4 点曲げ載荷実験による UHPFRC 梁の疲労試験

Fatigue tests of UHPFRC beams under four-point bending load

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1. INTRODUCTION

Insufficient load capacity of bridge deck slabs is mainly caused by two factors, severe environmental influences and high fatigue loading from increasing traffic demands. These factors cause degradation, and leads to the reduction in structural performance, and service life of the bridge. Therefore, it is important to improve the performance by using a proper rehabilitation method and material suitable for structures, such as a bridge, which are subjected to intensive fatigue loads. One of the methods of rehabilitation and strengthening of bridge deck slabs is overlaying Ultra-high Performance Fiber Reinforced Concrete (UHPFRC) with or without steel rebars on top of the existing slab. This method has proven to be technically more efficient and more economic than other conventional methods[1).

UHPFRC is a cementitious fiber reinforced concrete material with excellent mechanical properties in comparison to conventional concrete. It has relatively high tensile strength and compressive strength, extremely low permeability which help in resisting the penetration of detrimental substances, thus results in enhancing durability. The typical compressive and tensile strengths of UHPFRC are higher than 130 MPa and 9 MPa, respectively. These outstanding characteristics makes it an appropriate rehabilitation material for bridge deck slabs.

However, the studies on the fatigue performance and failure mechanisms of UHPFRC are still few. Investigations on this matter is necessary for proposing a proper repair method of fatigue intensive structures. It is also important when developing an analytical method for predicting the behaviors of structures subjected to fatigue loading. In order to verify this concept, the fatigue behavior and failure mechanisms of UHPFRC needs to be examined.

In this study, uniaxial compression test, static flexural test and fatigue flexural test are conducted. Then, the fatigue behavior and failure mechanisms of UHPFRC are investigated based on the results obtained from the experiments.

2. EXPERIMENTAL METHOD

2.1 Specimens and testing procedures

Two types of specimen shapes and dimensions are fabricated. The static and fatigue flexural experiments use the beam-shaped specimens with the same dimensions, while the compression experiments use the cylinder-shaped specimens. The beam-shaped specimens are fabricated with length of 240 mm, width of 60 mm, and thickness of 25 mm. The cylinder-shaped specimens are fabricated with 50 mm diameter and 100 mm height. The dimensions of specimens are shown in **Fig. 1**. 100 beam-shaped specimens and 9 cylinder-shaped specimens are made. After fabrication, all specimens are moist cured by putting them underwater. The tests start at a curing age of 28 days.

Static flexural tests and uniaxial compression tests are conducted before the fatigue flexural tests. The flexural strength of static flexural tests is determined by averaging the results obtained from five specimens. Based on the average static flexural strength, the maximum fatigue stress levels are determined, and a total of three levels are employed.

The original plan is to conduct static flexural test under 0.1 mm/min of loading speed and fatigue flexural test under 10Hz of loading frequency. However, irregular results are observed in fatigue flexural tests, where the specimens reach run-out cycles without failure even during the selected maximum fatigue stress level. This may be affected by higher loading speed in fatigue test than in static test, which results in high strength of specimens. Hence, static flexural tests under 60 mm/min and 400 mm/min of loading speed are run to observe the effect of loading speed. Finally, 60 mm/min of loading speed and 3 Hz of loading frequency is considered as the best option for static and fatigue flexural tests because it resembles the loading on the deck slabs of an actual bridge.

In term of the uniaxial compression test before the fatigue test, the No. 1 specimen used is named as CB-1, where C and B indicate the Compression test and Before fatigue test, respectively. The specimens are numbered 1 to 3 so that the three specimens could be distinguished. In the case of static flexural test specimens, S60 is used instead of CB to indicate the static test under 60 mm/min of loading speed. Similarly, the S60 is followed by a number from 1 to 5 to distinguish the number of specimens.

2.2 Uniaxial compression tests

Uniaxial compression tests are conducted in accordance with JIS Standards for Method of test for static modulus of elasticity of concrete, A1149:2017[2). The tests are run under a load-control condition at a loading speed of 0.25 MPa/s. Three specimens are used in each test. Two strain gauges are attached at the center on both sides of the cylinder specimen to measure the strain behavior under loading. The loading condition is shown in **Fig. 1 (a)**.

2.3 Static flexural tests

The static flexural tests are done in accordance with JCI Standard for Method of test for bending moment-curvature curve of fiber-reinforced cementitious composites, JCI-S-003-2007[3)] and also referred to flexural tests conducted by Suthiwarapirak[4) 5)]. The four-point flexural tests are run under displacement control condition at a loading speed of 60 mm/min, onto the simply supported specimens with a clear span of 180 mm and subjected to two-point loads at 60 mm shear span. Three strain gauges are attached at the center of the span, two on the upper surface and one on the bottom surface. A total of four laser sensors are additionally used at the midspan and supports of the beam specimen to measure the displacement (see. **Fig. 1 (b)**).

