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THE SHAKING TABLE TEST ON AN SDOF MODEL STEEL STRUCTURE FOR SIMULATED CRITICAL EARTHQUAKE USING TARGET EARTHQUAKE

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SUMMARY

Using the NS component of acceleration record with peak acceleration (PA) of 818 cm/s^2 observed by Japan Meteorological Agency (JMA) in the 1995 Kobe earthquake as target earthquake, a critical earthquake which causes greater response on a 1:8 SDOF model steel structure accompanied with a damper was simulated and shaking table test was carried out. Through static experiment nonlinear as bilinear parameters of the model were determined and used in the simulation process. By free vibration test the natural period (0.2 s) of the model was confirmed and the damping ratio (2%) was determined. The simulation was conducted by the product of artificial wave generated from modified power spectral density (PSD) function and envelope function at consecutive time intervals of target. The modification was performed by amplifying the PSD graph of target at each time interval in a specified width corresponding to the structural response and reducing it in the other parts in which the areas under the PSD-frequency diagrams in the original and modified ones to be same.

Because of inevitable difference between an input wave to shaking table and the output wave, shaking table experiments were carried out five times for each case of target and critical earthquakes. The results showed good agreement with those of theoretical analysis.

INTRODUCTION

In the aseismic check of a structure, time history of strong ground motion recorded during a severe earthquake such as the 1995 Hyogoken-nanbu (Kobe) earthquake, after being modified in frequency domain by adjusting its amplitude considering dynamic characteristics of structure, is often used. In this regard, according to recommendation of the Japan Road Bridges Code [1], it is better to employ some 3 acceleration records, and use average of the corresponding responses in aseismic check, which is based on

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the fact that expected earthquake motions on a specific site would be different with each other considering different characteristics of earthquakes, and that earthquake inputs are uncertain even with the present knowledge and it does not appear easy to predict forthcoming events precisely both in time and frequency contents [2]. Then, depending on dynamic characteristic of a structure, it is possible occurring of an earthquake which causes greater response than that of a recommended record of the Kobe earthquake or others. Many researchers dealt with this topic starting from Drenick [3] in the past, and e.g. Takewaki [4, 5] recently who studied critical excitation (on a given structure) which provides greater response but with restrictions such as same power of a typical earthquake motion.

On a 1:8 SDOF model steel structure, based on a simulated critical earthquake by modifying the PSD function of the Kobe (target) record, results of shaking table test are presented. The simulation can be conducted on MDOF structures [6] and by using different target records [7]. The authors studied simulation of critical earthquake by other 2 methods [8], in all of which restriction conditions were satisfied.

SIMULATION OF CRITICAL EARTHQUAKE

Critical earthquake is simulated in such manner that shows similar time and frequency characteristics as target but causes greater response on considered structure. At consecutive time intervals of target, amplifying the PSD graph in a specified width and reducing it in the other parts wherein the areas under the PSD-frequency diagrams in original and modified ones be equal is the main idea in simulating critical earthquake (Fig. 1). From modified PSD graph at each time interval, a stationary artificial wave is generated and then multiplied by envelope curve of target to get non-stationary critical wave. Critical earthquake is assembling of the obtained critical waves at each time interval, in which smooth connectivity between critical waves can be done by one of two ways [7, 8]. Simulated critical earthquake should satisfy restriction conditions that are: same PA and envelope curve, near (not more than 5%) PSD area, and near (within 20%) predominant frequency as those of target.

The central frequency f_p of the amplifying width in Fig. 1 is corresponding to the structural response. The amplifying width $2\Delta f_p$ and amplifying rate a together with random numbers needed in generating artificial waves are chosen arbitrarily but in such a way that simulated critical earthquake satisfy the restriction conditions. Therefore, the critical earthquake will be a best selected among simulated (nominal) critical earthquakes.

