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EXPERIMENTAL INVESTIGATION ON SHEAR BEHAVIOR OF RC BEAMS USING UFC U-SHAPED PERMANENT FORMWORK

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Abstract

Shear behaviour of RC beams using UFC U-shaped permanent formwork has been investigated. The UFC U-shaped permanent formwork with the interface shear key and bolts system is proposed. Four-point bending tests were conducted. Experimental parameters were the presence of shear keys and screwed bolts, the thickness of UFC permanent formwork and the presence of stirrups. The results of this investigation show the promising technology for practical applications. The UFC permanent formwork enhanced the shear capacity of RC beams more than twice. Moreover, the shear capacity increased with the increase in thickness of UFC formwork. The shear resistance mechanisms were investigated. By using a UFC formwork with shear keys and screwed bolts, the UFC formwork prevented the widening of diagonal cracks inside RC. Finally, the shear carried by a UFC permanent formwork was investigated and the calculation method was proposed.

Résumé

Le comportement cisaillement de poutrelles en béton armé utilisant des coffrages perdus en BFUP en forme de U est analysé. Le système proposé comprend des indentations à l'interface le béton ordinaire. Des essais de flexion 4 points ont été conduits. Les paramètres expérimentaux sont la présence des indentations, l'épaisseur des coffrages perdus en BFUP et la présence d'étriers. Les résultats de cette étude montrent que la technologie est prometteuse pour les applications pratiques. Le coffrage perdu améliore la performance des poutrelles d'un facteur supérieur à deux, et cette performance est d'autant améliorée que le coffrage perdu est épais. Les mécanismes de ruine ont été analysés. En utilisant un coffrage perdu avec indentations, le coffrage perdu s'oppose à l'ouverture des fissures diagonales dans le béton armé. Les efforts supportés par le coffrage ont été analysés, et une méthode dimensionnement proposée.

1. INTRODUCTION

Ultra High Strength Fiber Reinforced Concrete (UFC) is an advanced cementitious composite material which has been rapidly developed in the recent years and utilized in the bridge structures in Japan. Through the proper "Ultra High" strength parameters, UFC provides with characteristic values in excess of 150 N/mm^2 and 5 N/mm^2 in the compressive and tensile strengths with high bending toughness due to the existence of steel fibers [1]. Furthermore, with close-packed micro-structures, UFC has excellent durability properties such as the resistance to chloride ion attacks and abrasion.

The utilization of UFC as the structurally integrated permanent formwork is one of the innovative ways to implement UFC for realizable construction and design of concrete structures. These permanent formwork systems are maximizing the benefits of UFC and concrete while simplifying the construction process. To make structural elements, first the UFC permanent formwork is fabricated; then, normal concrete is cast. These advantages enable a UFC permanent formwork to yield longer service life of structures while still maintaining remarkable structural performance. Therefore, UFC permanent formworks are widely used in Japan [2], especially for increasing durability against abrasion and chloride ion penetration of concrete structures. Shirai *et al.* reported the application of UFC permanent formwork for repairing of Tedorigawa Bridge in Ishikawa prefecture, Japan. The report shows that a UFC formwork left in-place increased durability against chloride attacks, abrasion, and impact wear [2]. However, the research on the mechanical performance of RC beams using UFC formwork is insufficient. Also considering the relatively outstanding mechanical properties, a UFC permanent formwork may improve the load carrying capacity.

Following the aforementioned point of view, this study examined the construction method for RC beams using a UFC permanent formwork. The purpose of this paper is to investigate the mechanical performance of RC beams failing in shear with a U-shaped UFC permanent formwork. Four-point bending tests of RC beams using a U-shaped UFC permanent formwork were carried out. The U-shaped UFC permanent formwork with shear keys and screws and bolts system which was provided to fix the UFC permanent formwork to the inside reinforced concrete was introduced. Shear capacities, crack patterns and failure mechanism were investigated.

