Appendix G
Preliminary Multiple-Degree-of-Freedom System Studies

In focused analytical studies on single-degree-of-freedom (SDOF) systems, it was observed that nonlinear response of a system depends on the characteristics of the force-displacement capacity boundary. It was demonstrated that lateral dynamic instability of SDOF systems could be evaluated through the use of approximate equations or simplified nonlinear dynamic analyses based on the characteristics of the system force-displacement capacity boundary.

Multiple-degree-of-freedom (MDOF) systems are more complex, and their dynamic response is more difficult to estimate than that of SDOF systems. Recent studies have suggested that it may be possible to estimate the collapse capacity of MDOF systems by using static pushover analyses and performing dynamic analysis on equivalent SDOF systems (Bernal, 1998; Vamvatsikos, 2002; Vamvatsikos and Cornell, 2005a, 2005b). In particular, Vamvatsikos and Cornell (2005b) suggested that the seismic response of MDOF systems could be estimated through the use of incremental dynamic analyses on a reference SDOF system whose properties are determined through a nonlinear static (pushover) analysis.

This appendix presents the results of preliminary studies of multiple-degree-of-freedom (MDOF) systems. It explores the application of nonlinear static analyses combined with dynamic analyses of SDOF systems to evaluate the lateral dynamic instability of MDOF systems. On a preliminary basis, it tests how approximate measures of lateral dynamic instability developed for SDOF systems might work on more complex MDOF systems. These approximate measures include the proposed equation for R_{di} (Equation 5-8) and the open source software tool *Static Pushover 2 Incremental Dynamic Analysis*, SPO2IDA (Vamvatsikos and Cornell, 2006).

A total of six buildings ranging in height from 4 to 20 stories are used in this investigation. This set includes two steel moment-resisting frame structures and four reinforced concrete moment-resisting frame structures. Four were previously studied by Haselton (2006), and two were previously studied by

Vamvatsikos and Cornell (2005b). Results are described in the sections that follow.

G.1 Four-Story Code-Compliant Reinforced Concrete Building

The subject building is a four-story reinforced concrete special perimeter moment frame designed in accordance with modern building code provisions (ICC 2003, ASCE 2002, ACI 2002). The building has a story height of 15 ft in the first story, and 13 ft in the remaining stories. The design base shear coefficient was 0.092. The building was modeled in OpenSEES and analyzed using incremental dynamic analysis using 80 recorded time histories which were scaled at twenty-two different ground motion intensities. The pushover analysis was conducted using a lateral force distribution in accordance with ASCE/SEI 7-05 *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2006). Ground motions were scaled to increasing values of the pseudo-acceleration spectral ordinate at the fundamental period of vibration of the building (T_1=1.12s). For a more detailed description of the building and its modeling, the reader is referred to Haselton (2006).

Figure G-1 shows the results from the nonlinear static (pushover) analysis. The figure on the left shows the force-deformation curve while the figure on the right shows the distribution of story drift ratios at a roof drift ratio of 6%. It can be seen that story drifts primarily concentrate in the lower two stories. The force-deformation pushover curve is characterized by a gradual loss in lateral strength for roof drift ratios between 1% and 3.5%, followed by a more pronounced loss in lateral strength for roof drift ratios greater than 3.5%.

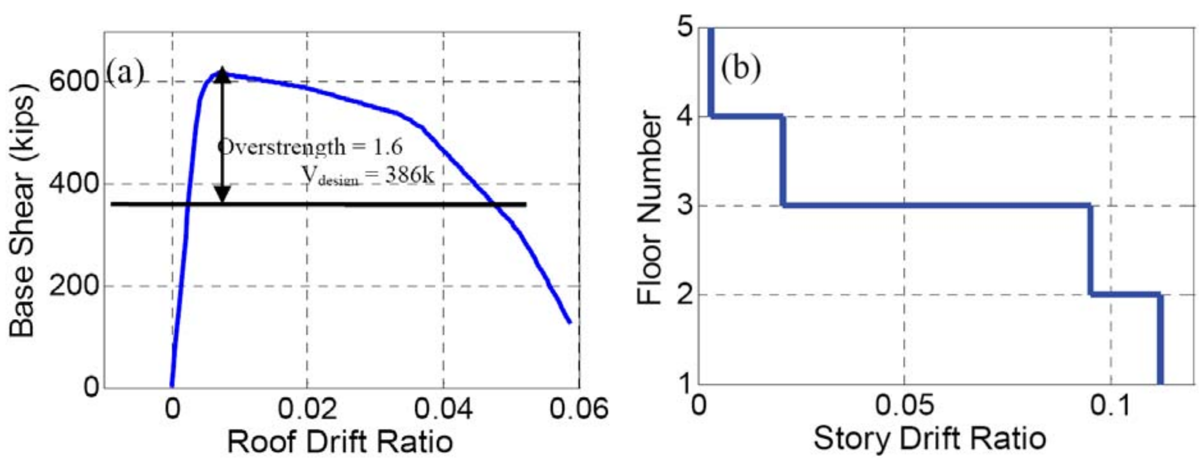

Figure G-1 (a) Monotonic pushover force-deformation curve and (b) story drifts at a roof drift ratio of the 0.06 in a four-story concrete frame building (Haselton 2006).

Figure G-2 shows one of three simplified tri-linear force-displacement capacity boundaries selected to estimate the seismic response of the structure. Alternates are shown in Figure G-4 and Figure G-5. Although a sloping intermediate segment might have been somewhat more appropriate for this structure, a horizontal intermediate segment was selected in order to evaluate the proposed equation for R_{di} and results using SPO2IDA.

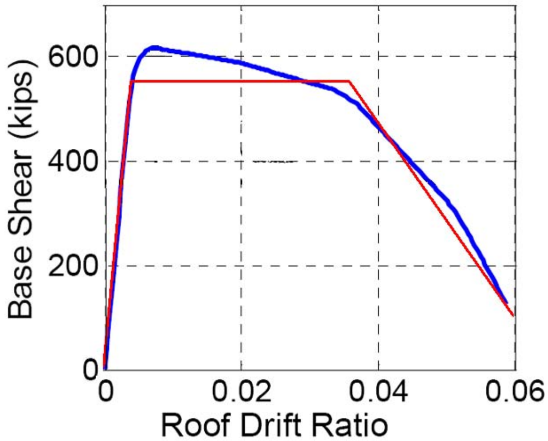

Figure G-2 Tri-linear capacity boundary selected for approximate analysis.

