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DYNAMIC RESPONSE OF STRUCTURES SUBJECTED TO MULTIPLE EXCITATIONS

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SUMMARY

In this paper, the results of experimental and analytical studies, which were carried out to investigate fundamental properties on elastic and elasto-plastic responses of the steel and reinforced concrete structures subjected to multiple earthquake excitations, are presented. The single-story portal framed models were tested by using two one-way shaking tables. The framed model has either two steel or reinforced concrete columns connected by the steel beams and they are standing on the different shaking tables. The test results were evaluated by the system identification method, and the validity of the mathematical models was verified by comparing the test results with the analytical results.

INTRODUCTION

The purpose of this study is to develop an aseismic design method for large scaled structures spanning over highways, railways or rivers. Consequently, these structures would become framed structures with long span, and thus input earthquake excitations to each basement of structures may be variable depending on the ground and geographical conditions. Therefore, it is required to consider multiple earthquake excitations with different wave forms for the aseismic design.

In this study, the shaking table tests were performed on the portal framed models to investigate the basic response characteristics of the steel and reinforced concrete structures subjected to mutiple excitations.

One of the important purposes in the shaking table test is to verify validity and generality of analytical models for dynamic systems. In this paper, the validity of the analytical model for the simple mass-spring systems subjected to the multiple excitations was examined according to the following procedure.

1) Experiment : The steel and reinforced concrete portal framed models of single story were tested by using two one-way shaking tables. In this test, the size of cross section for the steel columns and the failure mode of the reinforced concrete columns were varied.
2) Mathematical Model and Identification of Prameters : The systems subjected to multiple excitations were modeled into the mass-spring systems. The unknown parameters of the systems were identified by substituting the measured quantities such as accelerations, velocities and displacements into the corresponding equation of motion.
3) Comparison between Analytical and Test Results : The analytical results calculated by using the identified parameters were compared with the test results. The validity of analytical models for the structures subjected to

multiple excitations was verified through the comparison between the analytical and test results.

ANALYTICAL MODEL FOR HYPOTHETIC STRUCTURE

The structures examined are the simplified mass-spring systems as shown in Fig.1. The equation of motion for this model is given as follow:

$$\begin{bmatrix} m_1 & \\ & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix}+\begin{bmatrix} c_1 & \\ & c_2 \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix}+\begin{bmatrix} k_1 & \\ & k_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix}+\begin{bmatrix} c_{12} & \\ & -c_{12} \end{bmatrix}\begin{Bmatrix} \dot{x}_{12} \\ \dot{x}_{12} \end{Bmatrix}+\begin{bmatrix} k_{12} & \\ & -k_{12} \end{bmatrix}\begin{Bmatrix} x_{12} \\ x_{12} \end{Bmatrix}=-\begin{bmatrix} m_1 & \\ & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \end{Bmatrix} \qquad (1)$$

$$x_{12}=\{(x_1+y_1)-(x_2+y_2)\}$$

EXPERIMENTS

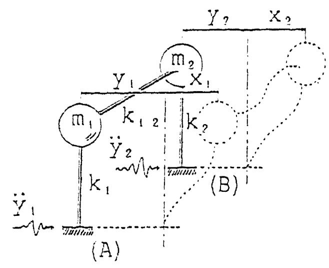


Fig. 1 Analitycal Model

The multiple shaking tables test system shown in Fig.2-1 is able to reproduce either independently the identical or different ground motions to each table simultaneously. The portal framed models are composed of either two steel or two reinforced concrete supporting columns connected by two steel beams and two steel mass weights are attached on the top of columns, as shown in Fig.2-2. The two supporting columns were fixed to two different shaking tables (V1 and V2). The connecting beams with H-shaped cross section were designed so as to keep their response in the elastic range. The two mass weights were provided with pantographs which are the devices to make the specimens shake horizontally.

Thus, the specimens can be considered to be the two-degrees-of-freedom systems subjected to multiple excitations. Now, as the preliminary test, the static loading and shaking tests of single-degree-of-freedom systems (SDOF) were performed for each specimen without connecting beams.

