Probabilistic assessment of dynamic instability of frame structures under seismic excitations

D. Deniz & J. Song
University of Illinois at Urbana-Champaign, Urbana, IL, USA

J.F. Hajjar & T.H. Nguyen
Northeastern University, Boston, MA, USA

ABSTRACT: Mitigation of collapses of structural systems caused by a strong earthquake shaking is crucial to reduce the potential casualties, injuries and economic losses. Hence, accurate risk assessment of structural collapse under seismic excitations is critical in efforts to promote hazard-resilience of the society. This paper summarizes the authors' recent efforts for accurate prediction of structural collapse with systematic incorporation of uncertainty. Computational simulation models are developed for collapse test frames in the literature and validated using experimental data. Through the validated computational simulations of collapse, alternative collapse criteria are proposed in terms of dynamic instability, i.e. the loss of the ability to sustain the gravity loads. Using the new collapse criteria, key parameters that govern collapse capacity and collapse limit state functions are identified for more effective risk assessment. A probabilistic framework is also being developed for systematic treatment of uncertainties in the ground motion time histories and for risk-informed design of frame structures under earthquake hazards.

1 INTRODUCTION

Hazard-resilience of a structure can be defined as the ability to recover the full functionality quickly after a hazardous event. In efforts to enhance the resilience of structures against earthquake hazards, collapse prevention is thus considered one of the most important objectives. Therefore, it has become crucial to understand the causes and effects of seismic collapse of structures in order to develop key documents such as national building codes, regional emergency response plans, and risk management strategies.

While numerous research efforts are reported in the literature to estimate collapse capacity of structures, accurate prediction of structural collapse with systematic incorporation of uncertainty still remains elusive. This is mainly due to the lack of collapse criteria based on dynamic instability of the structure, which are needed to identify the impact of uncertainties in earthquake loads on the dynamic instability. The incremental dynamic analysis (IDA) approach (Vamvatsikos & Cornell 2002, 2004, Zareian & Krawinkler 2007, Liel et al. 2009), and a similar approach adopted by a recent project of the Applied Technology Council (ATC-63, 2009) are considered state-of-the-art approaches to account for the uncertainty in nonlinear dynamic response, including collapse prediction. However, there have been no thorough investigations using validated computational simulations regarding the impacts of a structural model selection and the selected set of the ground motions on the predictions of collapse capacity, and potential contributions of various performance measures or predictive parameters to collapse predictions.

The IDA-based approach identifies the collapse capacity of a structural system for a given earthquake ground motion based on the behavior of the "IDA curve," which is the relationship between an "engineering demand parameter (EDP)" (e.g., maximum inter-story drift ratio) and an "intensity measure (IM)" (e.g., spectral acceleration of an earthquake ground motion) identified by nonlinear dynamic analyses at incrementally increased intensity levels. The main premise of the approach is that the structural system collapses when the IDA curve becomes almost flat, i.e. a slight increase in IM causes an exceedingly large increase in EDP. However, the IDA curve could flatten due to large residual EDPs and thus may not necessarily indicate the inability to sustain gravity loads. It is also noted that most of the recent research efforts based on the IDA-based approach used only one EDP (mostly maximum story drift ratio) while one might need alternative EDP or multiple EDPs to predict the collapse more accurately. It is also noteworthy that the collapse capacity of a structure evaluated by the IDA-approach may be sensitive to a particular selection of ground motions as well as possible chaotic behavior of the IDA curve such as “structural resurrection.” Although some deterministic rules have been proposed to handle such unusual behaviors of IDA (Vamvatsikos & Cornell 2002, 2004), it appears that there is a need for developing collapse criteria based on simulated collapse phenomena and a systematic procedure to identify impact of uncertainties in ground motions on the collapse capacity of a structural system.

In order to overcome these challenges, a new probabilistic framework has been developed for accurate assessment of collapse of frame structures under stochastic ground motions. First, nonlinear dynamic analyses are performed for selected experimental case studies reported in the literature (Kanvinde 2003, Rodgers & Mahin 2004, Lignos et al. 2008) by use of OpenSees, an object-oriented software framework developed by Pacific Earthquake Engineering Center (PEER). Using OpenSees computational models validated by corresponding experimental results, new dynamic-instability-based collapse criteria are developed in terms of energy from the input ground motions and the gravity loads. The selected case studies are then used to test the new collapse criteria and to identify key parameters that govern the collapse of a structural system. Currently, procedures are being developed for probabilistic prediction of collapse limit states and corresponding structural demands, and for identification of critical parameters in collapse predictions. Using these procedures, the impact of uncertain ground motion details on the collapse limit states and structural demands is being investigated to provide guidelines on selection of ground motions for IDA-based studies and designs.

This paper presents ongoing research activities in the proposed framework. First, the details of computational simulations of collapse test cases in the literature are presented. Second, the proposed collapse criteria based on dynamic instability, i.e. the loss of the ability to sustain the gravity loads are introduced. Using the selected experimental case studies, the new collapse criteria are compared with the traditional IDA-based approach. Finally, the paper introduces ongoing research activities for probabilistic assessment of collapse limit states, structural demands at collapse levels and for identification of critical parameters for collapse predictions.

