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SHAKING TABLE COLLAPSE TESTS OF TWO SCALE MODELS OF A 4-STORY MOMENT RESISTING STEEL FRAME

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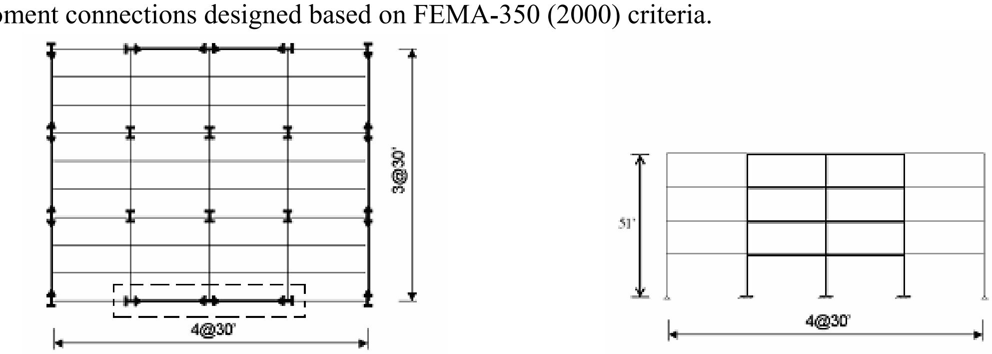
ABSTRACT:
In support of collapse assessment of structural systems under earthquake excitations, two earthquake-simulator collapse test series of two scale models of a two-bay steel frame with reduced beam section connections were conducted at the NEES facility at the University at Buffalo. Based on the comprehensive data set acquired from these shaking table collapse test series we are able to quantify important engineering demand parameters such as story forces and shears, story drifts, plastic rotations, floor accelerations and velocities, in the inelastic range up to incipient collapse. Based on analytical simulations with the use of relatively simple models it is demonstrated that sidesway collapse of frame structures, including the effects of P-Delta and component deterioration, can be predicted with good accuracy provided that component deterioration is accurately represented.

KEYWORDS:
Collapse, deterioration modeling, shaking table test, scale model, P-Delta effect, collapse mechanism

1. INTRODUCTION

Till recently, there was no comprehensive physical experiment on steel structures that could be used to validate that prediction of sidesway collapse is indeed feasible. For this reason, two scale models of a 4-story prototype moment resisting frame, part of an office building designed based on current seismic provisions (IBC-2003, AISC-2005) were tested on the shaking table of the NEES facility at University at Buffalo. The 4-story office building, shown in Figure 1a in plan view is located in the Los Angeles area on site class D. The structural system, which is shown in Figure 1b, is a special moment resisting frame (SMRF) with reduced beam section (RBS) moment connections designed based on FEMA-350 (2000) criteria.



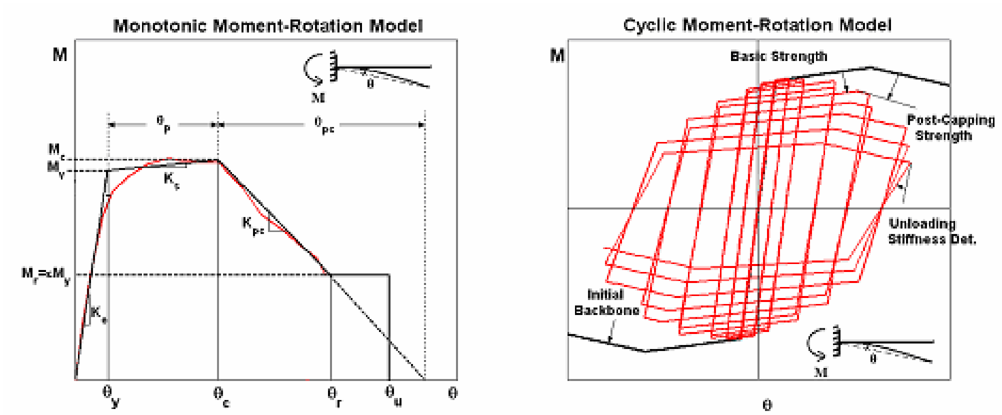
(a) (b)