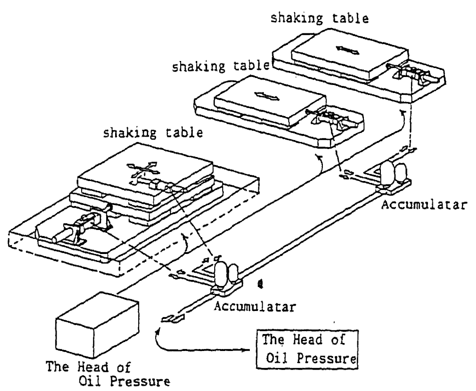


Fig.2-1 Multiple shaking tables test system

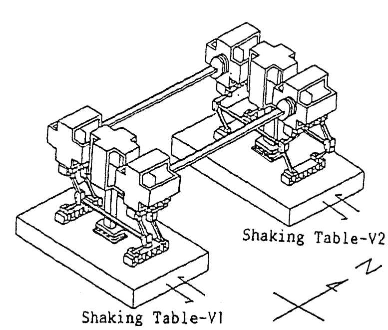


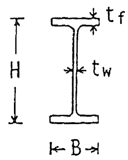
Fig.2-2 Test setup

<u>Test Specimens and Materials</u> The dimensions of the steel columns and the connecting beams with H-shaped cross section are listed in Table 1. The configuration and bar arrangement of the reinforced concrete columns are shown in Fig.3 and their structural variables are listed in Table 2. They were designed so as to fail in two different modes; that is, flexural failure or shear failure mode. The mechanical properties of concrete and reinforcing bars are listed in Table 3. Table 4 indicates the type of test specimens and input earthquake waves.

In this study, two shaking tables are operated under the same ground motions,

Table 1 Dimension steel columns and connecting beams

Specimen	Wide Flange Shape				Length
	H	B	t_w	t_f	
Column-A	30.1	30.0	3.00	3.00	640.0
Column-B	37.3	37.3	3.00	3.00	640.0
Beam-I	100.0	50.0	5.00	7.00	1340.0
Beam-II	100.0	100.0	6.00	8.00	1800.0



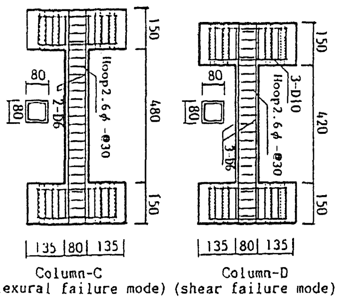


Fig. 3 Configuration and bar arrangement of the R/C columns

Table 2 Structural Variables of the R/C columns

	Main bar		Hoop		Shear-span ratio
	n-φ	Pg(%)	φ-@S(mm)	Pw(%)	M/QD
Column-C(flexural failure mode)	4-D6	2.00	2.6φ-@30	0.442	3.0
Column-D(shear failure mode)	6-D6	3.00	2.6φ-@30	0.442	2.6

Table 3-a Concrete

	Compressive strength (kg/cm^2)	Tensile strength (kg/cm^2)
Mean	276	27.0

Table 3-b Reinforcing Bars

Type	Yield strength (kg/cm^2)	Maximum strength (kg/cm^2)
D6	3438	5510
4φ	3779	4447
2.6φ	——	2656
2.0φ	——	2483

Table 4 List of Test Specimens and Input Earthquake waves

Test Specimen	Loading method	Description
SSA	static	Specimen;Column-A(steel) weight:2230 kg
SSB	static	Specimen;Column-B(steel) weight:2230 kg
SCF	static	Specimen;Column-C(R.C. flexural failure mode) weight:2230 kg
SCS	static	Specimen;Column-D(R.C. shear failure mode) weight:2230 kg
SDCF	SDOF	Specimen;Column-C(R.C. flexural failure mode) weight:2230 kg, Input II
SDCS	SDOF	Specimen;Column-D(R.C. shear failure mode) weight:2230 kg, Input II
MDS	Multiple excitations	Specimen;V1-Column-A(steel),Side near epicenter V2-Column-B(steel),Side far from epicenter weight:2230 kg×2 Connecting beam-I,Input I,Time lag 0.08sec
MDICF	Multiple excitations	Specimen;V1-Column-C(R.C.),Side near epicenter V2-Column-C(R.C.),Side far from epicenter weight:2230 kg×2 Connecting beam-II,Input II,Time lag 0.033sec
MDICS	Multiple excitations	Specimen;V1-Column-D(R.C.),Side near epicenter V2-Column-D(R.C.),Side far from epicenter weight:2230 kg×2 Connecting beam-II,Input II,Time lag 0.033sec

