Nonlinear seismic responses of a viaduct in high speed rail system considering train dynamics

X. Z. Lu(1), C. W. Kim(2), K. C. Chang(3)

(1) Student, Department of Civil and Earth Resources Engineering, Kyoto University, lu.xuzhao.37s@st.kyoto-u.ac.jp
(2) Professor, Department of Civil and Earth Resources Engineering, Kyoto University, kim.chulwoo.5u@kyoto-u.ac.jp
(3) Jr. Associate Professor, Department of Civil and Earth Resources Engineering, Kyoto University, chang.kaichun.4z@kyoto-u.ac.jp

Abstract

Existing studies showed that the train in train-bridge interaction system works as a damper and can suppress the vibration of bridge under moderate earthquakes and assumption of linear elastic behavior of bridges. However, when strong earthquake happens, bridge structures may show nonlinear behaviors, and it is not examined for the damper effect of train dynamics to the seismic response of bridges. In current seismic design code for railways structures, influence of train on bridge structure is simplified as additional mass. Few studies have investigated nonlinear seismic responses of the train-bridge interaction system. This study is intended to investigate the seismic responses of railway bridges considering material nonlinearity under strong earthquakes. The target bridge is a typical RC frame viaduct in Japanese high-speed railway system. Finite element method is utilized to build a train-bridge interaction system, which consists of the train, the bridge and the contact interaction between these two subsystems, with the commercial software ABAQUS/Standard. Several strong earthquakes were considered for the seismic response analysis of train-bridge interaction system. The effect of the train dynamics to the seismic responses of the viaduct is analyzed utilizing an energy transfer process. In detail, the effect of several influential factors on the bridge vibration, such as train's mass, train's loading effect, train's inner springs and dashpots and the motion of train, is examined through a comparative study utilizing a series of different train-interaction models Observations demonstrated that the mass of the train may cause more severe plastic damage under strong earthquakes. While the train as a dynamic system can help to dissipate input seismic energy to the whole system.

Keywords: Train-bridge interaction, nonlinear response, strong earthquakes, energy transfer process

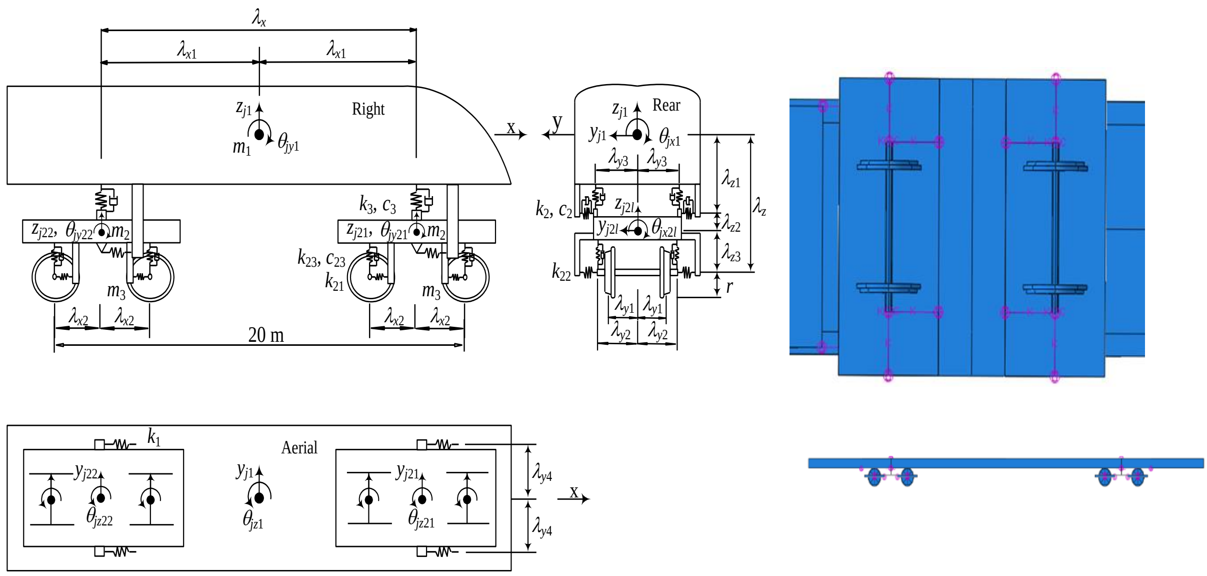
Introduction

Seismic responses of bridge structures in high-speed railway system is a keen technical in bridge engineering [1]. In this study, seismic performances of the train-bridge interaction system under strong earthquakes were investigated considering potential material non-linearity.

In previous researches [2, 3] of seismic responses of the coupled train-bridge interaction system, it was concluded that the mass of the train, train's motion of multiple components connected with springs and dashpots and the moving train can affect the seismic responses of bridge structure under moderate earthquakes [4]. In these researches, since ground motions are not intense, the linear structural assumption is utilized. However, when strong earthquake happens, the bridge may suffer from severe damage [5]. Therefore, it is reasonable to take the material non-linearity into consideration. Few studies have been proposed with this consideration, and the influence from these factors on bridge under strong earthquakes is unclear yet.

