- Technical Paper -

SHEAR BEHAVIOR OF RC BEAMS USING U-SHAPED UFC PERMANENT FORMWORK WITH SHEAR KEYS OR BOLTS

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ABSTRACT

Shear behavior of reinforced concrete beams using UFC as an U-shaped permanent formwork has been studied. Experimental parameters in this study are effect of shear keys and bolts. The experimental results indicated that UFC permanent formwork enhanced shear capacity of RC beams. Moreover, shear capacity of beam with providing screw and bolts was larger than that with providing shear keys. In addition, the shear resistance mechanisms were discussed. Furthermore, reduction of weight was compared with normal RC beams.

Keywords: permanent formwork, shear key, screwed bolts, UFC, shear mechanism

1. INTRODUCTION

Since the 1995 Great Hanshin earthquake, the specification for seismic design has started to be revised. As a result, in order to prevent the shear failure in reinforced concrete (RC) members which is well known as brittle behavior, many structures have required a large amount of reinforcing bars and concrete became difficult to be filled up in casting. Recently, ultra high strength fiber reinforced concrete (UFC) which is an advanced cementitious material has been developed, with many outstanding properties, such as compressive strength exceeding 200 N/mm^2, high bending toughness and durability [1]. Moreover, permanent formwork for structural members is one of the applications of UFC.

The definition of permanent formwork from CIRIA C558 [2] is given as follows:

(1) Permanent formwork is a structural element of whatever material that is used to contain the placed concrete, mould it to the required dimensions and remain in place for the life of the structure.

(2) Non-participating permanent formwork is structurally non-participating one which is assumed to do not contribute to the strength of the composite section.

(3) Participating permanent formwork is structurally participating one which makes a pre-determined contribution to the strength of the composite section.

Nowadays, many researches on UFC permanent formwork are focusing on the durability purposed; Shirai et al. [3] reported that UFC formwork left in-place increased durability against chloride attacks, abrasion, and impact wear. However, the research on the performance of the UFC formwork is insufficient. Also considering the relatively outstanding mechanical properties, UFC permanent formwork may improve load bearing capacity and deformability of the structure, however, studies focused on the mechanical performance cannot be found.

Therefore, the objective of this study is to investigate mechanical performance of RC beams failing in shear with U-shaped UFC permanent formwork. This paper focuses on the effect of shear keys at the internal surfaces, and screws and bolts which are provided to fix the UFC permanent formwork to the inside reinforced concrete. One reference specimen and two specimens using UFC permanent formwork with providing shear keys, or screws and bolts were tested. Shear capacities, crack patterns and failure mechanism were investigated. Finally, the weight reduction compared with normal RC beams was discussed.

2. EXPERIMENTAL PROGRAMS

2.1 Experimental parameters and specimens

To investigate shear behavior of a RC beam with U-shaped UFC permanent formwork, the loading test of three specimens listed in Table 1 was conducted. Experimental parameters are presence of bolts and

Table 1 Experimental cases

Name	Form thickness (mm)	Internal surface	Screws and bolts
Ref	-	-	-
UFC20-P	20	P type	-
UFC20-SB	20	Smooth	Provided

Meaning of the specimen's name: **UFC20 – S B**

Form thickness **Internal surface** **Bolt & screw**

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Table 2 Mix proportion of concrete

G_{max} [mm]	Water Cement Ratio [%]	Fine to Aggregate Ratio [%]	Unit weight (kg/m^3)							
			Water *W*	Cement *C*	Lime stone powder *L*	Fine aggregate *S*	Coarse aggregate *G*	Super plasticizer *SP*	Viscosity improver *V*
13	57	45	165	292	249	718	857	*C*×1.5%	*C*×0.15%

