

AUTHORS' RESPONSE TO REVIEWERS' COMMENTS

Journal: *Sustainability*

Title of the paper: Risk-cost optimised maintenance strategy for steel bridge subjected to deterioration

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Reviewer #1:

This paper develops a maintenance strategy for deteriorated bridges based on risk cost optimization. Five failure modes are considered for the deteriorated bridge, including flexure, shear, deflection and fatigue failure of the girder, and chloride attack on concrete deck. The manuscript is well written and has enough technical contribution for a journal paper.

Response: Many thanks for the comments.

1) *More information on the optimization technique should be added.*

Response: Many thanks for the comments. The following paragraphs have been added in the revised manuscript to further explain the optimization technique used in this paper.

Please see Lines 149 to 517 on Page 7, and Lines 334 to 340 on Page 15 of the revised manuscript.

“The optimization (Equation (1)) is to find the number of maintenances N_r and the time of each maintenance, i.e., t_i . The most influential component within the system can also be determined at each maintenance time through this optimization. To be specific, the probabilities of failure of different components are determined and ranked (shown later in Equation (5)) in this optimization process. The component with the highest probability of failure is treated as the critical component, as bridge structure is considered a series system in this study. The maintenance action is only performed on the critical component and the cost of failure related to the repair for this component.

This can be shown schematically in Figure 3. Furthermore, the failure mode with the highest failure probability is repaired for the critical component.”

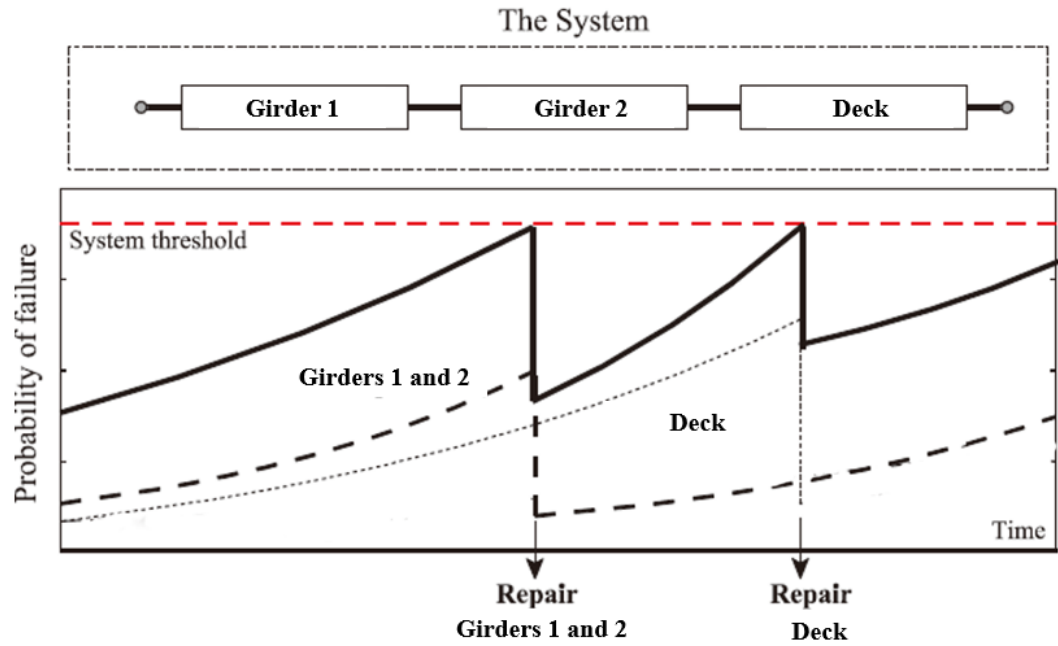


Figure 3 Maintenance strategy for the bridge system

“The search for N_r with given constraints is an iterative procedure. Based on Baji et al. (2017), Genetic Algorithm method (Deb, 2001) is an efficient method in finding optimum of complex problems with nonlinear constraints. Thus, in this paper, the flowchart in Figure 4 was coded using the Genetic Algorithm through MATLAB. As inputs, t_L , C_{jk0} and r are case-specific with values summarized in Section 7 for the case study bridge. $N_m = 9$ in this study. Since the maintenance of bridge is generally carried out every 5 years, the initial value of N_r can be determined by letting $N_r = \frac{t_L}{\Delta t}$, where $\Delta t = 5$ (Yang et al. 2016).”