Input Waves: Input I = Tokachi-oki Earthquake,Hachinohe(1968,N-S)
Maximum acceleration 168.75 gal
Input II = Imperial Valley Earthquake,El-Centro(1940,N-S)
Maximum acceleration 100.0 gal and 683.4 gal
Table time is one-third of the real earthquake time.

where the time lag between the ground motions is adjusted according to the test requirement. For the test specimens composed of reinforced concrete columns, the assigned maximum acceleration are 100 gal for the elastic-level-test, in which columns remain elastic, and 683.4 gal for the plastic-level-test, in which columns experience the plastic range. Furthermore, it must be noted that the shaking tables shall be operated at the faster speed than the original speed according to the similitude law listed in Table 4.

EVALUATION OF TEST RESULTS

Parameters of System Identification Method The absolute accelerations of each mass ($\ddot{X}_{ij}+\ddot{Y}_{ij}$), the relative displacements of each member (X_{ij}), and the shear forces of connecting beams ($Q_{12j}=C_{12}\dot{X}_{12j}+K_{12}X_{12j}$) were measured by the shaking table tests. The velocity ($\dot{X}_{ij}$) was calculated by differentiating the relative displacement. Since the masses are known , the unknown parameters in the equation of motion (Eq.1) are only the coefficients of viscous damping, C, and the elasto-plastic stiffnesses of each members, K. Now, assuming that the connecting beams behave in elastic range, the stiffness K_{12} and the coefficient of viscous damping C_{12} can be identified by using the recursive least square method from the relative displacement between two masses (m_1 and m_2 in Fig.1), X_{12} and the measured shear force of connecting beams.

Modeling of Restoring Force Characteristics When the elasto-plastic resposes of structures are analyzed by the mathematical model, an appropriate model for restoring force characteristics must be assumed for each structural member. In this study, the models were constructed from the hysteretic curves obtained by the static loading test for each member according to the following procedures. The procedures are described using SCF (R/C column-C) as an example.

1)To simplify the load-deformation curve obtained by the static loading test, as shown Fig.4, to a hysteresis model having a trilinear skeleton curve, it is assumed that such curve can be represented by a combination of simple hysteresis models having bilinear skeleton curve (see Fig.7).

2)The bilinear type model was determined so that the area of the stationary loop of the static test became equal to the loop area of the bilinear type model (Fig.5a).

3)The other models to be superimposed on the bilinear type model were determined from the residual loop configuration after removing the bilinear type model from the stationary loop and virgin loop.

4)From the shape of the curves obtained in 2) and 3), the hysteresis models except the bilinear type model were determined as a combination of the peak oriented bilinear type model and the slip model. The shapes of the stationary loop and the virgin loop synthesized from the peak oriented bilinear type and slip models are shown in Fig.6. The shapes of these model loops duplicate well the test results as shown in Fig.5.

From the above study, it was decided that the model of restoring force characteristics for the specimen SCF could be represented by the combination of three hysteresis models as shown in Fig.7. The models of restoring force characteristic for other members were also constructed according to the similar procedures.

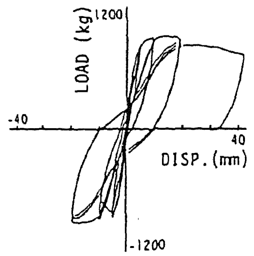


Fig. 4 Load-deformation Curve (SCF)

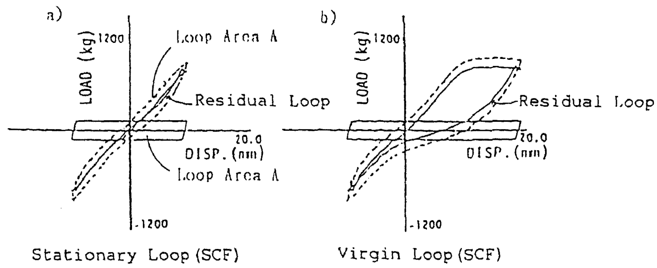


Fig. 5 Stationary Loop (a) and Virgin Loop (b), (SCF)

