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Remaining fatigue life assessment of in-service road bridge decks based upon artificial neural networks

Eissa Fathalla[a], Yasushi Tanaka[b], Koichi Maekawa[a,*]

[a] *The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan*
[b] *Institute of Industrial Science, The University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo, Japan*

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ABSTRACT

By using a multi-scale simulation together with the pseudo-cracking method, the remaining fatigue life of real RC bridge decks is estimated based upon their site-inspected surface crack patterns of a wide variety, and it is confirmed that the crack location and its orientation are primary factors on the remaining life together with crack width. For quick diagnosis for the remaining fatigue life at the site, an artificial neural network (ANN) to correlate the fatigue life with observed cracks is built up based upon large numbers of assessed fatigue life related to wide range of crack patterns and their widths. Artificially created crack patterns associated with the firm coupling of shear and flexure are also included in training dataset to cope with indeterminate crack events which may arise in future and to assure a robust and reliable artificial neural network model. It is recognized by conducting the cross-validations that the training data-set for ANN shall include crack patterns rooted in mechanically possible modes of failure. Otherwise, the risk of wrong assessment due to overlearning will arise.

1. Introduction

In-situ reinforced concrete (RC) bridge decks, which were specially constructed in Japan of 1960's–1970's, suffer from significant deterioration due to the limited deck thickness owing to the intended cost down under the requirement to fulfill the seismic resistance. In some current renewal plans of highway bridges, it is reported that more than 50% of the total maintenance cost is estimated to be spent for the repair and the renewal of RC bridge decks [1]. Therefore, the maintenance budget regarding RC bridge decks should be spent efficiently based on highly principled maintenance management. RC decks of road bridges are mainly subjected to moving loads from daily traffics. It was reported that RC slabs subjected to moving loads are highly deteriorated compared to the ones subjected to fixed point pulsating loads [2,3]. This phenomenon is mainly due to reversal cyclic shear along crack planes induced by moving wheel loads. This cyclic reversal shear stresses rapidly deteriorate the shear transfer mechanism rooted in so-called aggregates interlock. Finally, RC slabs rapidly lose their rigidity and do fail.

Core information for maintaining existing bridge decks sound is the current updated situation, and the most widely applied way to evaluate current status is digitalized gap grading. Any grading criteria of specifications and codes are based on an on-site visual inspection by engineers. Although this kind of inspections is practically useful for rough judgment of current damage conditions, it does not quantitatively offer the expected remaining fatigue life, which should be the basis of fatigue life assessment. In the past decade, some long-term performance simulation has been upgraded, and its practical application is being discussed in more detail on the scheme of asset management [4,5]. Here, the inspected data assimilation of current damages like cracks, material properties and magnitude of traffic loads with life simulation technology has been developed such as the pseudo-cracking method (PCM). The data assimilation technology with the use of multi-scale simulation programs & PCM was verified, and it was able to predict the remaining fatigue life of in-service bridge decks in previous research [6] under some limited conditions.

Moreover, the effect of stagnant water like rainfall on bridge concrete decks have been investigated to be hugely significant on the fatigue life as well. It was reported that the presence of stagnant water inside crack planes of concrete dramatically shortens the fatigue life [7–9], since the pulsating hydrostatic pressure is provoked when cracks are forced to be cyclic open and closed by repeated loads.

Firstly in this study, the remaining fatigue life of existing slabs is analyzed for various crack patterns by using already developed life assessment technology so that we may roughly capture the correlation of fatigue life with the inspected damages. This series of simulation is intended to clarify both the impact of crack width and geometrical patterns of cracking. Thus, the authors collected a wider variety of

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[*] Corresponding author.
E-mail address: maekawa@concrete.t.u-tokyo.ac.jp (K. Maekawa).

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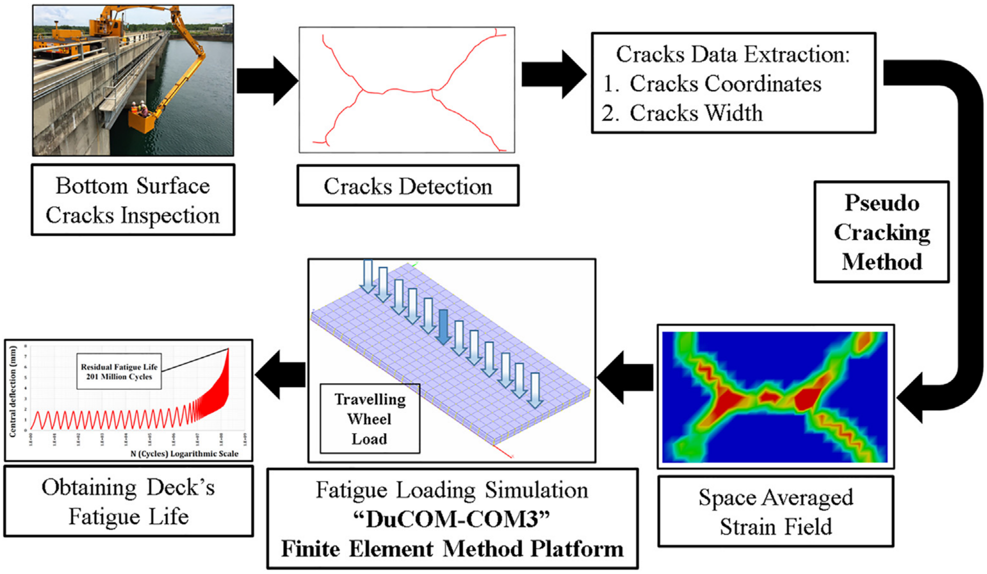