Figure 1. 4-story prototype structure; (a) plan view, (b) elevation

The main objectives of the shaking table tests of the two 1:8 scale models of the moment resisting frame shown in Figure 1b are (1) quantification of engineering demand parameters of the frame, such as story forces and shears, story drifts, plastic rotations, floor accelerations, in the elastic and inelastic range all the way to collapse; (2) demonstration that P-Δ sideway-induced collapse can occur under realistic structural and ground motion conditions and that P-Δ effect can be isolated and quantified up to collapse; (3) demonstration that reasonably accurate collapse prediction of deteriorating structural systems is indeed feasible with relatively simple analytical models and (4) quantification of the effect of component deterioration on collapse capacity of the test frames.

2. DETERIORATION MODELING

In order to model deterioration characteristics of components we use a modified version of the Ibarra–Krawinkler deterioration model (Ibarra et al. 2005). This model is based on a backbone curve that defines a reference skeleton for the behavior of a structural component, i.e., it defines strength and deformation bounds, and a set of rules that define basic characteristics of the hysteretic behavior between the bounds defined by the backbone curve. Four modes of deterioration are defined with respect to the backbone curve. Figure 2a shows the monotonic backbone curve of the modified Ibarra - Krawinkler deterioration model. Figure 2b shows the effects of basic strength and post – capping strength deterioration together with unloading stiffness deterioration. A detailed description of the Ibarra-Krawinkler model and its modifications is presented in Lignos (2008).



(a) backbone curve (b) basic modes of cyclic deterioration

Figure 2. Modified Ibarra–Krawinkler model used in this study

3. SHAKING TABLE TESTS

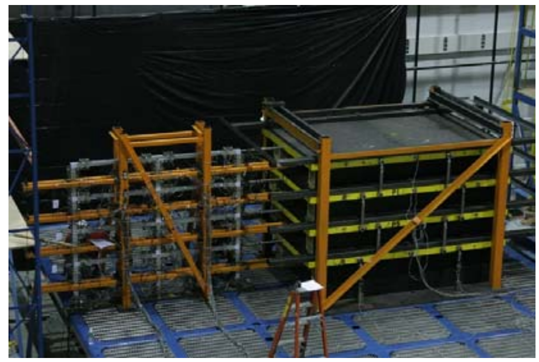
3.1 General Description

Two scale models of the moment resisting frame shown in Figure 1b are used to carry out a series of shaking table tests in which the ground motion intensity is incremented until collapse occurs. The scale is 1:8 due to weight limitations of the shaking table facility. Figure 3a shows the test frame in between its lateral support system. The overall setup on the shaking table is shown in Figure 3b. Based on similitude laws (Moncarz and Krawinkler, 1981), and considering the small self-weight of the test frame, it is necessary to add almost 1/64 of half of the weight (4350kips) of the prototype building to the test frame in order to properly simulate gravity and inertia forces. To solve this problem we add this weight in a mass simulator that is connected to the test frame with links at the four floor levels that are axially very stiff but provide no rotational restraint. The four links are instrumented and act as load cells that provide accurate measurement of story forces applied to the test frame, including P–Δ forces that are transferred from the mass simulator to the test frame. The mass plates, which approximately weigh 8.9 kips each, are connected together with four vertical links per story. Each vertical link has spherical hinges (rod ends) at both ends in order to permit free rotation. The mass simulator, illustrated in Figure 3b, is in essence a mechanism and has no lateral resistance if disconnected from the test frame.

