

# EXPERIMENTAL STUDIES ON THE FATIGUE PERFORMANCE OF RC BEAMS UNDER COMBINED WET FATIGUE AND FREEZING-THAWING

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## ABSTRACT

Lab-scale reinforced concrete (RC) beams were fabricated and subjected to three-point bending fatigue tests. Parameters changed in the tests include the fatigue load level, curing condition, curing age, fatigue type (dry or wet), and damage by freezing-thawing cycles (FTC). Experimental results show that the disintegration-like deterioration can only be observed in wet fatigue tests under bending failure. The significant reduction in fatigue life is observed in the small-scale specimen with severer FTC damage induced at earlier material age in relatively small specimen.

Keywords: fatigue test, wet fatigue, freezing-thawing, disintegration

## 1. INTRODUCTION

In Japan, some of the reinforced concrete (RC) bridge decks were found to deteriorate within a short time without apparent warning signs [1]. After removal of the pavement for the maintenance, the concrete at upper layer of bridge decks showed a significant separation of coarse aggregates and mortar, which is named concrete disintegration. The stagnant water in the RC deck and repeated high pressure of water at upper layer of concrete is reckoned as the main reason [2].

For predictions of the disintegration process, the disintegration propagation model considering pore water pressure was developed and validated via experimental studies [3,4]. Furukawa and Takahashi identified the occurrence threshold for disintegration through numerical simulation on both laboratory specimens and real bridges [5]. Now, the disintegration can be predicted accurately, but the study on the impacts of the additional other damage on disintegration, such as insufficient curing or material deterioration are still not enough. Also, the detection of invisible disintegration progress is other challenge in this research field.

The purpose of this study is to investigate the progress of concrete disintegration and the impact of other damages on disintegration via experiments. Beams are manufactured and subjected to static and fatigue three-point bending tests. The impact of fatigue load level, curing condition, curing age, fatigue type (dry or wet), and frost damage level on the fatigue performance of RC beams are investigated.

## 2. TEST PROGRAMS

### 2.1 Beam design and specimen preparation

Three-point bending tests were performed to

address the static bearing capacity and fatigue performance of RC beams. The beam specimen is scaled as 40×10×6 cm, considering the capacity of one box in freezing-thawing machine is 40 × 10 × 10 cm. The dimension and configuration of RC beams are shown in Fig. 1. Some of the specimens are made without stirrups and named as B-series, the other batch of specimens with stirrups are named as R-series. The locations of tensile main rebars in these two series are the same. Three Φ10mm SD295A rebars were arranged at the tensile portion of all beams. Sixteen Φ6mm SD295A stirrups were arranged along the tensile rebar at a spacing of 25 mm in R-series specimens.

The experimental cases are outlined in Table 1. The curing conditions for the beams include water curing, air curing, and sealed curing, which are denoted as “water”, “air”, and “sealed” in Table 1, respectively. There were two mix proportions in this test, as shown in Table 2. Water to cement ratio (W/C) of B1, B2, B3, and B4 specimens is 0.62, aiming at concrete strength around 40MPa, but at the test of B4 specimen, the compressive strength grew up to 49 MPa, which can lead to shear failure mode. So, other beams are of a W/C of 0.67,

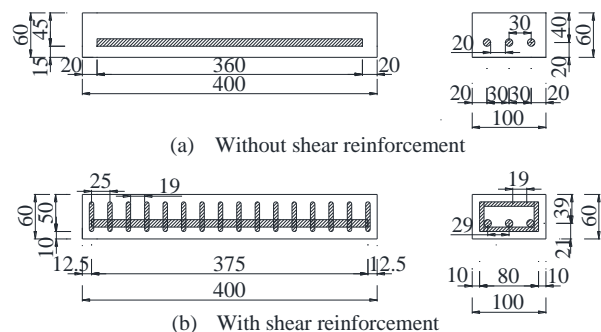


Fig. 1 Dimension and configuration of RC beams (Unit: mm)

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aiming at the lower-strength concrete. Used cement is ordinary Portland cement, and crushed sandstone is used as sand and gravel. Their fatigue load levels were determined according to their design bearing capacity. All beams were demolded one day after casting. Following demolding, the beams in B-series, excluding B5, were submerged in water for a period of 7 days, after which they were sealed. B5 was cured in the air after demolding. The specimens in R-series exposed to the air after water curing. The curing temperature of them was the same (20 °C). Two specimens are prepared for each R2, R3, and R4 series (shear reinforced and fatigue test series), which are specified such as Rka and Rkb ( $k = 2, 3$  or  $4$ ). The compressive strength of concrete was obtained via the uniaxial compression tests that were carried out on concrete cylinders ( $\Phi 100 \times 200$  mm). The mechanical properties of rebars were provided by manufacturers, as shown in Table 3.

