VEHICLE-BRIDGE DYNAMIC INTERACTION UNDER NEAR-FAULT GROUND MOTIONS

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Abstract

The possibility that earthquakes may happen while automobile vehicles are passing over highway bridges is negligible in the past but is considerably high nowadays, especially in the busy urban areas around the world where traffic congestion happens round the clock. Besides, the transportation demands are still increasing with population growth and the process of urbanization. Traditionally, attention has been given to the concurrent hazard of earthquake and live load on bridges. A load factor of 0.5 for live load can be used to combine with seismic load, or site-specific analysis shall be done to determine an appropriate live load factor. According to previous studies, when the inertial effect of actual live load is included, the effect of vehicle on seismic responses of the highway bridge depends on the characteristics of both vehicle and highway bridge, and on the frequency content of the ground motion. It is believed that the period elongation due to the additional mass of vehicle will move the bridge to a favorable part of the acceleration spectrum, together with the additional damping provided by the vehicle, beneficial effect is more frequently observed when vehicle is included in seismic analysis. Indeed, many researchers find that vehicles can often give a beneficial effect, especially when they are regarded as dynamic systems rather than as additional masses or without considering them. However, earthquake would cause cars turnovers, crashes, or even falling off bridges. Not only this could cause heavy casualties, but also the clearance of highway bridge would last days if not months. Such as the Yokohama Bay Bridge was closed for about 30 hours just for dealing with an overturned cargo truck after the 2011 Great East-Japan Tohoku Earthquake. Indeed, the highway bridge may survive destructive earthquakes with a chaotic car accident scene. Therefore, the effect of earthquake on vehicle should also be considered. In this study, vehicle-bridge systems consists of impact element in the vertical direction and friction elements in the horizontal directions are employed to investigate the dynamic interaction and seismic responses of both vehicle and highway bridge realistically. Several parameters of the vehicle are varied to study the earthquake effect on vehicle. Because each combination of these parameters leads to a new vehicle-bridge system and a large number of such combinations exist. For simplicity, simplified vehicle-bridge system is used and vehicle is assumed to be stationary on the highway bridge. A suite of near-fault ground motions downloaded from PEER Ground Motion Database with horizontal peak ground accelerations (PGA) range from 0.1g to 1.3g and mean periods (T_m) range from 0.17 s to 1.58 s are used to study the seismic responses of highway bridges and vehicles. Finally, the formulated nonlinear governing equations of vehicle-bridge system are solved numerically by using variable order Runge-Kutta-Fehlberg method. Vehicle mass is confirmed as a key parameter in this study. Horizontal displacements of vehicle can reach several meters under earthquake, endangering the traveling safety of vehicle.

Keywords: Near-fault ground motion; vehicle-bridge system; plastic(Wen) model; Hertz contact law; impact

1. Introduction

The effect of vehicle on seismic responses of highway bridge can be included by employing an appropriate load factor, *i.e.*, 0.5, according to current seismic specifications [1]. Previous researches found out that dynamic effect of vehicle on seismic responses of highway bridge will be beneficial [2–5], although mild adverse effects were also reported [6–8]. This is believed to be primarily the result of period elongation caused by the added vehicle mass which moves the highway bridge to a favorable part of the acceleration spectrum. The other persuasive explanation is vehicle provides additional damping to the system. Researches usually focus on the seismic responses of highway bridge without paying due consideration to the responses of vehicle which crossing viaduct during earthquake. With aggravated daily traffic congestion in the busy urban areas around the world, when an unpredictable earthquake happens, not only is it important to secure the safety of bridges, but also is it essential to protect the traveling safety of vehicles which traveling through the highway bridges. Even an overturned truck can cause the highway bridge close up to tens of hours [9], let alone what may cause by a chaotic car accident scene with heavy casualties after an severe earthquake event.

