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Shear Resistance Mechanisms of RC Beams Using U-Shaped UFC Permanent Formwork with Shear Keys and Bolts

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ABSTRACT

The objective of this paper is to investigate the shear behavior of RC beams using U-shaped UFC permanent formwork. Experimental parameters were the presence of shear keys and screwed bolts, the thickness of permanent formwork and the presence of stirrups. The specimens were subjected to four point bending. The experimental results indicated that 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. However, it was not proportional to the thickness of UFC formwork. The shear resistance mechanisms were investigated. By using UFC formwork with shear keys and screwed bolts, UFC formwork prevented the widening of diagonal crack inside RC by shear keys and screwed bolts. Finally, the shear carried by a UFC permanent formwork was investigated. The proposed calculation method can provide a good agreement with the experimental values.

Keywords. UFC, Permanent Formwork, Shear Resistance Mechanism, Shear Keys, Bolts

INTRODUCTION

In order to mitigate the seismic risk and social damage, the improvement of seismic performance of infrastructures is required. Since 1995 Great Hanshin earthquake, the standards specifications of Japan Society of Civil Engineers (JSCE) for seismic design of reinforced concrete structures (JSCE, 2007) 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 shear reinforcing bars and concrete became difficult to be filled up in casting. Moreover, as methods for shear retrofitting and strengthening of RC members, cross-sectional restoration, steel plate attachment and FRP sheet attachment have been started to be used. However, these methods have some problems such as corrosion of steel plate and brittle failure of FRP material. This demand can be achieved by the utilization of recently developed Ultra High Strength Fiber Reinforced Concrete (UFC). UFC is an advanced cementitious material which has outstanding properties, such as more than 150 MPa compressive strength, high ductility and durability (Katagiri et al., 2002).

Thus, newly-construction methods of UFC have been developed and started to be used. The permanent formwork for RC structures is one of the applications. Shirai et al. reported the application of UFC permanent formwork for repairing of Tedorigawa Bridge in Ishikawa prefecture, Japan. It shows that UFC formwork left in-place increased durability against chloride attacks, abrasion, and impact wear (Shirai et al., 2008). However, the research on the mechanical performance of the UFC formwork is insufficient. Also considering the relatively outstanding mechanical properties, UFC permanent formwork may improve the load bearing capacity.

Because of the above point of view, this study examined the construction method for RC beams using UFC permanent formwork. Therefore, the purpose of this paper is to investigate the mechanical performance of RC beams failing in shear with an U-shaped UFC permanent formwork. Four-point bending tests of RC beams using 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.

MATERIALS

Concrete

In this study, because of the presence of shear keys at the internal surface of U-shaped UFC permanent formwork, the self-compacting concrete was used in the experiment, and the details of mix proportion are summarized in Table 1. 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.

UFC and UFC Permanent Formwork

UFC is a material produced by mixing pre-mix powder of cement, silica fume, silica fine powder and silica sand in the optimum proportion with water and high performance

Table 1. Mix proportion of 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

Table 2. Mix proportion 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

polycarboxylic 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 performance of UFC is achieved to exhibit a flow value (JIS-R-5202.11) with around 260 mm for the material temperature of 20-25ºC even for including the steel fiber by 2% in volume. Therefore, it turns to be able to cast into the very thin complicated-shaped shell mold. After mixed materials have hardened, it undergoes the stream curing at 90ºC for 48 hours.

Steel Reinforcements and Screws and Bolts

The longitudinal reinforcing bars used in this research were deformed steel bar with 22 mm nominal diameter. The yield strength was 930 MPa and the ultimate strength was 1080 MPa. The specifications for the PC bars are according to JIS G 3109. The deformed steel bar of 10 mm in diameter was arranged as compression reinforcement. The yield strength was 339 MPa. The stainless steel with SUS304 specification grade screws and bolts with 10 mm diameter were used in this research. The yield strength and the tensile strength were 240 and 568 MPa, respectively.

EXPERIMENTAL PROGRAM

Experimental Parameters and Specimens

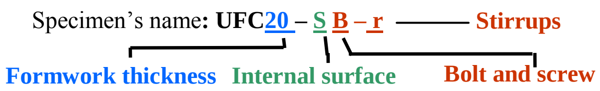
To investigate shear behavior of RC beams with U-shaped UFC permanent formwork, seven specimens were prepared. Four-point bending tests were conducted. The summary of test variables and details of specimens are provided in Table 3 and Fig. 1. The experimental cases can be classified into three series. 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 and the presence of screws and bolts were considered in Series-I, in which the name of specimens listed in Table 3 corresponds to them. Ref was the reference specimen in which the 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 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 same as Series-I, and shear keys and bolts were provided. The stirrups were provided in UFC20-KB-r, with stirrup ratio was 0.28% and spacing was 240 mm.