Figure G-3 shows the median seismic behavior computed from incremental dynamic analyses conducted by Haselton (2006). These results are indicated as MDOF IDA in the figure. Also shown are results computed using the proposed equation for R_{di} and approximate results from SPO2IDA. In the figure, R_{di} and SPO2IDA both provide a good approximation of the collapse capacity of the building.

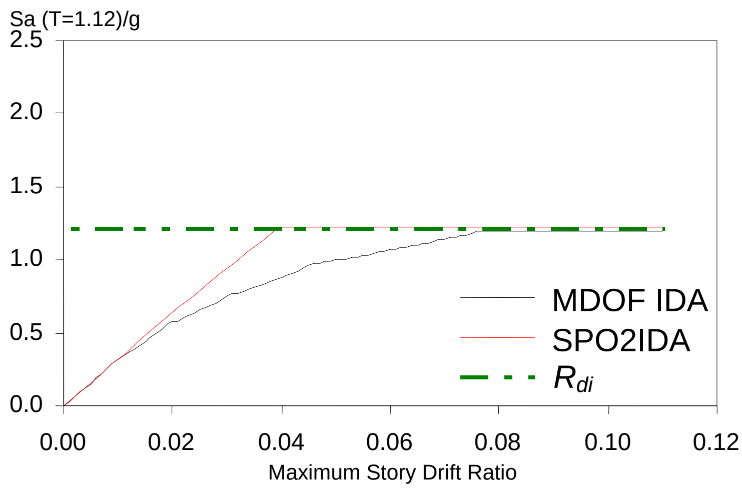

Figure G-3 Comparison of median collapse capacity for a four-story code-compliant concrete frame building computed using incremental dynamic analysis and approximate procedures.

To explore sensitivity to the idealization of the force-displacement capacity boundary, two alternate idealizations, along with corresponding results, are shown in Figure G-4 and Figure G-5. Although median collapse capacities change with the selection of the force-displacement capacity boundary, the observed changes are relatively small.

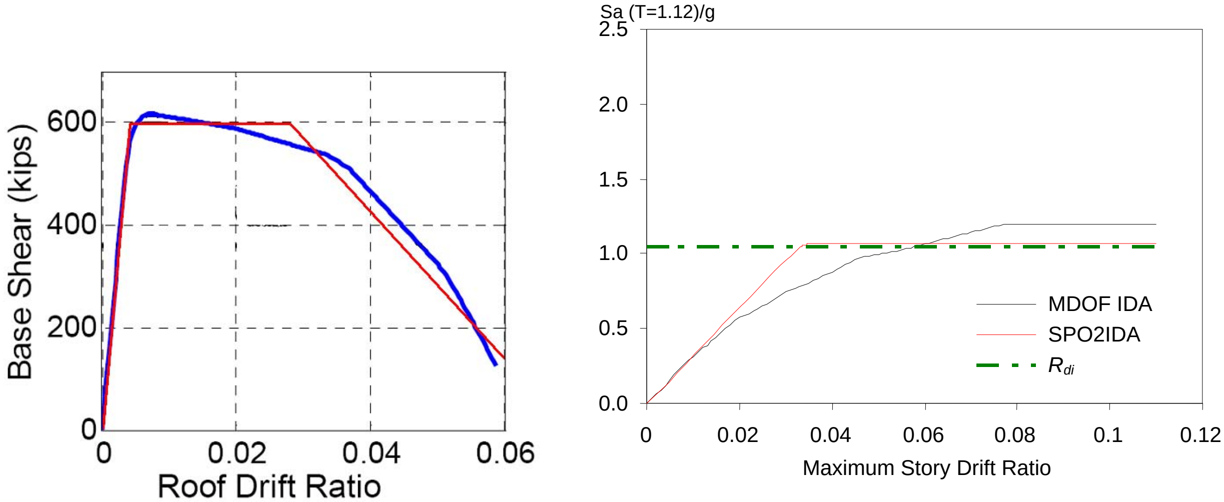

Figure G-4 Effect of selecting an alternate force-displacement capacity boundary on estimates of median collapse capacity for a four-story code-compliant concrete frame building.

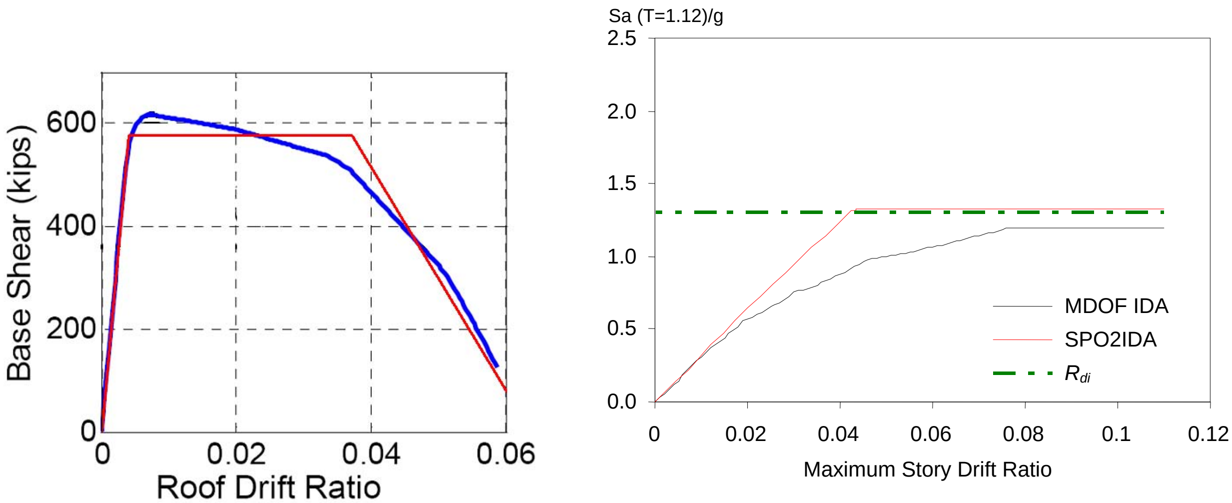

Figure G-5 Effect of selecting an alternate force-displacement capacity boundary on estimates of median collapse capacity for a four-story code-compliant concrete frame building.

