premix binder, water, high-performance polycarboxylic superplasticizer, and short steel fibers. The pre-mix binder is mixed from fine materials in optimum proportion, i.e., silica fume, cement, silica fine powder, and silica sand. The steel fiber, 0.2 mm in diameter and 15 mm in length, was mixed with the proper volume fraction about 2%. The mix proportion of UFC is shown in Table 2.

**b) PC strands**

Two PC strands from each kind of tendon in Table 3 were prestressed in the UFC panels. The diameters of PC strands were 6 mm, 9.3 mm, and 10.8 mm. All strands were 3-wire and 7-wire types that corresponded to the JIS G 3536.

#### (3) Bending test of pre-tensioned UFC panel

Four-point bending test of pre-tensioned UFC panels was conducted to examine the flexural behavior and mechanical properties of the panels. The experimental results were collected to calculate the exact prestressing level and the strain compatibility.

Table 2 Mix proportion of UFC material.

| Flow (mm) | Water | Premix binder | Steel fiber | High-performance water reducing agent |
|-----------|-------|---------------|-------------|----------------------------------------|
| 260±20    | 180   | 2254          | 157         | 24                                     |

$\Phi_{PC}$: The diameter of PC strand, $f_{pc}$: Yielding strength of PC strands and $f_{pu}$: Ultimate strength of PC strands.
between the PC strand and the UFC panel. The experiment was set up as shown in Fig. 6. To simplify the beam condition, a pre-tensioned UFC panel was put on the Teflon sheet and grease at the supporting points to reduce the horizontal friction. Four LVDTs were installed to measure the relative displacement: two on both sides at the mid-span and the others at the supporting plates. Six strain gauges were attached to observe the varying strains on top of the panel. The loading tests of UFC panels were conducted by applying the displacement rate of about 0.010-0.015 mm/sec until the peak load. The same displacement rate was given after the peak load until the end of testing.

(4) Results and discussion
a) Flexural capacities
All panels showed flexural compression failure with concrete crushing on top of the panel with many fine cracks as shown in Fig. 7. The results and mechanical properties of pre-tensioned UFC panels are shown in Table 4. Regarding the greater amount of PC strands in series P-I, it drastically provided a higher loading capacity as observed from the capacities of 40PS-5, 103PS-5, and 139PS-5. On the other hand, the capacities of series P-II were slightly different as 15.73 kN, 16.97 kN and 18.20 kN in 103PS-3, 103PS-5 and 103PS-7, respectively. Thus, the amount of PC strands predominantly influences the loading capacity.

b) Initial cracking load and stiffness of panels
The first cracking load can be specified at the end of the linear relationship between the load and relative displacement of pre-tensioned UFC panels. By applying a regression analysis for the linear portion of load-displacement curve (Fig. 8), the range of experimental data that allowed the coefficient of determination ($R^2$) about 0.98-0.99 was represented.
Table 4 Experimental results and mechanical properties according to loading test of pre-tensioned UFC panels.

| Name   | \( f'_{c,\text{UFC}} \) (MPa) | \( P_{U,\text{UFC}} \) (kN) | \( P_{\text{cr,UFC,exp}} \) (kN) | \( P_{\text{cr,UFC,reg}} \) (kN) | \( R^2 \) | \( f_i \) (MPa) | Failure mode               |
|--------|--------------------------------|-----------------------------|----------------------------------|---------------------------------|----------|----------------|--------------------------|
| 40PS-5 | 194.8                          | 9.50                        | 3.55                             | 3.67                            | 0.99     | 4.87           | Flexure compression failure |
| 103PS-5| 194.8                          | 16.97                       | 3.54                             | 3.60                            | 0.99     | 4.58           |                          |
| 139PS-5| 210.7                          | 18.04                       | 3.40                             | 3.61                            | 0.98     | 4.62           |                          |
| 103PS-3| 210.7                          | 15.73                       | 2.87                             | 3.07                            | 0.99     | 2.23           |                          |
| 103PS-7| 211.4                          | 18.20                       | 4.01                             | 4.17                            | 0.99     | 7.07           |                          |

\( f'_{c,\text{UFC}} \): Compressive strength of UFC, \( P_{U,\text{UFC}} \): Load carrying capacity of UFC, \( P_{\text{cr,UFC,exp}} \): Initial cracking load of pre-tensioned UFC panel from experimental data, \( P_{\text{cr,UFC,reg}} \): Initial cracking load of pre-tensioned UFC panel from linear regression analysis, \( R^2 \): Coefficient of determination and \( f_i \): the actual initial prestressing stress in pre-tensioned UFC panel from the calculation.

Fig. 7 Failure of 139PS-5 panel.

