CORRELATION BETWEEN SHAKING TABLE TEST AND PSEUDO DYNAMIC TEST ON STEEL STRUCTURES

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SUMMARY

The pseudo dynamic test system developed by the Building Research Institute, Japan, was examined for its capability to simulate the earthquake behavior of multi degrees of freedom systems. Four types of model steel structures were prepared. For each type, two identical specimens were fabricated, and tested one on a shaking table and the other by use of the pseudo dynamic test system. From the direct comparison between the two test results, it was found that correlation between the two tests was very satisfactory except for minor difference in the amount of plastic flow of displacement response.

INTRODUCTION

The pseudo dynamic (PSD) test method is a new technique for earthquake response simulation, in which numerical response analysis is effectively combined with experiment. Since first devised by Tanaka et al. (Ref. 1), this method has attracted many research bodies because of its capacity of directly simulating the earthquake response of structures. As a matter of fact, this method has been applied to many types of structures, and successful results have been reported. One good example is the PSD test of a full scale seven story RC building structure conducted as part of the US-Japan Cooperative Research Program Utilizing Large Scale Testing Facilities. In that test, PSD test system of the Building Research Institute (BRI), Ministry of Construction, was used to investigate the earthquake response behavior of the structure. The test, however, was made by treating the building as a single degree of freedom system (Ref. 2). The primary reason for this simplification was the inability of the then BRI PSD test system to accurately control the forces and displacements during the test. Through that test as well as some other studies, it was found that the accurate control of specimen displacements and the accurate measuring of actuator forces were very critical to the success of the PSD test. If the PSD test fails in the accurate control, it can either be hardly manipulated or at most produce erroneous results. To ensure the effective implementation of the PSD test, the BRI PSD test system was updated in several phases. They include the digital measuring of displacements, the piecewise loading, and the combined measuring of actuator and specimen displacements.

The objective of this study is to calibrate the effectiveness of this updated PSD test system specifically in view of its applicability to multi degrees of freedom systems. Four types of test specimens were prepared

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for this purpose. For each type, two identical specimens were fabricated, and one was tested on the shaking table of the Building Research Institute, while the other with the PSD test system. Since the same input ground accelaration was applied to the two tests, direct comparison between the two results is possible, and eventually the ability of the PSD test to simulate the real earthquake behavior can be investigated. This paper reports on the outline of the BRI PSD test system and the correlation results of two story unbraced frame specimens, designated Specimen - B1 in this study. The study was conducted as one of support test programs of the US-Japan Cooperative Research Program Utilizing Large Scale Test Facilities.

OUTLINE OF BRI PSEUDO DYNAMIC TEST SYSTEM

The BRI PSD test system comprises one computer for data processing, one computer for servo control, servo controllers, and electronic servo control actuators. They are connected effectively with each other and constitutes one closed loop, with which manual operation is minimized. The detailed description of the original BRI PSD system is given elsewhere (Ref. 3). To achieve accurate control of displacements, new techniques, called the combined measuring of specimen and actuator displacements and the piecewise loading, have been incorporated into the system. The outline of these techniques are as follows.

Combined Measuring of Specimen and Actuator Displacements

In BRI PSD test system, two separate displacements are monitored continuously for the control of each actuator motion. They are the structure displacement and the actuator displacement (Fig. 1). The structure displacement is measured by a digital displacement transducer (DLT), whereas the actuator displacement by an analog LVDT. Use of the digital DLT is because of (1) increasing the accuracy of displacement reading and (2) receiving noise free signals. The accuracy level of the DLT is 0.01 mm with the total measuring stroke of 2,000 mm. This means that the accuracy is 0.0005 % of the full scale. One can readily notice that analog LVDT's can hardly assure this level of accuracy. The actuator loading is yet controlled by the analog LVDT attached to the actuator since the BRI servo-control loop is an analog circuit.