The median results shown above represent a measure of the central tendency of the response of the system; however, considerable dispersion exists around the median. To illustrate record-to-record variability, Figure G-6 shows incremental dynamic analysis results for all 80 ground motions. It can be seen that there are ground motions that produce the collapse of the structure at intensities equal to one third of the median intensity. Similarly, there are ground motions that require an intensity that is twice as large as the median intensity in order to produce the collapse of the structure.

Also shown in Figure G-6 are the 16th and 84th percentiles of the results. Approximately 70% of the ground motions fall between these two dashed lines. When estimating the collapse probability of a structure, it is important to consider this variability. For more information, the reader is referred to Haselton (2006).

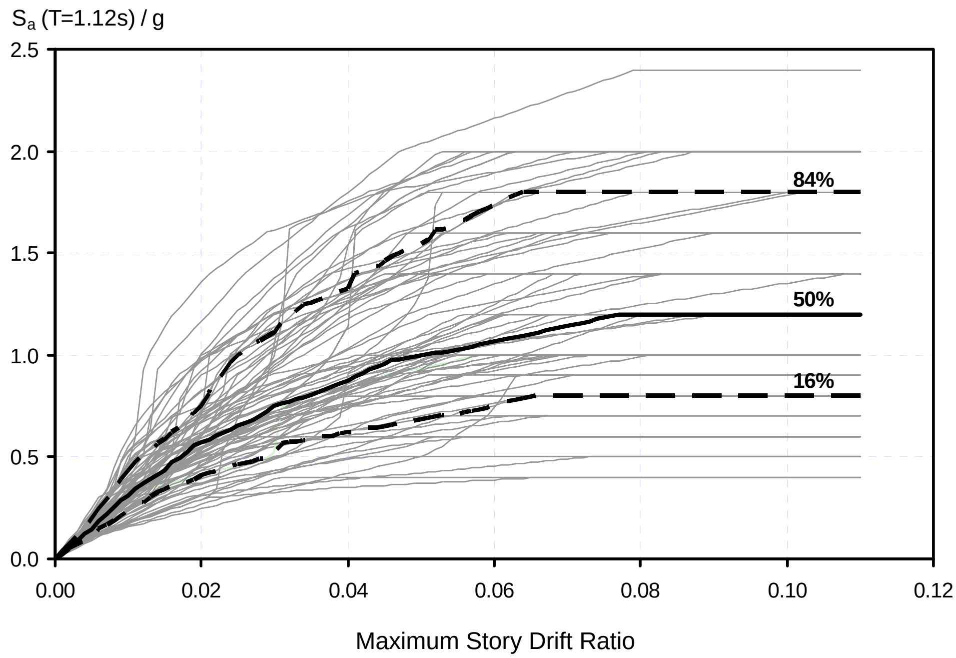

Figure G-6 Incremental dynamic analysis results for a four-story code-compliant concrete frame building subjected to 80 ground motions (adapted from Haselton, 2006).

G.2 Eight-Story Code-Compliant Reinforced Concrete Building

The subject building is an eight-story reinforced concrete special perimeter moment frame designed in accordance with modern building code provisions (ICC 2003, ASCE 2002, ACI 2002). The building has a story height of 15 ft in the first story, and 13 ft in the remaining stories. The design base shear coefficient was 0.05. The building was modeled in OpenSEES and analyzed using incremental dynamic analysis with the same 80 recorded ground motions that were used to analyze the four-story building. The pushover analysis was performed using a lateral force distribution in accordance with

ASCE/SEI 7-05. The fundamental period of vibration of the building is T_1=1.71s. For a more detailed description of the building and its modeling, the reader is referred to Haselton (2006).

Figure G-7 shows the results from the nonlinear static (pushover) analysis of the building. The figure on the left shows the force-deformation curve while the figure on the right shows the distribution of story drift ratios at a roof drift ratio of 2.6%. It can be seen that story drifts primarily concentrate in the lower four stories. The force-deformation pushover curve is characterized by a hardening segment for roof drift ratios between 0.3% and 0.8%, followed by softening segment for roof drift ratios greater than 0.8%.

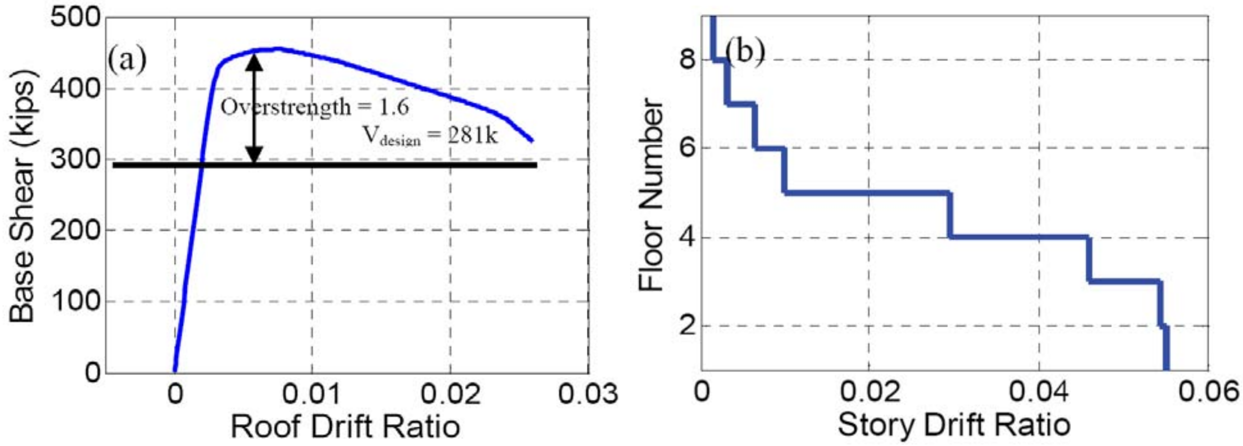

Figure G-7 (a) Monotonic pushover force-deformation curve and (b) distribution of story drift demands at a roof drift ratio of 2.6% in an eight-story concrete frame building (Haselton 2006).

