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Dynamic responses of prestressed bridge and vehicle through bridge–vehicle interaction analysis

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ABSTRACT

Existence of prestress in bridges affects the dynamic responses of both bridges and vehicles traveling over them. In this paper, the bridge is modeled as a continuous beam with eccentric prestress, and a half-vehicle model with 4 degrees of freedom is used to represent the vehicle passing the bridge. A new bridge–vehicle model with consideration of prestress effect is created through the principle of virtual works to investigate the continuous prestressed bridges and vehicle interaction responses. The correctness and accuracy of the model are validated with literature results and Abaqus model. Based on the created model, numerical simulations have been conducted using the Newmark integration method to perform a parametric study on effects of number of bridge span, span length, eccentricity and amplitude of prestress. It is shown that prestress has a significant effect on the maximum vertical acceleration of vehicles, which may provide a good index for detecting the change of prestress.

1. Introduction

Highway bridges serve as a vital component in modern infrastructures. The safety of these bridges is a great concern of government agencies and general public. Many destructive and nondestructive methods have been used to evaluate bridge fitness for serving the anticipated traffic flow [1–3]. In this paper, a model capturing the responses of prestressed bridges and vehicles will be created and later used as a structural health monitoring method for detecting prestress losses.

Many researches have been conducted to study the bridge vehicle interaction. Zhu and Law [4] studied the continuous bridge and vehicle interaction, in which the dynamics of the bridge deck under single and several vehicles moving in different lanes is analyzed using the orthotropic plate theory and modal superposition technique. The dynamic impact factor is also summarized for different vehicle traveling speeds. Yang and Papagiannakis [5] studied the composite bridge and vehicle interactions and found that the dynamic impact factors are increased for bridges using FRP sandwich decks. Green and Cebon [6] studied dynamic responses of highway bridges to heavy vehicle loads and good agreements are found for the measured dynamic bridge midspan displacement and the predicted bridge midspan displacement. Kocaturk and Simsek [7] utilized the Lagrange equations to solve the dynamic response of a simply supported beam subjected to an eccentric compressive force and a concentrated moving harmonic force. Khang et al. [8] investigated transverse vibrations of prestressed continuous beams under the action of moving bodies by using the method of substructure, which neglected the eccentricity of the prestress. Cai et al. [9–12] particularly studied adopting dynamic impact factor for performance evaluation of bridges and researched effect of wind and bridge approach length on responses of bridge vehicle interaction. However, the influence of the prestress with eccentricity on the dynamic responses of both continuous bridges and vehicles traveling over them has not been considered in these works.

In the present study, the dynamic responses of prestressed continuous bridges and vehicles traveling over them are investigated. The bridge is modeled as a continuous beam with eccentric prestress. A half-vehicle model with 4 degrees of freedom is used to represent the vehicle passing the bridge. A new bridge–vehicle model with consideration of prestress effect is created through the principle of virtual works. Based on the created model, the bridge–vehicle interaction response is solved by using the Newmark integration method. Through the conducted numerical simulations, effects of number of bridge span, span length, eccentricity and amplitude of prestress are analyzed and discussed. It is anticipated that results given in this paper will help quantifying the loss of prestress in field.

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2. Dynamic behaviors of prestressed bridge and vehicle

2.1. Equation of motion for the prestressed bridge

As shown in Fig. 1, a two-span continuous eccentrically-prestressed bridge can be simplified as a continuous beam subjected to one axial force (S) and one initial moment (M_o) at the two ends.

Based on the modal superposition principle, dynamic deflection $w(x,t)$ of the beam can be described as

$$w(x,t)=\sum_{i=1}^{N}W_i(x)q_i(t) \tag{1}$$

where $W_i(x)$, $q_i(t)$, and N are the ith mode shape function of the beam, the corresponding modal amplitude of the beam, and the selected number of mode shapes respectively.

