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# Corrosion fatigue effects on life estimation of deteriorated bridges under vehicle impacts

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ABSTRACT

Corrosion fatigue is more detrimental that of either one acting separately. The safety and reliability are greatly endangered by the combined effects from environmental corrosions and vehicle-induced fatigue damages, which could possibly lead to a catastrophic failure. In this paper, the corrosion fatigue effects on life estimation of deteriorated bridges subjected to dynamic vehicle loads are evaluated based on a reliability-based approach. Both the road surface deterioration and the structural member corrosion are considered in the vehicle-bridge dynamic system for stress range estimations. Varied material corrosion rates, vehicle types, vehicle speeds, and time-varied road surface conditions are considered. At the end of each stress block, the fatigue life is estimated by evaluating the cumulative probability of failure. The effects of the corrosion induced area loss and moment of inertia reduction are limited and are much less than the random effects from road surface condition. Corrosion induced fatigue strength reduction have a large effect on fatigue life. More than 60% reduction of fatigue life is predicted for different corrosion levels. The fatigue strength reduction is found more sensitive for the fatigue life estimation. With the refined vehicle-bridge dynamic analysis model and a refined material corrosion model, it is possible to assess the time-variant damages from random vehicle loads, environmental corrosion and their combined effects.

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## 1. Introduction

Corrosion fatigue, which refers to the joint interaction of corrosive environment and repeated dynamic stressing, is more detrimental than that of either one acting separately [48]. Bridges, which serve as a major link component in the infrastructure system, are extremely vulnerable to the combined action of corrosion and fatigue. The action could possibly bring major threats on structural safety and lead to catastrophic failure, such as the tragedy of the collapse of the Silver Bridge in 1967 [37]. With more than 30% of existing bridges exceeding their 50-year design lives and 35% of existing bridges classified either as structurally deficient or functionally obsolete in the U.S., great attention has been raised on the safety and reliability of the infrastructure system [6]. With potential significant deterioration and much heavier vehicle loads, the safety of the existing deteriorating bridges in their later life cycles is more critical. With a remarkable progress on vehicle-bridge dynamics and metal corrosion analysis, it is possible to assess the time-variant damage from random vehicle loads, environmental corrosion, and their combined effects.

In order to obtain the stress range history, a data analysis on on-site strain measurements or a structural dynamic analysis of bridges is necessary. Since the field measurements can be expensive and stress range spectra for bridges are strongly site-specific [36], it is impossible to take on-site measurement for every concerned location of every bridge. Therefore, finite element method (FEM) based structural dynamic analysis can be used to provide reasonable stress range histories for bridge details in various scenarios. The efforts on modeling the interactions of vehicles and bridges started from modeling the vehicle as a constant moving force or a moving mass [8,49]. Guo and Xu [25] built a fully coupled vehicle-bridge dynamic model, and later a framework for vehicle-bridge-wind dynamic analysis was established by Cai and Chen [10]. In their vehicle-bridge or vehicle-bridge-wind dynamic system, coupled equations of motions for the vehicle and the bridge were built. The coupling forces between the bridge and vehicles were modeled as coupling forces between the tires and the randomly generated road surface of the bridge deck. The dynamic effects of vehicles on bridges were proven significantly affected by the vehicle speed and road roughness conditions [7,44,46,56]. Later, a systematic fatigue damage assessment approach was built

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to include the effects of the progressively deteriorated road conditions and random dynamic vehicle loads in a bridge's life cycle [56]. However, no material corrosion in a bridge's life cycle was considered in the previous study on the vehicle-bridge dynamic analysis.

Corrosion fatigue is an electrochemical process dependent on the environment/materials/stressing interaction and has very complex mechanisms [48]. McAdam started a comprehensive air and corrosion fatigue test program from 1920s and very low corrosion fatigue strengths were found for the carbon and low-alloy steels [48]. In 1940s, large amount of data were collected on the rate of material loss of metal specimens in various environments and systematic studies on the environmental corrosion of metal [2]. Newman and Procter [39] reviewed the theory and practice of stress corrosion cracking (SCC) from 1965 to 1990. The main developments are related to the lack of specificity of SCC environments, fracture mechanics testing, studies of grain boundary structure, etc. In 1987 [31], Kayser and Nowak summarized the possible types of bridge corrosion. Large uncertainties of the structural performance were found due to the inherent randomness in the deterioration process [32]. Later, a deterioration model was developed and the major parameters for the corrosion of structural members were identified, including the deterioration rate (annual loss) and pattern (roughening and pitting) [17,41]. In addition, fatigue strength reduction curves were also defined in the model. With more accurate stress range prediction results based on the vehicle-bridge dynamic system and corrosion modeling of deteriorating bridges, it is possible to evaluate structural reliability considering both the environmental corrosion and the random vehicle dynamic impacts.

The objective of this paper is to evaluate the corrosion fatigue life of existing deteriorating steel bridges subjected to dynamic vehicle loads. The dynamic stress ranges were obtained based on vehicle-bridge dynamic analysis for varied vehicle speeds and road roughness conditions. Two types of bridge deterioration were considered. One is the deterioration of the road surface condition, which enters the vehicle-bridge dynamic system via the interaction forces between the vehicle tires and the bridge. Possible road surface renovations in the bridge's life-cycle are considered. The other type of deterioration is the corrosion of the bridge component, which includes sectional loss and downward shift of fatigue strength. Based on the proposed fatigue damage assessment approach, the deterioration effects are included when evaluating the limit state functions at the end of each stress cycle via updating the stiffness matrices and the fatigue strength. A nonlinear cumulative fatigue damage model based on continuum damage mechanics is used in the present study. Therefore, the fatigue life of the bridge can be obtained by checking the cumulative probability of failure and comparing it with the target value.