The designation "FTC" in Table 1 indicates that the beam has undergone freezing and thawing cycles (FTC) before fatigue test. There were two FTC machines, one equipped with liquid cooling and the other with air cooling. The liquid-cooling machine (B-series) was operated within a temperature range of  $-18$  °C to  $+5$  °C, following JIS A 1148. Due to availability constraints of FTC machines, the air-cooling machine was utilized for conducting FTC on R-series specimens. The temperature range was adjusted to  $-18$  °C to  $+10$  °C to ensure that the specimens were thawed through to the core. All specimens were sunk in water during FTC. One FTC comprised 1 h for temperature change followed by 3 h for temperature stabilization, totally 8 h in one cycle. As the B7 specimen exhibited netted cracks on lateral surfaces after 20 cycles of FTC, all FTC specimens underwent 20 cycles of FTC. As shown in Fig. 2, there was visible surface damage on specimens after FTC, and B7 specimen showed netted cracks. The core

temperature of the beams was monitored to verify the freezing and thawing of specimens at each cycle.

B1 and R1 specimens are for static loading test. B2 and B3 aim to compare the effects of fatigue load levels. B5 and B6 are focused on exploring the influence of curing conditions. R2 and R3 are conducted to understand the consequences of stagnant water and observe disintegration. Remaining B4, B7 and R4 are specifically designed to clarify the influence of FTC damage levels on disintegration. The FTC cycles are the same for these 3 series, but the material ages are different. FTC cycles at earlier age cause more damage due to lower concrete strength, so B7 specimen can have more severe FTC damage, while B4 and R4 can have limited FTC damage from the visual observations (Fig. 2).

## 2.2 Loading setup and apparatus

In this study, three-point bending tests were employed to evaluate the static bearing capacity and fatigue performance of RC beams. The loading setup and apparatus are shown in Fig.3. The distance between the two supports was 360 mm. During the test, the value of the external load and the displacement of the beam top surface was recorded. For B-series specimens, there was one rubber plate used beneath the actuator to average the

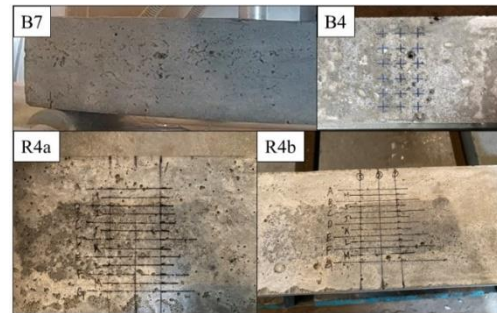


Fig. 2 Specimen surfaces after FTC

Table 1 Experimental research parameters

	W/C	Curing condition after 1-day demolding	Testing age (Day)	Concrete strength (MPa)	Load level (kN)	Load condition	FTC
B1	0.62	7-day water → sealed	22	37.4	28.5(static)	Dry	No
B2	0.62	7-day water → sealed	22	37.4	3.0-20.0	Wet	No
B3	0.62	7-day water → sealed	25	37.1	3.0-17.0	Wet	No
B4	0.62	7-day water → sealed	58	49.2	3.0-17.0	Wet	Yes
B5	0.67	air	23	21.7	2.0-14.0	Wet	No
B6	0.67	7-day water → sealed	27	34.9	2.0-14.0	Wet	No
B7	0.67	7-day water → sealed	36	39.1	2.0-14.0	Wet	Yes
R1	0.67	7-day water → air	26	42.4	31.9(static)	Dry	No
R2	0.67	7-day water → air	42	43.8	3.2-19.1	Dry	No
R3	0.67	7-day water → air	35	44.2	3.2-19.1	Wet	No
R4	0.67	7-day water → air	69	42.2	3.2-19.1	Wet	Yes