Fig. 8 Load-displacement relationship of pre-tensioned UFC panel.

to indicate the initial cracking load (\( P_{\text{cr,UFC,reg}} \)) as shown in Table 4. Regarding the first cracking load of specimens in series P-I, all three specimens showed close values at 3.67 kN, 3.60 kN, and 3.61 kN. The post-cracking stiffness of panel initially changes due to non-linear behavior, and the greater size of PC strands can provide higher stiffness as shown in Fig. 8(a). However, the increasing pre-stressing level in series P-II affected the distinct cracking value at 3.07 kN, 3.60 kN, and 4.17 kN for the prestressing level of 3, 5, and 7 MPa, respectively. The similarly post-cracking stiffness of those specimens are shown in Fig. 8(b). Accordingly, the higher prestressing level essentially delays the initial cracking load, which induces better durability.

c) Investigation of prestressing level

This calculation was carried out to ensure the actual prestressing level and determine the significance of prestressing losses in the UFC panels. The calculation of normal prestressing concrete as shown in Eq. (3a) was applied. In this study, the tensile strength of UFC was applied instead of the modulus of rupture, because, theoretically, the initial crack happens when the stress at an extreme fiber reaches the tensile strength. Moreover, the tensile strength is not affected by the height of a specimen. Hence, by using the cracking moment from experimental results, the exact prestressing level can be investigated from Eq. (3b).

\[
f_t = -\frac{F_i}{A} \left( \frac{F_{ec}}{I} + \frac{M_{cr,c}}{I} \right)
\]  
\[
F_i = \frac{M_{cr,c}}{I} - f_t
\]

where \( f_t \) is the modulus of rupture, \( e \) is eccentricity length, \( f_i \) is the tensile strength of UFC, \( M_{cr} \) is a cracking moment, \( A \) is a cross-section of UFC panel, \( F_i \) is the initial prestressing force, \( f \) is the moment of inertia, and \( c \) is a distance from center of gravity to
The tensile strength of the UFC panel was 11.27 kN; it was averaged from the experimental data. The cracking moment can be computed from the initial cracking load as mentioned previously. Regarding the actual prestressing levels of UFC panels from the calculation as shown in Table 4, the prestress levels of series P-I were 4.87 MPa, 4.58 MPa, and 4.62 MPa compared to 5 MPa of the target value. In series P-II, the computed prestresses were 2.23 MPa and 7.07 MPa for the specimen of 103PS-3 and 103PS-7, respectively. The results indicate that the exact prestressing levels were close to the expectation.

Moreover, significant prestressing losses could be shown through the distinction of prestressing level in the UFC panels between before and after including losses (see the value of $f_i,UFC$ and $f_{app},UFC$ in Table 1). Thus, considering the effect of prestressing losses is essential to obtain the required prestress, and the loss calculation in this study is suitable for fabrication of the pre-tensioned UFC panel.

d) Compatibility of pre-tensioned UFC panel

The compatibility between PC strands and the UFC panel is confirmed to verify the resistance of the panels during the loading. That verification can be carried out by the ratio of experimental and calculated bending moment ($M_{exp}/M_{cal}$) at the maximum load. The conventional section analysis was applied in the calculation. Figure 9 shows the strain distribution along the section of pre-tension UFC panel. The total strains of the UFC and PC strands ($\varepsilon_{c,UFC}$, $\varepsilon_{t,UFC}$, $\varepsilon_{t,PC}$) combine from the compressive and tensile strains according to the initial prestress ($\varepsilon_{c,UFC,i}$, $\varepsilon_{t,PC,i}$) and the applied loading ($\Delta\varepsilon_{c,UFC}$, $\Delta\varepsilon_{t,UFC}$, $\Delta\varepsilon_{t,PC}$). The calculating method is shown in Fig. 10.

For the comparison between the bending moments from the experiment and the calculation, all results of extreme fiber.

Fig. 9 The strain distribution of pre-tensioned UFC panel.

![Fig. 9 The strain distribution of pre-tensioned UFC panel.](image)

Assume the depth of neutral axis (x)

Obtain the strain distribution by using x and a measured strain in the compression fiber ($\Delta\varepsilon_{c,UFC}$) of panel as shown in Fig. 6. The assumption that the plane section remains plane and the actual initial stress in the previous section were applied as shown in Fig. 9.

Obtain the stress distribution by using the compressive and tensile stress-strain model of UFC based on the experimental data of Kakei et al.12) as shown in Figs. 11 - 12.

Check the force equilibrium

Obtain the calculated bending moment ($M_{cal}$)

Fig. 10 Calculation step for verifying compatibility.

![Fig. 10 Calculation step for verifying compatibility.](image)

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The tensile strength of the UFC panel was 11.27 kN; it was averaged from the experimental data. The cracking moment can be computed from the initial cracking load as mentioned previously. Regarding the actual prestressing levels of UFC panels from the calculation as shown in Table 4, the prestress levels of series P-I were 4.87 MPa, 4.58 MPa, and 4.62 MPa compared to 5 MPa of the target value. In series P-II, the computed prestresses were 2.23 MPa and 7.07 MPa for the specimen of 103PS-3 and 103PS-7, respectively. The results indicate that the exact prestressing levels were close to the expectation.