G_{max} = maximum size of coarse aggregate

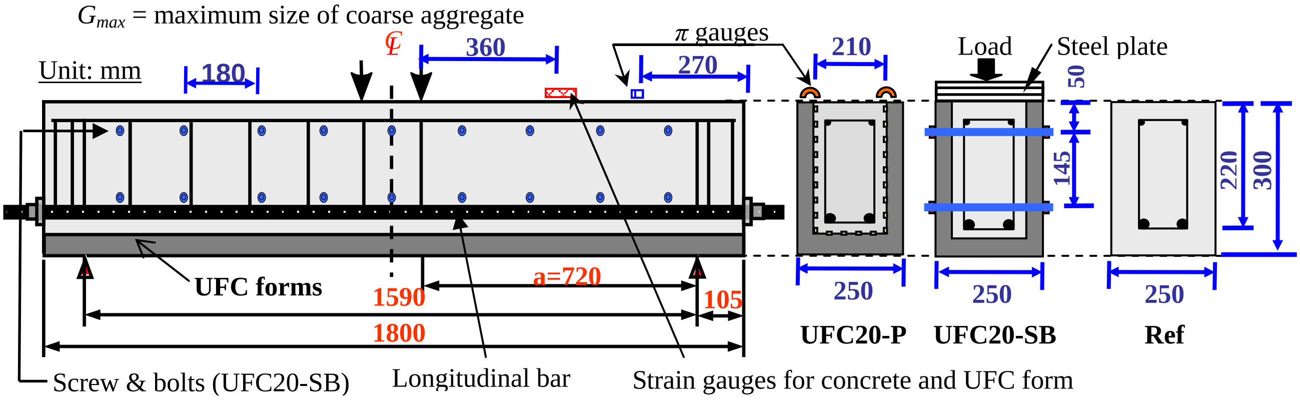

Fig. 2 Detail of specimens

Table 3 Yield strength of reinforcements

Term	Type	Yield strength (N/mm^2)
Longitudinal reinforcement	D22 SBPD930	1026
Compression reinforcement	D10 SD295	339

Table 4 Mix proportions of UFC

Flow (mm)	Unit weight (kg/m^3)			
	Water	Premix binder	Steel fiber	High performance water reducing agent
260±20	180	2254	157	24

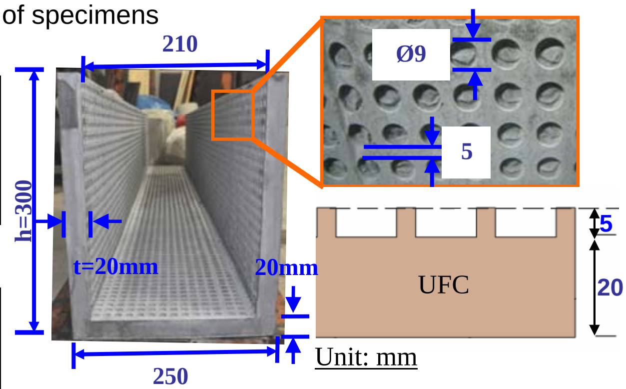

Fig. 1 Detail of UFC forms and shear keys of UFC20-P

shear keys at the internal surface between UFC form and inside RC part. In which name of the specimens listed in Table 1 corresponds to them. Ref is the reference specimen in which UFC U-shaped form is not used. UFC20-P is the specimen in which shear keys at the internal surface between UFC form and inside RC are provided. Figure 1 shows the detail of shear keys used in this study. UFC20-SB is the specimen, which has smooth interface between UFC form and inside RC, and bolts are provided from top and bottom as shown in Fig. 2. Designed locations are based on shear strength of bolts for transfer forces between RC and UFC [4].

Figure 2 shows dimension, reinforcing steel bar arrangement and cross section of all specimens. As constant variables for all specimens, shear span ratio, effective depth, width, height and longitudinal reinforcement ratio are a/d=3.27, d=220 mm, b=250 mm, h=300mm and p_w=1.41%, respectively. In order to control a side of failure, a number of stirrups were provided in only one shear span. No stirrups were provided in the test shear span.

2.2 Materials

(1) Concrete

The self-compacting concrete was used in this experiment, and detail of mix proportion is summarized in Table 2. The materials used in the concrete mixes were high-early strength cement, lime stone powder, fine aggregates, coarse aggregates, viscosity improver and superplasticizer, which was high-performance air entrained (AE) water reducing agent. The designed compressive strength of 7-day age concrete was 35 N/mm^2.

(2) Reinforcements

The longitudinal reinforcing bars used in this research were deformed steel bar with 22 mm nominal diameter. The yield strength was 1026 N/mm^2. The deformed steel bar of 10 mm in diameter was arranged as compression reinforcement. The yield strength was 339 N/mm^2 as shown in Table 3.

(3) UFC

The steel short fibers with 0.2 mm diameter and 15 mm length were used. Mix proportion of UFC forms is shown in Table 4. The volume fraction of steel fibers in all specimens was 2.0%.