Piecewise Loading

The actual loading procedure is shown in Fig. 2. As two displacements are measured simultaneously for the actuator motion control, the procedure is little complex. Suppose that the test structure be deformed from position Xn to Xn+1 in Fig. 2, first, A times dx0 (= Xn+1 - Xn) of displacement is asked for the actuator to travel. Here, A is a coefficient less than unity (say, 0.25) and can be specified as an initial input by a test operator. Because of the structure stiffness or loading apparatus flexibility, the displacement of the structure after this actuator motion is most likely not the same as the actuator displacement. At this point, the structure displacement is monitored by the digital DLT, and the remaining displacement is measured. Then, A times this remaining displacement is applied to the structure repeatedly until the structure displacement reaches Xn+1 with an allowable error of 2ε. This allowable error, ε, should also be specified as an initial input.

SPECIMENS

The four types of structures prepared for this study were 1) one story unbraced frame (Specimen - A), two story unbraced frame (Specimen - B1, Fig. 3), two story braced frame (Specimen - B3), and five story braced frame (Specimen - C). These specimens were one span steel frame models having an approximately one third (1/3) scale ratio. To preserve the prototype relationship in those model specimens, weight was added to each floor level so that the total specimen weight would be one ninth (1/9) of that of the prototype. In Specimen - B1, the one reported in this paper, the beams are much greater in both strength and stiffness than the columns as shown in Fig. 3. Then, the specimen can be considered as a shear type two degrees of freedom system. The material properties and other major characteristics of the specimen are listed in Table 1.

TEST PROCEDURES AND INPUT ACCELERATIONS

In each of the four pairs of specimens, the shaking table test was carried out first, and then the PSD test followed. In the PSD test, the acceleration recorded on the shaking table was used as the input ground motion in order to guarantee the identity of input motion between the two tests. The shaking table test comprises four stages of test:
(a) Initial Resonance Test (Test - S1), (b) Elastic Response Test (Test - R1), (c) Inelastic Response Test (Test - R2) and (d) Final Resonance Test (Test - S2). The resonance curves obtained from resonance tests of Specimen - B1 are shown in Fig. 4. The first and second natural frequencies are 2.1 and 6.1 Hz. The PSD test also comprises four stages of test: (a) Single Force Application test, (b) PSD test in Free Vibration Mode, (c) Elastic Response Test (Test - R1), and (d) Inelastic Response Test (Test - R2).

The input acceleration employed in this study was the N-S component of acceleration recorded at the Tohoku Univ. in the 1978 Miyagi-oki earthquake. The time scale was contracted to $1/\sqrt{3}$ to preserve the relationship between the prototype and model. In Test - R1 of Specimen - B1, the maximum acceleration was set at 238.5 gal. and, in Test - R2, at 500.2 gal. The power spectrum density with its predominant frequency of 2.0 Hz and time history of the input acceleration are shown in Figs. 5 and 6.

CORRELATION IN EARTHQUAKE RESPONSE

Comparison of Response Waveforms

Figures 7 and 8 show displacement and shear force waveforms of Test - R2 of Specimen - B1. In these figures, solid and broken lines indicate waveforms recorded from the shaking table and pseudo dynamic tests respectively. Corresponding hysteresis curves at the first story are shown in Fig. 9, verifying that the specimen sustained large inelastic deformation. The following remarks may be stated by comparing the results of the two tests.

i Correlation in both the displacement and shear force responses between the two tests is very satisfactory.

ii There is, however, little difference in the amount of plastic flow in displacement response between the two tests.

