Experimental Study on Mechanical Properties of Ultra High Strength Fiber Reinforced Concrete Beam

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In recent years, Ultra High Strength Fiber Reinforced Concrete (UFC) attracts attention as a new material corresponding to large-sized or high durability structures. Since UFC is reinforced with the steel fiber in addition to 200 N/mm² or more compressive strength, it is also excellent in toughness. In this research, an experiment with (1) static load or (2) running load was performed by three kinds of specimens with different height, and at the same time the influence by running load was evaluated.

1. INTRODUCTION

Attention is lately focused on the ultra high-strength fiber reinforced concrete (hereinafter called the “UFC”), or a concrete material produced by reinforcing a high-strength cementitious matrix with high-strength steel fiber\(^3\). The UFC is a composite material composed of cement, silica fume, fine aggregate and steel fiber, without using coarse aggregate. The UFC is a new material with its compressive strength increased up to 200 N/mm² at a low water-to-cementitious material ratio by the densest packing of powders and the high temperature curing.

Assuming the applications of the UFC for the elements of bridges, such as floor slabs and main girders, the authors conducted (1) a static load test and (2) a running load test using three types of UFC beams to clarify the mechanical properties of the UFC under a continuously running load. The objective of this research is to examine the mechanical properties of the UFC from the aspect of the strength and failure mechanism as well as to study the effects of the running load.

2. PREPARATION OF TEST SPECIMENS

2.1 Materials used

UFC test specimens are rectangular beams (unreinforced) manufactured by mixing a premix of powders, including Portland cement, silica fume and powdered silica sand, (Ductal FM manufactured by Taiheiyo Cement Corp.) with a water reducing agent, water and ultra high-strength steel fibers (0.2 mm in diameter

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Mix proportion of UFC (unit in kg/m³)</th>
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<tbody>
<tr>
<td>Water</td>
<td>Steel fiber</td>
</tr>
<tr>
<td>180</td>
<td>157</td>
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<tr>
<th>Table 2</th>
<th>Characteristic value of material strength (N/mm²)</th>
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<tbody>
<tr>
<td>Compressive strength</td>
<td>Flexural strength</td>
</tr>
<tr>
<td>216.3</td>
<td>25.5</td>
</tr>
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</table>

Fig. 1 Maximum dense filling image of UFC
and 15 mm in length). Table 1 lists the mix proportion of the UFC.

### 2.2 Features of the UFC

The UFC makes it possible to keep the hydration reaction limit as to well as control the size of particles based on the concept of the densest packing (Fig. 1). The UFC holds a self-filling function without changing the flowability before and after the mixing of steel fibers. In addition, because a large quantity of a water reducing agent is used, the setting time is long, such as 18-20 hours, and the UFC after casting is cured at normal temperatures for 48 hours (primary curing) and thereafter with steam at 90°C for 48 hours (secondary curing).

After the secondary curing, cracking is controlled by the bridging effect of steel fiber even after initial cracking occurs, and the UFC increases its flexural resistance and shows flexural ductility even after the stress reaches the maximum value. In addition, because of the high bond strength and high elastic modulus of steel fiber, the flexural resistance increases without a transient drop in stress or a sharp increase in displacement after the initial cracking 3).

### 2.3 Strength characteristics of the UFC

Table 2 lists the results of a bending test (JIS R5201) using 100×100×400 mm test specimens after the secondary curing, and a compression test (JIS A1106) and splitting tensile strength test (JIS A1113) using ∅100×200 mm test specimens. Figures 2, 3 and 4 show the relationship between the compressive stress and strain obtained from the compression test, the relationship between the tensile stress and strain obtained from the splitting tensile strength test, and the relationship between the flexural stress and strain at the bottom of the test specimen in the center of the span obtained from the bending test, respectively.

As can be seen from the increase in the strain in Fig. 2, the ultimate compressive strain of the UFC is about twice larger than that of ordinary concrete, about 2,100×10^-6,9 indicating that the UFC is highly deformable. In addition, the volumetric strain of the UFC shows a linear behavior until the ultimate state, indicating that the UFC has no such critical point 9) as is the case of the ordinary concrete. The reason for this is considered that no bond cracking (cracking along the boundary between coarse aggregate and mortar) takes place because coarse aggregate is not mixed in the UFC. The modulus of elasticity of the UFC calculated from the secant modulus of elasticity (JIS A1149) is 51.2 kN/mm². As is apparent from Fig. 3, although the hypothesis of linear elasticity holds true for the relationship between tensile stress and strain of the UFC in the initial stage, the strain increases sharply as the load increases. The values

![Fig. 2 Compressive stress-strain relation](image1)

![Fig. 3 Tensile stress-strain relation](image2)

![Fig. 4 Bending stress-Strain relation](image3)

![Fig. 5 Detail of test specimen](image4)