2.3 Specimen fabrication

The specimen consists of two parts. One is U-shaped UFC permanent formwork which is fabricated in advance. The other is, reinforced concrete which is cast in the formwork to make a structural

Table 5 Mechanical properties of concrete and UFC, and the result of loading tests

Name	Mechanical properties of concrete		Material properties of UFC		Results of loading test		
	Compressive Strength, f'_c (N/mm^2)	Tensile Strength, f_t (N/mm^2)	Compressive Strength, f'_c (N/mm^2)	Tensile Strength, f_t (N/mm^2)	Shear Capacity, V_u (kN)	Shear capacity of reference specimen, V_{ref} (kN)	Enhancement ratio of shear capacity, n
Ref	32.8	2.1	-	-	69.0	-	-
UFC20-P	36.6	2.7	191.5	13.9	167.3	71.5	1.34
UFC20-SB	33.5	2.5	192.6	11.4	177.9	69.5	1.56

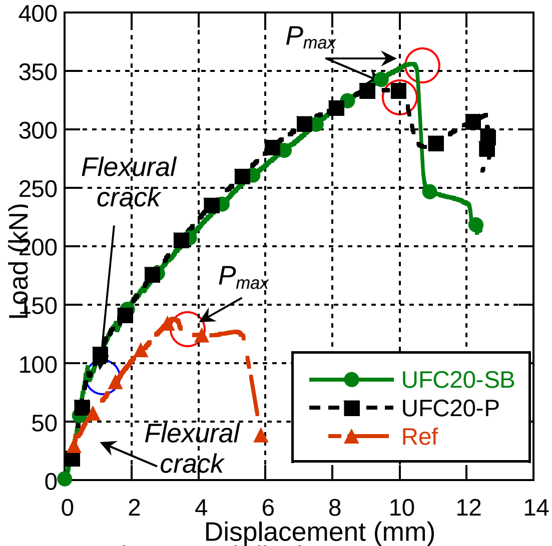

Fig. 3 Load-displacement curves

component. For example, in case of UFC20-SB, after UFC formwork has been already fabricated, reinforcing bars were arranged and put in UFC form, then, screws and bolts were provided. Location of the screws and bolts are shown in Fig. 2. After that concrete was cast and cured for 7 days.

2.4 Loading Method

Specimens were subjected to a four-point bending with load applied to both the UFC and RC at the same time. The detail is shown in Fig. 2. To satisfy the simple supporting condition, Specimens were placed on the roller supports. Teflon sheets and grease were inserted between the specimen and supports in order to prevent the horizontal friction. At loading points on the top surface of the specimen, after the application of gypsum, steel plates with 50 mm width, steel rollers and load distribution beam were placed.

2.5 Measurement items

During the loading test, the applied load was measured. Mid-span deflection was measured using transducers. Strain gauges were used for measuring strain of longitudinal steel bars at mid-span and concrete on the top fiber at mid-span. The opening width between concrete and UFC forms was measured by using π gauges as shown in Fig. 2. Moreover, the strain gauges were attached at top edge of UFC forms and RC to check the compatibility between UFC and concrete at support and mid of shear span in the longitudinal direction of the beam.

