A Proposal of Data Driven Maintenance of RC Decks Focusing on Deterioration Mechanism

T. Furukawa, T. Ishida, E. Fathalla, and J. Fang

Abstract Performance degradation of reinforced concrete (RC) bridge decks is one of the most serious problems in highway structures. Therefore, in order to secure safety and extend the service life, an efficient inspection and maintenance system is urgently demanded. In this paper, Cox regression survival analysis and fatigue life analysis are discussed. The first one is a statistical method which can quantitatively analyze the risk of each deterioration factor for RC decks. The other one, which utilizes multi-scale simulation and artificial intelligence, has the advantage to estimate residual life of RC decks quickly by considering bottom-surface crack patterns. Result of two methods are compared and it is found that they have a fairly high correlation. Although the reliability of the two methods is confirmed, their results are directly applied to establish a new inspection system. Then by comparing the fatigue life of dry and water-submerged conditions, the importance of water-proofing is highlighted. Additionally, impact of non-uniform stagnant water of RC slab is investigated, where it provides an analysis that is close to the actual situation by the utilization of non-destructive testing. Finally, a comprehensive maintenance system that can determine the priority of inspection is proposed to ensure a rational decision-making.

Keywords Survival analysis · Remaining fatigue life · RC deck · Stagnant water

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1 Introduction

During the period of high economic growth, massive bridge structures were constructed. After almost 40 year pasted, the safety of this aged structures become a non-negligible issue. In urban area of Japan, the fatigue damage of reinforced concrete (RC) bridge decks from accumulated traffic load is one of the most serious problem in highway structures. Therefore, a more effective inspection system which can prolong the life of RC decks is becoming highly demanded.

In this paper, we focus on the fatigue damage of RC decks in Tokyo region. By integrating existing technologies, a new inspection system is proposed referring to the concept of "Society5.0". Firstly, inspection data of decks regarding structural and traffic information together with the crack information are analyzed by using two different methods, which are survival analysis and fatigue life analysis. Then, the two methods are compared by analyzing real RC decks from site in dry and water submerged states. Finally, a comprehensive maintenance plan is introduced in terms of inspection system and countermeasures.

2 Methodology and Previous Results

In this chapter, the two technologies, 'survival analysis' and 'fatigue life analysis' are discussed and a part of previous results are shown.

Survival analysis is a statistical method that can be used to quantify risk factors for large amounts of data. On the other hand, fatigue life analysis is used for life prediction of RC deck based on site-inspected crack.

2.1 Methodology of Survival Analysis and Results

Survival analysis is based on the relationship between a time period start from the observation time until an event occurs. It does not only quantity the risk factors, but also has the advantage of considering censoring comparing with linear model. Cox regression model is one of the most frequently used survival analysis method. Moreover, there is no assumption about distribution of the hazard, which makes it more practical.

2.1.1 Cox Regression Analysis

Yamazaki and Ishida [1] conducted Cox regression analysis of RC decks. They suggest that the method can be used for risk assessment of RC deck slab. Fang et al. [2] used same method to analyze Metropolitan Expressway by considering repairing effect. In this paper, the definition of event is consistent with the previous research [2]. The event is defined as the appearance of two-dimensional cracks and the appearance of efflorescence at the bottom of an RC deck slab. Additionally, the deterioration rate will be changed since the repairing work is conducted before inspection. Therefore, the repairing should also be considered. If steel plate bonding, replacing, carbon fiber reinforcement and crack injection were conducted, an extra event will be assumed. The cox regression model is defined as Eq. (1).

$$h(t) = h_0(t)exp(x_1\beta_1 + x_2\beta_2 + \cdots + x_n\beta_n) \tag{1}$$

where x is a covariate and β is regression coefficient. $h_0(t)$ is baseline hazard which only changes with time. Hazard ratio is calculated using the function above. Hazard ratio of covariate vector and is defined as Eq. (2) [3].

$$HR = \frac{h_0(t)exp(x_1,\beta)}{h_0(t)exp(x_0,\beta)} = exp[\beta(x_1 - x_0)] \tag{2}$$

The hazard ratio can be interpreted as the ratio of mortality for two samples with covariate x_0 and x_1 for any time duration. Risk increases as variate increases when hazard ratio is higher than one, and vice versa. Efron method is used to estimate β. The partial likelihood function is shown in Eq. (3).

