Engineering Structures 176 (2018) 500–521

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Nonlinear dynamic response analysis of vehicle–bridge interactive system under strong earthquakes

Sudanna Borjigin, Chul-Woo Kim*, Kai-Chun Chang, Kunitomo Sugiura

Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University, Kyotodaigaku-katsura, Nishikyo-ku, Kyoto 615-8540, Japan

ARTICLE INFO

Keywords:
Bridge nonlinear behavior
Recursive substructure method
Seismic analysis
Vehicle effect
Vehicle–bridge interaction

ABSTRACT

Seismic design codes for highway bridges and viaducts in most countries do not specify the simultaneous presence of live vehicle loads and earthquake loads. However, urban highway bridges and viaducts are loaded constantly by heavy traffic, therefore it is important to elucidate the effects of moving vehicles on the seismic response of bridges. This paper proposed a seismic response analysis framework incorporating vehicle–bridge interactions (VBI) with nonlinear dynamic analysis. The proposed method integrates a commercial FEA package, ABAQUS, into the authors' in-house VBI-solving programs developed using MATLAB. With the proposed method, the effects of vehicle dynamics on seismic responses of a highway bridge could be clarified and the seismic performance of the bridge could be checked. For the bridge and ground motions studied herein, it was observed that continuously moving vehicles might yield larger longitudinal displacement responses at pier tops and plastic deformations at pier bottoms than those of the bridge alone, implying that ignoring vehicles' additional mass effect and dynamic effects during earthquakes might be on the non-conservative side. Acceleration responses of pier tops and relative displacements of bearings were generally reduced by the moving vehicles. Besides the reason that the vehicles act like dampers on the bridge, it was most probably that the vehicle-bridge in-phase modes were excited by specific ground motions to a level lower than the original bridge-alone mode was, which could be indicated from their corresponding pseudo acceleration response spectra. Although the out-of-phase modes were excited to a similar level to the original bridge-alone mode was, these modes might dissipate some seismic energy that would have been dissipated by the bridge components and reduced displacement of the bearing.

1. Introduction

Seismic design of bridges is an issue of great concern in earthquake-prone countries. Seismic design codes for highway bridges and viaducts in most countries do not specify the simultaneous presence of live vehicle loads and earthquake loads [1]. As one example, Japan Road Association (JRA) bridge design specifications do not suggest the inclusion of a vehicle load in the seismic design based on two assumptions. First, it is unlikely that the designed live load would be on the bridge exactly when an earthquake occurred. Second, on bridges, vehicle dynamics might have beneficial effects against earthquakes, i.e. they might reduce the seismic response of the bridge [2].

However, the first assumption above might not always be true in metropolitan areas because highway bridges and viaducts are loaded constantly by heavy traffic [1,3,4]. Considering the high probability of the simultaneous occurrence of heavy traffic and an earthquake, it is important to elucidate the effects of moving vehicles on the seismic response of bridges. Moreover, the second assumption might not always be true, either. The presence of moving vehicles would not always be beneficial to the bridges, as observed in many studies described below.

Before the 1995 Kobe earthquake, several studies had pointed out the effects of vehicle dynamics on bridge seismic responses. A study by Sugiyama et al. [5] showed that the dynamic effect of the vehicles was more dominant in the transverse direction and that the vehicle loading tended to reduce the bridge response. However, Kameda et al. [6] stated that the vehicles tended to amplify the bridge response when the vehicles and bridge were in phase and tended to decrease the response when they were out of phase. Moreover, Kameda et al. [7] concluded that the bridge seismic responses would increase or decrease depending on the phase difference between the bridge and the vehicle. Vehicle dynamics exhibited beneficial effects only when the period of the vehicle was greater than that of the bridge. The effect of a live load was considerably greater when the bridge remained in its elastic state.