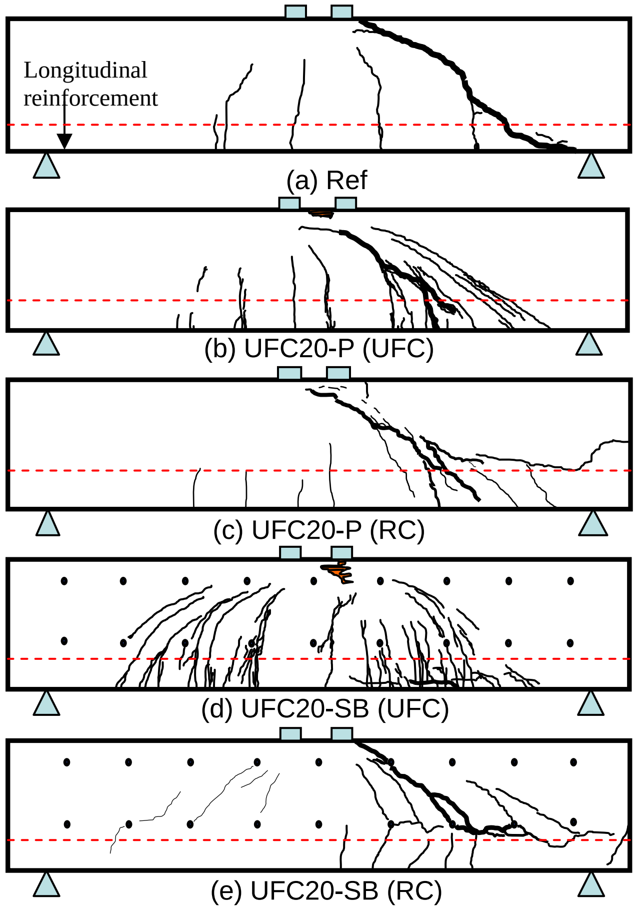

Fig. 4 Crack patterns

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Increase rate of shear capacities

Table 5 shows mechanical properties of concrete and UFC, and result of loading tests. The enhancement ratio of shear capacity (n), which is a ratio of increase to the shear capacity of reference specimen, was calculated by Eq. (1).

$$n = \frac{V_u - V_{ref}}{V_{ref}} \tag{1}$$

where, V_u is shear capacity, V_{ref} is the value expressed by the Eq. (2) which eliminates the effect of variation of compressive strength of concrete among the RC beams.

$$V_{ref} = \left(\frac{f'_c}{f'_{c\_ref}} \right)^{1/3} \cdot V'_{ref} \tag{2}$$

where, f'_c is compressive strength of concrete, f'_{c_ref} is compressive strength of concrete of the reference specimen, V'_{ref} is shear capacity of reference specimen obtained in the experiment.

From Table 5, specimens can be arranged as UFC20-P and UFC20-SB in order of enhancement ratio of shear capacity (n) with 1.34 and 1.56, respectively. It is indicated that using the U-shaped UFC forms replaced on the cross section of RC beams, shear capacity increased drastically. Furthermore, shear capacity of the beam with providing screws and bolts was larger than that with providing shear keys.

3.2 Load-deflection curves and crack patterns

Figure 3 shows the relationship between load and the mid-span deflection. The mid-span deflection was calculated by subtracting the displacements at the supporting points from the mid-span displacement. Figure 4 shows the crack patterns observed after the loading tests. For UFC20-P and UFC20-SB specimens, the crack patterns of both UFC and inside RC part are shown. The bold lines in Fig. 4 represent the critical cracks. The fracture process in each specimen is discussed below.

(1) Ref

Firstly, the specimen behaved in elastic manner until the first flexural crack occurred when the load was 45 kN. After the initiation of the flexural crack, the diagonal crack propagated from the support to the loading point at the peak load when the load was 138 kN as shown in Fig. 4(a). After the peak load, applied load rapidly decreased. The failure mode was diagonal tension failure.

(2) UFC20-P

In UFC20-P specimen, when the load reached to 90 kN, the initiation of the flexural crack on UFC form was observed. After that, many flexural shear cracks propagated with the load increasing. When the load reached to the peak, inclined crack located from the support to loading point propagated and widened, and crushing under the loading point on UFC permanent form was observed as shown in Fig. 4(b). Loading test was finished when the displacement reached 13 mm. After the loading test, UFC form was removed and diagonal crack of inside RC part and debonding failure of RC and UFC forms were observed. It seems that critical main crack of inside RC part was observed at the same location of that in UFC permanent form as shown in Fig. 4(c). The peak load of UFC20-B specimen was 334.6 kN.

(3) UFC20-SB

In UFC20-SB specimen, from the beginning, specimen behaved in elastic manner until the first flexural crack that occurred on UFC form around mid-span, when the load was 95 kN, which is reflected in the graph that loads a bit decreased and then increased again. After the first flexural crack, rate of inclination of load decreased. After that, flexural and

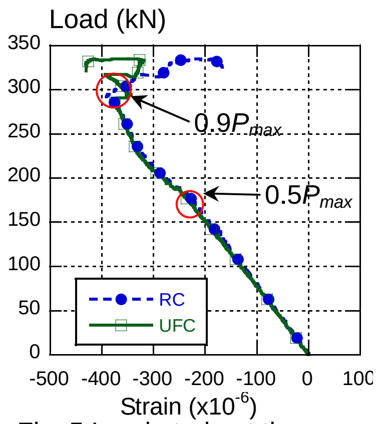

Fig. 5 Load-strain at the upper surface of the mid of shear span (UFC20-P)

