DESIGN OF DYNAMIC COLLAPSE TESTING SYSTEM FOR 2-STORY REINFORCED CONCRETE FRAMES

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ABSTRACT

This paper presents the design of an integrative testing system for observing dynamic collapse of 1:2.25 scaled two-bay two-story concrete frames subjected to one-directional shaking table motions. The testing system consisted of four major parts: lateral steel supporting frame with frictionless sliders and out-of-plane braces, protective transverse steel mega beam with rubber pads cushioned for global and/or local collapse impact, passive-controlled high axial load applying system, and on-table inertial mass system with anti-rocking mechanism. Taking advantage of such an advanced experimental setup, the two-story specimen frame was capable of representing the full-range dynamic structural behavior of the lower two stories of a seven-story concrete frame up to the point of structural collapse.

INTRODUCTION

Shaking table studies provide the most accurate means of assessing the performance of structures when subjected to earthquakes. The experimental data collected from shaking table tests can serve as a great platform evaluating simplified assessment models developed based on reversed cyclic test results, as well as validating nonlinear dynamic simulation methods. The ultimate goal of conducting dynamic collapse tests is to overcome existing technical barriers so that the full-range structural behavior of concrete frames can be accurately or satisfactorily predicted with affordable computational efforts as the failure of concrete structures involves both highly nonlinear structural plasticity and, to a certain extent, discontinuum mechanics.

The accuracy of structural response analysis up to the point of collapse largely depends on the capability of a numerical simulation method in reproducing realistic post-peak behavior of structural components. The development of reliable simulation methods must rely on laboratory observations and experimental data. The endeavor in current engineering research and practice to predict full-range structural behavior under earthquakes comes from the introduction of the "near collapse" performance objective at the 2%/50yr hazard level, and the intention to gain an understanding of the worst scenario or consequence that might happen in an extreme seismic event. It is to assure the worst consequence is within a well controlled upper bound, or at least an acceptable limit. A most famous example of such failure tests in other engineering industries would be the vehicle collision tests such as frontal head-on, offset, side, rollover, etc.

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To better understand the full range structural behavior of a wide variety of concrete columns, a good number of collapse tests using a shaking table have been conducted during the past few years at the National Center for Research on Earthquake Engineering of Taiwan since 2004 to experimentally observe three major types of column failure mechanisms, i.e., flexure, flexure-shear and pure shear failures in a dynamic manner. The test specimens were a single-story shear frame containing multiple columns (two, three, and four) interconnected at column top through a rigid giant beam to either allow or prohibit an alternative path for vertical load redistribution using different combinations of ductile and nonductile columns. The ones prohibiting vertical load redistribution using test frames having two identical concrete columns can be considered very similar to quasi-static reversed cyclic tests on double-curvature single columns. In contrast to the dynamic failure tests of concrete columns, the main objective of this international collaborative experimental program among Canada, USA, and Taiwan is to advance one more step further to study realistic whole frame interaction throughout the full-range structural responses, and, in particular, gravity load failure of frames. Among all, the loss of gravity load carrying capacity of reinforced concrete columns is the most critical factor leading to catastrophic structural collapse of buildings, and thereby causes tragic consequence of losses of lives.