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For the comparison between the bending moments from the experiment and the calculation, all results of
\( \frac{M_{\text{exp}}}{M_{\text{cal}}} \) at locations where the strain gauges were attached are shown in Fig. 13. Most of the calculated moments are underestimations even if these calculations were based on the compatibility assumption; thus, the reason for the scattering data seems to come from other sources. Nevertheless, these results suggest that the compatibility between the UFC and the PC strands is acceptable within the area with attached strain gauges. For the length where strain gauges were not attached near the end of a panel, it is the transfer length which is the length for transmitting the prestressing stress from the PC strand to the UFC panel; thus, it is possible that a slip of PC strands may occur in this length.

### 4. RC BEAMS STRENGTHENED BY PRE-TENSIONED UFC PANEL

#### (1) Experimental series and details of specimens

Experiments on RC beams strengthened by the panel were conducted to investigate the flexural behavior and other mechanical characteristics. Eight RC beams with different numbers of tensile bars were strengthened by a pre-tensioned UFC panel to examine the performance of the panel to the damaged RC beams. To simulate the damage level, the assumed RC beams with different amounts of tensile reinforcement ratios were pretended to compare with the other strengthened beams. Accordingly, 2.23% of tensile reinforcement ratio (reinforced by 4D16) was assumed to be a sound case for the tensile bar: it is a common limitation of tensile reinforcement ratio for utilizing in RC structures. The tensile reinforcement ratio was reduced to 1.03% (2D16) and 0.65% (2D13) for pretending the damage level of the assumed RC beams as 50% and 70%. These ratios referred to the amount of tensile bar as 253 mm\(^2\) and 397 mm\(^2\), respectively.

Table 5 shows the experimental cases in this study. All RC beams were cast with the dimension of 150×1800×300 mm with 257 mm as the effective depth. Based on the applied amount of PC strands and the prestressing level in this study, the flexural strength of RC beams was designed to be less than the shear strength about three times to prevent shear failure. Thus, the beams had 0.95% of stirrup ratio and 253 mm\(^2\) and 397 mm\(^2\), respectively.

#### (2) Materials

To fabricate the strengthened specimens, various materials were used (i.e., normal concrete with W/C ratio of 60%, steel bars, UFC, PC strands and undercut anchor bolts). Details of the UFC and PC strands were already mentioned in Chapter 3; thus, the details of other materials are specified as follows:

| Term            | Type    | Diameter (mm) | Grade    | \( f_{\text{yy}} \) (MPa) |
|-----------------|---------|---------------|----------|--------------------------|
| Tension bar     | D16     | 15.9          | SD345    | 412                      |
|                 | D13     | 12.7          |          | 408                      |
| Compression bar | D10     | 9.53          | SD345    | 411                      |
| Stirrup         | D10     | 9.53          | SD295A   | >295                     |

\( f_{\text{yy}} \): Yielding strength of reinforcing bar

### Table 5 The experimental cases of strengthened RC beam.

| Name              | \( A_S \) (mm\(^2\)) | \( A_{PC} \) (mm\(^2\)) | \( f_{UFC} \) (MPa) | Series |
|-------------------|----------------------|-------------------------|---------------------|--------|
| 0.3B-40PS-5       | 253                  | 40                      | 5                   | B-I    |
| 0.3B-10PS-5       | 103                  | 139                     |                     |        |
| 0.3B-139PS-5      | 40                   | 103                     | 5                   | B-I    |
| 0.5B-10PS-5       | 103                  | 139                     |                     |        |
| 0.5B-139PS-5      | 397                  | 139                     |                     | B-I    |
| 0.5B-10PS-3       | 103                  | 3                       | 7                   | B-II   |
| 0.5B-10PS-7       | 103                  | 7                       |                     |        |

\( A_S \): Total cross-section of tensile steel, \( A_{PC} \): Total cross-section of PC strand, \( f_{UFC} \): Target prestressing level in UFC

### Table 6 Mix proportion of concrete.

| Term               | W/C (%) | s/a (%) | Unit weight (kg/m\(^3\)) |
|--------------------|---------|---------|--------------------------|
| \( G_{\text{max}} \) (mm) | 17.9     | 15.8    | 859                      |
| \( W/C \)       | 60      | 45      | 296                      |
| \( s/a \)       | 178     | 127     | 956                      |
| Unit weight (kg/m\(^3\)) | 0.444   |         |                          |

\( W \): Water, \( C \): Cement, \( S \): Fine aggregate, \( G \): Coarse aggregate, \( SP \): Superplasticizer and s/a : Volume ratio of sand to aggregate

### Table 7 Material properties of reinforcing bars.

### Notes

- Table 5: The experimental cases of strengthened RC beam.
- Table 6: Mix proportion of concrete.
- Table 7: Material properties of reinforcing bars.
with 165 mm of length. Its yielding stress and tensile strength were 640 MPa and 800 MPa, respectively. To determine the number of bolts in this study, the allowable shear force of anchor bolt (37.77 kN) and the force transferring between the panel and RC beam at the ultimate load were used for the calculation. Then, the anchor bolts were arranged in zigzag alignment. The location of bolts depended on the width and length of UFC panel, and the position of PC strands and reinforcing steel.