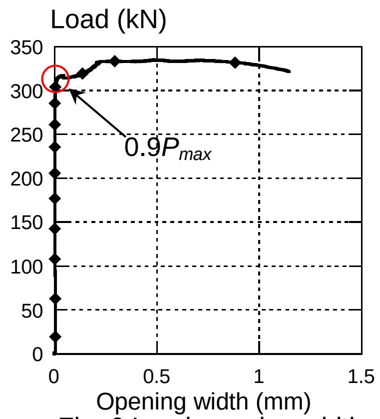

Fig. 6 Load-opening width between RC and UFC on the top surface (UFC20-P)

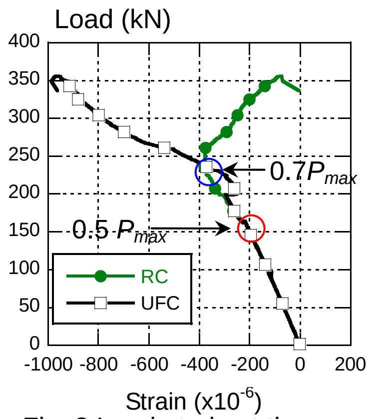

Fig. 8 Load-strain at the upper surface of the mid of shear span (UFC20-SB)

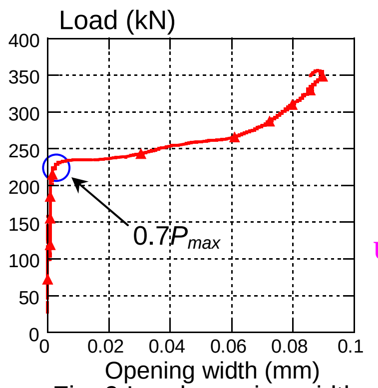

Fig. 9 Load-opening width between RC and UFC on the top surface (UFC20-SB)

