Earthquake damage and pseudo-dynamic test of reinforced concrete columns

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Abstract

This report presents a series of damages produced in reinforced concrete columns occurred during recently past earthquakes in Japan and other countries. The causes of damages are discussed as well as the possible solutions to avoid future damages.
On the other hand, an overview of the experimental research, developed in Japan, to investigate the behavior of these elements is presented. Special emphasis is devoted to the pseudo-dynamic test method as a suitable technique to simulate the inelastic seismic behavior of reinforced concrete columns when they are subjected to bi-directional input motion and simultaneous axial load.

1 Introduction

The design philosophy for earthquake resistance usually requires that under minor to moderate earthquakes structures should resist the intensity of ground motions without structural damage, but with some nonstructural damage. Under severe earthquakes, some structural damage is accepted. However, collapse must be avoided.
In the case of framed reinforced concrete structures, special care must be dispensed to the columns since they are the legs that support the structure. A column failure, specially those of the first floor, may have serious consequences and even may signify the collapse of the structure. For that reason, in assigning plastic hinges for collapse mechanism of multistory frames, the principle of strong column weak beam is often followed. However, the first story columns represent unavoidable localities, hence the columns are required to exhibit
ductile performance by developing plastic hinges.
On the other hand, the effect of the multidirectional nature of the earthquake is
more pronounced in the columns. Columns are subjected to biaxial bending due
to the two orthogonal components of the horizontal earthquake motion and are
subjected to time dependent axial loads because of overturning moments and
vertical earthquake motions.
It is evident that ground motions from earthquakes are random in nature, and take
place in variable directions. Therefore, recommendations or specifications for
shear strength or other parameters derived from unidirectional cyclic test may not
adequately represent the properties or characteristic behavior of the element
under two directional input motions. It is clear therefore, that a thorough
understanding of the elastic and specially inelastic behavior of reinforced
concrete columns under cyclic loads, or even better under dynamic loads, is
needed to take preventive measures against earthquake damages. Moreover, the
effects of multidirectional interaction on the response of the reinforced concrete
columns should be investigated to determine whether extra provisions should be
made in future building codes for the simultaneous occurrence of earthquake
motions in different directions.

2 Damages observed in columns

From damage of past earthquakes it can be observed that failures of columns are
critical for the structures and in the most of cases are the reasons for the collapse
of the structure. Even if the structure does not collapse, the failure of columns
may signify the disuse of it due to the potential danger of failure and moreover
the process of repair is more difficult and expensive than other structural
elements.
Figure 1 shows a failure of the columns of the first level occurred in an apartment
building during the great Kobe earthquake in 1995. During this earthquake, many
failures of the columns could be attributed to a soft-story configurations. The
damages occurred not only in the first floor but also in intermediate floors where
a change of dimensions of elements or change in the material characteristic was
observed. This failures of columns produced the collapse of the entire soft floor
and in some cases of first soft-floor the total collapse of the structure was
observed. On the other hand it is important to quote that many reinforced
concrete structures that collapse or fail during the Kobe earthquake were
constructed according to the old Japanese code, and failed constructions were
more than 25 years old. Moreover, in some cases the reinforcement bar were
plain bars or not deformed bars consequently poor adherence with the concrete
was the cause of failure.
During the Kobe earthquake it was observed also damages in civil or public
works like bridge, high-way structures, subway structures and so on. In Figure 2,
it can be observed the failure of the columns of a subway station that affect not
only the station itself and the train service but also produce the collapse of the
Figure 1: Collapse of columns of apartment building during Kobe earthquake

Figure 2: Collapse of columns of subway station during Kobe earthquake
Figure 3: Collapse of highway piers during Kobe earthquake

In Figure 3 the Collapse of a 635m section of single-piered bridges can be observed. Seventeen piers spanning 635 meters of pile bridges in Fukae area were destroyed and the bridges collapsed northward.