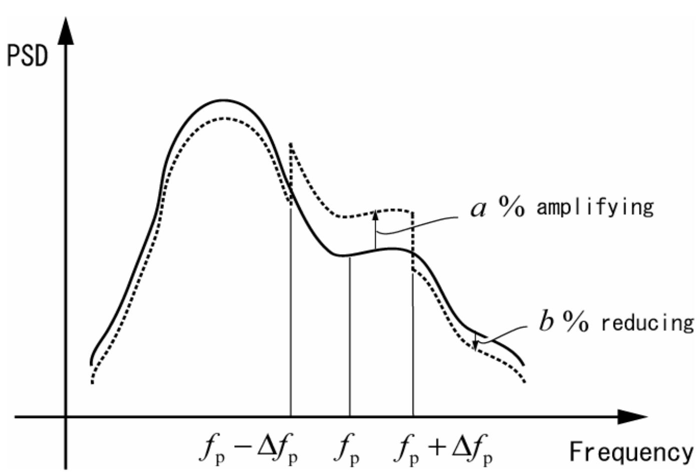

Fig. 1 Amplifying the PSD graph in a specified width and reducing it in the other parts

MODEL STRUCTURE AND ITS PARAMETRES

For a real SDOF pure frame with 3 m height and 4 m span, the respective dimensions of a 1:8 scale model will be 37.5 cm by 50 cm. The utilized model structure consists of two columns made of an identical plate of SS41 grade structural steel, and a rigid roof. The cross section of each column was considered 100-by-3-mm (Fig. 2); hence the initial stiffness k_1 of the model becomes k_1 = 21.5 kgf/cm. Considering characteristics of available shaking tables, the natural period of T_n = 0.2 s (the natural frequency of f_n = 5 Hz) was established for the model, and then the mass becomes m = 0.0218 kgf$\cdot$s^2/cm, which corresponds to the weight of 21.4 kgf.

Concerning use of damper, a damper set (Photo 1) consisted of small-size dampers with 3~5 cm length originally made for the radio controllers by Kyosho Company (SP-Pressure Damper-L; mark: IFW31) was utilized. The use of oils with different viscosity leads to different damping ratios of the damper. We used a special oil (Yokomo-150) leading to the damping ratio of some 2% determined from free vibration test.

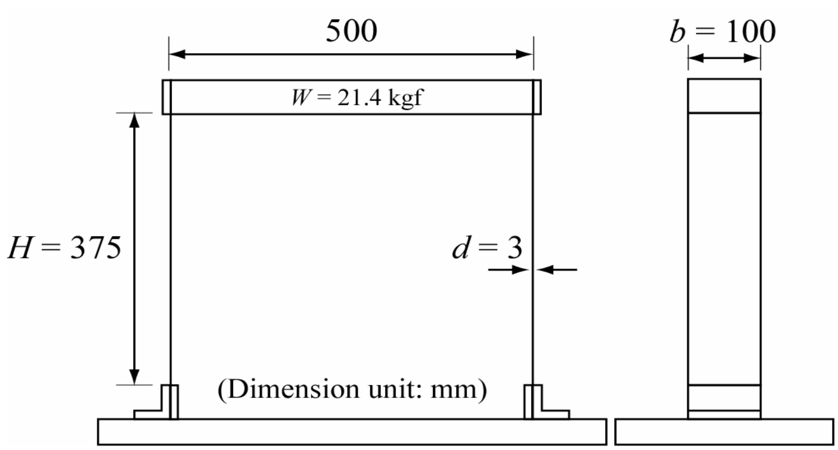

Fig. 2 Dimensions of the utilized model structure

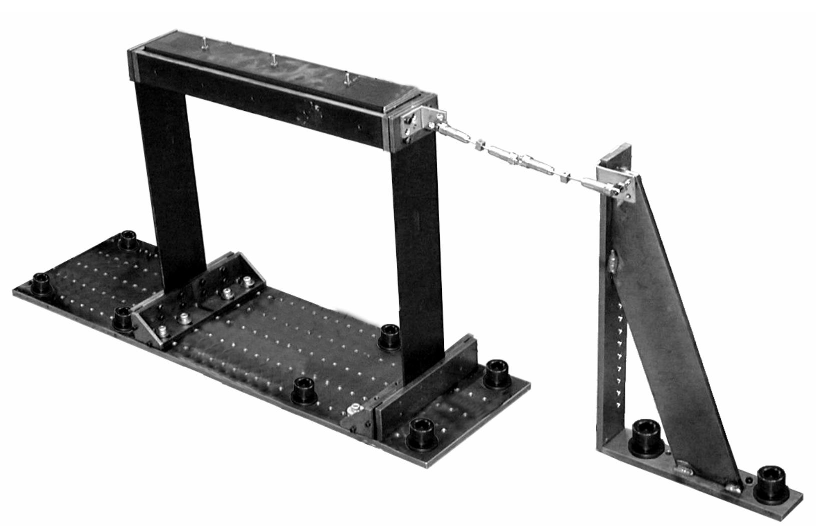

Photo 1 The utilized model structure accompanied with damper

Static Test to Obtain Nonlinear Parameters of the Model

In simulating critical earthquake nonlinear as bilinear parameters of the model structure are necessary. These parameters i.e. yield displacement and post-yield stiffness can be determined by static test.