2. EXPERIMENTAL PROGRAM

2.1 Experimental parameters and specimens

To investigate the shear behavior of RC beams with a U-shaped UFC permanent formwork, seven specimens were prepared. Four-point bending tests were conducted. The summary of test variables and details of specimens are provided in Table 1 and Figure 1. The experimental cases can be classified into three series. Series-I was to examine the effect of shear keys on the internal surface and presence of screws and bolts. Series-II investigated the effect of thickness of UFC permanent formwork and Series-III was for the presence of stirrups. Figure 1 shows dimension, arrangement of reinforcing steel bars and cross section of all specimens. As constant variables for all specimens, effective depth, width, height and tension reinforcement ratio were d=220 mm, b=250 mm, h=300 mm and p_w=1.41%, respectively. In order to control a shear span of failure, a number of stirrups were differently provided in each span.

First, the effect of shear keys at the internal surface between UFC formwork and inside RC

Table 1: List of the experimental cases

No.	Name	Thickness of formwork (mm)	Internal Surface	Screws and bolts	Stirrup ratio (%)	Series
1	Ref	-	-	-	0	I, II
2	UFC20-K	20	Shear keys	-	0	I
3	UFC20-SB	20	Smooth	Provided	0	
4	UFC20-S	20	Smooth	-	0	
5	UFC20-KB	20	Shear keys	Provided	0	I, II, III
6	UFC30-KB	30	Shear keys	Provided	0	II
7	UFC20-KB-r	20	Shear keys	Provided	0.28	III

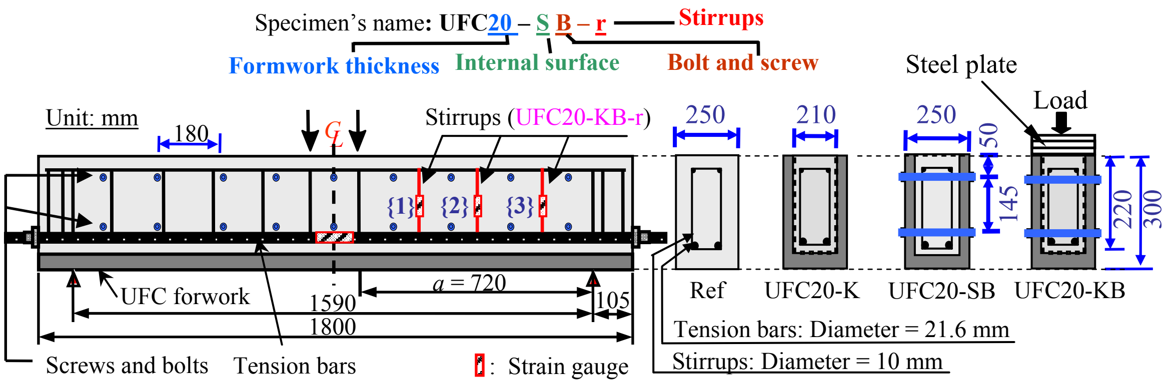


Figure 1: Detail of specimens

together with the presence of screws and bolts were considered in Series-I. The names of Series-I's specimens listed in Table 1 indicate the presence of shear keys and screws and bolts. Ref was the reference specimen in which a U-shaped UFC formwork was not used. UFC20-K was the specimen in which shear keys at the internal surface between UFC formwork and inside RC were provided. Smooth surface at the internal surface and screws and bolts were provided in UFC20-SB. On the other hand, UFC20-KB was the specimen which had shear keys on the internal surface between UFC formwork and inside RC, and screws and bolts were provided. In Series-II, total cross section of the specimen was the same, but the thickness of UFC formwork was increased to 30 mm in UFC30-KB in both sides and bottom part. In Series-III, the size of the specimen was the same as Series-I, and shear keys and bolts were provided. The stirrups were provided in UFC20-KB-r, with stirrup ratio of 0.28% and spacing of 240 mm.