2 VALIDATED COMPUTATIONAL SIMULATION OF COLLAPSE

In order to develop the framework described in the previous section, it is necessary to build computational simulation models of collapse that are validated by available experimental test results. This section briefly describes the simulation tool and provides details of the computational simulation models of the selected collapse-case studies considered in this study.

2.1 *Simulation tool*

OpenSees – The Open System for Earthquake Engineering Simulation – is a finite-element program developed by PEER to simulate the seismic behavior of structural and geotechnical systems (PEER 2004). OpenSees has been extensively used by many researchers in earthquake engineering for various finite-element applications because of its advanced capabilities in constitutive models, elements and solution algorithms. Moreover, it is open-source software platform that allows researchers to contribute to the framework. Therefore, this study uses OpenSees as the simulation tool to perform nonlinear dynamic collapse analysis for selected case studies for which collapse or near-collapse level experimental results are available.

Advanced high-fidelity analytical models can account for many factors needed for accurate simulation of structural collapse process, but are computationally demanding. These models are prone to convergence problems during nonlinear dynamic analysis because of the complexity of the modeling details. Therefore, these advanced models can be impractical for the aforementioned stochastic framework especially in design process. For this reason, this research employs macro-models available in OpenSees that correlate well with experiment results of selected case studies of collapse to achieve the aforementioned research objectives and perform large-scale parametric studies in collapse assessment of structures.

2.2 *Case studies on structural collapse*

Nonlinear dynamic collapse analyses are performed for selected experimental case studies reported in the literature by use of OpenSees. So far, three case studies have been explored using advanced capabilities of OpenSees in constitutive models, elements and solution algorithms: Kanvinde (2003), Rodgers & Mahin (2004), and Lignos et al. (2008). In developing the computational simulation models of the selected case studies, an emphasis was given on validation of collapse at the “system level” by considering the maximum and residual story drift responses as well as at the “component level” by considering the moment-rotation response obtained at the plastic locations at the element ends. Two of these case studies (Kanvinde 2003, and Lignos et al. 2008) are presented in this paper for describing these research activities.

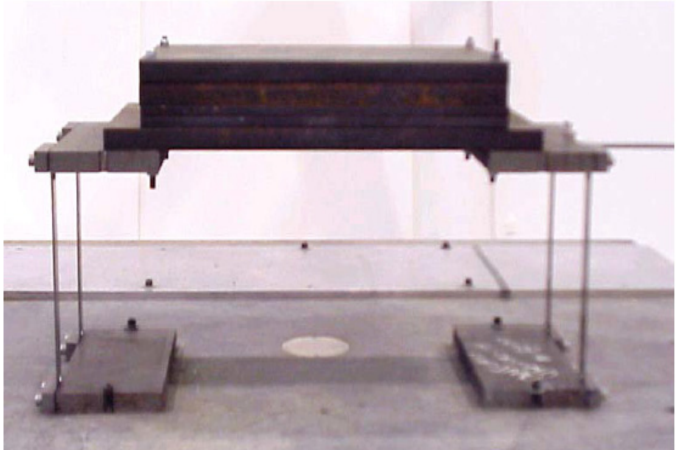

Figure 1. Specimen configuration (Kanvinde 2003).

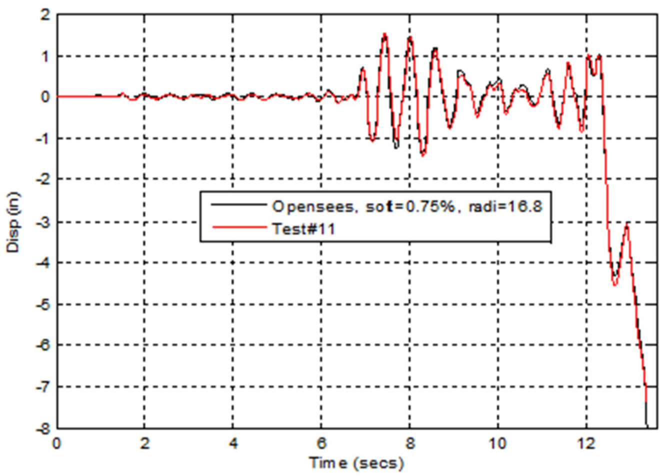

Figure 2. Displacement time history results by OpenSees for the test case by Kanvinde (2003) under the test ground motion record of the 1994 Northridge at Obregon Park. “soft” and “radi” in the plot refer to the softening amount and radius of transition from elastic to plastic branches in the springs respectively.