(3) Fabrication procedure

Fabrication of specimens considered of two steps. First, RC beams were cast by 100-liter mixing machine and cured for seven days before being strengthened by the panel. Epoxy was overlaid on the bottom side of RC beams to fill up the gap; then, the panels that were fabricated in advance were installed. The undercut anchor bolts were provided for sufficient bonding between interfaces. The bottom side of a beam was drilled for installing the anchor bolts before placing the panel as shown in Fig. 14(a). To fill the gaps between the UFC panel and bolt, the UFC without steel fiber was filled into the holes as illustrated in Fig. 14(b). A certain amount of torque was applied to the anchor bolt system to achieve friction resistance between the interfaces; however, it should not exceed the tensile strength and pull-out
Table 8 The experimental results and enhancement ratio of each specimen.

| Name    | Compressive strength, (MPa) | Loading capacity, $P_U$ (kN) | Failure mode | Enhancement ratio of capacity |
|---------|----------------------------|------------------------------|--------------|------------------------------|
|         | Concrete, $f'_c$          | UFC, $f'_{c, UFC}$          |              | $n_1$ | $n_{0.5}$ | $n_{0.3}$ |
| 1B      | 43.0                       | -                            | 166.6        | FT  | - | - |
| 0.5B    | 43.0                       | -                            | 96.4         | FT  | - | - |
| 0.3B    | 43.0                       | -                            | 65.0         | FT  | - | - |
| 0.3B-40PS-5 | 47.5                  | 194.8                        | 181.7        | FS  | 1.09 | 2.79 |
| 0.3B-103PS-5 | 47.6                 | 194.8                        | 229.1        | FS  | 1.38 | 3.52 |
| 0.3B-139PS-5 | 47.0                  | 210.7                        | 232.9        | FS  | 1.40 | 3.58 |
| 0.5B-40PS-5 | 44.5                  | 194.8                        | 191.4        | FT  | 1.15 | 1.99 |
| 0.5B-103PS-5 | 40.3                 | 194.8                        | 269.1        | FS  | 1.62 | 2.79 |
| 0.5B-139PS-5 | 43.6                 | 210.7                        | 294.9        | FS  | 1.77 | 3.06 |
| 0.3B-40PS-5 | 30.1                  | 210.7                        | 284.0        | FT  | 1.71 | 2.95 |
| 0.3B-103PS-7 | 45.4                 | 211.4                        | 268.3        | FS  | 1.61 | 2.78 |

$FT$: Flexure-tension failure, $FS$: Flexure-shear failure, $n_1$: Enhancement ratio of capacity to 1B, $n_{0.5}$: Enhancement ratio of capacity to 0.5B and $n_{0.3}$: Enhancement ratio of capacity to 0.3B.

Strength of the bolt system. Thus, 76 kN-mm of torque, as recommended by the production company, was introduced to tighten all bolts by a torque wrench as displayed in Fig. 14(c). The completed specimen is shown in Fig. 14(d).

(4) Loading method of strengthened specimens

All specimens were subjected to a four-point bending test. Various measurements were installed for collecting data during the loading test. Four LVDTs were set up to measure the relative displacement: two on both sides of the mid-span and the others at supporting points. Five strain gauges were attached to the tensile reinforcing bar to observe the yielding and to apply the strains for further calculation. Two strain gauges were attached in the mid-span on two tensile bars, while the others were attached on one tensile bar at every 150 mm from the mid-span. Six $\pi$-gauges were attached at both sides in the constant moment region of the UFC panel to measure the corresponding crack width as shown in Fig. 15. To observe the behavior of specimens carefully during a loading test, pictures of specimens were taken by cameras at every 10 kN from beginning until failure of specimen.