Vehicle-bridge system seems similar to a tuned mass damper system [4]. However, automobile vehicle makes contact with bridge deck through tires by gravity load. The contact force between vehicle and bridge in the vertical direction can only be compressive, no tension can be sustained. Therefore, basically distinguishing the vehicle-bridge system from tuned mass damper system. Seismic responses of vehicle-bridge system depend both on the characteristics of the vehicle and the bridge, and on the frequency content of the ground motion according to previous researches [10]. But the influence extent of every parameter is still open to discuss. Coupling between vehicle and bridge in the vertical direction is significant [11]. While near fault ground motions are characterized by their high vertical accelerations, contact force between vehicle and bridge in the vertical direction will therefore vary abruptly under this circumstance. In the horizontal direction, vehicle only restrained by forces provided through friction. At the same time the friction forces will vary with the fluctuation of vertical contact force between vehicle and bridge under seismic excitation. Thus, the vehicle-bridge system is a highly nonlinear system, sophisticated finite element analysis will be computationally expensive. It is necessary and efficient by employing simplified vehicle-bridge system to do parameter analysis first before proceeding to refined finite element analysis domain.

In order to figure out which parameter influence the responses of vehicle most, vehicle-bridge system subjected to near-fault ground motions is analyzed in this study. Vehicle and bridge are both simplified, higher mode contributions are neglected, and the vehicle on the bride is assumed to be stationary. Possible impact between vehicle and bridge during earthquake is considered by using Hertz contact model [12]. Friction forces between vehicle and bridge in the horizontal direction are simulated by employing plasticity model proposed by Wen (*i.e.*, plastic (Wen) model) [13,14]. These simplifications are believed to be reasonable according to previous researches [2,6]. The nonlinear ordinary differential equations of the vehicle-bridge system are solved by using variable order Runge-Kutta-Nyström method suggested by Cash and Karp [15,16].

2. Idealization of Vehicle and Bridge

Vehicle is idealized as dynamic system consisting of rigid bodies, springs and dashpots [11,17]. Translational vibration modes of vehicle in the vertical, lateral, and longitudinal directions are modeled by using two concentrated masses m_2 and m_3 representing the vehicle body and tires, respectively. Simplified vehicle model can provide insight into the fundamental dynamic response of vehicle subject to seismic excitations. Properties representing the fundamental modes of bridge in the vertical, lateral, and longitudinal directions are considered. Vehicle and bridge in the vertical direction is coupled through time dependent compressive load F_{2z}, and in the longitudinal and lateral directions are through friction forces F_{2x} and F_{2y}, respectively. Both amplitudes of friction forces in longitudinal and lateral directions are closely related to the compressive force in the vertical direction, *i.e.*, when the compressive force in the vertical direction becomes zero both friction forces will also be zeros. Simplified vehicle-bridge system is shown in Fig. 1. A series of automobile vehicles with different masses and frequencies are analyzed in the subsequent parameter analysis. Vehicle mass range is from 1.5×10^3 kg to 150×10^3 kg represents the mass range from family cars to overweight trucks. Vehicle frequency range is from 1.0 Hz to 2.5 Hz, covering the usual automobile vehicle frequency range. The longitudinal and lateral masses of the highway bridge, *i.e.*, m_{1x} and m_{1y}, both are 7159×10^3 kg. The vertical mass of the highway bridge m_{1z} is 1500×10^3 kg. The longitudinal and lateral frequencies of the highway bridge, *i.e.*, f_{1x} and f_{1y}, are 1.4 Hz and 3.1 Hz respectively. The vertical frequency of the highway bridge f_{1z} is 1.8 Hz.