After the 1995 Kobe earthquake, more numerical findings about this

---

* Corresponding author.
E-mail address: kim.chulwoo.5u@kyoto-u.ac.jp (C.-W. Kim).

https://doi.org/10.1016/j.engstruct.2018.09.014
Received 13 February 2018; Received in revised form 22 August 2018; Accepted 9 September 2018

issue were presented, although most of them were specifically related to frequent and moderate earthquakes. Kawatani et al. [8] demonstrated that heavy vehicles act as a damper, possibly reducing the seismic response of bridges under a moderate ground motion with lower frequency characteristics. However, under higher frequency ground motions, these vehicles have the opposite effect, slightly amplifying the seismic response of the bridge. Kim et al. [4] reported that acceleration responses of the bridge subject to moderate earthquakes were amplified when the vehicles were treated as additional mass. The amplification depends on the relation between the fundamental frequency of the bridge and the response spectra of the ground motion; acceleration responses of the bridge under moderate earthquakes were reduced when the vehicles were simulated as a dynamic system. The study also showed that the effect of a moving vehicle is negligible compared to that of a stationary vehicle. Kim and Kawatani [9] found that a train acts as a damper and tends to decrease acceleration response under a particular earthquake. He et al. [10] investigated the seismic responses of Shinkansen viaducts for high-speed trains under moderate earthquakes. Their results show that the train can act as a damper for the bridge. In addition, considering the train simply as an additional load or mass can either overestimate or underestimate the bridge response. A study by Zeng and Dimitrakopoulos [11] studied a horizontally curved railway bridge subjected to train crossings and moderate ground motions of different periods. Results verified the favorable damping effect that the running vehicles have on the deck vibration.

For strong earthquakes, however, the study by Kim et al. [12] idealized stationary monorail trains as structural members of FE model of bridge. They showed that consideration of the monorail train as additional mass rather than a dynamic system in numerical modeling overestimated the effect of the train load on seismic performance of monorail bridges. Earlier plastic deformation at the end bracing of the girder system absorbed seismic energy and reduced the stress at the pier base.

In addition to numerical studies, a few experimental studies were conducted to investigate the vehicle dynamic effects on bridge seismic response. Shaban et al. [13] conducted a large-scale experiment with a real vehicle parked on the deck of a simple-span bridge. Their results indicated that top slab transverse accelerations and bearing displacements were reduced in the presence of a vehicle during seismic tests, which can be ascribed to the tuned mass-damper-like behavior induced by the vehicle. To date, the most extensive testing of the effects of vehicle dynamics on bridge seismic response was conducted at the University of Nevada at Reno [14]. The study concluded that vehicles had a beneficial effect only when the seismic level was lower than that defined by the design earthquake. The vehicles had an adverse effect at greater levels. Again, the vehicles' beneficial effect was regarded as similar to that of a tuned mass damper, as shown in earlier analyses.

As reviewed above, several studies have examined vehicle–bridge interaction (VBI) systems under moderate earthquakes that engender nonlinear behaviors only slightly. Few studies have specifically examined strong earthquakes that cause nonlinear behaviors, partly because of the lack of proper analysis tools that are applicable to the interactions between vehicles and nonlinear bridge structures. Some analysis tools were proposed by implementing vehicle-bridge decoupled equations of motion with ABAQUS® and Matlab® (e.g. Wyss et al. [15] and Sun et al. [16]), but no seismic excitation and nonlinear behavior of bridge were considered therein. Moreover, although a few experimental studies have examined this issue as well, they were actually very limited in numbers and loading conditions. The test vehicles were constrained in a stationary state, most probably because of safety concerns and budget limitations. Studying the effects of moving vehicles on bridge seismic responses still relies heavily on numerical simulations.

This study was conducted to develop a seismic analysis framework incorporating vehicle–bridge interactions (VBI) with nonlinear dynamic analysis. Many commercial finite element analysis (FEA) packages are known to provide powerful visualized modelling interfaces and nonlinear dynamic analysis functions, but they fit only to a slight degree the VBI problems for which system matrices vary with vehicle locations, so-called *non-stationary problems*. These interaction problems are usually solved with in-house programs that can assemble the location-dependent system matrices at any time step (e.g. [17]). However, the modelling of complex three-dimensional bridges and nonlinear behaviors would be rather inefficient with in-house programs compared to commercial FEA packages. To use both tools, this study proposes to integrate a commercial FEA package, ABAQUS®, into the authors' in-house VBI-solving programs developed with MATLAB®. Details of the proposed method, designated as "Recursive Substructure Method," are presented in the next section. Using this analytical method, the representative cases were assessed to clarify the effect of vehicles on the seismic responses of an urban highway viaduct under strong earthquakes.