Table 2. Mix proportion of concrete

W/C	Water (kg/m <sup>3</sup> )	Cement (kg/m <sup>3</sup> )	Sand (kg/m <sup>3</sup> )	Gravel (kg/m <sup>3</sup> )	AE (ml/m <sup>3</sup> )
0.62	185.4	302.6	830.8	886.9	756.4
0.67	187	281.5	885.1	876	703.7

Table 3. Mechanical properties of rebars

	Section area (mm <sup>2</sup> )	Yield strength (MPa)	Ultimate strength (MPa)	Elastic Modulus (GPa)
Φ6	31.67	336.0	505.3	210
Φ10	71.33	379.5	488.0	210

stress and reduce stress concentration. In addition to this, R-series specimens adopted two more rubber plates above the supports for avoiding local concrete splitting, which has been observed in one specimen that was reckoned failed and not reported here.

Load level for B1 and R1 in Table 1 represents their static bearing capacity. B1 and R1 are designed to assess the static bearing capacity of beams within their respective sets. B1 specimen failed with shear, while R1 specimen failed with bending, as shown in Fig. 4. The upper and lower load limits of fatigue were set as shown in Table 1. The frequency of fatigue load was 10Hz. Due to higher frequency, load level of initial several cycles are unstable, and after about 100 cycles, the fatigue load can be stabilized at the designed level. The surface hardness of the midspan top surface of RC beams was tried to be measured using a Schmidt hammer as shown in Fig. 5 after every certain cycle ( $1, 2, 5 \times 10^n$ ,  $n=3, 4, 5, \dots$ ). At the mid-span top surface of test beams, there were 7 lines with an interval of 2 cm, and each line had 3 points at a spacing of 1.5 cm, serving as measurement points of the Schmidt hammer test. This test is adopted to try to observe the disintegration of upper layer concrete.

### 3. Results and discussion

#### 3.1 Cycle number and failure pattern

Figs.6-8 show the relationship between mid-span live load deflection (LLD) and cycle number. Fig.9

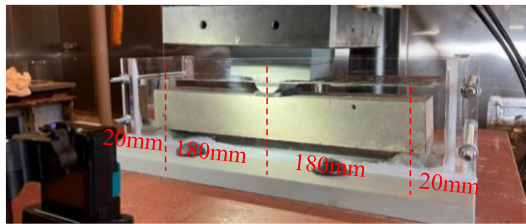


Fig. 3 Loading setup and apparatus



Fig. 5 Schmidt hammer rebound test

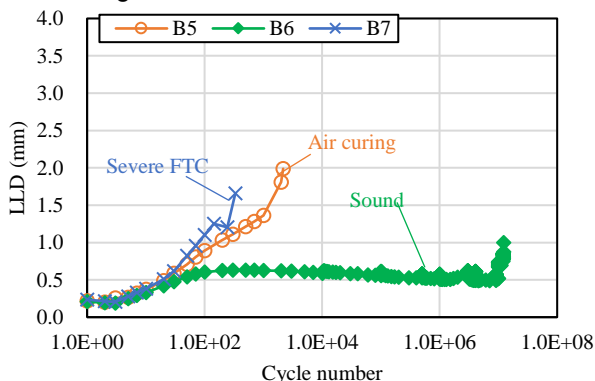


Fig. 7 LLD - cycle number curves (B5, B6, B7)

shows the failure pattern of all beams. Table 4 summarizes the fatigue life  $N$  and failure pattern of each beam.

A comparison between B2 and B3 shown in Fig. 6 and Table 4 confirms that the decreased load level significantly influences fatigue life. A 10% load level reduction in the upper load limit results in 1 order increase in fatigue life, with both specimens failed with shear (Figs. 9(a) and 9(b)). B4 specimen, with FTC damage, has about 1 order smaller fatigue life than B3. Due to the preceding FTC damage, the compression fracture of concrete at upper part of the beam seems to progress (Fig. 9(c)), which can change the failure mode from shear to bending failure.