Kanvinde (2003) conducted shake table tests on a single-story specimen configuration measured 12” by 24” in plan (the longer dimension aligned in the direction of motion) and 10” in height to investigate the concept of dynamic instability of structures during earthquakes. The specimen configuration was in the form of four flat columns connected to the base plate and a steel mass on top served as a rigid diaphragm as shown in Figure 1. For the proposed tasks described in this paper, a structural model was built in OpenSees using the 2-D analytical model details given in Kanvinde (2003). Elastic elements were assigned to the columns and beam, and the beam was assumed to behave rigidly. Concentrated nodal masses were placed at the ends of top beam. Inelastic single-degree-of-freedom (SDOF) zero-length rotational springs were modeled at the plastic locations at the ends of the columns by assuming Giufré-Menegotto-Pinto plasticity model (Menegotto & Pinto 1973) for the spring hysteretic response. The co-rotational formulation was used in order to include the nonlinear geometric effects through the specimen. Nonlinear dynamic collapse analyses under the test ground motion of Obregon Park were performed to provide the OpenSees result for the test case no. 11 in Figure 2, which almost coincides with available experiment data even at the near-collapse level.

Lignos et al. (2008) performed a series of collapse shake-table tests of a 4-story, 2-bay steel frame with reduced-beam sections (RBS) in 1/8 scale. Figure 3 shows the setup of the test frame on the NEES mass simulator at the University at Buffalo, which consists of elastic members with plastic hinges at the ends. The mass simulator is connected to the test frame by means of axially rigid horizontal links through which the simulator transfers P-Delta effects acting as a leaning column on the test frame. An analytical model for the 1/8 scale 4-story test frame was developed in OpenSees based on the deterioration parameters and mathematical model properties given in Lignos et al. (2008). The rotational springs were used to analytically model the plastic hinges in the frame with a modified Ibarra-Krawinkler deterioration model (Lignos et al. 2008) available in OpenSees, calibrated based on a steel component database of steel beams with RBS under cyclic loading. Panel zones were modeled at the connections considering the shear distortions. Furthermore, offsets from the panel zones were applied to take RBS into account following the method used by the researchers. Effects of the panel zones on the structural response were explored comparing to those of a developed clear span model. Time history analysis and IDA were performed using the OpenSees model and the results were compared with those by experiment (See Figure 4), which show good agreement. Note that a set of nonlinear dynamic analyses with four different levels of seismic intensity scales were performed sequentially to simulate the actual loading sequences of the tests.

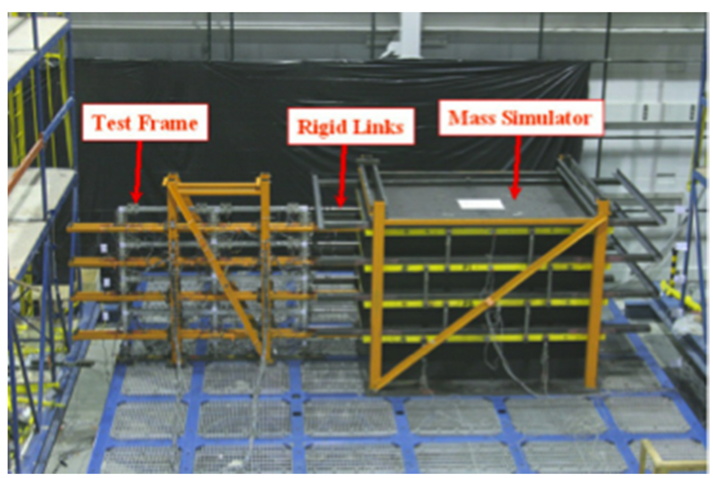

Figure 3. Shake-table-test of a 1/8 scale 4-story, 2-bay steel frame with reduced beam sections (Lignos et al. 2008).

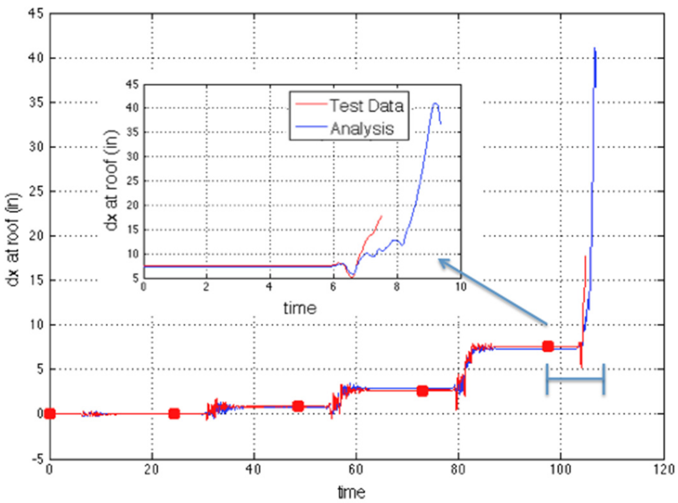

Figure 4. Comparison of experimental test results and simulation results of lateral displacement time history at the top of the frame for the test case by Lignos et al. (2008). Note that the simulation model here depends on the clear span model, and was continuously subjected to the ground motion record of the 1994 Northridge earthquake at Canoga Park with a scale factor of 0.4, 1.0, 1.5,1.9, and 2.2 following the test procedure.

