ANALYTICAL AND EXPERIMENTAL PREDICTION OF SIDEWAY COLLAPSE OF STEEL FRAMES

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1. ABSTRACT

A major issue in efforts to predict collapse of structural systems is the lack of physical experiments that demonstrate how collapse occurs and that can serve to validate analytical models of components and systems. For this reason two earthquake-simulator tests to collapse were conducted using the NEES facility at the University at Buffalo for a two-bay steel frame with reduced beam section connections. The effect of component deterioration on collapse capacity of the test frames was explored with a comprehensive component testing program at Stanford University

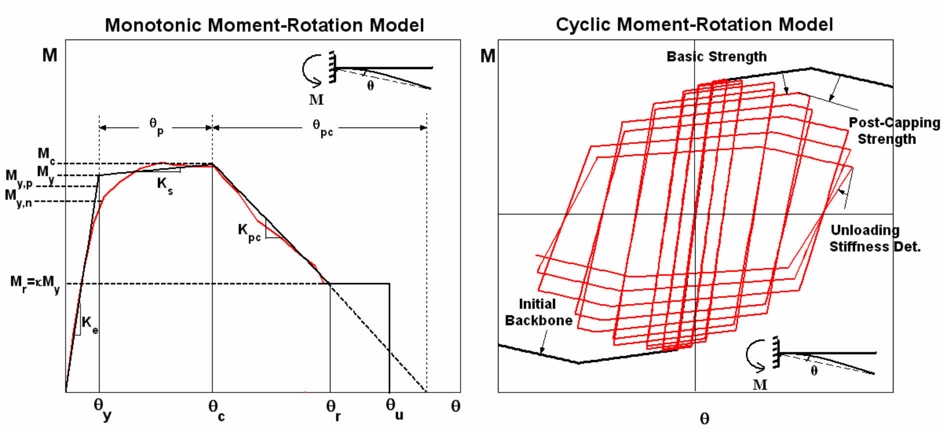
Through the successful completion of the earthquake-simulator collapse tests a landmark set of data became available that quantifies engineering demand parameters such as story forces and shears, story drifts, plastic rotations, floor accelerations and velocities, in the inelastic range through to collapse. We conclude that P-Δ sideway collapse can occur under realistic structural and ground motion conditions and that the P-Δ effect can be quantified up to collapse. Through the series of tests it is demonstrated that sidesway collapse of frame structures, including the effects of component deterioration, can be analytically predicted by means of relatively simple models that can be incorporated in presently available dynamic analysis programs.

2. INTRODUCTION

Understanding, predicting, and preventing collapse has always been a major objective of earthquake engineering since collapse is the main source of injuries and loss of lives. The primary objective of this research is to develop, through analytical and experimental research, a consistent approach to the prediction of collapse of structures and for incorporation of collapse safety concepts in the design process. In particular, this research prepares the road to predict one critical mode of collapse, namely that associated with sidesway (incremental) collapse in which an individual story (or a series of stories) displaces sufficiently so that the second order P-delta effects fully offset the first order story shear resistance and dynamic instability occurs, i.e., the structural system loses its gravity load resistance. Till recently, there was no comprehensive physical experiment on steel structures that could be used to validate that prediction of collapse is indeed feasible. With the use of an advanced shaking table and the associated infrastructure at the SUNY University at Buffalo NEES facility it is demonstrated the feasibility of collapse prediction by means of 2 comprehensive shaking table experiments in which a scale model of a 4-story steel frame was tested to collapse. Component deterioration is taken into consideration in the analytical prediction of collapse and was quantified with a comprehensive testing program at Stanford University in which 50 component tests were conducted.

3. DETERIORATION MODELING

In order to model deterioration characteristics of components in this study, we use a modified version of the Ibarra–Krawinkler deterioration model «[1]». 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 set of rules that define the 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. *Fig. 1a* shows the monotonic backbone curve of the modified Ibarra - Krawinkler deterioration model. *Fig. 1b* shows basic strength and post – capping strength deterioration together with unloading stiffness deterioration effects on the post–capping and unloading branch. A detailed description of current and further modifications is presented in «[2]».