Fig. 3 illustrates set-up of the test. The lateral force applied as tensile force by manual turning of a turn-buckle was measured by a digital load cell (made by Tokyo Sokki Kenkyujo Company, TCLZ-1000NA), and the displacement at top of the model was recorded by a laser displacement-meter (NAiS, LM100-ANL1251C). The gradually increased tensile force was continued; when the model entered the nonlinear region the force was increased more in order that the post-yield stiffness can be determined in a reasonable way; then the un-loading phase started and slowly proceeded until turning the turn-buckle had no effect on the model.

The plot of force against displacement is shown in Fig. 4, which indicates more than 6 cm residual displacement. The yield displacement, first stiffness, and idealized post-yield stiffness respectively were determined from the force-displacement plot as x_y=4.12 cm, k_1=20.6 kgf/cm, and k_2=0.86 kgf/cm. The relative difference between k_1 of the theoretical with that of the experimental is just 4%. And, the ratio of k_2/k_1 is about 5%.

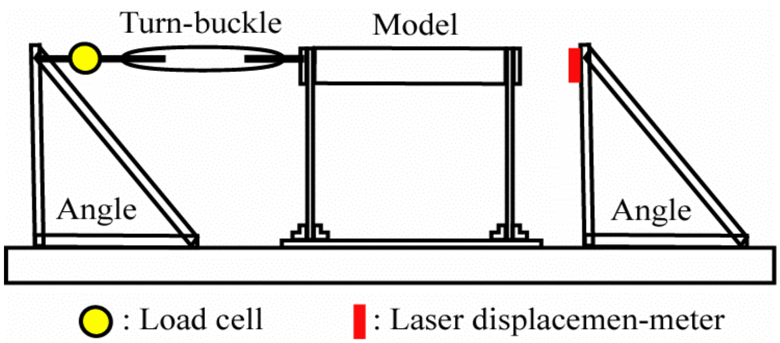

Fig. 3 Set-up of static test

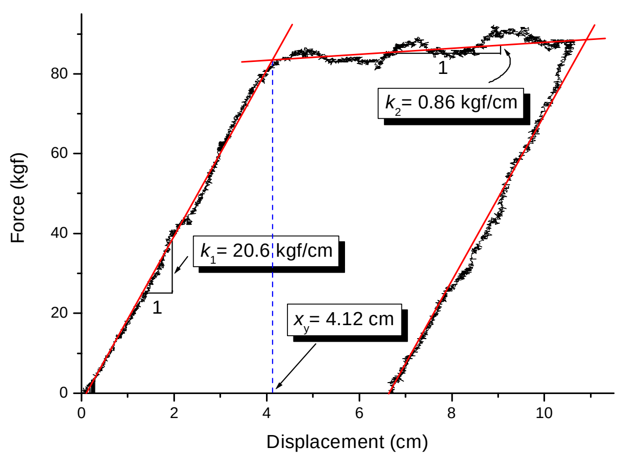

Fig. 4 The force-displacement curve from the static test

SHAKING TABLE EXPERIMENTS WITH TARGET AND CRITICAL EARTHQUAKES

Input Waves with Shortened Time Durations

As mentioned earlier, the natural period of the considered model structure is about 0.2 s. On the other hand, the predominant period of the original Kobe record with PA=818 gal and time duration of 1500x0.02 = 30 s is 0.7 s. In order to cause larger response in the model due to input wave, we condensed the original time duration to observe near resonance condition in response of the model.

The time step of the original wave with the predominant period T_1 = 0.7 s is $\Delta t_1 = 0.02$ s. Then, the time step of condensed wave with T_2 = 0.2 s from the following equation

$$\Delta t_2 = \frac{T_2}{T_1} \Delta t_1 \tag{1}$$

becomes $\Delta t_2 = 0.006$; thereby the time duration shortens to 1500x0.006 = 9 s.