2.4 Fatigue flexural tests

The four-point fatigue flexural tests are conducted under a load-control condition. Two strain gauges are attached on the upper surface at the midspan. A total of four laser sensors are used to measure the displacements at the midspan and the supports of the beam specimen, and a 100 mm of PI gauge is attached at the bottom to measure the deformation of the tension face of the specimen (see. **Fig. 1 (c)**).

The specimens are tested under a sinusoidal cyclic loading with a frequency of 3 Hz to resemble the loading frequency on the decks of an actual bridge, and the minimum stress level is set constantly at 0.2 to avoid slip between loading machine and specimens during the tests. The run-out cycle is set at two million cycles. The load is gradually increased to the maximum stress level in the first cycle before applying the 3 Hz of cyclic loading. The tests end either after fatigue failure occurs or when the number of cycles reaches two million.

Fatigue flexural tests are conducted under three fatigue stress levels in order to construct the fatigue stress-life (S-N) relation, and three to five specimens are used in each stress level. The fatigue stress levels and their number of specimens are listed in **Table 1**.

3. RESULTS

3.1 Uniaxial compression tests

The load capacity, compressive strength, Young's Modulus for each specimen and its average values are summarized in **Table 2**. **Fig. 2** summarizes the relationships between the compressive stress and strain of the specimens.

3.2 Static flexural tests

Load capacity and flexural strength of tested specimens under loading speed of 0.1 mm/min, 400 mm/min and 60 mm/min are shown in **Table 3**. The averaged flexural strength is also included. The flexural strength is calculated with the elastic flexural beam formulation using the experimental load capacity and the specimen dimensions. **Fig. 3** shows the flexural stress-displacement relationships for all three loading speed conditions.

3.3 Fatigue flexural tests

The typical multiple crack patterns on the tensile surface after static and fatigue tests is shown in **Fig. 4**, where specimen F0.85-1 is selected as an example. **Fig. 5** shows the stress-life (S-N) relationships plotted using the fatigue flexural test results. The dotted lines indicate the number of the run-out cycles which is adjusted to be two million. The arrows indicate the specimen that reached two million cycles without failure. **Fig. 5 (a)** shows the relationship between fatigue flexural strength and cycles to failure, while **Fig. 5 (b)** shows the relationship between fatigue stress level and cycles to failure.

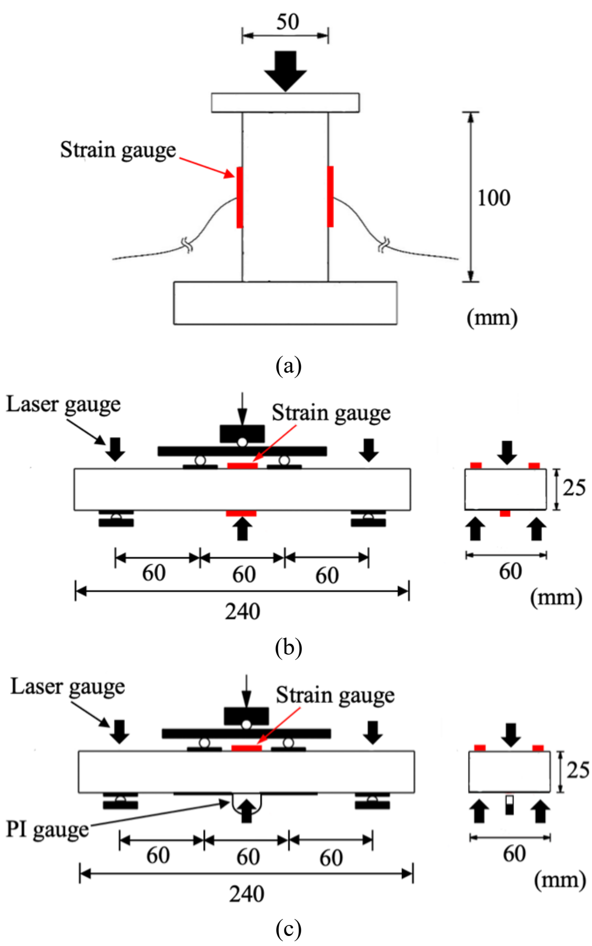


Fig. 1 Test setup (a)Uniaxial compression test (b)Static flexural test (c)Fatigue flexural test