2.3 *Virtual collapse simulations*

In order to develop a new stochastic framework for identifying collapse limit-state and important parameters in the collapse assessment of structures subjected to seismic loads, extensive IDAs are performed using validated OpenSees simulation models to obtain a large sample for multiple DMs and corresponding IM and for multiple ground motions. Since the ground motions considered in the methodology of ATC-63 project were selected in such a way that the methodology can be generally applied to building structures at any site, the "Far-Field" record set of ATC-63 project have been chosen in the development of the stochastic framework. This record set consists of twenty-two ground motion pairs (two-lateral components) recorded at sites located within 10km of fault rupture. Records were selected from strong earthquake ground motions with a magnitude changing from 6.5 to 7.9.

As a future work in the study, virtual collapse simulations considering a wide array of geometric and material parameters (Steelman & Hajjar 2009) will also be performed using the validated analytical models to account for the impacts of a structural model selection on the collapse prediction of structures.

3 COLLAPSE CRITERIA BASED ON DYNAMIC INSTABILITY OF FRAME STRUCTURES

This section presents new collapse criteria of frame structures based on the dynamic instability, i.e. the loss of the ability to sustain the gravity loads. Using the OpenSees computational models validated by corresponding experimental results, new dynamic-instability-based collapse criteria have been developed in terms of the energy from the input ground motions and the gravity loads. The selected case studies are then used to test the new collapse criteria of a structural system.

3.1 *Traditional IDA-based collapse limit states*

The flattening of IDA curves may be caused by large residual displacement, not by the occurrence of "collapse" necessarily. It is also noted that unusual behaviors of IDA curves such as non-monotonic behavior and discontinuities may occur (Vamvatsikos & Cornell 2002). As a result, the collapse capacity identified from the IDA-based approach might not account for the impact of the uncertainties in ground motion appropriately.

To identify collapse capacities from the behavior of IDA curves, some rules have been proposed (Vamvatsikos & Cornell 2002). According to the IM-based rule (Figure 5a), a building reaches its collapse capacity when the slope of the curve is reduced to 20% of the initial slope. If an IDA curve does not fulfill the IM-based rule, then one checks if the drift ratio exceeds an assumed global drift capacity, say 10% (DM-based rule; see Figure 5b). However, these IDA-based collapse identification rules depend on assumed threshold values on IM and DM, therefore not sufficient for objective and physics-based identification of a structural collapse based on actual dynamic instability of a structure. Therefore, new dynamic-instability-based collapse criteria are developed in terms of energies from the input ground motions, and the gravity loads. First, energy balance of a structural system under seismic excitation is introduced in the following section. Then, details of the new dynamic-instability-based collapse criteria are presented.

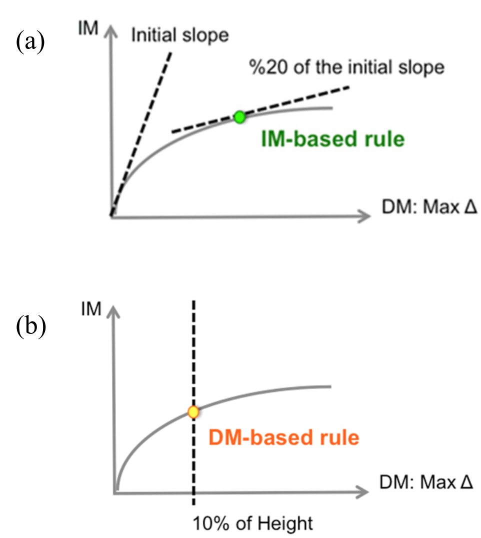

Figure 5. a) IM-based and b) DM-based rules.

3.2 *Energy balance of a structural system subjected to seismic forces*

The equation of motion at time t for a multi-degree-of-freedom (MDOF) structure under horizontal earthquake loads and gravity loads is given as

$$\mathbf{M}\,\ddot{\mathbf{u}}(t) + \mathbf{C}\,\dot{\mathbf{u}}(t) + \mathbf{F_S}(t) = -\mathbf{M}\,\ddot{\mathbf{u}}_{\mathbf{F}}(t) \tag{1}$$

where $\mathbf{u}$ is the relative nodal displacement vector, $\dot{\mathbf{u}}$ is the relative nodal velocity vector, $\ddot{\mathbf{u}}$ is the relative nodal acceleration vector, $\mathbf{M}$ is the structural mass matrix, $\mathbf{C}$ is the structural damping matrix, $\mathbf{F_S}$ is the structural restoring force vector, and $\ddot{\mathbf{u}}_{\mathbf{F}}$ is the acceleration vector of the applied loads.