![Fig. 6 Running vibration-load test unit](image5)
listed in Table 2 are based on the following definitions: the cracking strength is the stress at which the hypothesis of linear elasticity does not hold true; and the tensile strength is the maximum stress after cracking has occurred. The strain at which the cracking occurs is about $244 \times 10^{-6}$. As is clear from Fig. 4, the flexural stress of the UFC increases even after the initial cracking. This tendency is similar to the behavior of strains shown by a metal after yielding. This tendency seems due to the bridging effect of steel fibers, or the effect of controlling cracking and retaining the strength. Further, because no sharp decrease in flexural stress is seen after the initial cracking, the bond strength and elastic modulus of steel fiber are high, and the steel fiber is resistant to external forces. The above-mentioned test results prove that the UFC is a structural composite with high strength and high ductility.

2.4 Dimensions of test specimens

The dimensions of test specimens used for the static and running load tests are 1,000 mm in span and 100 mm in width, with three different heights: 100 mm for Type I, 150 mm for Type II, and 200 mm for Type III. Figure 5 shows the shapes of the test specimens.

3. OUTLINE OF THE TESTS

3.1 Running vibration test equipment

The running vibration test equipment used for the static running load tests is designed to reproduce the state in which a load is running by reciprocating a carriage, on which a test specimen is mounted, in the horizontal direction using a motor and crank arm, with a hydraulic vibration fatigue testing machine equipped with a steel wheel on the beam of a steel reaction frame (400 kN) fixed. The test equipment consists of (1) a vertical loading unit, (2) a carriage on which a test specimen is mounted, and (3) a unit for reciprocating the carriage in the horizontal direction. Figure 6 shows the running vibration test equipment.

(1) Static load bending test (M)

The static load bending test is a test in which a load is exerted on the test specimen while the wheel is in a resting condition in the center of the span where the maximum stress is induced, as shown in Fig. 7 (a). The load is added in increments of 5.0 kN until the test specimen fails. The load is applied repeatedly until the specimen fails, from 0.0 kN to 5.0 kN at the maximum for the 1st time, from 0.0 kN to 10.0 kN at the maximum for the 2nd time, for example.

(2) Running load test (R)

The running load test is a cyclic load test, with the following taken as one cycle: a load is first exerted on the test specimen while the wheel is in a resting condition at the support point A, and the wheel then starts running and turns at the support point B back to the support point A, as shown in Fig. 7 (b). The running speed is 22 cm/sec. The load is added in increments of 5.0 kN in one cycle until the test specimen fails.

4. FAILURE MECHANISM

Figure 8 shows the typical conditions of the test specimen cracked during the test. Because many fine cracks developed, only the area around the center of the span where the specimen suffered heavy cracking damage during the static load bending test and running
load test is shown.

In the static load bending test, relatively dispersed cracks developed immediately beneath the load point of the test specimens of Types I, II and III as the load increased, and eventually the specimens failed in bending. The cause of this is considered as follows: the flexural cracking was controlled by the bridging effect of steel fibers, and therefore the stress was distributed in a broad range.

In the running load test, many cracks developed near the center of the span during the running of the wheel, and eventually the specimens failed in bending. The failure mechanism is characterized by the fact that cracks developed in a broader range in the test specimens having smaller cross-sectional height. This seems dependent on the height of a test specimen: that is, because the test specimen with a smaller height has smaller flexural rigidity under the running load, the radius of curvature is smaller and the more bridging effect is produced, resulting in the more noticeable dispersing effect of cracking.

Comparing the conditions of cracks in the static load bending test with those in the running load test, more fine cracks developed in the latter than the former test, indicating that the bridging effect of steel fibers was sufficiently produced, as one of characteristic features of the UFC. As can be seen from this viewpoint, the UFC is an excellent structural material for members subjected to continuous loads, such as a running load.

5. FLEXURAL LOAD-CARRYING CAPACITY OF THE SPECIMENS

Table 3 lists the flexural load-carrying capacity and failure mode of the test specimens used. The average of the maximum flexural load-carrying capacity of test specimens of Types I, II, and III obtained from the static load bending test are 25.1 kN, 47.7 kN, and 77.5 kN, respectively. The average of the maximum flexural load-carrying capacity of test specimens of Types I, II, and III obtained from the running load test are 25.2 kN, 47.4 kN, and 75.4 kN, respectively. In both of the tests, an increase in the flexural load-carrying capacity is seen with an increase in the cross-sectional height of the beam. The following causes led to the variation in the strength of the test specimen of Type III in the running load test: an impactive force was exerted by the uneven surface of the test specimen; and, as already reported, the UFC has a difference of about 10% in the flexural load-carrying capacity as a strength characteristic of the material. A study will be done on these effects by further testing.