This study aims at investigating dynamic characteristics in nonlinear seismic responses of viaducts in Japanese high-speed rail system by means of numerical simulations. A series of models was built with the commercial software ABAQUS [6]. Influence from previously mentioned factors on bridge structures is examined through the comparison between these models. Besides, an energy transfer process, which is used in seismic analysis of building structures with TMD devices [7], was utilized to investigate the energy dissipation in the coupled system under strong earthquakes.

1 Train-bridge interaction system and numerical model



(a) Multiple degree of freedom carriage model [2] **(b) Finite element model [8]**
Figure 1 Simplified carriage and its finite element model in the train-bridge interaction system.

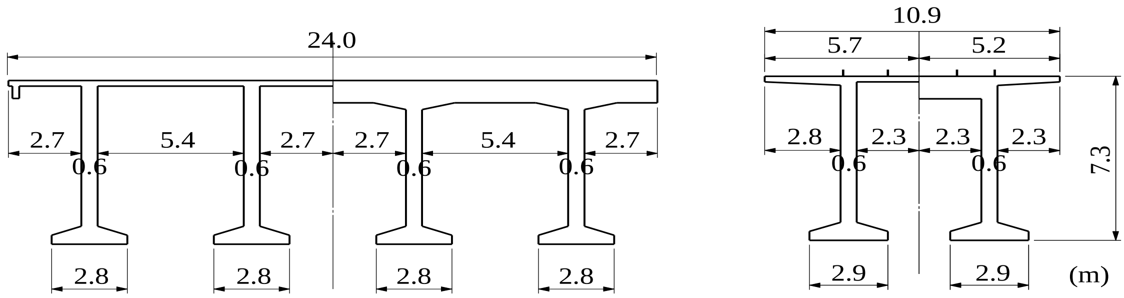
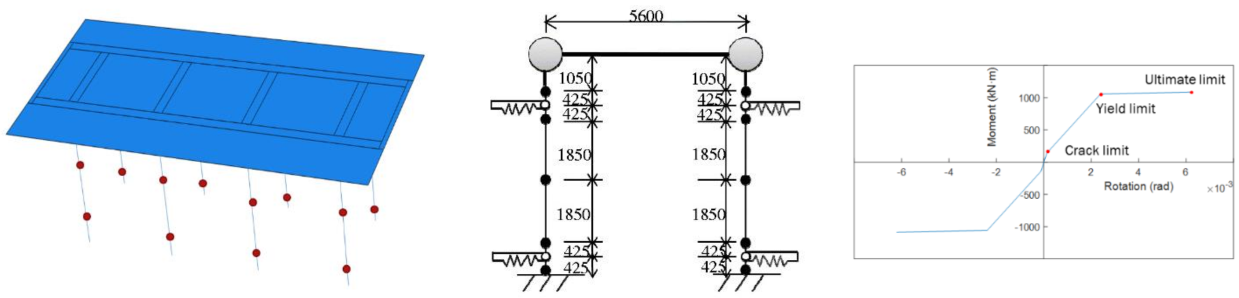


Figure 2 Dimension of the viaduct (Unit: m) [2]



(a) **(b)** **(c)**
Figure 3 Finite element model of the viaduct ((a) Viaduct model; (b) Frame model used in the previous research [9]; (c) Tri-linear model for rotation plastic hinges)

Train-bridge interaction system denotes a coupled system which consists of two sub-dynamic systems, the train and the bridge structure, and the interaction relationship between them. When an earthquake happens, seismic responses of the bridge will excite the train on the bridge to vibrate, and the vibration of train will also influence to seismic responses of the bridge structure through the contact between these two sub-systems. The whole system was simulated by means of a finite element model utilizing the commercial software ABAQUS. As for the train, its carriage was simplified as a multiple degree of freedom system according to pervious research [2] (shown in Figure 1(a)). Components (car body, bogie and wheelsets) of each carriage were set as rigid bodies connected with spring and dashpot elements [8]. Detailed parameters of the carriage, including is mass, inertia and geometric properties can be referred from the previous study [2].

Majority of bridge structures in the high speed rail system consists of viaducts. Elevation and cross-sectional views of the typical viaduct are shown in Figure 2. This is a reinforced concrete structure and in the finite element model, it was modeled with shell elements for superstructure and beam elements for columns elements as shown in Figure 3(a). As for the potential material non-linearity under strong earthquakes, only the flexural failure was taken into consideration according to experiment results in previous study [10]. Nonlinear rotation spring elements were utilized to model plastic hinges which were located on each end of columns as shown in Figure 3(b). This setting was based on a framework structure proposed in previous investigations on the seismic performances of these viaducts under strong earthquakes [9]. A tri-linear (Figure 3(c)) property was assigned to these nonlinear elements. The interaction relationship between these two sub-dynamic systems is formulated in consideration of the contact between track and wheel with the penalty method [8].

