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Finite element modeling of bridges with equivalent orthotropic material method for multi-scale dynamic loads

Wei Zhang, C.S. Cai *, Fang Pan

Dept. of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, United States

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ABSTRACT

An effective Finite Element (FE) model is important to evaluate the structural performance under multi-scale dynamic loads, for instance, the wind induced vibrations for the long span bridge in a kilo-meter scale and the vehicle induced dynamic impacts within limited influence areas in a meter scale. The superposition of the stresses from the multi-scale dynamic loads might cause serious fatigue damage accumulation for long-span bridges. This paper presents a multiple scale modeling and simulation scheme based on an equivalent orthotropic material modeling (EOMM) method that is capable of including the refined structural details. Bridge details with complicated multiple stiffeners are modeled as equivalent shell elements using equivalent orthotropic materials, resulting in the same longitudinal and lateral stiffness in the unit width and shear stiffness in the shell plane as the original configuration. The static and dynamic response and dynamic properties of a simplified short span bridge from the EOMM model are obtained. The results match well with those obtained from the original model with real geometry and materials. The EOMM model for a long-span cable-stayed bridge is built with good precision on dynamic properties and can be used for the wind induced fatigue analysis. Based on the modeling scheme, it is possible to predict a reasonable static and dynamic response of the bridge details due to the multi-scale dynamic loads effects, for instance, the wind induced low frequency vibrations in a kilo-meter scale and the vehicle induced high frequency vibrations in meter scale.

1. Introduction

With an increase of span lengths, bridge structures are becoming more flexible, which makes them more vulnerable to the wind-induced vibrations or flutter failure at a low critical wind speed. The wind induced buffeting vibrations can produce repeated dynamic stresses in bridge details [13,26]. Nevertheless, local vehicle dynamic loads can cause repeated dynamic stresses and induce local fatigue damages or cracks, as well. Such a local failure might develop and induce the whole structure failure, for instance, the collapse and failure of the King's Bridge in Melbourne, Australia (1962), the Point Pleasant Bridge in West Virginia (1967) and Yellow Mill Pond Bridge in Connecticut (1976).

For the long-span bridge details, fatigue damage estimation schemes were used to calculate the dynamic load effects from vehicles, trains and winds [6–8]. In the analysis, a global structural analysis using a beam element model is usually conducted firstly to determine the critical locations and a local analysis is carried out to obtain the local effects. The global beam element model of long-span bridges is usually in kilometers, and the majority of finite element models in the previous studies are built using beam elements. Such a model is usually called as a "fish-bone" model [4]. In the beam element model, the whole section is assumed to deform with respect to the centroid of the bridge deck system and all the mass and stiffness properties are transformed to the equivalent beams located along the centroid of each deck section. The equivalent beam forms the spine of the "fish-bone". Rigid beams are used to locate one end of the cables or hangers on the bridge decks for cable supported bridges, which form the ribs of the "fish-bone". The overall static and dynamic response can be obtained at each node located at each beam end. However, only the rigid body motion is considered in the plane of the bridge deck section and the local deformations are neglected.

Based on the St. Venant's principle, the localized effects from loads will dissipate or smooth out with regions that are sufficiently away from the location of the load [19]. The forces are obtained from the beam element model and implemented only on a portion of the overall geometry to obtain the local static effects [25]. Large computation efforts are needed for the refined section model with complicated structural details, and it is difficult to include the time-varying dynamic effects from both wind loads and vehicle loads. Chan et al. [5] merged a typical detailed joint geometry

* Corresponding author.
E-mail address: cscai@lsu.edu (C.S. Cai).

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model into the beam element model to obtain the hot-spot stress concentration factors (SCFs) of typical welded joints of the bridge deck. Then the hot spot stress block cycles were calculated by multiplying the nominal stress block cycles by the SCF for fatigue assessment. Li et al. [18] proposed a multi-scale FE modeling strategy for long-span bridges. The global structural analysis was carried out using the beam element modeling method at the level of a meter. The local detailed hot-spot stress analysis was carried out using shell or solid elements at the level of a millimeter. After introducing the mixed dimensional coupling constraint equations developed by Monaghan [20], the multi-scale model of the Tsing Ma Bridge was built, and the computed results were obtained and verified using the on-site measurement data. However, due to the limitations of the beam element modeling, the effects from distortion, constrained torsion, and shear lag were missing in the previous analyses, which might have a large effect on the local displacements, strains, and stresses for wide bridge decks with weak lateral connections.

With the increasing demand of traffic, the bridge decks are becoming wider and have a large mass distribution across the bridge deck or even have a separate deck section type, such as the Stonecutters cable-stayed bridge and Xihoumen suspension bridge in China. Therefore, it might not be reasonable to assume rigid body motion over the full bridge deck due to its weak lateral connections. Two or more parallel "fish-spines" are suggested for the beam element model to model the bridge deck with multiple centroids of separate decks in order to obtain a reasonable result [12]. Nevertheless, in order to enhance the bending resistance of the steel plate to carry local loads from vehicle wheels, steel plates of the bridge decks are often stiffened with multiple closed or open stiffeners. As a result, it is impossible to numerically model the long span bridges with complicated structural details with a simple beam element model. The stress histories in structural details due to the dynamic effects from vehicle loads and wind loads cannot be obtained, either. Therefore, a multiple scale modeling scheme is essential to effectively model the structure in detail and save the calculation cost with less numbers of elements and nodes. Based on the principle of equivalent stiffness properties in both the lateral and longitudinal directions of the steel plate with multiple stiffeners, equivalent orthotropic shell elements were proposed to model the long-span bridges and the local deformation effects can be taken into account [28].

