Fatigue analysis of UHPFRC-steel composite deck considering crack bridging and interface bond degradations

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1. INTRODUCTION

Due to the rapid increase in traffic volumes and the small slab thickness from the early state design, many fatigue cracks caused by repetitive loading have initiated and developed at the welded joints or edge of cut-out details in the orthotropic steel decks (OSDs), a popular structure used in the long span bridges. This deterioration may significantly reduce the structural performance and shorten the expected service lifetime of the steel bridge decks. For that reason, there is an urgent need to develop the rehabilitation methods that can extend the fatigue durability of the existing bridges using OSD structure. One method of overlaying Ultra-high Performance Fiber Reinforced Concrete (UHPFRC) on the top surface of OSDs has been reported to exhibit excellent performance. Owing to the outstanding properties such as high strengths under both tension and compression as well as a strain-hardening behavior, the UHPFRC overlay can effectively reduce the fatigue stress levels by improving the overall stiffness of the OSD even with a 25 mm of small thickness. Moreover, a highly dense matrix of UHPFRC provides the material an extremely low permeability, which means the UHPFRC overlay can work as an erosion protection layer to the severe environmental factors, e.g. water and chloride ion [1]. For this strengthening technique, despite the fatigue characteristics of composite structures may be investigated and assessed by experiment, this approach is time and cost consuming. Hence, it is necessary to develop an analytical tool that is advantageously applied to predict the fatigue performances of OSD structure strengthened by UHPFRC overlay.

This study aims to investigate the fatigue behaviors of the overlaid UHPFRC reinforced steel bridge deck subjected to repetitive moving load using an analytical model based on the finite element method. By considering the bridging stress degradation characteristic[3] in the UHPFRC overlay and the bond stiffness degradation[2] at the UHPFRC/steel interface, the current numerical method can provide an acceptable prediction of the behaviors, i.e. strain evolutions at critical locations, of the UHPFRC-steel composite deck under a moving load test, comparatively to the experimental data. It is found that the reductions of both the bridging stress in the cracked UHPFRC and the bond stiffness are the primary degradation mechanisms that can significantly reduce the effectiveness of the composite action between the steel bridge deck and the strengthening overlay under fatigue loading.

2. METHOD

2.1 Analytical model

In this study, a three-dimensional nonlinear analysis using the fixed smeared crack model is performed in a FEM software, i.e. MSC/MARC, to simulate the UHPFRC reinforced steel bridge deck under a moving wheel load. The initiation of the cracks in UHPFRC is based on the principal stress cracking criteria.

2.2 Material model

2.2.1 Steel material

The constitutive law of steel is represented by a bilinear isotropic hardening material as showed in **Figure 1**.

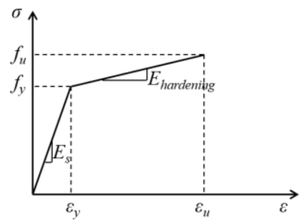

Figure 1 Stress-strain relation of steel

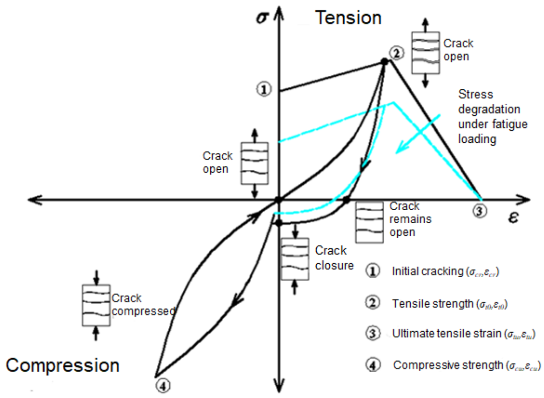

Figure 2 Constitutive law of cracked component of UHPFRC

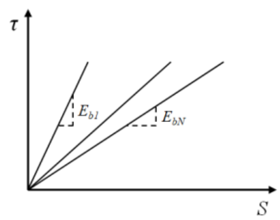

Figure 3 Interfacial bond-slip degradation model under fatigue loading

Yield strength, f_y, and ultimate strength, f_u, are chosen as 345 MPa and 490 MPa, respectively, in this study. The yield criterion in the model follows the von Mises' law. The Poisson's ratio and Young's modulus of steel are 0.3 and 200 GPa, respectively.