2 Comparative models and ground motions

In order to clarify potential effects of the factors mentioned above, a series of different models was built for comparison. For calculation efficiency, three carriages, instead of a full length train, and four viaduct blocks (total span: 96 m) are included in corresponding models. Details were listed as follows:

(1) Bridge-only model

This model consists of four viaduct blocks described in the previous section. Carriages were not included as shown in Figure 4(a);

(2) Train as additional mass model

This model follows the basic setting in current seismic design code [11] for railway structure in Japan. The total mass of three carriages, including car-body, bogie and wheelset, was distributed evenly onto bridge superstructure (Figure 4(b)). Comparing with the bridge-only model, this model was built to examine the effect of train mass on seismic responses of the viaduct;

(3) Partially loading model

Considering that in real cases, the train is in contact with the bridge through the interaction between track and wheelsets in several specific regions, a partially loading model was built on the basis of the train as additional mass model. Instead of the even distribution, several rigid blocks were modeled as a simplification of carriages. It is noted that these blocks are in contact with the bridge through interaction in specific regions (Figure 4(c));

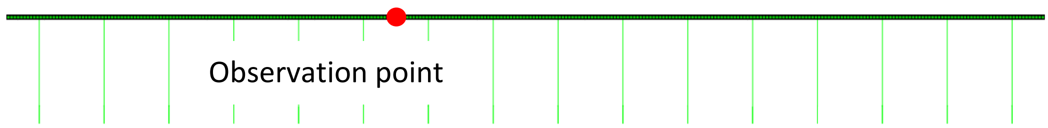
(4) Train standing model

A train standing model was built to examine the effect of the train as a dynamic system on seismic responses of the viaduct. Springs and dashpots were included in the partial loading model. While the train is resting on the rail throughout earthquakes (Figure 4(d));

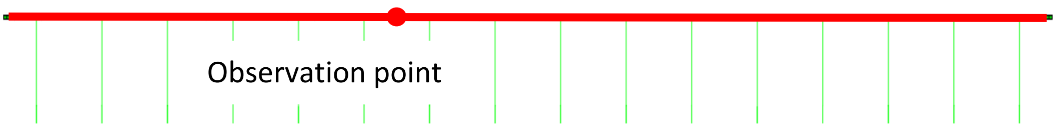
(5) Train running model

In this model, a motion was assigned to three carriages with a high speed (270 km/h, Figure 4(e)). Considering that the speed of the train is rather high, moving of the train was designed as a reciprocating motion. Carriages will move from one end of the bridge structure to the other and move back and repeat. Effects of the moving train on seismic responses of the viaducts is examined through comparisons with structural responses in the train standing model.

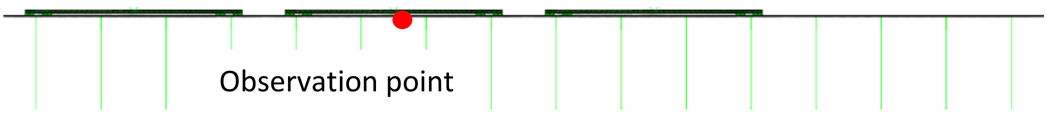
Records [12] of several strong earthquakes were set as ground motion inputs (shown in Figure 5) in the transversal direction. These records were selected because of the similarity in their linear spectra with the target spectrum used in the current design code (see in Figure 6).



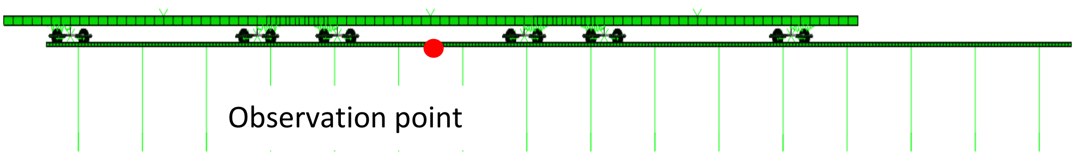
(a)



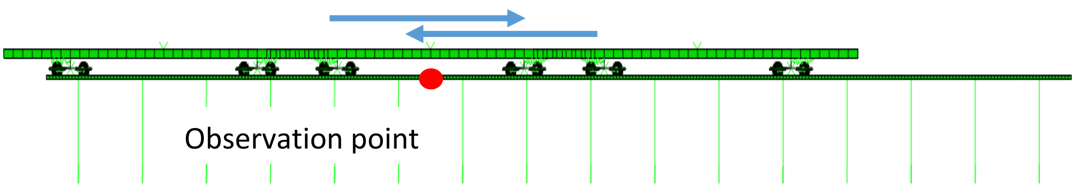
(b)



(c)

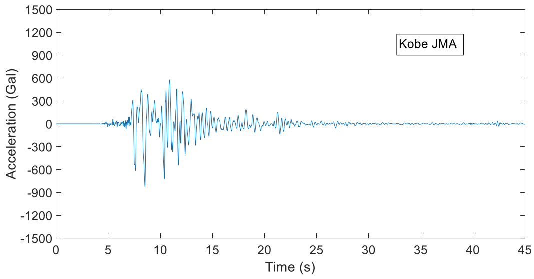


(d)

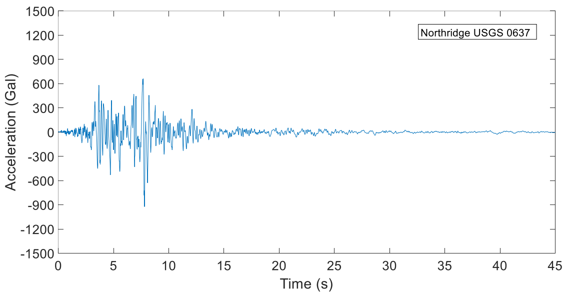


(e)