The test frame shown in Figure 3a consists of elastic beam and column elements and elastic T- or cruciform-shaped joint elements, all machined from aluminum stock, joined together by plastic hinge elements. A plastic hinge element, which is shown in Figure 4, consists of a spherical hinge (rod end bearing) whose function it is to transfer shear, two steel flange plates that are machined from bar stock so that plastic hinging (with appropriate deterioration) at the ends of beams and columns is realistically represented at model scales, spacer plates that permit adjustment of the distance between the flange plates and of the buckling length of the flange plates, and four bolts that are post-tensioned after all plastic hinge elements are installed and the test frame is carefully aligned (see Figure 4b). These plastic hinge elements are inserted at the ends of all beam and column elements of the model structure, recognizing the possibility of inelastic behavior in each element.

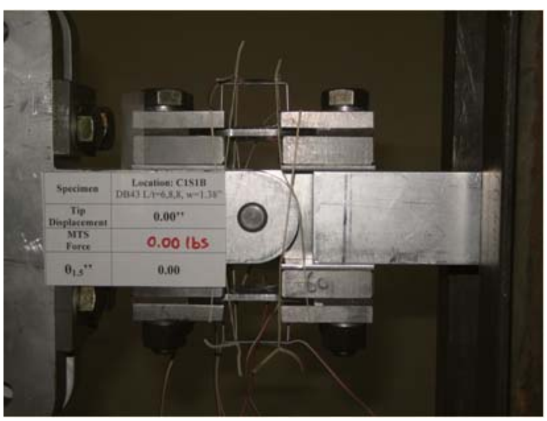
The erection sequence of the test setup on the shaking table made it possible to “swap” test frames with minimum effort after the completion of the collapse test series of Frame #1. The only parts that had to be replaced are the flange plates of the plastic hinge elements because many of them buckled or fractures in the later stages of the test series for Frame #1.

(a) test frame

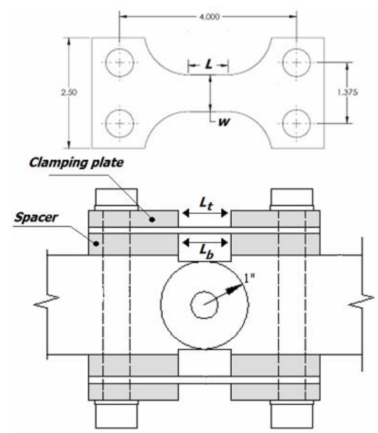


(b) 4-story test frame and mass simulator

Figure. 3. 4 story test frame on shaking table at the University at Buffalo NY after installation