$$l(\beta) = \prod_{i=1}^{m} \frac{e^{x_{i+}\beta}}{\prod_{k=1}^{d_i}\left(\sum_{j\in R(t_i)} e^{x_j\beta} - \frac{k-1}{d_i}\sum_{j\in R(t_i)} e^{x_j\beta}\right)} \tag{3}$$

2.1.2 Result for Metropolitan Expressway Co

Data come from Metropolitan Expressway are used for analysis. Table 1 shows the sample of input variables and hazard ratios of Cox regression for Tokyo region. Risk score, which is interpreted as the deterioration rate of each RC panel can be estimated by using the follow equation. By plotting the score in the map, it is possible to visualize the risk of deterioration.

$$risk\ score = \exp(x_1\beta_1 + x_2\beta_2 + \cdots + x_n\beta_n) \tag{4}$$

Table 1 Sample of input variables and results of Cox regression analysis for Tokyo region

Input variables	Hazard ratio
Traffic volume	1.357
Deck's thickness	0.621
Winter precipitation	1.180
Slope	0.808
Design code after S39	1.000
Design code before S39	3.923

2.2 Methodology of Fatigue Life Analysis

Fatigue life analysis is conducted with the data assimilation technology of the integrated system of the multi-scale simulation program (DuCOM-COM3) together with the pseudo cracking method (PCM) [4–7]. In the multi-scale simulation, the constitutive laws for high cycle fatigue loading were already integrated in order to consider the concrete's damage of high cycle fatigue loading in terms of reduction in both stiffness and strength and increase in time dependent deformation.

On the other hand, PCM is a numerical technique to estimate fatigue life of RC decks based upon site-inspected cracks. The visual cracks at the bottom surfaces are assumed to be flexure ones up to the neural axis of the RC decks and they are considered as the first candidates for fatigue lifetime simulation. Then, inner unknown cracks are numerically produced during the early age of fatigue cycles by the means of corrector-predictor approach based on energy principles. Finally, remaining fatigue life can be successfully achieved.

Moreover, multi-scale simulation was upgraded to consider concrete-water interaction based on Biot's theory, where the impact of stagnant water on RC decks can be simulated. It should be noted that multi-scale simulation program can deal with any crack patterns for fatigue life prediction of RC decks in dry or water-submerged states, but it takes huge computation cost. Thus, ANN models has been developed to achieve high-speed quantitative assessment [5, 6].

2.2.1 ANN Models

In order to reduce computational cost, an ANN model was developed [5, 6] for fatigue life prediction of RC decks based on site-inspected cracks. The target of these models is RC decks with thinner thickness less than 200 mm. Travelling wheel is chosen to be 98 kN in consideration of Japanese Speciation of Highway Bridges [8].

According to previous research [11], the criterion of fatigue failure is defined when the live load deflection (Eq. 5) is three times its initial value.

$$\delta_{L,N} = \delta_{1,N} - \delta_{2,N} \tag{5}$$

$$\frac{\delta_{L,N}}{\delta_{L,0}} \geq 3.0 \tag{6}$$

where $\delta_{L,N}$ is central live load deflection at N^{th} number of cycles, $\delta_{1,N}$ is central total deflection at N^{th} number of cycles during loading time, $\delta_{2,N}$ is central total deflection at N^{th} number of cycles during unloading time, $\delta_{L,0}$ is the initial live load deflection, N_f is the number of cycles at failure corresponding to ($\delta_{L,N}$ calculated from Eq. 6).

Figure 1 shows the methodology for building up the developed ANN models for dry and water-submerged states (Fathalla et al. [5, 6]).

3 Comparison of Survival Analysis and ANN Model

In order to develop an efficient inspection system, the prediction accuracy of the two method should be examined. Here, a comparison of two methods is conducted by analyzing RC decks in Tokyo region. Based on previous research [6], it has been demonstrated that the deterioration of RC decks can be greatly accelerated under stagnant water. To confirm the effect of stagnant water, a comparison is executed for both dry and water-submerged states.

