Damage evaluation of reinforced concrete columns under two directional earthquake motions

C. Cuadra¹, J. Ogawa¹, N. Inoue²
¹Department of Architecture and Environment System, Akita Prefectural University, Japan
²Department of Architecture and Building Science, Tohoku University, Japan

Abstract

In order to investigate the inelastic behavior and perform a damage evaluation of reinforced concrete columns subjected to constant axial load and two directional input motions, pseudodynamic test using conventional testing devices was implemented. The specimens were cantilever-type reinforced concrete columns with square cross section of 40×40 cm and 2.5 of shear span ratio. The input motions were simulated motions and actual recorded earthquake motions. The effect of two directional loading is investigated by comparing the test results with those for one directional loading. The effect of the bi-directional loading appears after reaching the yielding zone, and the damage becomes more severe than unidirectional loading. From experimental test results a damage evaluation index is proposed by taking into account the length of the cracks and crack pattern developed in the element during an earthquake.

1 Introduction

Pseudodynamic test method using conventional testing devices to test structural models subjected to two directional input motions was developed. In this research, hardware devices that permit the employment of conventional hydraulic jacks are used. These hardware devices consist of a hydraulic pump system that can adjust the rate of oil flow by using an inverter motor and a high-speed on-off valve. The movements of jacks are controlled by means of feedback signals obtained from external displacement transducers. This system was used to simulate the inelastic
behavior of reinforced concrete columns subjected to two directional input motions. The input motions were simulated input motions and actual recorded earthquake motions. The effect of the bi-directional loading appears after reaching the yielding zone, and the damage becomes more severe than unidirectional loading.

The development and crack pattern were observed during the tests and sketches were drawn for each important step. These plots permit to quantify the amount of cracks to establish an index for damage. This index is established as the ratio between the total length of cracks developed within a height equal to the width of the column (40 cm) and the column width. This amount of cracking is plotted versus the maximum experienced drift angle. Until a drift angle of 3/200 there are not big differences between the unidirectional and bi-directional input motions and the relation is almost linear. However, for bi-directional loading and large drift angles, it was observed that although the maximum experienced drift angle is not exceeded, the repeatedly applied bi-directional load produced additional cracks.

This damage index can be useful in the damage evaluation of actual structures, to estimate the maximum experienced drift angle of structural members by observing the amount of cracks in the element.

2 Test System

The pseudodynamic test method implemented in this research is applicable, in general, to specimens subjected to multidirectional loading. The specific application for reinforced concrete columns, subjected to the bi-directional horizontal input motions and simultaneously axial load, is presented. Cantilever type specimens are used and the lumped model corresponds to a system of one mass with two horizontal degrees of freedom.

The dynamic equations of motion, considering that the system has non-linear behavior, are solved by the Newmark's explicit integration method under any arbitrary external excitations.

Two separate personal computers are used for the main control of the whole testing process and for data acquisition, respectively. Outline of the test setup is presented in Figure 1. Displacements or loads are applied to the specimen by means of reversible-load hydraulic jacks. Jacks are driven by hydraulic pump units, which are constituted of an inverter motor and a high-speed on-off valve. The calculated or target displacements are sent to the controller as a digital signal by the computer, then the controller converts this signal into voltage signal and sends it to the pump unit. According to the difference between target displacements and actual displacements, loading or unloading tasks are performed. For loading process, the frequency of each inverter motor is set in proportion to the received voltage signal, and the loading is performed until the target value, within certain allowable error, is reached. In case of unloading, the oil is released from the loading chamber and a high-speed on-off valve controls this task. The rate of oil released by this valve is set also in proportion to the voltage signal. The movements of the jacks are 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 the allowable error specified prior to the test. At that moment a hold command is sent by the controller to keep that ram position until new target displacements are computed and sent as next loading step. For these tasks, the correspondent software was developed and implemented.

![Flowchart](image)

**Figure 1: Pseudodynamic test setup**

The lateral loading system is made up of two sets of reversible hydraulic jacks. Both jacks are equipped with vertical and horizontal free joints on both ends.

