SHEAR STRENGTHENING METHOD FOR RC BEAMS BY USING POST-TENSIONED UFC PANEL

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Abstract

Ultra-high strength fiber reinforced concrete (UFC) has been highly developed and applied to various infrastructures such as bridges over the past decade in Japan. This study aims to propose a new shear strengthening method for RC beams by using prestressed UFC panels. As a pilot study, prestressing level, which was the average compressive stress induced by the prestressing in UFC, was varied as the experimental parameter. Four RC beams strengthened by post-tensioned UFC panels were subjected to four-point bending in order to observe the shear behavior and clarify the effect of prestressing in UFC. The panels were applied on one side or on both sides of the RC beams. The experimental results showed that the post-tensioned UFC panels can improve the shear capacity of the RC beams substantially and the panels can also prevent the brittle fracture. Furthermore, the shear carried by the post-tensioned UFC panel showed a linear increase with the prestressing level. In the presence of two UFC layers, the strength increment nearly doubles.

Résumé

Le béton fibré à ultra-hautes performances (BFUP) a connu un développement important durant la dernière décennie au Japon, avec des applications variées en génie civil comme par exemple des ponts. Cette étude vise à proposer une nouvelle méthode de renforcement à l'effort tranchant de poutres en béton armé à l'aide de panneaux précontraints en BFUP. Dans cette première étape, on a fait varier le niveau de précontrainte (compression moyenne induite par la précontrainte dans le BFUP). Quatre poutres renforcées par des panneaux BFUP post-contraints ont été testées en flexion quatre points afin d'observer leur résistance au cisaillement et d'évaluer l'effet de la précontrainte dans le BFUP. Les panneaux ont été appliqués d'un seul ou des deux côtés des poutres. Les résultats des essais montrent que les panneaux BFUP peuvent améliorer nettement la résistance à l'effort tranchant des poutres en béton armé et éviter une rupture fragile. De plus l'effort tranchant repris par les panneaux BFUP précontraints croît linéairement avec le niveau de précontrainte. En présence de deux couches de BFUP, l'accroissement de résistance est aussi multiplié par près de deux.

1. INTRODUCTION

Ultra-high strength fiber reinforced concrete (UFC) is a kind of UHPFRC and has been highly developed over the past decade in Japan. Due to the compact particles of some fine-grained materials (i.e., cement, silica fume and silica sand) and steel fibers inside the UFC, outstanding properties are obtained such as high strength and ductility. Furthermore, UFC is also expected to have high durability. Kono et al. (2013) reported that the ten-year UFC footbridge can maintain the good conditions and mechanical properties even against severe environments [1]. Accordingly, UFC has been applied to various infrastructures in Japan [2].

Due to the high performance of UHPFRC, the studies of this material has been extended to various applications as a repair and strengthening material [3-6]. For instance, Wirojjanapirom *et al.* (2013) proposed the utilization of UFC as the U-shaped permanent formwork [4]. Aghani and Afshin (2016) reported the shear strengthening performance of the prefabricated UHPFRC sheets with 30 mm thick to RC beams [6]. In addition, the new idea for strengthening by introducing some prestressing force to UFC panels has been proposed by the authors, in order to improve the tensile resistance of the UFC panel and delay the crack opening. According to that, the authors proposed the pre-tensioned UFC panel as a new composite system and investigated the flexural strengthening effect of pre-tensioned UFC panel on RC beams [7]. To extend the application of prestressed UFC panel, this study aims to propose a new shear strengthening method to RC beams by using prestressed UFC panels. Some initial force was vertically introduced into the UFC panel before strengthening on the side of RC beams. This direction of prestressing aims to resist the opening of diagonal cracks on a shear span. This concept of prestressed UFC panels is expected to extremely enhance the structural shear strength of RC beams. As a pilot study of shear strengthening by prestressed UFC panel, this study investigated the shear strengthening effect of prestressing. In this study, four RC beams strengthened by post-tensioned UFC panels were subjected to four-point bending in order to observe the shear behaviour.

