SHAKING TABLE TESTS OF STEEL FRAMES

by

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SUMMARY

Shaking table tests, a dynamic response analysis and static loading tests were made for one-storied steel frames. Restoring force characteristics based on the static loading test were modified to apply in the response analysis taking the effect of a high strain rate in dynamic tests into account. The time history of the acceleration response of a model structure could be predicted with a sufficient accuracy by the response analysis but that of the story-drift response from the analysis did not fall completely on the experimental results, mainly because of the inaccurate estimation of an inelastic flow of a deformation response in a plastic region.

INTRODUCTION

For the establishment of a reasonable earthquake-resistant design method of building structures, it is important to investigate hysteretic restoring-force characteristics in an elastic-plastic range including a large deformation range and to understand the dynamic response behavior up to failure. In the process of a structural design of structures, dynamic response analyses using appropriately estimated restoring-force characteristics have been performed frequently to predict the behavior of a structure subjected to an earthquake motion. However, since most of the tests to investigate restoring-force characteristics were conducted under the static loading, it is required to confirm that the hysteretic rules which were formulated on the basis of the results of quasi-static tests are sufficient or not to predict the response of structures subjected to a dynamic excitation due to an earthquake. There are a few dynamic failure tests by a shaking table in the past.[1)-6)] The main objects of this investigation are to trace experimentally the dynamic behavior of steel frames subjected to an earthquake motion on a shaking table throughout the whole process up to failure, to examine the applicability of a simple model of hysteretic characteristics such as a bi-linear model for pure frames, to certify the applicability of the hysteretic rules for brace members which were formulated on the basis of the results of quasi-static tests and to investigate key points which are fundamental and essential in the work of formulation of hysteretic restoring-force characteristics, in comparison of the results of static and dynamic tests with those of static and dynamic analyses.

TEST STRUCTURES

Small size models of one-storied steel pure frames and braced frames composed of four columns and rigid roof and floor plates were tested. The span length and the bay width are 100cm and 80cm, respectively. The clear height of the specimen is 4, 8 or 12 cm. The total weight of roof blocks

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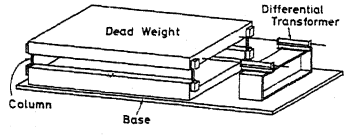
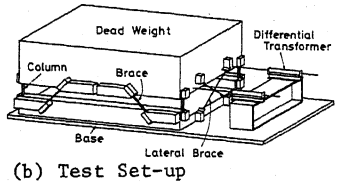
is 0.548 tons in the case of a pure frame and 1.946 tons in the case of a braced frame. Test specimens are shown in Figs. 1 and 2. The members were designed so that the horizontal yield load carrying capacity of the model neglecting the reduction of load carrying capacity of compressive braces due to buckling is about a half of the weight of the roof and the load carrying capacity of columns is about 30 % of that of braces in the case of braced frames. Columns and braces were made of an identical plate of SS41 grade steel with 9 mm thickness by machine cutting and finishing, and annealed after finishing. Both ends of the members were rigidly connected to a floor and a roof blocks. Nominal and measured dimensions of the specimens are shown in Fig. 2 and Table 1, respectively. Mechanical properties of the used material obtained from tension tests are shown in Table 2. "PF" and "BF" in the name of specimens denote a pure frame and a braced frame, respectively and the number denotes the clear height of the frame in millimeter. In the case of a braced frame, the number also denotes an effective slenderness ratio λ of a brace. Fundamental static and dynamic properties of the specimens are listed in Table 3, where Δ_{cy} and Δ_{by} denote story-drifts at the instance when columns and braces yield, respectively. Q_{cy} and Q_{by} denote the sum total of the horizontal yield load carrying capacities of four columns and four braces, respectively. T and n_o denote natural period and natural frequency of the model structure, respectively. W denotes the total weight of roof blocks. N_o denotes the sum of yield axial force of four columns. Q_y is equal to the sum total of Q_{cy} and Q_{by}.

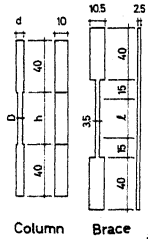


(a) Test Set-up of Pure Frames.



(b) Test Set-up of Braced Frames.

Fig. 1 Test Set-up.



h	ℓ	D	d
40	56.6	4.2	6.0
80	113.1	6.0	6.0
120	169.7	7.3	7.3

Fig. 2 Test Specimen.

