Fatigue analysis of UHPFRC-steel composite bridge deck considering self-healing behavior and fatigue life shortening of cracked UHPFRC under surface water condition

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1. INTRODUCTION

Owing to the outstanding properties such as high strengths in both tension and compression as well as the strain-hardening behavior, Ultra High Performance Fiber Reinforced Concrete (UHPFRC) has been used as a reinforcing overlay on the top surface of orthotropic steel bridge deck (OSD) to improve the fatigue performance of this kind of structure. The overall stiffness of OSD was thus enhanced leading to a significant reduction in fatigue stress range at the critical locations [1]. Following the study of Okuizumi et al. [2], UHPFRC also exhibited the high self-healing ability under water condition, represented by the high percentage of crack closure observed from the bottom of the flexural UHPFRC beams. After only one day of water exposure, the closure percentage of UHPFRC fine cracks with the maximum width of 0.014 mm in the specimens could reach over 77%. Moreover, it has been reported by Herbert and Li [3] that, accompanied with the closure of cracks caused by the continued hydration of un-hydrated cement grains, there were the mechanical recoveries of reloading stiffness and first cracking strength in the Engineered Cementitious Composite (ECC) specimens after the crack healing in water condition. However, under fatigue loading, water has a negative impact on the structural performance of concrete material. It has been reported that the stagnant water on the top surface of bridge decks caused by rainfall considerably degraded the fatigue performance of RC bridge slabs [4]. Similarly, as in the study of Matsushita [5], the fatigue life of concrete under water condition was drastically shortened in comparison to that of concrete tested in dry condition.

This study aims to investigate the fatigue behaviors of the UHPFRC/steel composite bridge deck under surface water condition subjected to a moving wheel load by performing a three-dimensional FEM analysis. Two stages of the material model considering self-healing behavior and reduction of fatigue life for cracked UHPFRC are assumed in the analysis. The transverse strain range in steel deck plate and cracking behaviors in UHPFRC layer are then investigated in this paper.

2. METHOD

2.1 Analytical model

In this study, a three-dimensional nonlinear finite element analysis is performed using an FEM software, i.e., MSC/Marc,

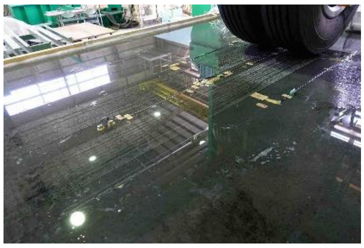


Figure 1 Fatigue test of the UHPFRC/steel bridge deck in surface water condition. [1]

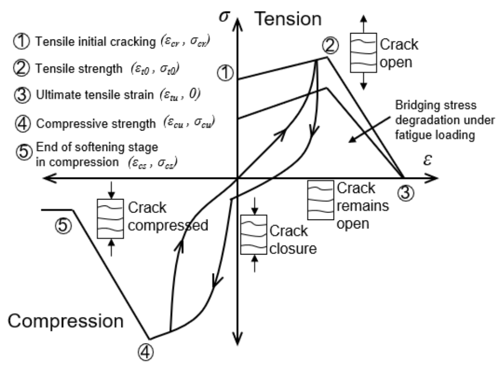


Figure 2 Constitutive law of cracked component of UHPFRC

to simulate the UHPFRC-OSD composite bridge deck which is subjected to a moving wheel load in surface water condition. The cracking behaviors, i.e., crack formation and propagation, in UHPFRC are represented based on the multi-fixed smeared crack model. The initiation of UHPFRC cracks is predicted based on the maximum principal stress criterion (or Rankine criterion).

2.2 Material model

2.2.1 Steel material

The constitutive law of steel material is represented by a bilinear isotropic hardening relationship, in which the Poisson's ratio and Young's modulus of steel are set as 0.3 and 200 GPa, respectively. The yield strength of 365 MPa and the ultimate strength of 490 MPa are used for steel members in OSD in the analysis. The yield criterion in the model follows von Mises' criterion.