2. EXPERIMENTAL OUTLINE

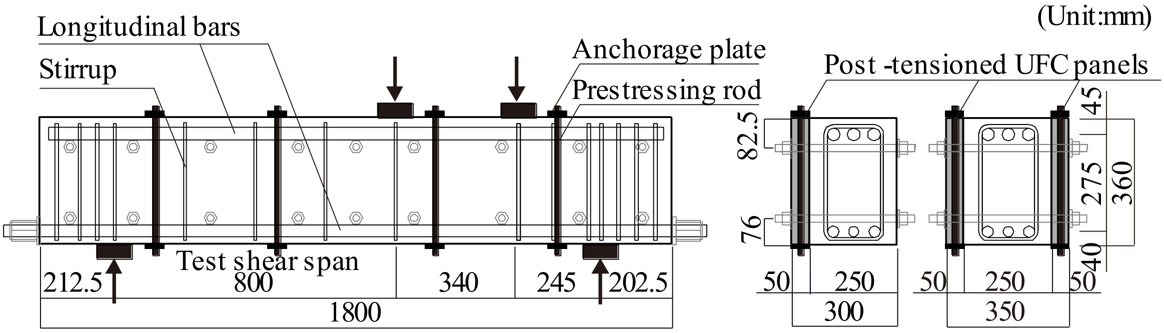
2.1 Test specimens

A total of five-beam specimens were prepared as shown in Table 1. Prestressing level, which was the average compressive stress induced by the prestressing in UFC, was varied as the experimental parameter. Figure 1 illustrates the dimensions of the specimen. Excepting the specimen REF, four RC beams were strengthened by the post-tensioned UFC panels on one side or both sides of the RC beams. In the specimen S-PL0, the UFC panel was not prestressed. In this study, the cast-in-place concrete after setting the UFC panel and screw-bolt system, which anchored throughout the section of RC beam and UFC panel, were applied. However, other anchor systems such as epoxy resin [5] and mechanical anchor bolts [7] can be adopted for the connection between RC beams and the UFC panel in the real practice. It is necessary to clarify the effect of anchor systems for the further study. In addition, since the development length in the direction of prestressing force in case of pre-tensioning was insufficient within the beam depth, the post-tensioning was adopted instead of pre-tensioning in this study.

Table 1: Test specimens

Specimens	Number of UFC panels	Prestressing level* (MPa)	Diameter of prestressing rod (mm)	Thickness of panels (mm)	Test shear span (mm)	Effective depth (mm)
REF	-	-	-	-	800	320
S-PL0	1	0	11.0	50		
S-PL1		1	9.2	50		
S-PL2		2	11.0	50		
D-PL2	2	2	9.2	50 + 50		

* Prestressing level is the average compressive stress induced by the prestressing in UFC



(a) Side view (b) Cross-sections

Figure 1: Dimensions of the specimens and test setup

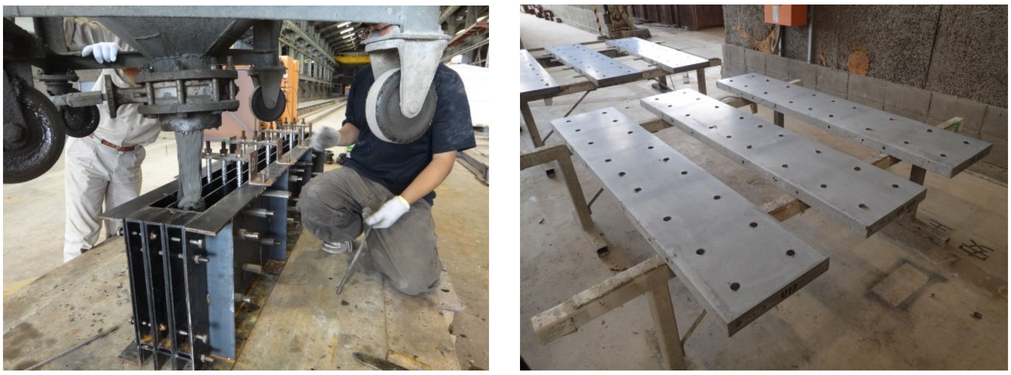
Table 2: Mix proportion of UFC

Unit content (kg/m^3)				
Tap water	Pre-mix binder	Steel fiber	superplasticizer	defoamer
163	2212	157	16	1

2.2 Post-tensioned UFC panels

The dimensions of the post-tensioned UFC panel were 1800 mm in length, 360 mm in width and 50 mm in thickness. Eighteen holes with diameter of 26 mm were made so that the bolts could pass through and fixed the UFC panels with the RC beams.