Two triangular steel frames were used to introduce the lateral forces. These frames are fixed to the floor slab. Each jack was attached to the load-inducing jig at one end and to the reaction frame in the other end.

The axial load is applied to the free end of the column through the load-
inducing jig and a universal joint attached to a loading girder. Four central-hole hydraulic jacks of 100 tons of capacity are used for the axial loading. These jacks are setting at the bottom surface of the testing floor. These four jacks are controlled by one controller, which is also connected to the computer for control. According to the test requirements, the system can apply constant axial load or variable axial load. Four 32 mm of diameter high strength steel rods connect these jacks and the loading girder. For the sake of safety and stability of the axial load inducing system, the contact points of the girder ends and the tension rods are made to be lower than the free end of the column like a balancing toy.

Other data like bar strains, vertical displacements, etc., which are not used for control, are collected through the data acquisition system. The data acquisition system consists of two electrical scanning boxes, one universal digital data logger (UCAM) and a personal computer. The electrical signals from load cells, displacement transducers and strain gauges are captured by the scanning boxes and are sent to the UCAM. Here, the electrical signals are transformed into digital signals and are sent to the computer where the data are stored in the hard disk for its posterior processing.

3 Specimens and Test Conditions

Cantilever type column specimen was adopted to have the critical section located only at the bottom of the column. The concrete has a nominal strength of 240 kg/cm$^2$ and the steel has a yielding point of 3800 kg/cm$^2$. Details of the specimen can be observed in Figure 2.
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 96 tons was applied to the specimen (which represents 25% of the maximum axial force of the concrete section). A mass corresponding to a weight of 28 tons was used to set up the initial period of the system at 0.2 seconds. Also 0% of viscous damping was considered.

Simulated earthquakes corresponding to design level 1 (moderate), level 2 (severe) and actual earthquake records were used. 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).

### 4 Test Results

In Table 1 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. The comparison of the behavior of reinforced concrete columns subjected to unidirectional input motion and bi-directional input motion is presented. Also results for the Kobe earthquake input motion are presented.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Input Motions</th>
<th>Maximum Displacements (mm)</th>
<th>Maximum Loads (tonf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N-S</td>
<td>E-W</td>
</tr>
<tr>
<td>PSD-R1</td>
<td>Simulated L-1</td>
<td>1.44</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Simulated L-2</td>
<td>3.24</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Simulated L-3</td>
<td>12.25</td>
<td>---</td>
</tr>
<tr>
<td>PSD-R2</td>
<td>Simulated L-1</td>
<td>1.52</td>
<td>-1.60</td>
</tr>
<tr>
<td></td>
<td>Simulated L-2</td>
<td>3.27</td>
<td>-3.23</td>
</tr>
<tr>
<td></td>
<td>Simulated L-3</td>
<td>-23.43</td>
<td>17.37</td>
</tr>
</tbody>
</table>

### 4.1 Unidirectional versus bi-directional response

In Figure 3 the results for the specimen PSD-R1 (subjected to unidirectional simulated input motions) and results for specimen the PSD-R2 (subjected to bi-directional simulated input motions) are compared. In Figure 4, the correspondent load displacement curves are shown. The damage or crack condition after finishing each level of loading is shown in Figure 5. Here is shown only the south face of the
specimen. In Figure 6, the orbits corresponding to the interval from 1.3 to 3.0 seconds, where the maximum response occurs, are shown for the specimen PSD-R2.

Figure 3: Time history displacement response

Figure 4: Load displacement response
For the simulated input motion corresponding to level 1, the maximum drift angle for the unidirectional loading was 1/420 while for the bi-directional input motion was 1/350. Some small cracks were observed in both cases, however, the behavior was almost elastic.

In case of the level 2 simulated input motion, the maximum drift angle for the unidirectional input was 1/190 while for the bi-directional input motion was 1/180. In this case, for the bi-directional loading, a little larger energy dissipation can be observed from the load-displacement curve. However, after finishing this level 2, there are not important differences in the crack condition between both specimens.