2.2 Materials and fabrication of the specimens

UFC is a material produced by mixing premixed powder of cement, silica fume, silica fine powder and silica sand in the optimum proportion with water and high performance superplasticizer and steel short fiber. The volume fraction of steel short fiber (0.2 mm diameter x 15 mm length) was 2%. Table 2 shows the mix proportion of UFC. The U-shaped UFC permanent formwork was fabricated in advance before casting of concrete. Plywood which is designed for concrete casting was used to build a mold for casting the U-shaped UFC formwork. The plywood was cut and made to form a pattern of shear keys. The flowability

Table 2: Mix proportion of UFC

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

Table 3: Mix proportion of self-compacting concrete

G_{max} (mm)	W/C (%)	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	165	292	249	718	857	W×1.5%	C×0.15%

G_{max} = maximum size of coarse aggregate

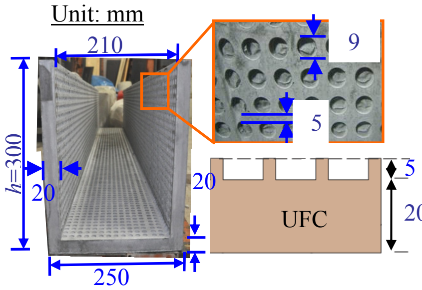


Figure 2: Detail of UFC formwork and shear keys

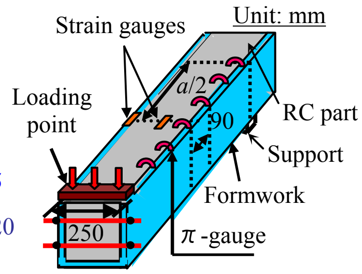


Figure 3: Measurements and loading condition

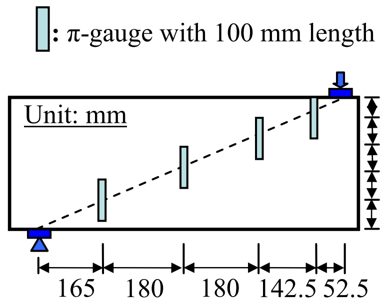


Figure 4: Arrangement of π- gauges

performance of UFC is achieved to exhibit a flow value of around 260 mm for the material temperature of 20-25ºC even with the steel fiber by 2% in volume. Therefore, it was able to cast into the very thin complicated-shaped shell mold. After the mixed materials had hardened, it underwent the stream curing at 90ºC for 48 hours. In this study, because of the presence of shear keys at the internal surface of UFC permanent formwork, self-compacting concrete was used in the experiment, and the details of mix proportion are summarized in Table 3. The designed compressive strength of 7-day age concrete was 35 N/mm^2. The designed compressive and tensile strength of UFC was 180 and 8 N/mm^2, respectively.

The longitudinal reinforcing bars used in this research were deformed steel bars with 21.6 mm nominal diameter. The yield strength was 930 N/mm^2 and the ultimate strength was 1080 N/mm^2. The stainless steel screws and bolts with 10 mm diameter were used in this research. The yield strength and the tensile strength were 240 and 568 N/mm^2, respectively.

Figure 2 shows the details of UFC permanent formwork. The specimen consisted of two parts. One was a U-shaped UFC permanent formwork which had been fabricated in advance. The other was reinforced concrete which was cast in the formwork to make a structural component. For example, in the case of UFC20-KB, after UFC formwork had already been fabricated, reinforcing bars were arranged and put in a UFC formwork, then, screws and bolts were provided. The location of the screws and bolts are shown in Figure 1. After that concrete was cast and cured for 7 days.

