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Reliability-based model to determine the residual life of bridges

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The deterioration of large transport infrastructure systems represents trillions of dollars in public and private domains world-wide. In practice, decisions related to the assessment of bridges are based on uncertain and incomplete information. Uncertainties arise due to the variability in environmental factors, methods of inspection and data collection, lifetime traffic load prediction, to name a few. Therefore, there is a clear and significant need for uncertainty analysis of the structural performance of bridges. This study focuses on the recent advances in structural performance assessment of bridges in areas related to reliability model development and its application in life-cycle performance assessment of bridges.

Keywords: Reliability, life-cycle, performance assessment, road structure.

1 Introduction

Reliability-based performance assessment of engineering structures is a complex problem due to the uncertainty in the system performance and the external conditions that may occur throughout its lifetime [1, 2]. For a long expected lifetime road structure (*e.g.*, bridge) that last on overage 50-75 years, the structure may be exposed to progressive deterioration and some damaging extreme events, *i.e.*, earthquakes, truck impacts, etc. [3]. Consequently, the structural capacity of the system will inevitably decline and possibly fail (*e.g.*, unable to perform its designated function) before completion of the mission [4]. Further, information relating to uncertain nature of degradation that consider the effect of structural damage accumulation on residual life of a structure is of great important to support decisions with respect to structural health assessment.

Predicting of residual life of any structure requires the life-cycle performance model to describe the different structural deterioration mechanisms throughout its lifetime. In general, structural performance deterioration mechanism is divided into two broad categories; progressive deterioration and shock-based degradation. While progressive degradation (*e.g.* corrosion) is a time-dependent phenomenon which continuously depleted at a rate over structural life time, shock-based degradation (*e.g.* truck impact) describes sudden changes in the structural performance over small time intervals [5-7].

Structural deterioration models have been thoroughly researched over many years. Numerous mathematical models have been developed for progressive deterioration and shock degradation [8-12]. However, the majority of shock-based degradation and failure models developed are mainly focus on earthquakes [13, 14]. Detail application of reliability of degrading system related to earthquake damages can be found in the study of Sanchez-Silva and Rackwitz [15, 16]. In addition, the combined effect of shock and progressive deterioration on structures has also been investigated. However, bridges could also be subjected to accidental damage (*e.g.*, heavy truck impacts) and their effects on bridge damage accumulation have not been fully understood so far.

The objective of this paper is to present the recent advances in structural performance assessment of bridges using a reliability-based theoretical model which could be used to predict the residual life of degrading systems.

2 Modelling Reliability Performance Assessment of Bridges

2.1 *Shock-based degradation*

In shock-based degradation model, the damage of a structure caused by shock events is usually modelled as a random variable with randomly distributed shock size S_i and the time interval between shocks is also a random variable $X=\Delta t_i^s$ (Figure 1). The shock size does not necessarily describe to the intensity or hazard of the shock event but the damage subjected to the structure. It should be noted that the inter-arrival time of shocks Δt_i^s and their sizes S_i are independent, identically distributed. Thus, the damage accumulation at particular time $D_s(t)$ can be expressed as,

$$D_s(t) = \sum_{i=0}^{N} S_i \tag{1}$$

Then, the remaining structural capacity $V_s(t)$ can be obtained,

$$V_s(t) = u_0 - \sum_{i=0}^{N} S_i - s^* \tag{2}$$

where u_0 is the structural initial capacity and s^* the limit state threshold value. The structural intervention (*e.g.*, preventive or maintenance) is required when $V_s(t) < 0$. If $V_s(t)$ follows a known probability distribution (G_s), the probability of failure $P_s(V_s(t) < 0)$ is given by:

$$P_s(V_s(t) < 0) = 1 - \int_0^{V_s(t)} G_s(y)dy \tag{3}$$

2.2 *Progressive deterioration*

In practise, the time-dependent nature of the progressive deterioration rate is not always available at hands. In this case, the progressive degradation can be approximated by a sequence of small countable fictitious shocks (*jump process*) to simulate discrete changes in structural system (Figure 2). If Z_i describes a series of fictitious shocks occurring at a certain fix time interval (Δt_i^p), the damage accumulation $D_z(t)$ is given by,

$$D_z(t) = \sum_{i=0}^{n} Z_i \tag{4}$$

Then, the remaining structural capacity of a structure $V_z(t)$ due to progressive deterioration at a given time t can be obtained as

$$V_z(t) = u_0 - \sum_{i=0}^{n} Z_i - s^* \tag{5}$$

If $V_z(t)$ follows a known probability distribution (G_z), the probability of failure of the bridge $P_z(V_z(t) < 0)$ can be expressed as,