An insight into the dynamic instability of structures can be gained by considering energy balance of a structural system under dynamic and gravity forces. If each term in Equation 1 is integrated with respect to $\mathbf{u}$, the energy balance of the structural system can be derived as (Uang & Bertero 1990):

$$\int_0^t \mathbf{M}\ddot{\mathbf{u}}(t)\,d\mathbf{u} + \int_0^t \mathbf{C}\dot{\mathbf{u}}(t)\,d\mathbf{u} + \int_0^t \mathbf{F_S}(t)\,d\mathbf{u} = -\int_0^t \mathbf{M}\ddot{\mathbf{u}}_{\mathbf{F}}(t)\,d\mathbf{u} \tag{2}$$

The integrals in Equation 2 give the following energy components of a structural system respectively, i.e.

$$E_K + E_D + E_S = E_I \tag{3}$$

where E_K is the relative kinetic energy, E_D is the damping energy, E_S is the strain energy, and E_I is the relative dynamic input energy.

Using $d\mathbf{u} = \dot{\mathbf{u}}(t)dt$, the input energy component can be decomposed as follows:

$$E_I = -\int_0^t \mathbf{M}\,\ddot{\mathbf{u}}_{\mathbf{F}}(t)\,\dot{\mathbf{u}}(t)\,dt \tag{4}$$

If the structure is subjected to the horizontal earthquake excitation and the gravity loads only, then the input energy can be separated into dynamic input energy due to horizontal seismic actions, E_{EQ}, and gravity energy due to applied gravity loads on the structure, E_G, i.e.

$$E_{EQ} = -\int_0^t \mathbf{M}\,\ddot{u}_{EQ}(t)\,\dot{\mathbf{u}}_{\mathbf{x}}(t)\,dt \tag{5}$$

$$E_G = -\int_0^t \mathbf{M}\,g\,\dot{\mathbf{u}}_{\mathbf{y}}(t)\,dt = -\mathbf{M}\,g\,\mathbf{u}_{\mathbf{y}}(t) \tag{6}$$

Where $\ddot{u}_{EQ}$ is the acceleration of the horizontal earthquake excitation, $\dot{\mathbf{u}}_{\mathbf{x}}$ is the relative nodal velocity vector in x-direction, $\mathbf{u}_{\mathbf{y}}$ is the relative nodal displacement vector in y-direction, and g denotes the gravity acceleration, which is constant.

The earthquake energy applied on the structure is dissipated through the work done by the damping and hysteretic forces. Therefore, the damping and hysteric energies are irrecoverable while the elastic and kinetic energies are recoverable vibrational energy. If all the individual energy components are gathered together, the energy balance of a structure in Equation 3 is now defined as:

$$E_K + E_D + E_S = E_G + E_{EQ} \tag{7}$$

Akiyama (2002) stated that the gravity energy can be considered as a release of the potential energy as a result of the P-Delta effects, and takes a part in the total resistance of a structure against a seismic excitation. Therefore, the gravity energy can be alternatively shown on the left side of the energy balance:

$$E_K + E_D + E_S - E_G = E_{EQ} \tag{8}$$

3.3 *Identification of dynamic instability by structural gravity energy*

Dynamic instability is a complex phenomenon, which cannot be effectively predicted by a ground intensity measure and/or an engineering parameter roughly representing structural damage. The most commonly used criterion for identification of simulated collapse under dynamic loads is boundless drifts towards collapse. However, this approach requires checking displacement demands at each degree-of-freedom (DOF), but most studies consider only the roof or story drifts to check the stability of the global structural behavior. Therefore, the dynamic instability of structural systems is investigated from the viewpoint of the energy balance because energy is an overall indicator of the systems.

Progressive accumulation of permanent lateral drifts during a strong ground shaking may render gravity forces the dominant forces and make the structure collapse under significant P-delta effects due to governing gravity forces (Jennings & Husid 1968). Therefore, new collapse criteria have been developed based on comparison between the amount of dynamic energy released by the earthquake to the structure and the amount of gravitational work done by the vertical static loads during the dynamic analysis.

The sudden increase of the gravity energy, which eventually causes the gravity energy to exceed the dynamic energy, can be considered as an indicator of the domination of gravity loads over dynamic loads. Figure 6 presents the input-energy-time histories for the validated single-story model of Kanvinde (2003) under the ground motion record of the 1994 Northridge earthquake at Obregon Park, Los Angeles. If the intensity of the ground motion is not strong enough to trigger the large geometric effects in the frame (e.g. the non-collapse case at the scale of 0.8), the structure obtains a steady state in terms of the gravitational energy, which is found insignificant comparing to the quantity of dynamic input energy coming from the ground motion (Figure 6a). At the intensity scale of 1.0 (Figure 6b), geometric nonlinearities in the structure become significant near the collapse, causing the frame to show very large displacement in vertical directions and thus result in a sudden increase in the gravitational energy as the structure gets close to collapse. Since this approach employs system-level measures, i.e. gravity and dynamic input energies, one does not need to check each degree-of-freedom of the structure to check the dynamic instability. Moreover, the approach may facilitate developing a mathematical description of dynamic instability, which can be particularly useful as limit-state functions during structural reliability analysis of collapse.