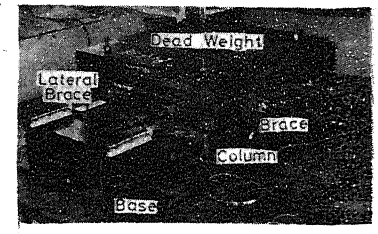


Photo. 1 View of Test of BF120D.

Table 2 Mechanical Properties of Material.

	Columns	Braces
Yield Stress	2.76 t/cm^2	2.73 t/cm^2
yield strain	0.00131	0.00130
Strain hardening Strain	0.0295	0.0339
Ultimate Strength	4.22 t/cm^2	4.01 t/cm^2
Ultimate Strain	0.35	0.21

Table 1 Measured Dimensions of Test Specimens(unit;mm).

SPECIMEN NAME	COLUMN B(mm)	COLUMN D(mm)	COLUMN h(mm)	BRACE B(mm)	BRACE D(mm)	BRACE ℓ(mm)	BRACE λ
PF 40D	10.02	4.07	40.16				
PF 80D	9.97	5.90	79.99				
PF120D	10.01	7.26	120.00				
BF 40D	10.01	4.12	40.99	3.59	2.51	57.12	39
BF 80D	9.97	5.92	79.99	3.45	2.42	113.00	81
BF120D	10.00	7.27	120.00	3.62	2.52	169.90	117
PF 40S	9.99	4.05	40.10				
PF 80S	9.98	5.90	79.98				
PF120S	10.00	7.25	120.03				
BF 40S	10.00	4.04	40.13	3.43	2.49	56.52	39
BF 80S	9.99	5.90	80.01	3.42	2.44	112.99	80
BF120S	9.98	7.26	119.90	3.64	2.51	170.05	117

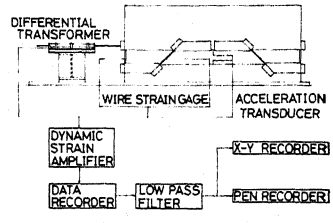


Fig. 3 Measuring system.

SHAKING TABLE TEST

A test specimen was set on an electro-magnetic type shaking table of Disaster Prevention Research Institute, Kyoto University. The basic characteristics and capacities are listed in Table 4. Test set-up is illustrated in Fig. 1 and the whole view of the experiment is shown in Photo. 1. In the case of braced frames, lateral braces were set to prevent the deformation in the direction perpendicular to a motion as shown in Fig. 1(b) and Photo. 1. A pickup of an accelerometer was placed on the floor to catch the motion of the shaking table and three pickups of accelerometers were placed on the undersurface of the roof plate to measure the motion in two horizontal and a vertical directions. Relative displacement between a floor and a roof was measured by two linear differential transformers. The signals from sensors were continuously recorded on the magnetic tape and monitored during the test. Block diagram of measuring system is shown in Fig. 3. The fundamental dynamic properties of test specimens were examined under sinusoidal wave excitation with small amplitude and various frequencies before the test sujected to a simulated earthquake. The ratio ξ of the maximum amplitude of an acceleration response to that of an input wave was measured. Free vibration test after a small shock by a mallet was also made. Examples of elastic response curves are shown in Fig.4, where n denotes the frequency of input sinusoidal wave and ζ is a critical damping ratio. Fundamental dynamic properties obtained from the test are listed in Table 3. Natural periods obtained from tests are a little longer than those obtained from calculation,

Table 3 Fundamental Properties of Specimens.