Table 4: Mechanical properties of concrete and UFC and the result of loading tests

Name	f'_c (N/mm^2)	f_t (N/mm^2)	f'_{c_UFC} (N/mm^2)	f_{t_UFC} (N/mm^2)	P_{cr} (kN)	V_u (kN)	R
Ref	32.8	2.1	-	-	45.0	69.0	1.00
UFC20-S	43.5	2.5	194.7	10.1	105.1	159.8	2.32
UFC20-K	36.6	2.7	191.5	13.9	90.6	167.3	2.42
UFC20-SB	33.5	2.5	192.6	11.4	95.3	177.9	2.58
UFC20-KB	40.4	2.1	184.2	11.9	82.1	192.0	2.78
UFC30-KB	36.2	2.2	181.8	12.0	92.0	223.5	3.24
UFC20-KB-r	36.4	2.7	170.5	12.4	92.6	213.8	3.10

f'_c: Compressive strength of concrete, f_t : Tensile strength of concrete, f'_{c_UFC} : Compressive strength of UFC, f_{t_UFC} : Tensile strength of UFC, P_{cr} : Load at the flexural crack*,* V_u : Shear Capacity, R : Ratio of shear capacity

2.3 Loading method and measurement items

Figure 3 shows the measurement items and loading condition. Specimens were subjected to a four-point bending with the load applied to both the UFC and RC at the same time. 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 horizontal friction. During the loading test, the applied load and mid-span deflection were measured. The strain gauges were attached at the top edge of UFC formwork and RC part to check the compatibility between UFC and concrete in the longitudinal direction of the beam. The opening width between concrete and UFC formworks was measured by using π- gauges. Moreover, on the side surface of a UFC permanent formwork, four π-gauges were attached to measure the diagonal crack opening width along the diagonal line between the loading point and support as shown in Figure 4.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Shear capacities, load-deflection relationships and failure patterns in Series I

Table 4 shows mechanical properties of concrete and UFC, and the result of loading tests. From Table 4, specimens can be arranged as UFC20-S, UFC20-K, UFC20-SB and UFC20-KB in the order of ratio of shear capacity which are 2.32, 2.42, 2.58 and 2.78, respectively. It indicates that when using the U-shaped UFC formworks on the cross section of RC beams, the shear capacity increased drastically. The shear capacity of the beam with screws and bolts was larger than that with providing shear keys. Furthermore, the shear capacity of the beam with shear keys and screws and bolts was the largest.

Figure 5 shows the relationship between the load and the mid-span deflection. Figure 6 shows the crack patterns observed after the loading tests. For specimens with UFC formwork, the crack patterns of both UFC and inside RC part are shown. After the loading test, UFC formworks were removed and the diagonal crack of inside RC part was observed. The bold lines in Figure 6 represent the critical cracks.

In the Ref specimen, the first flexural crack occurred when the load was 45 kN. The diagonal crack propagated when the load was 138 kN as shown in Figure 6(a). In UFC20-K specimen, the flexural cracks initiated when the load was 90 kN. When the load reached to the