Figure G-8 shows the simplified tri-linear force-displacement capacity boundary selected to evaluate the proposed equation for R_{di} and results using SPO2IDA.

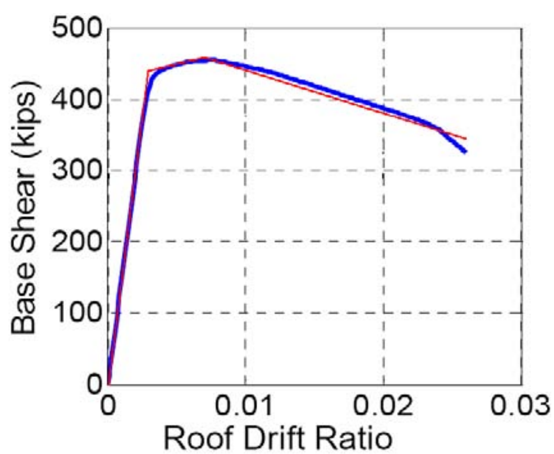

Figure G-8 Tri-linear capacity boundary selected for approximate analyses using *SPO2IDA*.

Figure G-9 shows the median seismic behavior computed from incremental dynamic analyses conducted by Haselton (2006). These results are indicated as MDOF IDA in the figure. Also shown are results computed using the proposed equation for R_{di} and approximate results from SPO2IDA. In the figure, R_{di} provides a good estimate of the median collapse capacity, while SPO2IDA overestimates the collapse capacity somewhat. Figure G-10 shows incremental dynamic analysis results for all ground motion records.

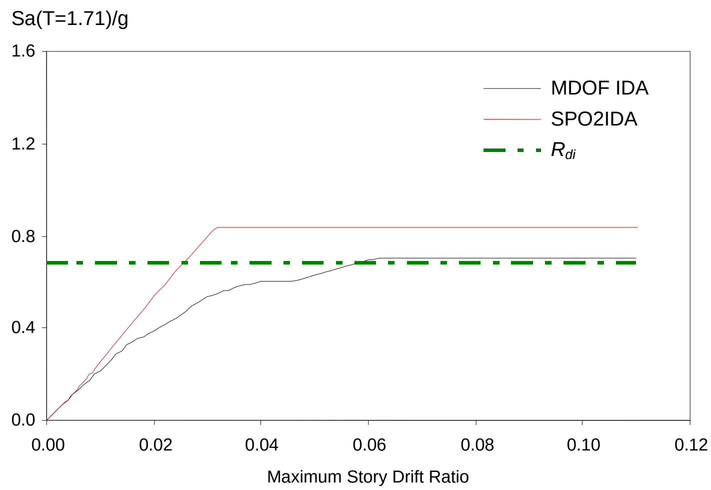

Figure G-9 Comparison of median collapse capacity for an eight-story code-compliant concrete frame building computed using incremental dynamic analysis and approximate procedures.

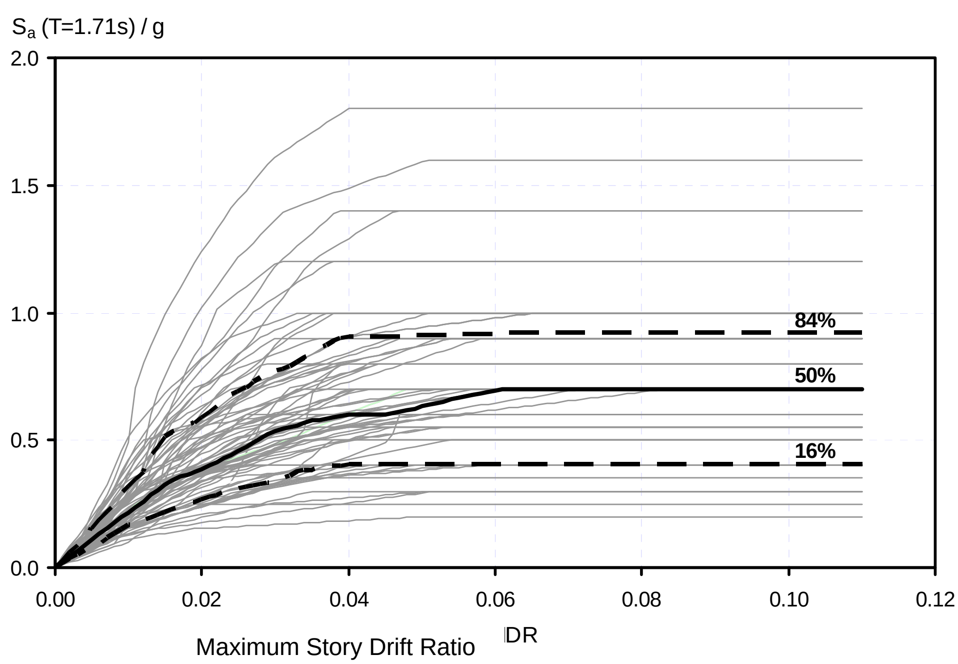

Figure G-10 Incremental dynamic analysis results for an eight-story code-compliant concrete frame building subjected to 80 ground motions (adapted from Haselton, 2006).

G.3 Twelve-Story Code-Compliant Reinforced Concrete Building

The subject building is a twelve-story reinforced concrete special perimeter moment frame designed in accordance with modern building code provisions (ICC 2003, ASCE 2002, ACI 2002). Similarly to the two previous buildings, the story height is 15 ft in the first story and 13 ft in the remaining stories. The design base shear coefficient was 0.044. The building was modeled in OpenSEES and analyzed using an incremental dynamic analysis using the same 80 recorded ground motions that were used to analyze the four-story building. The pushover analysis was again done using a lateral force distribution in accordance with ASCE/SEI 7-05. The fundamental period of vibration of the building is T_1=2.01s. For a more detailed description of the building and its modeling, the reader is referred to Haselton (2006).