According to the principle of virtual displacement [13], the external virtual work δW_E is equal to the internal virtual work δW_I:

$$\delta W_E=\delta W_I \tag{2}$$

The virtual displacements $\delta q_i W_i(x)$, $i = 1,2,\ldots,N$ are selected to be consistent with the assumed shape functions. The external virtual work is the sum of the works (δW_{in}, δW_P, δW_C, δW_S and δW_{M_o}) performed by the inertia force $\left(\bar{m}\frac{\partial^2 w}{\partial t^2}\right)$, the moving loads ($F_b^{int}$), the damping forces $\left(-c_{bi}\frac{\partial w}{\partial t}\right)$, the prestress force ($S$), and the moment ($M_o$), which can be written as,

$$\delta W_E=\delta W_{in}+\delta W_P+\delta W_C+\delta W_S+\delta W_{M_o} \tag{3}$$

where

$$\begin{aligned}
\delta W_{in}&=-\delta q_i\int_0^L W_i(x)\bar{m}\frac{\partial^2 w}{\partial t^2}dx\\
\delta W_P&=\delta q_i\int_0^L\sum_{k=1}^{2}F_b^{int}(k)\delta[x-\widehat{x_k}(t)]W_i[\widehat{x_k}(t)]dx\\
\delta W_C&=-\delta q_i\int_0^L c_{bi}\left(\frac{\partial w}{\partial t}\right)W_i(x)dx\\
c_{bi}&=2\bar{m}\omega_i\zeta_i\\
\delta W_S&=\delta q_i\int_0^L S\left(\frac{\partial w}{\partial x}\right)W_i'(x)dx\\
\delta W_{M_o}&=\delta q_i[M_oW_i'(0)-M_oW_i'(L)]
\end{aligned} \tag{4}$$

and $\bar{m}$ is the mass of the beam per unit length; ω_i, ζ_i, c_{bi} is the natural frequency, damping ratio and damping coefficient for the ith mode of the beam respectively; $F_b^{int}(k)$ is the kth interaction force between the wheel of the vehicle and the bridge; $\widehat{x_k}(t)$ is the location of the kth interaction force $F_b^{int}(k)$; $\delta(x)$ is the Dirac function; $W_i'(x)$ denotes the first derivative of $W_i(x)$ with respect to x.

The internal virtual work performed by the bending moment is:

$$\delta W_I=\delta q_i\int_0^L EI\left(\frac{\partial^2 w}{\partial x^2}\right)W_i''(x)dx \tag{5}$$

where EI is flexural rigidity of the beam; $W_i''(x)$ denotes the second derivative of $W_i(x)$ with respect to x.

Substituting Eq. (1) and Eqs. 3–5 into Eq. (2) and cancelling δq_i at both sides give

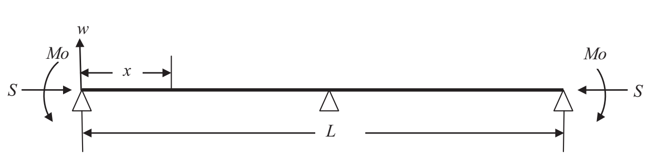

Fig. 1. Schematic of eccentrically continuous prestressed bridge.

$$\sum_{j=1}^{N}\ddot{q}_jM_{bij}+\sum_{j=1}^{N}\dot{q}_jC_{bij}+\sum_{j=1}^{N}q_j(K_{bij}-K_{Gij})=W_{pi}+(W_{M_o})_i \tag{6}$$

where

$$\begin{aligned}
M_{bij}&=\int_0^L\bar{m}W_i(x)W_j(x)dx \quad K_{bij}=\int_0^L EIW_i''(x)W_j''(x)dx\\
K_{Gij}&=\int_0^L SW_i'(x)W_j'(x)dx \quad C_{bij}=\int_0^L c_{bi}W_i(x)W_j(x)dx\\
W_{pi}&=\sum_{k=1}^{2}F_b^{int}(k)W_i(\widehat{x_k}(t)) \quad (W_{M_o})_i=M_oW_i'(0)-M_oW_i'(L)
\end{aligned} \tag{7}$$

$\dot{q}_j$ and $\ddot{q}_j$ denote the first and second derivative of $q_j(t)$ with respect to time t.