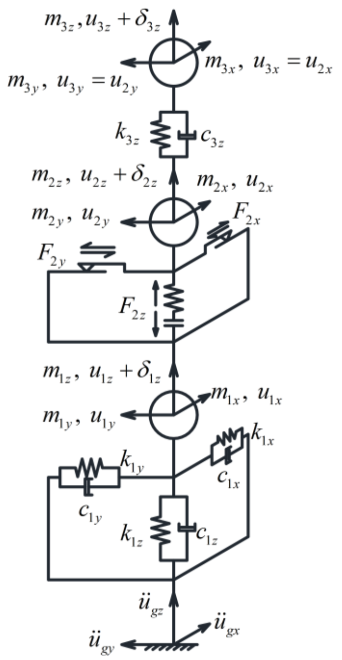

Fig. 1 – Simplified vehicle-bridge system

3. Near-Fault Earthquake Records

Near-fault earthquake records containing strong velocity pulses are downloaded from PEER Ground Motion Database and are listed in Table 1 [18,19]. Horizontal peak ground acceleration (PGA) range of the selected earthquake records is from 0.1g to 1.3 g. Mean period (T_m), which averages periods of the earthquake record in the Fourier spectrum, is one of the best simplified frequency content characterization parameters [20]. The mean period range of the selected near-fault earthquake records is from 0.17 s to 1.58 s.

Table 1 – Selected near-fault earthquake records

No.	Earthquake Name	Record Sequence Number	PGA (g)	Mean Period (s)
1	Chi-Chi_ Taiwan	RSN1511	0.43	0.62
2	Chi-Chi_ Taiwan	RSN1481	0.14	0.92
3	Chi-Chi_ Taiwan	RSN1483	0.16	0.86
4	Chi-Chi_ Taiwan	RSN1515	0.23	0.86
5	Chi-Chi_ Taiwan	RSN1530	0.15	0.95

Table 1 (continued) – Selected near-fault earthquake records

No.	Earthquake Name	Record Sequence Number	PGA (g)	Mean Period (s)
6	Chi-Chi_ Taiwan	RSN1480	0.14	1.02
7	Chi-Chi_ Taiwan	RSN1531	0.10	1.05
8	Chi-Chi_ Taiwan	RSN1526	0.11	1.20
9	Chi-Chi_ Taiwan-03	RSN2627	0.52	0.71
10	Chi-Chi_ Taiwan-03	RSN2495	0.47	1.03
11	Coyote Lake	RSN150	0.42	0.67
12	Gazli_ USSR	RSN126	0.86	0.39
13	Imperial Valley-06	RSN158	0.31	0.67
14	Imperial Valley-06	RSN184	0.48	0.55
15	Imperial Valley-06	RSN159	0.29	0.58
16	Imperial Valley-06	RSN180	0.53	0.66
17	Imperial Valley-06	RSN181	0.45	1.28
18	Imperial Valley-06	RSN182	0.47	1.32
19	Imperial Valley-06	RSN171	0.32	1.06
20	Irpinia_ Italy-01	RSN292	0.32	0.87
21	Kobe_ Japan	RSN1120	0.67	0.99
22	Landers	RSN879	0.79	0.17
23	Morgan Hill	RSN451	1.30	0.55
24	N. Palm Springs	RSN540	0.63	0.31
25	Northridge-01	RSN1085	0.85	0.76
26	Northridge-01	RSN1086	0.84	0.76
27	Northridge-01	RSN1084	0.92	0.99
28	Northridge-01	RSN982	0.62	1.00
29	Northridge-01	RSN1045	0.42	1.58
30	Parkfield-02_ CA	RSN4066	0.46	0.19
31	Parkfield-02_ CA	RSN4099	0.51	0.20
32	San Salvador	RSN568	0.70	0.61
33	Whittier Narrows-01	RSN614	0.35	0.51

4. Seismic Analysis Results of Vehicle-Bridge System

To investigate the effect of vehicle on vertical seismic response of bridge, incremental dynamic analysis is used [19]. The selected intensity measure is peak longitudinal ground acceleration. Because most of the peak ground accelerations of the selected earthquake records are less than 0.705g, the analysis will stop once impact between vehicle and bridge in the vertical direction is detected or the peak ground acceleration reaches 0.705g.

4.1 Parameters influencing impact in the vertical direction between vehicle and bridge

There are 197 impact cases out of total calculated 1056, as given in Fig. 2. In these cases, the average PGA when impact happening is 0.54g with a coefficient of variance of 19.8%. There is no impact happening when the vehicle frequency is 1.0 Hz. Number of impact cases when vehicle frequency is 1.8 Hz, 2.0 Hz, and 2.5 Hz, respectively, are 45, 57, and 95. Clearly, impact is prone to happen when the vehicle is stiff. Number of impact cases distributed with vehicle masses is shown in Fig. 3. As illustrated in Fig. 3, impact is most likely to happen when vehicle mass is 20×10^3 kg, but impact can hardly happen when vehicle mass is extremely large, *e.g.*, 150×10^3 kg.