5. RESULTS AND DISCUSSION OF RC BEAMS STRENGTHENED BY PRE-TENSIONED UFC PANEL

(1) Loading capacity

Table 8 shows the experimental results and material properties of each specimen. The loading capacities of three reference beams were simply computed by the flexural section analysis due to the precise flexural calculation of RC beam. The calculated beams are 1B beam (the assumed non-damaged beam), 0.5B (the assumed 50% damaged RC beams), and 0.3B (the assumed 70% damaged RC beams). Moreover, the high load enhancement ratios between the strengthened beams and the reference beams in Table 8 indicate that the pre-tensioned UFC panel can predominantly enhance the flexural performance of RC beams without significant increase of structural weight. The efficiency of the new strengthening
system can be performed through the load enhancement ratio, which is affected by each variable parameter as follows:

**a) Series B-I: The effect of amount of PC strand**

The load enhancement ratios of specimens are shown in Table 8. The enhancement ratios of strengthened specimens with 0.5B were 1.99, 2.79, and 3.06 with the greater amount of PC strands. Similarly, the enhancement ratios of 0.3B were 2.79, 3.52, and 3.58 with the greater size of PC. It indicates that the increasing amount of PC strands in the UFC panel (i.e., 40 mm², 103 mm², and 139 mm²) significantly affected the increase of loading capacity in both strengthened 0.3B and 0.5B beams, but the increase was not proportional to the amount of PC strands as displayed in Fig. 16. Thus, the increasing amount of PC strands in the UFC panels affects the high enhancement of loading capacity. Moreover, the capacities of all strengthened beams were more than that of the non-damaged beam (1B). This indicates that the loading capacity of damaged beams can be recovered by using the pre-tensioned UFC panel.

**b) Series B-II: The effect of prestressing level**

In this series, the target prestressing levels were increased from 3, 5, and 7 MPa. According to Table 8, the loading capacities indicate that the higher prestressing levels insignificantly affect the increase of loading capacity as 2.95, 2.79, and 2.78. However, the results showed very high load enhancement ratios; i.e., more than twice. Furthermore, these strengthened specimens can recover the loading capacity more than that of 1B as well.

(2) Initial cracking load of strengthened beams

The crack width of UFC in the constant moment region was measured to investigate the initial cracking load of each specimen. The load level at 0.1 mm of crack width was observed to specify the initial cracking load because the crack can be clearly seen and abruptly widens after this point. According to Table 9, the initial cracking loads of series B-I were about 103.4-114.7 kN for the strengthened 0.3B beams and 123.5-130 kN for the strengthened 0.5B beams. These results insignificantly varied with the
amount of PC strands. For series B-II, the initial cracking loads notably increased to 105.8 kN, 130.0 kN, and 143.9 kN for the prestress of 3, 5, and 7 MPa, respectively. Considering the number of cracks in the UFC panels after the loading test as shown in the blue line of Fig. 17, the crack pattern in the UFC portion of specimens in series B-II showed different patterns, although the higher prestress in the UFC panel insignificantly affected the different load enhancement ratios as discussed in the previous section. The large number of cracks was observed on the UFC panel of 0.5B-103PS-3 beam as shown in Fig. 17(g). The cracks were reduced with the higher prestressing in the UFC panels of 0.5B-103PS-5 and 0.5B-103PS-7 as illustrated in Figs. 17(e) and 17(h). Consequently, by applying more prestressing levels in the UFC panel, it significantly affects slower crack opening and reduces the number of crack, which subsequently influences the durability of strengthened structures. Moreover, the calculation of initial cracking load was determined and compared with the experimental results. The cracking strain of UFC, which was computed from the tensile strength, was used in the calculation of section analysis as mentioned in Chapter 3. According to Table 9, the values from the analysis are lower than those of the experimental results, but the significant increase in the cracking load with higher prestressing level is still correct. It means that the first cracking initially occurred with a very fine crack (smaller than 0.1 mm) and it was rarely noticed in general. However, the load corresponding to the crack width of 0.1 mm was used to specify the initial cracking load in this study because the significant crack causes corrosion in a severe environment.

(3) Load-displacement relationship and crack patterns

Figure 17 shows the crack patterns after the loading test where the critical crack was marked by red lines. It can be observed that two failure modes happened in this experiment: flexure-tension failure (FT) and flexure-shear failure (FS). The load-displacement relationships in Fig. 18 are discussed as follows:

a) The strengthened beams of 0.3B in series B-I:
All three specimens, 0.3B-40PS-5, 0.3B-103PS-5, and 0.3B-139PS-5, had flexure-shear failure as shown in Figs. 17(a) to 17(c). The similar behavior of load-displacement relationships are shown in Fig.
First, the specimen showed a linear behavior until the first crack occurred in the RC beams. Then, the stiffness obviously reduced after the initial cracking on the UFC panels. Beyond this stage, cracks were propagated faster in the constant moment region and the shear span area. The highest post-cracking stiffness in this step can be observed in the specimen with maximum amount of PC strands (0.3B-139PS-5). The inclined crack in the shear span widened and induced debonding between the RC beam and the UFC panel. This crack was the critical crack that elongated to top of the RC beam. Finally, the specimens reached their peak load at 181.7 kN, 229.1 kN, and 232.9 kN as the amount of PC strands increased.

