- Technical Paper -

EVALUATION ON SHEAR CAPACITY OF RC BEAMS USING U-SHAPED UFC PERMANENT FORMWORK

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ABSTRACT

Shear resistance mechanism of RC beams using U-shaped UFC has been examined. Experimental parameter was effect of thickness of formwork, presence of stirrup and shear span to effective depth ratio(*a/d*). The results showed that UFC permanent formwork enhanced the shear capacity of RC beams and the failure mode changed depending on *a/d*. Moreover, the shear capacity increased with increasing in thickness of formwork and presence of stirrup. Finally, the evaluation methods for shear carried by UFC permanent formwork in RC beams were investigated.

Keywords: permanent formwork, shear capacity, UFC, tension softening relationship, *a/d*

1. INTRODUCTION

Ultra High Strength Fiber Reinforced Concrete (UFC) is an advanced cementitious material which has outstanding properties, such as more than 150 MPa compressive strength, high ductility and high durability. The permanent formwork for RC structures is one of the applications of UFC. The definition for permanent formwork derived from CIRIA C558 is that the permanent formwork is a structural element of whatever material that is used to contain the placed concrete, mold it to the required dimensions and remain in place for the life of the structure [1].

Nowadays, UFC permanent formwork has started to be used in Japan. Shirai et al. [2] 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. Moreover, the U-shaped UFC permanent formwork with shear keys and screws and bolts system which were provided to fix the UFC permanent formwork to the inside RC was introduced by the authors [3]. The results show that the shear capacity of RC beams using UFC U-shaped permanent formwork increased drastically.

However, the available studies on the mechanical performance of RC beams using UFC permanent formwork is insufficient and the effect of shear span to effective depth ratio (*a/d*) has not been considered. In addition, the evaluation method for shear carried by U-shaped UFC permanent formwork has not been clarified yet. Therefore, the objective of this paper is to evaluate the shear capacity of RC beams using UFC permanent formwork with considering the effect of thickness of formwork, presence of stirrup and *a/d*. The specimens were subjected to four-point bending. Shear capacities, crack patterns and failure mechanism were investigated.

2. EXPERIMENTAL PROGRAMS

2.1 Experimental parameters and specimens

To evaluate the shear capacity of RC beams with U-shaped UFC permanent formwork, six specimens were prepared. Four-point bending test variables and details of specimens are provided in Table 1 and Fig. 1, respectively. The experimental cases can be classified into two series. Series-I was to examine the effect of thickness of UFC permanent formwork and presence of stirrups inside RC. Figure 1 shows dimension, arrangement of reinforcing steel bar and cross section of all specimens in Series-I. 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. Series-II

Table 1 Experimental cases

Name	t (mm)	r_w (%)	a/d	Series
Ref	-	0	3.27	I
UFC20-KB	20	0	3.27	I, II
UFC30-KB	30	0	3.27	I
UFC20-KB-r	20	0.28	3.27	I
UFC20-KB-ad21	20	0	2.16	II
UFC20-KB-ad1	30	0	1.00	II

t = Thickness of UFC formwork, r_w = Stirrup ratio, a/d =Shear span to effective depth ratio

Specimen's name: **UFC20–K B -r — *a/d* or stirrups**

Form thickness (20), **Internal surface** (K), **Bolt & screw** (B)

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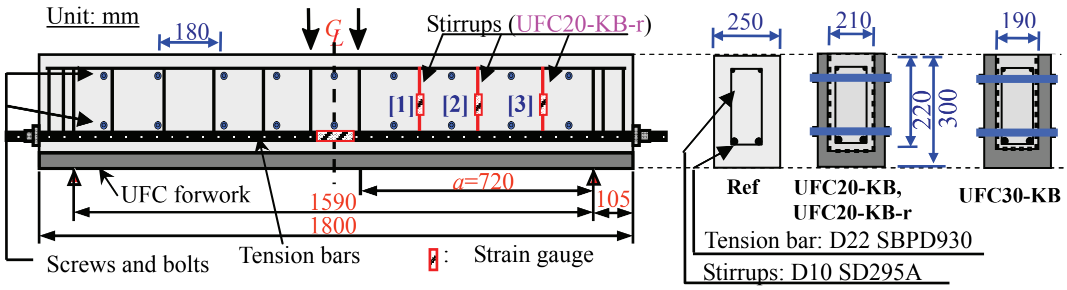
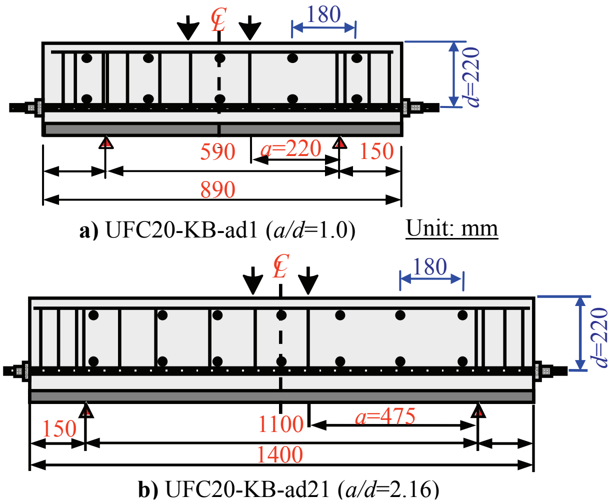