PROGRAM DESCRIPTION

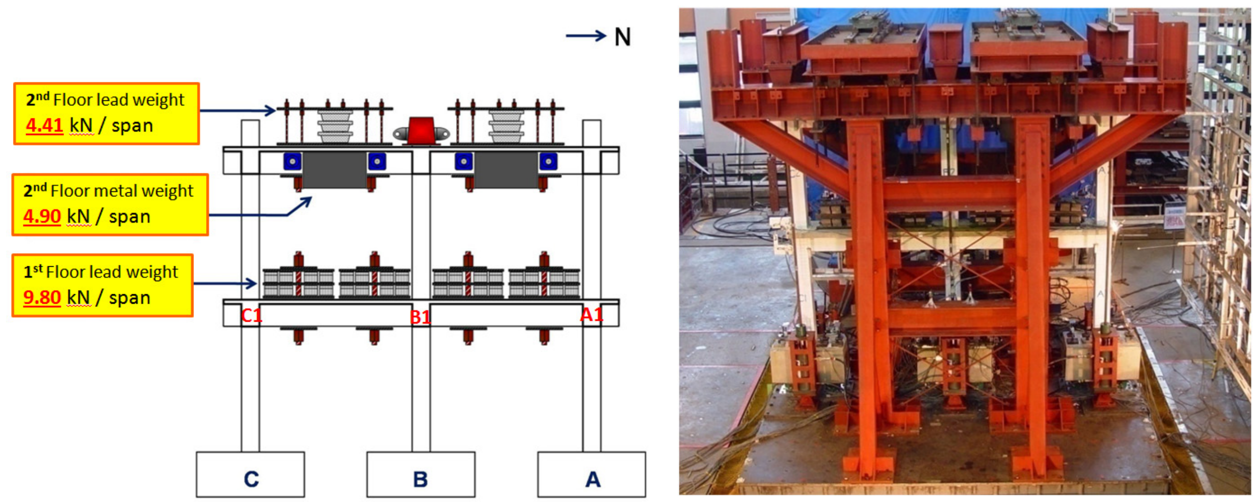
In order to experimentally investigate the whole frame interaction of 1:2.25 scaled two-bay two-story reinforced concrete frames up to the extreme state of structural collapse, four frame specimens were built at the National Center for Research on Earthquake Engineering (NCREE), Taiwan in 2008-2009. The challenge of designing the testing rig mostly came from the intention of building a low-rise model to mimic a seven-story hospital building in Taichung City; thereby, the integrative testing rig was comprised of four major parts: lateral steel supporting frame with frictionless stainless sliders and out-of-plane braces, protective transverse steel mega beam with rubber pads cushioned for global and/or local collapse impact, passive-controlled nearly constant level high axial load applying system, and on-table inertial mass system with anti-rocking mechanism. This two-story planar concrete frame will be subjected to one-dimensional earthquake excitation up to the intensity of structural collapse. The major test parameters in the experimental program were axial load, joint confinement, and transverse reinforcements of column (Fig. 1); four specimens were built to match this test need.

Figure 2(a) shows lead packets installed on each story to account for the contributory dead and live loads as per the existing Building Technical Regulations of Taiwan (MOI, 2009). The structure was intended to represent a hospital building with higher dead and live load demand than regular residential buildings. Gravity load on the beams was calculated by scaling the dead and live loads defined by the Building Technical Regulations of Taiwan (MOI, 2009) for such occupancy. Each beam was loaded with two sets of lead packets, representing a distributed load of a total weight of 9.8kN per span. Each lead bundle consisted of two layers with four lead ingots in each layer. Lead-weights were pre-stressed onto the beams with contact points being one rubber shim and one steel shim per bundle. The flexible rubber shims were used to reduce the stiffening effects of lead packets on beams, while steel shims in this arrangement provided the lateral load transfer between lead packets and concrete beams and were always placed towards the middle of the span where flexural deformations were smallest. Due to requirements for the connection of the inertial mass to the specimen, layout of lead packets on the second-story beams could not be identical to that on the first-story beams. Therefore, less lead packets

(4.4kN per span) with different arrangement were used on these beams, while additional steel weights (4.9kN per span) were securely hung on the sides of the beams to compensate the shortage of gravity load on the second story.

Specimen MCFS: Moderate Axial Load Confined Joints Flexure-Shear Columns	**Specimen HCFS:** High Axial Load Confined Joints Flexure-Shear Columns
Specimen MUFS: Moderate Axial Load Unconfined Joints Flexure-Shear Columns	**Specimen MUF:** Moderate Axial Load Unconfined Joints Flexure Columns

Fig. 1. Descriptive matrix of major test parameters.



(a) Lead packets installed in the frame

(b) Photographical view of the experimental setup

Fig. 2. The experimental setup of a 1:2.25 scaled two-story two-bay concrete frame: (a) lead packets installation; (b) photographical view.

DESIGN OF TESTING FRAME SYSTEM

To fulfil the research tasks aforementioned, the testing rig was determined to consist of four major sub-systems to be discussed in the following.

Lateral Steel Supporting Frame

As the specimen was a planar concrete frame with its weak axis in the out-of-plane direction, a reliable lateral steel supporting frame was thus required to be capable of preventing the specimen from unfavorable out-of-plane movement, but yet allowed the specimen be able to move freely in both horizontal and vertical directions up to structural collapse. This was achieved through installing two pairs of frictionless stainless sliders at each floor level. Two photographs of the actual supporting frame setup including both elevation and side view are shown in Fig. 2(b) and Fig. 4(b), respectively. The out-of-plane steel braces (Fig. 4(b)) helped reduce unfavorable transverse displacement to a minimum level. The top wide flange steel girders of the supporting frame had perfectly machined smooth surface that could serve as perfect guiding rails for running inertial mass cars to be introduced later.