UFC is a material produced by mixing a pre-mix powder; i.e., cement, silica fume, silica fine powder, and silica sand in the optimum proportion, with tap water, superplasticizer, defoamer, and dispersed steel fibers. Table 2 shows the mix proportion of UFC in this study. Two percent in volume of steel fibers (0.2 mm in diameter and 15 mm in length) were used. This mix proportion provided the average flow value of 265 mm with the average air content of 3.0%. The direction of pouring was from one side to another side of the panels as shown in Figure 2(a). All UFC panels were treated to steam curing at 90°C for 48 hours according to the standard recommendation of JSCE (2006) [8]. Figure 2(b) shows the precast UFC panels after the steam curing. The average compressive strength after the curing was 189.7 MPa in ϕ50 × 100 mm of cylinder specimens.



(a) Casting of UFC (b) Prefabricated UFC panels

Figure 2: Fabrication of UFC panels

Before the fabrication of strengthened beam, four prestressing rods were prestressed in the UFC panel by using a hand wrench. To obtain the target prestressing level, the strains in the prestressing rods and UFC panel were recorded. Prestressing rods with diameters of 9.2 mm and 11.0 mm had yield strength of 1089 MPa and 1073 MPa, respectively. To ensure anchorage of prestressing rods, anchorage plates and nuts were provided at the end of prestressing rods. Sheaths and grouting were used for all UFC panels. The grouting material was injected immediately by the mortar pump after applying the prestressing force. The average compressive strength of this grouting material was about 71.7 MPa at 7-day age.

2.3 RC beams

The RC beams had the total length of 1800 mm, width of 250 mm, height of 360 mm, length of test-shear span of 800 mm and effective depth of 320 mm. In all five RC beams, High-strength deformed steel bars (As = 804.2 mm^2) and deformed steel bar (As' = 956.6 mm^2) with yield strength of 1137 MPa and 433 MPa were provided as the tensile and compression reinforcements, respectively. To ensure sufficient anchorage of tensile bars, anchorage plates and nuts were provided at the end of the tensile bars. Deformed steel bars (As = 71.3 mm^2) with yield strength of 374 MPa were also arranged as the stirrups. The design cylinder compressive strength of concrete was 40.0 MPa.

2.4 Fabrication processes of specimens

The specimens in this study consisted of the UFC panels and the cast-in-place concrete for ease of fabrication. SUS304 stainless bolts were used for the anchoring system. Bolts had the diameter of 21 mm and tensile strength of 558 MPa. The wood formworks were made for using as the bottom and the both side formworks. Eighteen holes for anchor bolts were made on the wood formworks in advance to fit with the location of bolts on the UFC panels. After the wood formworks were set up, the UFC panels were put into the formworks on one side or both sides, and the prestressing force was applied to the UFC panels. Then, the reinforcements were placed into the formworks. The bolts could be installed through the wood formworks and the UFC panels. After that, the UFC panels were fixed to the wood formworks by several stainless nuts. Lastly, the concrete casting was conducted. After casting, the specimen was cured for 7 days before preparing for the loading test.

2.5 Loading test and instrumentations

The specimens were subjected to four-point bending with a simply supported condition. Steel plates with 100 mm in width were placed at the supporting points. In order to reduce the horizontal friction, Teflon sheets and grease were inserted between the specimens and supporting steel plates. Other steel plates with 100 mm in width were also placed at the loading points. The applied load was monitored and the displacement of the specimens was measured by two displacement transducers at half distance between the two loading points. The strain values of the tensile bars, the stirrups, the prestressing rods, and the UFC panel in several sections were measured by strain gauges. The strain gauges were attached on each surface before casting. Pi-gauges were attached along the interface between the UFC panel and the RC beam at the test-shear span to check the separation. In addition, digital cameras were set to record the propagation of cracks on the side surfaces.

