車両との連成を考慮した斜橋の交通振動応答予測
Prediction of skew bridge vibration incorporating interaction with road traffic

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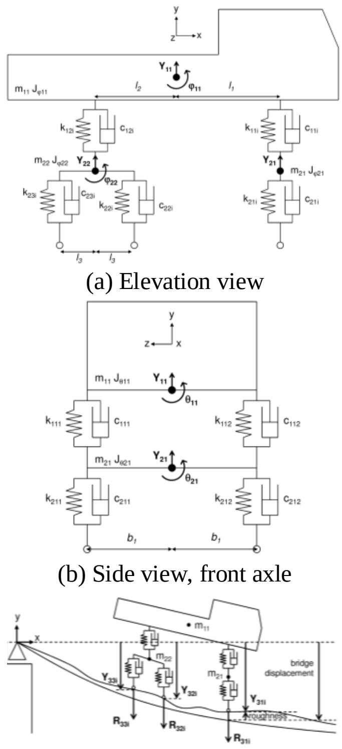
1. Introduction

Although skew bridges are widely used, they are usually designed without particular attention to their skewness. Their structural properties are, however, different from those of non-skewed bridges. Very few researchers have considered the dynamic response of skew bridges under moving-vehicle loads, and their surveys are mainly based on field measurements [1]. It is essential to predict their structural responses to in-service loads. In this study, the vehicle-bridge decoupled equations of motion are implemented with the commercial software ABAQUS and MATLAB. This analytical procedure is applied to a full-scale steel I-girder skew bridge that has been monitored. The validated model is further used to investigate the particular behaviors caused by the skewness and to identify critical structural members.

2. Vehicle-bridge system modeling

A versatile numerical procedure is developed in order to simulate the dynamic interaction between the bridge and the vehicle, incorporating the effect of road surface roughness. The vehicle is represented as three rigid bodies connected by linear springs and dashpots, as illustrated in Fig. 1. The model has a total of eight degrees of freedom (DOF). The equations of motion for the vehicle are derived from Lagrange's equation and can be written in a matrix form as

$$[\mathrm{M}_v]\{\ddot{u}\}+[\mathrm{C}_v]\{\dot{u}\}+[\mathrm{K}_v]\{u\}=\{F_g\}+\{F_c\} \qquad (1)$$



(a) Elevation view

(b) Side view, front axle

(c) Contact condition

Fig. 1 Vehicle model.

where $\{u\}$ is the vector of the vehicle's DOF, $[\mathrm{M}_v]$, $[\mathrm{C}_v]$ and $[\mathrm{K}_v]$ are the vehicle structural matrices, $\{F_g\}$ is the gravity force vector and $\{F_c\}$ is the eight-dimensional vector of the forces and moments exerted by the bridge on the vehicle. Each component of vector of the wheel displacements $\{v_c\}$ is equal to the sum of the roughness and the bridge displacement at the corresponding contact point. The roughness of the roadway is treated as a stationary normal random process with zero-mean in this study. The matrix equation of the bridge is given by

$$[\mathrm{M}_b]\{\ddot{v}\}+[\mathrm{C}_b]\{\dot{v}\}+[\mathrm{K}_b]\{v\}=[\Gamma]\{F_{vb}\} \qquad (2)$$

in which $[\mathrm{M}_b]$, $[\mathrm{C}_b]$ and $[\mathrm{K}_b]$ are the bridge structural matrices assembled by any FEM software, $\{v\}$ is the bridge DOF vector and $\{F_{vb}\}$ is the six-dimensional vector of the vertical forces exerted by the wheels on the bridge at the contact points [Fig. 1(c)]. In practice, the n-dimensional force $\{[\Gamma]\ \{F_{vb}\}\}$ exerted on the bridge is implemented in the FE software by means of a subroutine. The vehicle-bridge system is coupled because of the existence of the interaction forces $\{F_c\}$ and $\{F_{vb}\}$.

The coupled equations of motion (1) and (2) of the vehicle-bridge system are decoupled and solved step by step using Newmark's numerical integration scheme. Initially, the bridge remains stationary while the vehicle's displacements and the wheel forces acting on the bridge are caused only by the static weight of the vehicle. If the vehicle's displacements $\{u\}_t$ velocities $\{\dot{u}\}_t$ and accelerations $\{\ddot{u}\}_t$; the bridge displacements and velocities, and the vector of forces exerted by the vehicle on the bridge $\{F_{vb}\}_t$ are known at any time t, it is possible to derive these quantities at time $t + \Delta t$ by using this algorithm[2]. The bridge's displacements at time $t + \Delta t$ are obtained with ABAQUS by applying the force $\{F_{vb}\}_t$ at the

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contact points during the step time Δt. Next, the wheel-displacement vector $\{v_c\}_{t+\Delta t}$ is derived from the bridge's displacements at time $t + \Delta t$ and the roughness data. Finally, $\{u\}_{t+\Delta t}$ and $\{f_{vb}\}_{t+\Delta t}$ are computed with MATLAB.