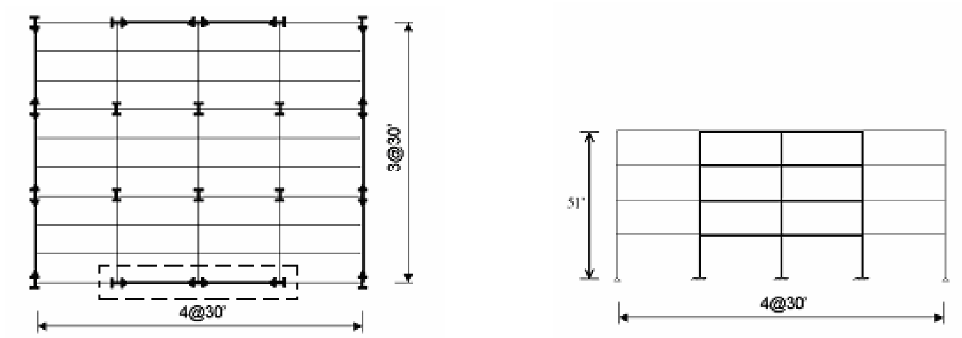
(a) backbone curve *(b) basic modes of cyclic deterioration*

Fig. 1. Modified Ibarra – Krawinkler model

4. PROTOTYPE STRUCTURE

A 4-story office building, shown in *Fig. 2a* in plan view, is used as a case study to illustrate the collapse methodology and obtain the global (sidesway) collapse capacity. The building was designed in accordance with «[3]» and is located in the Los Angeles area. Site class D is used in order to obtain the design response spectrum. The structural system is a special moment resisting frame (SMRF) with fully restrained reduced beam section (RBS) moment connections designed based on «[4]».

The east-west (EW) perimeter frame, shown in *Fig. 2b*, has been evaluated using a mathematical model that includes deformations of the panel zones as suggested «[5]». Material nonlinearity is taken into account with concentrated plasticity springs. Deterioration parameters for both columns and beams are extracted from a steel database that is under development by «[2]», «[6]». The behavior of the building has been evaluated based on nonlinear static and dynamic analysis procedures, as it is discussed in great detail in «[2]».



(a) *(b)*

Fig. 2. NEESR 4- story prototype structure (a) plan view and (b) elevation

5. SHAKING TABLE TESTS

Part of the NEESR project was the execution of a collapse test using the NEES facility at the University at Buffalo. For this purpose we use a model of the prototype office building described in the previous section. The scale of the model building is 1/8 due to weight limitations of the shaking table at Buffalo.

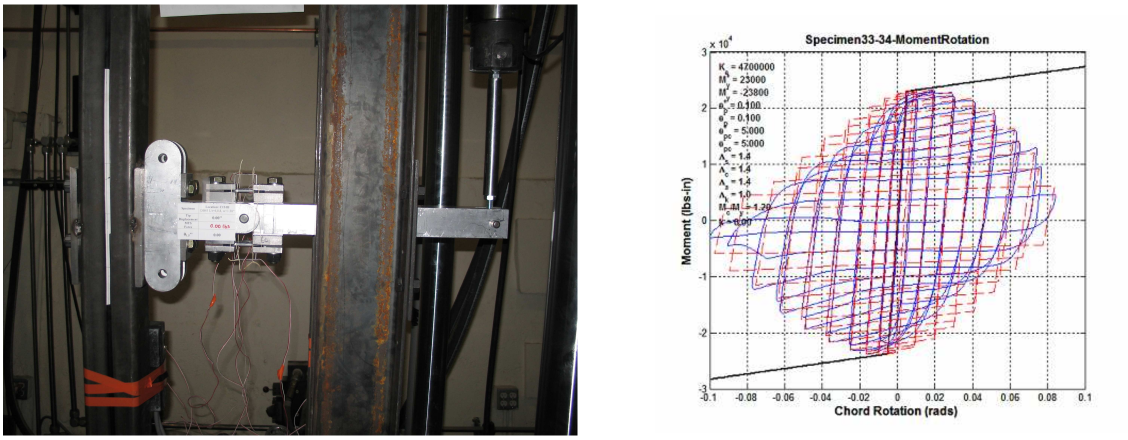
(a) 4 story test frame and mass simulator *(b) test frame*

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

Fig. 3a shows the overall setup of the EW moment resisting frame together with a mass simulator that is used to support the weights needed to model inertia forces and to simulate P-Delta effects. The photo also shows the braced frames (with orange color) used to provide lateral bracing for the test frame and the mass simulator. In *Fig. 3b* there is a closer view of the test frame with its bracing system. The test frame and mass simulator are connected with 4 “rigid” horizontal links (one per floor). All four links are acting as load cells in order to measure the individual story forces transferred from the mass simulator to the test frame, including the P-Δ effect.