2. Recursive Substructure Method

The Recursive Substructure Method (RSM) was developed to simulate the dynamic responses of bridges and moving vehicles under seismic loadings, especially strong earthquakes. It integrates the conventional nonlinear dynamic analysis in ABAQUS into the authors' in-house VBI-solving programs developed with MATLAB. ABAQUS is used to model the bridge and to conduct nonlinear dynamic analysis subject to both seismic ground motions and vehicle–bridge interaction forces. MATLAB provides a platform to control the recursive ABAQUS executions and to perform time integrations in VBI problem. The tasks include extraction of the dynamic responses of the bridge from ABAQUS output files, solving the equation of motion for vehicle, reconstructing vehicle–bridge interaction forces, relocating vehicle positions when permanent displacement of bridge occurs, and checking the force equilibriums or compatibility conditions. The theoretical background and operational procedures are given as follows.

The equation of motion for a vehicle is written as [17,18]

$$\boldsymbol{M}_v\ddot{\boldsymbol{u}} + \boldsymbol{C}_v(\dot{\boldsymbol{u}}-\dot{\boldsymbol{y}}_c) + \boldsymbol{K}_v(\boldsymbol{u}-\mathbf{y}_c) = 0 \tag{1}$$

where $\boldsymbol{M}_v$, $\boldsymbol{C}_v$, and $\boldsymbol{K}_v$ respectively denote the mass, damping, and stiffness matrices of the vehicle, and where $\boldsymbol{u}$ represents the vector of vehicle's displacements and rotations at its degrees of freedom. A dot denotes the derivative with respect to time. $\boldsymbol{y}_c$ is the wheel displacement vector at the contact point. It is the summation of bridge displacement $\boldsymbol{w}_c$ and roughness $\boldsymbol{r}_c$ at that point.

$$\boldsymbol{y}_c = \boldsymbol{w}_c + \boldsymbol{r}_c \tag{2}$$

The equation of motion for the bridge model is written as

$$\boldsymbol{M}_b\ddot{\boldsymbol{w}} + \boldsymbol{C}_b\dot{\boldsymbol{w}} + \boldsymbol{K}_b\boldsymbol{w} = \boldsymbol{f}_{ext} + \boldsymbol{f}_{vb} \tag{3}$$

where $\boldsymbol{M}_b$, $\boldsymbol{C}_b$ and $\boldsymbol{K}_b$ respectively stand for the mass, damping, and stiffness matrices of the bridge, and where $\boldsymbol{w}$ represents the vector of bridge's displacements and rotations at its degrees of freedom. It is noteworthy that the bridge's stiffness matrix can be either linear or nonlinear, i.e. either independent of or dependent on $\boldsymbol{w}$. Also, $\boldsymbol{f}_{ext}$ is the vector of external forces, which is the seismic loading herein but which can be generalized to any other external force acting on the bridge. The force exerted by vehicle to bridge $\boldsymbol{f}_{vb}$ is the summation of vehicle weight, spring forces, and damping forces. It can be expressed as shown below.

$$\boldsymbol{f}_{vb} = \boldsymbol{M}_v g - \boldsymbol{K}_v(\boldsymbol{u}-\boldsymbol{y}_c) - \boldsymbol{C}_v(\dot{\boldsymbol{u}}-\dot{\boldsymbol{y}}_c) \tag{4}$$

The two equations of motion (1) and (3) above are solved in a direct time integration manner to solve them at a certain time step $t + \Delta t$ (Δt is a finite small time increment) using the solution in previous time step t and the approximations for the derivatives. In ABAQUS, the Hilber–Hughes–Taylor (HHT) method [19] is available, which is an extension of the Newmark β-method [20]. HHT method uses the same Newmark