To look into this difference in plastic flow, the waveforms obtained from the pseudo dynamic tests were slightly modified as shown in Fig. 10. In this figure, the base line of the original waveform is shifted from a certain time so that the modified waveform would be in the closest match with the corresponding waveform of the shaking table test. This figure also shows the amount of base line shift, which is an direct indication of the difference in the amount of plastic flow between the two tests. The amount of the base line shift increases with time. At the end of the test, the amount of the base line shift reached approximately 40 percent of the maximum peak amplitude of the waveform obtained from the shaking table test. Two reasons are conceivable to explain this discrepancy in the amount of plastic flow. One is associated with the intrinsic difference in the test method. For instance, the pseudo dynamic test cannot include the effect of velocity (strain rate) in response. Note, that, in the PSD test, the forces are applied quasi statically. In the PSD test, the time scale was expanded to approximately ten thousand times mainly because of the limitation of actuator speed and scanning speed during the loading and measuring.

Errors introduced in various stages of experiment can be the second reason. Considering that the amount of plastic flow changes greatly even with a small difference in force level, slight difference in properties between the two specimens (although they were supposed to have been fabricated under the identical condition) most likely caused this discrepancy in the amount of plastic flow.

Figure 11 shows an analytically obtained displacement response waveform together with the experimental waveforms. In the analysis, the test structure was assumed as a lumped mass model having bi-linear hysteretic characteristics. Parameters in this model such as the spring constant and yield force were determined on the basis of the experimental results shown in Fig. 9. The damping coefficient used in the analysis was 0.7 percent which was obtained from the resonance test on the shaking table. Correlation between the analytical and experimental waveforms is good despite the various simplifications employed in the analysis. For the first 3.5 seconds, the analytical waveform almost traces the waveform obtained from the shaking table test, whereas, in the succeeding time history, the waveform rather matches the PSD waveform particularly in the large amplitude range.

Correlation of Peak Displacement Amplitude

The amplitude ratio defined by Ap/As is shown in Fig. 12. Here, As and Ap are the peak-to-peak amplitudes of the displacement response waveforms recorded from the shaking table and pseudo dynamic tests, respectively. As shown in this figure, most of Ap/As values scatter in the proximity of 1.0, and more than 90 percent of the total plotted points in this figure are in a range of between 0.8 and 1.2.

The overall correlation between the two tests can be examined by taking into account possible errors generated in the process of experiment. Figure 13 is a flow diagram of error propagation process in the shaking table and pseudo dynamic tests. Each box in the diagram includes a few error factors. Assuming suitable values for every error factor and applying an error propagation formula, one can obtain as much as 10 percent systhetic error even without the inclusion of errors associated with the PSD test. Taking into account of this level of synthetic error, it is readily recognized that the peak-to-peak amplitude ratio is in very high correlation between the two tests.

CONCLUSION

Through the comparison in displacement and shear force response waveforms between the shaking table and pseudo dynamic tests, it was found that the correlation between the two tests is very satisfactory despite potential errors that can be amassed to a level of as much as 10 percent. Slight difference in the amount of plastic flow in displacement response was observed. Two reasons are conceivable to explain this discrepancy. One is the effect of difference in the strain rate between the tests. Study of this effect on the dynamic response should be made prior to evaluating the ultimate correlation between the two tests. Subtle difference in properties between the two identical-to-be specimens is an another possible candidate to have caused this discrepancy.

REFERENCES

1. Tanaka, H.,"A Computer-Actuator On-Line System for Non-Linear Earthquake Response Analysis of Structures," Seisan Kenkyu, Institute of Industrial Science, The University of Tokyo, Vol. 27, No. 12, December 1975, pp.15-19. (in Japanese)
2. Okamoto, S., Nakata, S., Kitagawa, Y., Yoshimura, M., and Kaminosono, T.,"A Progress Report on the Full-Scale Seismic Experiment of a Seven Story Reinforce Concrete Building," Research Paper, Building Research Institute, Ministry of Construction, No. 94, March 1982, 92pp.
3. Okamoto, S., Kaminosono, T., Nakashima, M., and Kato, H.,"Techniques for Large Scale Testing at BRI Large Scale Structure Test Laboratory," Reserch Paper, Building Research Institute, Ministry of Construction, No. 101, May 1983, 38pp.