Fig. 1 Detail of specimens



a) UFC20-KB-ad1 (a/d=1.0)

b) UFC20-KB-ad21 (a/d=2.16)

Fig. 2 Detail of specimens in Series-II

Table 2 Mix proportions of concrete

G_{max}	W/C	Unit weight (kg/m^3)						
[mm]	[%]	W	C	L	S	G	SP	V
13	57	165	292	249	718	857	4.38	0.25

W: Water, C: Cement, L: Lime stone powder, S: Fine Aggregate, G: Coarse Aggregate, SP: Superplasticizer, V: Viscosity improver

Table 3 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

investigated the effect of shear span to effective depth ratio (a/d). Series-II consisted of three specimens with different shear span. Effective depth of the beams was same, but the shear span was varied. The original specimen was UFC20-KB with a/d=3.27. The a/d of UFC20-KB-ad1 and UFC20-KB-ad21 were 1.00 and 2.16, respectively. Figure 2 shows the dimension of UFC20-KB-ad1 and UFC20-KB-ad21 specimen. The shear keys and screws and bolts system was provided to fix the UFC permanent formwork to the inside reinforced concrete for all specimens excepted Ref. Figure 3 shows the detail of UFC formwork and shear keys.

2.2 Materials

The self-compacting concrete was used in this experiment, and the detail of mix proportion is summarized in Table 2. The designed compressive strength of 7-day age concrete was 35 MPa. The tension bars used in this research were deformed steel bar with 21.6 mm nominal diameter. The yield strength was 1026 MPa. The deformed steel bar of 10 mm in diameter was arranged as compression reinforcement. The yield strength was 339 MPa.

Mix proportion of UFC formwork is shown in Table 3. The steel short fibers with 0.2 mm diameter and 15 mm length were used. The volume fraction of steel fibers in all specimens was 2.0%.

2.3 Specimen fabrication

Firstly, the U-shaped UFC permanent formwork was fabricated. After that, reinforcing bars and screws and bolts were arranged and put in UFC formwork. Finally, concrete was cast in the formwork to make a structural component.

2.4 Loading method and measurement items

Specimens were subjected to a four-point bending with load applied to both the UFC and RC at the same time. 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. Moreover, on the side surface of UFC permanent formwork, four π-gauges were used to measure the diagonal crack opening width along the diagonal line between the loading point and support (See Fig. 14(a)). Figure 4 shows the measurement items and loading condition. In addition, in UFC20-KB-ad1, strains of concrete and UFC were measured by using the acrylic bars and concrete strain gauges, respectively. Figure 5 shows the arrangement of acrylic bars inside concrete. Concrete strain gauges were attached at the same position of those on acrylic bars.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Load-deflection relationships and failure pattern in Series-I

Table 4 shows mechanical properties of concrete and UFC, and the result of loading tests. Figure 6 shows the relationships between the load and the mid-span deflection. From Table 4, specimens can be arranged as UFC20-KB, UFC20-KB-r and UFC30-KB in order of the ratio of shear capacity (R) which is a