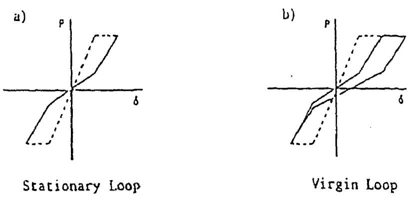


Fig. 6 Residual Loop

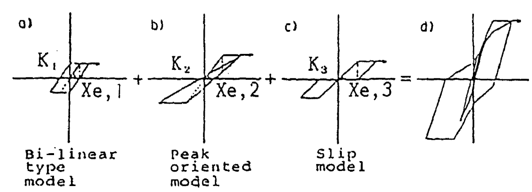


Fig. 7 Model of Restoring Force Characteristics(SCF)

Parameter Identification by Nonlinear Least Square Method To identify four parameters ; that is, the coefficient of viscous damping C and the elastic stiffnesses of the restoring force characteristics models k_1, k_2 and k_3, the nonlinear least square method (Levenbarg-Marquardt-Morrison procedure(Ref.2)) was applied. Among the factors of the restoring force characteristics model, the bilinear factor and the deformation of each singular point were selected to be known from the results of the static loading test. Each parameter was corrected every mass point by using the shearing forces employed as the error function so that the sum of the squares of errors (S_i) becomes the least, as given by the following equation:

$$S_i = \sum_{j=1}^{n} \{m_1(\ddot{X}_{ij}+\ddot{Y}_{ij})+Q_{12j}-k_1(X_{ij})+C_i(\dot{X}_{ij})\}^2 \qquad (2)$$

where,

i	:	mass point
j	:	number of steps
$m_i(\ddot{X}_{ij}+\ddot{Y}_{ij})$	:	inertia force obtained from the test
Q_{12j}	:	shearing force of the beam obtained from the test
$K_i(X_{ij})$	:	restoring force obtained from the model
$C_i(\dot{X}_{ij})$	:	damping force obtained from the model

The above equation is the equation for the mass point 1, and $+Q_{12j}$ becomes $-Q_{12j}$ for the mass point 2.

COMPARISON BETWEEN TEST AND ANALYTICAL RESULTS

The results of parameter identification for SDCF and MD1CF whose columns are similar to SCF are summarized in Table 5. The numerical simulation was performed on SDCF and MD1CF using these parameters.

Figures 8 and 9 show the response hysteresis curve and the time history of response displacement for SDCF, and Figures 10 and 11 show those for MD1CF. The numerical simulation was also performed for other specimens in similar ways, and their response hysteresis curves are compared with the test results as shown in Fig.12. Table 6 shows the maximum response values of experimental and analytical results. Note that the time history of accelerations of the shaking table measured by the test were used as the analytical input excitation.

In SDCF and MD1CF, as shown in Figures 8 through 11, although there are some differences between the time histories of response displacements for analytical and test results, the response hysteresis curves of the analysis simulate the test results wells.

Analytical results of MDS with steel columns agree with the test results very well. The simulated response hysteresis curves of the other specimens also agree with the test results (Fig.12).

In the elastic level test, little difference in maximum response displacements even under the different conditions of excitations was observed between the SDOF system and the multiple excitation systems. In the plastic level test, the maximum response displacements of MD1CF and MD1CS were larger on the side far from epicenter than those on the side near epicenter.

Table 5 Results of Identification

Specimen	SDCF	MD1CF V1 side	MD1CF V2 side
C (kg·sec/cm)	2.381	2.521	4.733
K_1 (kg/cm)	820.8	371.8	351.2
K_2 (kg/cm)	1152.4	1507.8	1014.4
K_3 (kg/cm)	288.1	301.5	253.7
		C_{12}=0.910 (kg·sec/cm) K_{12}=189.9 (kg/cm)	