$$P_z(V_z(t) < 0) = 1 - \int_0^{V_z(t)} G_z(y)dy \quad (6)$$

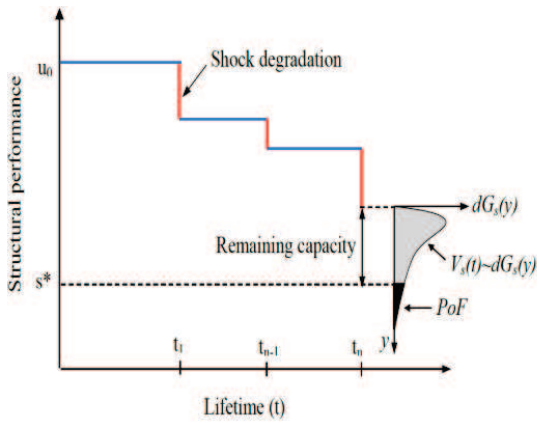

Figure 1. Shock-based degradation model

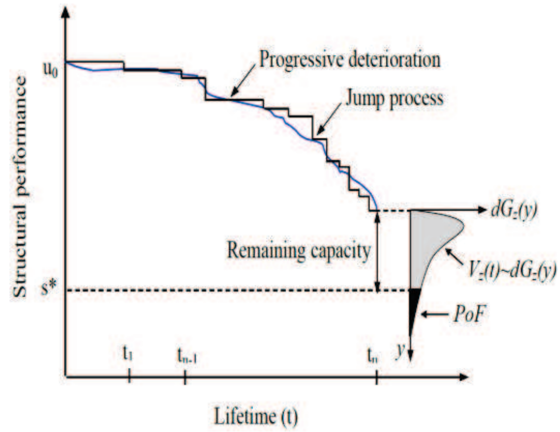

Figure 2. Progressive deterioration model

2.3 *Combined deterioration*

Based on the assumption that the structure is subjected to both shocks and continuous deterioration that they are independent, the damage accumulation $D_c(t)$ in Figure 3 can be defined as,

$$D_c(t) = D_s(t) + D_z(t) \quad (7)$$

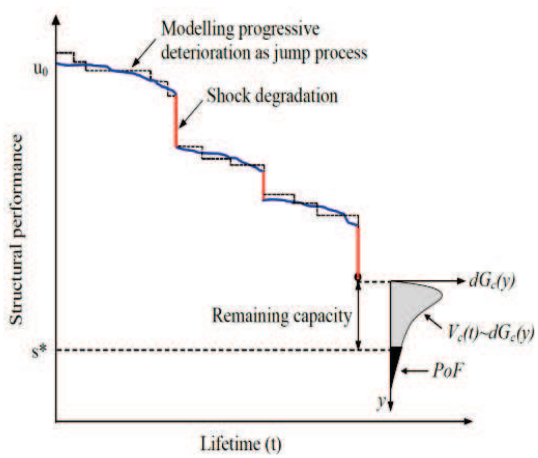

Figure 3. Combination deterioration model

Then, the remaining capacity $V_c(t)$ can be rewritten as,

$$V_c(t) = u_0 - D_z(t) - D_s(t) - s^* \quad (8)$$

Similarly, assuming that $V_c(t)$ follows an exponential distribution (G_c), the probability of failure of the structure $P_c(V_c(t) < 0)$ can be expressed as,

$$P_c(V_c(t) < 0) = 1 - \int_0^{V_c(t)} G_c(y)dy \tag{9}$$

3 Numerical Simulation

The reliability based-performance assessment procedure described in Section 2 was implemented to Montague Bridge Victoria, Australia using numerical simulation. The simulation model was developed using MATLAB program to compute the system's probability of failure. The initial capacity of a structure u_0 is considered 100% with a threshold limit $s*$ of 25%. The progressive deterioration is approximated by jump process which the size of every jump is exponentially distributed with an average rate Z_i of 0.75%. The mean damage size caused by shocks (*e.g.*, truck impacts) and their occurrences were also assumed exponentially distributed with S_i of 2% and μ of 1.5 years. Assume further that the remaining structural capacity is governed by an exponential distribution with an average rate θ of 0.05. The structural performance lifetime of the bridge were computed after 100 simulation runs.

4 Results and Discussion

The comparison between the average expected structural performance lifetime caused by progressive deterioration, shock-based degradation, and the combined of both is shown in Figure 4. It can be seen in Figure 4a, the average expected structural performance lifetime subjected to progressive deterioration only is around 100 years. As shown in Figure 4b, the average residual life of a road structure subjected to multiple shocks (*e.g.*, multiple truck impacts) could be significantly reduced (*e.g.*, 33%). Furthermore, when the combined effect of deterioration are considered, the reduced of the average residual life of a road structure is significantly higher (*e.g.*, 65%) in comparison to that of progressive deterioration only. In the context of reliability analysis, the simulation results clearly indicate that the prediction of the structural performance lifetime of bridges subjected to the combined deterioration may be useful for road authorities in making future decision (*e.g.*, maintenance).