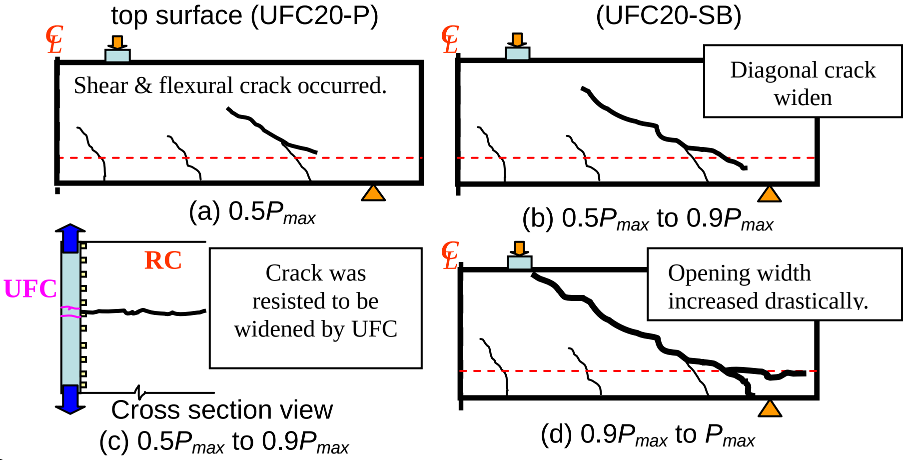

Fig. 7 Prediction of crack for UFC20-P

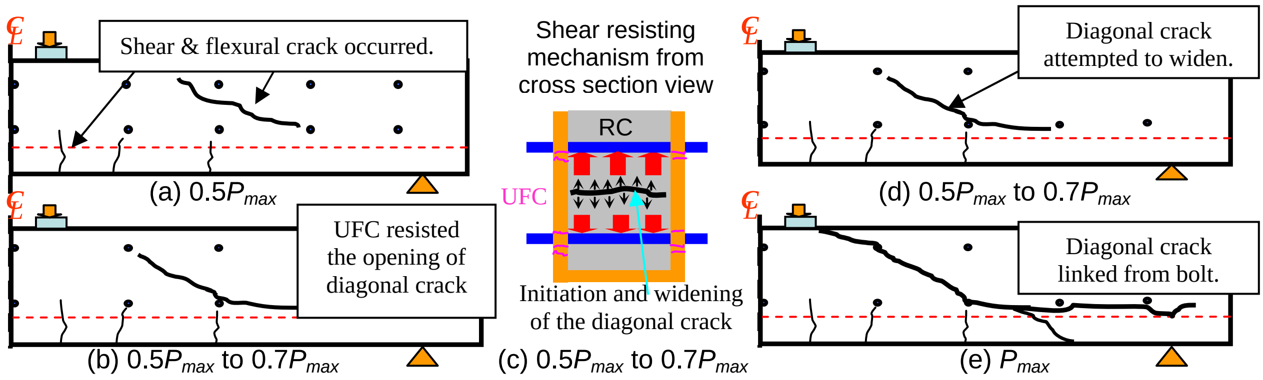

Fig. 10 Prediction of crack for UFC20-SB

flexural shear cracks appeared in a sequence from the mid-span to mid of shear span. When the load reached to the peak (355.9 kN), number of cracks occurred in the UFC forms increased, and those cracks are connecting from bolt to bolt. After the peak load, crushing of UFC under the loading point and the horizontal cracks on the bottom plate of UFC forms propagated from the loading point to support as shown in Fig. 4(d). Loading test was terminated when the displacement reached 13 mm in the post peak region. After the loading test, UFC form was removed. Fig. 4(e) shows the diagonal crack of inside RC part, where the critical cracks are shown with bold lines. Cracks in RC part are very different from that in UFC form. In addition, the critical crack penetrated from bolt to bolt and then to the loading point.

3.3 Shear resisting mechanism

The shear resisting mechanisms of UFC20-P and UFC20-SB were different because of the effect of shear keys at the internal surface of UFC20-P and effect of screws and bolts of UFC20-SB. The shear resistance mechanism in each specimen is discussed below.

(1) UFC20-P

Figure 5 shows the relationships between load and strain at the top surface of RC and UFC form at the mid of shear span of UFC20-P specimen. Figure 6 shows the relationship between load and opening width between RC and UFC form on the top surface of UFC20-P specimen (see Fig. 1). Figure 7 shows the shear resisting mechanism of UFC20-P.

In UFC20-P specimen, with the graph changed to nonlinear at 0.5P_{max} as shown in Fig. 5, it can be predicted that a diagonal crack initiated inside RC part as shown in Fig. 7(a), shear failure did not occur since UFC on the side of the form prevented the widening of the diagonal crack. Since the diagonal crack was resisted to be widened by shear keys at the internal surface between UFC form and RC, the interlock action became effective, therefore, shear forces can be increased as shown in Fig. 7(b) and (c). After that, the load increased and diagonal crack was widened, thus, resisting forces were redistributed from RC part to UFC through the bond stress of the internal surface. It caused stress concentration along the diagonal crack, therefore, inclined cracks on UFC form propagated from near the support to loading point. Since the load increased until 0.9P_{max}, resisting forces could not be redistributed from RC part to UFC through the bond stress of the internal surface. As a result, the opening width between RC and UFC form increased drastically at 0.9P_{max} as shown in Fig. 6, and the UFC form and RC part showed different behavior after 0.9P_{max} as shown in Fig. 5. After that, the load reached to the peak and failure occurred. The failure mode was interface failure between UFC and concrete and cracking of UFC.

(2) UFC20-SB

For UFC20-SB specimen, the shear resisting mechanism was different from that of UFC20-P specimen because of the effect of screws and bolts and also the smooth internal surface are provided for this specimen. Figure 8 shows the relationships between load and strain at the top surface of RC and UFC form at the mid of shear span of UFC20-SB specimen. Figure 9 shows the relationship between load and opening width between RC and UFC form on the top surface of UFC20-SB specimen. Moreover, Fig. 10 shows the shear resisting mechanism of UFC20-SB.

In UFC20-SB specimen, at around 0.5P_{max}, with the graph changed to nonlinear as shown in Fig. 8, it can be predicted that a diagonal crack initiated as shown in Fig. 10(a), however, failure did not occur. Because UFC on the sides of the formwork prevented the crack opening of the diagonal crack in the RC part, therefore, the aggregate interlock in RC part could be remained as shown in Fig. 10(b). After that, as the load increased, the diagonal crack in RC part attempted to widen as shown in Fig. 10(d), but it was resisted by forces, which were generated at the top and bottom of bolts. Due to these forces, the UFC form can carry the shear force that transferred by the screws and bolts, thus, the load was still increasing as shown in Fig. 10(c). As a result, the forces were concentrated around the bolts, the critical diagonal crack was widened and propagated to connect from bolt to bolt, and many cracks were observed around the holes for screws and bolts on the UFC form as shown in Fig. 4(d) and (e). Moreover, the opening width between RC and UFC form was slightly increased at 0.7P_{max} (see Fig. 9). After that, the UFC form and RC showed different behavior as shown in Fig. 8. Finally, the load reached to the peak because crack propagated to the loading point. The failure mode was cracking failure of UFC.