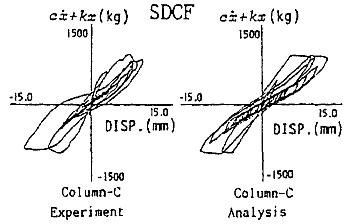


Fig. 8 Response Hysteresis Curve

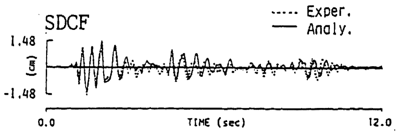


Fig. 9 Time History of Response Displacement

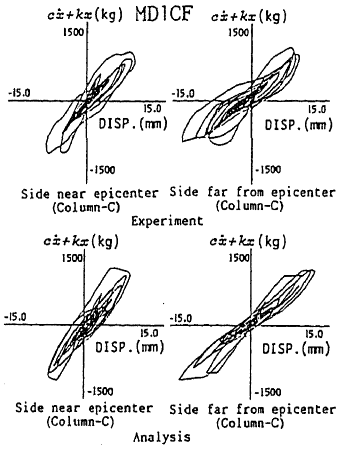


Fig. 10 Response Hysteresis Curve

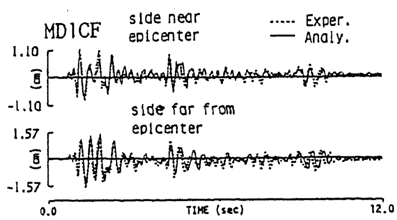


Fig. 11 Time History of Response Displacement

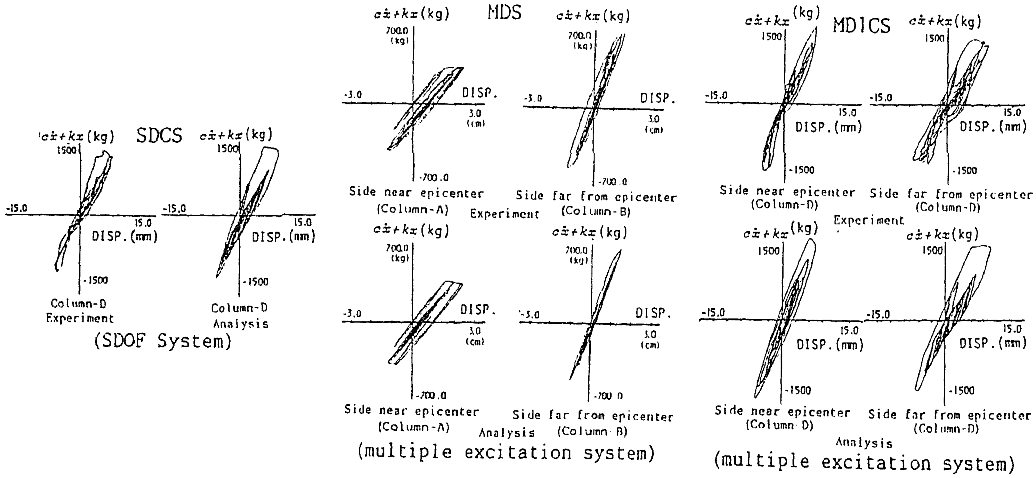


Fig. 12 Response Hysteresis Curve

CONCLUSION

The multiple shaking table tests were performed on the steel and reinforced concrete portal framed models, and the following conclusions were obtained;

1)The fundamental response properties of systems subjected to multiple excitations were clarified on the basis of the test results.

2)The validity of the adopted mathematical model was verified by comparing the test results with the analytical results calculated by using the identified parameters.

3)The adopted structural model was effective to investigate fundamental response properties of structures subjected to multiple earthquake excitations.

Table 6 Maximum Response Values

Specimen		ELASTIC		ELASTIC-PLASTIC		
		maximum shearing force (kg)	maximum displacement (mm)	maximum shearing force (kg)	maximum displacement(mm)	
					Experimental Value	Analytical Value
SDCF		339.1	0.92	1081.8	14.79	14.87
SDCS		303.6	0.91	1531.5	7.56	9.04
MDS	Column-A	——	——	447.45	2.39	2.39
	Column-B	——	——	731.42	1.46	1.43
MD1CF	Column-C	349.6	0.99	1132.9	11.05	11.30
	Column-C	341.0	1.00	1166.2	15.68	16.18
MD1CS	Column-D	326.1	0.70	1724.2	7.25	7.29
	Column-D	378.4	0.68	1475.3	9.52	10.33

Multiple excitation system : upper column = epicenter side

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