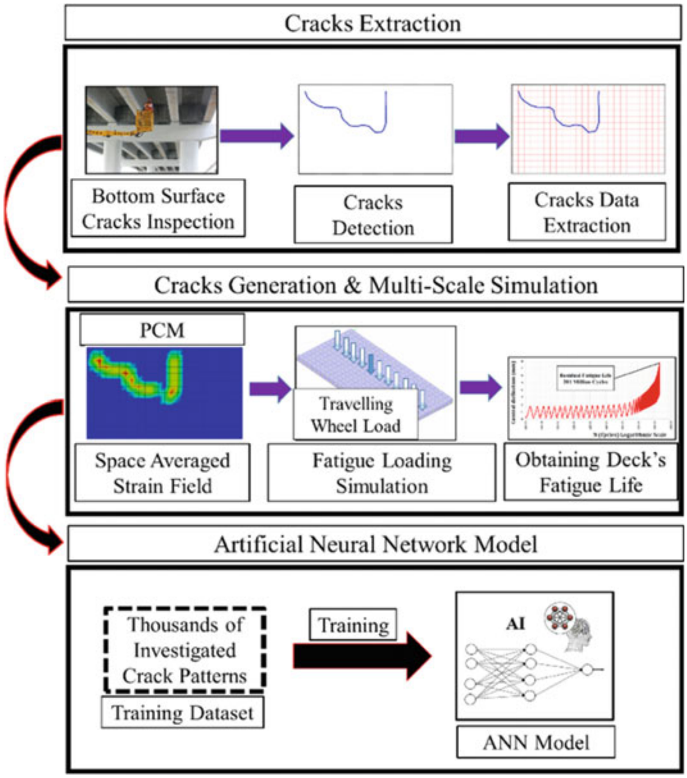

Fig. 1 Methodology of building ANN models for fatigue lifetime prediction

3.1 About Targeted RC Slab

Fatigue failure is the main reason to cause the deterioration of RC bridge in Tokyo region [2] and up to now our ANN model can only deal with specific environmental condition. Therefore, in this research, data of RC slab from Metropolitan Expressway is randomly selected. The analysis object is a panel, which is defined as an area surrounded by longitudinal-main girders and transverse-cross girders. For survival analysis, all data are simulated in the same process which have been done before to calculate the risk score [2]. Then, 55 panels from Line 5 under different situations are selected. On the other hand, for ANN model, not only structural information but also the crack information, which are extracted from slab bottom-side photos of the slab are used to conduct ANN models. However, since the crack width cannot be determined from the photo, all crack width is assumed as 0.1 mm for simplification based on previous site investigations.

3.2 Comparison Result

The relation of ANN model and risk score from the target RC slab are shown in Fig. 2. The vertical axis expresses the remaining fatigue life estimated by ANN model in dry case in logarithmic scale and the horizontal axis expresses the risk score calculated by survival analysis. High-risk score means serious deterioration possibility with low remaining life. Although the two methods are completely different, it can be seen that as the risk score increases, the remaining fatigue life reduces with a high correlation coefficient of R = 0.83. Thus, the reliability of both terminologies to be integrated together is demonstrated.

Now, in Japan, all bridges are under a 5-years periodic inspection, which was launched by government. However, it has been pointed out that the current inspection strategy is not smart enough to handle different deterioration stages. Therefore, depending on these results, inspection interval can be updated based on