The 0.5B-40PS-5 specimen had a flexure-tension failure. The crack pattern and load-displacement curve are shown in Figs. 17(d) and 18(b), respectively. The elastic behavior was presented in the beginning. The initial crack occurred in the mid-span of the UFC panel at 123.5 kN, which induced the lower stiffness of a beam. More cracks could be seen and the flexural crack in the constant moment region obviously widened at 185 kN. Then, the maximum load was reached at 191.4 kN before two consecutive drops due to the rupture of PC strands.

Specimens 0.5B-103PS-5 and 0.5B-139PS-5 had flexure-shear failure as shown in Figs. 17(e) and 17(f). Their behaviors were similar to the strengthened 0.3B specimens. The flexure-shear crack induced debonding at the interface and the crushing on top of the RC beam occurred near the loading point. The specimens reached the maximum load at 269.1 kN and 294.9 kN for 0.5B-103PS-5 and 0.5B-139PS-5, respectively. The load gradually decreased and the concrete along flexure-shear crack was spalled with the further displacement.

c) The strengthened beams in series B-II:

The load-displacement relationships of this series are illustrated in Fig. 18(c). The strengthened specimen with the lowest prestressing level (0.5B-103PS-3) had flexure-tension failure. The linear behavior started until the first cracking at 105.8 kN in the UFC panel. Afterward, the stiffness decreased while the number of cracks increased through the entire length of the beam especially in the pre-tensioned UFC panel as shown in Fig. 17(g). The crack at the mid-span widened and the specimen reached the peak load at 284 kN.

Lastly, the behavior of 0.5B-103PS-7, which had flexure-shear failure, was similar to 0.5B-103PS-5. The stiffness was reduced due to the initial crack at 143.9 kN. The flexure-shear crack opened and induced debonding between interfaces. Before the failure of a specimen, the crack near the loading point was split and the load dropped. The load increased again until it reached the peak point at 268.3 kN. Only a few cracks occurred in the panel as shown in Fig. 17(h).

(4) Failure mechanism

a) Flexure-tension failure:

The mechanism is illustrated by the 0.5B-103PS-3 beam. From Fig. 19, the linear relationship persisted until 105.8 kN (point (1)). This point was the initial cracking load in the UFC panel where the crack width suddenly widened after this load level as shown in Fig. 20. Beyond this stage, the tensile force in the UFC transferred to the PC strands, which resulted in the lower stiffness. In stage (2), when the tensile stress at the bottom edge of the RC beam or UFC panel was higher than the tensile strength, more inclined cracks or flexural cracks subsequently happened in both portions. In the case of UFC, many small cracks developed due to the restraint of steel fibers. Figure 21 shows the relationship between load and tensile strains of a tensile bar at different locations. The strain at 300 mm from the mid-span initially yielded and the stiffness was reduced again (at point (3)). Toward point (4), all locations where strain gauges were attached yielded at 254 kN, but the beam still gradually resisted the load. Finally, the panel fully restrained the tensile force. The stiffness of the beam gradually reduced until the mid-span crack in UFC panel opened at the peak load of 283 kN. This flexural crack still widened with the constant load beyond point (5). It is supposed that this behavior was caused by the yielding of the PC strand and it indicates that the pre-tensioned UFC panel shows its performance until the damage of specimen.

b) Flexure-shear failure:

The mechanism of flexure-shear failure is revealed by 0.5B-103PS-7. According to Fig. 22, the beam behaved in an elastic manner in the beginning. When the tensile stress at the bottom of the UFC and concrete exceeded its tensile strength, cracks occurred from the bottom edge. At point (1), the load level related to the first cracking load of UFC panel is shown in Fig. 20. The inelastic behavior of a specimen was observed after this point, and stiffness of the
beam initially reduced. Point (2), the strain in a tensile bar reached yielding strain at 150 mm from the mid-span as shown in Fig. 23, then, cracks propagated faster in both mid-span and shear-span areas. At 265 kN (point (3)), all strain gauges attached on the tensile bar reached the yield strain. The inclined crack at 450 mm from the mid-span widely opened prior to the flexural crack at the mid-span. At 265.3 kN, the top of concrete was split and caused the load to descend from point (4) as illustrated in Fig. 24. The strain on top of the concrete at 150 mm exceeded 3,500μ. The load gradually increased again and reached the maximum at point (5). More cracks between the loading point and the inclined crack opened. The concrete crushed near the loading point as shown in Fig. 25.