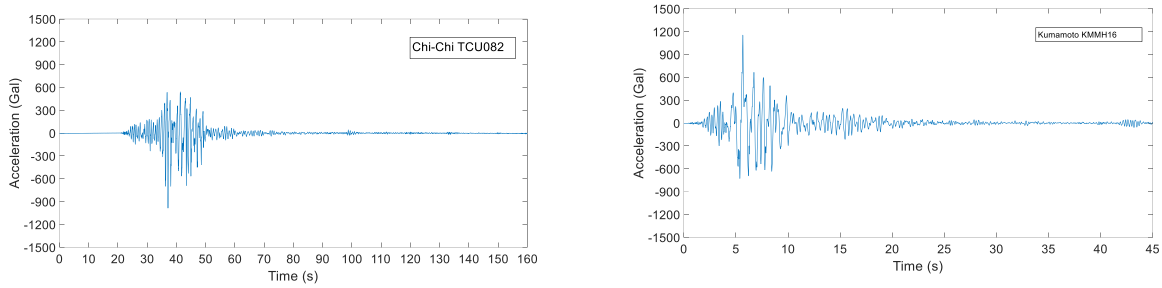
Figure 4 Series of comparable models: a) Bridge only model; b) Train as additional mass model; c) Partially loading model; d) Train standing model; e) Train running model.



(a)



(b)



(c) **(d)**

Figure 5 Input ground motions: a) Kobe earthquake; b) Northridge earthquake; c) Chi-Chi earthquake; d) Kumamoto earthquake.

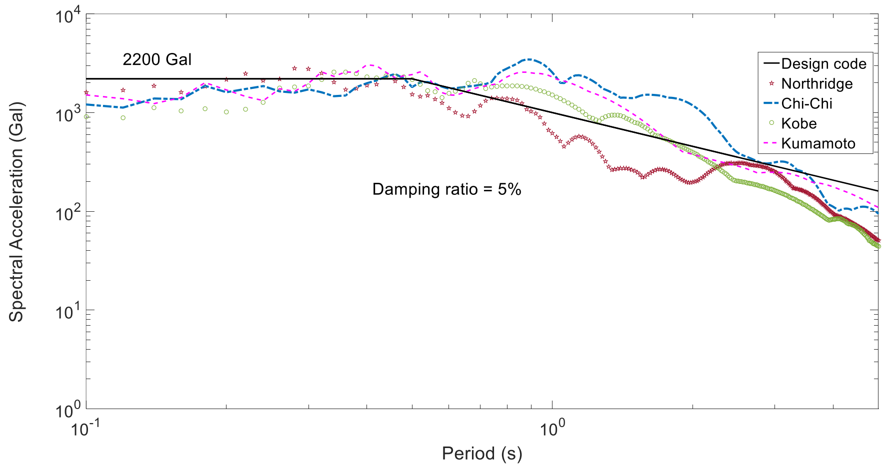


Figure 6 Elastic acceleration spectrum of ground motions.

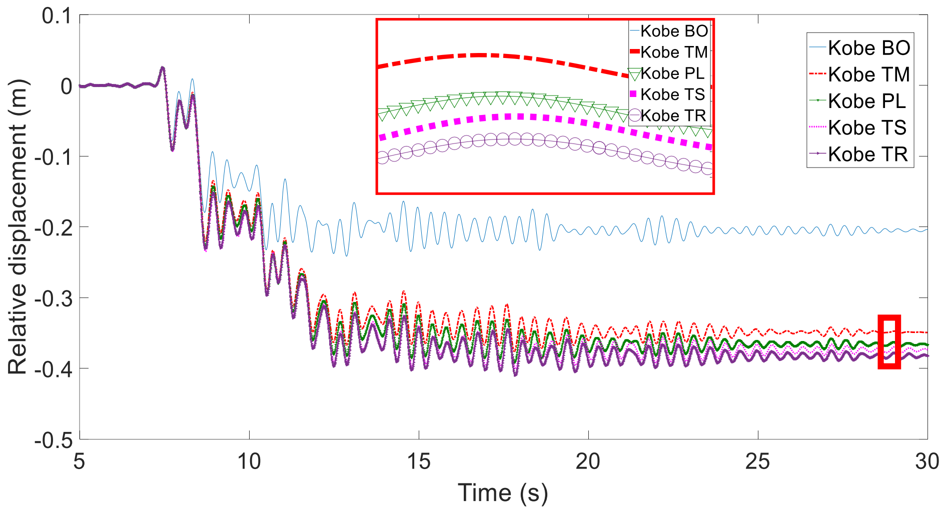


Figure 7 Relative displacement between bridge super- and substructure in the comparable series under Kobe earthquake. (BO is short for Bridge-only model; TM is short for train as additional mass model; PL is short for partially loading model; TS is short for train standing model; TR is short for train running model.)