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Table 1 Properties of Specimen - B1

Entry	Unit	Flange	Web
Yield Stress	kg/cm^2	3,140	3,720
Yield Strain	m/m	0.00157	0.00190
Young's Modulus	$10^6 \times kg/cm^2$	2.00	1.99
Ultimate Strength	kg/cm^2	4,370	4,540
Maximum Strain	m/m	0.24	0.19

Specimen	Number of Stories	Story	Weight W_i (ton)	Elastic* Stiffness (ton/cm)	Natural* Peirod (sec.)	Yield Shear* Force Q_y (ton)	Q_y/W_i	Ultimate* Shear Force Q_u (ton)
A	1	1	2.23	1.42	0.253	1.35	0.605	3.80
B1	2	2	2.21	1.15	T_1:0.430			
		1	2.23	1.31	T_2:0.157	1.21	0.273	3.42

* Values obtained from preliminary numerical analysis

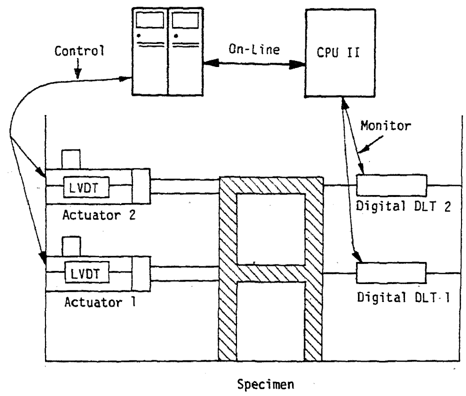

Fig. 1 Combined Measuring of specimen and Actuator Displacements

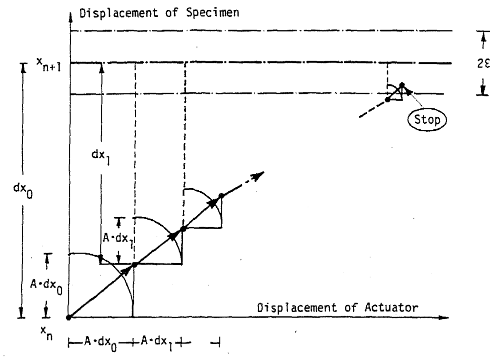

Fig. 2 Piecewise Loading Procedure

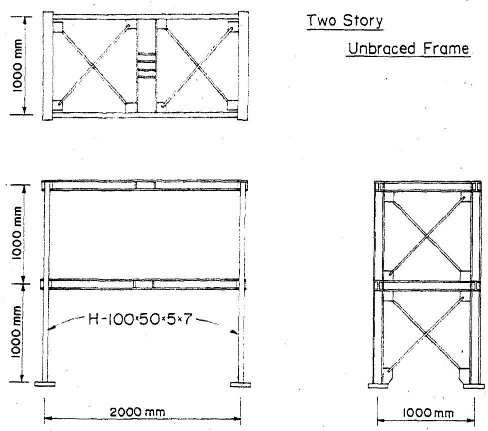

Fig. 3 Dimensions of specimen - B1

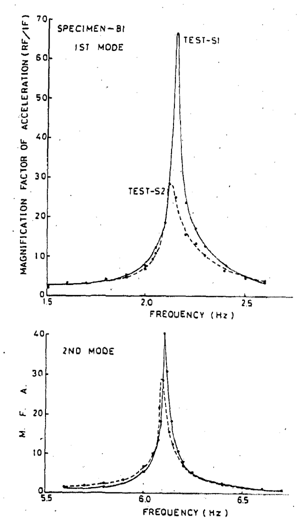

Fig. 4 Resonance Curves

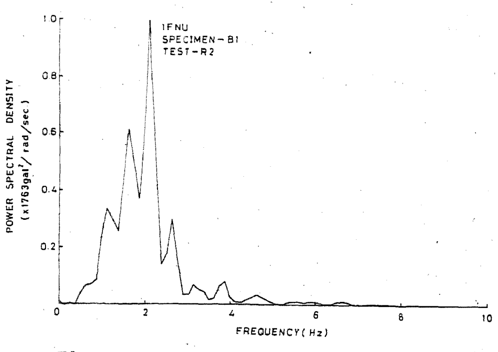

Fig. 5 Power Spectrum Density of Input Ground Motion

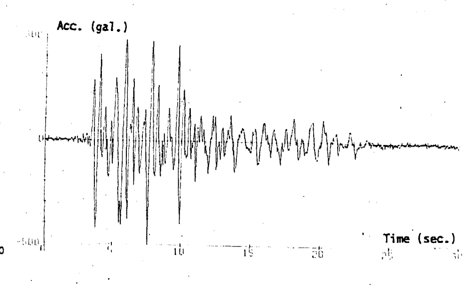

Fig. 6 Time History of Input Ground Motion

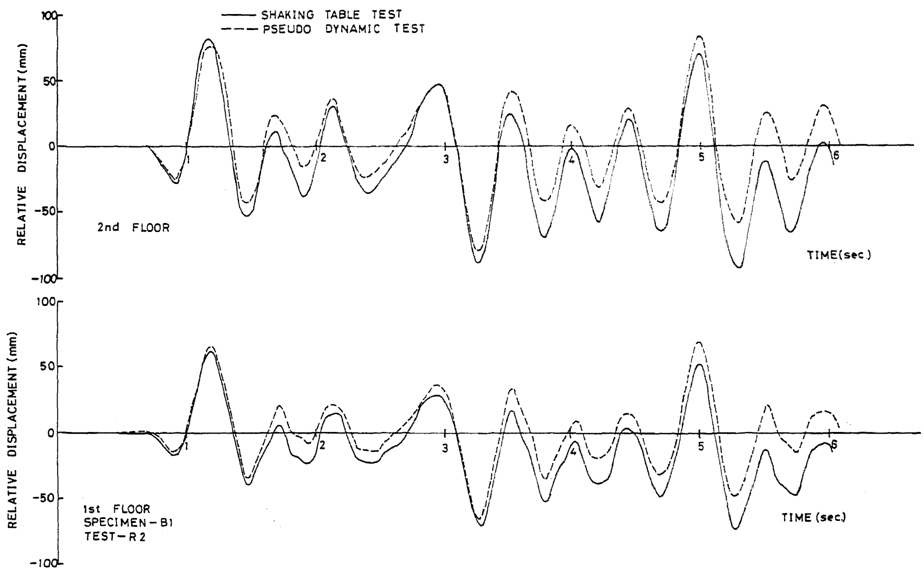