SPECIMEN NAME	Δ_{cy} (mm)	Δ_{by} (mm)	Q_{cy} (ton)	Q_{by} (ton)	Q_y (ton)	Q_{by}/Q_y	W (ton)	Q_y/W	W/N_o	Analysis T(sec)	Analysis n_o(Hz)	Test T(sec)	Test n_o(Hz)	Test ξ(%)
PF 40D	0.256		0.221		0.221		0.548	0.403	0.122	0.051	19.8	0.058	17.3	0.6
PF 80D	0.707		0.233		0.233		0.548	0.425	0.084	0.082	12.2	0.092	10.9	1.5
PF120D	1.297		0.235		0.235		0.548	0.429	0.068	0.110	9.1	0.124	8.1	1.0
BF 40D	0.219	0.105	0.176	0.697	0.873	0.798	1.946	0.449	0.428	0.032	30.8	0.040	25.3	1.2
BF 80D	0.647	0.208	0.204	0.645	0.849	0.760	1.946	0.436	0.299	0.048	20.9	0.054	18.7	0.8
BF120D	1.226	0.312	0.209	0.705	0.914	0.771	1.946	0.470	0.243	0.057	17.6	0.080	12.4	2.0
PF 40S	0.256		0.218		0.218		0.548	0.398	0.123	0.051	19.6			
PF 80S	0.707		0.233		0.233		0.548	0.425	0.084	0.082	12.2			
PF120S	1.299		0.234		0.234		0.548	0.427	0.069	0.111	9.0			
BF 40S	0.212	0.104	0.171	0.660	0.831	0.794	1.946	0.427	0.437	0.033	30.2			
BF 80S	0.650	0.208	0.202	0.645	0.847	0.762	1.946	0.435	0.299	0.048	20.9			
BF120S	1.225	0.313	0.208	0.706	0.914	0.772	1.946	0.470	0.244	0.057	17.6			

Table 4 Basic Properties of Shaking Table.

Maximum Power	4 tons
Frequency Range	0.2 ~ 200 Hz
Maximum Displacement	±50 mm
Maximum Load	8 tons
Size of Platform	2.5x2.5 m

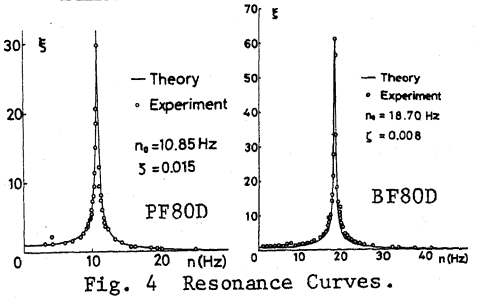


Fig. 4 Resonance Curves.

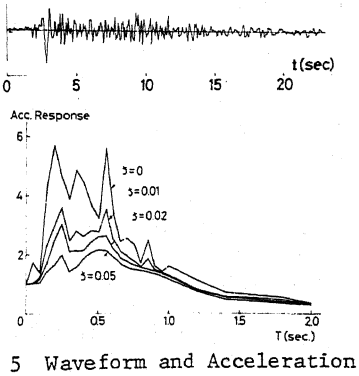


Fig. 5 Waveform and Acceleration Response Spectra of Input Wave.

because the elastic rigidity of the test structure is smaller than that of the calculated one due to the slight imperfection in rigidness of supporting blocks for columns and in case of braced frames, mainly due to the imperfection of straightness of braces. Natural periods calculated using the initial slope of the load-deflection curves from the shaking table tests coincide with the results of the sinusoidal vibration test.

The acceleration waveform pattern of the N-S component of the 1940 El Centro record shown in Fig. 5 was used as the input wave for the shaking table test. The peak acceleration for each specimen was determined referring the analytical results. Real time record was used only in the test of PF80D, and the time axis of the input wave was compressed by a factor 2.0 for the tests except PF80D. The response spectra of the used wave are also shown in Fig. 5. Absolute acceleration of a floor α_g, that of a roof α and story-drift Δ versus time t relationships for each specimen observed in the shaking table tests are shown in Figs. 6(a) - 6(f). In these figures, the product of mass of a floor and measured acceleration of a roof, which approximately corresponds to the story-shear, versus story-drift relationships are also shown. The roof deflects alternately and approximately symmetrically about the original position in the case of the frames whose restoring-force characteristics has an ascending slope in yielding range, as observed in PF80D and PF120D. On the other hand, in the case of the frames whose slope in a plastic region is flat or descending, the deflection tends to incline toward one direction as observed in PF40D and BF40D. In the cases of BF80D and BF120D, the deflection increased suddenly at about 1.5-1.7 seconds from the beginning of the test and it reversed toward a final collapse.