Using the shortened Kobe record as target, on the model structure with parameters determined from the static and free vibration tests, simulation of critical earthquake by making many nominal earthquakes was conducted. The best one of them showing about 40% greater response displacement than target was selected, which is shown in Fig. 5 together with target.

Experimental Results

The shaking table experiments were carried out five times for each case of target and critical earthquakes as input waves, in which columns of the model were replaced by new ones after each test.

Although PA of input wave in both cases of target and critical earthquakes in all five tests were identical, PA of output wave at each test was almost different with another in the both cases. The output acceleration time histories as well as response displacement time histories of the model at five tests in the both cases of target and critical earthquakes respectively are shown in Fig. 6 and Fig. 7. As seen, at each test critical earthquake represents greater response than that of target. Considering average values, in spite of less PA of critical case (714 cm/s^2) comparing to target (806 cm/s^2), it shows nearly 60% greater response displacement (4.49 cm comparing to 2.84 cm). Among the five tests at each case, the output waves of test numbers 5 and 3 respectively in target and critical cases showed the best coincidence with the corresponding input waves, which are illustrated in Fig. 8 together with their PSD graphs. General results of these two tests are compared with theoretical results in the next section.

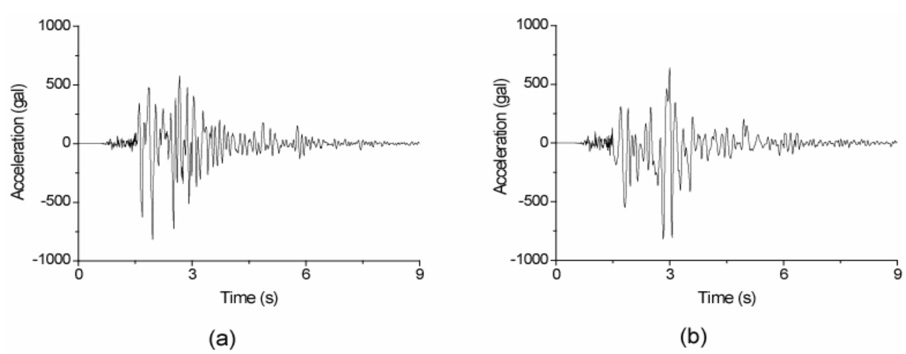

Fig. 5 Acceleration time histories of (a) target (shortened Kobe record) and (b) simulated critical earthquake for the model structure