Table 1 Number of specimens at each fatigue stress level

Level	Fatigue stress range	Number of specimens
1	0.2 – 0.95	5
2	0.2 – 0.90	5
3	0.2 – 0.85	3

Table 2 Results of uniaxial compression tests

Specimen	Load capacity (kN)	Compressive strength (MPa)	Average compressive strength (MPa)	Young's Modulus (GPa)	Average Young's Modulus (GPa)
CB-1	324.8	165.4	152.0	38.7	39.0
CB-2	270.4	137.3		39.0	
CB-3	301.0	153.4		39.2	

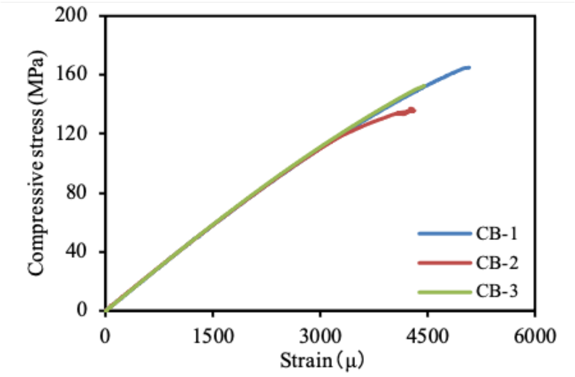
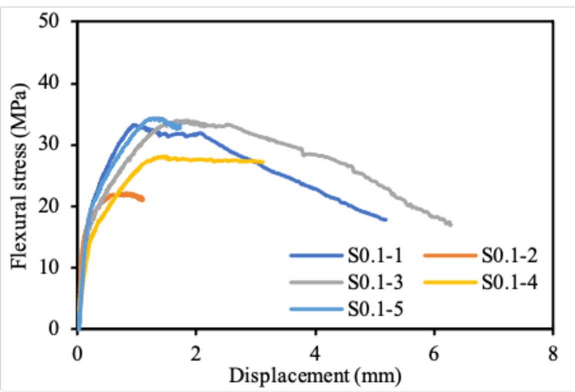


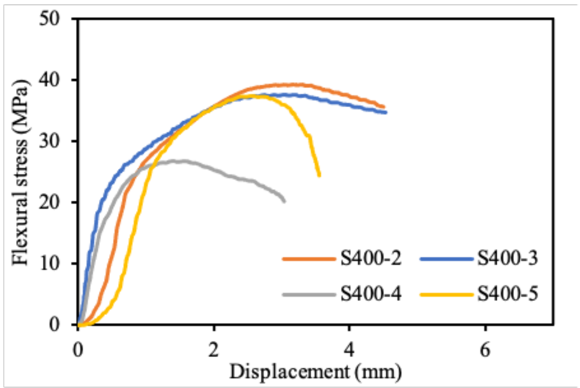
Fig. 2 Compressive stress-strain relationships

Table 3 Results of static flexural tests

Loading speed (mm/min)	Specimen	Load capacity (kN)	Flexural strength (MPa)	Average flexural strength (MPa)
0.1	S0.1-1	7.780	33.45	30.42
	S0.1-2	5.189	22.18	
	S0.1-3	8.675	33.94	
	S0.1-4	7.018	28.13	
	S0.1-5	8.056	34.41	
400	S400-1	10.63	47.11	36.80
	S400-2	7.638	33.78	
	S400-3	8.966	38.02	
	S400-4	6.832	27.22	
	S400-5	8.400	37.89	
60	S60-1	11.03	44.29	39.44
	S60-2	5.738	25.10	
	S60-3	9.725	42.05	
	S60-4	9.541	41.12	
	S60-5	10.12	44.61	



(a)



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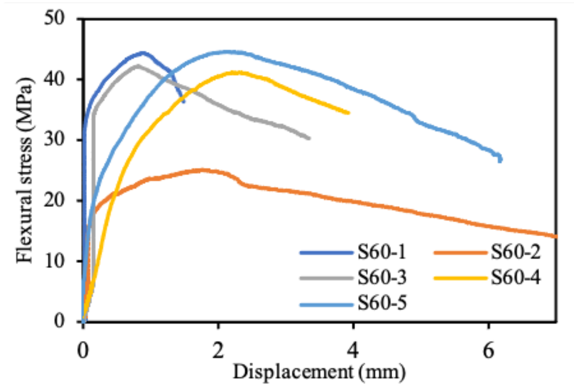

(c)

Fig. 3 Flexural stress-displacement relationships
(a)0.1mm/min (b)400mm/min (c)60mm/min

Fig. 4 Crack patterns on tension face of specimen F0.85-1

4. DISCUSSION

The average compressive strength and Young's Modulus obtained from the uniaxial compression tests are 152.0 MPa and 39.0 GPa, respectively. These represent the typical UHPFRC properties, which has a compressive strength higher than 130.0 MPa and Young's Modulus of 40.0 GPa.