3 Numerical analysis

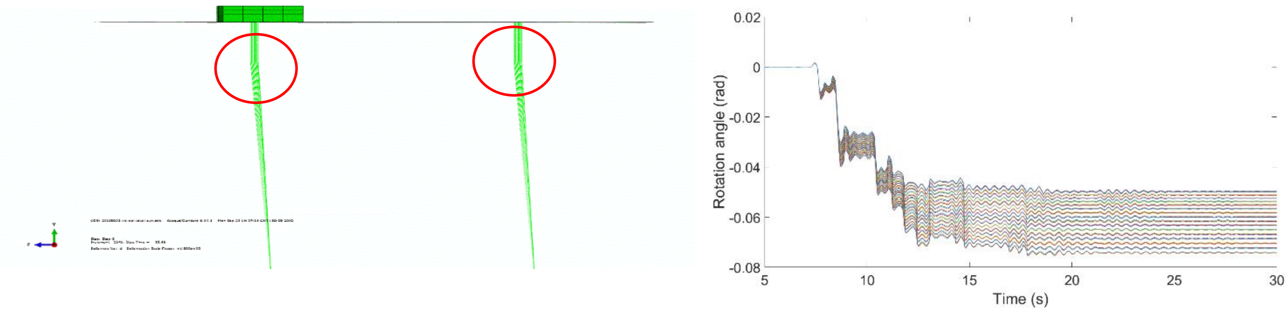
Seismic responses of the bridge under the strong earthquakes were analyzed. As an example, responses under the Kobe earthquake were shown here. Firstly, the relative displacement between bridge super- and substructure was examined. Then an energy transfer process was used to check the influences of potential factors on viaducts from the view of energy.

3.1 Relative displacement between bridge super- and sub-substructure

Time history of relative transversal displacement between bridge super- and substructure under Kobe earthquake is shown in Figure 7. The observation point of the superstructure was the mid-span point in the second middle block. Comparison of residual displacement in these models indicates that the mass of the train seems to play a vital role among all these potential factors. An obvious difference can be observed comparing train as addition mass model with the bridge-only model. While differences caused by other factors were obvious. Similar results can be found under other earthquakes.

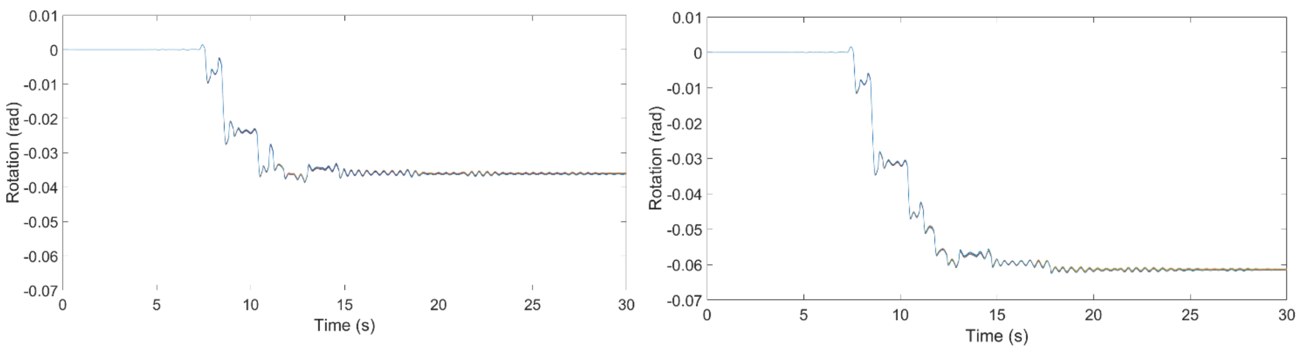
3.2 Energy transfer in the coupled system

An interesting phenomenon observed in the seismic responses of this series of models is the inconsistent vibration of columns in the partially loading model. This kind of vibration can be observed at some time-points (an example was shown in Figure 8(a)) in the end of columns. Also, this phenomenon was represented as a wide band in time histories of ration angle for all these plastic hinges (shown in Figure 8(b)). The "wide band" also exists in the simulation results of train standing model and train running model in which carriages were in contact with the bridge in several specific regions. While in the bridge-only model and train as additional mass model, curves of rotation time histories were overlapped as a "single line".



(a) Front view (b) Rotation time histories of plastic hinges

Figure 8 Inconsistent vibration of columns in partially loading model under the Kobe earthquake.



(a) **(b)**

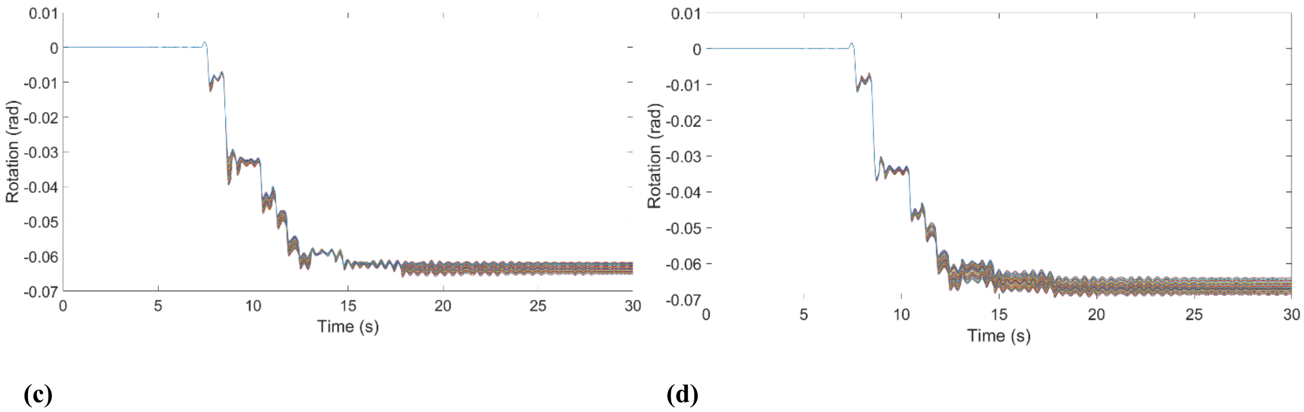


Figure 9 Rotation time histories of plastic hinges in the series of model under Kobe earthquake: a) Bridge-only model; b) Train as additional mass model; c) Train standing model; d) Train running model.