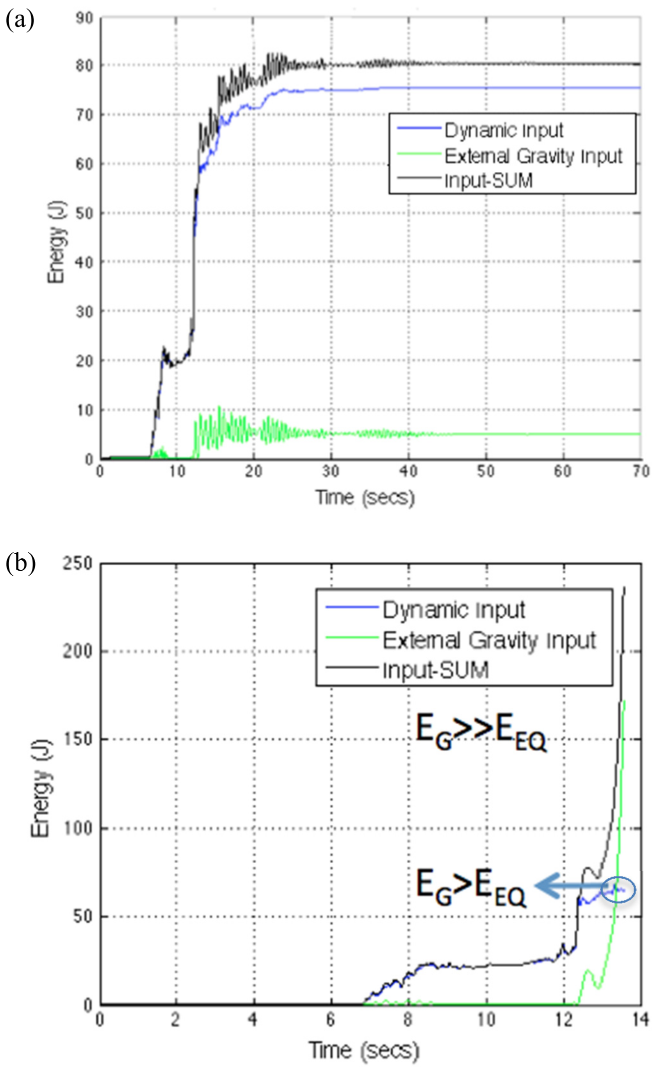

Figure 6. Input energy components near collapse under the test earthquake of 1994 Northridge earthquake at Obregon Park a) non-collapse case at the ground motion scale of 0.8 and b) collapse case at the ground motion scale of 1.0.

3.4 *Comparison of new collapse criteria with traditional IDA-based rules*

Traditional IDA-based rules are compared to the new criteria called "energy rule" in terms of the maximum intensity level observed before the dynamic instability occurs, i.e., gravity energy exceeds dynamic energy. Most recent research efforts based on the IDA-based approach assume the intensity level of ground motion at which the structure loses the dynamic stability as the collapse capacity. However, the structural collapse capacity should be evaluated based on the maximum intensity level before occurrence of dynamic instability (Krawinkler et al. 2009, Haselton et al. 2009). The capacity at this intensity level is actual representation of the largest structural resistance against dynamic collapse.

The validated model for the case study by Lignos et al. (2008) is utilized here to perform nonlinear dynamic analyses using the ATC-63 far field set. Figure 7 shows the IDA curves of peak ground acceleration (PGA) to top lateral displacement obtained from the validated OpenSees model. Traditional IDA-based rules are compared to the new criteria called "energy rule" based on the maximum intensity level observed before the dynamic instability occurs, i.e., gravity energy exceeds dynamic energy. Much variability is observed in collapse capacity level for all rules due to the effect of randomness in the selected ground motions on structural collapse. It is also noted that the traditional IDA-based approach and the proposed criteria result in significant differences in predictions of collapse capacity (in PGA) and the structural demand at the collapse level (in roof displacement).

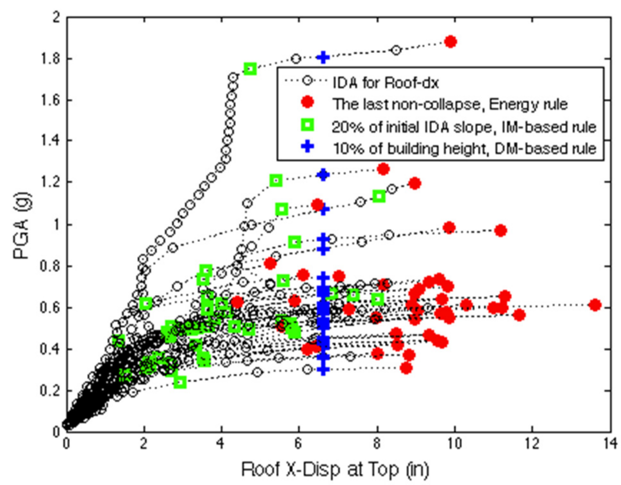

Figure 7. IDA curves and comparison of collapse criteria for the test case of Lignos et al. (2008) subjected to ATC-63 far field record set (44 ground motions).