2.2.2 UHPFRC material

2.2.2.1 Testing conditions and assumed stages for material model of cracked UHPFRC

The full-scale UHPFRC/steel composite bridge deck were experimentally tested under multi-phases of moving wheel loadings in Civil Engineering Research Institute (CERI) for

Cold Region, Hokkaido. After the first phase with 1,100,000 cycles under moving wheel loading with rubber tire under dry condition, the composite deck was subsequently tested for 60,000 cycles under surface water condition in one day. A thin layer of water had been supplied on the top surface of UHPFRC overlay for one night before the fatigue test under surface water condition (see **Figure 1**). Correspondingly, in the current fatigue analysis, two stages are assumed for the material model of cracked UHPFRC as follows

- Stage 1: self-healing of cracked UHPFRC for one night from the 1,100,000th to the 1,100,0001st loading cycles.
- Stage 2: a higher degradation speed of cracked UHPFRC caused by the stagnant water for 60,000 cycles.

The modelling of the behaviors for each stage of cracked UHPFRC is presented in detail in the following sections.

2.2.2.2 Constitutive relation of UHPFRC

The constitutive relation and cracking behaviors of UHPFRC are defined in a material user subroutine by using programming language FORTRAN. Total strain of a cracked UHPFRC is decomposed into the uncracked and cracked components. The non-cracked component of UHPFRC is defined by a linear elastic isotropic relationship, in which the Poisson's ratio and Young's modulus of 0.22 and 31.3 GPa are set. As shown in **Figure 2**, a bilinear relationship including the strain hardening and strain softening domains is used to represent the tensile stress-strain law of the cracked component of UHPFRC, following the JSCE Recommendations [6]. Compressive constitutive law for cracked component is defined by a parabolic relationship and a descending linear relation for post-peak behavior. The material properties for cracked component of UHPFRC are listed in **Table 1**.

2.2.2.3 Fatigue bridging stress degradation of cracked UHPFRC in dry and surface water condition

Under fatigue loading, the progressive reduction in bridging stress between crack surfaces caused by the fatigue deteriorations of fiber components is considered as a primary degradation mechanism of the crack propagation in UHPFRC. The bridging stress degradation can be simply assumed by a function of maximum tensile strain ε_{tmax} and number of cycles N. According to the study of Jimi et al. [7], the bridging stress degradation law of UHPFRC material under dry condition is presented as follows

$$\frac{\sigma_N}{\sigma_1} = 1 - (0.015 + 5\varepsilon_{t\max})\log(N) \quad \text{for } 1 \le N \le 1{,}100{,}000 \tag{1}$$

where σ_N/σ_1 is bridging stress degradation ratio of the Nth to the first cycle in dry condition.

Following Matsushita [5], for the case of the applied minimum stress equal to zero, it was reported that the fatigue stress range ratio at 2 million cycles for concrete in water condition is about 70% of that in dry condition. Applying this reduction percentage to the fatigue life of UHPFRC, the corresponding bridging stress degradation relation of UHPFRC under surface water condition is obtained as follows

$$\frac{\sigma_N}{\sigma_{1,100,001}} = 1 - (0.058 + 3.5\varepsilon_{t\max})\log(N - 1{,}100{,}000) \quad \text{for } 1{,}100{,}001 \le N \le 1{,}160{,}000 \tag{2}$$

in which $\sigma_N/\sigma_{1,100,001}$ is bridging stress degradation ratio of the Nth to the 1,100,001st cycle in surface water condition.