Protective Transverse Steel Mega Beam

At each floor level, two protective transverse steel mega beams ran 45cm underneath the beam and were bolt connected to the mega columns of the lateral supporting frame to catch the specimen at structural collapse. At each floor level, one set of 30cm thick rubber pads (Fig. 3) were provided on the top of each transverse mega beam to cushion the impact force from directly transmitting onto the shaking table should global frame collapse occur. This design allowed for a 15cm free vertical drop of the floor and observation on shear and axial failure of the concrete columns.

Fig. 3. Rubber pads installed on the top of protective transverse steel mega beam.

High Axial Load Applying System

The high axial load applying system employed for each column, mimicking the gravity load from the upper stories, consisted of mainly a pair of hydraulic jacks (capacity 500kN, stroke 300mm), an accumulator and fast pressure reducing and relieving valves, and an oil pump to passively control the axial force approximately at the desired level (Fig. 4). The two hydraulic jacks were both connected to oil pipelines of an equal length and pipelines were set as short as possible to ensure fast pressure compensating and reducing response. The axial force was applied to the cross-sectional center of the column through a rigid steel loading beam equipped with an out-of-plane hinge in the middle of the beam bottom as well as a force transducer to record the actual vertical force applied to the column. The force transducer sat atop the column stub taking advantage of the frictional force generated by the two hydraulic jacks such that there was no bending moment applied to the column; however, there was a small horizontal component of hydraulic force transmitted into the column due to frictional force whenever there was a lateral drift of the column, which should be appropriately accounted for in data reduction and subsequent analytical studies. Each of the hydraulic jacks was fastened onto the table surface with an in-plane clevis pin, and there was another in-plane clevis pin prepared underneath both ends of the loading beam (Fig. 4) so that the $\phi 40$ high-strength connecting threaded steel rod functioned actually like a truss member. The hydraulic jack was protected by a steel cage (Fig. 4(b)) to avoid possible accidental collisions from falling concrete debris and spalling during the progress of structural collapse. The lateral inertial force resulting from the weight of the upper stories was compensated using an on-table inertial mass system to be mentioned later. In spite of using accumulators and fast pressure reducing and relieving valves to ensure the applied axial load approximately constant at the desired level, fluctuation in applied axial load was noticed during all tests. The performance of the axial force applying system was first evaluated in reversed cyclic tests of a full-scale two-story concrete frame (Tseng et al, 2009) except that pneumatic jacks were used instead. The actual achieved axial force was some 3%-5% higher than the desired force level. Then, another assessment test using hydraulic jacks in the axial force system was conducted on a single-curvature concrete column specimen using a shaking table but without reaching shear failure of the column. The error was within 10% fluctuation about the desired force level. When it came to collapse tests in this study, a total of three sets of high axial load applying system were employed. The center column was subjected to double axial force of the outer column according to the rule of contributory load in a building. It should be noted that a passive control algorithm was adopted because of safety concerns of more or less unpredictable structural collapse. The error was increased to some 15% about the specified force level in the collapse tests.

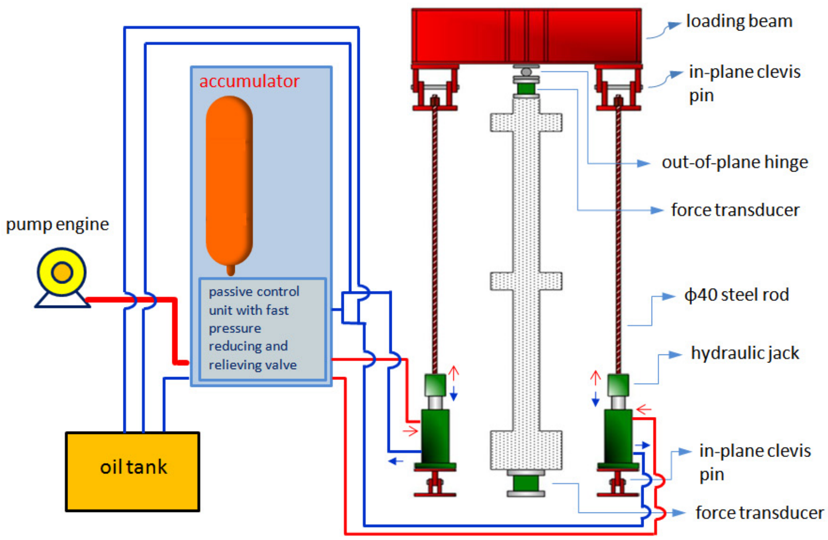


Fig. 4. High axial load applying system: (a) schematic plot; (b) photographical side view.