Table 3. List of the experimental cases

No.	Name	Thickness* (mm)	Internal Surface	Screws and bolts	Stirrup ratio (%)	Series
1	Ref	-	-	-	0	I, II
2	UFC20-K	20	Shear keys	-	0	
3	UFC20-SB	20	Smooth	Provided	0	I
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

*Thickness of UFC permanent formwork



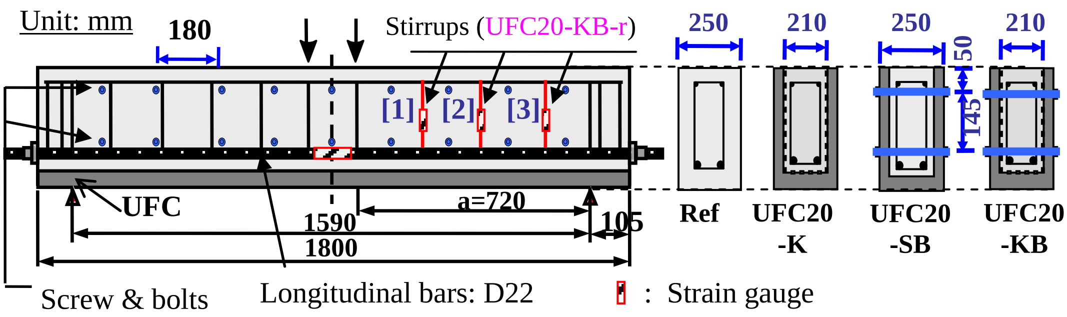


Figure 1. Detail of specimens

Fabrication of the Specimens

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

Loading Method and Measurement Items

Figure 3 shows the measurement items and the loading condition of specimens. 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 the horizontal friction. At the loading points on the top surface of the specimen, steel plates with 50 mm width, steel rollers and a load distribution beam were placed.

During the loading test, the applied load was measured. Mid-span deflection was measured using transducers. Strain gauges were used for measuring concrete strain on the top fiber at

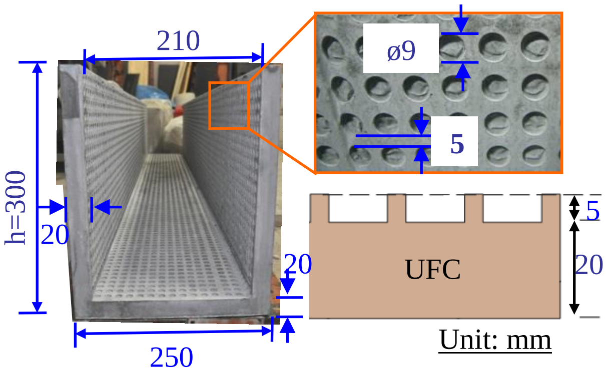


Figure 2. Detail of UFC formwork and shear keys

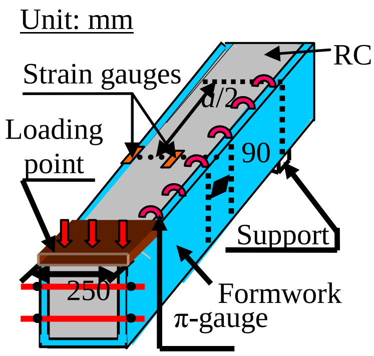


Figure 3. Measurements and loading condition

mid-span. The opening width between concrete and UFC formworks was measured by using π- gauges. Moreover, the strain gauges were attached at top edge of UFC formworks and RC to check the compatibility between UFC and concrete at support and mid of shear span in the longitudinal direction of the beam.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Increase Rate of Shear Capacities 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 order of ratio of shear capacity with 2.32, 2.42, 2.58 and 2.78, respectively. It indicates that 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 providing screws and bolts was larger than that with providing shear keys. Furthermore, the shear capacity of the beam with shear keys and providing screws and bolts was the largest.