2.2.2.4 Self-healing behavior of cracked UHPFRC under surface water condition

In the current analysis, the mechanical recoveries in term of reloading stiffness and tensile strength are applied to the cracked UHPFRC under surface water condition, as shown in **Figure 3**. The recovery ratios for the reloading stiffness, β, and the tensile strength, γ, in the cracked UHPFRC are represented as follows

$$\beta = \frac{K_{1,100,001} - K_{1,100,000}}{K_1 - K_{1,100,000}} \tag{3}$$

$$\gamma = \frac{\sigma_{1,100,001} - \sigma_{1,100,000}}{\sigma_1 - \sigma_{1,100,000}} \tag{4}$$

where K_1 is the elastic stiffness at the first cycle, $K_{1,100,000}$ and $K_{1,100,001}$ are the reloading stiffnesses at the 1,100,000th and 1,100,001st cycle in fatigue analysis. Since the exposure time of the top surface of UHPFRC overlay under surface water condition is one night, the reloading stiffness and tensile strength recovery ratios in this study are roughly chosen as 70%, $\beta = \gamma = 70\%$, following the research of Okuizumi et al. [2].

2.2.3 UHPFRC/steel interface

Under surface water condition, the fatigue degradation at the interface between the two materials is simply governed by the expansion of the interfacial delamination area. The total expansion of 28 mm in transverse direction is applied for

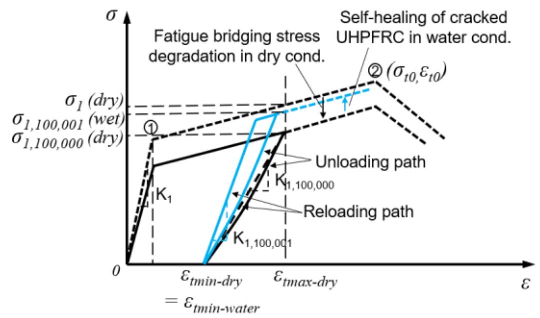


Figure 3 Tensile stress-strain relation of cracked UHPFRC

Table 1 Material properties for UHPFRC

Point	Material properties	Values (unit)	
①	Tensile initial cracking	σ_{cr}	6 (MPa)
		ε_{cr}	0.00019
②	Tensile strength	σ_{t0}	9 (MPa)
		ε_{t0}	0.00175
③	Ultimate tensile strain	ε_{tu}	0.01200
④	Compressive strength	σ_{cu}	133 (MPa)
		ε_{cu}	0.00850
⑤	End of softening stage in compression	$\sigma_{cs} = 0.2\sigma_{cu}$	
		$\varepsilon_{cs} = 1.5\ \varepsilon_{cu}$	

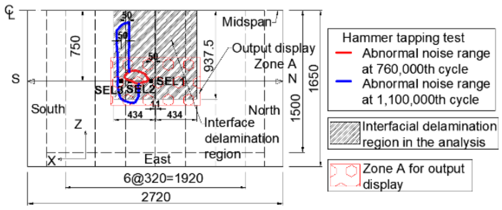


Figure 4 Interfacial delamination area at the 1,160,000 cycle

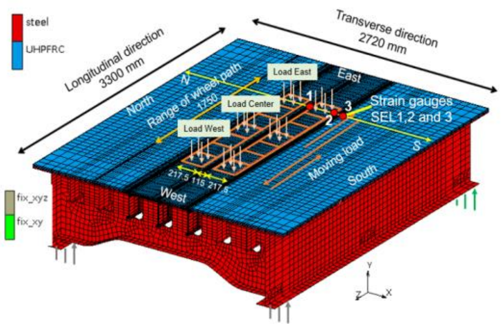


Figure 5 Boundary conditions of the composite bridge deck

the interfacial debonded area in the analysis, which gives the same expansion speed of that from the previous stage in dry condition from the 940,000th to 1,100,000th cycles [8]. That is, from the 1,100,000th to 1,160,000th cycles, the transverse dimension of the delamination area is gradually increased from 840 mm to 868 mm (see **Figure 4**).