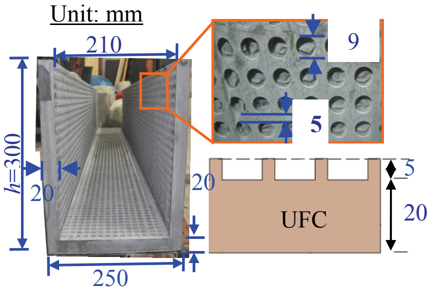


Fig. 3 Detail of UFC formwork and shear keys

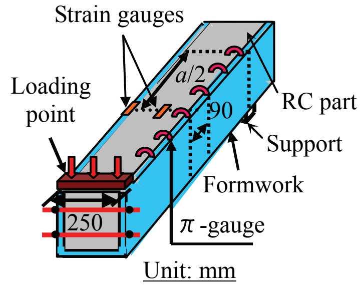


Fig. 4 Measurements and loading condition

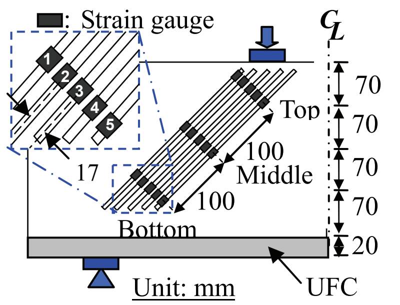


Fig. 5 Arrangement of acrylic bars

Table 4 Mechanical properties of concrete and UFC, and the 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)	Flexural cracking load (kN)	V_u (kN)	Failure mode	R
Ref	32.8	2.1	-	-	45.0	69.0	*DT*	1.0
UFC20-KB	40.4	2.1	184.2	11.9	82.1	192.0	*DT*	2.78
UFC30-KB	36.2	2.2	181.8	12.0	92.0	223.5	*DT*	3.24
UFC20-KB-r	36.4	2.7	170.5	12.4	92.6	213.8	*DT*	3.10
UFC20-KB-ad21	33.1	2.2	182.7	23.6	142.8	248.1	*SC*	-
UFC20-KB-ad1	30.6	2.3	177.8	10.8	334.2	529.3	*SC*	-

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, V_u : Shear capacity, *DT*: Diagonal tension, *SC*: Shear compression, R : Ratio of shear capacity

ratio of shear capacity in each specimen divided by a Ref specimen. It indicates that by using the U-shaped UFC formwork on the cross section of a RC beam, the shear capacity increased drastically. In addition, the shear capacity of RC beams with using U-shaped UFC permanent formwork significantly increased with increasing in thickness of formwork. Moreover, the opening of diagonal crack in concrete was resisted by UFC formwork and stirrups. Hence, since the stirrups were provided in RC part, the shear capacity of the beams was increased.

Figure 7 shows the crack pattern of UFC20-KB specimen. After the loading test, UFC formwork was removed and diagonal crack of inside RC part was observed. The red lines in Fig. 7 represent the critical cracks. 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. 7(a). Figure 7(b) 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.

In comparison, the cracking process and shear resisting behavior of UFC30-KB and UFC20-KB-r were the same as that of UFC20-KB mentioned above. When the thickness of formwork was increased and stirrups were provided, the compatibility and efficient bonding of RC and UFC formwork by using shear keys and bolts can be secured.

3.2 Effect of shear span to effective depth ratio

Figure 8 shows the relationships between the load and the mid-span deflection of UFC20-KB-ad21, UFC20-KB-ad1 and UFC20-KB where the first two specimens failed in shear compression failure mode. Table 4 shows the experimental results in Series-II.

For UFC20-KB-ad21, although a diagonal crack on UFC formwork initiated, the diagonal tension failure did not occur since UFC prevented widening of diagonal crack inside RC part. Consequently, the compressive stress acted above the diagonal crack. As a result, the top fiber strains of both UFC and concrete (see Fig. 4) were changed into the reverse direction as shown in Fig. 9. Here, the tensile strain is shown as positive, conversely, negative shows the compressive strain. The flexural tension stress occurred at the upper edge of both UFC and RC. After that, the load reached to the peak because of the crushing of UFC near the loading point as shown in Fig. 10(a1). Moreover, the visible sliding along the diagonal crack was also observed.

From the descriptions above, it can be said that when the *a/d* ratio changed from 3.27 to 2.16, the failure mode changed from the diagonal tension failure to the shear compression failure because of the compression stress acted above the diagonal crack and crushing of the UFC occurred near the loading point.