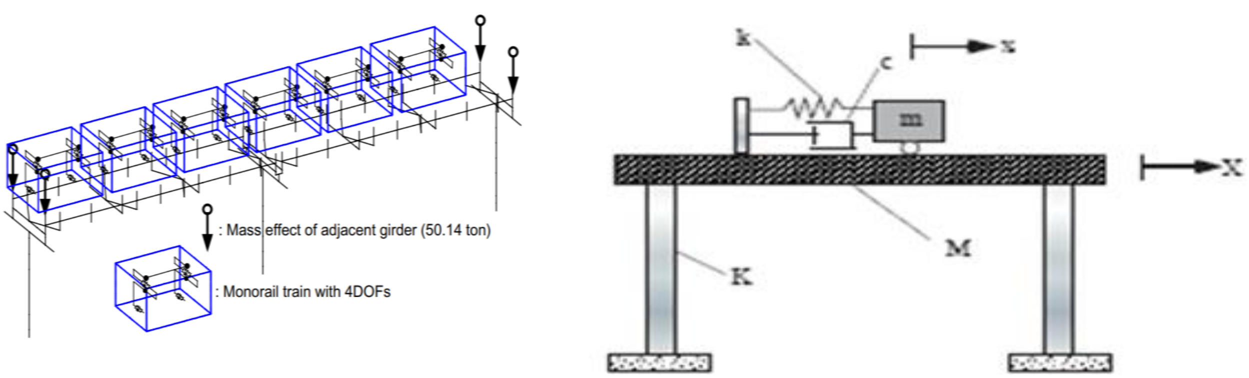
Considering the existence of the inconsistent vibration, investigation with a single specific observation point might be not enough to get an overall understanding of seismic responses for the whole system. Considering the similarity between the train-bridge interaction system (shown in Figure 10(a)) [4]and the common building structure with a tuned mass damper (TMD, shown in Figure 10(b)) [13], the energy transfer process [14] in seismic response analysis for building structures was utilized here to examine the effect from potential factors on viaducts under strong earthquakes.

The total input energy from ground motions to a building structure with a TMD device would be transferred into several kinds of energy following the equation:

$$\boldsymbol{IE} = \boldsymbol{KE} + \boldsymbol{SE} + \boldsymbol{VD} + \boldsymbol{PD} \tag{1}$$

where ***IE*** is input energy of the whole system under earthquakes; ***KE*** is the total kinetic energy of the building structure and the TMD device; ***SE*** is the total strain energy includeing both the strain energy of building and spring in the TMD; ***VD*** is the energy dissipated by structural damping and dashpot in TMD; ***PD*** is the energy dissipated by plastic behavior of plastic hinges in building structure.

As an analogy, the energy transfer in the coupled system is shown in Figure 11. In partially loading, train standing and train running models, energy transfer in both whole model and bridge structure were examined. Detailed results were summarized in Table 1. Energy transfer of this series of models under other earthquakes can be found in the Appendix.



(a) Train-bridge interaction system [4] **(b) Building structure with a TMD device[8]**
Figure 10 Analogy between train-bridge interaction system and the build structure with a TMD device.

Table 1 Energy transfer in the train-bridge interaction system under the Kobe earthquake.

		TR**	TS	PL	TM	BO
Total Input	Whole	9.158	8.954	8.630	8.699	7.768
(× 10^6 J)	Bridge	8.583	8.346	8.628	8.699	7.768
SE + KE*	Whole	1.208	1.322	1.194	1.189	1.180
(× 10^6 J)	Bridge	1.011	1.077	1.099	1.189	1.180
VD	Whole	2.791	2.566	2.180	2.302	2.146
(× 10^6 J)	Bridge	2.332	2.093	2.180	2.302	2.146
PD(× 10^6 J)	Bridge	6.241	6.243	6.437	6.366	5.593

(* Maximum value of SE + KE. Similarly, hereinafter.)
(** Energy transfer magnitude of in TR is estimated value for transversal vibration. Kinetic energy of longitudinal train motion and local vertical damping energy dissipated by bridge deck are excluded.)

Results in energy transfer process indicated that:
(1) Mass of train can increase the whole system energy input under strong earthquakes. This result coincides with the general conclusion for nonlinear seismic responses of building structures [14];
(2) Comparing with the train as additional mass model, the partial loading effect can cause more serious plastic damage to the bridge structure, which is supposed to be resulted from the inconsistent vibration of columns;
(3) Comparing train standing model with partially loading model, in the train standing model, the input seismic energy dissipated by plastic hinges decreases. While the energy dissipated by structural damping also decreases. It is supposed that dashpots in carriages help to dissipate some input energy to the whole system.
(4) The energy dissipation between the train standing and train running is not obvious. The effect from the train running can be neglected under the Kobe earthquake;
(5) In general, mass of carriages plays a vital role among all these potential factors.