Figure G-11 shows the results from the nonlinear static (pushover) analysis of the building. The figure on the left shows the force-deformation curve while the figure on the right shows the distribution of story drift ratios at a roof drift ratio of 2.7%. It can be seen that story drifts decrease approximately linearly with increasing height with the largest story drifts occurring in the two lower stories. The force-deformation pushover curve is characterized by a hardening segment for roof drift ratios between 0.3% and 0.8%, followed by softening segment for roof drift ratios greater than 0.8%.

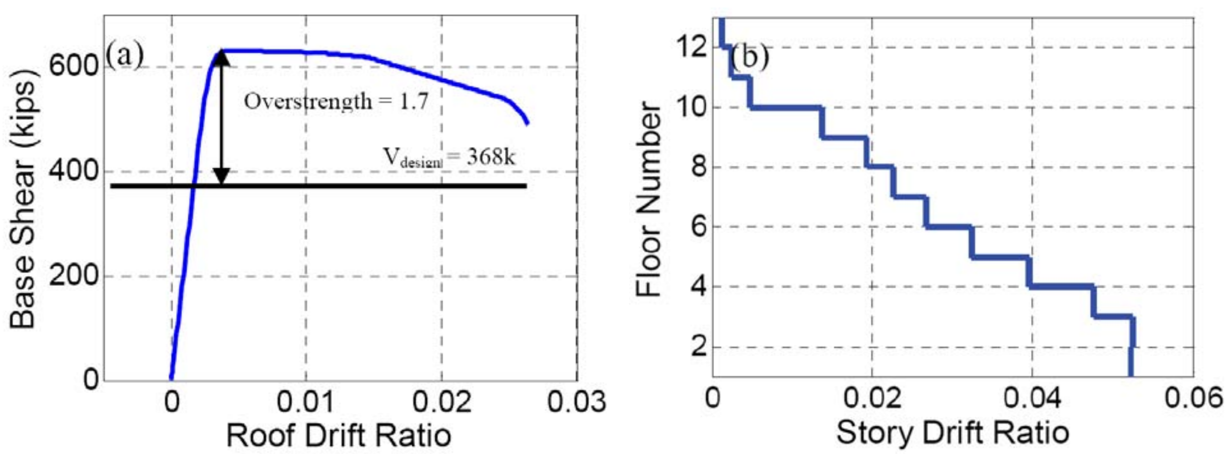

Figure G-11 (a) Monotonic pushover force-deformation curve and (b) distribution of story drift demands at a roof drift ratio of 2.7% in a twelve-story concrete frame building (Haselton 2006).

Figure G-12 shows the simplified tri-linear force-displacement capacity boundary selected to evaluate the proposed equation for R_{di} and results using SPO2IDA. It is assumed that at a roof drift ratio of 2.6% the structure reaches its maximum deformation capacity and a total loss in strength occurs.

Figure G-13 compares the median seismic behavior computed from incremental dynamic analyses conducted by Haselton (2006), indicated in the figure as MDOF IDA, with results computed using the proposed equation for R_{di} and approximate results from SPO2IDA. In the figure, both approximate methods somewhat overestimate the collapse capacity of the structure. Figure G-14 shows incremental dynamic analysis results for all ground motion records.

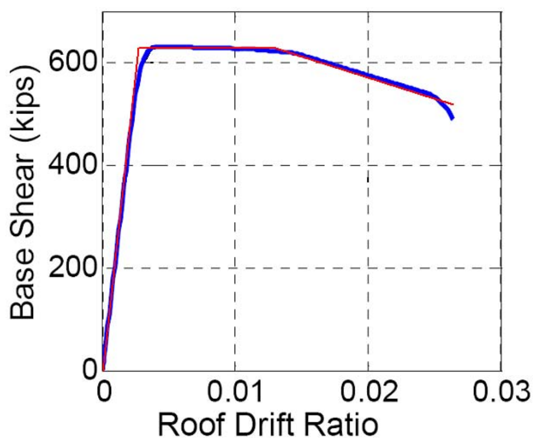

Figure G-12 Tri-linear capacity boundary selected for approximate analyses using *SPO2IDA*.

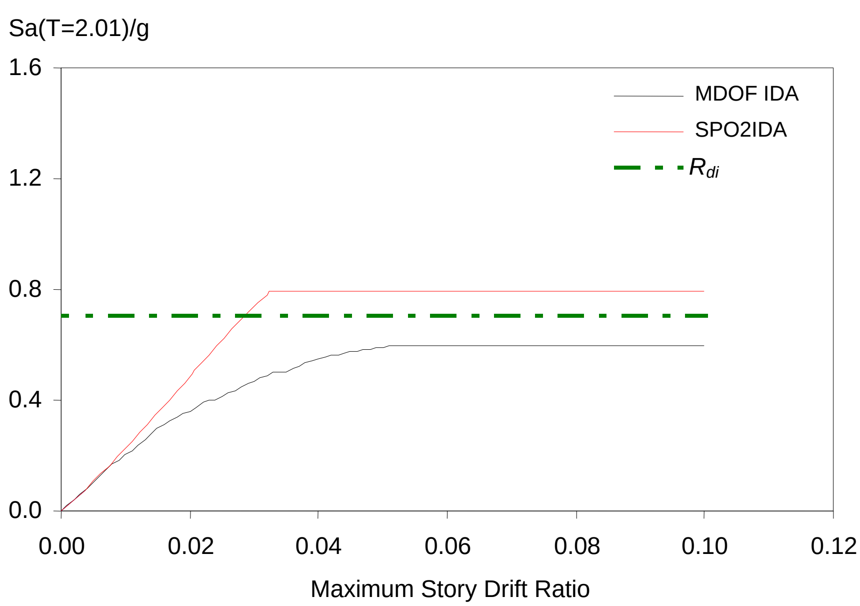

Figure G-13 Comparison of median collapse capacity for a twelve-story code-compliant concrete frame building computed using incremental dynamic analysis and approximate procedures.