(a) plastic hinge element

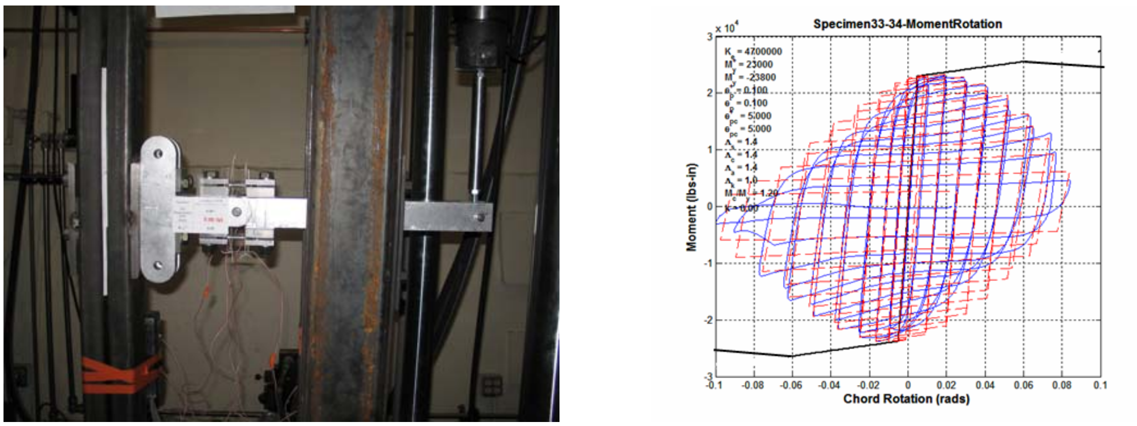


(b) control parameters for plastic hinge element

Figure 4. Typical plastic hinge element

3.2. Component Deterioration

Deterioration modeling and planning for the shaking table tests of the two test frames necessitates a series of component tests. The component tests aim to identify (1) the configuration of plastic hinge elements (2) final flange plate dimensions of each plastic hinge element of the test frame, (3) the geometry and boundary conditions in order to replicate the hysteretic behavior of the prototype connections, and (4) the deterioration characteristics of each component of the test frame. A program of 50 component tests is carried out in which the basic dimensions of the flange plates together with their boundary conditions, shown in Figure 4b, are varied systematically. Specimens with single and double plate arrangements are tested both monotonically and cyclically, using a universal testing machine and the test setup shown in Figure 5a. Flange plates for each specimen are instrumented with strain gages and clip gages. A typical calibrated moment rotation diagram of a component subassembly with two steel plates, using the AISC (2005) loading protocol, is shown in Figure 5b. For all the pre-test collapse predictions of both test frames we used deterioration model parameters based on the component tests discussed in this paragraph.

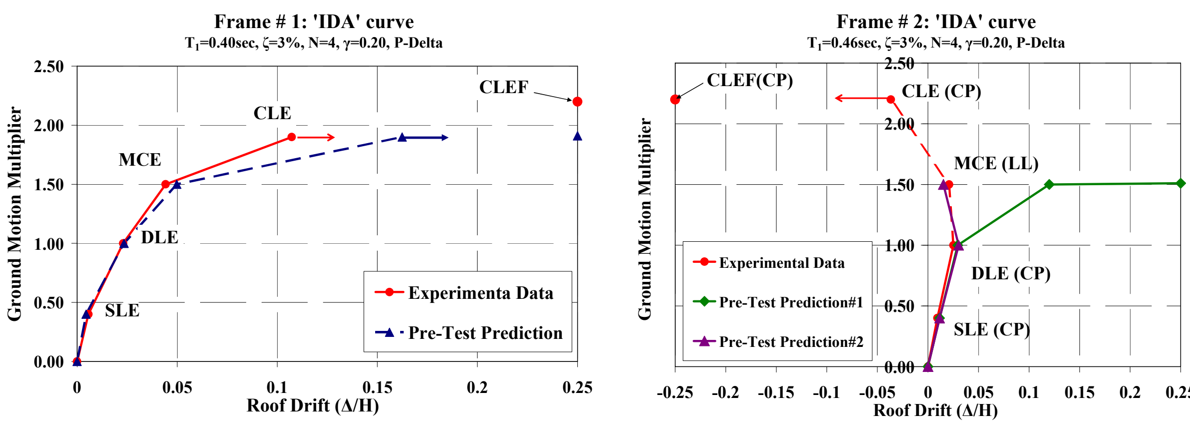


(a) component subassembly in the testing apparatus (b) calibrated M-θ diagram of a plastic hinge element

Figure 5. Typical component subassembly of the test frame

3.3. Testing Phases and Overall Behavior of Test Frames

A "physical" Incremental Dynamic Analysis (IDA) is conducted for both test frames. The basic difference with a standard IDA is that each inelastic test causes permanent damage that creates different initial conditions for each subsequent test. In the shaking table testing of Frame #1 we used the Northridge 1994 Canoga Park record in order to evaluate performance of the frame from elastic behavior up to collapse. Four tests were planned [Service Level (SLE), Design Level (DLE), Maximum Considered (MCE) and Collapse Level (CLE) earthquakes], see Figure 6a. Frame #1 was expected to collapse at the CLE level but stabilized at about 11% roof drift, which necessitated a fifth test, denoted as CLEF.