Table 4. Mechanical properties of concrete and UFC and result of loading tests

Name	Mechanical properties of concrete		Mechanical properties of UFC		Results of loading test			
	f'_c (MPa)	f_t (MPa)	f'_{c_UFC} (MPa)	f_{t_UFC} (MPa)	P_{cr} (kN)	P_{max} (kN)	V_u (kN)	n
Ref	32.8	2.1	-	-	45.0	138.0	69.0	1.0
UFC20-S	43.5	2.5	194.7	10.1	105.1	319.6	159.8	2.32
UFC20-K	36.6	2.7	191.5	13.9	90.6	334.6	167.3	2.42
UFC20-SB	33.5	2.5	192.6	11.4	95.3	355.8	177.9	2.58
UFC20-KB	40.4	2.1	184.2	11.9	82.1	384.0	192.0	2.78
UFC30-KB	36.2	2.2	181.8	12.0	92.0	447.0	223.5	3.24
UFC20-KB-r	36.4	2.7	170.5	12.4	92.6	427.6	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, P_{max}: Peak load, V_u: Shear Capacity, n : Ratio of shear capacity

Load-Deflection Relationship and Cracks Patterns in Series I

Figure 4 shows the relationship between load and the mid-span deflection. Figure 5 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 Fig. 4 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 Fig. 5(a). In UFC20-K specimen, the flexural cracks initiated when the load was 90 kN. When the load reached to the peak, the inclined crack located from the support to loading point propagated and widened as shown in Fig. 5 (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 Fig. 5(c1). Figure 5(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 to the peak (384 kN), the critical diagonal crack was propagated and widened, and the crushing of UFC under the loading point occurred as shown in Fig. 5(d1). Figure 5(d2) shows the diagonal crack of inside RC part. It seems that the diagonal crack of inside RC part occurred at the same location of that in the UFC permanent formwork.

Shear Resistance 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 mechanism in UFC20-K and UFC20-KB specimens are explained below.

In UFC20-K specimen, although a diagonal crack occurred, but UFC on the side of the RC part prevented the widening of the diagonal crack, then the interlock action became effective,

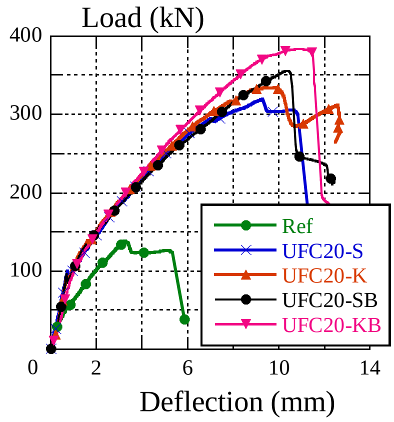


Figure 4. Load-deflection relationships (Series–I)

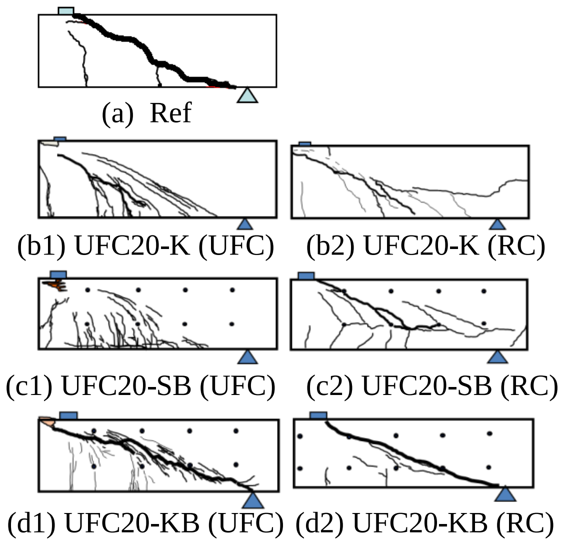


Figure 5. Crack patterns (Series-I)

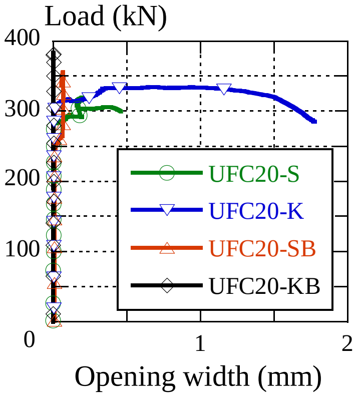


Figure 6. Load-opening width in Series-I

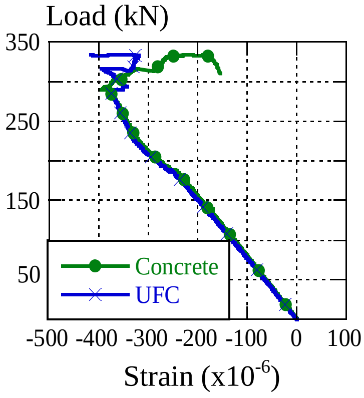


Figure 7. Load-strain at the top surface (UFC20-K)