It can be noticed that the resistance of the beam could be continued even though the tensile bar at the mid-span yielded and extended outward to the shear span, because the pre-tensioned UFC panel significantly enhanced the flexural resistance of the RC beams. However, this phenomenon similarly affects the possibility of flexure-shear failure since it extends the yielding region of tensile bar toward the shear span. Thus, shear failure is predominant over flexure failure. Generally, the shear resisting mechanism of RC beams is carried by the aggregate interlocking ($V_{ag}$), dowel action ($V_d$), and compression zone ($V_c$) in the upper portion ($V_{up}$) as shown in Fig. 25. In this study, when the yielding of tensile bar in the shear span occurred, it affected the loss of bond stress between concrete and tensile bar. Consequently, the existing inclined crack in the shear span widened and induced the debonding at the interface. This phenomenon would disrupt the shear contribution by dowel action and aggregate interlocking. Finally, the critical crack opened widely, resulting in the residual shear resistance by the compression zone, which finally resulted in the concrete crushing near the loading point.

(5) Compatibility between RC beam and pre-tensioned UFC panel

To ensure the strain-compatibility assumption of the strengthened beams, the same calculation conducted for the pre-tensioned UFC panel was applied. Five components of forces were considered as shown in Fig. 26. Due to the attached strain gauges on a tensile bar at every 150 mm from the mid-span, the strains were primarily used to compute the other strain components along the section based on strain compatibility as described by Eq. (4).

$$ \frac{\epsilon'_c}{x} = \frac{\epsilon'_{sc}}{x-d'} = \frac{\epsilon_s}{d-x} = \frac{\Delta \epsilon_{t, UFC}}{h + \frac{t}{2} - x} = \frac{\Delta \epsilon_{t, PC}}{h + \frac{t}{2} - x} $$

By assuming the distance of neutral axis (x), the strain values can be computed and transformed to stress by using the stress-strain model of each material. The compressive and tensile models of UFC, which corresponded to Kakei’s experiment(12) as displayed in Figs. 11 and 12, were applied. For concrete, the model of Thorenfeldt et al.(13) was applied to calculate the stress using Eq. (5).

$$ \sigma'_c = \begin{cases} \frac{n(\epsilon'_c / \epsilon'_p)}{n-1(\epsilon'_c / \epsilon'_p)} f'_c & \text{if } 0 \leq \epsilon'_c \leq \epsilon'_p \\ 0.67 \frac{f'_c}{62} & \text{if } \epsilon'_c \geq \epsilon'_p \end{cases} $$

where $\sigma'_c$ is the compressive stress of concrete (MPa), $\epsilon'_c$ is the compressive strain of concrete, $\epsilon'_p$ is the concrete strain at the maximum stress, and $E_c$ is the modulus of elasticity of concrete (GPa).

Therefore, the value of x can be satisfied and the

![Fig. 26 Strain and stress distribution along section (Unit : mm).](image)

![Fig. 27 The compatibility ratio of strengthened specimens.](image)
corresponding moment capacity is obtained by considering the equilibrium equation. The compatibility in each load level can be verified throughout the comparison between the experimental and calculated moment capacity ($M_{\text{exp}}/M_{\text{cal}}$).

**Figure 27** indicates the results of compatibility at four load levels: initial cracking load, first yielding of tensile bar, 0.95 $P_{\text{max}}$, and $P_{\text{max}}$. The ratios of $M_{\text{exp}}/M_{\text{cal}}$ at the mid-span (0 mm) present the excellent compatibility between the RC beam and the pre-tensioned UFC panel due to the value close to 1. However, at 300 mm and 450 mm from the mid-span, the results do not show a compatibility. **Table 10** shows the average ratios of $M_{\text{exp}}/M_{\text{cal}}$ at each load level and each location along the beam. At mid-span, the ratios are about 0.94–1.01, which reveal the satisfaction of compatibility until the failure of specimens. For 150mm far from the mid-span, the compatibility is satisfied until the level of initial cracking load, but there appears to be incompatibility at the further load level. In the case of the two farthest locations in the middle of shear span, the results at 300 mm and 450 mm do not show a compatibility along the cross-section at all levels. The reason is the predominant effect of shear behavior caused by the inclined crack in the shear span. Thus, the beam mechanism has been changed and the force equilibrium in the vertical section cannot be maintained. Consequently, the force equilibrium in that vertical direction is not satisfied, and other mechanisms are required to consider this behavior.

**Table 10** The average ratio of $M_{\text{exp}}/M_{\text{cal}}$ at different load level.

| Location from mid-span (mm) | 0    | 150  | 300  | 450  |
|-----------------------------|------|------|------|------|
| Initial cracking load       | 0.94 | 0.92 | 0.75 | 0.58 |
| First yielding of tensile   | 0.94 | 0.84 | 0.67 | 0.50 |
| bar                         | 0.95 | P_{\text{max}} | 1.00 | 0.82 | 0.67 | 0.48 |
| $P_{\text{max}}$            |      |      | 1.01 | 0.86 | 0.71 | 0.49 |