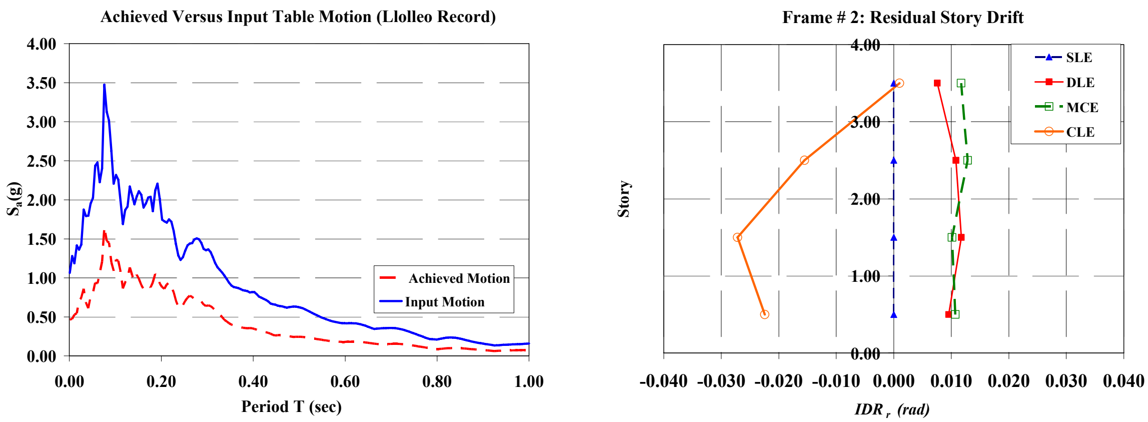


(a) Frame #1 (b) Frame #2

Figure 6. Analytical pre-test collapse prediction versus experimental 'IDA'

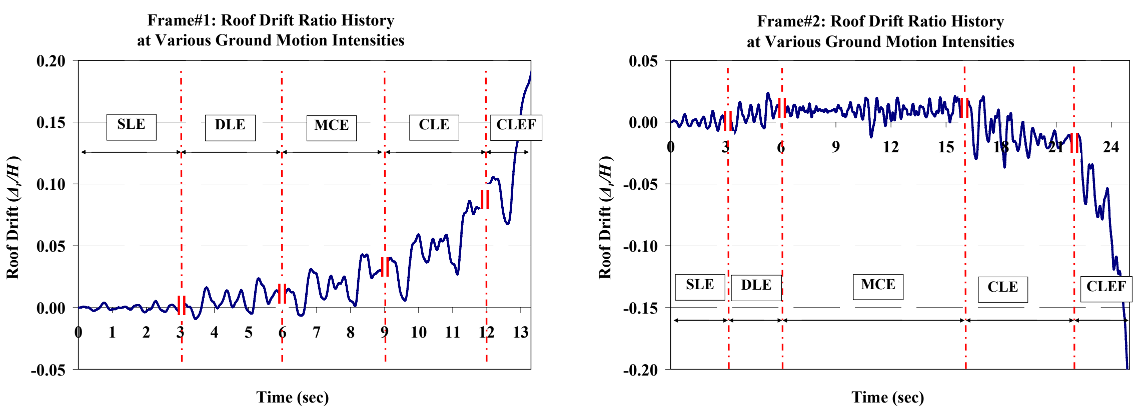
In the CLEF test Frame #1 collapsed after the first reversal of the ground motion. The fact that the frame collapsed very early in the CLEF test indicates that the analytical pre–test prediction was fairly close to the intensity at which the frame did collapse in the experiment.