2.3 Boundary conditions of the composite deck

The geometry and boundary conditions of the composite bridge deck are shown in **Figure 5**. The dimensions of the UHPFRC/steel bridge deck are 3300 and 2720 mm in longitudinal and transverse directions, respectively. The bridge deck is composed of two main girders, three cross beams, seven longitudinal open bulb ribs, and a 12-mm steel deck plate overlaid by a layer of UHPFRC with thickness of 25 mm. Four outer edges of the main girders are simply supported on a 3000-mm span. In the analysis, seven distributed loads with the level of 100 kN are assigned along the loading lane. For convenience, the applied wheel load at Center and East (West) locations are named as Load Center and Load East (West) as shown in **Figure 5**. At first, the wheel load is applied at the center location (Load Center). These elements are then unloaded after reaching the peak value, simultaneously with the loading process of the adjacent elements with the same increasing rate. This procedure is continuously applied along the loading lane reproducing the moving process of the wheel load. Throughout the wheel load moving process, the bridging stress degradation equation, as well as the unloading behavior, at each node of smeared crack elements in UHPFRC is modified based on the recorded maximum tensile strain from the previous cycle of fatigue analysis. The analysis is continued until the number of cycles reaches 1,160,000, i.e., the end of fatigue test under surface water condition.

3. RESULTS AND DISCUSSIONS

3.1 Strain range evolutions in steel deck plate

The transverse strain range evolutions obtained from the positions of strain gauges SEL1 and SEL2 (see Figure 5) under Load East are plotted comparatively with the experimental data in **Figures 6** and **7**, respectively. As can be seen from those two figures, there are reductions in strain range levels at the beginning of fatigue test in surface water condition. This is attributed to the self-healing of the fine cracks in UHPFRC overlay after one-night exposure in water. As shown in **Figure 8**, with the existence of the healing part inside UHPFRC crack, the decrease in reloaded maximum strain can be obtained, leading to the decrease in strain range levels in both UHPFRC and steel deck plate.

After the healing stage of UHPFRC cracks at the 1,100,001st cycle, the increase in degradation speed of bridging stress in cracked UHPFRC is applied in the analysis, as presented in Equation (2). This leads to the sharp increases in transverse strain range levels from the early cycles of fatigue analysis in steel deck plate (cycles from 1,100,001st to 1,105,000th in **Figures 6** and **7**). It is clearly seen that the contribution of bridging stress degradation on the increases of strain range is dominant in the early stage of fatigue analysis under surface

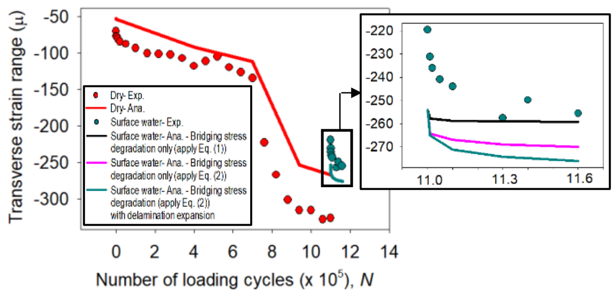


Figure 6 Strain range vs. number of cycles at SEL1

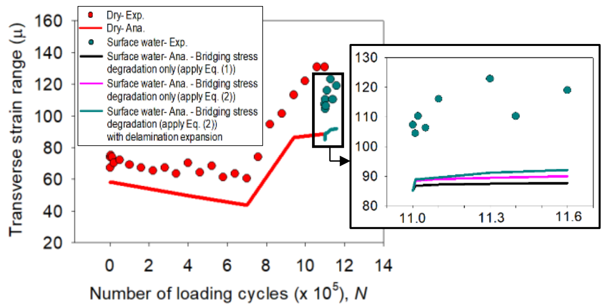
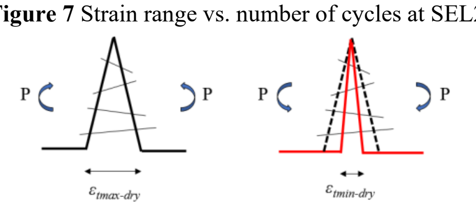
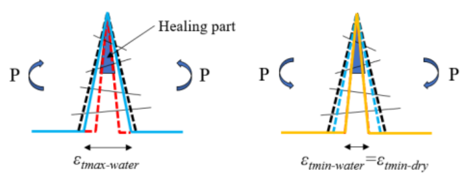


Figure 7 Strain range vs. number of cycles at SEL2



(a) Loading in dry cond. (b) Unloading in dry cond.