3. Modeling adjustment and verification

The numerical procedure described above is applied to a full-scale skew bridge monitored by the Japanese Public Works Research Institute. It is a simply supported, single-span, 46°-skewed composite bridge. The 230 mm reinforced concrete slab is supported by four steel I-girders. The bridge is 32 m long and 9.95 m wide. All the bearings allow rotational displacements in three directions. In 2003, the bridge was equipped with strain gauges, whose positions are indicated in Fig. 2. A FE model of the bridge was developed with the commercial software ABAQUS. By comparing the natural frequency results with the measurement, the case in which all the degrees of freedom are restricted is chosen as the boundary conditions in the analysis.

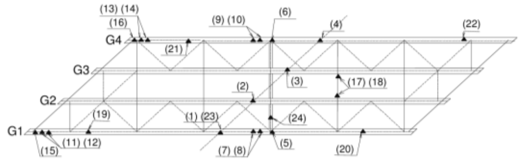


Fig. 2 Bridge structure and locations of strain gauges

The boundary conditions and road roughness were adjusted to fit the numerical model to the field-test results at a single channel. For instance, the responses at the midpoint of Girder 3, seen in Fig. 3, show that the simulations were in good agreement with the measurements. This comparison demonstrates that simulation can reasonably approximate the real state of the bridge.

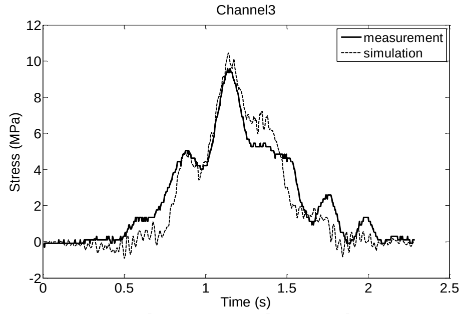
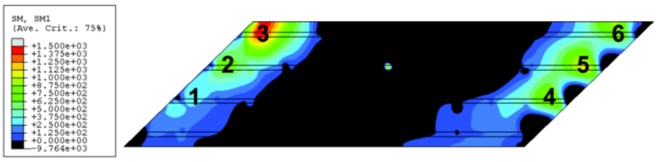


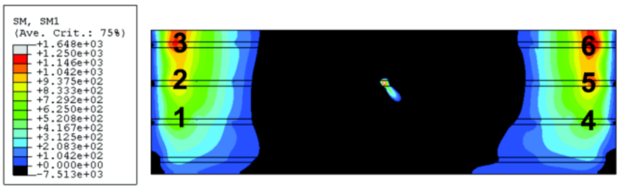
Fig. 3 Comparison between simulation and measurement

4. Analysis of the skew bridge

To indentify the effects caused solely by the skewness and distinguished from effects that also occur in regular bridges, a non-skewed reference model was prepared with the same structural design properties as the skew bridge. The distributions of negative longitudinal slab-bending moments were graphically investigated and are shown in Fig. 4. The moments concentrate in the numbered regions above the girders at the extremities of both structures. When the time histories are precisely output for the six regions of both bridges, the greatest response is observed in the obtuse corner of the skew bridge (Region 3). The result shows that in this critical area, the maximum negative moments are 22% higher than in the non-skewed bridge.



(a) Skew bridge



(b) Non-skewed bridge

Fig. 4 Comparison of the slab negative moments

Sensor points were defined in the girder part of the reference model at locations equivalent to those in the skew bridge. Minimally and moderately stressed components generally exhibit higher responses in the reference model, at the midpoints of the main girders, for instance (Fig. 5).

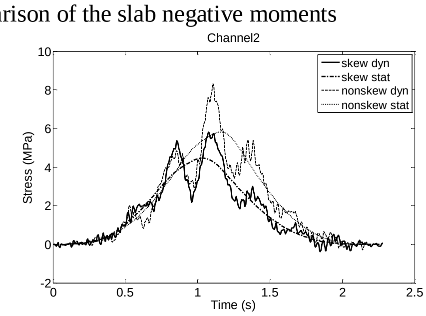


Fig. 5 Comparison of the girder stresses

5. Conclusion

This study confirms that it is essential to consider a bridge's dynamic responses in order to correctly assess its structural condition.

Reference

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[2] Xia Y, Fujino Y, Abe M, Murakoshi J: Short-term and long-term health monitoring experience of a short highway bridge: case study. Bridge Structures 2005;1:43-53.