On-Table Inertial Mass System

As mentioned earlier, the specimen frame was assumed to be part of a seven-story hospital building; however, only the first two stories of the frame were constructed due to consideration of shaking table capacity limitations, safety issues in case of global collapse, and the fact that damage oftentimes concentrated at the lower stories. At total, some 10,000kg inertial mass was required to account for the inertial force from the upper stories. A brief introduction of a good number of different inertial mass systems ever built in Japan and the multipurpose inertial mass system fabricated for E-Defense steel project can be referred to Takeuchi et al. (2007). An off-table inertial mass system has been used for bridge column tests in Laplace et al. (1999). The advantage of utilizing an off-table inertial mass system is that the payload limitation of a shaking table can be effectively loosened so that a specimen of higher strength can be tested for its dynamic behavior under earthquake excitation. The usage of an off-table inertial mass system will incur the issue of phase angle should the drift at failure be a main concern because such a test setup may not well represent the phase angle characteristics of a real building subjected to earthquake excitation. In the extreme case of complete out-of-phase between the inertial mass system and the specimen, the lateral inertia force is even helping stabilize the specimen; thereby the measured drift at failure is inevitably inaccurate even though accurate ultimate strength can be still obtained.

An on-table inertial system was adopted in this study because this test setup can provide complete dynamic characteristics of both strength and deformation capacity. The on-table inertial mass system built for the study is shown in Fig. 5, which was comprised of two mass cars with anti-rocking frictionless sliders. Two mass cars were running on wide-flange guiding rails made of A572 Gr. 50 steel with stiffeners and perfect machined low-friction surface such that the inertial mass system did not transmit its weight onto the specimen but still provided sufficient lateral force through steel rigid links connecting to the specimen top floor. As aforementioned, the gravity load of the column is mainly supplied by the high axial load applying system that simulated the weight from above the second story and partly by the lead packets installed on the floors. Each mass car consisted of four 20mm cushioning rubber pads for shock absorbing, and four stainless steel main wheels running on the top of flanges, and 16 smaller stainless steel side wheels running along the side of flanges for better in-plane motion stability, and the anti-rocking mechanism comprised of four stainless steel wheels running on the machined surface of the bottom flanges to avoid unfavorable car rocking at reversal of the direction of car motion. The rigid link connecting the mass car and concrete specimen was made of tubular steel strut with cylindrical bearings (fish-eye hinge) at its two ends. The cylindrical bearing allowed the steel linking strut to have free in-plane rotation to allow for vertical drop of the specimen frame at failure, and moderate out-of-plane rotation capability to accommodate construction tolerance in specimen geometry and vertical alignment, and technical difficulties in precision frame positioning on the table. One end of the linking strut was connected to the steel-jacketed center column stub on the roof of the specimen, and the other end of the strut was based on the steel transverse reaction beam in the mass car away from the center column stub to keep the generated inertial force mainly in the horizontal direction after the initiation of progressive collapse. The other adjustment capability for precision alignment came from the slotted holes in the steel transverse reaction beam of the mass car to have more allowance for construction and positioning imperfections. The stroke of the mass car was ±200mm.