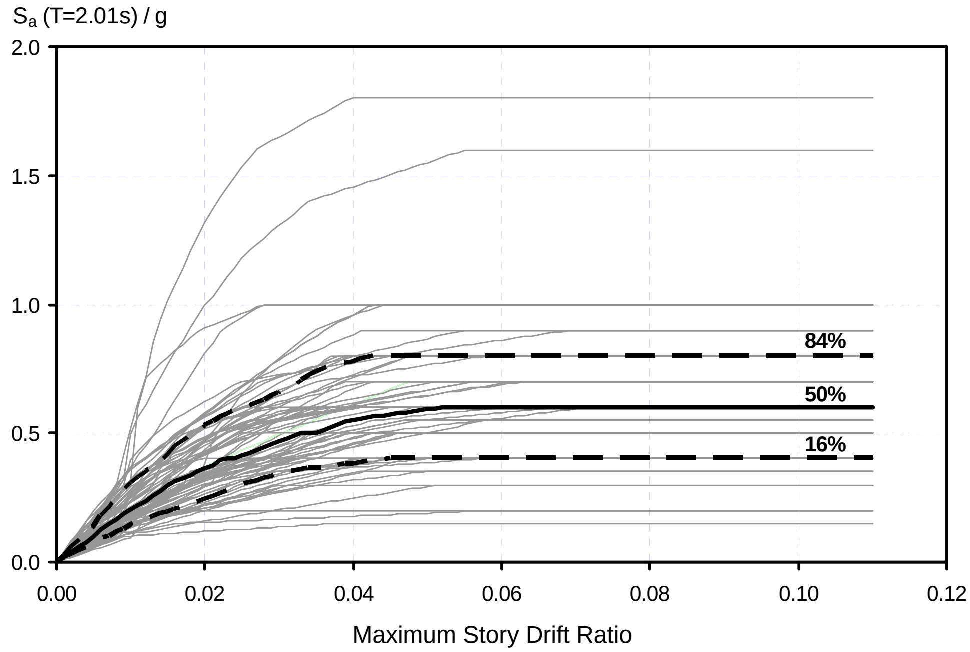

Figure G-14 Incremental dynamic analysis results for a twelve-story code-compliant concrete frame building subjected to 80 ground motions (adapted from Haselton, 2006).

G.4 Twenty-Story Code-Compliant Reinforced Concrete Building

The subject building is a twenty-story reinforced concrete special perimeter moment frame designed in accordance with modern building code provisions (ICC 2003, ASCE 2002, ACI 2002). The story height is 15 ft in the first story and 13 ft in the remaining stories. The design base shear coefficient was 0.044. The building was modeled in OpenSEES and analyzed using an incremental dynamic analysis using the same 80 recorded ground motions that were used to analyze the four-story building. The pushover analysis was again done using a lateral force distribution in accordance with ASCE/SEI 7-05. The fundamental period of vibration of the building is T_1=2.63s. For a more detailed description of the building and its modeling, the reader is referred to Haselton (2006).

Figure G-15 shows the results from the nonlinear static (pushover) analysis of the building. The figure on the left shows the force-deformation curve while the figure on the right shows the distribution of story drift ratios at a roof drift ratio of 1.8%. It can be seen that story drifts decrease approximately linearly with increasing height, with the largest story drifts occurring in the lower two stories. The force-deformation pushover curve is characterized by a slight softening segment for roof drift ratios between 0.3%

and 0.9%, followed by steeper softening segment for roof drift ratios greater than 0.9%.

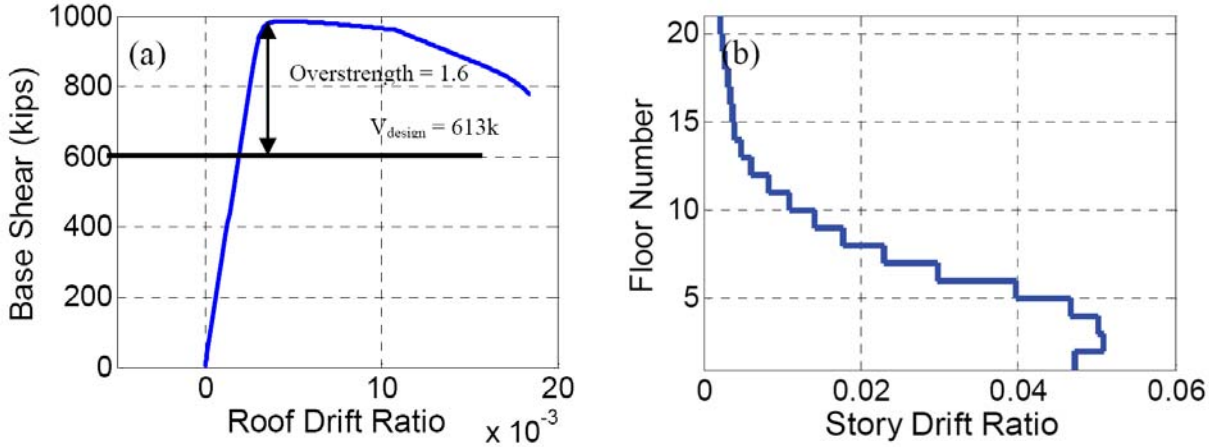

Figure G-15 (a) Monotonic pushover force-deformation curve and (b) distribution of story drift demands at a roof drift ratio of 1.8% in a twenty-story concrete frame building (Haselton 2006).

Figure G-16 shows the simplified tri-linear force-displacement capacity boundary selected to evaluate the proposed equation for R_{di} and results using SPO2IDA. It is assumed that at a roof drift ratio of 1.85% the structure reaches its maximum deformation capacity and a total loss in strength occurs.