## 2. Vehicle induced dynamic stress ranges

### 2.1. Vehicle-bridge dynamic system

In the vehicle-bridge dynamic system, the vehicle is modeled as a combination of several rigid bodies, and the tires and suspension systems are modeled as linear elastic spring elements and dashpots [10]. They are idealized as a combination of several axle mass blocks, springs, and damping devices and the equations of motions are built for both the vehicle and the bridge. The equations of motions for the vehicle and the bridge are coupled through the wheel-bridge contact forces acting on road surfaces and vehicle tires. The contact forces are transferred to equivalent nodal forces and are substituted into the mass and stiffness matrices. The final equations of motions for the coupled system are as follows [46]:

$$\begin{bmatrix} M_b & \\ & M_v \end{bmatrix}\begin{Bmatrix} \ddot{d}_b \\ \ddot{d}_v \end{Bmatrix} + \begin{bmatrix} C_b + C_{bb} & C_{bv} \\ C_{vb} & C_v \end{bmatrix}\begin{Bmatrix} \dot{d}_b \\ \dot{d}_v \end{Bmatrix} + \begin{bmatrix} K_b + K_{bb} & K_{bv} \\ K_{vb} & K_v \end{bmatrix}\begin{Bmatrix} d_b \\ d_v \end{Bmatrix} = \begin{Bmatrix} F_{br} \\ F_{vr} + F_v^G \end{Bmatrix} \quad (1)$$

where $\boldsymbol{d_b}$ and $\boldsymbol{d_v}$ are the displacement vectors for all DOFs of the bridge and the vehicle; $\dot{\boldsymbol{d}}_{\boldsymbol{b}}$, $\ddot{\boldsymbol{d}}_{\boldsymbol{b}}$ and $\dot{\boldsymbol{d}}_{\boldsymbol{v}}$, $\ddot{\boldsymbol{d}}_{\boldsymbol{v}}$ are the first and second derivative of $\boldsymbol{d_b}$ and $\boldsymbol{d_v}$, respectively; $\boldsymbol{M_b}$, $\boldsymbol{M_v}$, $\boldsymbol{C_b}$, $\boldsymbol{C_v}$, $\boldsymbol{K_b}$, and $\boldsymbol{K_v}$ are the mass, damping and stiffness terms for the bridge and the vehicle; $\boldsymbol{F_v^G}$ is the self-weight of the vehicle; the terms $\boldsymbol{C_{bb}}$, $\boldsymbol{C_{bv}}$, $\boldsymbol{C_{vb}}$, $\boldsymbol{K_{bb}}$, $\boldsymbol{K_{bv}}$, $\boldsymbol{K_{vb}}$, $\boldsymbol{F_{br}}$, and $\boldsymbol{F_{vr}}$ in Eq. (1) are the expansion terms for the damping, stiffness matrices, and force vectors due to the contact force. The bridge-vehicle contact points change with the vehicle position and the road roughness along the bridge. The time independent terms in mass, stiffness, and force matrices or vectors are built via finite element method. In each time step, the new position of each vehicle is identified and the time dependent terms are updated. The equations of motions are solved in time domain using Rouge-Kutta method. At each time step, when the contact force turns into tension, the vehicle tire are assumed to leave the riding surface and the force is set to zero. The corresponding time dependent terms in the equations of motions are updated simultaneously.

After obtaining the bridge dynamic response $\boldsymbol{d_b}$, the stress vector can be obtained by [57]:

$$[\boldsymbol{S}] = [\boldsymbol{E}][\boldsymbol{B}]\{\boldsymbol{d_b}\} \quad (2)$$

where $[\boldsymbol{E}]$ is the stress–strain relationship matrix and is assumed to be constant over the element, and $[\boldsymbol{B}]$ is the strain–displacement relationship matrix assembled with $x$, $y$ and $z$ derivatives of the element shape functions.

### 2.2. Modeling of road surface conditions

According to the AASHTO LRFD bridge design specifications [1], the dynamic effects due to moving vehicles are attributed to two sources namely, the hammering effect due to the vehicle riding surface discontinuities, such as deck joints, cracks, potholes and delaminations, and dynamic response due to long undulations in the roadway pavement. The long undulations in the roadway pavement are assumed as a zero-mean stationary Gaussian random process, and it is generated through an inverse Fourier transformation [52]:

$$r(x) = \sum_{k=1}^{N} \sqrt{2\phi(n_k)\Delta n}\cos(2\pi n_k x + \theta_k) \quad (3)$$

where $\theta_k$ is the random phase angle uniformly distributed from 0 to $2\pi$; $\phi()$ is the power spectral density (PSD) function (m$^3$/cycle) for the road surface elevation; $n_k$ is the wave number (cycle/m). The PSD functions for road surface roughness were developed by Dodds and Robson [19], and the PSD function was simplified by Wang and Huang [52] as:

$$\phi(n) = \phi(n_0)\left(\frac{n}{n_0}\right)^{-2} \quad (4)$$

where $\phi(n)$ is the PSD function (m$^3$/cycle) for the road surface elevation; $n$ is the spatial frequency (cycle/m); $n_0$ is the discontinuity frequency of $1/2\pi$ (cycle/m); and $\phi(n_0)$ is the road roughness coefficient (m$^3$/cycle) whose value is chosen depending on the road condition.

The surface discontinuities that cause hammer effects, these irregularities, such as the uneven joints, the potholes, and faulting (bumps), have a significant influence on bridge dynamic responses. The discontinuities were isolated and treated separately from the pseudo-random road surface profiles according to ISO [28] and

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