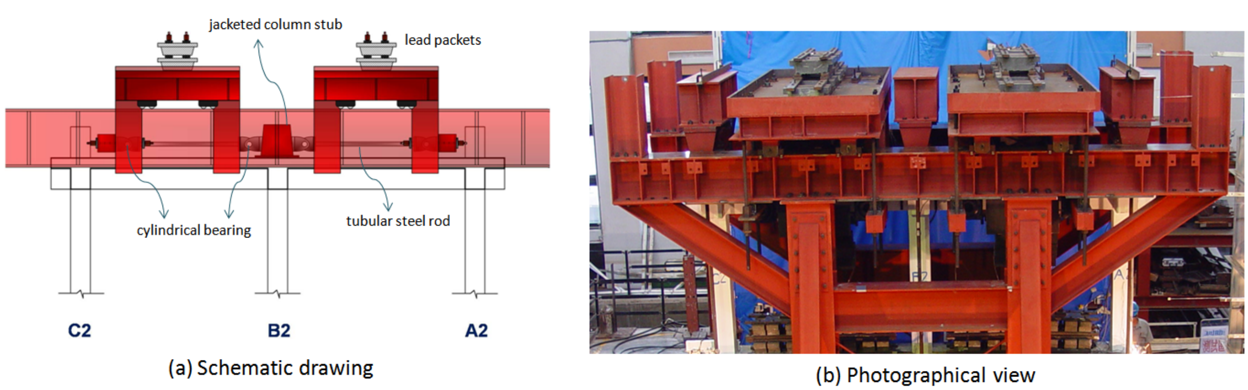
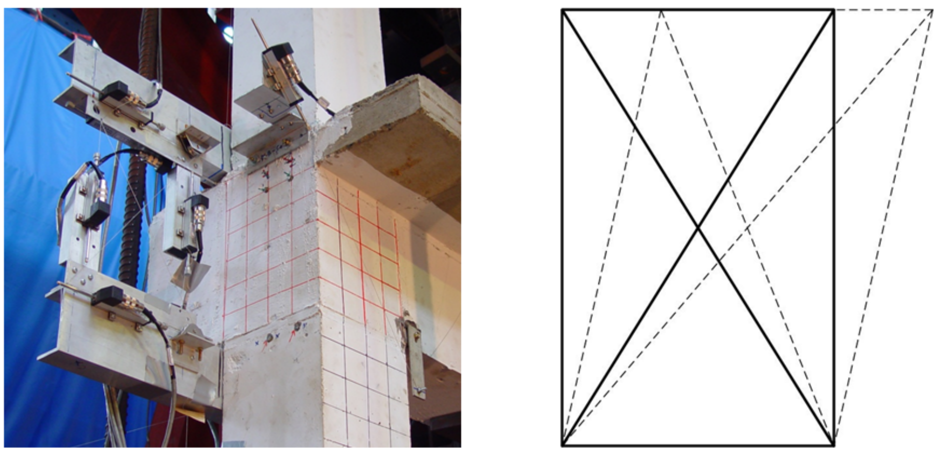


Fig. 5. Schematic drawing of the on-table inertial mass system.

Instrumentation

In addition to the testing rig design reported above, instrumentation layout included global and local measurements of the structural responses during earthquake excitation. The instrumentation used in the experimental program can be grouped into five major categories: (1) shaking table instruments that measured horizontal and vertical displacements, velocities, and accelerations averaged using sensors installed at four corners of the table; (2) force transducers that measured shear and axial forces at the base of the frame footings and at the top of columns; (3) strain gauges that measured longitudinal and transverse reinforcements in columns, beams, and joints; (4) accelerometers that measured horizontal and vertical accelerations at points of interest on the frame; (5) displacement transducers that measured local column, local joint, and global frame deformations. An innovative measuring frame made of aluminum channels and angles for recording the beam-column joint deformation is shown in Fig. 6. This type of measuring technique was especially helpful in collecting valuable dynamic joint deformation data from MUF and MUFS specimens. Displacement transducers with restoring springs provided 10-14Hz operating frequency and ±0.002mm accuracy in the joint local deformation measurement. The local deformation of column was measured at its two plastic zones at top and bottom and its middle elastic zone, in which another type of local instrumentation frame was employed to measure local deformation resulted from flexure, shear and bar slip actions (Elwood, 2002).



(a) Local instrument measuring joint rotation

(b) Schematic plot for calculating joint rotation

Fig. 6. Local instrumentation for measuring beam-column joint deformation: (a) photographical view; (b) schematic drawing.