For Frame #2 the objective was to investigate the effect of cumulative damage prior to collapse; thus we used the Chile 1985 Llolleo record for the MCE level. Figure 6b shows the physical 'IDA' obtained from the experimental data and *pre-test* analytical predictions. The analytical prediction indicates that Frame #2 would be close to collapse at the MCE level. However, in the shaking table test the Llolleo record did not cause an increase in residual drift, which was very puzzling until it was found out (much later) that the input ground motion was not reproduced successfully in the shaking table as seen from Figure 7a. Using the recorded MCE table motion the pre-test analysis prediction for Frame #2 (see Figure 6b pre-test prediction #2) indicates that the response of Frame #2 is analytically predicted fairly well at the MCE level. After the puzzling MCE level response we switched back to the Canoga Park record. During CLE Frame #2 started drifting in the opposite direction, and it collapsed in this opposite direction at the CLEF level ground motion (2.2 times Canoga Park) (see Figure 6b). The roof drift response of both frames is shown in Figure 8, in which we show only the response during the large amplitude motions of the full test series from SLE to CLEF. Each test is separated with a dashed line from the other.



(a) (b)

Figure 7. Frame #2; (a) recorded versus input motion at MCE level, (b) residual story drift after various ground motion intensities



(a) Frame #1 (b) Frame #2

Figure 8. Roof drift ratio history for both test frames at various ground motion intensities

3.4. Collapse Mechanism

Figure 9a illustrates the 3–story collapse mechanism of Frame #1 after the end of CLEF. The upper portion of the mechanism is formed by column plastic hinges at the top of the 3rd story, even though the weak beam - strong column (WBSC) criterion was fulfilled in the design process of the prototype moment resisting frame. Using the same ground motion for the CLEF but different sequence of ground motions prior to collapse, Frame # 2 collapsed with an identical mechanism as Frame #1, but in the opposite direction for reasons stated in the previous paragraph. The collapse mechanism of Frame #2 is shown in Figure 9b.

(a) Frame #1 (b) Frame #2

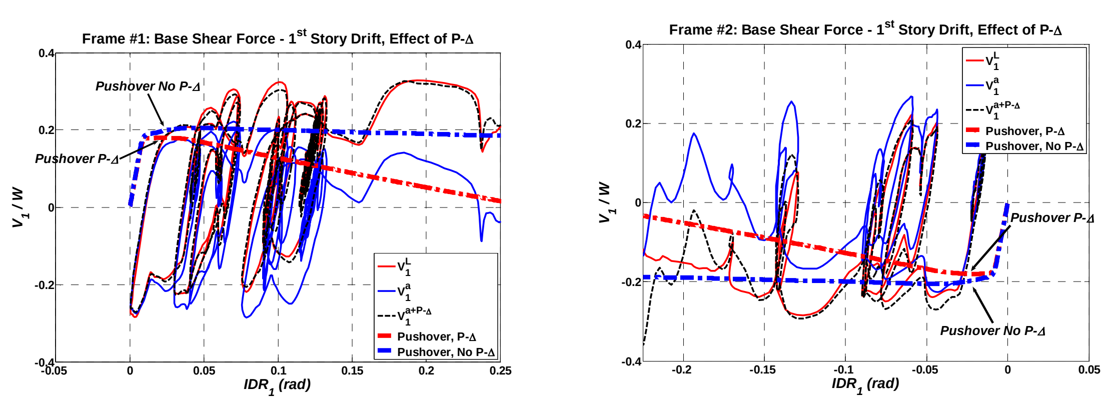
Figure 9. Collapse mechanism of both test frames after the completion of CLEF

3.5. *Base Shear – 1st Story Drift and Quantification of P-Delta Effects*

The test setup, with the "weightless" test frame driven by a mass simulator that is connected to the test frame by a series of instrumented links, provides an excellent opportunity to measure and quantify P-Delta effects in an explicit manner up to collapse. Figure 10 shows the normalized base shear – 1st story drift ratio diagram of both frames up to collapse. The red curve (gray in black – white print) is the "base shear" as obtained from the horizontal links (V_1^L) connecting the mass simulator to the test frame, normalized with respect to the total weight. These are the actual "shear forces" applied to the essentially weightless frame including the effect of P-Delta (actual resistance of both frames). The blue curve (black in black-white print) is the "base shear" obtained from masses times floor accelerations, i.e., the inertia forces (V_1^a). The difference between the two measurements is fully attributable to P-Delta effects.