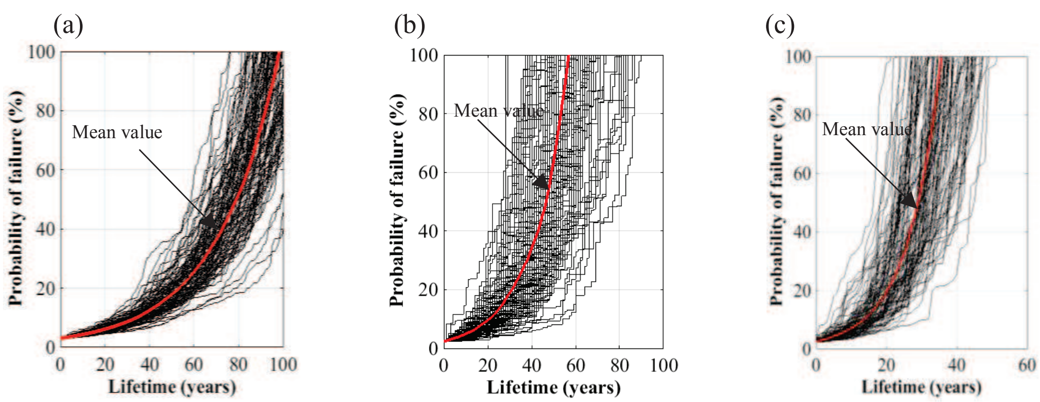

Figure 4. Structural performance lifetime of a structure as a result of (a) progressive deterioration only (b) shock only (c) combination of both deterioration mechanisms

Impact of a series of key parameters which could potentially affect the structural performance lifetime of bridges as a result of the combined deterioration was investigated. It includes initial structural capacity, damage size caused by shock event and progressive deterioration rate. Figure 5 shows the average expected structural performance lifetime as a result of loss of initial structural capacity (u_0). It can be seen that the effect of loss of the initial structural capacity would have significant consequences on the expected of structural lifetime. It can be seen that the decrease of about 10% of initial structural capacity may decrease the residual lifetime by nearly double (*e.g.*, 20%).

The amount of damage caused by shock events on structures was simulated by using three different mean damage sizes of 2%, 4% and 6%. The effect of shock' damage sizes on the structural performance lifetime are shown in Figure 6. It shows that damage sizes of 4% and 6% could reduce to 60% and 30% of the residual lifetime of a structure compared to that of damage size of 2%. The results indicate that long-term performance of bridges is sensitive to damage sizes caused by shocks.

In this study, the effect of progressive deterioration rate on the residual lifetime of road structure were assumed as 0.75%, 1% and 1.25%, respectively. The simulation results are shown in Figure 7. It can be seen that the progressive deterioration rate has insignificant impact on the decrease of the residual lifetime of bridges. A sensitivity analysis of model parameters relative to baseline values of the parameter from -20% to +20% is shown in Figure 9.

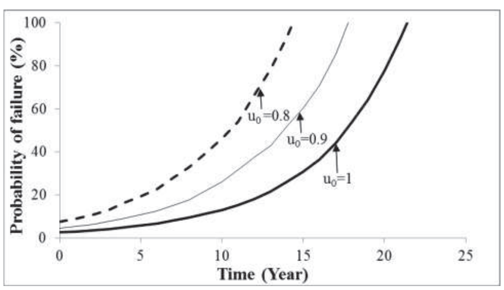

Figure 5. Structural performance lifetime of under different of initial capacity

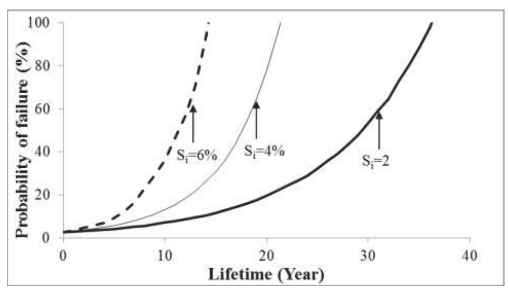

Figure 6. Structural performance lifetime of under different of damage sizes

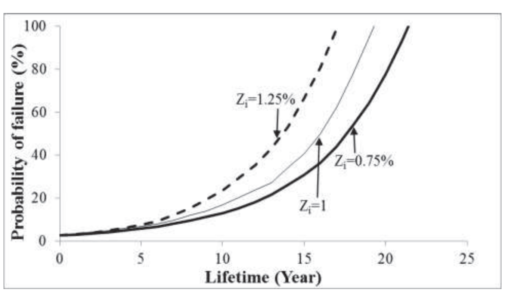

Figure 7. Structural performance lifetime of under different of progressive rates

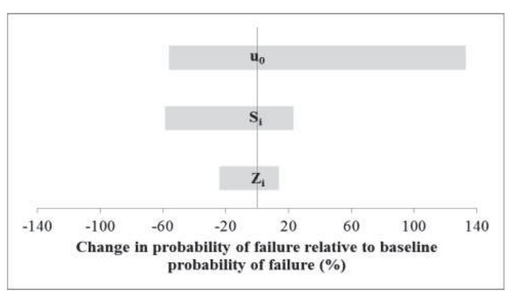

Figure 8. Sensitivity analysis of model parameters

5 Conclusion

This paper presents a structural performance assessment framework for predicting the residual life of bridges using a reliability-based theoretical analysis. The damage accumulation of bridges was treated as a result of the combination of both deterioration mechanisms was studied. The results demonstrate that the proposed model can effectively capture the life-cycle deterioration behavior of the bridges.

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