In Fig. 7 and Table 4, B5 (poor curing) and B7 (FTC damage) specimens has significantly smaller fatigue lives compared to B6 specimen. This result demonstrates that the preceding deterioration of concrete due to poor curing and severe FTC damage can considerably diminish the fatigue lives and flexural stiffness of RC beams. The reductions in fatigue lives are notable, with a decrease of 4 orders for B5 and 5 orders for B7. Due to the poor curing, the strength development of concrete stagnates (Table 1), which cause faster shear



(a) B1 specimen

(b) R1 specimen

Fig. 4 Failure mode of static loading test

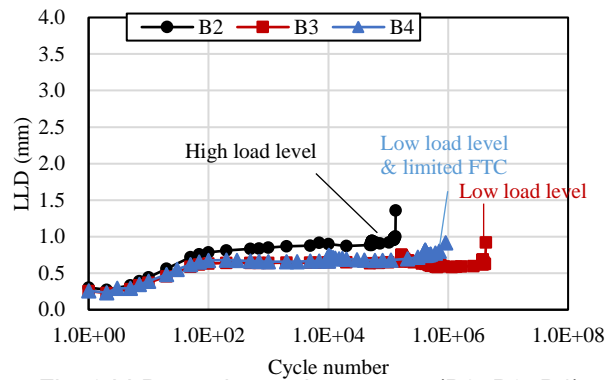


Fig. 6 LLD - cycle number curves (B2, B3, B4)

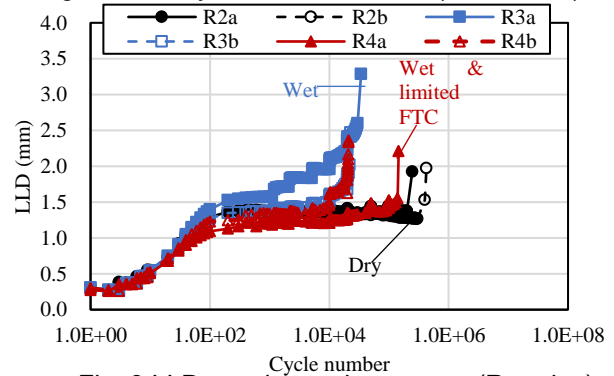


Fig. 8 LLD - cycle number curves (R-series)

failure with fatigue (Fig. 9(d)). In specimen B7, horizontal crack propagated along the specimen (Fig. 9(f)), which is characteristic in this specimen and reminds us of the existence of horizontal cracks frequently observed in RC decks in cold region. It is expected from this result that the preceding cracks due to FTC can guide horizontal cracks of RC decks.

In Fig. 8 and Table 4, comparing R2 and R3 highlights a notable one-order decrease in the fatigue life of RC beams attributed to the effect of water existence. In contrast, the comparison between R3 and R4 indicates that minor FTC damage does not exert a significant impact on fatigue life when the concrete has undergone sufficient curing. All R-series specimens failed with bending failure, while severe fracture at compression side is observed only with wet fatigue condition series (R3 and R4 specimens). The cyclic water pressure can accelerate the disintegration when the RC beam fails with bending under wet fatigue.

Comparing the situation for FTC-damaged specimens, B4 and R4 specimens (minor FTC damage with matured material age) had limited effect on fatigue lives, while B7 specimen (more FTC damage with younger material age) had significant effects on fatigue lives. In future, the quantitative evaluation of induced damage with FTC should be conducted to quantify the effect of FTC damage on fatigue lives. In the previous studies with real scale RC slabs [6], effect of FTC damage on fatigue lives are limited, which can be

understood that the FTC damage is small to induce the effect on fatigue lives. In this study, small dimensions of the specimen and FTC cycles at earlier material age causes significant reduction in fatigue lives and it is succeeded to see the horizontal crack propagations. This kind of experiment can help to understand the combination of FTC and disintegration.

As shown in Figs. 9(a)-(f) and Table 4, many of the specimens in B-series showed shear failure due to no shear reinforcement. Additionally, the flexural and shear capacity of the B-series specimens are 18.6 kN and 19.4 kN, which are very close to each other. Therefore, B4 and B6 specimens showed bending failure. In the R-series, all the RC beams experienced bending failure with concrete fracture, as shown in Figs. 9(g)-(l). As the occurrence of disintegration needs stress concentration to cause high pore water pressure in compressive concrete, R-series specimens are more likely to suffer from disintegration.