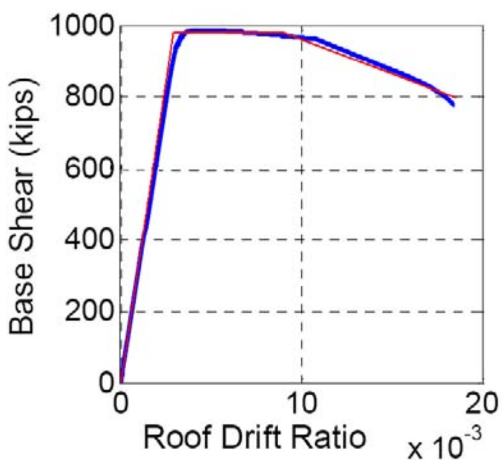

Figure G-16 Tri-linear capacity boundary selected for approximate analyses using *SPO2IDA*.

Figure G-17 compares the median seismic behavior computed from incremental dynamic analyses conducted by Haselton (2006), indicated in the figure as MDOF IDA, with results computed using the proposed equation for R_{di} and approximate results from SPO2IDA. In the figure, proposed equation for R_{di} provides a good estimate of the median collapse capacity, while SPO2IDA somewhat overestimates the collapse capacity. Figure G-18 shows incremental dynamic analysis results for all ground motion records.

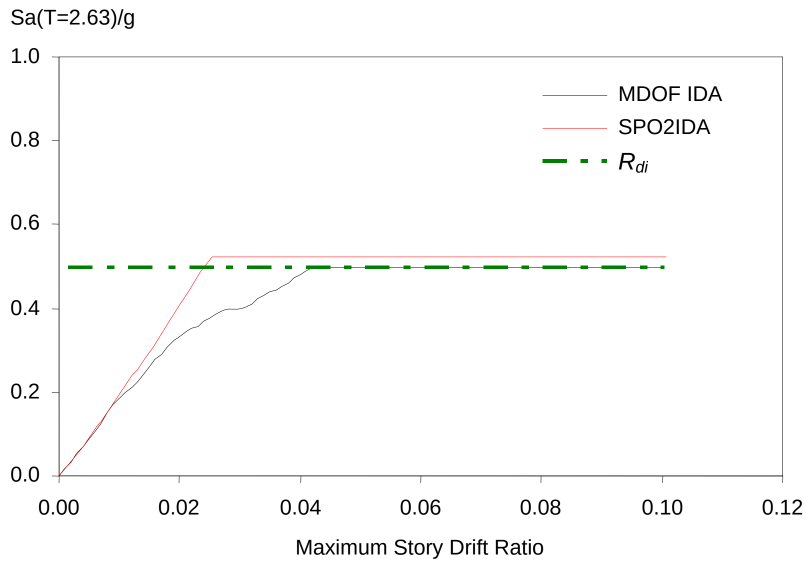

Figure G-17 Comparison of median collapse capacity for a twenty-story code-compliant concrete frame building computed using incremental dynamic analysis and approximate procedures.

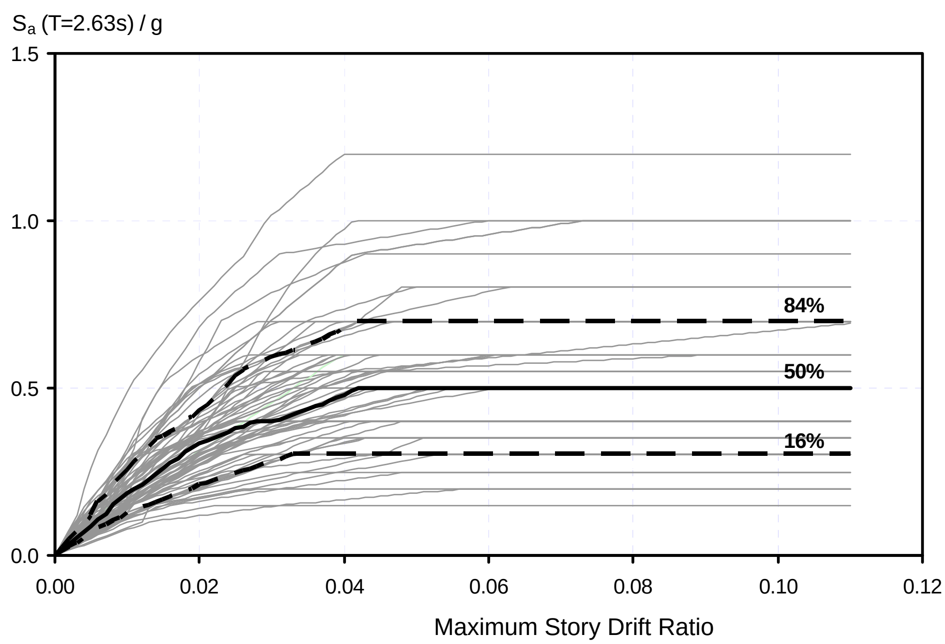

Figure G-18 Incremental dynamic analysis results for a twenty-story code-compliant concrete frame building subjected to 80 ground motions (adapted from Haselton, 2006).

G.5 Nine-Story Pre-Northridge Steel Moment-Resisting Frame Building

The subject building is a nine-story steel moment-resisting frame designed for the FEMA-funded SAC project in accordance with pre-Northridge code requirements for Los Angeles (ICBO, 1994). The building has a single-story basement that is 12 ft in height. The first story height is 18 ft and the remaining stories are 13 ft uniformly. The building is symmetric in plan with six bays of 30 ft in each direction. There is a perimeter moment-resisting frame designed for lateral-force-resistance, while internal gravity columns carry most of the vertical load. The building was modeled in OpenSEES and analyzed using incremental dynamic analysis with 30 “ordinary” ground motions. The pushover analysis was done using a triangular lateral force distribution. The fundamental period of vibration of the building is T_1=2.3s. For a more detailed description of the building and its modeling, the reader is referred to Gupta and Krawinkler (1999).

The results from a nonlinear static (pushover) analysis of the building are shown in Figure G-19. The force-deformation pushover curve is characterized by a hardening segment for roof drift ratios between 1% and 2.5%, followed by a softening segment that terminates when the building reaches zero strength at 5% roof drift. The simplified tri-linear force-displacement capacity boundary, also shown in Figure G-19, was selected to evaluate the proposed equation for R_{di} and results using SPO2IDA. In both cases the hardening segment has 13% of the elastic stiffness while the negative stiffness is -74% of elastic.