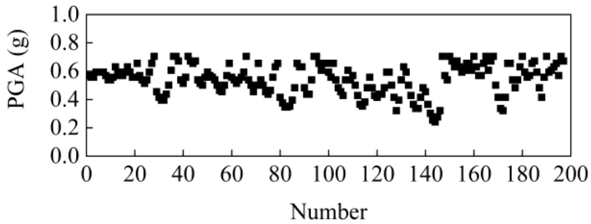

Fig. 2 – Distribution of peak ground acceleration when impact happening

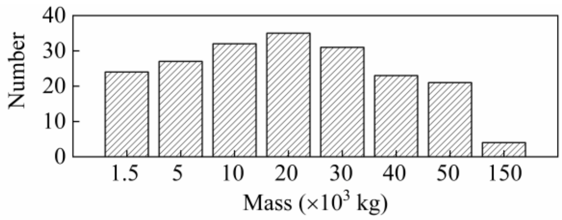

Fig. 3 – Histogram of impact cases distributed with vehicle mass

4.2 Parameters influencing vertical impact force between vehicle and bridge

Primary parameter which influences vertical impact force between vehicle and bridge is vehicle mass, as shown in Fig. 4, Fig. 5 and Fig. 6. Vehicle frequency has little influence on vertical impact force. The heavier the vehicle mass, the larger the impact force.

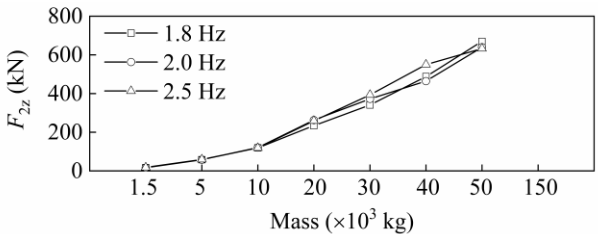

Fig. 4 – Vertical impact force between vehicle and bridge when subject to earthquake record RSN126

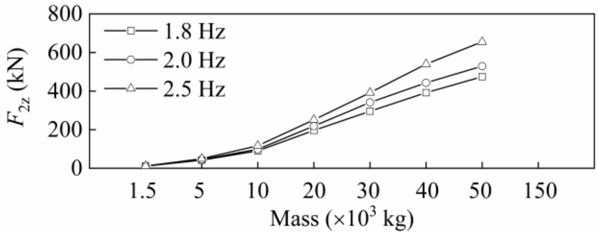

Fig. 5 – Vertical impact force between vehicle and bridge when subject to earthquake record RSN1045

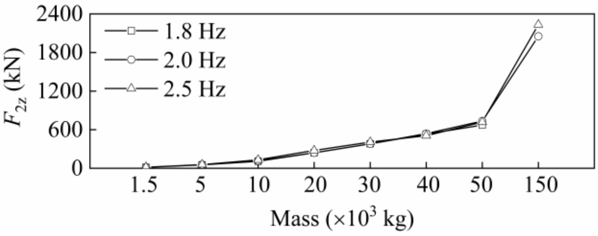

Fig. 6 – Vertical impact force between vehicle and bridge when subject to earthquake record RSN1531

4.3 Parameters influencing relative horizontal displacements between vehicle and bridge

As plotted in Fig. 7, Fig. 8, and Fig. 9, primary parameter which influences relative horizontal displacements between vehicle and bridge is vehicle mass, the influence of vehicle frequency is only secondary. Relative horizontal displacements between vehicle and bridge when subject to near-fault earthquake can reach several meters, especially when the vehicle is heavy. This is caused by the weak friction connection between vehicle and bridge in the horizontal directions. Large relative horizontal displacement will cause vehicles turnovers, crashes, or even falling off bridges, unavoidably endanger the traveling safety of vehicle.