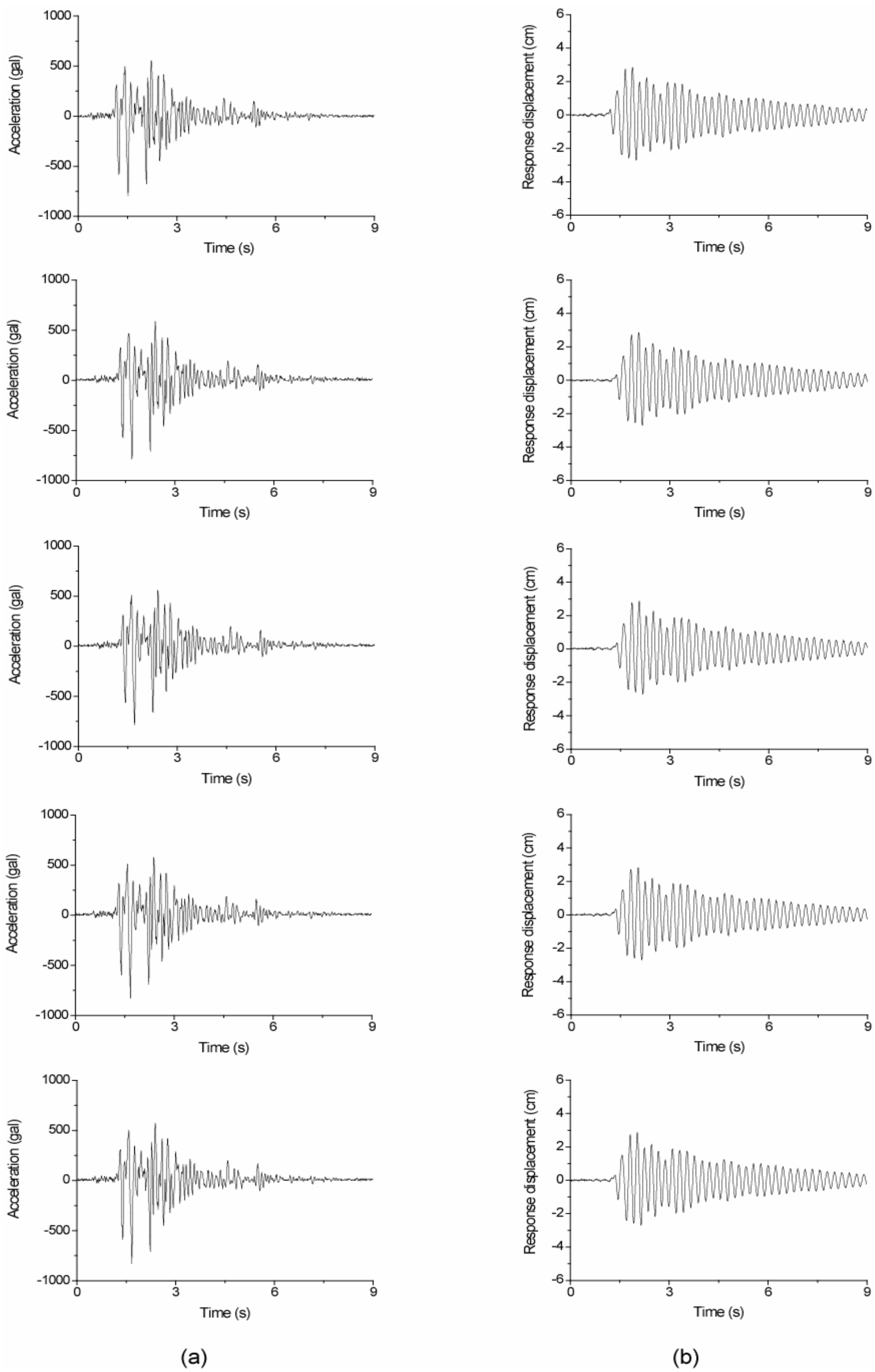

Fig. 6 Results of five shaking tests of target earthquake:
(a) Output acceleration time history; (b) response displacement time history

