DYNAMIC RESPONSE OF STRUCTURES SUBJECTED TO MULTIPLE EXCITATIONS

Hiromi ADACHI¹, Shinji ISHIMARU², Mitsukazu NAKANISHI¹ and Takahiro NIYA²

¹ College of Science & Technology, Nihon University, Funabashi-shi, Chiba-ken, Japan
² College of Science & Technology, Nihon University, Chiyoda-ku, Tokyo, Japan

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 multiple 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 Parameters: 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:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\end{bmatrix} + \begin{bmatrix}
c_1 \\
c_2 \\
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} + \begin{bmatrix}
k_1 \\
k_2 \\
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} + \begin{bmatrix}
c_{12} \\
c_{22} \\
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} + \begin{bmatrix}
k_{12} \\
k_{22} \\
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} = \begin{bmatrix}
m_1 \\
m_2 \\
\end{bmatrix} \begin{bmatrix}
\ddot{y}_1 \\
\ddot{y}_2 \\
\end{bmatrix}
\]

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

EXPERIMENTS

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.

Test Specimens and Materials 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

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Wide Flange Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Column-A</td>
<td>30.1</td>
</tr>
<tr>
<td>Column-B</td>
<td>37.5</td>
</tr>
<tr>
<td>Beam-1</td>
<td>100.0</td>
</tr>
<tr>
<td>Beam-2</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 2 Structural Variables of the R/C columns

<table>
<thead>
<tr>
<th>Main Bar Hoop</th>
<th>Shear-span ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-g</td>
<td>P(f/k)</td>
</tr>
<tr>
<td>Column-C (flexural failure mode)</td>
<td>4–06</td>
</tr>
<tr>
<td>Column-D (shear failure mode)</td>
<td>6–06</td>
</tr>
</tbody>
</table>

Table 3-a Concrete

<table>
<thead>
<tr>
<th>Compressive strength (kg/cm²)</th>
<th>Tensile strength (kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>276</td>
</tr>
<tr>
<td></td>
<td>27.0</td>
</tr>
</tbody>
</table>

Table 3-b Reinforcing Bars

<table>
<thead>
<tr>
<th>Type</th>
<th>Yield strength (kg/cm²)</th>
<th>Maximum strength (kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>3439</td>
<td>5510</td>
</tr>
<tr>
<td>4#</td>
<td>3779</td>
<td>4447</td>
</tr>
<tr>
<td>2.66</td>
<td>—</td>
<td>2656</td>
</tr>
<tr>
<td>2.0#</td>
<td>—</td>
<td>2483</td>
</tr>
</tbody>
</table>

where the time lag between the ground motions is adjusted 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 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 (Xi,j, Yi,j), the relative displacements of each member (Xi,j), and the shear forces of connecting beams (Qi,j = C12Xi,j+1+K12Xi,j) were measured by the shaking table tests. The velocity (Xi,j) 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 elastic-plastic stiffnesses of each member, K. Now, assuming that the connecting beams behave in elastic range, the stiffness K12 and the coefficient of viscous damping C12 can be identified by using the recursive least square method from the relative displacement between two masses (m1 and m2 in Fig.1). X12 and the measured shear force of connecting beams.

V-211
Modeling of Restoring Force Characteristics When the elasto-plastic responses 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 (K/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 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.

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 (Levenberg-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:

V-212
\[ S_1 = \sum_{j=1}^{n} (m_i(\dot{x}_{ij} + \dot{y}_{ij}) + Q_{12} - k_1(x_{ij}) + C_1(\dot{x}_{ij}))^2 \]

where,

- \( i \) : mass point
- \( j \) : number of steps
- \( m_i(\dot{x}_{ij} + \dot{y}_{ij}) \) : inertia force obtained from the test
- \( Q_{12} \) : shearing force of the beam obtained from the test
- \( k_1(x_{ij}) \) : restoring force obtained from the model
- \( C_1(\dot{x}_{ij}) \) : damping force obtained from the model

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

**COMPARISON BETWEEN TEST AND ANALYTICAL RESULTS**

The results of parameter identification for SDCF and MDICF whose columns are similar to SCF are summarized in Table 5. The numerical simulation was performed on SDCF and MDICF 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 MDICF. 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 MDICF, 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 well.

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 MDICF and MDICS were larger on the side far from epicenter than those on the side near epicenter.
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.

ACKNOWLEDGMENTS

This is a part of the Commission Research Project on "Study for Practical Utilization of Track Space (Transportation-Polis: TRAPOLIS)" from the Japan Science Society supported by a grant under the Japan Shipbuilding Industry Foundation and has been promoted by the Research Institute of Science & Technology Nihon University since 1983. The authors express their gratitude to the Japan Science Society and the Japan Shipbuilding Industry Foundation and the affiliates of "the Research Committee of TRAPOLIS" established in the College of Science & Technology, Nihon University.

REFERENCES