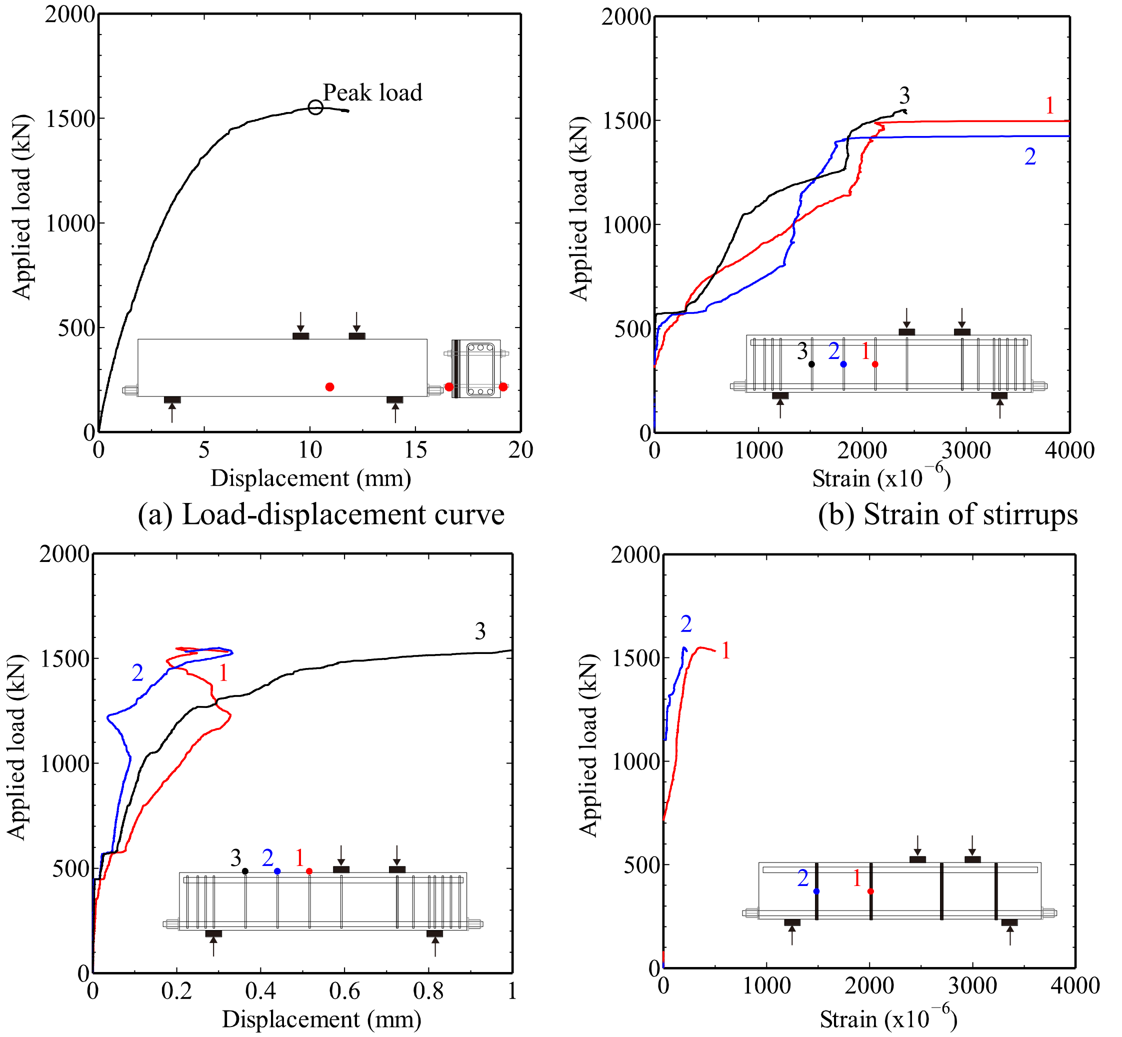
3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Shear behavior of RC beams strengthened by post-tensioned UFC panels

The fracture behavior of RC beams strengthened by post-tensioned UFC panels could be divided into certain stages with the output data and the observation of the cracks. As an example, the failure behavior of the specimen S-PL1, that was strengthened by one post-tensioned UFC panel with the prestressing level of 1 MPa, is discussed as follows. Figure 3 shows the load-displacement curve, the strain of stirrups and prestressing rods, and the separation displacement of the specimen S-PL1. For the specimen S-PL1, the flexural crack could be observed at the mid-span of the beam when the applied load reached around 90 kN. The diagonal crack could be observed on the beam when the applied load reached to 550 kN. At the same time, the strains of three stirrups were initially observed (Fig. 2 (b)). On the other hand, the angle and position of the diagonal cracks on the UFC panel were different from that of the RC beam. Actually, the measurement values of the separation displacement also increased from around 500 kN (Fig. 2 (c)). It indicates that the separation of the panel and the RC beam gradually starts after the diagonal cracks occur. At around 1400 kN, the stirrups of the RC beam yielded, while the prestressing rods did not yield until failure (Fig. 2 (d)). After the yielding of the stirrups, the stiffness rapidly decreased. Finally, the diagonal cracks propagated close to the loading point and the width of the diagonal cracks increased as well. This fracture behavior was confirmed in each specimen strengthened by the UFC panels in this study.