For a given drift the P-Delta effect in the first story can be approximated by an equivalent story shear equal to $P\delta_1/h_1$ with P being the total weight of the plates of the mass simulator, h_1 being the first story height, and δ_1 being the first story relative displacement. When this quantity is added to V_1^a, the shear forces shown dashed in Figures 10a and 10b are obtained. The observation that the dashed shear force - drift diagrams are close to the measured V_1^L – drift diagrams confirms that all measurements are of adequate accuracy and that the P-Delta effect can indeed be represented reasonably by the simple term $P\delta/h$.

Superimposed on the shaking table results in Figures 10a and 10b, and shown in dotted lines, are static pushover curves without and with P-Delta obtained from post-test analytical predictions. A comparison of these curves with envelopes of the dynamic test results provides insight into the value of a pushover analysis for response prediction close to collapse for a first mode-controlled frame.

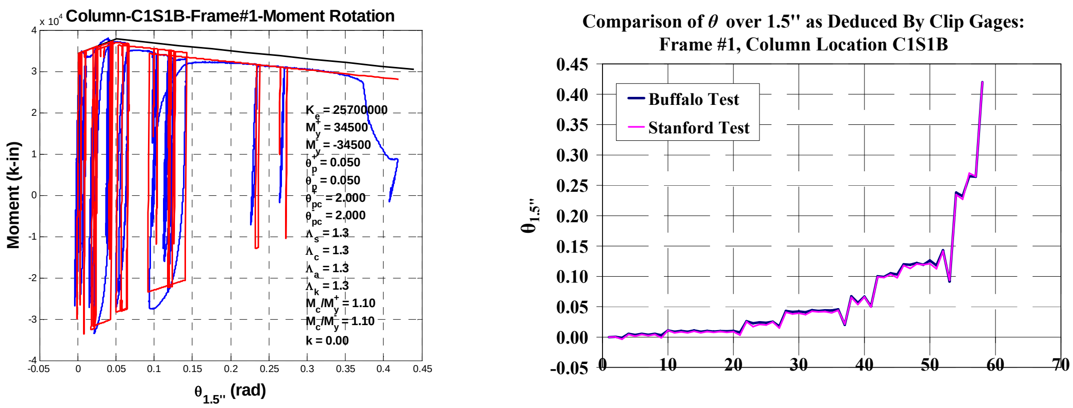


(a) Frame #1 (b) Frame #2

Figure 10. Normalized base shear - first story drift relationship for both test frames (CLE & CLEF)