In the present study, a multiple scale finite element modeling scheme is presented based on the equivalent orthotropic material modeling (EOMM) method. Bridge details with multiple stiffeners are modeled with shell elements using an equivalent orthotropic material. The static and dynamic responses and dynamic properties of a simplified short span bridge from the EOMM shell element model are obtained and compared with the results from the original shell element model with its real geometry and materials. The EOMM shell element model for a long-span bridge is also built more accurately on dynamic properties. The paper is organized as the following three main sections. In the first section, the equivalent orthotropic modeling method is introduced, followed by the control equations for the finite element analysis on static and dynamic performance and dynamic properties. In the second section, the vehicle-bridge dynamic system and its parameters are introduced. In the third section, two numerical examples are presented, including one short span bridge and one long span bridge. For the short span bridge, comparisons are made on static and dynamic analysis and dynamic properties between the EOMM shell element model and the original shell element model. For the long-span bridge, the dynamic properties are compared between the results from the EOMM shell element model and the beam element model. Conclusions are drawn from the case study results at the end of the paper.

2. Equivalent orthotropic material modeling method

2.1. Orthotropic bridge deck

Most of the metallic alloys and thermoset polymers are considered isotropic i.e., their properties are independent of directions. In their stiffness and compliance matrices, only two elastic constants, namely, the Young's modulus E and the Poisson's ratio v are independent. In contrast, the orthogonal materials have independent material properties in at least two orthogonal planes of symmetry. A total number of 21 elastic constants are needed for fully anisotropic materials without any plane of symmetry.

In order to enhance the bending resistance of the steel plate to carry local loads from vehicle wheels, orthotropic bridge decks were developed by German engineers in the 1950s [24]. As a result, the total cross-sectional area of steel in the plate was increased, and the overall bending capacity of the deck and the resistance of the plate to buckling were increased, as well. The creative orthotropic bridge design not only offered excellent structural characteristics, but were also economical to build [22]. From short span bridges to large span cable-supported bridges, the orthotropic bridge design was used throughout the world, for instance, the Golden Gate Bridge and the Akashi–Kaikyo Bridge. Many design manuals for orthotropic steel deck bridges had been presented from many institutions, such as American Institute of Steel Construction [1], Federal Highway Administration [9]. In addition to the bridge deck, the orthotropic steel plates are used in the other parts of the bridge deck systems, such as the cross plates or the side plates. For example, the Donghai Cable-stayed Bridge in China with a main span of 420 m has a prestressed concrete deck, while the web, cross plates and bottom plates have multiple various open and closed rib stiffeners. The bridge deck system is shown in Fig. 1 [25]. In order to model the bridges with small stiffeners, large computational efforts are needed if all the stiffeners are modeled in details, and it is almost impossible to carry out the corresponding dynamic analysis. Due to the orthotropic properties of the deck plate, it is possible to use equivalent orthotropic shell elements to model the plate with various stiffeners.

2.2. Orthotropic shell element

A typical shell element is subjected to both membrane forces and bending forces. The quadrilateral flat shell element can be assembled by the four node quadrilateral plane stress element and the quadrilateral plate bending element based on the discrete Kirchoff theory (DKQ) [2]. For an x–y plane shell element, the assembly of the quadrilateral flat shell element can be represented as shown in Fig. 2 [16]. The translations and rotations are represented by single and double arrows, respectively.

Each node of a typical shell element has six degrees of freedom and the corresponding nodal displacements are

$$\{U_i\} = \{\, u_i \quad v_i \quad w_i \quad \theta_{xi} \quad \theta_{yi} \quad \theta_{zi} \,\} \tag{1}$$

where u, v, w are the translations and θ_{xi}, θ_{yi}, θ_{zi} are the rotations in the x, y, and z direction, respectively.

For orthotropic materials, the Hooke's law in stiffness form can be given by:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1-v_{yz}v_{zy}}{E_yE_z\Delta} & \frac{v_{yx}+v_{zx}v_{yz}}{E_yE_z\Delta} & \frac{v_{zx}+v_{yx}v_{zy}}{E_yE_z\Delta} & 0 & 0 & 0 \\ \frac{v_{xy}+v_{xz}v_{zy}}{E_zE_x\Delta} & \frac{1-v_{zx}v_{xz}}{E_zE_x\Delta} & \frac{v_{zy}+v_{zx}v_{xy}}{E_zE_x\Delta} & 0 & 0 & 0 \\ \frac{v_{xz}+v_{xy}v_{yz}}{E_xE_y\Delta} & \frac{v_{yz}+v_{xz}v_{yx}}{E_xE_y\Delta} & \frac{1-v_{xy}v_{yx}}{E_xE_y\Delta} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2G_{yz} & & \\ 0 & 0 & 0 & & 2G_{zx} & \\ 0 & 0 & 0 & & & 2G_{xy} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix} \tag{2}$$