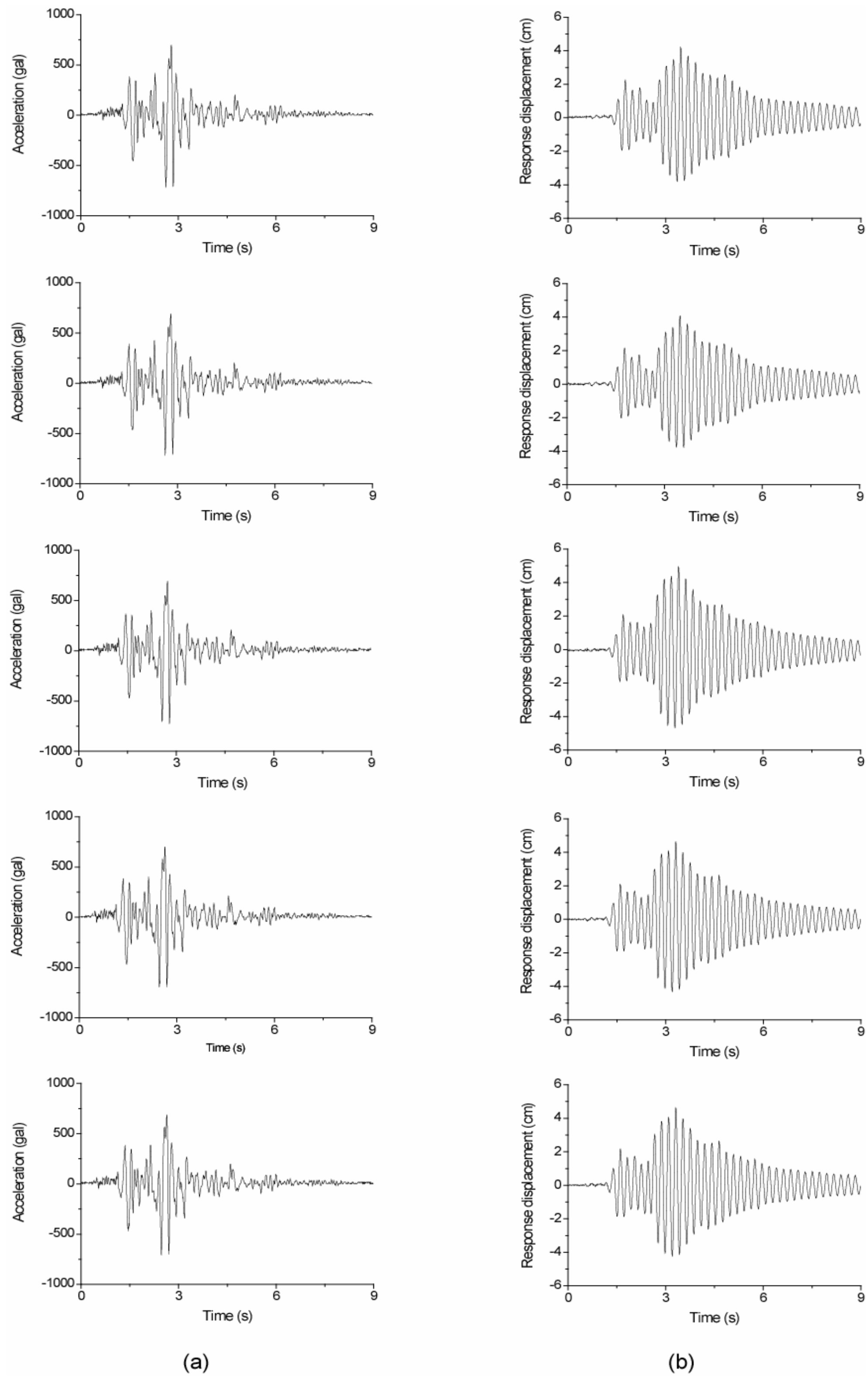

Fig. 7 Results of five shaking tests of critical earthquake:
(a) Output acceleration time history; (b) response displacement time history

