Engineering Structures 118 (2016) 156–166

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Shaking table test on the collapse process of a three-story reinforced concrete frame structure

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ARTICLE INFO

Article history:
Received 26 February 2015
Revised 11 March 2016
Accepted 14 March 2016
Available online 2 April 2016

Keywords:
RC frame structure
Shaking table test
Collapse process
Dynamic property
Collapse mechanism
Benchmark test

ABSTRACT

This study explores the collapse process of a reinforced concrete (RC) frame structure subjected to earthquake shakings, by applying the shaking table test on a three-story, one-bay, 1/5-scaled RC structural model. The frame specimen transformed from an elastic state to a highly nonlinear state, then experienced dynamic instability, and finally collapsed to the ground. The structural responses that have been monitored in the presented test include the specimen's dynamic properties, displacements, and accelerations. The data collected from this benchmark test program can be used for the verification of existing analytical and numerical simulation methods, especially for cases involving the large displacement and rotation or collapse process simulation of RC frame structures. It is observed from the test that: (1) the frame survived when the maximum story drift ratio and the residual drift ratio reached 12.51% and 9.60% respectively, indicating that the RC frame structure may have a much high ductility capacity; (2) the collapse of the 1st, 2nd, and 3rd stories was due to failure of the plastic hinges at columns; and (3) during the collapse process, the collisions and the damage-induced local oscillation can generate very large horizontal and vertical acceleration responses. More specifically, the collapse of the 1st story was the result of the failure of plastic hinges, caused by seismic excitation, while collapse of the 2nd and 3rd stories resulted from the combined results of plastic hinge failures and punching shear failures in the slab due to impact effects.

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1. Introduction

Prediction of the probability of structural collapse within a high confidence interval has become a major impediment to the development and promotion of *Performance-Based Earthquake Engineering* (PBEE) [1]. While it is a well-accepted idea that the collapse of reinforced concrete (RC) structures in earthquakes normally occurs to old buildings whose designs are based on obsolete seismic codes, case observations from past and recent earthquake events reveal that sometimes collapses take place even where the structures are designed in accordance with contemporary design principles [2–4]. The causes of this kind of unexpected structural collapse can be explained from several aspects, e.g., the uncertainties inherent in the ground shakings [5], featured ground motions with larger damage potentials [6–9], and deficiencies in our knowledge regarding the collapse resistant design.

As quantification of the collapse potential of existing and newly designed structures is an essential element to implementing the PBEE methodology [10], a number of numerical studies (e.g., finite element methods [11–17], discrete element methods [18–21], and applied element methods [22–24]) have been conducted in an attempt to gain a greater understanding of the structural collapse mechanism at a relatively lower cost (as compared to performing experimental tests). Nonetheless, structural collapse is a complicated process in which an interconnected system deteriorates into discrete parts. To investigate the collapse mechanism utilizing numerical simulation methods, the adopted theories and computer programs must be able to address various modeling issues including the handling of extremely large displacement and rotation, and the assessing of damage and fracture propagation in structural components, as well as the detection of collision and evaluation of the impact of falling structural fragments on the slabs of lower stories. Although many commercial software packages in the

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http://dx.doi.org/10.1016/j.engstruct.2016.03.032
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market claim to feature some, or even all, of these modeling capabilities, very few have actually been verified by a realistic, complete collapse test – i.e., an experimental study in which the structure specimen transforms from an elastic state to a highly nonlinear state, then experiences dynamic instability, and finally collapses to the ground. That said, a predicted collapse process based solely on numerical simulations may be questionable.