2.2.2 UHPFRC material

The constitutive relation of UHPFRC is defined in a material user subroutine by using programming language FORTRAN. For the fixed smeared crack approach, the stress-strain relationship of the cracked body is defined by non-cracked and cracked components. The linear elastic isotropic relationship is defined for the non-cracked component of UHPFRC. The Poisson's ratio and Young's modulus of 0.22 and 31.3 GPa are used for the elastic state of UHPFRC in the analysis. For the cracked component of UHPFRC, the tensile constitutive law is defined by a bilinear relationship, i.e. strain hardening and strain softening, following the JSCE Recommendations [4] as shown in **Figure 2**. Stress-strain law for cracked component in compression is presented by a parabolic relationship. The material properties of UHPFRC are listed in **Table 1** according to the experimental design. Referring to Fairbairn et al. [5], a shear retention factor, γ, is introduced in this study as follows

$$\gamma = \frac{1}{1+4447\varepsilon_{t\max}} \tag{1}$$

where ε_{tmax} is maximum tensile strain.

The reduction in bridging stress between crack surfaces caused by the deterioration of aggregate/fiber components under fatigue loading is considered as a primary degradation mechanism of the crack propagation in normal concrete and fiber reinforced concrete. The bridging stress degradation can be simply assumed by a function of the maximum tensile strain ε_{tmax} and the number of cycles N [3]. According to the experiment of UHPFRC beam under fatigue flexure, the bridging stress degradation law of UHPFRC material is chosen as follows

$$\frac{\sigma_N}{\sigma_1} = 1-(0.05+6\varepsilon_{t\max})\log(N) \tag{2}$$

where σ_N/σ_1 is bridging stress ratio between the N^{th} and the first cycles.

2.2.3 UHPFRC/steel interface

By applying the GLUE option in MSC/MARC, the interfacial bond-slip model between the UHPFRC overlay and the steel deck is represented by a linear elastic relationship with the elastic modulus, E_{b1}, of 2.66 GPa (see. **Figure 3**). Based on the experimental observations, the interface delamination may occur from the 700,000th loading cycles.

In this study, the degradation of bond stiffness in shear direction is simply assumed by a function of the number of cycles N from the beginning to 700,000th loading cycles

$$\frac{E_{bN}}{E_{b1}} = 0.9908-0.1707\times\log N \tag{3}$$

Table 1 Material properties of 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}	0.0085

where E_{bN} and E_{b1} are the interfacial stiffness of the N^{th} and the first cycles. The bond stiffness degradation area of 540×1750 mm (transverse × longitudinal) below the wheel path is chosen as shown in **Figure 4**.

From the 700,000th to 1,100,000th loading cycles, the FEM model at the interface between two materials is modified from partial slip to total slip regime to reproduce the interfacial delamination. The interfacial delamination area in this stage is gradually expanded in transverse direction with an average rate of 160 mm per 100,000 load cycles. At the 1,100,000th cycle, the delamination area is 1180×1750 mm (transverse × longitudinal). This area is approximate to the experimental obsrevation (see. **Figure 5**).

2.3 Boundary conditions and procedure of fatigue analysis

The boundary conditions of the composite deck with the dimension of the wheel loading path are shown in **Figure 4**.