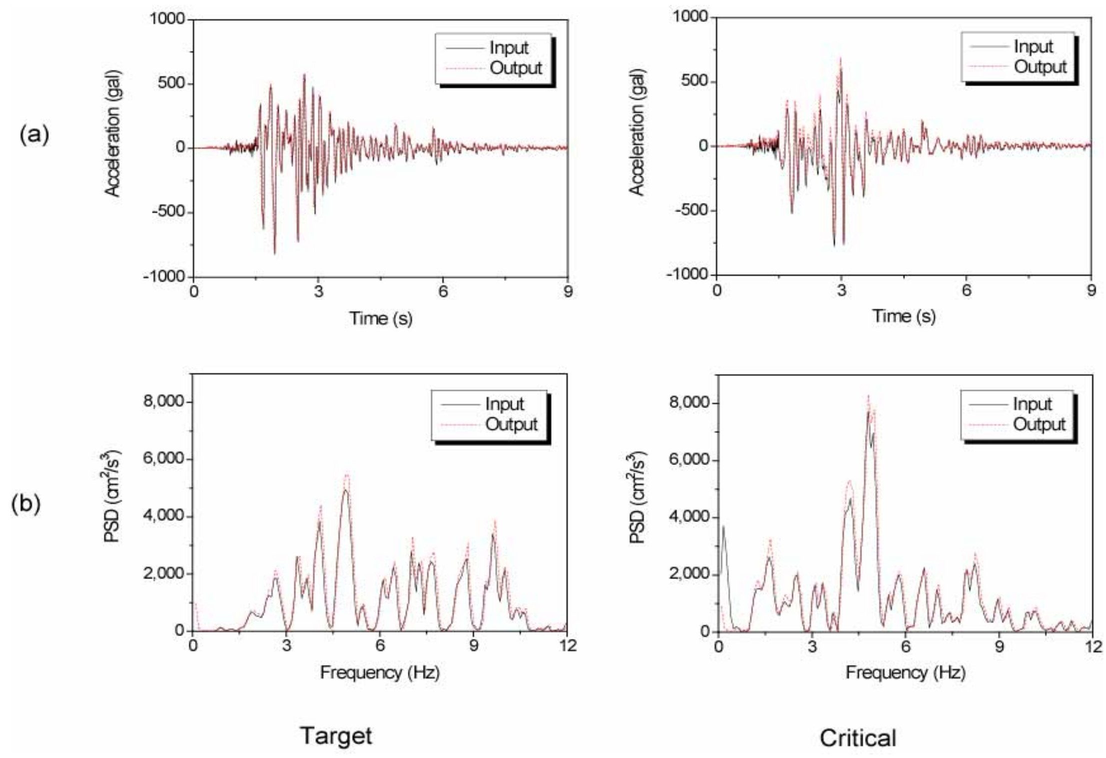

Fig. 8 Comparison between input wave and selected output wave in target and critical earthquakes: (a) Acc. time history; (b) the PSD graph

COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

In theoretical analysis, nonlinear as bilinear response analysis was carried out using Wilson θ method, which is based on the assumption that the acceleration varies linearly over an extended time step $\theta\Delta t$ where θ is always greater than 1, taken 1.4 in our analysis. In this section, results of the selected shaking table tests in each case of target and critical earthquakes are compared with the corresponding theoretical results. Fig. 9 represents plots of theoretical and experimental results as acceleration time histories, their PSD graphs, response displacement time histories, and restoring force-response displacement curves due to target and critical earthquakes.

Same as those of theory, the shaking table results clarify that the critical earthquake causes greater response than the target on the model structure. However, it is expectable to see difference between theoretical and particularly dynamic experimental results. In addition to the adjusting problem of especially PA between input and output waves, the difference here appears in the shape of force-displacement curve. This curve due to critical earthquake in the theory is bilinear, whereas such condition is not clear in the experimental curve. In this regard, probable phase difference between accelerometer and displacement-meter can be a factor; but after doing relevant calculations we recognized that the phase difference was not remarkable. It should be pointed out that restoring force in theoretical analysis is calculated by the product of stiffness and response displacement, whereas in the experimental result shown in Fig. 9 it is the product of mass and absolute response acceleration. Taking into account the damping term was not also effective here. Beside effect of damping which increases with increasing amplitude of motion [9], the difference might be justified by this fact that in theory we assume clear bilinear response of structure, while we can