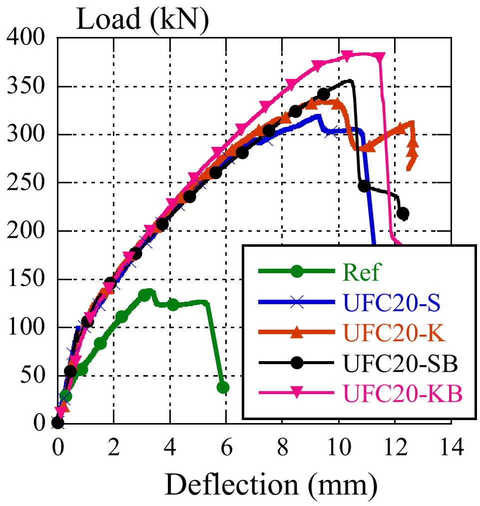


Figure 5: Load-deflection relationships in Series-I

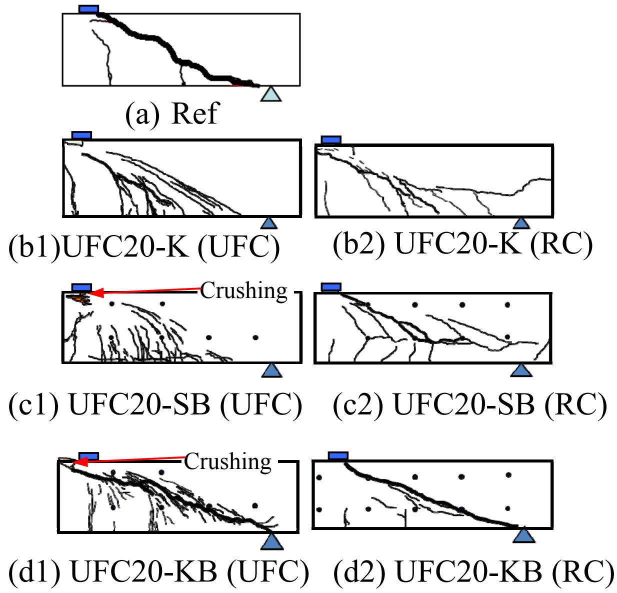


Figure 6: Crack patterns of Seiries-I

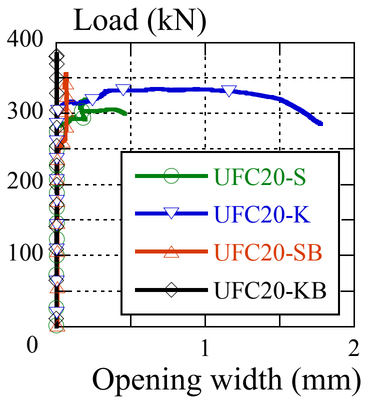


Figure 7: Load-opening width in Series-I

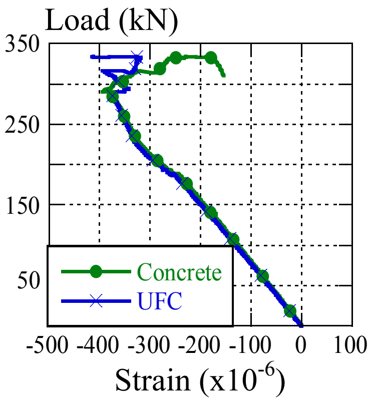


Figure 8: Load-strain at the top surface (UFC20-K)

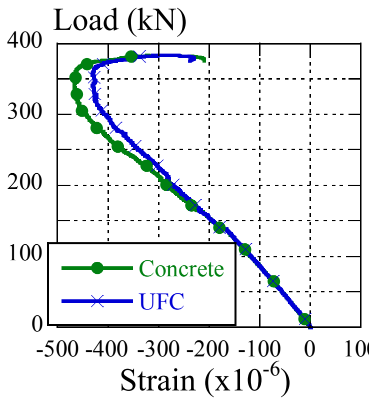


Figure 9: Load-strain at the top surface (UFC20-KB)

peak, the inclined crack located from the support to the loading point propagated and widened as shown in Figure 6 (b1). In UFC20-SB specimen the first flexural crack occurred when the load was 95 kN. When the load reached to the peak (355.9 kN), a number of cracks occurred in the UFC formwork, and those cracks were connected from bolt to bolt as shown in Figure 6(c1). Figure 6(c2) shows the diagonal crack of inside RC part. The critical crack penetrated from bolt to bolt and then to the loading point and looked very different from those in UFC. In UFC20-KB specimen, flexural cracks on the UFC formwork appeared when the load was 82 kN. When the load reached its peak (384 kN), the critical diagonal crack propagated and widened, and the crushing of UFC under the loading point occurred as shown in Figure 6(d1). Figure 6(d2) shows the diagonal crack of inside RC part. It seemed that the diagonal crack of inside RC part occurred at the same location of that in the UFC permanent formwork.