(c) Reloading in water cond. (d) Unloading in water cond.

Figure 8 Opening-closing behaviors of UHPFRC cracks before (a and b) and after (c and d) self-healing water condition, since the expansion of debonding area is relatively small at the beginning cycles. Comparing the models with and without the expansion of the delamination area, more increases in strain ranges in steel plate are obtained with the increase of the loading cycles due to the continuous loss in composite action between UHPFRC and steel plate when the delamination area is progressively expanded in transverse direction. At the end of fatigue test of composite deck in surface water condition (1,160,000th cycle), the experimental strain range levels are still lower than those from the 1,100,000th cycle in dry condition. This may be due to the neglect of the permanent bond slip at the UHPFRC/steel interface, leading to the underestimation of the unloading strain levels of steel plate in the analysis. Overall, for the current FEM model considering the two stages for the material model of cracked UHPFRC under surface water condition, the transverse strain range results in steel deck plate show an acceptable agreement in tendency with those from experiment.

3.2. Maximum principal tensile strain in UHPFRC

The maximum principal strain distribution from the cracked elements obtained on the top of UHPFRC overlay under Load East are showed in **Figures 9** from the 1,100,000th, 1,100,001st and 1,160,000th. The strain results are displayed in zone A (see **Figure 4**). The cracked regions on UHPFRC surface are represented by the band from blue to red colors. It can be observed that the cracked elements are distributed on the local regions above the longitudinal ribs, since the wheel load produces the large negative bending moments at these regions. It is also found that the direction of the UHPFRC cracks above the longitudinal ribs are mainly in longitudinal direction. At the beginning of fatigue analysis in surface water condition (1,100,001st cycle), due to the increase in tensile strength caused by the self-healing of UHPFRC cracks, the maximum principal strain value at the stiffeners decreased as compared to that from dry condition. On the contrary, the increases in maximum principal strain levels in UHPFRC are obtained at the end of surface water condition owing to the significant increase in degradation speed of bridging stress in healed UHPFRC with stagnant water.

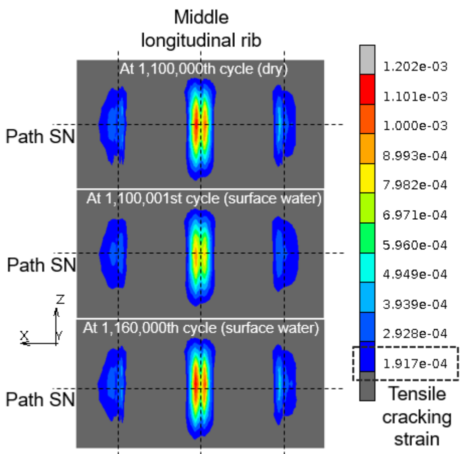


Figure 9 Max. principal strain on the top surface of UHPFRC

4. CONCLUSIONS

In this study, the 3D non-linear FEM analysis is performed to analyze the fatigue behaviors of the UHPFRC-OSD composite structure under moving wheel load under surface water condition. Due to the self-healing of the fine cracks in the UHPFRC overlay, the mechanical recoveries of reloading stiffness and tensile strength from these cracks are obtained leading to the decreases in strain range results in both steel plate and UHPFRC layer. On the other hand, later under the moving wheel loading, the fatigue degradation in the UHPFRC cracks may be accelerated due to the existence of stagnant water. By considering a higher speed of the bridging stress degradation in cracked UHPFRC, it is found that the analytical strain range results of steel deck plate exhibit an acceptable agreement in tendency in comparison to those from the experiment. Therefore, it can be stated that the assumed behaviors in the material model of cracked UHPFRC in the analysis are plausible for reproducing the experiment. However, due to the neglect of the permanent bond slip at the UHPFRC/steel interface, the unloading strain levels in the steel deck plate may be underestimated in the analysis. This is also a topic for future studies of the composite bridge deck under moving wheel load.

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