3.3 Compressive strain of concrete in the strut formation of UFC20-KB-ad1

The failure mechanism of UFC20-KB-ad1 was examined by using the strains measured in the compressive strut of both concrete and UFC. The

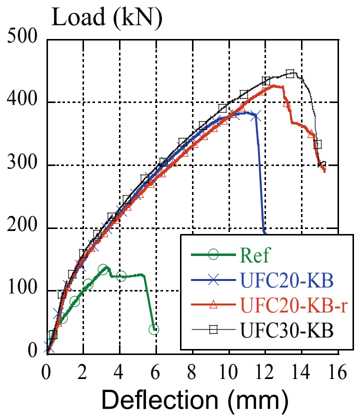


Fig. 6 Load-deflection relationships in Series-I

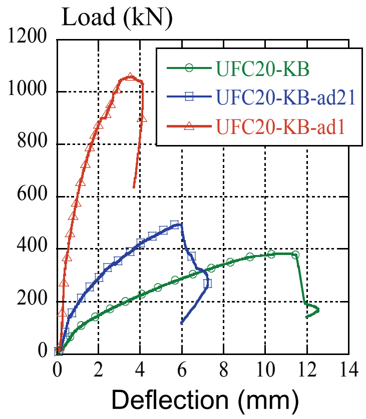


Fig. 8 Load-deflection relationships in Series-II

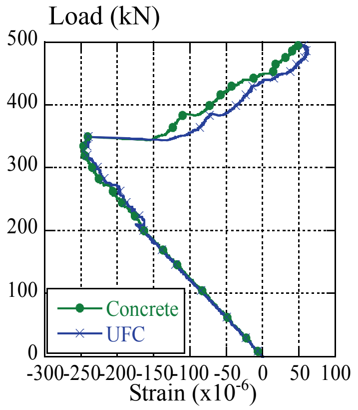


Fig. 9 Load-strain at the upper surface (UFC20-KB-ad21)

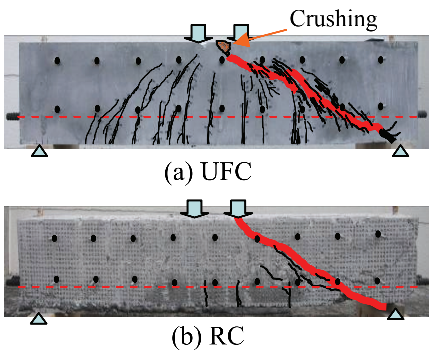


Fig. 7 Crack patterns of UFC20-KB

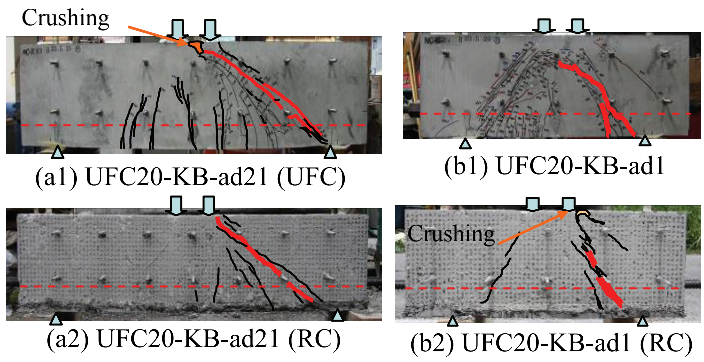


Fig. 10 Crack patterns (Series-II)

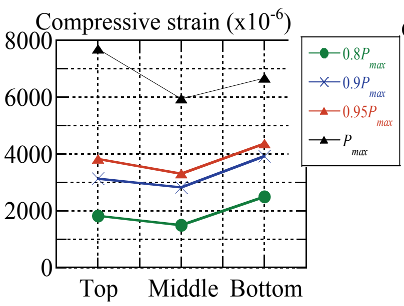


Fig. 11 Maximum compressive strain of concrete

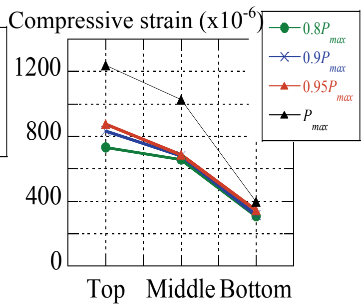


Fig. 12 Maximum compressive strain of UFC

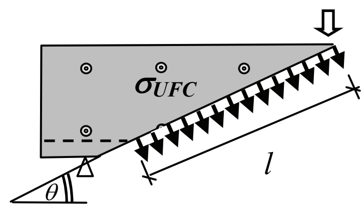


Fig. 13 Shear carrying model for UFC formwork in diagonal tension

strains of concrete and UFC were measured by using the acrylic bars and concrete strain gauges, respectively. Figures 11 and 12 show the development of the maximum compressive strain of concrete among the five strain gauges (see Fig. 5) near the loading point (Top), center of the strut (Middle) and near the supporting point (Bottom) of concrete and UFC, respectively. In both concrete and UFC, compressive strains increased drastically near the peak load because the compression struts were formed in both concrete and UFC formwork. Therefore, the compressive strains reached ultimate strain and the crushing of concrete occurred. It should be noted that the distribution of compressive strain of both concrete and UFC seems to be different.