In the running load test, all test specimens failed in bending. Comparing the flexural load-carrying capacity in the running load test with that in the static load bending test, the test specimen of each type shows a relatively close value, indicating that there is no drop in the flexural load-carrying capacity by the action of the running load. According to a report, the strength of reinforced concrete decreases by about 10% by the action of a running load. Considering the report, the UFC is an effective structural material subjected to continuous loads, such as a running load.

6. RELATIONSHIP BETWEEN LOAD AND DEFLECTION
Figure 9 shows the relationship between load and deflection at the center of the span. As is evident from Fig. 9 (a) and (b), the increase in the deflection in proportional to the increase in the load is seen in the test specimens of all types even after the initial cracking.

The average of deflections at the maximum load in the static load bending test (Fig. 9 (a)) is 2.46 mm for Type I, 2.19 mm for Type II and 1.72 mm for Type III, and the ratio of the deflection to the span is 1/410 for Type I, 1/460 for Type II, and 1/580 for Type III. In addition, the average of deflections at the maximum load in the running load test (Fig. 9 (b)) is 3.45 mm for Type I, 3.11 mm for Type II, and 1.62 mm for Type III. The ratio of the deflection to the span is 1/290 for Type I, 1/320 for Type II, and 1/620 for Type III. As can be seen from these results, the flexural rigidity of the UFC increases with the cross-sectional height, as is the case of ordinary concrete.

7. CROSS-SECTIONAL DISTRIBUTION OF STRAIN AND NEUTRAL AXIS

Figure 10 shows the distribution of strains measured with strain gauges on the side face of the test specimens at the center of the span. As is apparent from the figure, the strain in each test specimen increased with an increase in the load and the neutral axis moved upward from the center of cross section. This indicates that the compressive strength of the UFC is much larger than the tensile strength. For this reason, although a linear stress distribution is shown in the compression region until the maximum load, a sharp increase in the strain is seen in the tension region as the load increases. The strain at the outermost tension end of the beam estimated by extending the strain distribution line at the elastic limit strength where the strain distribution in the static load bending test does not show linearity is $227-297 \times 10^{-6}$. This is comparable to the strain at which the initial cracking occurs in the splitting tensile strength test.

The ratio of the height of a neutral axis to the cross-sectional height at the maximum load in the static load bending test is 0.89, 0.85, and 0.84 for Types I, II, and III, respectively, and 0.86 on average. Similarly, the ratio in the running load test is 0.70, 0.80, and 0.75 for Types I, II, and III, respectively, and 0.75 on average. Comparing the height of the neutral axis in the static load bending test with that in the running load test, the neutral axis in the static load bending test moves upward to the compression side by about 11% on average than in the running load test.

8. FLEXURAL ANALYSIS OF CROSS SECTION
The above-mentioned results reveal that the distribution of strains in the UFC beam in the ultimate state is almost linear in the compression region, and that a large increase in the strain is shown on the bottom of the beam in the tension region. Assuming that the stress distribution is a linear model and a perfect rigid-plastic model on the compression side and tension side, respectively, in the ultimate state, as shown in Fig. 11, the bending moment is given by Equation (1). For the calculation of the tensile stress of the perfect rigid-plastic model, the inverse analysis model of the tension softening curve as specified in the Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures, Japan Society of Civil Engineers 3, is used, and the value determined in the previous section is used for the location of the neutral axis.

\[ M_u = f_t \cdot D \left( \frac{2}{3} - \frac{D}{6} \right) B \cdot H^2 \]

where \( f_t \) = tensile strength, \( D \) = ratio of the height of a neutral axis to the cross-sectional height, \( H \) = beam depth, and \( B \) = beam width.

Table 4 lists the relationship between the experimental and theoretical values of bending moment in the ultimate state. Comparing the experimental values with theoretical ones in the table, they are in close agreement, but the theoretical values tend to exceed the experimental values with an increase in the cross-sectional height of each test specimen. This seems due to the effect of the tensile stress handled in the analysis and the scale effect of the cross section. Further research will be conducted to figure out the causes.

9. CONCLUSIONS

(1) The stress-strain relationship obtained from the compression test indicates that the UFC has about twice higher compressive and tensile deformability, in spite of high modulus of elasticity, than ordinary concrete.

(2) The UFC exhibited an increase in its strength even after the initial cracking and failed in bending after fine cracking occurred. This suggests that the bridging effect of steel fibers was shown dominantly.

(3) In the running load test, cracks developed in a broader range in the test specimens having smaller cross-sectional height.

(4) No noticeable difference was seen in the strength or deflection at the maximum load between the running and static load cases within the extent covered by the tests.

(5) The ratio of the height of a neutral axis to the cross-sectional height was 0.86 and 0.75 in the static and running load cases, respectively. The neutral axis in the static load case moved upward to the compression side by about 11% on average than in the running load case.

(6) Based on the relationship of the neutral axis in the ultimate state obtained from the tests, theoretical bending moment was calculated using the perfect rigid-plastic model. As a result, theoretical and experimental values were in close agreement for all the test specimens.

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