Experimental errors in pseudodynamic test using conventional testing devices

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Abstract

The pseudodynamic test technique, used to simulate the seismic behavior of structural elements, usually has been related to the use of actuators controlled by servo valves. However, recently, new hardware devices have been developed like a hydraulic pump system that can adjust the rate of oil flow by using an inverter motor and a high-speed on-off valve. This equipment permit to use conventional hydraulic jacks by controlling their movements by means of external signal obtained from displacement transducers.

In this report an analysis of the experimental errors, occurred during the test using this new implementation of the pseudodynamic technique, is presented. It is shown that an appropriate implementation of the control program can reduce the undershooting errors. Some results of the test of reinforced concrete column under bi-directional input motion are compared with analytical results to verify the accuracy and applicability of the implemented procedure.

1 Introduction

The pseudodynamic test method combines the numerical techniques used in dynamic analysis of structures and experimental procedures of conventional static testing to evaluate the performance of structures subjected to earthquake loads. The structure or test specimen has to be modeled as a discrete mass system such that equations of motion are represented by second-order differential equations. The mass and viscous damping of the system are prescribed analytically. Then the equations of motion are solved by means of a direct integration scheme. The
computed displacements are imposed on the specimen by means of jacks or actuators, and the restoring forces are measured with load cell transducers and are used to compute the response in the next time step.

The pseudodynamic technique usually has been related to the use of actuators controlled by servo valves. However, recently new hardware devices that permit to use conventional equipment have been developed. The advantage of this new type of pseudodynamic test system is the maximum use of devices for conventional static tests that are available in many structural test laboratories.

In the present research, the pseudodynamic technique, using conventional devices to test non-planar specimens subjected to two directional input motions, was developed. Full-scale specimens were employed in order to avoid the problem of size effect when small size specimens are used. The specimens were reinforced columns. Problems encountered during the implementation and execution of the test are discussed as well as the experimental errors that affect the results. The experimental results are compared with analytical results, showing good agreement.

2 Pseudodynamic test system

2.1 Formulation for bi-directional input motion

The pseudodynamic test method implemented in this research is applicable, in general, to non-planar specimens. However, to facilitate the description, the specific application for reinforced concrete columns is presented. To study the behavior of reinforced concrete columns subjected to two directional input motions, cantilever type specimens are used. Therefore, the lumped model corresponds to a system of one mass with two horizontal degrees of freedom. Then the equations of motion can be represented by a family of second-order ordinary differential equations, which can be expressed in a matrix form as:

$$m\ddot{a} + c\dot{v} + r = f$$

where \(a\) and \(v\) are the acceleration and velocity vectors. The mass matrix and damping matrix are denoted by \(m\) and \(c\) respectively. The restoring force vector \(r\) is

$$r = kd = \begin{pmatrix} r_x \\ r_y \end{pmatrix}$$

where \(k\) and \(d\) are the stiffness matrix and the displacement vector respectively. In this case the stiffness matrix is not analytically prescribed since the restoring forces are measured experimentally.

The external input force vector \(f\) is given by:

$$f = - ma_g = - \begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix} \begin{pmatrix} a_{gx} \\ a_{gy} \end{pmatrix} = \begin{pmatrix} f_x \\ f_y \end{pmatrix}$$
where $a_g$ is the base acceleration or ground acceleration input.

These equations of motions, considering that the system has nonlinear behavior, can be most conveniently solved by a direct step-by-step integration method under any arbitrary external excitations. One of the most general integration methods in structural dynamics is the Newmark algorithm, which assumes that

$$m a_{i+1} + c v_{i+1} + r_{i+1} = f_{i+1}$$  \(4\)

$$v_{i+1} = v_i + \Delta t \left[ (1 - \gamma)a_i + \gamma a_{i+1} \right]$$  \(5\)

$$d_{i+1} = d_i + \Delta t v_i + \Delta t^2 \left[ \left( \frac{1}{2} - \beta \right) a_i + \beta a_i \right]$$  \(6\)

in which $a_{i-1}$, $v_{i-1}$, and $d_{i-1}$ are the acceleration, velocity, and displacement vectors, respectively, at time equal to $(i+1)\Delta t$; and $\beta$ and $\gamma$ are parameters selected by the user to achieve desirable stability and accuracy properties. In this research, $\beta$ was set as zero and $\gamma$ as 1/2, therefore the $a_{i-1}$ term, in Equation 6 disappears and the method becomes explicit. In Figure 1 the flow chart for the numerical algorithm is presented. The restoring force of the element is obtained directly from the load cells attached to the jacks.