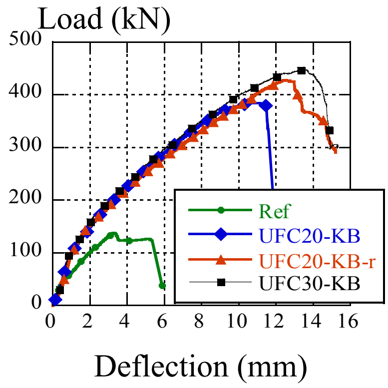


Figure 10: Load-deflection relationships (Series-II and III)

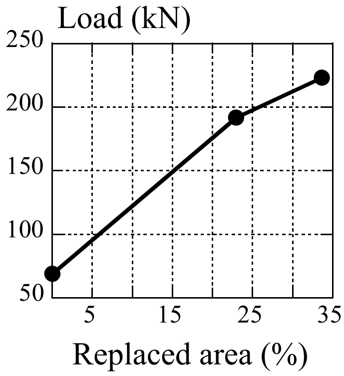


Figure 11: Shear capacity-replaced area of UFC relationship

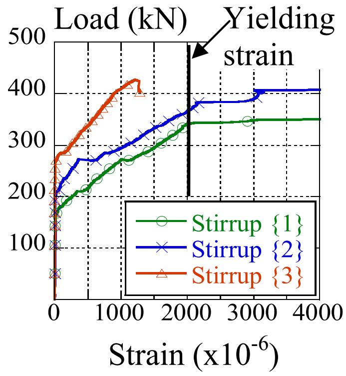


Figure 12: Load-stirrup strain relationships

3.2 Shear resisting mechanisms

The shear resisting mechanisms of UFC20-K, UFC20-KB and UFC20-SB were different because of the effect of shear keys at the internal surface and effect of screws and bolts. The shear resistance mechanisms in UFC20-K and UFC20-KB specimens are explained below.

In UFC20-K specimen, although a diagonal crack occurred, UFC on the side of the RC part prevented the widening of the diagonal crack, then the interlock action became effective; therefore, shear forces increased. After the load increased until 90 percent of the peak load ($0.9P_{max}$), the opening width between RC and UFC formwork increased drastically at $0.9P_{max}$ as shown in Figure 7, and the UFC formwork and RC part showed different behavior after $0.9P_{max}$ as shown in Figure 8. After that, the load reached the peak and the failure occurred.

For UFC20-KB, as shown in Figure 9, the strain at the top surface at the middle of shear span of RC part and UFC formwork showed similar values. So, it can be said that the beam had compatibility through to the end of the test. It is noted that the opening width between RC and UFC formwork was very small as shown in Figure 7. Firstly, a diagonal crack initiated in RC part, however, the failure did not occur because UFC on the sides of the RC part prevented the opening of the diagonal crack and the aggregate interlock in RC part remained. After that, as the load increased, the diagonal crack in RC part attempted to widen but a UFC formwork was still resisting by forces which were generated at the top and bottom of bolts and from the shear key interface. As a result, many cracks could be observed on the UFC formwork as shown in Figure 6(d1). The main diagonal crack on UFC occurred at $0.7P_{max}$ and the opening width of diagonal crack kept growing with the increasing load. Then, the load reached the peak and the failure occurred.

3.3 Effect of thickness of permanent formwork

The influence of thickness of UFC formwork is discussed based on the experimental results of Ref, UFC20-KB and UFC30-KB specimens in Series-II. From Table 4 and Figure 10, specimens can be arranged as UFC20-KB and UFC30-KB in order of enhancement ratio of shear capacity (R). Also, Figure 11 shows that with replacement percentages of UFC formwork per total cross section area of beams, the shear capacity increased by 0, 22.9 and 33.6%, and the actual shear capacity of each case was 69, 192.0 and 223.5 kN, respectively. It indicates that the shear capacity of RC beams with using a U-shaped UFC permanent formwork increased drastically but not proportionally with the increase in thickness of formwork. It is because the crack opening width between concrete and UFC slightly increased compared to UFC20-KB and the shear transfer from the internal surface decreased. Therefore, the shear capacity slightly decreased. In UFC30-KB specimen, the failure pattern was the same as observed in UFC20-KB specimen. The shear resisting mechanism of UFC30-KB was also the same as observed in UFC20-KB specimen as already explained. Therefore, even if the thickness of formwork increased, shear keys and screws and bolts system contributed to the compatibility and sufficient bonding between UFC formwork and RC part.