Fig. 1. Overview of remaining fatigue life prediction methodology.

typical cracking patterns for life assessment in consideration of practical use. At the same time, fictitious cracking patterns, which has never been observed but possibly may appear logically and mechanically, are purposely included in the frame of parametric study in consideration of deeper learning to produce practical assessment method as discussed in late section.

Second, in analyzing the correlation of structural life and inspected crack information (location and magnitude), the authors try to develop an artificial neural network model (ANN) for quick quantitative diagnosis of the fatigue life of bridge decks by using only the inspected bottom surface cracks on site without running the time-consuming specific life simulation. As a matter of fact, the quick judgment of remaining life is crucial for practical management at the sites where engineers cannot have any sufficient time to run simulation programs. In the training dataset of the ANN, collected real crack patterns are included for artificial intelligent machine learning, while artificial crack patterns are included to secure the robust prediction of indeterminate crack patterns that may occur logically in future as stated above. Finally, possible modes of failure are discussed in view of training artificial intelligence (AI) technology to clarify what sorts of "learning dataset" is necessary and sufficient in engineering practice. For this purpose, multi-fold validation is applied for the computationally trained AI model.

In this study, the dry condition without any impact of stagnant water is assumed as a basis of life assessment, and the impact of stagnant water on RC slabs will be discussed in future studies. If we may have inspection data of crack patterns and its width of both top and bottom surfaces of RC slabs, the accuracy of life estimation will be significantly upgraded. Since it is practically a hard work to get the inspection data on the top surfaces of bridge slabs, only the bottom surface's cracking is used for life estimation in this study. The authors expect the recent development of sensing the damage appearing on top surfaces of RC slabs covered by pavement. Then, in the near future, we may couple and assimilate the top and the bottom surface information with life simulation.

2. Methodology for predicting the remaining fatigue life

As the first step to develop ANN, the authors try to build up large numbers of a dataset of crack patterns (its orientation and width) and corresponding remaining fatigue life of RC slabs as the "learning data" for training the artificial intelligence. Then, the inspected crack patterns observed at the bottom surfaces of in-service slabs were collected from highway bridges, and the corresponding remaining life was estimated by running the life-simulation based upon the multi-scale thermo-hygral analysis [4] and the pseudo-cracking method [6] as summarised in Fig. 1. In this stage, a wide variety of crack widths was also specified to increase in the learning data to cope with future indeterminate events. At the same time, unknown crack patterns were also produced intentionally to firmly train the artificial neural network even though they were not experienced in the past. Then, the numerical lifetime analyses are learning to the premature AI, and it must be a role of structural engineers to select a necessary and sufficient dataset to meet the challenge so that the damage assessment can be efficiently conducted at the site. The following is the summary of the methods which we use, and their details are given to the Refs. [4–6,10,11].

2.1. *Multi-scale life-time simulation*

For fatigue loading simulation, the multi-scale simulation program is used, which is widely validated [3–6,10]. Fig. 2 shows the set of constitutive laws of the cracked concrete for high-frequency path-dependent constitutive models [4,6] used in the simulation program. These constitutive laws explained the damage caused by fatigue loading by a decrease in both stiffness and strength, and increase in time-dependent deformations. Each constitutive model was designed to deal with any loading path of complexity. Thus, the multi-scale analysis can estimate the fatigue strength in the case of convoluted stress paths like moving wheel loading.

2.2. *Pseudo cracking method (PCM)*

The pseudo-cracking method (PCM) is a numerical technique to estimate the remaining fatigue life of bridge deck. Inner unknown cracks are numerically generated in the early stage of fatigue cycles in the finite element model by using the predictor-corrector approach which is based on energy equilibrium principles [6,11]. The procedure of PCM is as follows.

1. Internal cracks are generated based on inspected bottom surface cracks. The location of the crack tip where crack width equals zero is assumed to be a flexural neutral axis. The width of the internal cracks is assumed to develop linearly starting from neutral axis to bottom face according to the in-plane hypothesis.