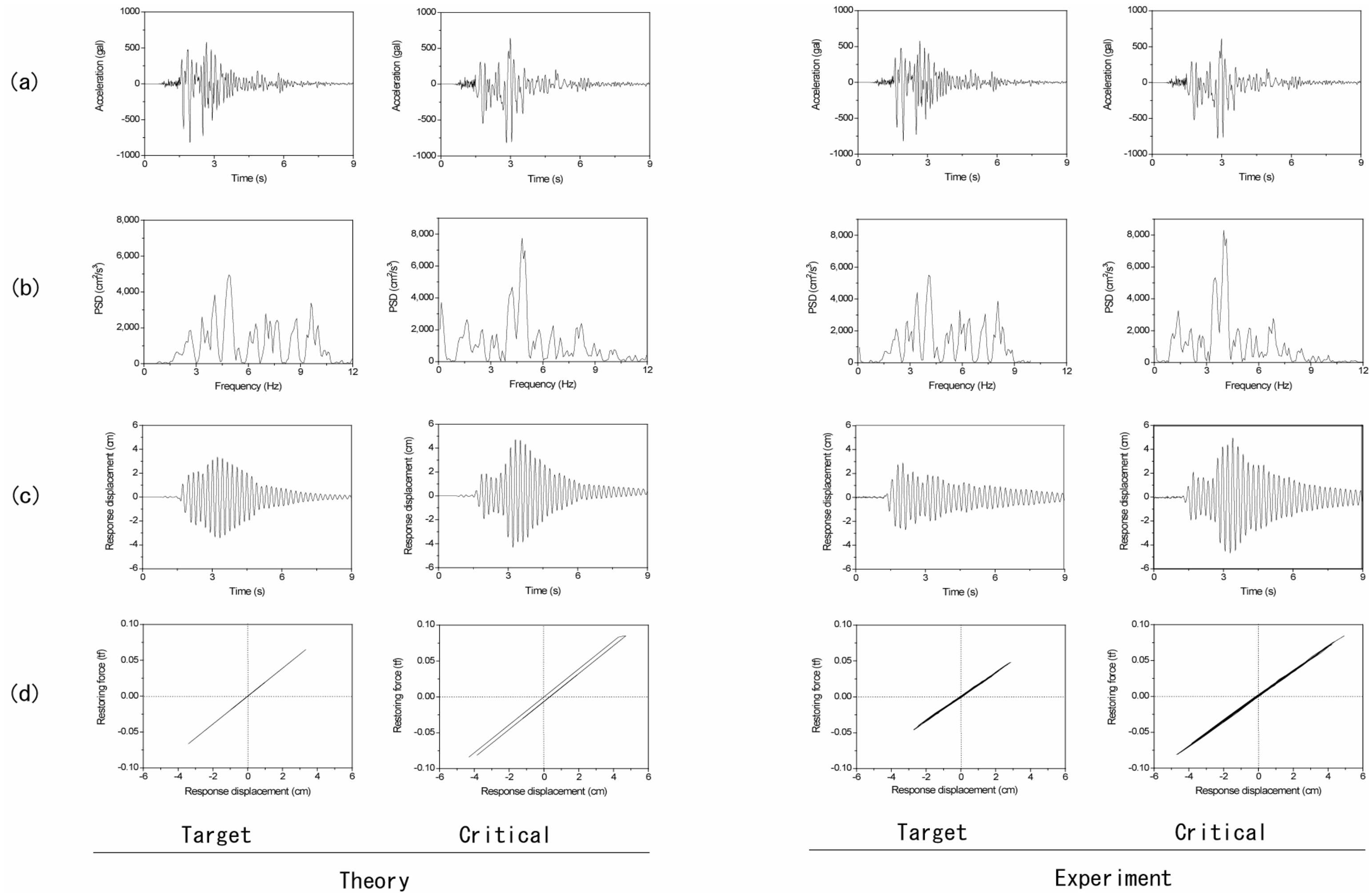

Fig. 9 Comparison between theoretical and experimental results in target and critical earthquakes:
(a) Acc. time history; (b) the PSD graph; (c) response displacement time history; (d) force-displacement curve

not observe it explicitly in experiment (Fig. 4). If theoretical analysis shows wide bilinear force-displacement curve, it will not be difficult no longer to observe such behavior in experiment. In this regard, we have been performing more theoretical analysis and shaking table experiments by utilizing other model structures [10].

PA's, absolute maximum response displacements, the PSD areas, and the predominant frequencies due to target and critical earthquakes in theoretical analysis and the selected experimental tests are listed in Table 1. Also shown in the parentheses are normalized quantities by corresponding target values. This Table indicates that the selected output wave of the critical earthquake (recorded on the shaking table) causes about 70% greater response than target on the model structure, while satisfies all restriction conditions.

Table 1 Comparison between absolute peak values of theoretical and experimental results in target and critical earthquakes (inside parentheses: normalized quantities by corresponding target values)

	Theoretical		Experimental	
	Target	Critical	Target	Critical
Peak Acc. [gal]	818 (1)	818 (1)	830 (1)	728 (0.88)
Max. Res. Displ. [cm]	3.4 (1)	4.7 (1.38)	2.9 (1)	4.9 (1.69)
The PSD area [gal^2]	12,777 (1)	14,138 (1.1)	14,445 (1)	15,113 (1.05)
The Pred. Freq. [Hz]	4.9 (1)	4.8 (0.98)	4.9 (1)	4.8 (0.98)

CONCLUSIONS

Results of experiments carried out on a 1:8 steel pure frame model structure accompanied with a viscous damper were presented. The objective of experiments was verifying theoretical analysis that critical earthquake causes greater response than target. After establishing initial parameters of the model, by static test the nonlinear parameters and by free vibration test the damping ratio of the model were determined. Using the shortened Kobe record as target, a critical earthquake for the model structure was simulated by modifying the PSD function of target at consecutive time intervals, and shaking table experiments were performed, from which following conclusions can be derived.

1. For each case of target and critical earthquakes, five shaking table tests were carried out, all of which were in good agreement with theoretical analysis. In comparison with target, the average result represents about 60% greater response of the model due to critical earthquake even with less PA.

2. From the five tests, for each target and critical case one output wave (recorded on the shaking table) that coincided well with the corresponding input wave (to the shaking table) was selected and compared with each other. The selected critical earthquake shows nearly 70% larger response while satisfies all the restriction conditions.

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