![Figure 1: Numerical Integration scheme](image)
2.2 Implementation of the test method

In Figure 2, outline of the test setup is presented. Displacements or loads are applied to the specimen by means of hydraulic jacks. Jacks are driven by hydraulic pumps that use inverter motors that can adjust their frequencies making it possible to control the rate of oil flow and thus the ram speed of jacks. For loading process, pumps send oil to the pull or push chamber that is selected by a solenoid valve. The frequency of each motor is set in proportion to a voltage signal. In case of unloading, the oil is released from each chamber and this task is controlled by a high-speed on-off valve. The voltage signals, for loading and unloading processes, are sent from the controller that also receives the digital signal from the computer for control. The conversion of digital signal into analog signal, is performed by the controller. For this conversion, the controller has a fixed range of $\pm 1000$ units which is equivalent to $\pm 5.0$ volts. In the case of displacements, the full stroke of the transducer is equivalent to $\pm 1000$ units or $\pm 5.0$ volts. The movement of the jacks is controlled by a feedback signal obtained from external displacement transducers attached to the test specimen. The movement of jacks continues until the measured displacements reach the target values within an allowable error specified prior to the test. At that moment a hold command is sent by the controller to keep that condition until new target displacements are computed and sent as next step of the test.

![Plan View of Test Setup](image)

**Figure 2: Test setup**
The computer for control calculates and sends the target displacements and the time set for loading and monitors and plots on screen the progress of loading. When target values are reached, the values of displacements and forces are stored in this computer.

Other data that are not used for control are collected through scanner boxes and universal acquisition system (UCAM) which is connected to the personal computer for data acquisition.

2.3 Control of undershooting errors

In pseudodynamic test method a source of error is due to the undershooting or when the actual displacement does not reach the target displacement. In this implementation, the target displacement is shifted slightly in order to reduce the undershooting error. This shifting is done after converting the displacements to units of the controller. The number of units to be shifted is chosen according to the stiffness characteristic of the specimen and the type of displacement transducers. For the LVDT displacement transducers and the specimens of this research, 1 unit was selected as the shifting value.

\[ \text{Computed Target Displacement} \]

(UT-2) \quad UT \quad (UT+2)

\[ \text{Shifted Target} \]

(UT-1) \quad (UT+1) \quad (UT+3)

Figure 3. Reduction of undershooting errors

The technique to reduce the undershooting error is shown schematically in Figure 3. If the calculated target displacement, expressed in units of the controller, is UT, due to the sensitivity of the controller, the movement of the jack will be stopped when the actual displacement enters to the tolerance range. In this case, for the used equipment, the range is of ±2 unit or in other words, from (UT-2) to (UT+2). Considering that the direction of loading is as it is shown in Figure 4, the movement of jacks will stop when the displacement enters to the tolerance range and it is clear that more of times will stop at (UT-2) or (UT-1), sometimes will stop just at UT,
there are few chances to reach (UT+1), and almost never will reach (UT+2). This systematic undershooting error is reduced by shifting the target displacement in the direction of the loading as is shown in Figure 3. This shifting is done only to perform the loading task. For the computation of next steps, the original calculated target value is used.

In Figure 4, the errors during the loading process of the pseudodynamic test of some specimens are presented as illustrative examples of the effectiveness of the implemented algorithm. Displacement transducers of 20 mm and 100 mm of full stroke were used for specimens PSD-HC1 and PSD-HC2, respectively. It can be observed that the errors have parts of undershooting and overshooting components and, in general, they look like random type errors.

![Figure 4. Error during the loading process](image)

### 3 Test specimen

Cantilever type column specimen was adopted to have the critical section located only at the bottom of the column and the axial load inducing procedure becomes simple. The concrete has a nominal strength of 58.8 MPa and the steel has an yielding point of 608 MPa. Details of the specimen can be observed in Figure 3.
Material Characteristics:

Concrete:
\[ \sigma_c = 58.8 \text{ MPa} \]

Main reinforcement:
\[ \sigma_y = 608 \text{ MPa} \]
\[ \rho_f = 0.94 \% \]
12-D19

Transverse reinforcement:
\[ \sigma_y = 1408 \text{ MPa} \]
\[ \rho_w = 0.57 \% \]
4-RB7.1@80mm

Figure 5: Column specimen for pseudodynamic test

Since the specimen corresponds to a cantilever type column, the system was modeled as a single mass with two degrees of freedom. Therefore, two jacks to control each degree of freedom were used. Considering that specimens correspond to a center column of a medium rise building, a constant axial load of 1370 kN was applied to the specimen (which represents 20% of the maximum axial force of the concrete section). A mass of 40.8 kg/s^2/cm was used to set up the initial period of the system at 0.4 second. Also 2% of viscous damping was considered.

Simulated earthquakes corresponding to design level 1 (moderated), level 2 (severe) and actual earthquake records were used. Specimens and input motions used in this research are presented in Table 1.