4 Conclusions

This study utilized finite element method to investigate the seismic responses of the train-bridge interaction system in high-speed rail system under strong earthquakes. A series of finite element models were built considering the potential material non-linearity of the bridge structure. Records in several strong earthquakes were considered as ground motion inputs. Influences from several potential factors, mass of the train, partially loading effect, springs and dashpots between components of the train and train's running motion, were examined through comparison between these models.

Comparison of relative displacement between super- and substructure of viaducts in the transversal direction under the Kobe earthquake indicates that the mass of the train plays a vital role among of all these factors. While the effect from other factors seems not obvious.

An inconsistent vibration of columns was observed in the partially loading model. The same phenomenon can be also observed in train standing and train running models, which indicates that it might not be appropriate to use one specific point for investigation of seismic responses of the whole system. In order to clarify the overall seismic responses of the coupled system, an energy transfer process was proposed.

Results of energy transfer analysis shows that, firstly, the mass of the train play a vital role among these factors, which coincides with the result of relative displacement comparison. Besides, mass of carriages would increase the whole energy input to the whole system. While the partially loading effect can change the distribution of load from the train on the bridge structure. Consequently, the uniform vibration of columns, which can be observed in the bridge only model and train as additional mass model, will be replaced with the inconsistent vibration. It is supposed that the inconsistent vibration can induce more plastic damage than the uniform vibration in specific columns. As a result, the total dissipated plastic damage in bridge structure would increase. Besides, vibration of carriages with springs and dashpots can help to dissipate some input seismic energy to the bridge structure. Moreover, the effect from train running is not obvious.

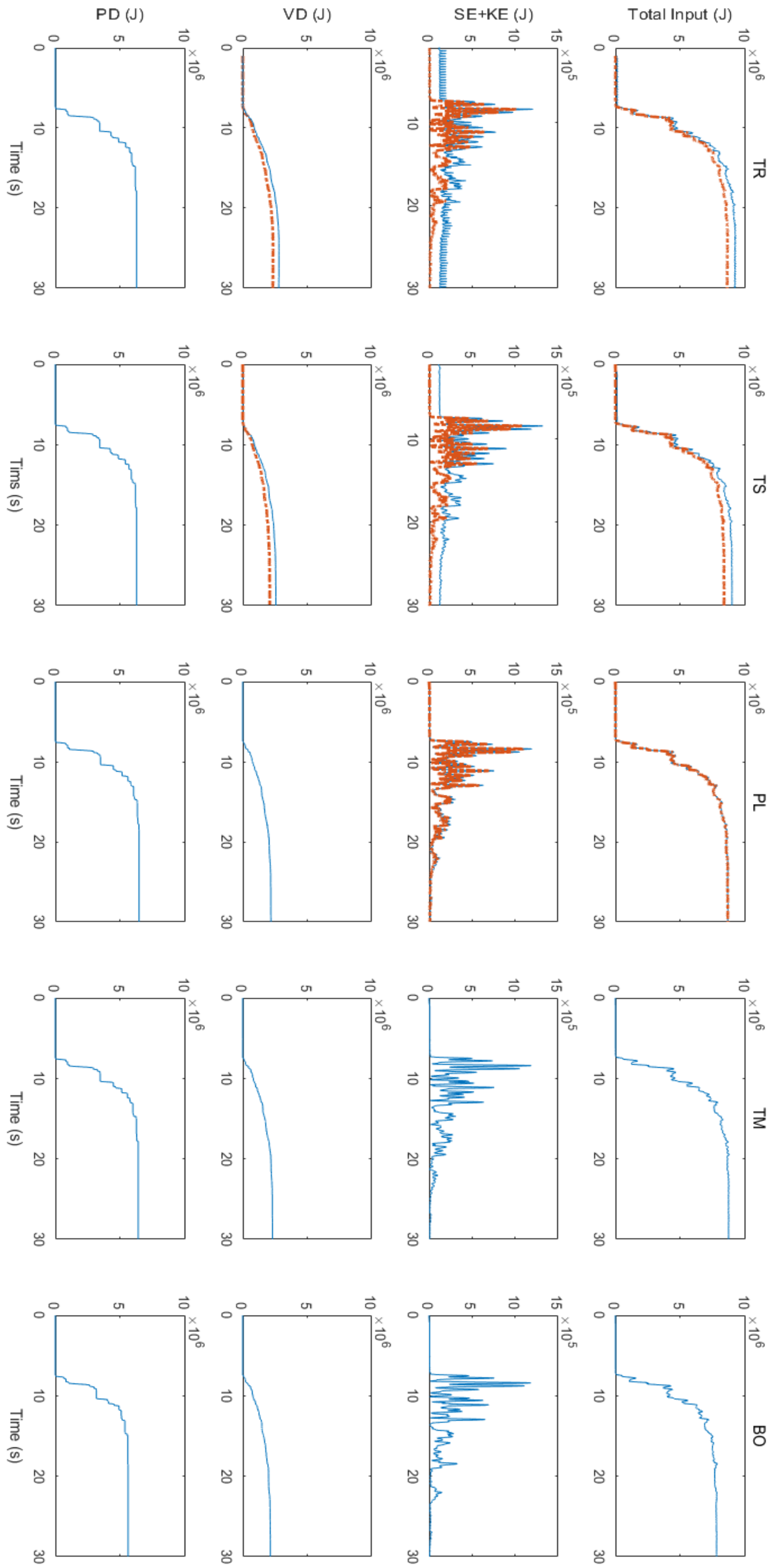


Figure 11 Energy transfer in the series of models under Kobe earthquake (Red: Whole system; Blue: Bridge structure).