2) *The limitation of the study should be discussed.*

Response: Many thanks for the comments. Section 8 has been added in Lines 426 to 443 on Pages 19 to 20 of the revised manuscript.

“8. LIMITATIONS

Although the study proposed a maintenance strategy for bridges, there are still several limitations. Firstly, the autocorrelation coefficient ρ is assumed to be 0.9 in failure probability calculation for each failure mode. Technically, ρ needs to be determined by measuring the corrosion effects (corrosion loss, degradation in yield strength and fatigue strength) of bridge at different times and calculated based on Li and Melchers (1993). Thus, future works will be carried out to measure the corrosion effects for bridges and acquire a more reliable ρ value. Secondly, the loading S is treated as a deterministic value in calculating the probability of failure for each failure mode. In future work, it is worthwhile to treat structural resistance $S(t)$ as a stochastic process and consider various factors influencing $S(t)$. Thirdly, the probability of failure is determined by assuming the structural components and failure modes are probabilistically independent. However, there is a correlation among different structural components and failure modes (e.g., the correlation between flexure and shear failure mode is high as they are determined using the same girder's loading condition). This correlation needs to be considered in future studies. Fourthly, it is assumed that the probability of failure for the critical component is reduced to the value at the initial time when it is repaired in the risk cost optimization algorithm. This is not realistic, and more work needs to be carried out to determine the changes in the probability of failure after repairing.”

3) More work on life-cycle management can be reviewed.

Response: Many thanks for the comments. The following review findings have been added in the Lines 46 to 53 on Page 2, and Lines 66 to 70 on Page 3 of the revised manuscript.

“For the deterministic method, Yanev and Chen (1993) and Mohammadi et al. (1995) used condition rating and rating deterioration model for lifecycle performance prediction and maintenance of bridge. Al-Subhi et al. (1990) and Tam and Stierner (1996) developed a bridge maintenance strategy through the lifecycle cost analysis and discounted cash flow method. For reliability theory, Frangopol (1999) incorporated reliability theory and lifecycle cost in bridge maintenance. Frangopol et al. (2001), Estes and Frangopol (2001), Yang and Hsu (2010) and Zhu and Frangopol (2013) further developed a maintenance strategy through risk cost optimization.”

“For example, Stewart and Rosowsky (1998), Itoh and Liu (1999), and Lounis (2006) considered the failure modes (e.g., Chloride penetration) only for bridge decks in their

risk cost optimization. The failure modes of other components (e.g., fatigue failure of bridge girder) have not been considered. Saydam and Frangopol (2015) and Liu et al. (2021) considered the girders' flexure, shear, and deflection failure modes in the risk cost optimization.”

Reviewer #2:

(1) Equation 2 has to be explained with probability theory in detail, since $P[G(S,R,t)]$ is less than zero.

Response: Many thanks for the comments. The following paragraphs have been added in Lines 159 to 178 on Pages 7 to 8 to explain the first passage probability theory.

“The probability of bridge failure p_f for each failure mode in Equation (1) can be determined as follows:

$$p_f(t) = P[G(S, R, t) \leq 0] = P[R(t) \leq S(t)] \quad (2)$$

where P denotes the probability of an event. $S(t)$ is the bridge response and $R(t)$ is the structural resistance. G is the limit state function, which is $G(S, R, t) = R(t) - S(t)$.