STATIC TEST AND RESTORING-FORCE CHARACTERISTICS

After the shaking table test, static horizontal loading tests were performed for the same size models tracing the history of the story-drift which was measured in the shaking table test to investigate the effect of a high strain rate in dynamic loading on hysteretic restoring-force characteristics. Restoring-force in a column was calculated from the strain data measured by means of two pairs of the foil-type electric resistance strain gages which were mounted at the portion near the mid-height of the column where only elastic deformation would be expected. Examples of the relationship between restoring-force in a column and story-drift are shown in Fig. 8, by solid curves. The restoring-force of the overall frame and story-drift were measured by a load-cell and linear differential transformers, respectively. The relationships between the measured restoring-force of the overall frame and story-drift are shown in Fig. 9. In Figs. 8 and 9, dashed curves denote the corresponding results obtained from the shaking table tests. Horizontal load carrying capacities of the frames in the shaking table tests are about 10 - 25 % higher than those of the frames in the static loading tests in in-elastic range, due to the effect of a high strain rate. Orders of a strain rate at critical sections in a column and stretching rate of a brace which were estimated by the analysis on the basis of the rate of story-drift measured in the shaking table test are in the range about 0.01 - 1/sec. Under such high strain rate, it was confirmed experimentally that the yield stress of steel becomes 10 - 25 % higher than that in a static test.[8] The yield level and the load carrying capacity in the model of restoring-force characteristics of columns and braces which were applied to the dynamic analysis were averagely increased to the amount of 15 % higher than the

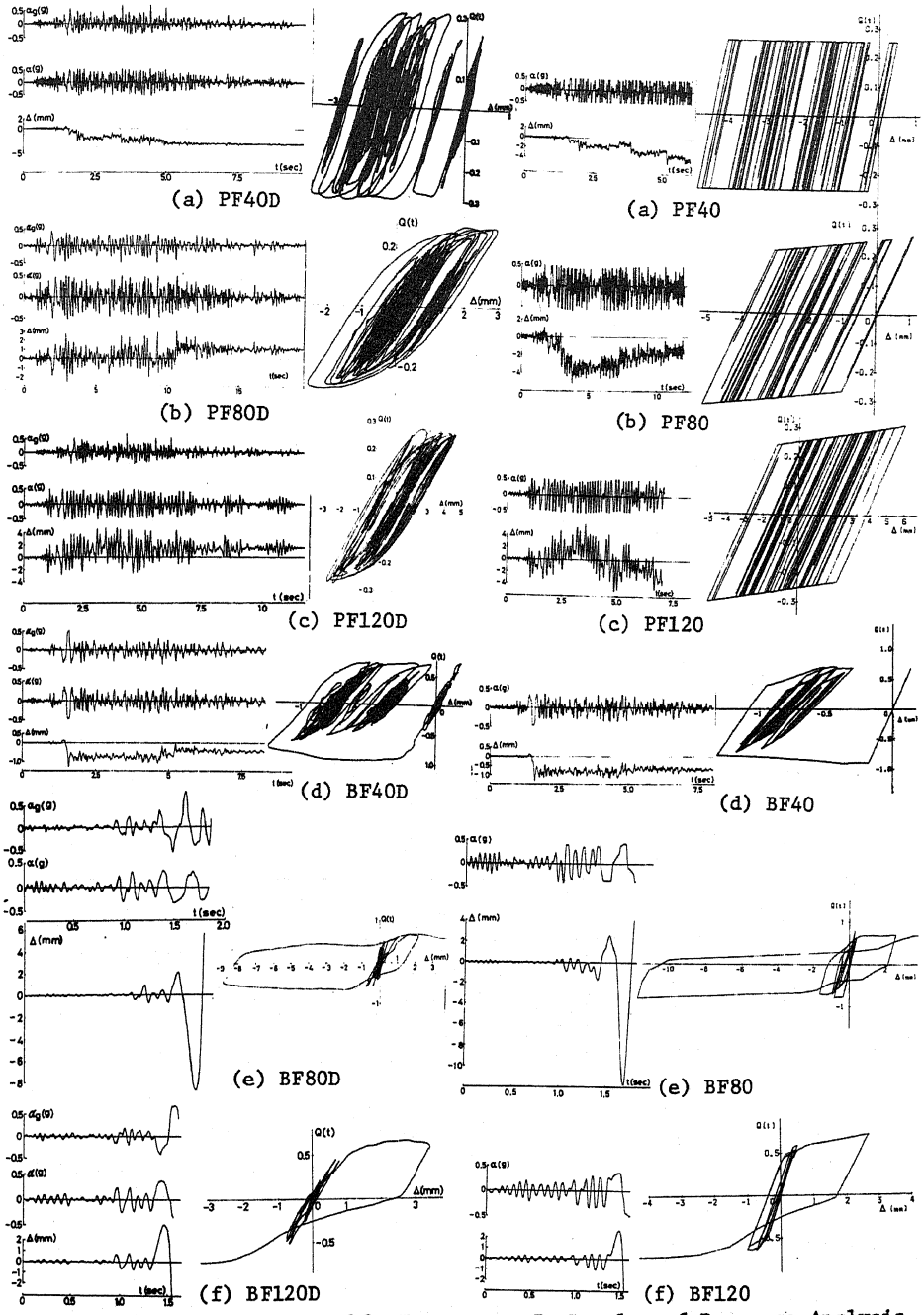
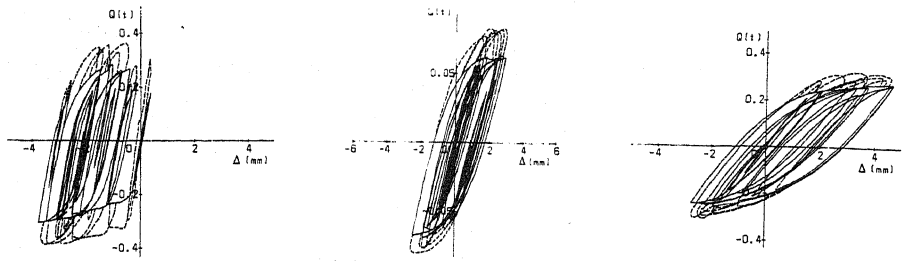
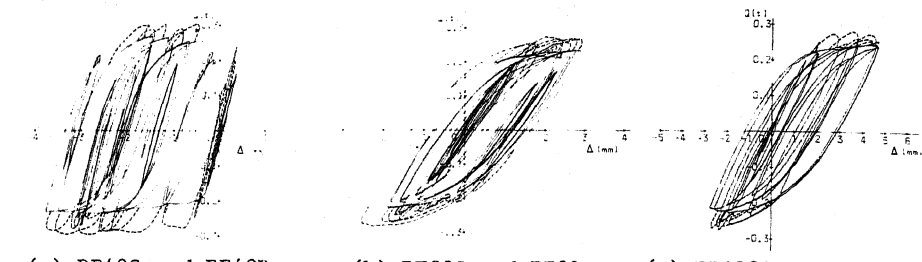