One of the major obstacles to the advancement of knowledge regarding the RC frame collapse process is the lack of experimental data documenting the realistic dynamic responses of structures tested under the extreme performance level (i.e., during the collapse stage). In recent years, several shaking table tests have been performed to inspect the structural collapse mechanisms, and/or to evaluate the accuracy of numerical approaches used to simulate the collapse process, of structures. For example, the shaking table tests on two one-story, two-bay RC frame structures conducted by Elwood and Moehle [25], featuring outside ductile columns which can provide an alternative load path for load redistribution after the middle nonductile column loses its capacity, were used to verify the predicted axial and shear failures of RC columns obtained from nonlinear numerical analysis [26]. Wu et al. [27] performed a shaking table test to investigate the dynamic softening and global collapse behaviors of a one-story, one-bay frame designed with low-ductility columns. A few years later Wu et al. [28] conducted another shaking table test on a one-story, three-bay frame, collapsed in the flexure-shear and axial failure modes. The results were used to evaluate the accuracy of existing simplified assessment methods in predicting structural collapse. Ghannoum and Moehle [29] performed a shaking table test on a three-story, three-bay frame to study the structural framing effects on local column failures. They also used the data to examine the potential consequences of localized column failures in inducing structural vulnerability against global collapse. Kim et al. [30] carried out a test on a RC structure with considerable eccentricity in stiffness and strength in the first story, to investigate the effects of an eccentric structural plan on the seismic capacity of buildings designed following the 1970s Japanese codes, most of which are characterized by columns of low shear strength.

Despite the fact that these shaking table tests were designed to collect data relating to dynamic structural responses at the failure stage, most were either terminated or enforced with certain collapse-prevention measures at the moment the test specimens demonstrated any possibility of collapse, so as to protect the expensive testing equipment and devices from damage. To the best of the authors' knowledge, currently only one complete dynamic collapse test on frame structure (i.e., collapse to the ground) is available in the literature. The said test was conducted by Huang [31], and a series of photos were taken at various time instances during the collapse process. However, in that test program, recording of the displacement time history was stopped as soon as the maximum displacement at the top of the frame reached around 10 cm (about 1/30 of the total height of the test frame), which is the maximum measuring limit of the adopted displacement sensors.

In summary, the existing RC frame collapse shaking table tests do not piece together a complete picture from which to fully study and understand the collapse mechanism of structures, because: (1) exceptional large displacements are not allowed in most tests; (2) the measuring range of traditional displacement sensors, such as the widely used linear variable differential transformer (LVDT), is insufficient for the measurement of structural response in a full collapse test; and (3) tests on one-story structural specimens do not disclose the effects of collision and impact due to upper stories collapsing on lower stories. In this study, a shaking table test on a three-story RC frame structure was carried out to provide additional experimental data on this topic and to document the complete structural performance during the collapse process.

2. Test specimen

The test frame specimen was a 1/5-scaled three-story, one-bay, three dimensional RC structure, as shown in Fig. 1. Its corresponding prototype structure was designed according to the current Chinese building codes [32,33]. Fig. 2 shows the specimen geometry and reinforcement details of the test frame specimen. All beams in all three stories were identical (with the same cross-sectional area, length, and reinforcement), as were the columns in all three stories. To minimize the unfavorable effects associated with the out-of-plane movement, the test frame was designed to be symmetric about the two perpendicular axes in the horizontal plane, the column sections were rectangular in shape, and the ground motion was input to the system along the direction perpendicular to the long dimension side of the column section. Additional masses were deployed on the slabs of the 1st, 2nd, and 3rd stories. Traditionally, groups of mass blocks attached to the slabs are utilized as additional masses but these mass blocks may slide and pound with each other when the frame specimen undergoes large deformation; the frame specimen's responses at the collapse stage may thus be altered. To ensure the integrity between the additional masses and the slabs throughout the test, welded layer steel plates (as shown in Fig. 2b) were adopted in this experimental program, instead. The total additional masses, including the steel plates, tie reinforcements, and adhesive mortar (used at the interface between the slab and the steel plate), on the 1st, 2nd, and 3rd stories, were 1197.5 kg, 1197.5 kg, and 726.5 kg, respectively.

The stress–strain curve obtained from the standard concrete specimen ($150 \times 150 \times 300$ mm) compression test. The values of elastic modulus E, compressive strength f_c, and the stress and strain values on the softening branch of the stress–strain curve (corresponding to 50%, 40%, 30%, 20%, and 10% of the maximum strength f_c) are presented in Table 1. The #8 steel rebars (with a diameter of 3.98 mm) were used for longitudinal reinforcement,

Fig. 1. Geometry of the RC frame specimen.

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