**Figure 28** Stress and strain distribution along the cross-section for computing flexural capacities.

**Table 11** The comparison of loading capacity.

| Specimen     | Failure mode | Loading capacity (kN) | $P_{\text{u,exp}}/P_{\text{u,cal}}$ |
|--------------|--------------|-----------------------|--------------------------------------|
| 0.3B-40PS-5  | FS           | 181.7                 | 0.97                                 |
| 0.3B-103PS-5 | FS           | 229.1                 | 0.87                                 |
| 0.3B-139PS-5 | FS           | 232.9                 | 0.76                                 |
| 0.5B-40PS-5  | FT           | 191.4                 | 0.90                                 |
| 0.5B-103PS-5 | FS           | 269.1                 | 0.91                                 |
| 0.5B-139PS-5 | FS           | 294.9                 | 0.87                                 |
| 0.5B-103PS-3 | FT           | 284.0                 | 0.99                                 |
| 0.5B-103PS-7 | FS           | 268.3                 | 0.90                                 |

$P_{\text{u,exp}}$: Loading capacity from experiment, $P_{\text{u,cal}}$: Loading capacity from calculation, $FT$: Flexure-tension failure and $FS$: Flexure-shear failure

The flexure-shear failure prior to the flexure-tension failure happened in some specimens. The ratios between the experimental results and the calculations show an overestimation. These results indicate very high flexural strengthening with the pre-tensioned UFC panel. Especially in specimen 0.3B-139PS-5, it shows the most overestimation of the calculation because the highest amount of PC strands can predominantly increase the high flexural capacity over the shear capacity of the RC beam. Accordingly, the lowest ratios of $P_{\text{u,exp}}/P_{\text{u,cal}}$ is obtained in this specimen, and subsequently are obtained in 0.3B-103PS-5 and 0.3B-40PS-5 (i.e., 0.76, 0.87, and 0.97, respectively). Besides, the ratios of 0.3B-40PS-5, 0.5B-103PS-5, and 0.5B-103PS-7 are noticed to be close to 1 even if they do not fail in the flexure-tension failure. It shows the sufficient performance of bonding between RC beams and UFC panels to transfer loads until almost the ultimate stage of the calculation. For the failure of specimens as flexure-tension failure (i.e., 0.5B-40PS-5 and 0.5B-103PS-3) where the ratios of $P_{\text{u,exp}}/P_{\text{u,cal}}$ were 0.90 and 0.99, it indicates that the bonding between RC beams and pre-tensioned UFC panels by using the undercut anchor bolts was sufficient at the critical.

(6) Comparison between calculation and experimental results

A method to estimate the flexural capacity of RC beams strengthened by pre-tensioned UFC panel was proposed. The ultimate condition was considered by assuming the concrete’s strain on the top fiber to be 3,500με as shown in **Fig. 28**. According to the compatibility between the RC beams and pre-tensioned UFC panels at the mid-span, each strain component was computed according to the strain-compatibility assumption. The initial strains induced by the prestressing force were also included for the calculation. The equivalent stress block and the stress-strain model of UFC proposed by Kakei et al. were used to investigate each stress component. The comparison between the experimental results and calculation values is summarized in **Table 11**.
section, and the assumption of perfect compatibility in the design calculation was acceptable. In future studies, higher durability should be considers by using other types of anchor bolts such as stainless bolts, which are more durable against severe environment while providing equivalent strength.

6. CONCLUSIONS

Pre-tensioned UFC panel is a new composite system that uses UFC panel prestressed by PC strands. It has been applied for strengthening RC beams in flexure. To attach the panel to the RC beam, undercut anchor bolts are used for sufficient bonding between interfaces. By using this strengthening system, the enhancement in flexural behavior and durability of structure can be summarized as follows:

1. By considering the losses of prestress due to elastic shortening and shrinkage of the UFC material in this study, there is good correspondence of the prestressing level in the UFC panel with the expected results. The elastic shortening loss can be calculated based on the compatible movement of the UFC and PC strands, thus the variation in strain due to the initial prestress and shrinkage in the UFC should be the same as that of the varying strain in PC strands in the same level. For the shrinkage loss, the strain value of shrinkage is considered to account for loss of shrinkage during fabrication.

2. According to the bending tests of pre-tensioned UFC panel, sufficient compatibility between the UFC and PC strands can be achieved except for the transfer length of the PC strands near the end of panel where the slippage possibly occurs.

3. The loading capacity of RC beams can be drastically enhanced by using a larger amount of PC strands but it is not proportional.

4. The effect of higher prestressing level in the UFC panel significantly influences the increase of initial cracking load and reduces less distributing crack along the UFC panel. Thus, the durability of a structure can be improved.

5. By using undercut anchor bolts to fix the pre-tensioned UFC panel to RC beams, sufficient compatibility between the RC beam and pre-tensioned UFC panel can be achieved. Consequently, the flexural capacity of RC beams strengthened by pre-tensioned UFC panel can be calculated by assuming the strain compatibility and conventional flexural section analysis.

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