4. POST TEST ANALYSIS PREDICTIONS

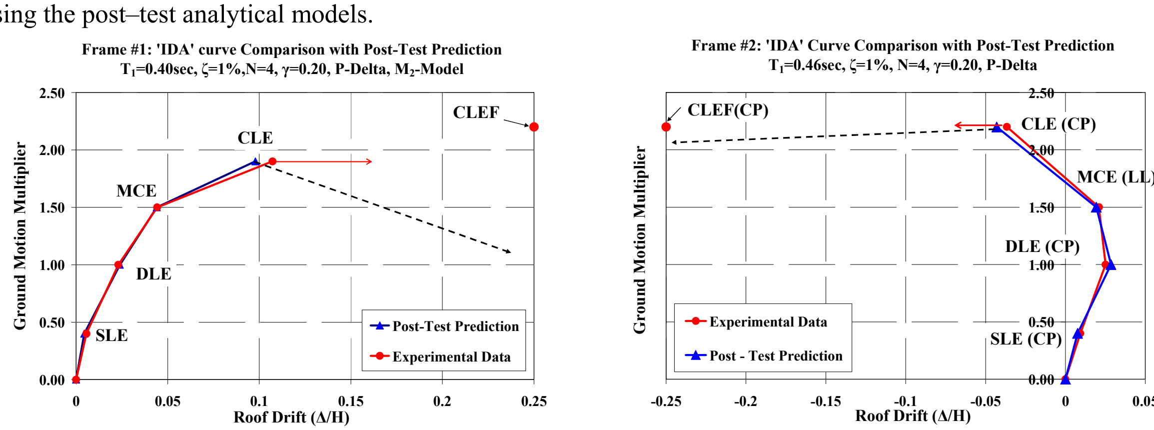
In order to deduce moment rotation relationships for critical plastic hinge elements of the test frame and demonstrate the effect of component deterioration on the collapse capacity of the test frame we performed a series of post–shaking table component tests, using the rotation histories recorded in the shaking table tests as input for the displacement history of the component tests. The component subassembly setup shown in Figure 5a was used again for this purpose. Figure 11a shows the moment rotation diagram for the exterior column base of Frame #1 from elastic behavior up to collapse. In the same figure we have superimposed the modified Ibarra–Krawinkler deterioration model after calibration. As seen in Figure 11b, the two rotation histories for the same plastic hinge element from Buffalo and Stanford tests, as deduced from clip gage instrumentation over 1.5" length, are almost identical indicating confidence in the reproduction of the shaking table test rotation histories.



(a) (b)

Figure 11. Post shaking table component tests; (a) moment rotation diagram for exterior column base of Frame #1 together with the calibrated analytical model (b) comparison between $\theta_{1.5"}$ from Buffalo and Stanford tests for the same location

For the post–test analytical response prediction of the two frames we use the recorded shaking table ground motions. The deterioration parameters of critical plastic hinge elements of the test frames are modified based on the moment rotation diagrams obtained from post test component tests discussed in the previous paragraph. Figure 12 shows the experimental 'IDA' curve for both frames together with the post-test analytical predictions. The analytical predictions at CLE are fairly close to the experimental data for both frames, indicating that analytical prediction near collapse can be rather accurate but is sensitive to the accurate representation of deterioration parameters of critical components of both test frames. The analytical predictions also indicate (see dashed line) that both frames would collapse even if we apply a lower intensity motion to both model frames after CLE. The dashed lines are based on analytical predictions using the post–test analytical models.



(a) Frame #1 (b) Frame #2

Figure 12. Experimental 'IDA' curve versus post-test analytical prediction for both model frames

5. SUMMARY AND CONCLUSIONS

Two recent collapse experiments of 1:8 scale models of a prototype moment resisting frame, part of a 4-story building designed based on current U.S seismic provisions, are presented and evaluated. As a result of shaking table tests series conducted at the NEES facility at the University at Buffalo, a comprehensive set of well documented data is available that quantifies engineering demand parameters such as story forces and shears, story drifts, plastic rotations, floor accelerations, in the elastic and inelastic ranges all the way to collapse. The experimental data is available through (http://central.nees.org).

Collapse of both frames is caused by P-Δ effects and component deterioration. As is shown through the shaking table collapse test series, P-Δ effects can be isolated and quantified for the full range of response from elastic behavior up to collapse. P-Delta effect can indeed be represented reasonably by the simple term $P\delta/h$, with P being the total weight of the plates of the mass simulator, h being the first story height, and δ being the first story relative displacement of the test frame. The availability of experimental data that permits calculation of all relevant force and deformation quantities facilitates the study of phenomena that otherwise could be evaluated only from results of numerical investigations.

Reliable analytical prediction of collapse of deteriorating structural systems is sensitive to the adequate representation of deterioration characteristics of critical components from analytical component hysteresis models. The component tests of critical plastic hinge elements of the test frame, using the rotation histories of the shaking table collapse test series and the post-test collapse predictions of the two scale models of the prototype moment resisting frame, did demonstrate that the response near collapse is sensitive to the loading history every component experiences as part of the frame.

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