SHAKING TABLE TESTS OF A THREE-STORY SINGLE-BAY STEEL FRAME MODEL

by

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SYNOPSIS

A three-story single-bay steel frame model was tested on the shaking table, which can generate simulated earthquake motions. And also numerical response analysis was carried out based on the mathematical formulation of restoring force characteristics considering Bauschinger effect and strain-hardening peculiar to steel material. The predicted responses fairly agree with the measured responses.

INTRODUCTION

It is widely held as design phylosophy that buildings may suffer damage from inelastic deformations to some extent but they must avoid failure during a major earthquake. In past decades, with the availability of efficient computation algorithm, it becomes possible to predict inelastic seismic response of a complicated structure once its analytical model is determined. And also large amounts of experimental and analytical works on structural components have been made and currently it becomes possible to formulate a mathematical model of structure. In order to corroborate the validity of these mathematical models, the comparison with more realistic behavior simulated by shaking table tests is indispensable [1,2,3].

This paper describes an outline of a shaking table test, which has been carried out in order to investigate global inelastic responses of a 3-story 1-bay moment-resistant steel frame model during earthquakes. The study has been made with the availability of the electro-hydraulic shaking table(1.5m×2.0m, maximum driven capacity: 4.7ton-g, maximum weight: 5.0ton), equipped in the Chiba Experiment Station, the Institute of Industrial Science, University of Tokyo. The table is supported by hydraulic floating system and the table acceleration is also chosen as one of the control parameters for feed back system.

TEST STRUCTURE AND TEST PROCEDURE

The test structure is composed of two parallel three-story single-bay moment-resistant frames, about one-tenth scale model, shown in Fig.1. The aim of experimental study with these scale models seems to be more reasonable to investigate only fundamental inelastic responses than to examine more complicated phenomena such as the buckling in inelastic range or the influence of connections. Therefore it is not necessary to make precise miniature models of actual buildings, and members of rectangular-section are used in this study. Dimmensions of sections used are summarized in Table 1, and also section properties such as the elastic-limit moment and

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the full-plastic moment calculated from the yield stress observed in coupon tests are shown in Table 1.

The strength and the stiffness of girders are much greater than those of columns and the test structure can be regarded as a weak-column frame model and as so-called shear type. The sizes of column-sections in the upper stories are smaller than in the first story aiming at the vertical story shear strength distribution recommended in the Enforcement Order of Building Standard Law of Japan, as shown in Fig.2.

The two parallel frames were tied at the column-top of each story by rolled-angle beams through shear bolted connections in both flange planes, and considerable amounts of steel plates were added to the rolled-angle beams. The measured weights of steel plates and other structural components were almost the same value in each story, 0.586 tons. Horizontal absolute accelerations in the direction of the table motion were measured on all floors and the table, and also relative displacements between floors were measured as shown in Fig.1.

In this study the N-S component of Imperial Valley Earthquake recorded at El Centro in 1940 was chosen for input exitation. The acceleration record with the duration of 10.24 sec including major parts of El Centro NS exitation was condensed in time scale to have the duration of 5.12 sec, for the natural period of the test structure was 0.42 sec and rather small for the natural period of actual 3-story steel moment-resistant frames. First in the test procedure a resonance vibration test by sinsoidal exitation was carried out in elastic range. Then earthquake simulating tests were carried out using moderate magnitudes of input exitation, so that the test structure remained within elastic range. After these tests greater amplitude of exitation was put in and inelastic deformation was observed in the 1st and the 2nd story columns. The extreme values of global responses in the elastic and the inelastic tests are summarized in Table 2. The table acceleration records observed in the two tests are shown in Fig.3, normalized by the maximum amplitude, and compared with the original wave shape. It seems totally that the simulated earthquakes match with the original one.

RESONANCE VIBRATION TEST RESULTS

In the resonance vibration test sinsoidal waves of various frequencies were put in. Observed floor acceleration records seem to be sinsoidal waves of the aimed frequencies. On the other hand the table acceleration records are apt to include considerable amounts of noizes with different frequencies from the aimed ones, especially near the resonance points. Then the method of finite Fourier approximation was applied to all the records in data processing, and only the Fourier components of the aimed frequency were separated in order to calculate acceleration magnification factors. These magnifination factors are plotted to the frequencies and they form an experimental resonance curve as shown in Fig.4. Natural frequencies, participation vectors, and modal damping factors derived from the experimental results are summarized in Table 3.