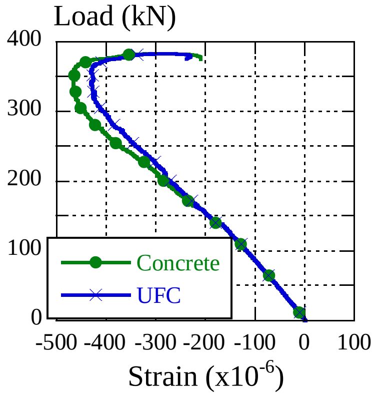


Figure 8. Load-strain at the top surface (UFC20-KB)

therefore, shear forces increased. After that, since 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 Fig. 6, and the UFC formwork and RC part showed different behavior after $0.9P_{max}$ as shown in Fig. 7. After that, the load reached to the peak and failure occurred.

For UFC20-KB, as shown in Fig. 8, the strain at the top surface at the mid of shear span of RC part and UFC formwork showed similar values. So, it can be said that the beam have compatibility until the test finished. It is noted that the opening width between RC and UFC formwork was very small as shown in Fig. 6. Firstly, a diagonal crack initiated in RC part, however, 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 was remained. After that, as the load increased, the diagonal crack in RC part attempted to widen and 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 were observed on the UFC formwork as shown in Fig. 5(d1). Then, the main diagonal crack on UFC occurred at $0.7P_{max}$ but the load was still increasing, while the opening width of diagonal crack was increasing. Then, the load reached to the peak and the failure occurred.

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 Fig. 9, specimens can be arranged as UFC20-KB and UFC30-KB in order of enhancement ratio of shear capacity (R). Also, Fig. 10 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 U-shaped UFC permanent formwork increased drastically with increasing in thickness of formwork but it is not proportional. It is because the crack opening width between concrete and UFC slightly increased compared to UFC20-KB and the shear transfer from 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

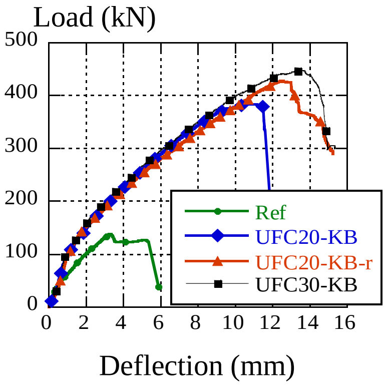


Figure 9. Load-deflection relationships (Series-II and III)

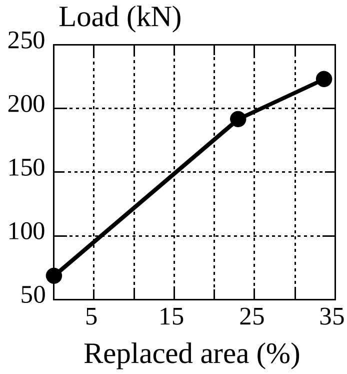


Figure 10. Shear capacity-replaced area of UFC relationship

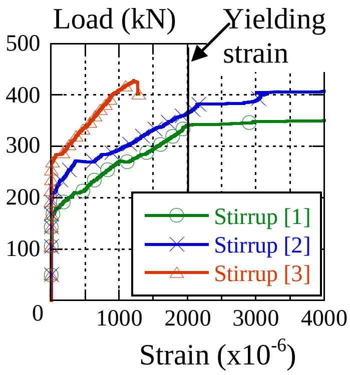


Figure 11. Load-stirrup strain relationships

increased, shear keys and screws and bolts system contributed to the compatibility and sufficient bonding between UFC formwork and RC part.

Effect of Presence of Stirrups

Figure 9 shows the load-deflection relationship of Ref, UFC20-KB and UFC20-KB-r specimen. From Table 4, in order of ratio of shear capacity, specimens can be arranged as UFC20-KB and UFC20-KB-r with 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 Fig. 5(d1) and (d2). Moreover, the cracking process of UFC20-KB-r was similar to UFC20-KB and UFC30-KB as explained before.