6. COMPONENT DETERIORATION

In the 1/8 scale model of the prototype structure it was convenient to machine the elastic portions of the structural elements from aluminum stock in order to follow similitude laws for stiffness. The plastic hinge regions in the model structure are simulated by a spherical hinge whose function it is to transfer shear, and two steel flange plates that are machined from bar stock. The thickness of the flange plates is 0.15”, and the width is adjusted to the required bending strength of the individual elements. A typical plastic hinge region of the model structure is shown in *Fig. 4a*.



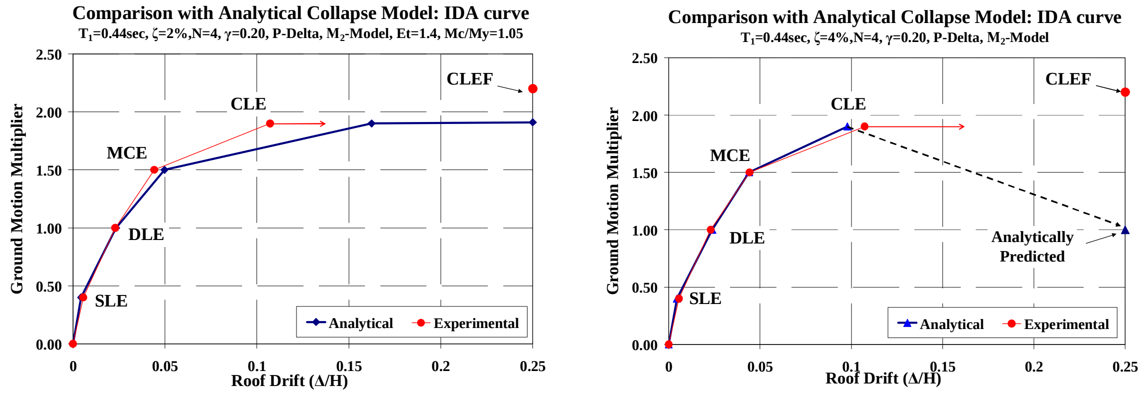
(a) *(b)*

Fig. 4. Typical component subassembly of NEESR- 4 story frame (a) connection details (b) calibrated moment rotation diagram of a typical connection of the test frame

The dimensions of the flange plates are tuned such that the pre-and post-buckling behavior of the model plastic hinge regions is comparable with the moment rotation relationships of prototype plastic hinges at the end of structural member. Since different deterioration characteristics were targeted, a comprehensive component testing program was conducted by «[2]» in which the length/width/thickness ratio of the flange plates was varied systematically. This testing program was carried out at Stanford University in the John A. Blume Earthquake Engineering Laboratory, using an available universal testing machine and 50 beam-column subassemblies as test specimens. Flange plates for each specimen were instrumented with strain gages and clip gages to serve as calibration gages for the shaking table test structure. A typical calibrated moment rotation diagram of a component subassembly with 2 steel plates, using the «[7]» loading protocol, is shown in *Fig. 4b*. The component was tested till both flange plates fractured. The flange plates, often called “dogbones” because of their shape, fracture in a ductile manner at about 8% chord rotation.

7. OVERALL BEHAVIOR AND COLLAPSE PREDICTION

Using white noise tests of relatively low acceleration amplitude (0.1g) together with a series of sine–sweep tests we determined the first mode period of #2 to be 0.44sec and 0.46sec, respectively. Frame #1 had a period of 0.44sec due to the fact that friction (Coulomb) damping was observed in the system. It should be noted that the target scaled period of the test frame, based on similitude rules by «[8]», was 0.47sec. A “physical” Incremental Dynamic Analysis (IDA) «[9]» was performed for the 4-story frame using the NEES shake table facility at Buffalo. The basic difference with a standard IDA is that each inelastic test causes permanent damage that creates different initial conditions for each subsequent test. *Fig. 5a* compares the “physical” IDA curve from the shake table experiment of frame #1 with analytical pre-test predictions. The results are fairly close, except that physical collapse did not occur at the 190% Canoga Park record level as predicted by pre – test analysis. But the frame collapses very early in the 220% Canoga Park record test (2.8sec after the motion started), indicating that the collapse capacity is not much larger than the predicted 190% and less than 220%. Thus the experimental IDA curve in *Fig. 5* is not connected with a line between the 190% and 220% Canoga Park record test.
For the post–test analytical prediction of collapse for the two frames tested at the NEES facility at University at Buffalo we use the ground motions recorded in the Buffalo tests as the earthquake input for the mathematical model of each test frame. The deterioration parameters of the critical components of the test frames were modified based on the calibrated moment rotation diagrams of the critical plastic hinge locations that were tested at Stanford University after the completion of the shaking table tests. *Fig. 5b* shows the experimental IDA curve for frame #1 together with the analytically predicted curve after the aforementioned modifications to the analytical model. The analytical prediction at 190% Canoga Park record is relatively close to the experimental data. In *Fig. 5b*, it is shown (see dashed line) that even if we would apply the unscaled Canoga Park motion to the model frame after the CLE level, the frame would collapse. The dashed line is based on analytical predictions using the post – test analytical model.