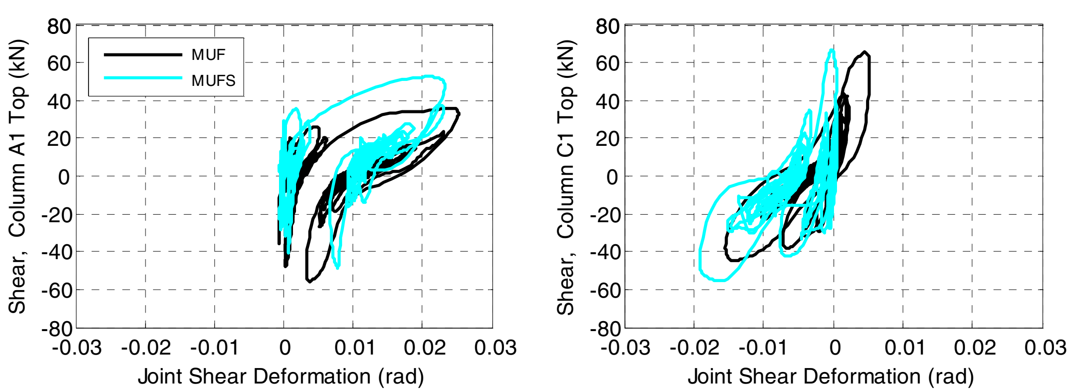


Fig. 7. Shear hysteretic responses of exterior joints A1 and C1 of specimens MUF and MUFS subjected to 1.8g TCU047ns motions.

PRELIMINARY FINDINGS AND DISCUSSIONS

The integrative testing system presented here provided a perfect testing platform for observing dynamic structural collapse, particularly under high axial load that was common in mid- to high-rise buildings. A total of four 1:2.25 scaled two-bay two-story concrete frames were tested in this experimental program and all specimens were subjected to one-directional ground motions at various peak acceleration levels using the north-south component of the strong motion record at station TCU047 during the 1999 Chi-Chi (Taiwan) earthquake. Although the collapse testing system reached the test goal with success, yet there remain further improvements that can be made in the rig design should a similar type of shaking table tests be favorable in the future. There exist many possible ways of reducing axial load fluctuation, such as increasing the volume of the accumulator, shortening the oil pipelines, enlarging the diameter of the oil pipelines, or even considering an active control algorithm if more confidence in predicting structural failure can be achieved in the future. On the other hand, the lateral inertial mass system was connected to the jacketed extension stub of the center column, but this would have likely caused a concentration point of the lateral load applied to the frame, which can be further improved in the future by utilizing a distributed force transmitting mechanism. In addition to the testing rig design, there were preliminary major findings in the structural behavior. Experimental observations suggest that the layout of critical elements was crucial in determining the sequence of progressive collapse and ultimately global frame collapse mechanisms, and that the level of axial load can also have a significant impact on the failure mode of the frame. The unconfined beam-column joints played an important role in the overall structural behavior of the nonductile frames as large shear deformations at the joints reduced local rotation at the column top. In particular, the behavior of specimen MUFS indicated that inter-story drifts might not correlate well with the shear failure of flexure-shear-critical columns; instead, the shear failure initiation appeared to be more related to column end rotations than column drifts. The final damage states of all four specimen frames are provided in Fig. 8.