ELASTIC RESPONSE TO SIMULATED EARTHQUAKE

In this chapter measured elastic responses of floor accelerations and relative floor displacements to the table are compared with computed results. The structural system was modelled as three-degree of freedom lamped-mass system, in which masses were linked by shear-type elastic springs. Only the flexural deformation of the columns was considered in the estimation of each story stiffness. As for the damping mechanism, three different assumptions were made as follows:

1) Internal viscous damping

$$[C] = \beta\ [K]$$

where [C]: damping matrix
[K]: elastic stiffness matrix

2) External viscous damping

$$[C] = \alpha\ [M]$$

where [M]: mass matrix

3) Rayleigh damping

$$[C] = \alpha\ [M] + \beta\ [K], \quad h_1 = h_2$$

where h_i : i-th modal damping factor

Over the three assumptions the constants, α and β, were determined so that the modal damping factor of the fundamental mode were set to the same value, 0.5% of critical damping. The measured and the computed time histories of the third floor acceleration and the displacement are shown in Fig.5. The difference in the assumptions of damping mechanism makes no fatal errors in the prediction of global responses so far as the fundamental damping factor is appropriately estimated. This implies that the fundamental mode vibration was very dominant in the experiment.

INELASTIC RESPONSE TO SIMULATED EARTHQUAKE

The fundamental problem in inelastic response analysis is how to formulate the mathematical model of restoring force characteristics. In this study the direct modelling of relationship between story resistances and inter-story displacements was chosen in order to explain the test results. After some trials the simple hysteretic law was determined as follows:

1) The relationship between structural resistance of i-th story Q_{fi} and i-th inter-story displacement δ_i is modelled as bilinear hysteresis so far as δ_i does not exceed δ_{Bi} shown in Fig.6.
2) Once δ_i reaches to δ_{Bi} the hysteretic law is modified into tri-linear hysteresis as shown in Fig.6, considering Bauschinger effect. In Fig.6 the yield strength Q_{Yi} is estimated as the value of $1.1 \cdot 4 \cdot 2M_{pi}/l_i$, where M_{pi} denotes the full-plastic moment of the i-th story column and l_i denotes the i-th column length ignoring the size of fillet-welds in the both ends. Parameters γ_1 and γ_2 in Fig.6 are set to 0.3 and 0.03, respectively.
3) To gain the overall resistance of i-th story Q_i, the decrement due to P-Δ effect $Q_{P-\Delta i}$ is considered besides the structural resistance Q_{fi}. $Q_{P-\Delta i}$ can be estimated as:

$$Q_{P-\Delta i} = -\left\{ \sum_{j=i}^{3} W_j \,/\, l_i \right\} \delta_i$$

where W_j : weight of j-th floor

In the response analysis the equation of motion in incremental form was integrated using the linear acceleration method. As for damping mechanism the assumption of Rayleigh damping and $h_1=h_2=0.015$ were used. The comparison between the measured and the computed response is shown in Fig.7 and Fig.8. The predictions seem to match the measured responses with sufficient accuracy.

CONCLUDING REMARKS

1) The shaking table test provides an effective means for studying the inelastic behavior during earthquakes, and especially makes it possible to verify the formulation of mathematical model for inelastic behavior of structural systems.
2) The resonance vibration test provides an effective means to estimate the dynamic properties of test structures in elastic range.
3) The modified tri-linear hysteresis illustrated herein, in which Bauschinger effect and strain hardening are considered, provides a good prediction of the inelastic response of moment-resistant steel frame models.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the Ministry of Education, Japanese Government, Grant in Aid for Scientific Research, No.00555220, which made this work possible. Also the authors would like to express their appreciation to Dr. H.Taniguchi, Mr. Y. Shimawaki, Mr. H.Kondo, and Mr. T.Kohno for their supports during this study.

