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Stochastic dynamic finite element analysis of bridge–vehicle system subjected to random material properties and loadings

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ABSTRACT

This paper performs the statistical dynamic analysis on the bridge–vehicle interaction problem with randomness in material properties and moving loads. The bridge is modeled as a laminated composite beam with Gaussian random elastic modulus and mass density of material with random moving forces on top. The mathematical model of the bridge–vehicle system is established based on the finite element model in which the Gaussian random processes are represented by the Karhunen–Loéve expansion. Some statistical response such as the mean value and standard deviation of the deflections of the beam are obtained and checked by Monte Carlo simulation.

1. Introduction

Recently, the dynamic response of a bridge structure under moving loads has been investigated by many researchers. Fryba [1] obtained the analytical solutions for simply supported and continuous beams with uniform cross-section. Green and Cebon [2] presented the solution on the dynamic response of an Euler–Bernoulli beam in the frequency domain subjected to a "quarter-car" vehicle model by adopting an iterative procedure in conjunction with the experimental verification. Yang and Lin [3] obtained closed-form solution on the dynamic interaction between a moving vehicle and the supporting bridge using the modal superposition technique. Zheng et al. [4] performed the research on a multi-span non-uniform beam subjected to a moving load. Based on the Lagrange equation and modal superposition, the beam bridge model was extended by Zhu and Law [5] to an orthotropic rectangular plate under a series of moving loads. Marchesiello et al. [6] also proposed an analytical approach to the vehicle–bridge dynamic interaction problem with a seven degrees-of-freedom vehicle system moving on a multi-span continuous bridge deck.

For more complex bridge–vehicle models, the finite element method has been utilized to perform the dynamic interaction analysis. Henchi et al. [7] presented an efficient algorithm for the dynamic analysis of a bridge discretized into three-dimensional finite elements with a stream of vehicles running on top at a prescribed speed. The coupled equations of motion of the bridge–vehicle system are solved directly without an iterative method. Similar work has been conducted by Lee and Yhim [8] and Kim et al. [9] with experimental and field test data respectively. There are also other kinds of finite element methods, such as the "moving element method" [10] and "moving mass element method" [11,12], which are developed to solve the problem of moving forces on frame and plate structures.

Generally speaking, the conventional deterministic analysis obtains only an approximation of the actual response due to uncertainties in the structural properties and the external loadings. Therefore, it is quite necessary to perform the stochastic analysis for the bridge–vehicle interaction problem. Recently, some research work has been conducted on the dynamic response of a bridge deck with the road surface roughness modeled as Gaussian random processes. Some researchers

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[13–17] considered the randomness in the loadings due to the road surface roughness where the system parameters of both bridge and vehicle were treated as deterministic. Others had the randomness in the mass, stiffness, damping and moving velocity [18–20] of the moving vehicle and perturbation method was adopted to estimate the statistics of the structural dynamic response under random excitations. To model the uncertainties in structural analysis, stochastic finite element method is often used. Fryba et al. [21] computed the statistics of the dynamic response of a beam under a single moving force using the stochastic finite element analysis by using the first order perturbation in which the stiffness and damping were modeled as Gaussian random variables.

Due to the fact that the perturbation method tends to lose accuracy when the level of uncertainty increases [22,23], the Karhunen–Loéve (K–L) expansion is used in the present study to represent the Gaussian random processes in the equation of motion of the bridge–vehicle system. The bridge response under Gaussian random vehicular forces which may have non-Gaussian properties will be approximated by Gaussian random processes. This approach is similar to that proposed by Ghanem and Spanos [24] noted as the spectral stochastic finite element method in which the random responses with non-Gaussian properties are presented on a polynomial chaos basis. Nevertheless, a large numbers of Karhunen–Loéve components are required to represent the system parameters and excitation [25,26]. Recently, Wu and Law [27] proposed a new method to study the dynamic behaviors of bridge–vehicle system with uncertainties; their mathematical model is established based on finite element model in which the Gaussian random processes are presented by the Karhunen–Loéve expansion.

To study the vehicle induced vibrations, a simply supported beam with various constitutive materials is often used. Laminated composite and functionally graded beams due to their appropriate properties are extensively adopted in the engineering structures. Therefore, it is quite essential to know the dynamic characteristics of these structures under the dynamic moving loads. Kadivar and Mohebpour [28] obtained a solution based on a FEM for three deformation theories to investigate the dynamic response of the orthotropic laminated composite beams with shear effect and rotary inertia under the actions of moving loads. Chen [29] derived the dynamic equilibrium equations of composite nonuniform beams made of anisotropic materials considering the effects of transverse shear deformations and structural damping using Hamilton's principle. Lin and Chen [30] studied the problems of dynamic stability of spinning pre-twisted sandwich beams with a constrained damping layer subjected to periodic axial loads by using the FEM. Kim [31] presented the dynamic stability behavior of the damped laminated beam under the uniformly distributed subtangential forces using the finite element formulation. The effects of various boundary conditions, fiber orientation and external and internal damping have been studied. Simsek and Kocatürk [32] investigated the free and forced vibration behavior of a functionally graded (FG) beam subjected to a concentrated moving harmonic load. They derived the equations of motion by using Lagrange's equations under the assumptions of Euler–Bernoulli beam theory. Simsek [33] studied the vibration of FG beams under a moving mass considering the different beam theories using the Lagrange's equations. In addition, he studied the non-linear vibration analysis of a FG Timoshenko beam under action of a harmonic load [34]. Recently, Mohebpour et al. [35] investigated the dynamic response of composite laminated beams subjected to the moving oscillator by using an algorithm based on the finite element method. The first order shear deformation theory (FSDT) is assumed in their beam model.

A stochastic finite element model is proposed in the present study for the dynamic response calculation of a bridge structure considering stochastic loading with inherent randomness in a bridge–vehicle system. The algorithm based on the proposed model can handle complex random excitation forces with large uncertainties and relatively small uncertainties in system parameters. The bridge is modeled as a simply supported laminated composite beam with Gaussian random elastic modulus and mass density of material and random moving forces on top. The forces have time-varying mean values and a coefficient of variation at each time instance, and they are considered as Gaussian random processes. The equation of motion of the bridge–vehicle system is presented using the Karhunen–Loéve expansion and the response statistics are obtained by solving the system equation of motion using the Newmark-β method. Some of the numerical results based on the proposed stochastic approach are checked by those obtained from the Monte Carlo simulation.

2. Mathematical formulation

2.1. Beam model

A simply-supported laminated composite beam of length L, width b and thickness h is considered, with the coordinate system placed at the mid-plane of the laminate, with the moving loads on the top of the beam, as shown in Fig. 1.

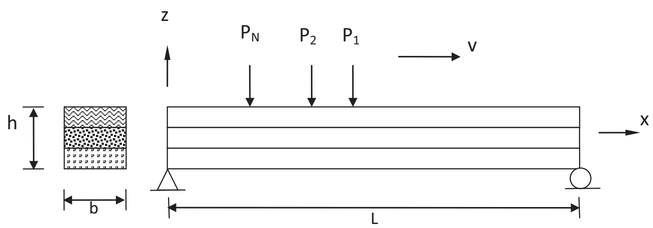

Fig. 1. Bridge–vehicle system: geometry and coordinate system of the laminated composite beam.