The average flexural strength of static test under 0.1 mm/min, 400 mm/min and 60 mm/min of loading speed are calculated to be 30.42 MPa, 36.80 MPa and 39.44 MPa, respectively. When comparing 400 mm/min and 60 mm/min to 0.1 mm/min, it can be observed that high loading speed can results in high flexural strength. However the flexural strength also shows that the 60 mm/min is higher than 400 mm/min, which contradict with the theory. This means that, in some cases, it is conceivable that the distribution and amount of fibers inside the specimens may also affect the flexural strength. In this paper, 60 mm/min of loading speed is used because it resembles the loading on the deck slabs of an actual bridge.

The displacement obtained in **Fig. 3** is the summation of average displacement of laser sensors that have been installed at the middle and support part of each specimen. The failure mechanism of UHPFRC is observed by a multiple cracking characteristic under loading. In **Fig. 3**, an elastic behavior can be observed under static loading at the initial stage. After microcracks occur, a nonlinear behavior is observed upon the continuous rise of flexural strength curves. New cracks are then formed and progressively distributed along the tensile surface of the specimens until finally one of the cracks turned into a localized crack. The strain softening can be observed after the crack localization.

The S-N relationships shown in **Fig. 5** are plotted on a semi-logarithmic scale based on the fatigue test results. Overall, three specimens reached two million cycles without failure, one is from 0.90 stress level and another two is from 0.85 stress level. **Fig. 5 (b)** shows the stress level-life relationship of S-N curve, where the fatigue flexural strength is divided by the static strength. The fatigue stress level, S is defined as the ratio of the maximum flexural fatigue stress to the average flexural strength[4].

By judging the results of fatigue flexural tests, it can be noted that the S-N relationships of UHPFRC exhibit a typical linear relationship on a semi-log plot. When comparing with the flexural tests conducted by Suthiwarapirak[4) 5)] on FRC (Fiber Reinforced Concrete) and ECC (Engineered Cementitious Composite), the S-N relation of UHPFRC is resemble to the S-N relationship of FRC, which also characterized by a linear relationship on the same plot. However, compared to the FRC and ECC, UHPFRC exhibits a much slower degradation speed and a higher fatigue endurance limit which is over 0.7. Thus, it is concluded that the UHPFRC should have a better durability.

5. CONCLUSIONS

In this paper, uniaxial compression tests and four-point flexural tests under static and fatigue loading are conducted to understand the fatigue behavior and failure mechanisms of UHPFRC. The specimens show a multiple cracks behavior under loading, and successively distributed on the tensile surface before a localized crack occurred. UHPFRC shows a typical linear S-N relation and have higher durability compared with FRC and ECC.

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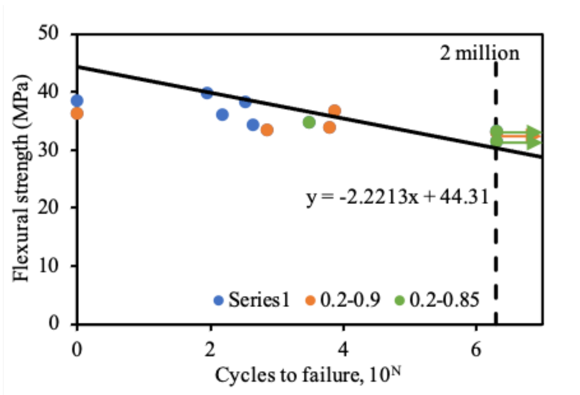
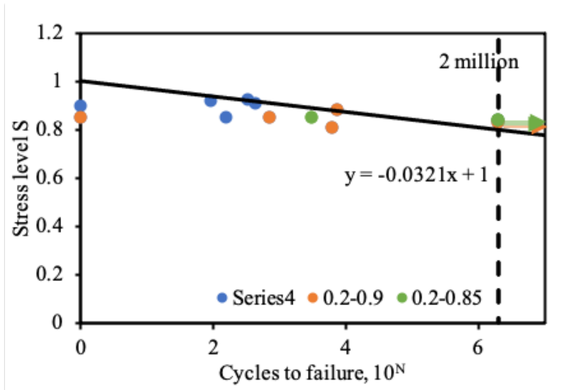


(a)



(b)

Fig. 5 Stress-life (S-N) relationships of UHPFRC (a)Flexural strength-life relationship (b)Stress level-life relationship