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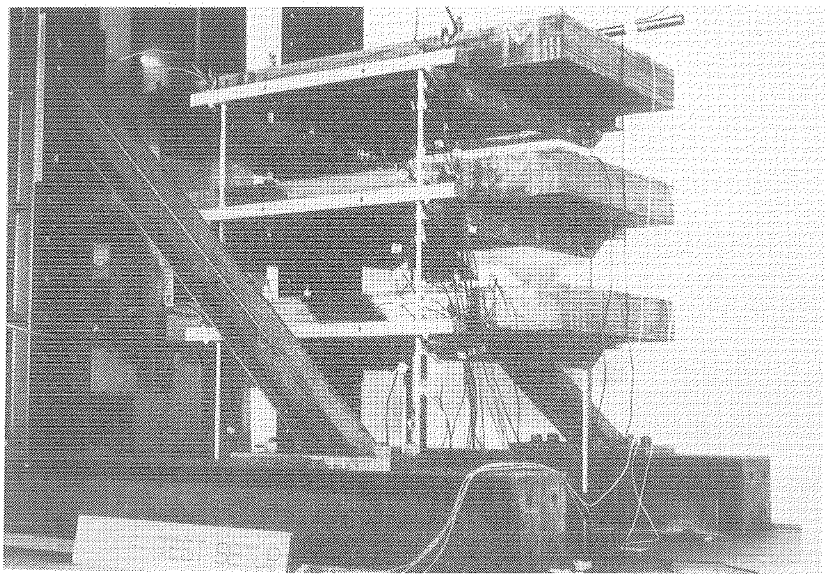


Photo. 1 Test Structure on Shaking Table

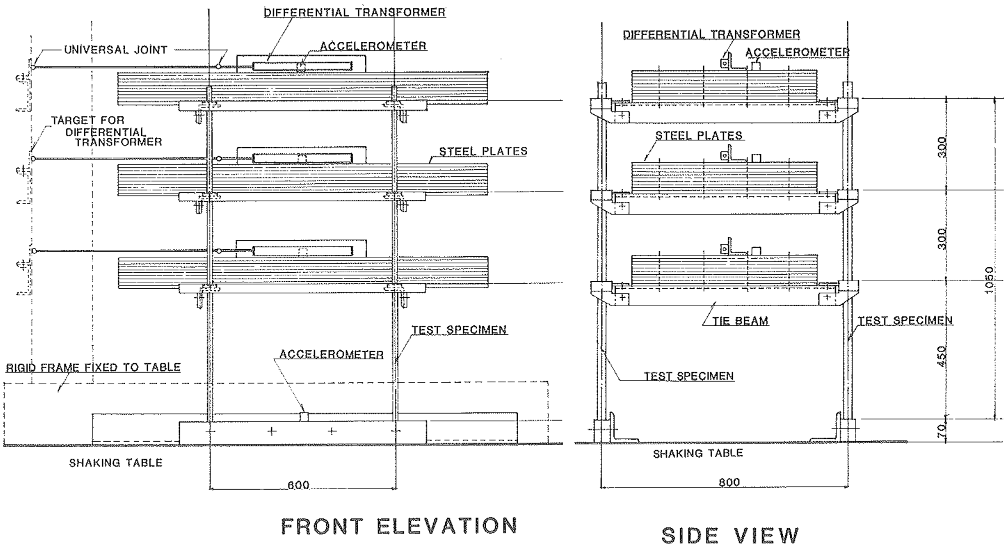


Fig.1 Front Elevation and Side View

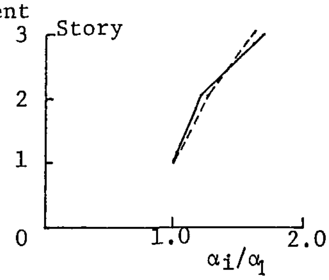
Table 1 Properties of Sections Used

LOCATION	1ST STORY COLUMN	2ND STORY COLUMN	3RD STORY COLUMN	GIRDER	FOOTING GIRDER
CROSS-SECTION	3.0 1.2 Bending	1.5 1.2	1.1 1.2	6.0 3.2	5.0 7.0
bxd (cm)	3.0x1.2	1.5x1.2	1.1x1.2	6.0x3.2	5.0x7.0
M_Y (t·cm)	1.99	1.00	0.73	21.9	87.4
M_P (t·cm)	2.99	1.50	1.10	32.9	131.1
P/P_Y	0.044	0.059	0.040	—	—

P/P_Y : Ratio of Existing Axial Force to Full-Plastic Axial Force
M_Y : Elastic-Limit Moment M_P : Full-Plastic Moment