References

[1] Dimitrakopoulos, Elias G., Qing Zeng, A three-dimensional dynamic analysis scheme for the interaction between trains and curved railway bridges, Computers & Structures, 2015; 149: 43-60.

[2] He, X., Kawatani, M., Hayashikawa, T., Matsumoto, T., Numerical analysis on seismic response of Shinkansen bridge-train interaction system under moderate earthquakes, Earthquake Engineering and Engineering Vibration, 2011; 10(1): 85-97.

[3] Kim, C. W., Kawatani, M., Lee, C. H., Nishimura, N., Seismic response of a monorail bridge incorporating train-bridge interaction, Structural Engineering and Mechanics, 2007; 26(2): 111-126.

[4] Kim, C. W., Kawatani, M., Effect of train dynamics on seismic response of steel monorail bridges under moderate ground motion, Earthquake Engineering and Structural dynamics, 2006; 35(10): 1225-1245.

[5] Ashford, S. A., Kawamata, Y., Performance of transportation systems during the 2004 Niigata Ken Chuetsu, Japan, earthquake, Earthquake Spectra, 2006; 22(S1): 111-132.

[6] ABAQUS 2014. Inc.

[7] Wong, K.K. and Yang, R., Earthquake response and energy evaluation of inelastic structures. Journal of Engineering Mechanics, 2002; 128(3): 308-317.

[8] Lu, X.Z., Kim, C. W., and Chang K. C., A numerical framework to solve train-bridge interaction for high speed railway system. ACEM 18, 2018, Inchon, South Korea.

[9] Akiyama, M., Frangopol, D. M., Mizuno, K., Performance analysis of Tohoku-Shinkansen viaducts affected by the 2011 Great East Japan earthquake, Structure and Infrastructure Engineering, 2014; 10(9): 1228-1247.

[10] Yoshida K., Structural safety evaluation under railway traffic. PhD thesis, Kobe University, 2006. (In Japanese)

[11] Railway Technical Research Institute, Seismic design code of Japanese railways system, Maruzen Publishing Co., Ltd., Tokyo, Japan, 2012.

[12] http://www.kyoshin.bosai.go.jp/kyoshin/

[13] Sadhu, A., S. Narasimhan, Identification of de-tuning level of tuned-mass-damper system using time-series analysis, Journal of Mechanics Engineering and Automation, 2012; 2(1): 1-8.

[14] Wong, K. K., Seismic energy dissipation of inelastic structures with tuned mass dampers, Journal of Engineering Mechanics, 2008; 134(2): 163-172.

Appendix

Table A-1 Energy transfer in different models under Chi-Chi earthquake

		TR	TS	PL	TM	BO
Total Input ($\times 10^6$ J)	Whole	19.004	19.474	17.937	18.259	16.260
	Bridge	17.673	17.978	17.808	18.259	16.260
SE + KE* ($\times 10^6$ J)	Whole	3.667	4.244	3.890	3.876	3.492
	Bridge	3.251	3.724	3.589	3.876	3.492
VD ($\times 10^6$ J)	Whole	9.625	9.920	8.622	9.389	8.713
	Bridge	8.420	8.657	8.622	9.389	8.713
PD($\times 10^6$ J)	Bridge	9.185	9.243	9.083	8.667	7.379

(* Maximum value of SE + KE. Similarly, hereinafter.)
(** Energy transfer magnitude of in TR is estimated value for transversal vibration. Kinetic energy of longitudinal train motion and local vertical damping energy dissipated by bridge deck are excluded.)

Table A-2 Energy transfer in different models under Kumamoto earthquake

		TR	TS	PL	TM	BO
Total Input ($\times 10^6$ J)	Whole	10.218	10.439	10.011	10.059	9.132
	Bridge	9.535	9.620	9.976	10.059	9.132
SE + KE* ($\times 10^6$ J)	Whole	2.210	2.548	2.380	2.372	2.282
	Bridge	1.918	2.223	2.195	2.372	2.282
VD ($\times 10^6$ J)	Whole	3.314	3.338	2.786	2.952	2.972
	Bridge	2.631	2.670	2.786	2.952	2.972
PD ($\times 10^6$ J)	Bridge	6.904	6.944	7.185	7.067	6.121

Table A-3 Energy transfer of different models under Northridge earthquake

		TR	TS	PL	TM	BO
Total Input ($\times 10^6$ J)	Whole	4.311	4.296	4.251	4.231	3.937
	Bridge	3.897	3.869	4.250	4.231	3.937
SE + KE* ($\times 10^6$ J)	Whole	0.818	0.811	0.630	0.668	0.794
	Bridge	0.590	0.637	0.607	0.668	0.794
VD ($\times 10^6$ J)	Whole	1.701	1.685	1.455	1.548	1.421
	Bridge	1.403	1.378	1.455	1.548	1.421
PD ($\times 10^6$ J)	Bridge	2.487	2.484	2.788	2.760	2.495