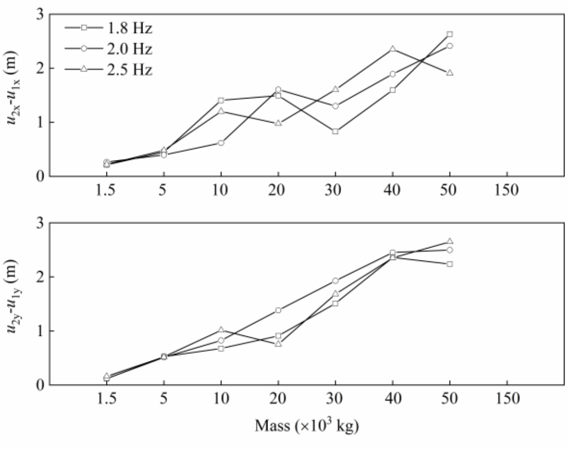

Fig. 7 – Relative horizontal displacements between vehicle and bridge when subject to earthquake record RSN126

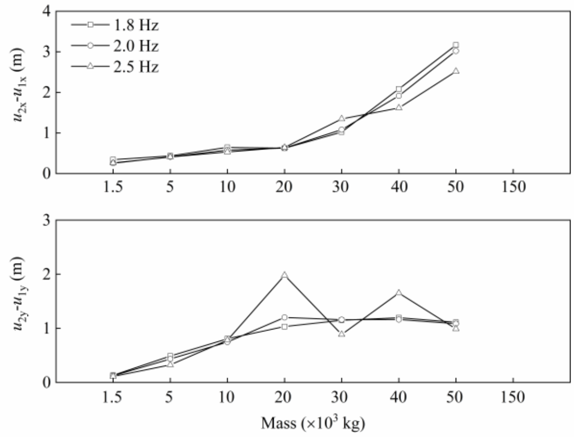

Fig. 8 – Relative horizontal displacements between vehicle and bridge when subject to earthquake record RSN1045

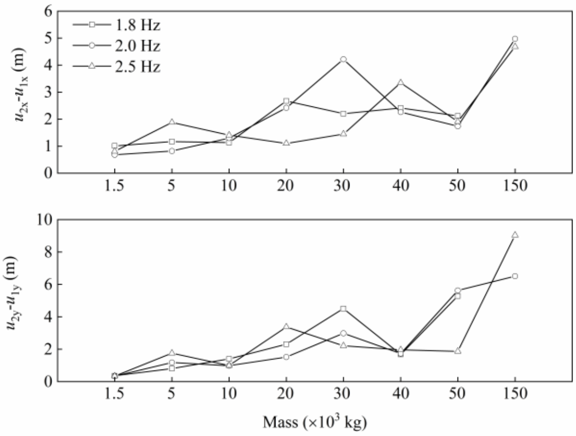

Fig. 9 – Relative horizontal displacements between vehicle and bridge when subject to earthquake record RSN1531

5. Conclusions

Seismic responses of vehicle-bridge systems are analyzed in this study. Vertical impact between automobile vehicle and highway bridge, as well as horizontal frictions are included. Automobile vehicle frequency and mass are confirmed as two primary parameters which influencing the vertical impact between automobile vehicle and highway bridge. The higher the automobile vehicle frequency, the more likely the happening of impact. Impact is prone to occur when automobile vehicle mass is moderate, *e.g.*, 20×10^3 kg. While when the automobile vehicle is very heavy, *e.g.*, 150×10^3 kg, impact can hardly happen. Automobile vehicle mass controls the impact force between automobile vehicle and highway bridge in the vertical direction. The heavier the automobile vehicle mass, the larger the impact force. Due to the weak connection provided by friction forces in the horizontal directions, relative horizontal displacements between automobile vehicle and highway bridge can reach several meters, which will unavoidably endanger the traveling safety of automobile vehicle under earthquake.

6. Acknowledgements

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7. Copyrights

8. References

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