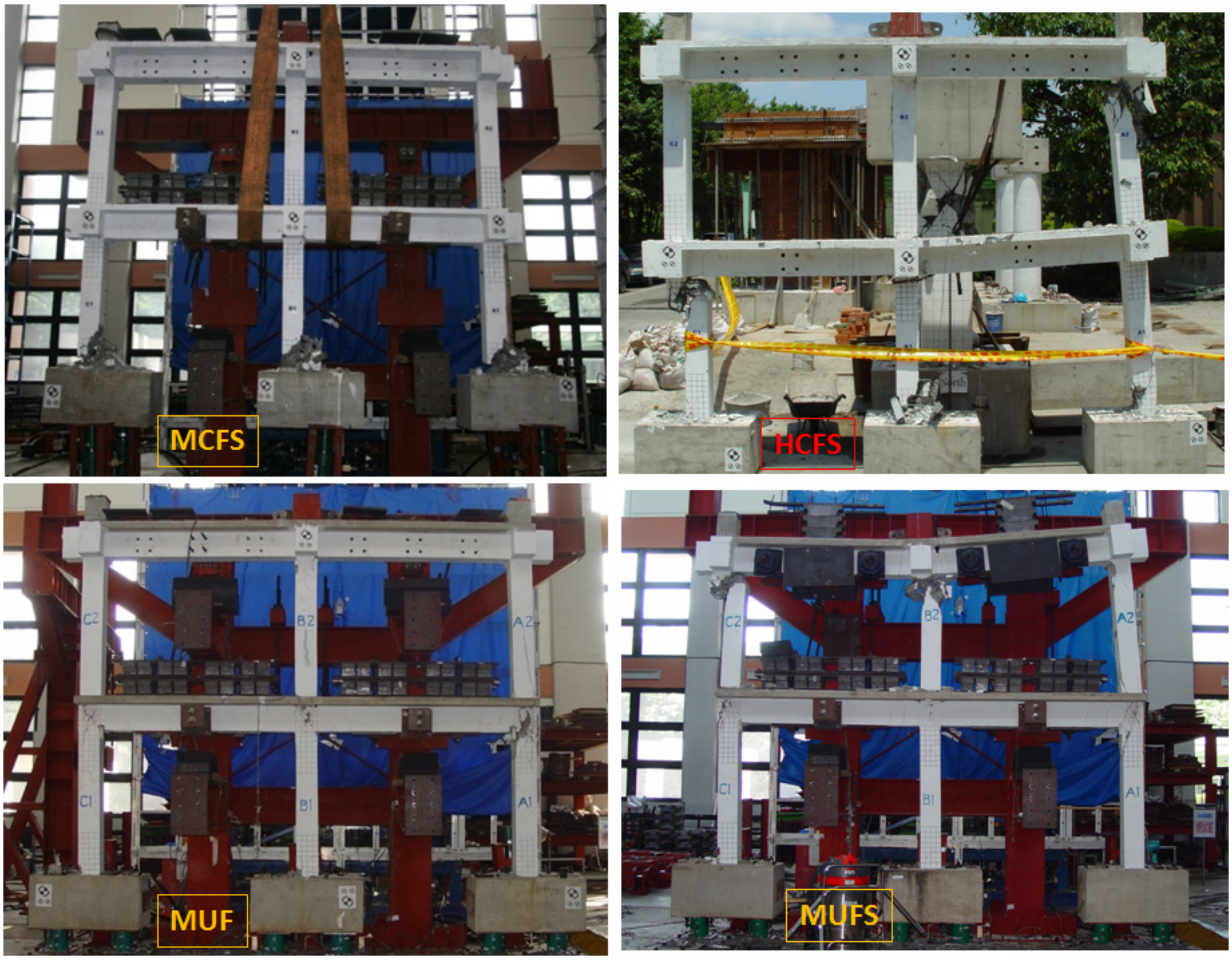


Fig. 8. Final damage states of the frame specimens at the end of tests.

CONCLUSIONS

The design of an integrative testing system for observing dynamic collapse of 1:2.25 scaled two-bay two-story concrete frames subjected to one-directional shaking table motions is reported. Through activating the high axial load and inertial mass system of the testing rig, the two-story frame specimen was able to reasonably represent the dynamic behavior of a seven-story concrete frame up to the point of structural collapse. The proper proportioning of structural component dimensions allowed for experimental observation of the realistic whole frame interaction. The unconfined beam-column joints played an important role in the overall structural behavior of the nonductile frames as large shear deformations at the joints reduced local rotation at the column top so that the column end rotation seemed to be a better index for identifying the onset of column shear failure than the column drift.

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REFERENCES

Elwood, K.J. 2002. *Shake table tests and analytical studies on the gravity load collapse of reinforced concrete frames*, Department of Civil and Environmental Engineering, University of California, Berkeley, PhD dissertation, (advisor: Jack P. Moehle).

Laplace, P., Sanders, D., Saiidi, M.S., and Douglas, B. 1999. *Shake table testing of flexure dominated reinforced concrete bridge columns*. CCEER Report 99-13, Center for Earthquake Engineering Research, Department of Civil Engineering, University of Nevada, Reno.

Takeuchi, T., Kasai, K., Midorikawa, M., and Matsuoka, Y. 2007. E-Defense tests on full-scale steel buildings: Part 4 - Multipurpose test bed for efficient experiments. *ASCE Structures Congress*, Long Beach, CA, USA, May 16-20.

Tseng, C-C., Hwang, S-J., Yeh, Y-K., Lee, Y-T. 2009. Experiment of RC building frame subjected to bi-directional cyclic loading. *2008 NCREE Research Programs and Accomplishments*: 17-20, published by the National Center for Research on Earthquake Engineering, Taiwan.

MOI, Taiwan 2009. *Building Technical Regulations*. Construction and Planning Agency, Ministry of the Interior, July, Taipei, Taiwan, ROC. (in Chinese)