In more recent earthquakes occurred in Turkey (2000) and Taiwan (2000), failures of reinforced concrete structures were also observed. In both countries most of residential buildings as well as mid-rise commercial buildings are built with reinforced concrete structural systems. After the earthquake, shear failures were observed, specially in old buildings. The mechanism of shear failure in reinforced concrete columns has been almost understood now, however some poor details can be observed sometimes even in new buildings. For example 90 degree bent of shear reinforcement, insufficient quantity of the shear reinforcement and wide spacing were observed in failed columns. Further, the congestion of the main reinforcement in beams and columns makes it difficult to put enough shear reinforcement into beam-column connections. This congestion of reinforcement could be due to the reduced cross section of the members which was found smaller than the ideal size for a good design. The quality of concrete is very important for a good seismic performance of reinforced concrete buildings, however in small towns or local areas good quality concrete can not be expected since they do not have any mixing plant in neighboring areas. There are also some cases where building are extended upward after a few years of use. In this cases the reinforcing bars of the upper columns of the original building are left exposed to the weather attack and consequently an inadequate bond strength at
the lapped splice joint is the cause of failure during earthquake motions.

3 Pseudodynamic Test Method

Recently, some studies have been made on the behavior of reinforced concrete columns subjected to two dimensional input motions. However, most of them are analytical studies. In case of experimental studies, most of them consist of static tests which use prescribed loading or prescribed displacement paths. On the other hand, very few experiments on shaking table are reported, and all of them were carried out on small size specimens.

The pseudodynamic technique is an alternative to investigate the behavior of reinforced concrete columns subjected to two dimensional earthquake motions using a real wave as input instead of prescribed paths. Also, this methodology permits to use full scale specimens avoiding, therefore, the problem of size effect when small specimens are used.

3.1 Antecedents

The pseudodynamic test method was first devised more than twenty five years ago by K. Takanashi et al [1]. The subsequent development, improvement, and refinement have shown the promise of the test as a powerful tool for verifying the earthquake behavior of structural components and systems. The pseudodynamic 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. First the structure is idealized as a lumped mass system. 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 have been developed like a hydraulic pump system that can adjust the rate of the oil flow using an inverter motor and a controller that controls jack's motions with displacement feedback signal transmitted from external displacement transducers. These new devices permit to use conventional hydraulic jacks instead of servo actuators. An implementation of the pseudodynamic test, for planar specimens and a single jack, using conventional testing devices is reported by Nakajima et al [2]. 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 testing laboratories.
3.2 Test system

The pseudodynamic test method presented 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 reported here. 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 4. 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.

![Figure 4: Pseudodynamic test setup](image)
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 pump unit has an inverter motor that can adjust its frequency 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 by mean of a high-speed on-off valve. 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.

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 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 data logger. 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.

4 Applications of the implemented method

The implemented test method was applied to simulate the inelastic seismic behavior of reinforced concrete columns subjected to bi-directional input motion and simultaneous axial load. Also the method has been used to study the effect of variable axial load in the behavior of the column. For that purpose the substructure technique has been employed to estimate the variation of the axial load in a column.
which was part of a frame structure. This frame structure was analyzed numerically and simultaneously a column of this frame was tested experimentally using the pseudodynamic test.

Other application of this methodology is the study of the effect on the type of earthquake motion in the response of reinforced concrete elements. For this study two types of input motion were used, one was a near-source input motion and the other one was a far-source input motion.

As illustrative example of the applicability of the method, results for the Kobe earthquake input motion are presented. The time history displacement response for Kobe earthquake is shown in Figure 5, as well as the corresponding load displacement relationship. Figure 6 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 6) 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 5: Displacement response and load-displacement curve for Kobe earthquake](image)

At 3.1 sec the specimen reaches a drift angle of 1/80 (point 2 in Figure 6) 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 6).

5 Conclusions

During earthquakes many damages can be observed in structural elements and specially in the case of columns the failure of this elements can produce the collapse of the whole structure.

Among the experimental methods to study the behavior of structural elements when they are subjected to earthquake motions, the pseudodynamic test method represents a good option for that purpose.

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.

6 References