Fig. 7 Displacement Time History

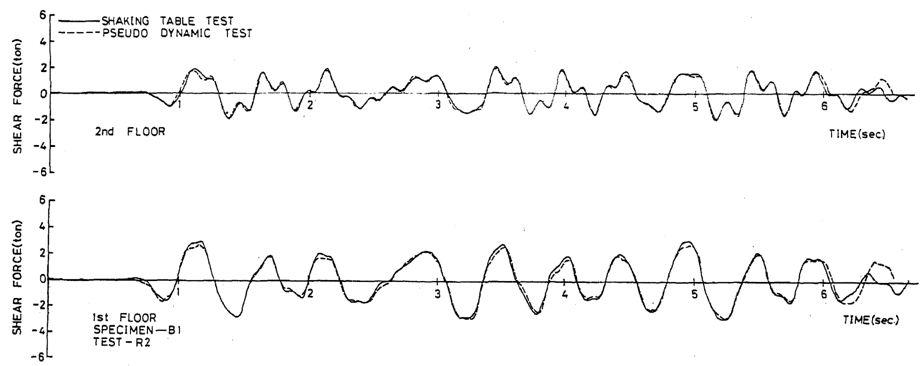

Fig. 8 Shear Force Time History

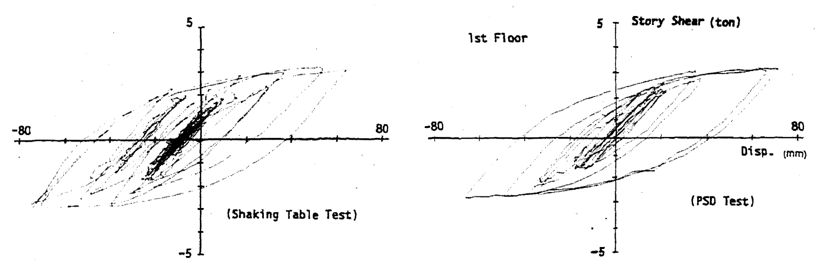

Fig. 9 Story Shear Force and Interstory Displacement Relationship

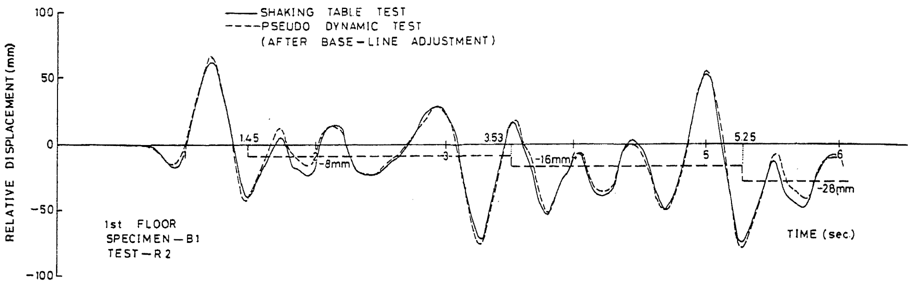

Fig. 10 Displacement Time History After Base-Line Adjustment

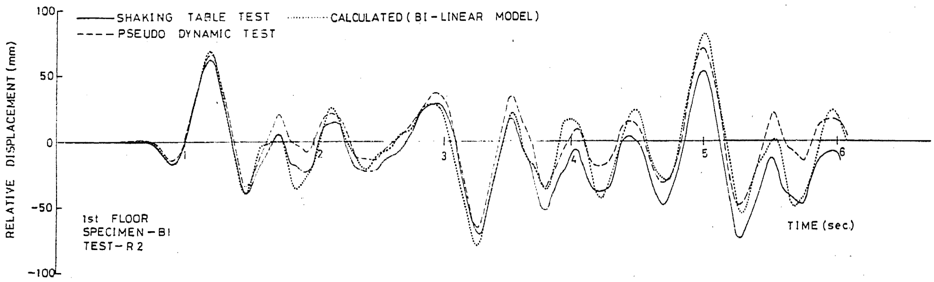

Fig. 11 Comparison in Displacement Time History Between Tests and Analysis

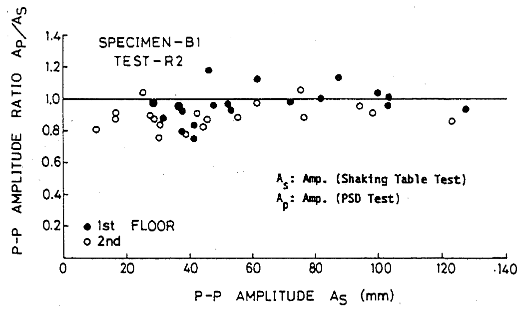

Fig. 12 Peak-to-Peak Amplitude Ratios

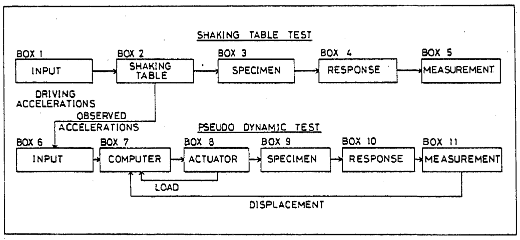

Fig. 13 Flow Diagram of Error Propagation Process