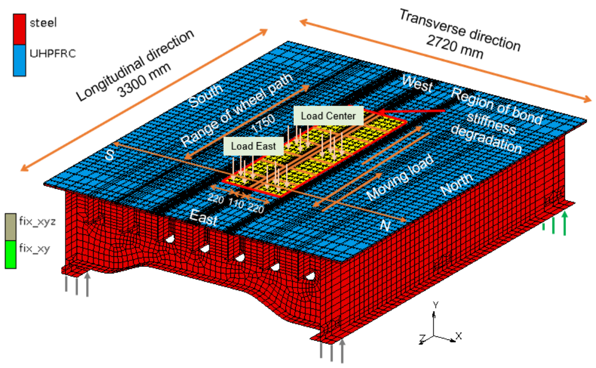

Figure 4 Geometry of UHPFRC-steel composite deck

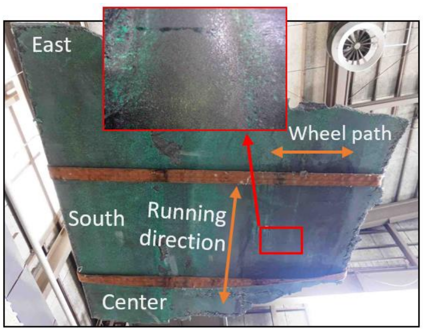

Figure 5 Interfacial bond layer after removing UHPFRC

The bridge deck is composed of a 25-mm UHPFRC overlay, a steel deck plate with thickness of 12 mm, 2 main girders, 3 cross beams and 7 longitudinal open bulb ribs. The dimensions of the deck plate are 3300 and 2720 mm in longitudinal and transverse directions, respectively. Four outer edges of the main girders are simply supported on a 3000-mm span. A total of seven distributed loads are assigned along the loading lane with the level of 100 kN referring to the experimental design. Firstly, the wheel load is applied at the center position. After reaching the peak from zero, these elements are unloaded. At the same time, the adjacent elements start the loading process with an equal augmented rate. Applying this procedure along the loading lane, one cycle of fatigue analysis is finally completed at the center position. After finishing one loading cycle, the data of the maximum tensile strain and cracking state at each node of 3D smeared crack elements in UHPFRC are recorded. The bridging stress degradation equation coded in the user subroutine is then modified based on the history maximum tensile strain for the following cycle of fatigue analysis. Simultaneously, the interfacial bond stiffness is decreased with the number of cycles. The procedure is continued until the number of cycles reaches 1,100,000, i.e. the end of fatigue experiment under dry condition.

3. RESULTS AND DISCUSSIONS

3.1 Strain evolutions under the bottom of steel deck plate

The transverse strain distribution under steel deck plate obtained from East location are plotted versus the number of cycles in **Figure 6**. Due to the continuous reduction in shear component of interfacial bond stiffness, the transferred shear stress between two materials decrease with the number of cycles. Owing to the local constraint from the stiffer parts without interfacial degradation, the contact shear stress concentrations are observed at the boundaries of bond stiffness degradation area under wheel loading region from the 700,000th cycle in **Figure 7**. It is noted that the normal component of bond layer is also degraded along with the shear component due to the increase in bond slip displacement, especially at the local regions above middle longitudinal

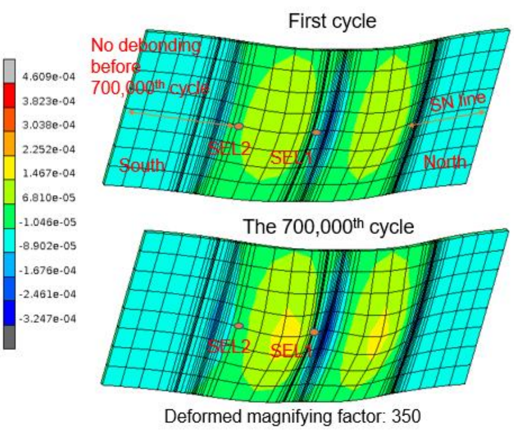

Figure 6 Transverse strain distributions under East location

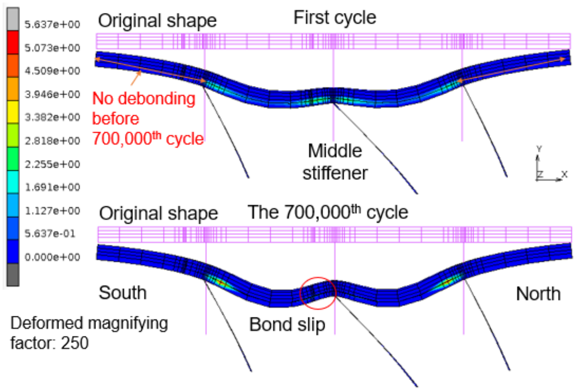

Figure 7 Contact shear stress distribution at SN cross section

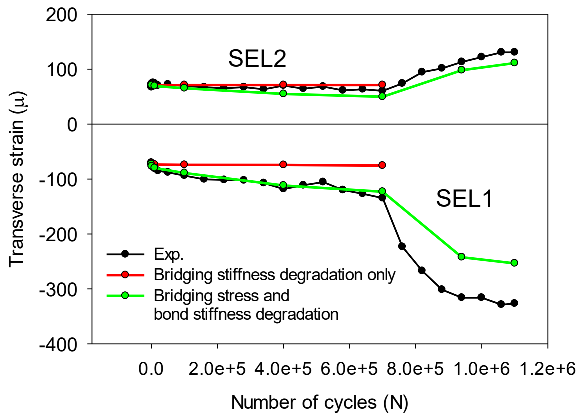

Figure 8 Transverse strain versus number of cycles at SEL1 and SEL2

stiffeners. Therefore, with the loss in the composite action between steel bridge deck and reinforced layer, the overall stiffness of composite deck gradually decreases with the increase of moving load cycles causing the deformation increases in both UHPFRC and steel deck plate under moving load. On the other hand, the decrease in stiffness of composite deck is also contributed by the degradation of bridging stress in cracked UHPFRC. After the crack initiation, due to the stress concentration at the crack tips lead by the reduction in the tensile strength, the fatigue cracks propagate with the newly formed length. The strain re-distributions in both compression and tension with the higher strain levels can be then observed (see. **Figure 6**). It is noted that the loss in interfacial bond stiffness under fatigue loading considerably accelerates the bridging stress degradation in UHPFRC which is depends on the maximum tensile strain level.