Figure 11 shows the relationship between load and stirrup strain of UFC20-KB-r specimen. Stirrup [1], [2] and [3] are corresponding to those in Fig. 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. It indicates that after stirrups yielded, the opening of diagonal crack was resisted by UFC formwork, and UFC permanent formwork still carried the load until the peak load.

INVESTIGATION ON SHEAR CARRIED BY UFC U-SHPAED PERMANENT FORMWORK

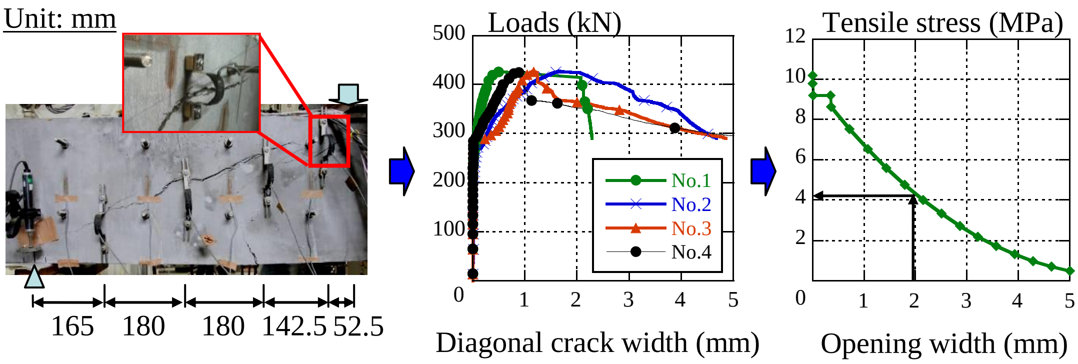
Shear Force Carried by UFC Permanent Formwork Observed in Experiment

The shear force carried by UFC formwork was calculated by subtracting the shear force 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 force carried by UFC formwork, V_c is the shear force carried by concrete, V_s is the shear force carried by stirrups.

In this research, the shear carried by stirrups was calculated using the stirrup strain measured by strain gauges and shear carried by concrete was obtained by Eq. (2) (Niwa et al., 1987)



(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

Figure 12. Investigation procedures of tensile stress

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

where, V_c is the shear capacity of normal RC beams without stirrups (N), f'_c is compressive strength of concrete (MPa) , p_w is tension reinforcement ratio (%), b_w is web thickness (mm) and d is effective depth (mm).

Shear Force Carried by UFC Permanent Formwork Obtained in Calculation

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

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

where, t is the thickness of UFC permanent formwork, d is effective depth and θ is the angle of diagonal crack .

Shear forced carried by UFC is assumed to be the tensile force along the crack line, the tensile stress (σ_{UFC}) was determined by the tension softening curve of UFC. Investigation

Table 5. Shear force carried by UFC formwork obtained in the calculation

Specimens	Thickness of UFC, t (mm)	Angle, θ (°)	Tensile stress σ_{UFC} (MPa)	$V_{UFC\text{-}exp}$ (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)

procedures of tensile stress are shown in Fig. 12. The diagonal crack width was measured by using four π-gauges along the diagonal crack (Fig. 12 (a) and (b)). Therefore, the specimen was modelled as four elements corresponding to the interval of the π-gauge (Fig. 12(a)). Then, the diagonal crack width along the shear span was transformed to the tensile stress by the tension softening curve (Fig. 12(c)). Then, the average value of tensile stress was substituted into Eq. (3) and the shear carried by UFC permanent formwork was calculated.

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 the same position, and also the diagonal crack width of UFC was measured.

CONCLUSIONS

(1) The shear capacity of RC beams using U-shaped UFC permanent formwork with shear keys and bolts greatly increased. This is because UFC permanent formwork carried shear force and resisted the opening of diagonal cracks in RC part.

(2) Shear resistance mechanisms of RC beams using 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 RC inside and the presence of screws and bolts.

(3) By using shear keys and screwed bolts system, the sufficient compatibility behavior between UFC and RC can be formed. Since a UFC formwork prevented widening of diagonal crack inside RC by shear keys and screws and bolts, the shear capacity drastically increased.

(4) By assuming and using the tensile stress obtained from the tension softening curve, the shear carried by a UFC formwork in RC beams was examined. The calculated values showed the good agreement with the experimental values.

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