4 PROBABILISTIC ASSESSMENT OF COLLAPSE USING NEW COLLAPSE CRITERIA

Collapse assessment of structures based on IDA curves depends on the selection of IM and DM used to construct these IDA curves as well as variability in the set of ground motions considered in the analysis (Villaverde 2007). IDA curves usually reach a flat plateau as an indication of collapse (i.e., a large increase in the structural response corresponding to a small increase in the ground motion intensity), but this plateau may occur at several different intensity levels of ground motions. Large dispersion observed in collapse-causing intensities of ground motions and damage thresholds has initiated search for alternative performance measures to assess collapse capacity of structures. However, most of recent research on the IDA-based approach still uses only one DM and one IM (mostly maximum story drift ratio and elastic spectral acceleration). This section describes ongoing research efforts to obtain optimal selection and/or combination of multiple performance measures that describe the limit-state most effectively and the benefit of having more than one DM or IM for collapse capacity prediction.

4.1 *Statistical analysis on collapse capacity by new criteria*

The collapse capacity data obtained for the case study by Lignos et al. (2008) using ATC-63 far field set was investigated here to perform statistical analyses on the levels of IMs (denoted by IM_{col}) and the conditional distributions of the corresponding DMs (denoted by DM_{col})

Empirical cumulative distribution functions (CDF) for IM_{col} identified by the energy rule are presented in Figure 8. CDFs of different kinds of IM_{col} (normalized by their means) such as peak ground acceleration-velocity-displacement (*PGA-PGV-PGD)*, spectral acceleration for 2% damping (*Sa (2%)*), undamped intensity of Arias (*IA (0%), Arias 1970*), root of integral of square of ground acceleration-time history (*ars*), average cycle of crossings over zero in the strong part of accelerogram ($T_{v,\ strong}$, where strong duration is based on definition by Trifunac & Brady 1975), and earthquake input energy (E_{EQ}) were compared. These CDFs provide probabilistic estimation of the collapse capacities (in IM). In order to make a numerical comparison, their normalized standard deviation, which is coefficient of variation (cov), were obtained in Table 1. IM with the smallest cov is found to be *ars* from which collapse can be predicted with more confidence comparing to other candidates.

Currently, the following linear combinations of IMs and/or DMs in Equation 9 or nonlinear combinations are also being investigated to obtain new performance measures (PM) that can predict the collapse capacities with smaller covs:

$$PM = \sum_{i=1}^{n} a_i\ IM_i + b_i\ DM_i \tag{9}$$

where a_i and b_i are the coefficients of the IM and DM that result in smallest covs, found by statistical analysis.

Conditional distribution of structural demand (DM_{col}) given IM_{col} is also being obtained. Partial descriptors such as conditional mean and variance of DM_{col} given IM_{col} can be obtained through linear/nonlinear regression analysis. Such regression models provide probabilistic estimation of the structural demand at near-collapse level.

4.2 *Effect of variability in ground motions*

Effects of uncertain characteristics of ground motions used for IDA on the probabilistic models described in section 4.1 are being investigated to develop guidelines regarding selection of a suite of ground motions to be used in nonlinear collapse analyses. Moreover, a new analysis framework is being developed for probabilistic evaluation of collapse using artificial models representing possible ground motions at a given site instead of a suite of selected ground motions. This approach allows us to perform site-specific probabilistic collapse assessment. The approach will perform random vibration analysis by employing a discrete representation of a ground motion database (Rezaeian & Der Kiureghian 2008, 2010). The developed probabilistic method will be integrated with performance-based earthquake engineering (PBEE) framework, which will provide collapse fragility models through systematic treatment of uncertainties in seismic capacity, demand and models.

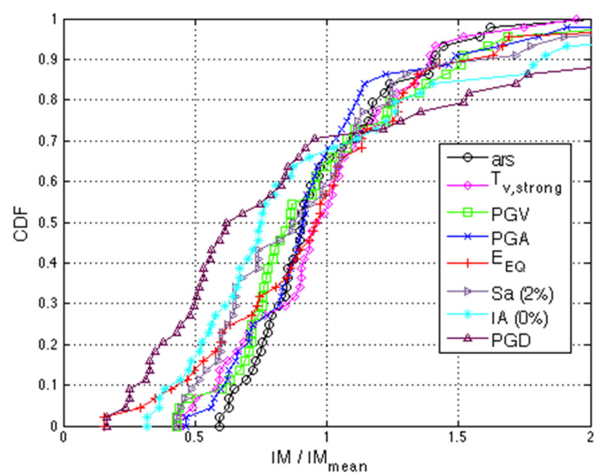

Figure 8. Cumulative distribution function of IM-collapse level for the test case of Lignos et al. (2008) subjected to ATC-63 far field record set (44 ground motions).