3.4 Effect of presence of stirrups

Figure 10 shows the load-deflection relationship of Ref, UFC20-KB and UFC20-KB-r specimen. From Table 4, in the order of the ratio of shear capacity, specimens can be arranged as UFC20-KB and UFC20-KB-r with the ratio of 2.78 and 3.10, respectively. The crack patterns of UFC formwork and RC part in UFC20-KB-r was similar to those observed in UFC20-KB as shown in Figure 6(d1) and (d2). Moreover, the cracking process of UFC20-KB-r was similar to that of UFC20-KB and UFC30-KB as explained before.

Figure 12 shows the relationship between load and stirrup strain of UFC20-KB-r specimen. Stirrup {1}, {2} and {3} correspond to those in Figure 1. The strain of stirrup {1} and {2} reached the yielding strain before the peak load, but stirrup {3} did not reach the yielding strain at that time. This indicated that after stirrups yielded, the opening of diagonal crack was resisted by a UFC formwork, and a UFC permanent formwork still carried the load until the peak load.

4. INVESTIGATION OF SHEAR CARRIED BY UFC PERMANENT FORMWORK

The shear carried by UFC permanent formwork that failed in diagonal tension was investigated. The shear capacity of RC beams using a UFC U-shaped permanent formwork was assumed to be the summation of shear carried by concrete, stirrups and UFC formwork. The calculation method for UFC formwork is discussed.

4.1 Shear carried by UFC permanent formwork observed in the experiment

The shear carried by UFC formwork was calculated by subtracting the shear carried by concrete and stirrups from the total shear capacity obtained from the loading test as calculated from Eq. (1).

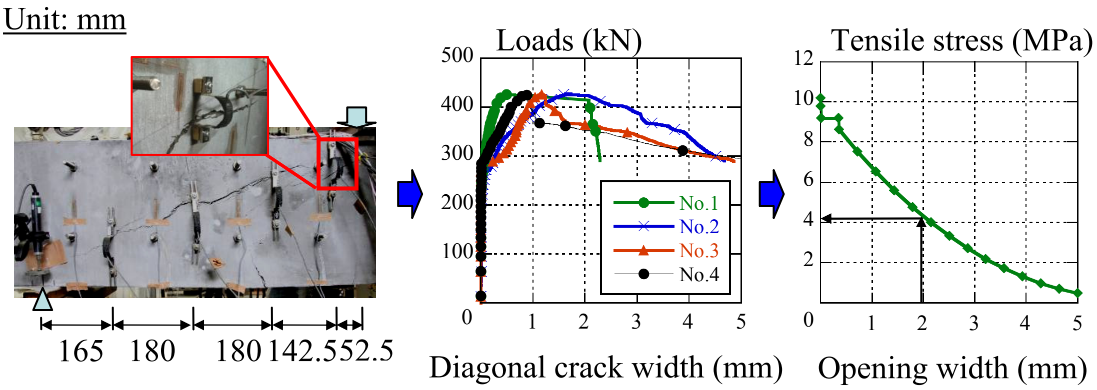
$$V_{UFC} = V_u - V_c - V_s \qquad (1)$$

where, V_{UFC} is the shear carried by UFC formwork, V_c is the shear carried by concrete and V_s is the shear carried by stirrups.