### 3.2 Observations of top surface deteriorations

Fig. 10 shows the damage pattern of the top surface of all beams after failure. The marks drawn on the top surfaces are the marks for Schmidt hammer tests. As diagonal cracks impact shear transfer in RC beams, the beams in the B-series that experienced shear failure did not exhibit the phenomenon of disintegration. When the shear crack is the main crack, the stress concentration on top surface is not so significant compared to bending

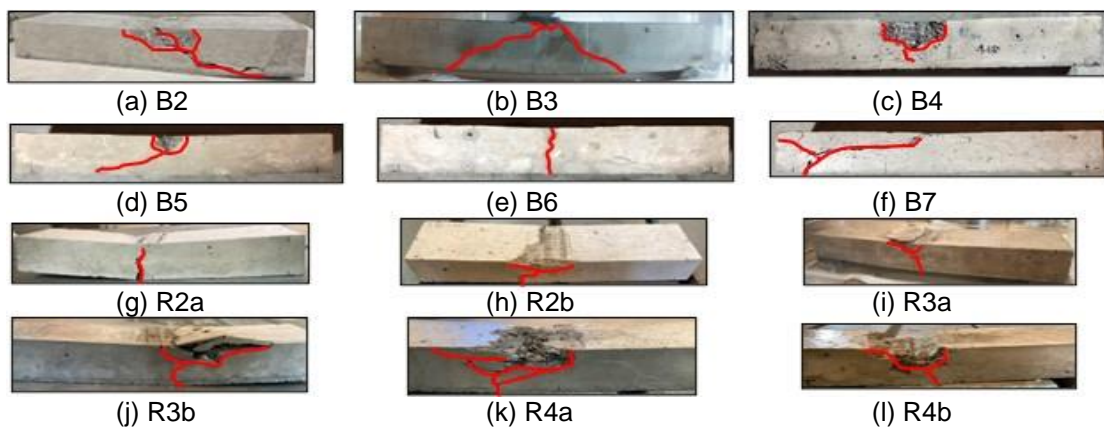


Fig.9 Failure patterns after fatigue tests

Table 4 Results of fatigue test of beams

Beam	$N$	$\lg(N)$	Failure pattern	Disintegration
B2	133026	5.12	Shear	-
B3	4276445	6.63	Shear	-
B4	910000	5.96	Bending	Not clear
B5	2171	3.34	Shear	-
B6	12229953	7.09	Bending	Not clear
B7	333	2.52	Shear (horizontal crack)	-
R2a	245556	5.39	Bending	-
R2b	424152	5.63	Bending	-
R3a	34089	4.53	Bending	Observed
R3b	22727	4.36	Bending	Observed
R4a	145222	5.16	Bending	Observed
R4b	21011	4.32	Bending	Observed

case. As a result, it is more possible to observe disintegration in bending specimens. In B6 and B4, even though they all show bending failure, it still failed to see obvious concrete disintegration from the concrete surface. A comparison between R2 and R3 specimens shows that R2 specimens with dry fatigue experienced a concrete collapse at one corner of the top surface. In contrast, the top surfaces of R3 specimens with wet fatigue were damaged across the whole beam section. Especially in the damage pattern of R3 and R4 specimens (Figs. 10(i)-(l)), there is an evident separation of gravels and mortar, which is the phenomenon of disintegration. The specimens with bending failure have higher compressive stress at loading point, which can cause higher pore water pressure at that point. It is shown that under the repetitive pore water pressure caused by fatigue loading, the compressive concrete will undergo disintegration. R4b has the most severe disintegration after wet fatigue, due to the initial deterioration on concrete top surface induced by FTC.

### 3.3 Load level vs. number of fatigue life

The stress amplitude and the number of fatigue life diagram (S-N diagram) is always used to analyze the fatigue performance of structures. In this study, the load levels are used to analyze the S-N relationships of specimens, as the load level is basically proportional to

the stress amplitude. The S-N diagrams of all beams are shown in Figs. 11 and 12.

As shown in Fig. 11, a comparison between B2, B3 and B4 specimens shows that increasing the fatigue load level by 10% bearing capacity, the failure occurs 1 order earlier reasonably. FTC-damaged B4 has a decreased fatigue life by 1 order compared to B3 specimen which has the same load level. Comparing B5, B6, and B7 specimens indicates that under the same load level, the fatigue life can be reduced by 3 and 4 orders by poor curing and severe FTC damage, respectively.