3.2 Crack patterns

Figure 4 shows the crack patterns on both sides of the test shear span after the loading tests. In each specimen, the flexural cracks occurred on the UFC panels and RC beam. Thereafter, some of the flexural cracks developed into diagonal cracks. In the specimens S-PL0, S-PL1, S-PL2, and D-PL2 that were strengthened by the UFC panels, the angle and the position of the diagonal cracks on the UFC panels was different from that of the RC beams. The diagonal cracks of the RC beams opened wider than that of the UFC panels. It indicates that the UFC panels are not integrally structured with the RC beam until the failure. The improvement of the compatibility between the UFC panels and the RC beams is a future issue. On the other hand, the crack patterns of each strengthened specimen were similar. The effect of the different prestressing level was not observed in the crack patterns.



(a) Load-displacement curve (b) Strain of stirrups

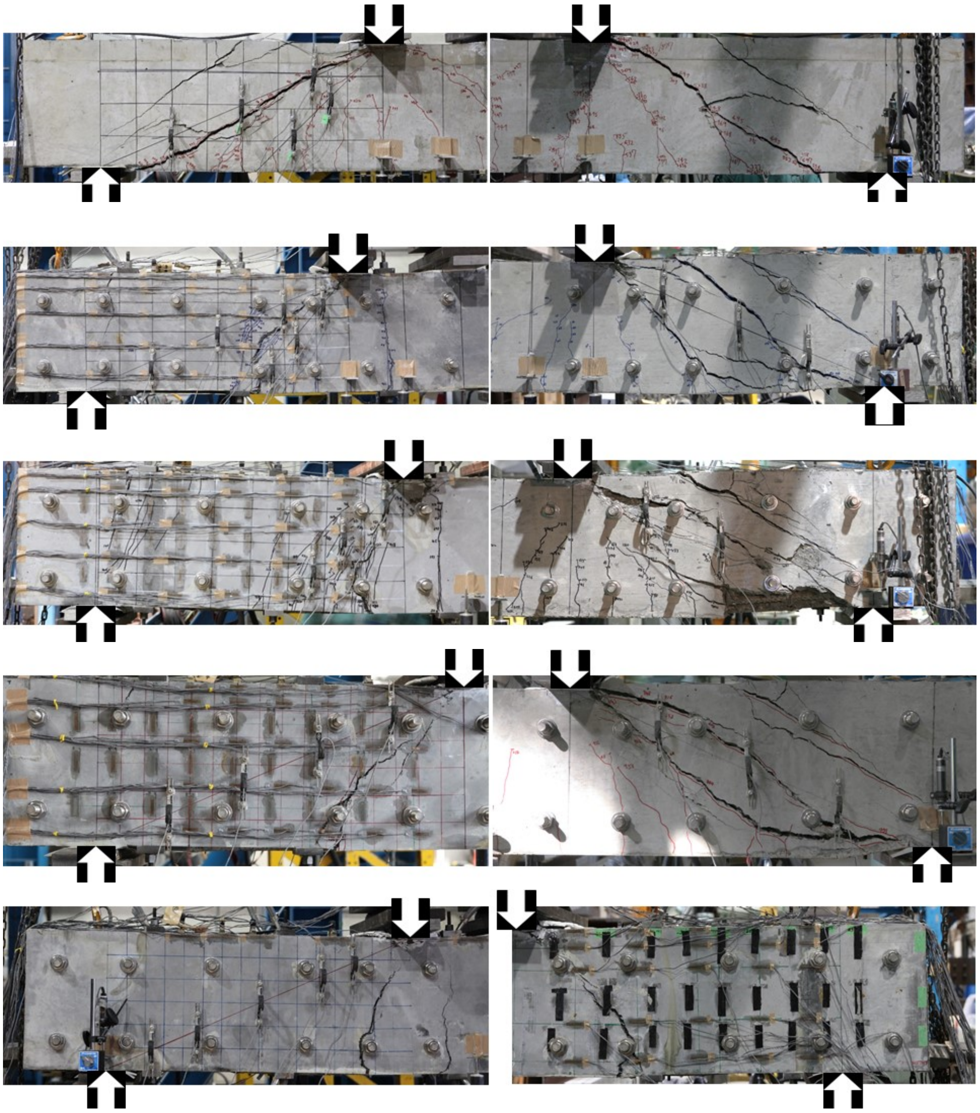
(c) Separation displacement (d) Strain of prestressing rods