Table 1. Specimens and input records

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Input record</th>
<th>Maximum Acceleration</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EW(cm/s^2)</td>
<td>NS(cm/s^2)</td>
</tr>
<tr>
<td>PSD-HC1</td>
<td>MEL101</td>
<td>213.4</td>
<td>245.3</td>
</tr>
<tr>
<td>PSD-HC1</td>
<td>MEL102</td>
<td>386.4</td>
<td>373.7</td>
</tr>
<tr>
<td>PSD-HC1</td>
<td>MEL102*2</td>
<td>772.8</td>
<td>747.4</td>
</tr>
<tr>
<td>PSD-HC2</td>
<td>Kobe</td>
<td>617.1</td>
<td>-817.8</td>
</tr>
<tr>
<td>PSD-HC3</td>
<td>Miyagi-Ken-Oki</td>
<td>202.6</td>
<td>258.2</td>
</tr>
<tr>
<td>PSD-HC3</td>
<td>Miyagi-Ken-Oki*2</td>
<td>405.2</td>
<td>516.4</td>
</tr>
</tbody>
</table>
The simulated earthquakes were obtained using the well known El Centro record and modifying this record by successive iterations to match its response spectrum with the basic design spectra specify in the Guideline for Evaluating Design Earthquake Motion for Building proposed by BRI and BCJ (1992). The simulated earthquake for design level 1 is called MEL101 and for design level 2 is called MEL102. These records were used successively to test the specimen PSD-HC1. Then as a final stage, the record for level 2 was amplified twice (this amplified input is called MEL102*2) and applied to the same specimen PSD-HC1. For specimen PSD-HC2, the Kobe earthquake, recorded at Kobe Marine Meteorological Observatory, was used. Only 8 seconds of the main part of the record is used. In case of specimen PSD-HC3, the Miyagi Ken Oki earthquake was used for a first running and then the wave was amplified by two and applied as a second running.

4 Test results analysis

In Table 2 the experimental maximum responses of the specimens subjected to the corresponding earthquakes are shown. The maximum displacements correspond to those measured at 60 cm from the base of the column specimen.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Input Record</th>
<th>Maximum Displacements (mm)</th>
<th>Maximum Loads (kN) (Experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Experiment</td>
<td>Analysis</td>
</tr>
<tr>
<td>PSD-HC1</td>
<td>MEL101</td>
<td>-2.72</td>
<td>-2.54</td>
</tr>
<tr>
<td>PSD-HC1</td>
<td>MEL102</td>
<td>-8.84</td>
<td>-6.37</td>
</tr>
<tr>
<td>PSD-HC1</td>
<td>MEL102*2</td>
<td>29.59</td>
<td>27.86</td>
</tr>
<tr>
<td>PSD-HC2</td>
<td>Kobe</td>
<td>20.39</td>
<td>19.77</td>
</tr>
<tr>
<td>PSD-HC3</td>
<td>MiyagiKenOki</td>
<td>1.62</td>
<td>1.56</td>
</tr>
<tr>
<td>PSD-HC3</td>
<td>MiyagiKenOki*2</td>
<td>-9.66</td>
<td>-10.41</td>
</tr>
</tbody>
</table>

Main limits values established in the PRESSS guidelines (1992) for inter-story drift angles are used only as a reference to compare the effect of different input motions. For simulated earthquake, it can be observed that in case of level 1 earthquake, the maximum displacement corresponds to a drift angle of 1/221 that is smaller than 1/200. This value satisfies the criteria for serviceability limit state specified in the PRESSS guidelines. However it be stated that the value of this maximum displacement is close to the upper limit, although the actual shear coefficient is relatively large (0.59) compared with the value of 0.2 specified in the Press Guidelines. For level 2 earthquake, which is assumed that corresponds to ultimate limit state, the maximum displacement or drift angle (1/68) exceeds the design limit deformation (1/100); however, it is smaller than the design proof deformation (1/50). In case of level 2, the drift angle is smaller than 3/200. In case of Kobe earthquake, the maximum displacement exceeds largely the upper limit of ultimate state, which means that this record is larger than level 2 earthquake.
As illustrative example, plots of analytical and experimental results for Kobe earthquake are presented. Figure 6 and Figure 7 show displacement responses and hysteretic curves respectively.

The experimental results are compared with analytical results which were obtained using the proposed fiber model method. In Table 2, this comparison of the maximum responses from tests and from analysis are also presented. In general, a good agreement is observed between both results.

![Figure 6: Time history displacement responses for Kobe Earthquake](image)

![Figure 7: Load displacement response for Kobe earthquake](image)
5 Conclusions

Pseudodynamic test method using conventional testing devices was implemented and its applicability to simulate the behavior of reinforced concrete columns subjected to two directional input motions was verified. The undershooting errors, associated with the method, are controlled appropriately having random-like error with overshooting and undershooting components. Using a fiber model formulation an analysis were performed and these analytical results were compared with experimental ones. Analytical and experimental results agreed very well.

References