The transverse strain evolutions under load East obtained from the points SEL1 and SEL2 are plotted comparatively with the data from the experiment in **Figure 8**. The strain results at SEL1 are significantly influenced by the local region above the middle stiffener where a large negative bending is obtained. While the transverse strains at SEL2 are affected by the positive bending region under wheel load. Since the position of SEL2 is right below the boundary of bond degradation region, the contact shear stress concentrate in this local region causing the decrease in strain level at this point. After 700,000th cycle,

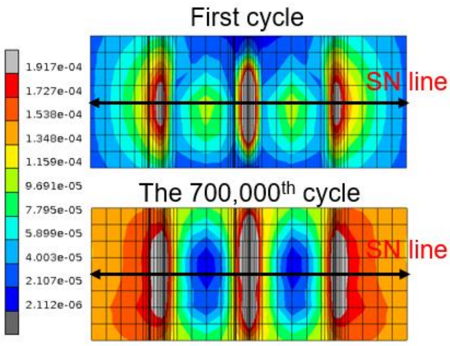

Figure 9 Maximum principal strain distribution at East location

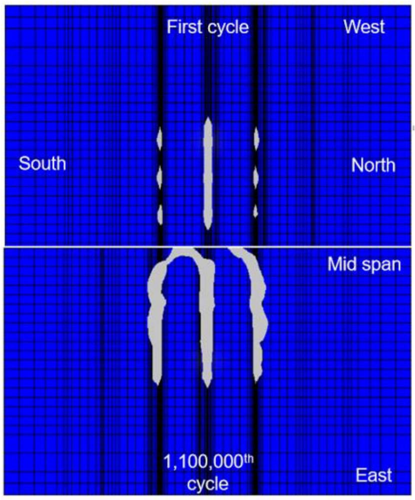

Figure 10 Crack pattern

when the interfacial degradation area has already expanded across the left stiffener, the increasing tendency can be obtained at SEL2. As can be seen from **Figure 8**, with the expansion of delamination area, the transverse strain levels increase significantly after 700,000th loading cycle, which is caused by the progressive loss of composite action. For the current FEM model considering the two kinds of degradations, the transverse strain results under steel deck plate show an acceptable agreement with those from experiment.

3.2. Crack propagation in UHPFRC overlay

The maximum strain distribution under load East and crack pattern obtained on the top of UHPFRC overlay from the first and 1,100,000th cycles are showed in **Figures 9** and **10**, respectively. The cracked regions on UHPFRC surface are displayed in grey color. It can be observed that the cracked elements are distributed on the local regions above the longitudinal stiffeners, where the large negative bending moments are obtained. With the interaction effects of the degradation in bridging stress and the interface failure, the tensile strain magnitudes considerably increase causing the crack development in UHPFRC. The crack spreading speeds above the regions of the first left and right longitudinal ribs are especially accelerated after 700,000th loading cycle when the debonding area covers these local regions. With the only consideration in transverse expansion of delamination area, the crack propagation in longitudinal direction is limited. Similar to the case of longitudinal ribs, the moving load produces negative bending at the local region above middle cross beam due to its strengthening effect, and the crack propagation can be observed from this region from the last cycle in **Figure 10**.

4. CONCLUSIONS

In this study, the non-linear FEM model using three-dimensional smeared crack elements is performed to analyse the fatigue behaviors of the steel bridge deck strengthened by an UHPFRC overlay under moving wheel load. With a further consideration of bond stiffness degradation at the UHPFRC/steel interface, there is an improvement in fatigue behavior reproduction in the current model, in comparison with the previous model which is based only on the bridging stress degradation characteristic applied for UHPFRC reinforced layer. The experimental and numerical investigations indicate that the progressive deficiency in bonding performance at the interface may considerably influence the effectiveness of composite action between two materials. Therefore, the interfacial bond behavior under fatigue loading should be conservatively considered for the future investigation of OSD-UHPFRC composite deck.

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