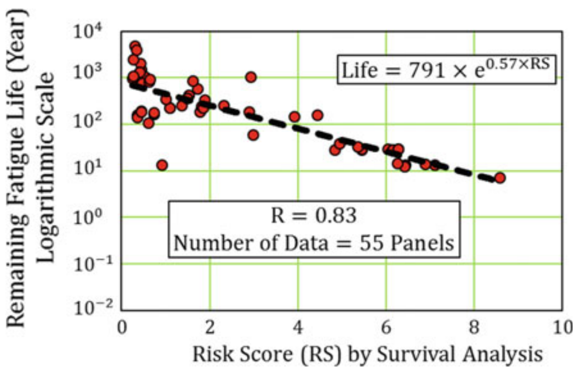

Fig. 2 Relation of remaining fatigue life and risk score for analyzed RC decks

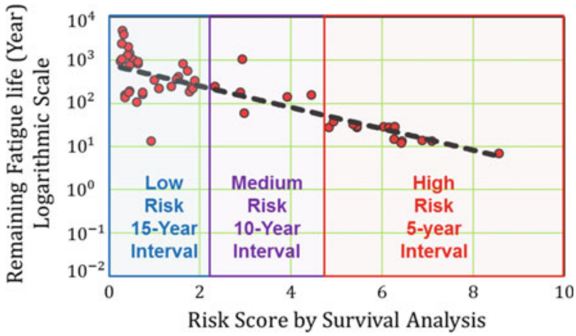

Fig. 3 Inspection interval base on remaining fatigue life and risk score

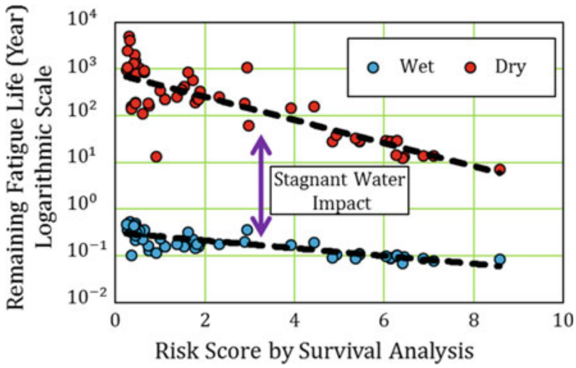

Fig. 4 Comparison of dry case and wet states for the analyzed RC decks

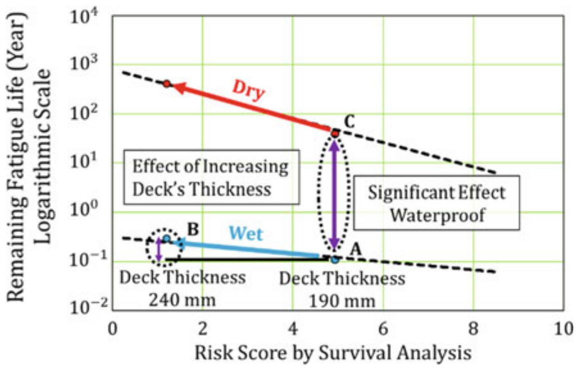

Fig. 5 Comparison of increasing deck's thickness and waterproof installation for extending life of RC decks

the real performances of RC decks in order to save unnecessary and excessive costs. As shown in Fig. 3, for high-risk zone, the inspection can be set as 5-years, and for the low-risk zone, the inspection can be set as 15-years. In this graph, the threshold is based on 95% confidence interval. Considering the actual application of deciding the inspection-span by using these results, the threshold can be set depending on company's circumstance and budget.

Furthermore, in comparison with the dry case, the RC decks in water-submerged (wet) case are also analyzed. The comparison result is shown in Fig. 4. It can be clearly seen that fatigue life in dry case is around 100-times higher than the fatigue life in wet case, which indicates that RC decks is extremely risky under wet case.

The important of waterproof installation is illustrated by comparing the remaining life of thin and thick RC decks in dry and wet states, as shown in Fig. 5. Point A represents a bridge panel under wet condition with a thickness of 190 mm. Since the remaining life is less than 1 year, two reinforcing ways which include increasing deck's thickness and waterproof installation can be used to slow down and prevent further deterioration. By increasing the slab thickness to 240 mm, point A turns to point B. Risk score changes from about 5.0 to about 1.0 and remaining fatigue life is increased about 3 times. On the other hand, by installing complete waterproof, Point A jumps up to Point C, remaining fatigue life increases dramatically comparing with slab thickening method. According to the above discussion, it can be concluded that waterproof has a significant effect on slowing down deterioration of RC decks. Here, it should be noted that the first priority of inspection should focus on stagnant water detection.

4 Impact of Stagnant Water on Fatigue Life

In reality, RC decks under water-submerge state are very rare, in most of the cases, where this assumption is overestimating their deterioration risk. In the past few decades, there was no feasible technique to detect the location of the stagnant water on RC decks below the pavement layers. Recently, a non-destructive testing (NDT) has been developed to detect stagnant water locations by signal processing of data collected from site by utilizing ground penetration radar (GPR) installed on vehicle that can travel up to 80 km/h [9].

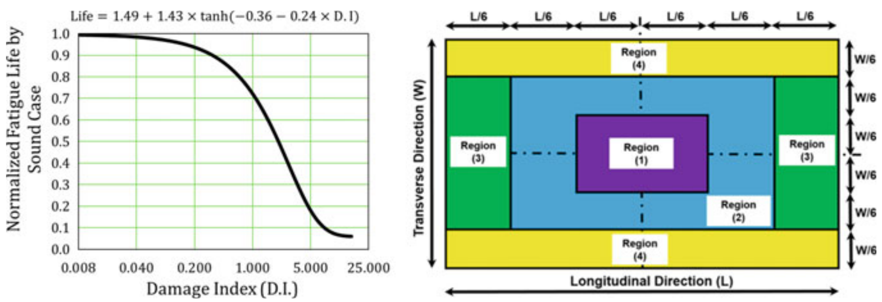

Fig. 6 Proposed model for life prediction based on site-inspected wetting locations