4. INVESTIGATION OF SHEAR CARRIED BY U-SHAPED UFC PERMANENT FORMWORK

4.1 Shear Carried by UFC Permanent Formwork Failed in Diagonal Tension

(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)

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

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

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

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

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

(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 as shown in Fig. 13. The crack length of permanent formwork and the angle of diagonal crack are represented by l and θ, respectively. Therefore, 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), and d is effective depth (mm).

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 Fig. 14. The diagonal crack width measured by using four π-gauges along the diagonal crack. Then, the diagonal crack width along the shear span was transformed to the tensile stress by the tension softening curve. Then, the average value of tensile stress was substituted into Eq. (3) and the shear carried by UFC permanent formwork can be calculated.

(3) Result of the calculation

The ratio of experimentally observed shear carried by UFC formwork to computationally obtained value by using the tension softening curve is shown in Table 5. In all specimens, the calculation values present a good agreement with the experimental values. Thus, the proposed model was able to give a reasonable result by using the tensile stress that was 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.

4.2 Shear carried by UFC permanent formwork failed in shear compression

As mentioned, UFC20-KB-ad1 specimen failed in the shear compression failure mode. The shear carried by UFC permanent formwork failed in the shear compression failure mode is examined in this session.

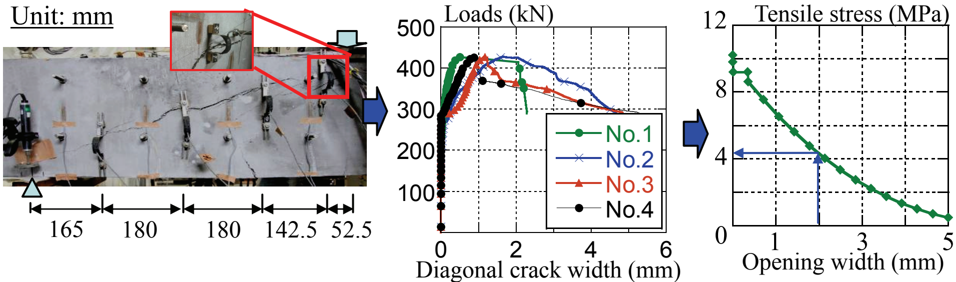
(1) Compressive stress distribution and width of strut

Figure 15 presents the method for determining width of the compressive strut. The maximum strain point and both minimum strain points at 95 percentage of peak load ($0.95P_{max}$) were connected by straight dashed lines and the width of compression strut was assumed to be the distance between the 2 points where the dashed lines cut the x-axis which means that the strains equal to 0. Assuming that the strains of acrylic bars and concrete were the same and the stress state was assumed as uni-axial compression and the strain measured on UFC was considered also in the same way. From the stress-strain model, the measured strains of both concrete and UFC were transformed to stress. For

Table 5 Experimentally observed and calculation obtained shear carried by UFC formwork

Specimens	t (mm)	θ (°)	f_{t_UFC} (MPa)	σ_{UFC} (MPa)	$V_{UFC-exp}$ (kN)	$V_{UFC-cal}$ (kN)	$V_{UFC-exp}/V_{UFC-cal}$
UFC20-KB	20	22.1	11.9	3.8	127.3	118.8	1.07
UFC30-KB	30	21.0	12.0	5.0	160.9	156.3	1.03
UFC20-KB-r	20	25.3	12.4	4.0	102.7	103.0	1.00

σ_{UFC}: the tensile stress obtained from tension softening curve, $V_{UFC-exp}$: experimental value of shear carried by UFC permanent formwork, $V_{UFC-ca2}$: calculated value of shear carried by UFC permanent formwork



(a) Picture of test span at the peak load (b) Load-diagonal crack width (c) Tension softening curve of UFC

Fig. 14 Investigation procedures of tensile stress (UFC20-KB-r)