Table 2 Measured Extreme Values

		Elastic Test		Inelastic Test	
Table Acc.(gal)		61	-68	530	-518
Absolute Acc.(gal)	1FL	194	-202	457	-495
	2FL	252	-262	488	-483
	3FL	251	-263	600	-585
Relative Disp.(cm)	1FL	0.78	-0.76	1.75	-2.88
	2FL	1.06	-1.05	2.48	-3.58
	3FL	1.25	-1.20.	2.77	-3.73



---- Recommended
—— Test Structure

α_i:Yield Story Shear Coefficient of i-th Story

Fig. 2

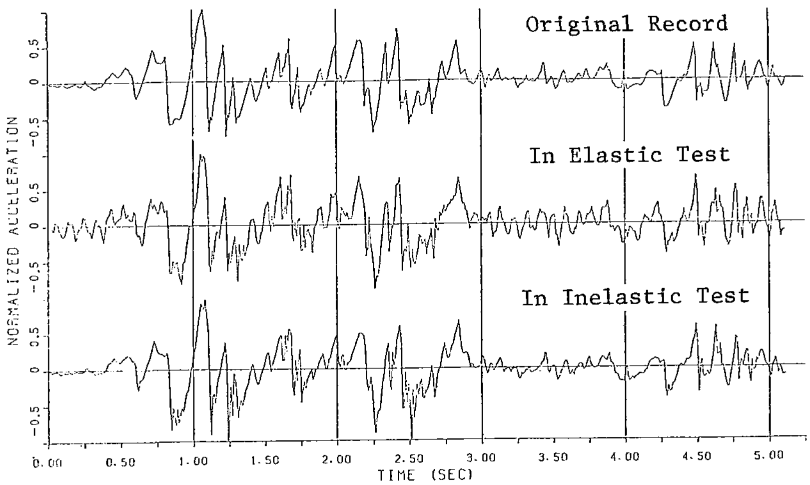


Fig. 3 Measured Table Accelerations Normalized by Maximum Amplitudes

Table 3 Summary of Resonance Vibration Test

Mode		1st	2nd	3rd
Natural Frequency (Hz)		2.39	7.11	11.6
Modal Damping Factor		.0082	.0036	.0015
Partici-pation Factor	1FL	.717	.202	.055
	2FL	.980	.080	-.074
	3FL	1.188	-.197	.028