In this research, the shear carried by stirrups was calculated using the stirrup strain measured by strain gauges and a shear carried by concrete was obtained by Eq. (2) [3].

$$V_c = 0.2(f'_c)^{\frac{1}{3}}(p_w)^{\frac{1}{3}}\left[\frac{1000}{d}\right]^{\frac{1}{4}}\left[0.75+\frac{1.4}{a/d}\right]b_w d \qquad (2)$$

where, p_w is tension reinforcement ratio (%), b_w is web thickness (mm) and d is effective depth (mm).



(a) Picture of test span at the peak load (UFC20-KB-r) (b) Load-diagonal crack width (UFC20-KB-r) (c) Tension softening curve of UFC [4]

Figure 13: Investigation procedures of tensile stress

Table 5: Shear carried by UFC permanent formwork obtained in the calculation

Specimens	Thickness of UFC, *t* (mm)	Angle, θ (°)	Tensile stress, σ_{UFC} (N/mm²)	$V_{UFC\text{-}exp}$ (kN)	$V_{UFC\text{-}cal}$ (kN)	$V_{UFC\text{-}exp}/V_{UFC\text{-}cal}$
UFC20-KB	20	22.1	3.8	127.3	118.8	1.07
UFC30-KB	30	21.0	5.0	160.9	156.3	1.03
UFC20-KB-r	20	25.3	4.0	102.7	103.0	1.00

$V_{UFC\text{-}exp}$: experimental value of shear carried by UFC permanent formwork, $V_{UFC\text{-}cal}$: calculated value of shear carried by UFC permanent formwork by Eq. (3)

4.2 Shear carried by UFC permanent formwork obtained in the calculation

The shear carried by UFC formwork was computationally obtained based on a simplified shear carrying model. To compute the shear carried by UFC formwork, a linear crack with the constant angle of diagonal crack is assumed. The angles of diagonal cracks were measured from pictures taken at the peak load. As a result, the shear carried by UFC formwork based on this model is given by Eq. (3).

$$V_{UFC} = \frac{2 \cdot t \cdot \sigma_{UFC} \cdot d}{\tan\theta} \quad (3)$$

where, *t* is the thickness of UFC permanent formwork (mm), *d* is effective depth (mm) and θ is the angle of diagonal crack (°).

According to the tension softening curve of UFC measured by Kakei et al. [4], the tensile stress (σ_{UFC}) was determined. Investigation procedures of tensile stress are shown in Figure 13. The diagonal crack widths were measured by using four π-gauges along the diagonal crack (Figure 13 (a) and (b)). Therefore, the specimen was modeled as four elements corresponding to the interval of the π-gauge (Figure 13(a)). Then, the diagonal crack width along the shear span was transformed to the tensile stress by the tension softening curve

(Figure 13(c)). Then, the average value of tensile stress was substituted into Eq. (3) and the shear carried by UFC permanent formwork was calculated.

4.3 Result of the calculation

Table 5 summarizes the results of experimentally observed and computationally obtained shear carried by UFC formwork by Eq. (1) and Eq. (3), respectively. In all specimens, the calculation values present the good agreement with the experimental values. Thus, the proposed model was able to give a reasonable result by using the tensile stress obtained from the tension softening curve of UFC. This is because the diagonal crack on both UFC formwork and RC part was located almost in the same position, and also the diagonal crack widths of UFC were measured.

5. CONCLUSIONS

By using a U-shaped UFC permanent formwork, the shear carrying capacity of RC beams increased drastically. This is because a UFC formwork carried shear force and resisted the opening of diagonal cracks in RC part.

Shear resistance mechanisms of RC beams using a UFC U-shaped permanent formwork with shear keys and bolts were investigated. The shear capacity varied depending on the internal surface between UFC formwork and inside RC and the presence of screws and bolts.

With the increase in the thickness of UFC formwork, the shear capacity of RC beams using a UFC permanent formwork increased. However, it was not proportional to the thickness of a UFC permanent formwork.

The shear carried by a UFC formwork in RC beams that failed in the diagonal tension mode was investigated by assuming and using the tensile stress obtained from the tension softening curve. The computational values showed a good agreement with the experimental values.

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