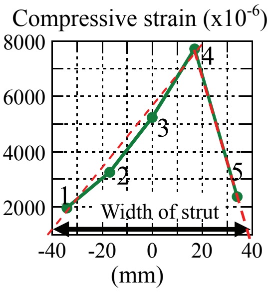


Fig. 15 Definition of the compressive strut

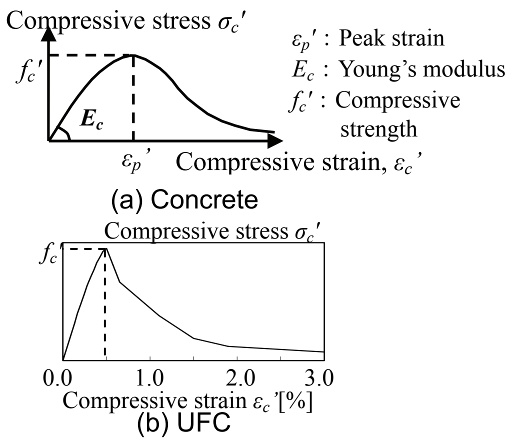


Fig. 16 Stress-strain relationship for concrete and UFC in compression

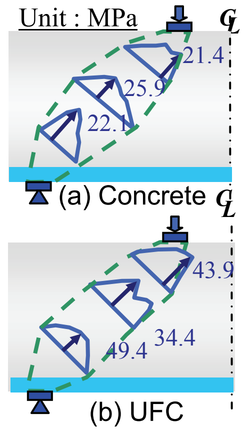


Fig. 17 Compressive stress distributions

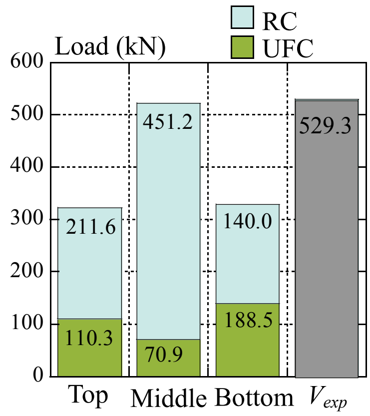


Fig. 18 Shear resisting force of UFC20-KB-ad1

concrete, the stress-strain model proposed by Thorenfeldt et al. [5] shown in Fig. 16(a) was used to calculate the compressive stress. For UFC, the stress-strain model of UFC based on the experimental results proposed by Kakei et al. [4] shown in Fig. 16(b) was used to calculate the compression stress. Figure 17(a) and (b) show the compressive stress distributions of concrete and UFC permanent formwork, respectively. In a concrete part, the strut width at the middle was wider than that near the loading point and near the support. It means that the stress concentrations were observed in both near loading and supporting points.

(2) Calculation of the compressive force

The stress distributions of both concrete and UFC were converted to the vertical component of the compressive force acting on the concrete strut and UFC strut by using Eqs. (4) and (5).

$$F_{st} = D \times b_i \quad (4)$$

$$F' = F_{st} \times \sin\alpha \quad (5)$$

where, F_{st} is the compressive force acting on the concrete or UFC strut, D is the force per unit width under the compressive stress distribution curve, b_i is the width of cross section of concrete or both of UFC formwork thickness, F' is the vertical component of F_{st}, α is the angle of the strut with respect to the longitudinal axis of beams.

Figure 18 shows the comparison of the summation of calculated value F' from RC and UFC with the experimental shear capacity V_{exp}. The summation of F' at the middle provided the good agreement with V_{exp}. However, the summation of F' underestimated V_{exp} at the top and bottom location. It can be predicted that because the uni-axial stress-strain model (Thorenfeldt's model) was used while the compression strut of inside concrete was constrained by the formwork with screws and bolts.

5. CONCLUSIONS

(1) The failure mode of RC beams using a UFC U-shaped permanent formwork changed depending on the shear span to effective depth ratio (*a/d*). Compression strut was formed in a UFC formwork in the case of *a/d* equal to 2.16 and 1.0.

(2) The shear carried by a UFC formwork in RC beams 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 the good agreement with the experimental values.

(3) Compression forces of a UFC formwork and RC part in the specimen with *a/d*=1.0 calculated by using uni-axial stress-strain model did not show the good agreement near the screwed bolts. It indicated that the constraint effect of screwed bolts should be considered to evaluate the shear compressive capacity.

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