Life extension and defect tolerance analysis of HFMI treated welds in bridge application

別紙様式第１５号（論文内容の要旨及び論文審査の結果の要旨）

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学 位 授 与 日 付	令和４年３月２５日
専　　　攻	工学専攻
学 位 論 文 題 目	Life extension and defect tolerance analysis of HFMI treated welds in bridge application （HFMI 処理された橋梁溶接部の延命効果と許容欠陥寸法の数値解析的検討）
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論 文 内 容 の 要 旨
(Abstract of Thesis)

Many steel bridges around the world were constructed several decades ago, with a current need for continuous maintenance where the major challenge in old steel bridges is fatigue cracks. High Frequency Mechanical Impact (HFMI) treatment has been gathering a lot of interest nowadays as one of the post-weld fatigue strength improvement techniques. HFMI treatment is conducted to the weld toe using a hardened pin or hammer with an operation frequency of more than 90 Hz. Owing to that, beneficial compressive residual stresses can be introduced locally in/around the weld toe, and therefore the fatigue strength of welds can be improved remarkably. On the other hand, utilization of HFMI treatment for repairing and life extension of pre-fatigued welds of the fatigue-damaged steel bridges has gained interest as a robust method nowadays. Although fatigue cracks are inevitably involved in the HFMI treated welds and become “defects” against the HFMI treated welds when HFMI treatment is performed to the pre-fatigued welds, defect tolerance is not clearly stipulated in the International Institute of Welding (IIW) recommendation for HFMI treatment. Therefore, the objective of this thesis is to propose defect tolerance of HFMI treated welds in bridge application for life extension based on numerical FE simulations.

In Chapter 1, the background and problem statement were given. The objectives and disposition of this thesis were also explained in this chapter. In Chapter 2, the review of literature including the author’s previous study was conducted, and the subjects that are addressed in subsequent chapters of this thesis were determined based on the review.In Chapter 3, the validity of 3D FE HFMI simulations using an isotropic hardening model for residual stress estimation was verified for two models: flat steel plate and bead on steel plate. The HFMI simulations were carried out to the flat steel plate model, where feed rate and the number of hits of the HFMI indenter were varied in order to investigate the influence of different HFMI treatment processes, such as under- and over-treatment on the residual stress state. The results show that a high feed rate can influence the residual stress state near the treated surfaces, whereas the number of hits is independent of the amount of induced residual stress. Then, the HFMI simulations were carried out to the bead on steel plate model. The results show a reasonable estimation of the residual stresses near the treated surface compared with experimental measurement results, even when welding residual stresses are not considered in the model. In Chapter 4, the effect of HFMI treatment on pre-fatigued welds and crack opening-closing behavior in HFMI treated welds were investigated based on the HFMI simulation using a combined hardening model. A rat-hole weld, which is one of the fatigue-prone details in steel bridges, was used in the HFMI simulation. In order to simulate initial cracks, the detailed rat-hole models included a rectangle slit with different depths in their weld toes. The results show that the slit size influences the amount of induced compressive residual stress at the slit tip and the amount of closed slit size. The results also show that the slit closed by HFMI treatment opens from the inside prior to the surface. Additionally, the crack opening-closing behavior was investigated experimentally using pre-fatigued out-of-plane gusset welded joints treated by Impact Crack-Closure Retrofit (ICR), with the aid of an ultrasonic testing system. The results indicate that the behavior can be identified based on the change of echo height ratio from the crack, and similar crack opening-closing behavior was observed in the FE simulations. In Chapter 5, the influence of cracks in HFMI treated welds on life extension was investigated in 3D Crack Propagation Analysis (CPA) based on Linear Elastic Fracture Mechanics (LEFM), using the rat-hole models with different fatigue crack depths in HFMI treated welds. At first, compressive residual stress introduced by HFMI

treatment simulation was considered over those cracks faces in HFMI treated welds. Crack opening stress at the crack tip in HFMI treated weld was investigated considering the crack opening-closing behavior. The results indicate that cracks in HFMI treated welds would propagate after the HFMI treated surface crack is opened. Then, CPA based on LEFM was carried out under fatigue load. The results show that it is difficult to represent crack propagation behavior in a deeper region in the 3D CPA considering compressive residual stress. Finally, the fatigue life was calculated based on the CPA results. The calculated results demonstrated that the life extension can be obtained effectively when HFMI treatment is performed to pre-fatigued welds including fatigue cracks that are shallower than 1.5 mm in depth. In conclusion, in Chapter 6, the author proposes fatigue cracks that are shallower than 1.5 mm in depth as a defect tolerance of HFMI treated rat-hole detailed welds for fatigue life extension based on the numerical FE simulation results. Furthermore, the author recommends the defect tolerance of HFMI treatment based on the current numerical and experimental studies results.

論文審査結果の要旨
(Abstract of thesis examination report)

This thesis aimed at proposing defect tolerance of HFMI treated welds in bridge application for life extension based on numerical FE simulations. Specifically, this work made three original developments: first, re-validating the 3D FE HFMI simulations using isotropic hardening model for residual stress estimation; second, investigating the effect of HFMI treatment on pre-fatigued welds and crack opening-closing behavior in HFMI treated welds: and third, investigating the influence of cracks in HFMI treated welds on life extension using 3D CPA based on LEFM. Then, using the outcomes of the above, the defect tolerance of HFMI treated pre-fatigue welds was proposed.

As a first development, the 3D FE HFMI simulations on the flat steel plate, in order to investigate the influence of differences in HFMI treatment processes on residual stress state, were performed with an isotropic hardening model. Then, the HFMI simulations on the bead on steel plate were shown to be a reasonable estimation of the residual stresses near the treated surface in comparison with experimental measurement results. As a second development, the HFMI simulations on rat-hole welds, which appear in steel bridges as one of the fatigue-prone details, were performed with a combined hardening model and rectangle slits of different depths at the weld toes to simulate initial cracks. Additionally, experimental investigation using pre-fatigued out-of-plane gusset welded joints treated by ICR treatment, with the aid of the ultrasonic testing system, was performed and both the HFMI simulation and the experimental investigation showed good agreement in the crack opening-closing behavior. As a third development, the 3D CPA on the rat-hole welds based on LEFM was conducted. The crack re-propagation of closed crack by HFMI treatment due to fatigue load was simulated by implementing the analytically characterized compressive residual stress state. From the above, this thesis finally proposed the quantitative defect tolerance to evaluate the superiority of the HFMI fatigue crack closure effect, which contributes to the improvement of life extension and efficient repair of steel bridges. It is excellent in novelty and usefulness. Therefore, as a result of the thesis examination, the dissertation review committee decided that the submitted thesis is accepted as a doctoral dissertation.

最終試験結果の要旨
(Thesis examination final report)

The dissertation review committee confirmed that the main part of the submitted thesis consists of three research papers as shown below; two papers already published and one paper accepted for publication. The thesis examination was conducted as a public oral defense held on February 10, 2022. Based on it, the committee decided that the applicant passed the thesis examination.

発表論文（論文名、著者、掲載誌名、巻号、ページ）

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