As shown in Fig. 12, under the same load level of 60%, R3a and R3b show fatigue lives which are about one order shorter than that of R2a and R2b, due to the disintegration caused by the cyclic pore water pressure. R4b has a fatigue life equal to that of R3b, indicating that the limited FTC damage does not influence the fatigue performance of RC beams significantly. The fatigue life of R4a is even longer that of R3a and R3b, which also indicates the slight impact of small FTC damage on sufficiently cured concrete.

### 3.4 Schmidt Rebound Numbers

The Schmidt Rebound Numbers (SRN) of each beam were recorded to observe and monitor the disintegration progress on the concrete surface. Some specimens in B-series that underwent long fatigue

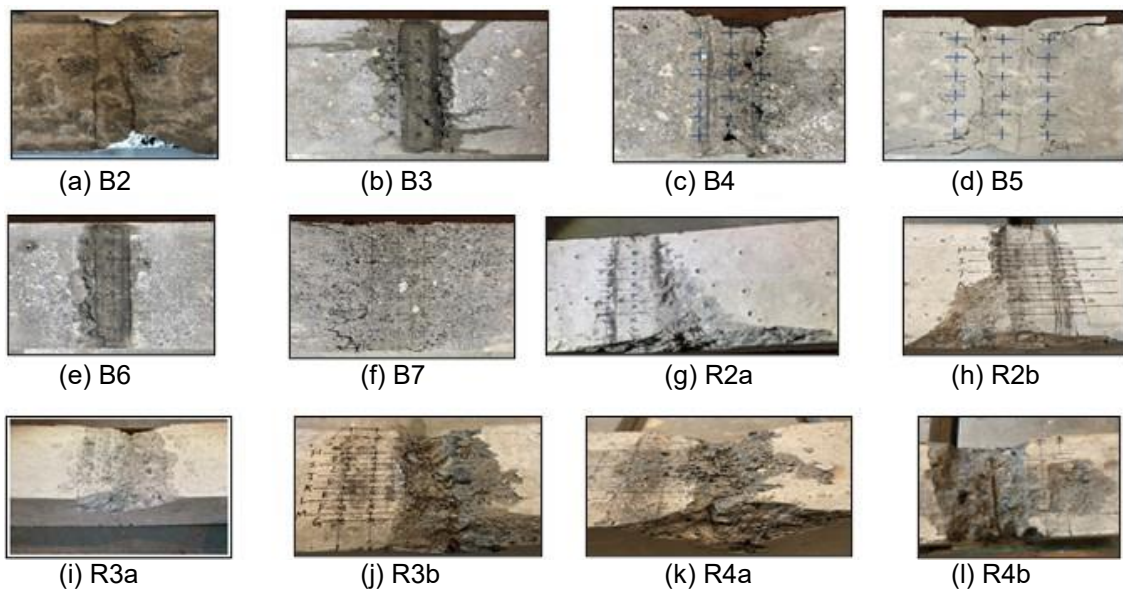


Fig.10 Top surface of specimens after fatigue

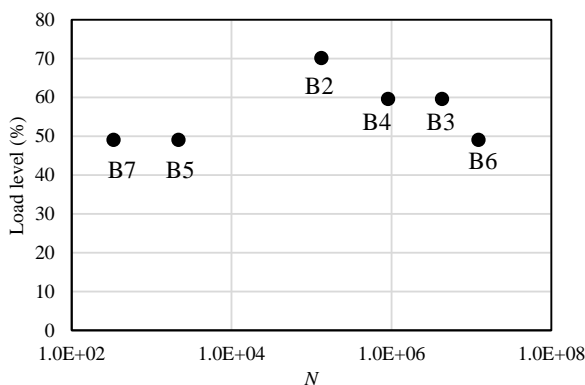


Fig.11 S-N diagram (B-series)

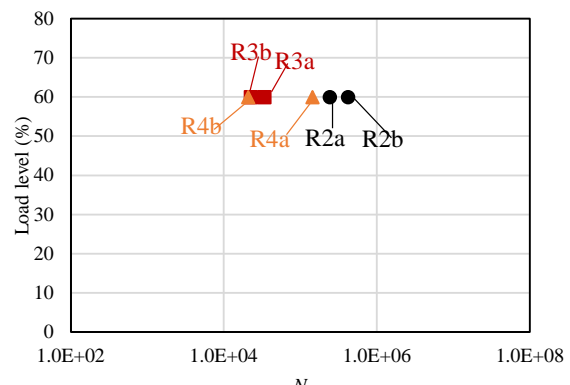


Fig.12 S-N diagram (R-series)