Equation (2) represents a typical down-crossing problem, which can be determined using first-passage probability theory (Li and Melchers 2005). In time-dependent reliability methods, the structural failure depends on the time that is expected to elapse before the first occurrence of the stochastic process, $R(t)$, down-crossing a critical limit, S , sometimes in a given time period $[0, t_L]$. Equally, the probability of failure, $p_f(t)$, can be determined based on the probability of the first occurrence of such an excursion during that period. This is known as ‘first-passage probability’ and under the assumption of Poisson processes, it can be expressed as follows (Li and Melchers 2005)

$$p_f(t) = 1 - [1 - p_f(0)]e^{-\int_0^t v dt} \quad (3)$$

where $p_f(t)$ is the probability of structural failure at time $t = 0$ and v is the mean rate for $R(t)$ to down-cross critical limit (S). Based on Li and Melchers (2005), the mean down-crossing rate is very small in practical problems. Thus, Equation (3) can be re-written as follows

$$p_f(t) = p_f(0) + \int_0^t v dt \quad (4)$$

The down-crossing rate in Equation (4) can be determined by Li and Melchers (1993) by assuming $R(t)$ follows Gaussian distribution.”

(2) Author has explained in detail about the bridge response $S(t)$ with various influencing parameters. But there is no explain for the structural resistance $R(t)$ and various factors influencing the structural resistance.

Response: Many thanks for the comments. In fact, $R(t)$ in this paper is treated as stochastic process and S is assumed to be deterministic. This assumption is widely used in first-passage probability theory analysis, as the cases in Li and Melchers (2005) and Baji et al. (2017). The paper has been revised to replace $S(t)$ with $R(t)$ in the description of stochastic process, and the following paragraphs have been added in Lines 276 to 280 on Page 13.

“All the limit state functions presented in this section can be rewritten into the formats in which $R(t)$ is a stochastic process and down-crosses the deterministic threshold S (e.g., $R(t)$ and S can be $-\Delta_S(t)$ and $-\Delta_R$ in Equation (14)). Thus, time-dependent probability of failure for each performance criteria of the bridge can be calculated by Equations (3) to (4) and Li and Melchers (1993).”

It is still worthwhile to consider S as a stochastic process, and thus, the following paragraphs have been added in Lines 433 to 435 on Page 20 of the revised manuscript.

“Secondly, the loading S is treated as a deterministic value in calculating the probability of failure for each failure mode. In future work, it is worthwhile to treat structural resistance $S(t)$ as a stochastic process and consider various factors influencing $S(t)$.”

(3) A Computational procedure of optimization is developed, but the details about the programming language or package should be to specified with its limitations and range of values.

Response: Many thanks for the comments. The following paragraphs have been added in Lines 334 to 340 on Page 15 to show the details about the programming language or package. Also, the limitation is summarized in Section 8 (Lines 426 to 443 on Pages 19 to 20).

“The search for N_r with given constraints is an iterative procedure. Based on Baji et al. (2017), Genetic Algorithm method (Deb, 2001) is an efficient method in finding optimum of complex problems with nonlinear constraints. Thus, in this paper, the flowchart in Figure 4 was coded using the Genetic Algorithm through MATLAB. As inputs, t_L , C_{jk0} and r are case-specific with values summarized in Section 7 for the case study bridge. $N_m = 9$ in this study. Since the maintenance of bridge is generally carried out every 5 years, the initial value of N_r can be determined by letting $N_r = \frac{t_L}{\Delta t}$, where $\Delta t = 5$ (Yang et al. 2016).”

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Although the study proposed a maintenance strategy for bridges, there are still several limitations. Firstly, the autocorrelation coefficient ρ is assumed to be 0.9 in failure probability calculation for each failure mode. Technically, ρ needs to be determined by measuring the corrosion effects (corrosion loss, degradation in yield strength and fatigue strength) of bridge at different times and calculated based on Li and Melchers (1993). Thus, future works will be carried out to measure the corrosion effects for bridges and acquire a more reliable ρ value. Secondly, the loading S is treated as a deterministic value in calculating the probability of failure for each failure mode. In future work, it is worthwhile to treat structural resistance $S(t)$ as a stochastic process and consider various factors influencing $S(t)$. Thirdly, the probability of failure is determined by assuming the structural components and failure modes are probabilistically independent. However, there is a correlation among different structural components and failure modes (e.g., the correlation between flexure and shear failure mode is high as they are determined using the same girder’s loading condition). This correlation needs to be considered in future studies. Fourthly, it is assumed that the probability of failure for the critical component is reduced to the value at the initial time when it is repaired in the risk cost optimization algorithm. This is not realistic, and more work needs to be carried out to determine the changes in the probability of failure after repairing.”