For the level 3 simulated input motion, the maximum drift angle in case of the unidirectional input motion was 1/50 and for the bi-directional input was 1/20. For the bi-directional loading, the maximum lateral load is a little smaller than for the unidirectional loading. Also the decreasing of strength after yielding is more pronounced in case of the bi-directional loading, therefore, the maximum observed displacement is notoriously larger than in case of the unidirectional loading. Comparing the crack and the spall-off, it was observed that for the bi-directional input motion crushing failure occurred at 2.0 sec while this type of failure was not observed for the unidirectional input motion until 5.0 sec. For the bi-directional loading, a spall-off ratio of 25% was observed at 2.5 sec and this index becomes 40% at 5.3 sec. For the unidirectional loading, spall-off of concrete was not observed.
In case of the bi-directional input motion, the observed displacement path for the level 1 is almost circular, while for the level 3 this path have not a defined shape. The shape for the level 2 is an intermediate shape between shape of the level 1 and shape for the level 3.

4.2 Damage due to Kobe input motion

The time history displacement response for Kobe earthquake is shown in Figure 7, as well as the corresponding load displacement relationship. Figure 8 shows the displacement path and the crack and spall-off condition of the specimen after finishing the test.

The first visible crack appears at a drift angle of 1/660. In the vicinity of 2.3 sec (represented by point 1 in Figure 8) at a drift angle of 1/170, the displacement response path looks like a inclined unidirectional path in the NW direction. Then cracks appear in ES direction and crushing failure is observed in the NS direction.

Figure 7: Displacement response and load-displacement curve for Kobe earthquake

Figure 8: Displacement orbit and crack and spall-off for Kobe earthquake
At 3.1 sec the specimen reaches a drift angle of 1/80 (point 2 in Figure 8) and after that a great decay of the stiffness is observed. From 5 to 6 seconds a large input acceleration in observed in the NS direction and, therefore, a large displacement response is observed in this direction while not so large displacement is observed in the EW direction. Then the displacement path for this interval looks like a unidirectional path. At approximately 6.4 seconds the peak displacement is observed with a maximum drift angle of 1/40. Near this maximum, the displacement path has a circular shape (point 3 in Figure 8).

4.3 Damage index according to the amount of cracks

The development and crack pattern were observed during the tests and sketches were drawn for each important step. This plots permit to quantify the amount of cracks to establish and index for damage. This index is established as the ratio between the total length of cracks developed until a height equal to the width of the column (40cm) and the column width. In Figure 9 this amount of cracking is plotted versus the maximum experienced drift angle.

Until a drift angle of 3/200 there are not big differences between the unidirectional and bi-directional input motions and the relation is almost linear. For bi-directional simulated earthquake motion a sudden change can be observed at a drift angle of 9.5/200. Similarly, for Kobe earthquake this sudden change is observed at a drift angle of 3.5/200. It can be said that this is due to the large cyclic loading observed near these points. In other words, although the maximum experienced drift angle is not exceeded, the repeatedly applied bi-directional load produced additional cracks. For small drift angles this effect is not observed.

The damage index can be useful in the evaluation of damage of actual structures, to estimate the maximum experienced drift angle of structural elements by observing the amount of cracks in the element.

Figure 9: Amount of cracks versus maximum drift angle
5 Conclusions

Pseudodynamic test method using conventional testing devices was implemented and its applicability to simulate the inelastic seismic behavior of reinforced concrete columns subjected to multi-directional input motions was verified.

The method was applied to study the behavior of reinforced concrete columns subjected to unidirectional and bi-directional horizontal input motions. Before the maximum load the behavior responses are almost the same for unidirectional and bi-directional input motions. Also observing the crack condition of the specimen, the effect of the bi-directional loading is not appreciated. However, after reaching the yielding zone the effect of the bi-directional loading appears, and the damage becomes more severe than the unidirectional loading.

For the specimen used in this research the damage index, expressed as the amount of cracks or total length of cracks, has a linear relation with the maximum observed drift angle when this angle is smaller that 3/200.

6 References