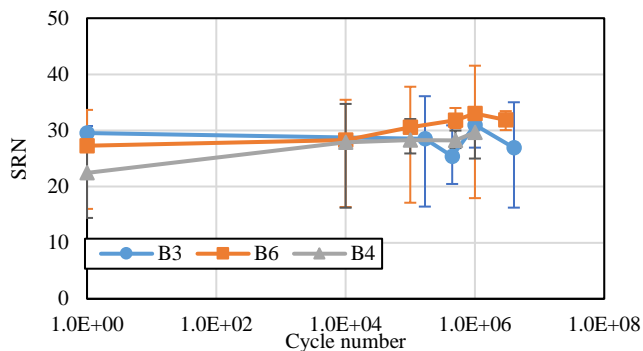


Fig.13 SRN-cycle number curves (B3, B6, B4)

loading are chosen for analysis, as shown in Fig.13, because they are likely to have some invisible deterioration that can be observed by Schmidt hammer tests. The SRN curves for R-series specimens are shown in Fig.14. The plots in Figs.13 and 14 represent the mean value of each measurement, and their error bars are also included.

In B-series (Fig.13), the SRN for B3, B6, and B4 does not show significant change during wet fatigue, and errors seem to become larger during each measurement. The SRN of R series specimen shown in Fig.14 also have similar trends, which indicates that no invisible deterioration was clearly observed, and the measure results seem not stable enough for assessment of disintegration. Because the Schmidt hammer is commonly utilized to measure the surface concrete strength of the large-scale concrete structure, as the rebound has even no impact on the structure stability. But in small-scale tests, the beams were vibrated by the Schmidt hammer due to the deformed beam soffits after fatigue. The accidental vibration can cause unstable measure results. Therefore, in the range of this study, simple data analysis with Schmidt hammer is difficult to be utilized for the assessment of disintegration progress. Other non-destructive inspection techniques need to be tried for this purpose in future.

#### 4. Conclusions

Based on the experimental studies on the fatigue performance RC beams with multiple parameters, some principal conclusions are drawn.

- (1) In the specimens failed with bending under wet fatigue condition, the disintegration can be observed with the phenomenon of obvious separation of coarse aggregates and mortar, while there is no evident disintegration in the beam with shear failure and dry fatigue tests.
- (2) The high fatigue load level, inadequate curing condition and age lead to a significant decrease in fatigue life under wet fatigue condition. The fatigue life of RC beams can be reduced by one order by cyclic pore water pressure. The frost damage in sufficiently cured concrete has little impact on the fatigue life, while more frost damage at earlier material age significantly reduces the fatigue lives, which can be utilized to study the mechanism of combined FTC and disintegration.

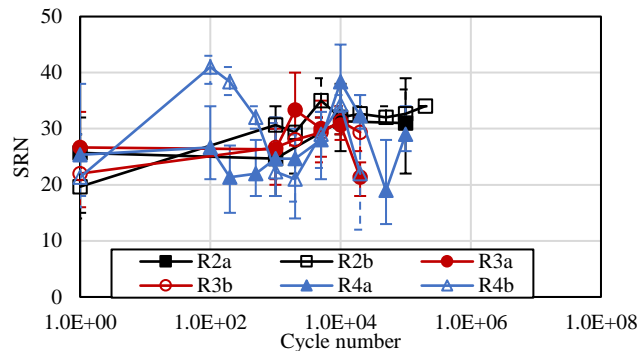


Fig.14 SRN-cycle number curves (R-series)

- (3) With the Schmidt hammer test results, it is difficult to detect the disintegration. More reliable or useful measurement techniques need to be investigated.

#### ACKNOWLEDGEMENT

This study is financially supported by Japan Concrete Institute research grant 2021, and JSPS KAKENHI Grand No, 22K18825. We express our gratitude. We are thankful to Tatsuki Takahashi and Kazunori Miyanaga from SHO-BOND corporation for their help to conduct fatigue experiments.

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