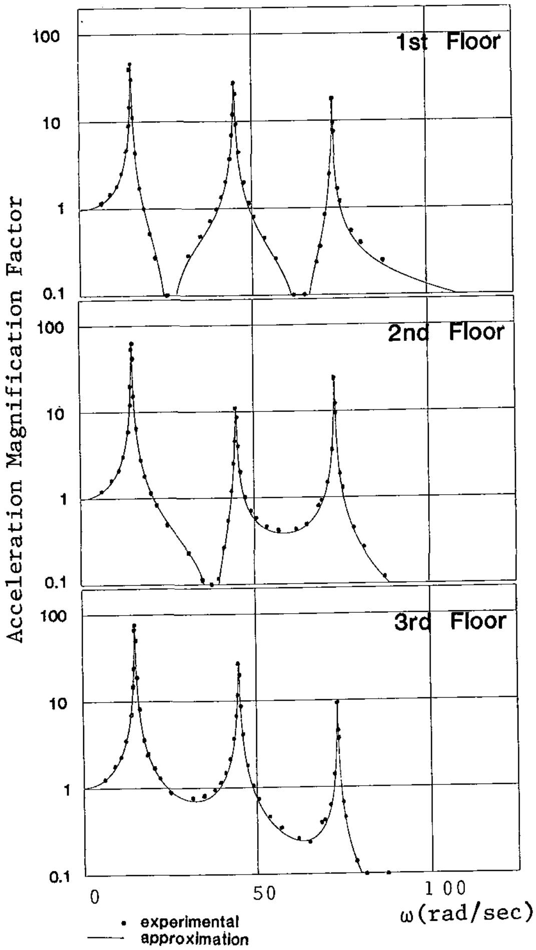


Fig. 4
Resonance Curves

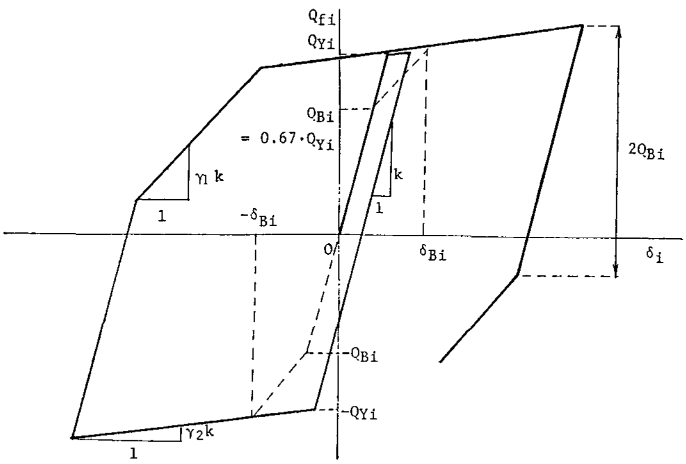


Fig. 6 Formulation of Restoring Force Characteristics