Table 1. Collapse-initiating intensity measure and coefficient of variations (cov)

IM_{col}	cov
ars	0.31
$T_{v,\ strong}$	0.33
PGV	0.41
PGA	0.42
E_{EQ}	0.48
Sa (2%)	0.56
IA	0.68
PGD	0.87

5 CONCLUSIONS AND FUTURE WORK

New collapse criteria were developed based on dynamic instability of structures near collapse through validated computational simulations of collapse test frames reported in the literature. Using the criteria, various quantitative criteria are being explored to facilitate performing structural reliability analysis and identifying critical measures.

New collapse criteria based on computational simulations of dynamic instability give rise to new research opportunities to gain better understanding of complex collapse of structural systems, identify key parameters requiring more comprehensive and accurate measurements during experiments, achieve more accurate and systematic prediction of collapse, and incorporate uncertainties into collapse prediction.

The study described here is expected to have potential impact across several structural engineering research and practice constituencies seeking to improve building code provisions for preventing disproportionate collapse; regional emergency response plans and risk management strategies that rely on accurate assessment of collapse within fragility analysis; and collapse assessment of new structural systems. In addition, through this work, life safety will be enhanced, as avoiding structural collapse due to extreme loads is a critical component to ensuring a safe infrastructure and its resilience against earthquake hazards.

6 ACKNOWLEDGEMENT

The authors would like to thank National Science Foundation (NSF) for their funding in this research under grant number CMMI 1000666. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF.

REFERENCES

Akiyama, H. 2002. Collapse modes of structures under strong motions of earthquake. *Annals of Geophysics* 45(6): 791-798.

Applied Technology Council, 2009. *Quantification of building seismic performance factors*. ATC-63 Project Report FEMA.

Arias, A. 1970. A measure of earthquake intensity. In R. J. Hansen (ed), *Seismic design for nuclear power plants*: 438–483. Cambridge: M. I. T. Press.

Haselton, C.B, Liel, A.B., & Deierlein, G.G. 2009. Simulating structural collapse due to earthquakes: Model idealization, model Calibration, and numerical solution algorithms. *2nd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rhodes, Greece, 22-24 June*.

Jennings, P. C. & Husid, R. 1968. Collapse of yielding structures during earthquakes. *Journal of Engineering Mechanics Division* 94(5): 1045–1065.

Kanvinde, M. 2003. Methods to evaluate the dynamic stability of structures—shake table tests and nonlinear dynamic analyses. *EERI Annual Student Paper Competition, Earthquake Engineering Research Institute, Oakland, Calif.*

Krawinkler, H., Zareian, F., Lignos, D., & Ibarra, L. F. 2009. Prediction of collapse of structures under earthquake excitations. *2nd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rhodes, Greece, 22-24 June*.

Liel, A.B., Haselton, C.B., Deierlein, G.G., & Baker, J.W. 2009. Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings. *Structural Safety* 31: 197-211.

Lignos, D.G., Krawinkler, H., & Whittaker, A.S. 2008. Shaking table collapse tests of two scale models of a 4-story moment resisting steel frame. *Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12-17 October*.

Menegotto, M., and Pinto, E. 1973. Method of analysis for cyclically loaded reinforced concrete plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending. *Proceedings of IABSE Symposium, Lisbon, Portugal*.

Pacific Earthquake Engineering Research Center. 2004. Open System for Earthquake Engineering Simulation. University of California, Berkeley, CA.

Rezaeian, S. & Der Kiureghian, A. 2008. A stochastic ground motion model with separable temporal and spectral nonstationarities. *Earthquake Engineering and Structural Dynamics* 37: 1565-1584.

Rezaeian, S. & Der Kiureghian, A. 2010. Simulation of synthetic ground motions for specified earthquake and site characteristics. *Earthquake Engineering and Structural Dynamics* 39: 1155-1180.

Rodgers, J.E., & Mahin, S.A. 2004. *Effects of connection hysteretic degradation on the seismic behavior of steel moment-resisting frame.* Pacfic Earthquake Engineering Research Center Report, PEER 2003/13.

Steelman, J. S. & Hajjar, J. F. 2009. Influence of inelastic seismic response modeling on regional loss estimation. *Engineering Structures* 31(12): 2976-2987.

Trifunac, M.D., & Brady, A.G. 1975. On the correlation of seismic intensity scales with the peaks of recorded ground motion. *Bulletin of the Seismological Society of America* 65(1): 139-162.

Uang, C. M. & Bertero, V. V. 1990. Evaluation of seismic energy in structures. *Earthquake Engineering and Structural Dynamics* 19: 77–90.

Vamvatsikos, D. & Cornell, C.A. 2002. Incremental dynamic analysis. *Earthquake Engineering and Structural Dynamics* 31 (3): 491-514.

Vamvatsikos, D. & Cornell, C.A. 2004. Applied incremental dynamic analysis. *Earthquake Spectra* 20(2): 523-53.

Villaverde, R. 2007. Methods to assess the seismic collapse capacity of building structures: State of the art. *Journal of Structural Engineering* 33(1): 57-66.

Zareian, F. & Krawinkler, H. 2007. Assessment of probability of collapse and design for collapse safety. *Earthquake Engineering and Structural Dynamics* 36(13): 1901-14.