Fig. 6 Results of Shaking Table Tests. Fig. 7 Results of Response Analysis.

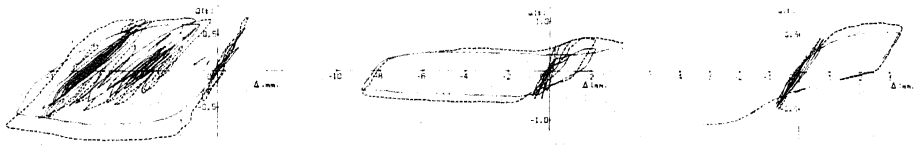


(a) PF40S and PF40D (b) PF80S and PF80D (c) PF120S and PF120D

Fig. 8 Comparison of Restoring-Force of Columns.



(a) PF40S and PF40D (b) PF80S and PF80D (c) PF120S and PF120D



(d) BF40S and BF40D (e) BF80S and BF80D (f) BF120S and BF120D

Fig. 9 Comparison of Restoring-Force of Frames.

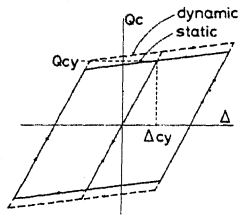
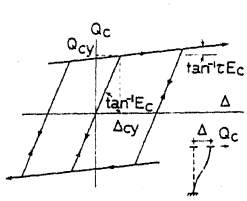


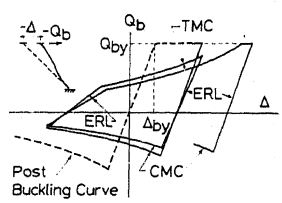
Fig. 10 Consideration of Strain Rate.

Table. 5 Summary of Results of Tests and Analysis.