(a) Pre – test prediction *(b) Post – test Prediction*

Fig. 5. IDA curve for NEESR 4 story building as obtained experimentally and analytically

Of particular interest are the normalized base shear - 1st story drift results presented in *Fig. 6* for the two frames. The red curve (gray in black – white print) is the base shear as obtained from the horizontal links linking 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. The blue curve (black in black-white print) is the "base shear" obtained from masses times the acceleration, i.e., the inertia forces. Clearly, the two are very different. But when $P\delta/h$ is added to the blue (black) curve, in which P is the applied gravity load, δ is the recorded first floor displacement, and h is the corresponding story height, the resulting dashed curve is close to the red (grey) curve. This illustrates how P-Delta can be isolated and quantified up to collapse.

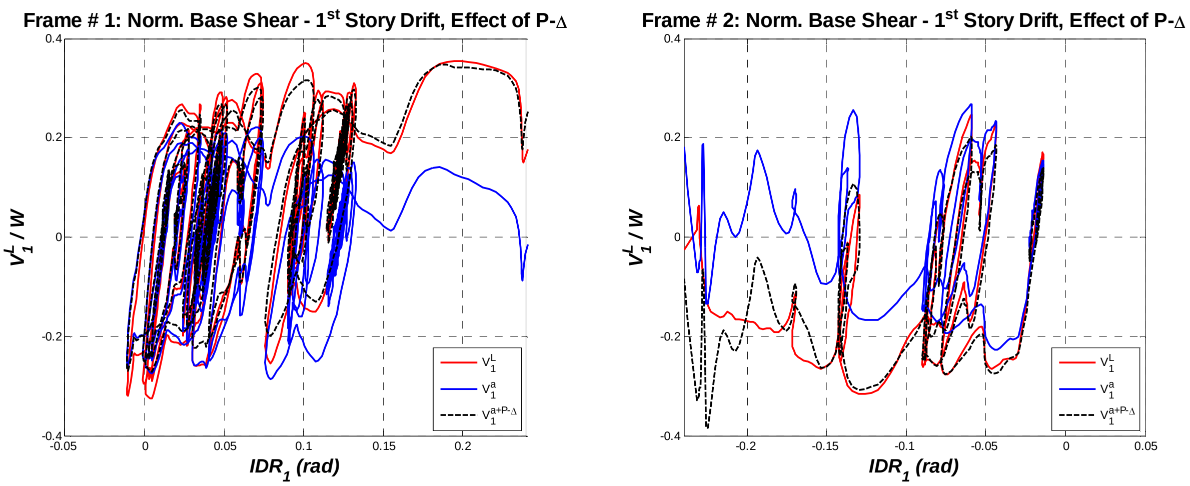


Fig. 6. Normalized Base shear - first story drift relationship at collapse level for frames #1, #2

8. SUMMARY OBSERVATIONS

Adequate safety against collapse is of fundamental concern in the design decision process. It is closely tied to life safety considerations and may also be an important factor in economic loss estimation. This paper focused on a certain mode of collapse, the one associated with incremental or “sidesway” collapse in which the displacement of an individual story, or a series of stories, is very large and P-Δ effects fully offset the deteriorated first-order story-shear resistance.

Based on two recent collapse experiments of scale models of a 4 story building, which was designed based on current seismic provisions and tested at the NEES facility at the University at Buffalo it is demonstrated that incremental collapse is indeed feasible under realistic ground motion conditions. Collapse of both frames was primarily caused by P-Δ effects and was accelerated by component deterioration. As was shown through the shaking table tests, P-Δ effects can be isolated and quantified for the full range of response from elastic behavior to collapse. With the use of relatively simple analytical models that explicitly model deterioration and incorporate P-Δ effects in the analysis, incremental collapse prediction is feasible with a satisfactory accuracy.

The strong column - weak beam criterion, the period independent R-factors for different structures and the design for allowable drift requirements are some of the design criteria that should be re-evaluated in the design process for collapse protection of structural systems.

