学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Multi-stage fatigue analysis of an orthotropic steel bridge deck reinforced with UHPFRC overlay considering crack bridging and interfacial bond stiffness degradations
(架橋応力と界面付着の劣化を考慮した UHPFRC 合成直交異方性鋼床版の多段階疲労解析)

Over the past few decades, orthotropic steel decks (OSDs) have been widely used in long-span bridge structures due to their advantages compared with reinforced concrete bridge decks. However, due to the rapid increase in traffic volumes, premature damages caused by the repetitive loadings at some fatigue sensitive locations of OSDs have been reported in recent years.
On the other hand, with the outstanding properties such as high strengths under both tension and compression as well as a tensile strain-hardening behavior, Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) has been demonstrated to be effective in improving the fatigue durability of OSD structures. Many studies have been conducted to investigate the fatigue performances of OSDs reinforced with UHPFRC overlay, which are primarily based on experimental approach.
However, despite the necessary information about the fatigue performances of composite bridge decks can be assessed by experiments, this experimental approach is still time- and cost- consuming. Moreover, since the comprehensive consideration of fatigue failure mechanisms is insufficient along with the lack of theoretical support from the limited cases of experimental investigations, this approach is not practical for predicting the fatigue performances of existing structures with different geometries and boundary conditions.
Therefore, this leads to the necessity to develop a reliable analytical model that can be rationally and insightfully applied to understand the fatigue behaviors of UHPFRC-OSD composite structure with arbitrary geometries and boundary conditions.
To investigate the beneficial effects of UHPFRC overlay in terms of improving the fatigue durability of OSD, a full-scale UHPFRC-steel composite bridge deck was experimentally tested in Civil Engineering Research Institute (CERI) for Cold Region, Hokkaido, under multi-stages of moving loadings (i.e., with rubber tire wheel or steel wheel) and environmental (i.e., dry or surface water) conditions. Especially, the fatigue behaviors of the composite bridge deck were then evaluated for the stage in which high mechanical wheel loading combined with severe environmental condition (i.e., surface water) were considered, since this case has been demonstrated to reduce the structural performances and the service life of the bridge decks from previous studies.
In this thesis, a numerical model developed with a finite element method was proposed to predict the fatigue performances of an orthotropic steel bridge deck (OSD) strengthened with UHPFRC overlay under multi-stages of wheel loadings and environmental conditions which accorded to the stages from the above fatigue test. The analytical results were then validated using the experimental data.
In stage 1, the composite bridge deck subjected to a moving wheel loading with rubber tire under dry condition was investigated in the fatigue analysis. The 100-year equivalent design traffic load was applied to evaluate the strengthening effect of UHPFRC overlay in fatigue durability enhancement on the OSD. For the analysis in this stage, the primary degradation mechanisms, i.e., the fatigue degradation of bridging stress in cracked UHPFRC caused by local transverse bending and the deterioration in the bond stiffness at UHPFRC/steel interface, were considered and examined in the analytical model. It was found that the effect of the latter deterioration from interface, which was often neglected from the previous analytical studies, on steel stain results was predominant in comparison to that of the former degradation in cracked UHPFRC. In this stage, the current analytical model can provide an acceptable agreement with the strain range results in steel deck plate by the experiment, validating the reliability

of the proposed method.
In stage 2, the composite deck was tested under surface water condition to examine the negative impact of stagnant water on the fatigue behaviors of the UHPFRC overlay. Two phases of the material model considering the self-healing behavior and the more severe bridging stress degradation for cracked UHPFRC were assumed in the analysis. In phase 1, under the only environmental condition of surface water, the mechanical recoveries in term of reloading stiffness and tensile strength caused by the autogenous self-healing behavior were applied to the material model of cracked UHPFRC. Thereafter, in phase 2 under the combined action of moving wheel loading and surface water conditions, the more severe bridging stress degradation of cracked UHPFRC were considered by applying its higher speed with the presence of water. It was found that the analytical strain range results of steel deck plate exhibited an acceptable agreement in tendency in comparison to those from the experiment. Therefore, it can be stated that the considered scenarios for UHPFRC cracks mentioned as two phases could have happened in stage 2 of the experiment.
In stage 3, the fatigue analysis of the UHPFRC-steel composite bridge deck was carried out under a furthermore severe condition of mechanical loading, i.e., a moving steel wheel load which was equivalent to 118-year design traffic load. Fatigue damage of the composite deck in this stage was primarily caused by the propagation of UHPFRC cracks and the continuous degradation at the UHPFRC/steel interface. It was found that the speed of bridging stress degradation in cracked UHPFRC, which is dependent on the maximum tensile strain level, was considerably accelerated in this stage, leading to the significant development of cracked regions in UHPFRC overlay. For UHPFRC/steel interface, the gradual expansions in both transverse and longitudinal directions of the debonded area were assumed to govern the fatigue deterioration of the interfacial bond layer in the analysis. It was indicated that, by considering different speeds of expansion from interfacial delamination area, the strain range results in steel deck plate obtained from the analytical model in this stage also acceptably agreed with those from the experiment. At the end of this stage, the fatigue crack was not found in the steel deck plate from the fatigue test. UHPFRC overlay, therefore, still maintained the high fatigue resistance of the composite deck even when a part of the overlay delaminated from the OSD.
In this study, the fatigue degradation in bond stiffness at the UHPFRC/steel interface was comprehensively investigated through the assumed scenarios for each considered stage. It is known that this kind of deterioration which may always occur right under the wheel loading contact region had a dominant effect on the strain evolution results in steel deck plate compared to bridging stress degradation of UHPFRC cracks, owing to the high fatigue durability of UHPFRC material. However, the interfacial deterioration caused by fatigue moving loadings is often neglected from the previous studies of OSD structure. This may lead to the unexpected shorten of fatigue lifetime estimated from the design of UHPFRC-steel composite deck, caused by the inaccurate prediction of stress (strain) ranges at the critical locations in the steel members of OSD. Generally, the understandings about the interfacial bond stiffness degradation which was revealed from the analysis have not been clearly indicated by only experimental measurement and observations at limited locations, that not only demonstrated the advantage of the current analytical model, but also provided a reference for the future investigations of the OSD reinforced with UHPFRC overlay under moving wheel loadings.