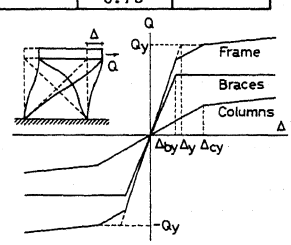
SPECIMEN NAME	TEST		ANALYSIS		COMPARISON	
	Δmax(A) (mm)	Δmin(B) (mm)	Δmax(C) (mm)	Δmin(D) (mm)	(C)/(A)	(D)/(B)
PF 40D	0.37	-3.71	0.48	-4.86	1.30	1.31
PF 80D	2.93	-2.53	1.07	-5.12	0.37	2.02
PF120D	4.70	-2.69	6.00	-5.05	1.28	1.88
BF 40D	0.18	-1.26	0.14	-1.31	0.78	1.04
BF 80D		-8.81		-11.79		1.34
BF120D	3.42		2.68		0.78	



(a) Bi-linear Model for Columns



(b) Hysteretic Rule of a Brace



(c) Superposition of Restoring-Forces

Fig. 11 Formulation of Hysteretic Restoring-Force Characteristics.

value calculated from the analysis on the basis of the yield stress obtained from the static tensile test of material, taking the effect of the varying strain rate at every moment in the shaking table test into consideration, as shown in Fig. 10. The second slope of the bi-linear model of the restoring-force characteristics of columns was determined from the average slope in the corresponding static test and in a cosideration of the P-Δ effect.

DYNAMIC RESPONSE ANALYSIS AND COMPARISON WITH TEST RESULTS

Dynamic response analysis was made regarding the model of one mass elastic-plastic system. A bi-linear model shown in Fig. 11(a) was used for the restoring-force characteristics of columns. For the hysteretic rules of a brace, formulated curves shown in Fig. 11(b) schematically which were based on the previously formulated equations by the authors[7] were used. They are composed of straight lines corresponding to elastic recovery(ERL) and tension and compression mechanism curves(TMC and CMC).

Governing differential equation of motion of the structure was solved by means of a linear acceleration method. The results are shown in Figs. 7(a) - 7(f). The time history of the acceleration response of a roof are predicted by the response analysis in a sufficient accuracy for all of the tested frames, as observed in comparison of Figs. 6(a) - 6(f) with Figs. 7(a) - 7(f), respectively. On the other hand, difference in the maximum values of story-drifts of the experimental results and those of the analytical results are comparatively large. Maximum story-drifts predicted by the response analysis are compared with those observed in the tests in Table 5. In the analysis, it is difficult to predict accurately the in-elastic flow in a story-drift of a specimen in the plastic region of hysteretic characteristics, using a simple model such as a bi-linear model, because a slight difference in the amplitude of an input excitation and a slight difference in the second slope induce a serious difference in the magnitude of a plastic deformation response. The time history of a story-drift response obtained from the analysis does not fall completely on the experimental results and tends to separate from the experimental curve due to the difference in a plastic flow in a story-drift. This tendency is larger in the case of pure frames than braced frames in which braces are more effective against an external excitation and the hysteretic restoring-force characteristics of braces were formulated tracing the experimental results exactly. It would be needed to analyze the response behavior of the pure frames using more accurate hysteretic rule for columns which could represent the subtle behavior in the in-elastic range.

CONCLUSIONS

On the basis of the experimental and analytical results, the following remarks can be drawn.

1) Dynamic elastic-plastic behaviors of steel pure frames and braced frames were experimentally followed well in the satisfactory performance of a shaking table, test apparatus and measuring instruments till a model failed.

2) It is needed to pay a careful consideration for a strain rate effect on the load carrying capacity in the formulation of hysteretic restoring-force characteristics which could be applied to the response analysis to well predict the load carrying capacity and the dynamic response behavior of the

models in dynamic tests.
3) The time history of the acceleration response of the model are well predicted by the response analysis.
4) The time history of the response for s story-drift obtained from the response analysis does not fall perfectly on the experimental results and tends to separate from the experimental curve by the difference in a plastic flow in a story-drift.

ACNOWLEDGEMENT

This research was financially supported by the Grant in Aid for Scientific Research of the Ministry of Education, Japan, for the project No. 202018, 1977 by Prof. M. Wakabayashi as a project manager. The authors express their gratitudes to Prof. M. Wakabayashi, Director of Disaster Prevention Research Institute, Kyoto University, for his leading and valuable suggestion, and wish to thank Prof. R. Minai and Mr. N. Ichikawa, Disaster Prevention Research Institute, for cooperation to use the shaking table, and Prof. T. Fujiwara, Disaster Prevention Research Institute and Mr. T. Kamada, Research Associate of Department of Architecture, Kyoto University, for offering of digital and analog records of the earthquake and for valuable discussion on a response analysis.

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