Corresponding to the N independent virtual displacements $\delta q_i W_i(x)$, $i = 1,2,\ldots,N$, there are N virtual work equations in the form of Eq. (6). Together they can be expressed in matrix form as,

$$\boldsymbol{M_b}\ddot{\boldsymbol{Q}}+\boldsymbol{C_b}\dot{\boldsymbol{Q}}+(\boldsymbol{K_b}-\boldsymbol{K_G})\boldsymbol{Q}=\boldsymbol{W_b}\boldsymbol{F_b^{int}}+\boldsymbol{W_{M_o}} \tag{8}$$

where

$$\boldsymbol{Q}=\{q_1(t),q_2(t),\ldots,q_N(t)\}^T \quad \boldsymbol{W_b}=\begin{bmatrix}W_1(\widehat{x_1}(t))\ W_1(\widehat{x_2}(t))\\ \vdots\\ W_N(\widehat{x_1}(t))\ W_N(\widehat{x_2}(t))\end{bmatrix}$$

$$\boldsymbol{F_b^{int}}=\begin{bmatrix}F_{t1}\\F_{t2}\end{bmatrix} \quad \boldsymbol{W_{M_o}}=\begin{Bmatrix}M_o[W_i'(0)-W_i'(L)]\\ \vdots\\ M_o[W_N'(0)-W_N'(L)]\end{Bmatrix} \tag{9}$$

$\boldsymbol{M_b},\boldsymbol{K_b},\boldsymbol{C_b},\boldsymbol{K_G}$ are the mass, stiffness, damping, and geometric stiffness matrices of the bridge respectively with their (i, j)th element calculated in Eq. (7); $\dot{\boldsymbol{Q}},\ddot{\boldsymbol{Q}}$ are the first and second derivatives of $\boldsymbol{Q}$ with respect to time t; F_{t1},F_{t2} are the bridge–vehicle interaction forces at the front and rear wheel locations shown in Eq. (19); m_f, m_r, m_c, s_1 and s_2 are parameters of vehicle shown in Fig. 2; g is the acceleration of gravity.

clsActually, due to the axial force (S) and moment (M_o) at the two ends, the prestressed bridge has initial deflection (w_0) before it vibrates under the moving vehicle. The initial deflection of the bridge can be determined by Eq. (8) with $\dot{\boldsymbol{Q}}_0=\ddot{\boldsymbol{Q}}_0=(\boldsymbol{W_b}\boldsymbol{F_b^{int}})_{t=0}=[\boldsymbol{0}]_{\boldsymbol{N}\times\boldsymbol{1}}$ at the time $t = 0$ and Eq. (1) as following:

$$\begin{aligned}
(\boldsymbol{K_b}-\boldsymbol{K_G})\boldsymbol{Q}_0&=\boldsymbol{W_{M_o}}\\
w_0&=\boldsymbol{W}\boldsymbol{Q}_0
\end{aligned} \tag{10}$$

where

$$\begin{aligned}
\boldsymbol{W}&=\{W_1(x),W_2(x),\ldots,W_N(x)\}\\
\boldsymbol{Q}_0&=\{q_1(0),q_2(0),\ldots,q_N(0)\}^T
\end{aligned} \tag{11}$$

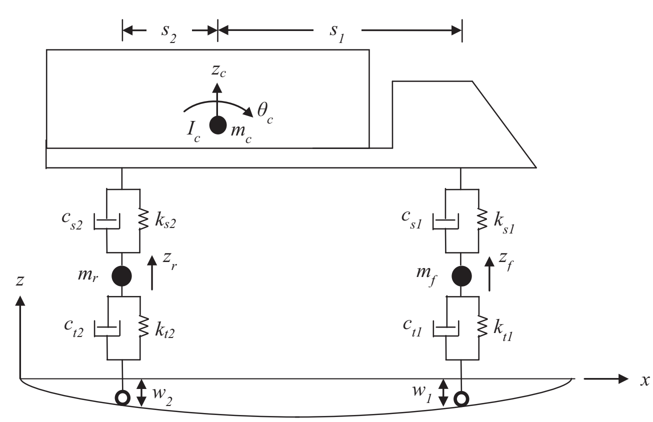

Fig. 2. Half-vehicle vibration model.