Figure 3: Shear behaviour of the specimen S-PL1

3.3 Load and displacement relationships and shear capacities

The relationships between the applied load and the displacement for all specimens are presented in Figure 5. The circles in this figure indicate the peak load of each specimen. The shear capacity of the strengthened specimen increased with the increase in the prestressing level and the number of the panel. In addition, the UFC panels improved the stiffness of the RC beams. In the specimens S-PL0, S-PL1, and S-PL2, after the stirrups yielded, the stiffness of the beam clearly changed because the shear slipping of main diagonal crack and the widening of upper diagonal crack were observed on the RC beam part. The diagonal crack on the panel also widened. On the other hand, the applied load of the specimen D-PL2 dropped suddenly because concrete near the anchorage plate was spalling and lost the bearing resistance.

Figure 6 shows the increment of the applied load for strengthened specimens. Each increment was calculated by subtracting the peak load of the specimen REF from that of the specimen strengthened by the UFC panel. The prestressing levels in this figure were measured



(a) REF

(b) S-PL0

(c) S-PL1

(d) S-PL2

(e) D-PL2

Figure 4: Crack patterns on both sides of the test shear span after the loading tests

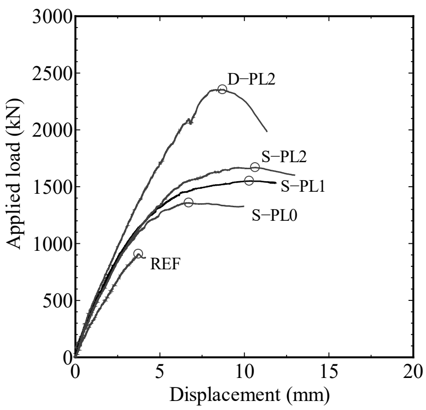


Figure 5: Load and displacement curves

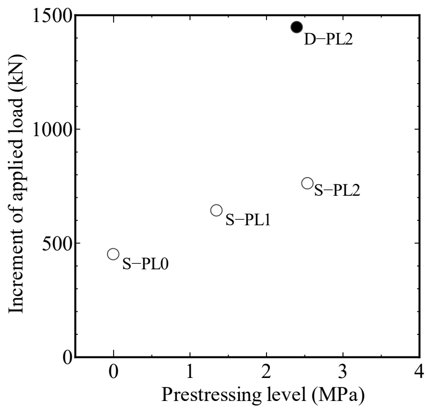


Figure 6: Strengthening effects

by strain gauges attached on the surface of the UFC panels before conducting a loading test. The increment of the applied load showed the linear increase with the prestressing level. Therefore, the prestressing level greatly affects the shear carried by the UFC panel. Furthermore, when two panels were provided, the increment of applied load became almost doubled.

4. CONCLUSIONS

To investigate the shear behavior of RC beams strengthened by the post-tensioned UFC panels, a total of five specimens were subjected to four-point bending. Based on the experimental investigation, the following conclusions can be drawn.

- The post-tensioned UFC panels can improve the shear capacity of the RC beams substantially and the panels can also prevent the brittle fracture.
- The shear capacity of the RC beam strengthened by the post-tensioned UFC panel increased with the increase in the prestressing level. The shear carried by the post-tensioned UFC panels showed the linear increase with the prestressing level. Moreover, in the presence of two UFC layers, the strength increment nearly doubles.
- The crack patterns of the post-tensioned UFC panels were different from that of the RC beams in this study. It indicates that the UFC panels are not integrally structured with the RC beam until the failure. The improvement of the compatibility between the UFC panels and the RC beams is a future issue.

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