In comparison, shear resistance mechanism of the beam with providing screws and bolts was different from that with providing shear keys. For the beam with providing shear keys, the diagonal crack was resisted to widen by shear keys at the internal surface, thus, resisting forces were redistributed from RC part to UFC with depending on the bond stress of internal surface. On the other hand, the beam with providing screws and bolts, resisting forces are transferred from RC part to UFC formwork more effective by screws and bolts that fixed UFC form to inside RC. Therefore, the shear capacity of the beam with providing screws and bolts was larger than that with providing shear keys.

3.4 Discussion about weight reduction compared with normal RC beams

(1) Design of normal RC beams

Normal RC beams that have the same load carrying capacity as UFC20-P and UFC20-SB were designed in order to examine the level of weight reduction of the member. The characteristics of designed RC beams are the same as in the RC beams with U-shaped UFC forms as shown in Fig.1 and described in section 2.1. The shear carrying capacity of normal RC beams can be obtained from Eq. (3) [5].

$$V_c = 0.2(f'_c)^{1/3}(100p_w)^{1/3}(\frac{1000}{d})^{1/4}(0.75+\frac{1.4}{a/d})b_w d \quad (3)$$

where, V_c is shear capacity of normal RC beam without stirrups (kN).

By setting the value of V_c corresponding to the half of the load carrying capacity of composite beams from the experiments, the width of beams (b_w), was obtained. Thus, the width thickness and weight of RC beams with the same load carrying capacity as composites beams were determined. From the densities of RC and UFC are 2.5 t/m^3, the weights of the normal RC and composite beams were compared.

(2) Comparison of weight

Table 4 and Fig. 11 show the calculation results of weight reduction by using UFC permanent formwork.

Table 6 Comparison of the weight using experimental results

Name	Vc (kN)	b_w (kN)	W_{RC} (kg)	W_{UFC} (kg)	R_w (%)
UFC20-P	167.3	915.6	1091.8	298.1	72.7
UFC20-SB	177.9	1049.4	1251.4	298.1	76.2

W_{RC}=Total weight of normal RC beams,
W_{UFC}=Total weight of composite beams,
R_w=Rate of reduction (= (W_{RC}-W_{UFC}) x100/ W_{RC}) [6]

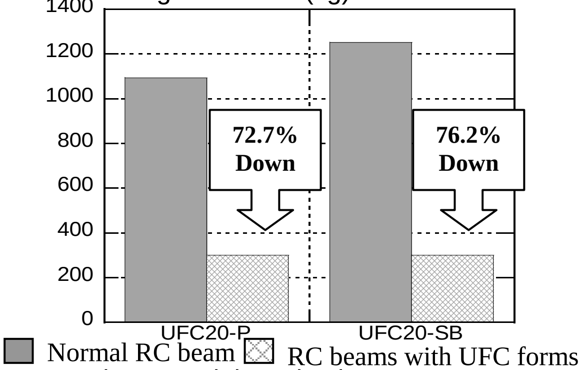

Fig. 11 Weight reduction rates

It was found that the weight of the members can be reduced with 72.7 and 76.2% in UFC20-P and UFC20-SB, respectively. It means that the composite beams using U-shaped UFC formworks can make a large contribution to the weight reduction of the members.

4. CONCLUSIONS

(1) The shear capacity of RC beams with U-shaped UFC permanent formwork increased compared to normal RC beam, with enhancement ratio (*n*) of 1.34 in a beam with providing shear keys and 1.56 in a beam with providing screws and bolts. This is because the diagonal crack was resisted to widen by UFC form on lateral and bottom sides.

(2) Shear resistance mechanism of a beam with providing screws and bolts was different from that with providing shear keys, due to the effect of screws and bolts that resisted widening of the diagonal crack in RC part more effective than shear keys. Consequently, shear capacity of the beam with providing screws and bolts was larger than that with providing shear keys.

(3) By comparing RC beams with replaced cross section with U-shaped UFC permanent formwork with normal RC beams having the same shear capacity, the weight of the member can be reduced 72.7% and 76.2% in a beam with providing shear keys and a beam with providing screws and bolts, respectively.

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