9. ACKNOLEDGEMENTS

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10. REFERENCES

[1] Ibarra, L.F., Medina, R.A., and Krawinkler, H. (2005). “Hysteretic models that incorporate strength and stiffness deterioration”, *International Journal for Earthquake Engineering and Structural Dynamics*, Vol. 34, (11).

[2] Lignos, D. G. (2008). “Sidesway collapse of deteriorating structural systems under seismic excitations”, *Ph.D. Dissertation*, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, 2008 *(To appear).*

[3] IBC (2003). “International Building Code *IBC* 2003”, *International Code Council*, Birmingham, AL.

[4] FEMA-350. (2000). “Recommended seismic design criteria for new steel moment – frame buildings”, *Federal Emergency Management Agency*, Washington D.C.

[5] Gupta, A., and Krawinkler, H. (1999). “Prediction of seismic demands for SMRFs with ductile connections and elements”, *SAC Background Document, Report No. SAC/BD-99/06*.

[6] Lignos, D.G., Krawinkler, H. (2007), “A database in support of modeling of component deterioration for collapse prediction of steel frame structures”, *proceedings of ASCE Structures Congress*, Long Beach CA, SEI institute.

[7] AISC 2005. “Seismic *Provisions for Structural Steel Buildings”*, *American Institute of Steel Construction*, Chicago, IL.

[8] Moncarz, P.D., and Krawinkler, H. (1981). "Theory and application of experimental model analysis in earthquake engineering", *John A. Blume Earthquake Engineering Center*, *Report No. 50*, Department of Civil Engineering, Stanford University, Stanford, CA.

[9] Vamvatsikos, D., and Cornell, C.A. (2002). “Incremental dynamic analysis”, *Journal of Earthquake Engineering & Structural Dynamics*, Vol. 31, (3), pp. 491-514.

ΑΝΑΛΥΤΙΚΗ ΚΑΙ ΠΕΙΡΑΜΑΤΙΚΗ ΠΡΟΒΛΕΨΗ ΠΛΕΥΡΙΚΗΣ ΚΑΤΑΡΕΥΣΗΣ ΜΕΤΑΛΛΙΚΩ ΠΛΑΙΣΙΩΝ

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ΠΕΡΙΛΗΨΗ

Βασικό μειονέκτημα στη πρόβλεψη κατάρρευσης των κατασκευών είναι η απουσία φυσικών πειραμάτων που αποδεικνύουν το πώς πραγματοποιείται η κατάρρευση. Τα πειράματα αυτά μπορούν να χρησιμοποιηθούν για να επαληθεύσουν αναλυτικά μοντέλα περιγραφής της συμπεριφοράς μελών αλλά και των κατασκευών. Χρησιμοποιώντας τη σεισμική τράπεζα του πανεπιστημίου του Μπάφαλο, πραγματοποιήθηκαν 2 πειράματα κατάρρευσης ενός υπό κλίμακα τετραώροφου μεταλλικού πλαισίου. Για την συνεισφορά της φθοράς των μελών των υπό κλίμακα πλαισίων στη κατάρρευση των μεταλλικών πλαισίων πραγματοποιήθηκαν 50 πειράματα μονοτονικής και ανακυκλιζόμενης φόρτισης στο πανεπιστήμιο του Στάνφορντ των Ηνωμένων Πολιτειών. Μετά από την επιτυχημένη ολοκλήρωση των δύο πειραμάτων στη σεισμική τράπεζα, είναι διαθέσιμο ένα σύνολο από δεδομένα που ποσοτικοποιούν βασικά μεγέθη του κτιρίου και καλύπτουν το εύρος συμπεριφοράς του από την ελαστική περιοχή έως και την κατάρρευσή του. Όπως αποδεικνύεται, η πλευρική κατάρρευση κατασκευών μπορεί να συμβεί κάτω από ρεαλιστικές συνθήκες σεισμικής φόρτισης. Τα φαινόμενα δευτέρας τάξεως λόγω της βαρύτητας είναι δυνατό να ποσοτικοποιηθούν από την ελαστική περιοχή έως και την κατάρρευση. Ακόμα, επιβεβαιώνεται ότι η πλευρική κατάρρευση κατασκευών, λαμβάνοντας υπόψη τη φθορά των στοιχείων τους λόγω της ανακυκλιζόμενης φόρτισης, είναι εφικτό να προβλεφθεί αναλυτικά με σχετικά απλά μαθηματικά μοντέλα τα οποία μπορούν να συμπεριληφθούν στα διαθέσιμα προγράμματα δυναμικής ανάλυσης.