Moreover, a predictive model was proposed for the fatigue life prediction of RC decks based on site-inspected wetting locations [10], as shown in Fig. 6 and Eqs. 7 and 8.

$$D.I. = 0.55WR_1 + 0.23WR_2 + 0.17WR_3 + 0.05WR_4 \tag{7}$$

$$WR = \frac{\sum_{k=1}^{k=n} A_k}{A} \times 100 \tag{8}$$

where *D.I.* is the damage index of water impact, (WR_1, WR_2, WR_3, WR_4) are wetting rates for each of the zones shown in Fig. 6, k is the kth ponding region at the top surface, A_k is the wetting-area of the kth ponding region, and A is the total area of top surface of RC deck. This *D.I.* can be used as a threshold for checking the significance of water impact.

5 Proposal of New Inspection System

Based on the previous result, it is found that inspection interval can be changed according to the level of risk. In addition, it is important to install waterproof in order to prevent further deterioration of RC decks. Finally, a new inspection system is introduced by combining the current developed technologies, as shown in Fig. 7.

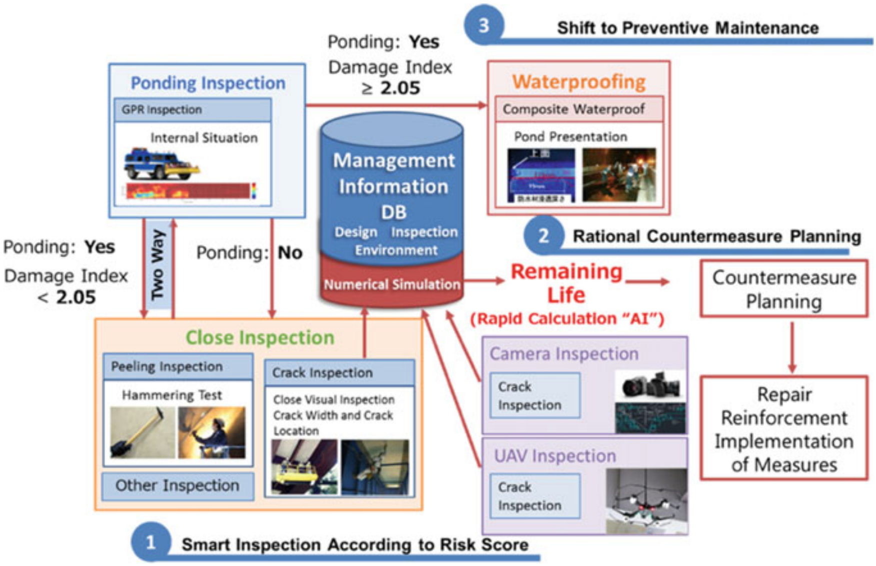

Fig. 7 Proposal for comprehensive inspection system

At first, GPR is used to check the stagnant water at the top layer of RC slab. Then, D.I. can be calculated based detected wetting locations. If D.I. is higher than the threshold, the panel is needed to be waterproofed quickly or replaced. If D.I. is lower than the threshold, monitoring the progress and dispersion of ponding by GPR system is needed in order to check whether D.I. exceeds the threshold value or not. Then, for close inspection, crack and peeling information need to be collected. Any missing information (compressive strength, reinforcement details, etc.) can be obtained by NDTs. Moreover, by using the information of cracks, remaining fatigue life can be estimated and updated. In dry case, inspection interval of crack can be changed regrading to risk score as discussed in Sect. 3. For the RC decks with higher risk of fatigue failure, more investigations should be conducted by using high definition cameras, UAV, etc., in order to obtain reliable estimation. Finally, this information is accumulated in database and combined with environmental information in order to provide rational counter measure plans.

6 Conclusion

In this paper, survival analysis and ANN models for fatigue life are discussed. Then, these two methods are compared by using real decks from site. Finally, new inspection system is proposed. The conclusions can be summarized as follows.

(1) Although the terminologies and methodologies of two model are different, they are integrated together for decision making of deterioration risk of RC decks since their results show high correlation. Here, inspection interval can be extended for RC decks with lower risk to reduce costs.
(2) Stagnant water has been proven to be the main factor to cause the reduction of lifetime of RC decks. Thus, applying waterproof works with regular maintenance is an indispensable way to effectively slow down the degradation rate of RC decks.
(3) A comprehensive inspection system of RC decks is proposed in detail. Thus, feasible maintenance plans can be successfully implemented.

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