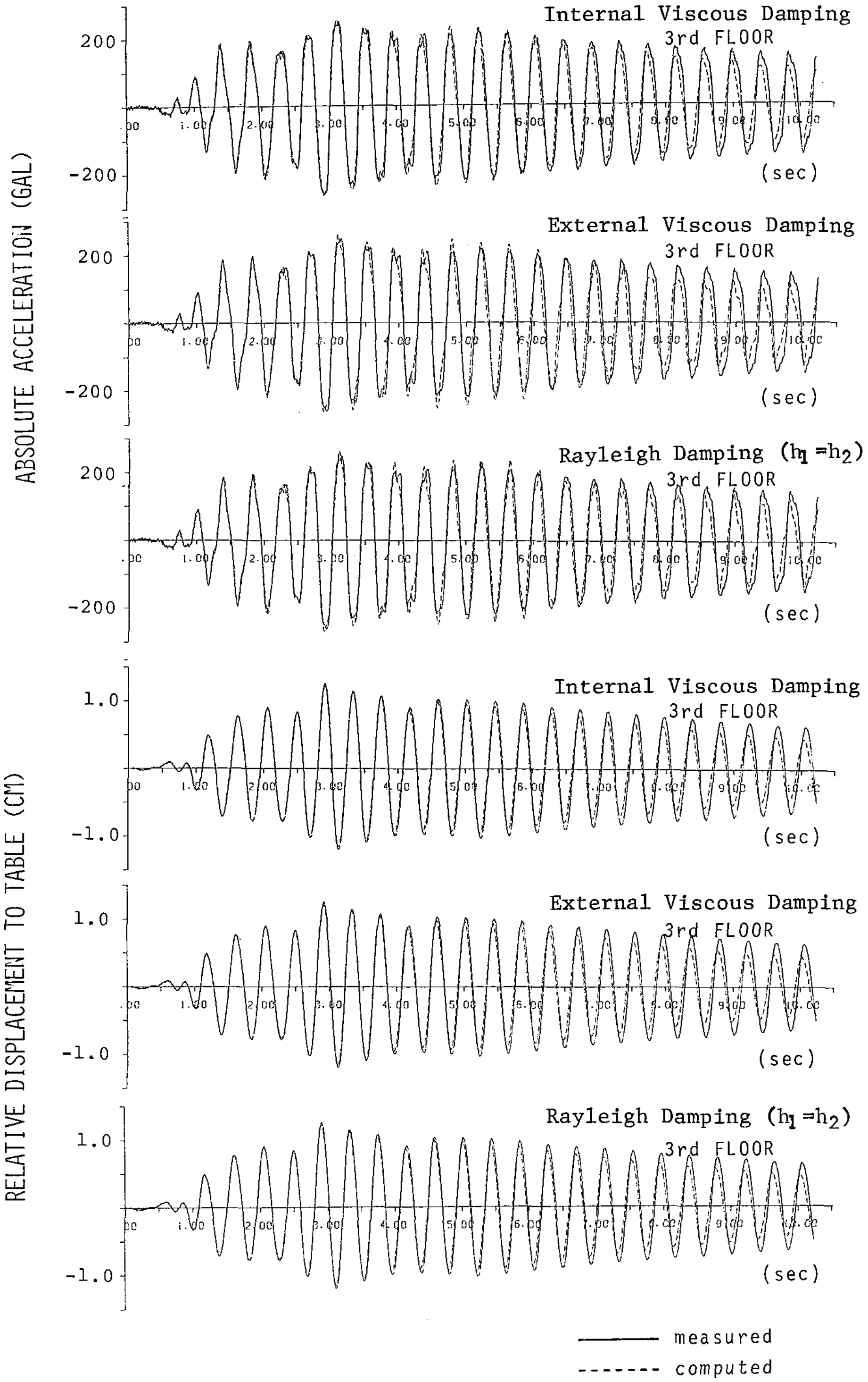


Fig. 5 Measured and Computed Elastic Responses to Simulated Earthquake

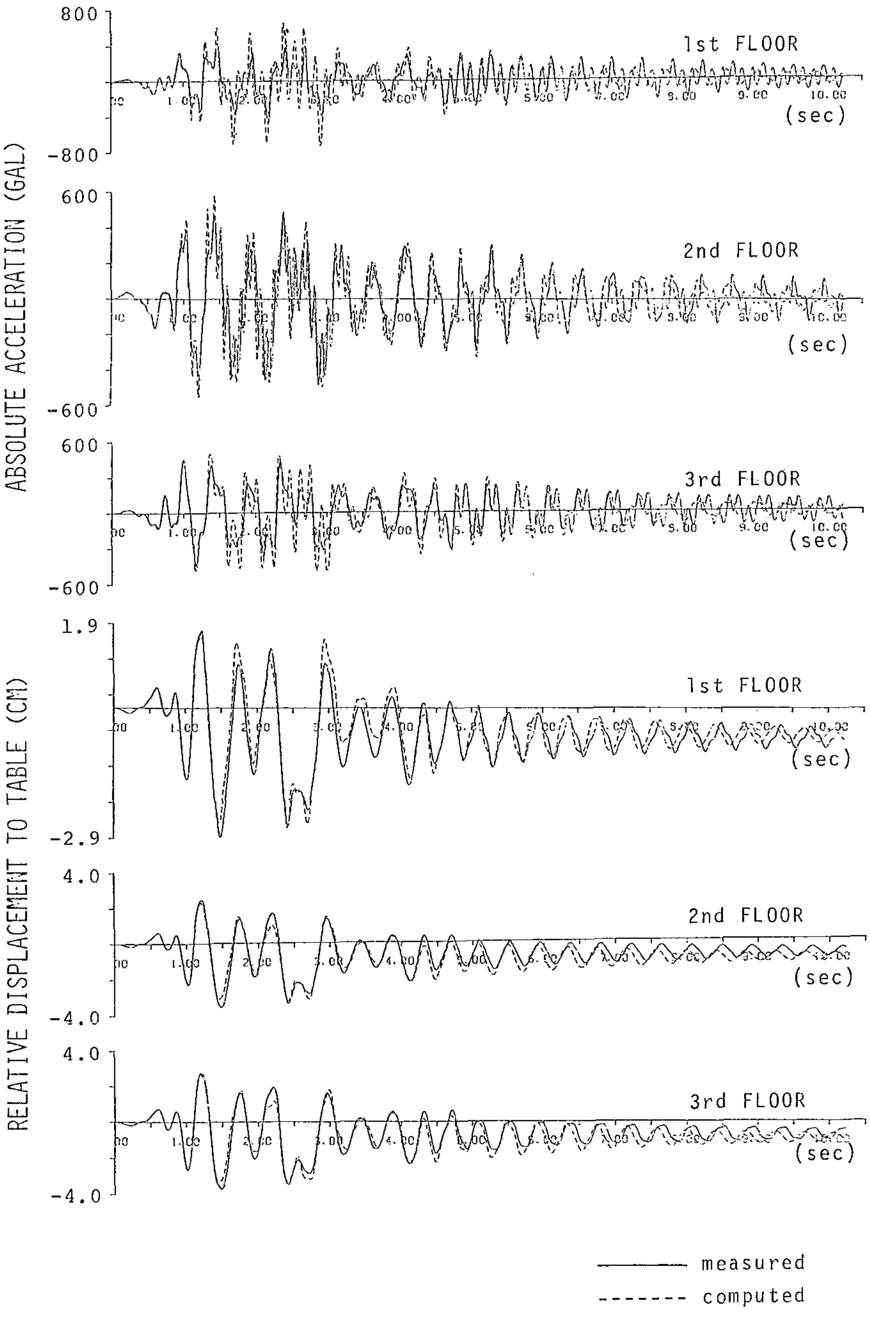
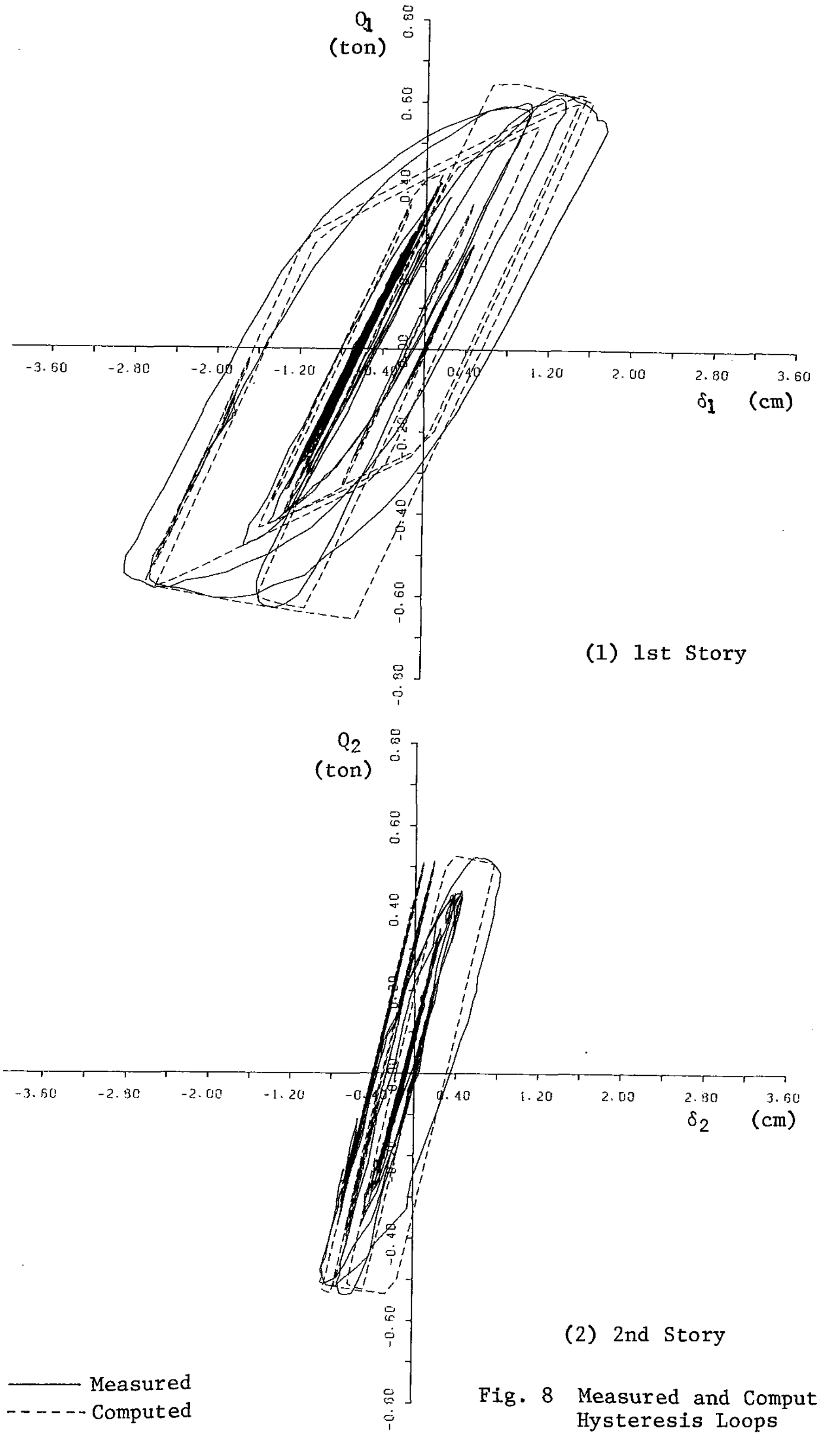


Fig. 7 Measured and Computed Inelastic Responses to Simulated Earthquake



(1) 1st Story

(2) 2nd Story

Fig. 8 Measured and Computed Hysteresis Loops