Figure G-20 shows the median seismic behavior computed from incremental dynamic analyses conducted by Vamvatsikos and Fragiadakis (2006). These results are indicated as MDOF IDA in the figure. Also shown are results computed using the proposed equation for R_{di} and approximate results from SPO2IDA. In the figure, both R_{di} and SPO2IDA provide a good approximation of the collapse capacity of the building.

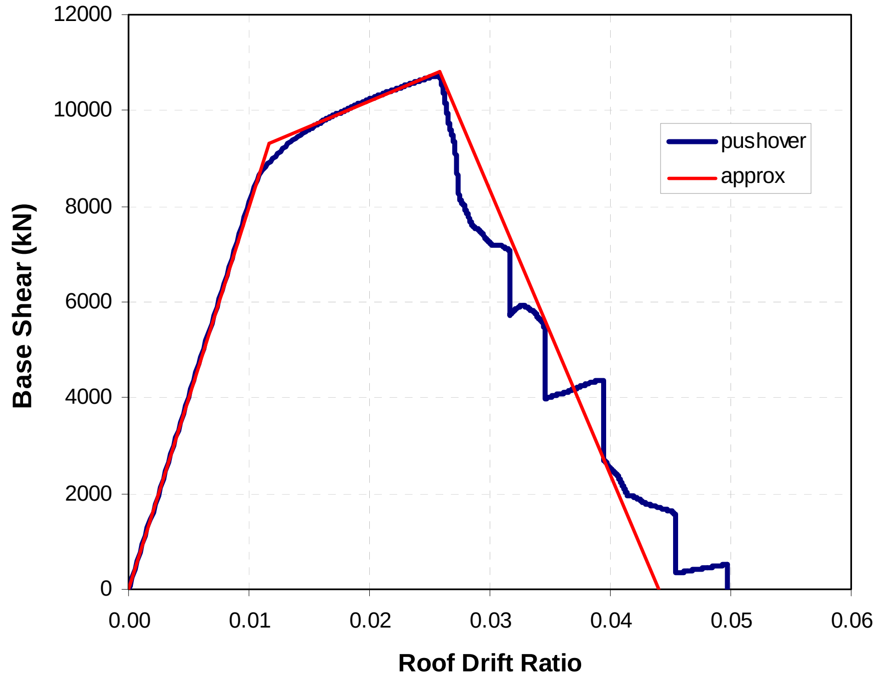

Figure G-19 Monotonic pushover force-deformation curve, and tri-linear approximation, for a nine-story pre-Northridge steel moment frame building (adapted from Gupta and Krawinkler, 1999).

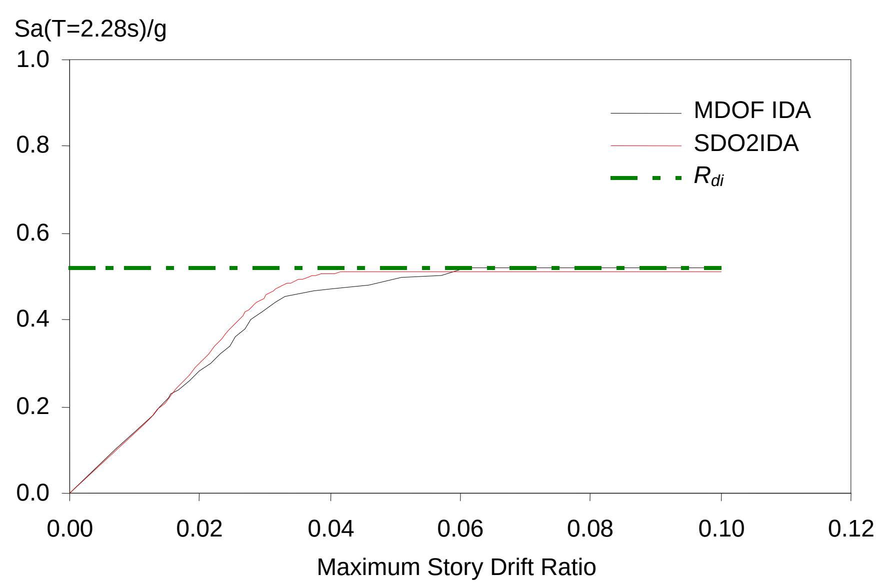

Figure G-20 Comparison of median collapse capacity for a nine-story pre-Northridge steel moment frame building computed using incremental dynamic analysis and approximate procedures.

G.6 Twenty-Story Pre-Northridge Steel Moment-Resisting Frame Building

The subject building is a twenty-story steel moment resisting frame designed for the FEMA-funded SAC project in accordance with pre-Northridge code requirements for Los Angeles (ICBO, 1994). The building has a basement consisting of two stories that are 12 ft in height. The first story height is 18 ft and the remaining stories are 13 ft uniformly. The building is slightly asymmetric in plan, with five bays of 20 ft in one direction and six bays of 20 ft in the other direction. There is a perimeter moment-resisting frame designed for lateral-force-resistance. Four internal gravity columns carry the vertical loads. The building was modeled in Drain-2DX and analyzed using incremental dynamic analysis with 30 “ordinary” ground motions. The pushover analysis was done using a parabolic (k = 2) lateral force distribution. The fundamental period of vibration of the building is T_1=4.0s. For a more detailed description of the building and its modeling, the reader is referred to Gupta and Krawinkler (1999).

The results from the nonlinear static (pushover) analysis of the building are shown in Figure G-21. The force-deformation pushover curve is characterized by a short hardening segment (5% stiffness ratio) from 0.7% to 1.2% roof drift ratio that then turns negative (-24% stiffness ratio) and terminates when the building reaches zero strength at 4% roof drift. The simplified tri-linear force-displacement capacity boundary, also shown in Figure G-21, was selected to evaluate the proposed equation for R_{di} and results using SPO2IDA.

Figure G-22 shows the median seismic behavior computed from incremental dynamic analyses conducted by Vamvatsikos and Cornell (2006). These results are indicated as MDOF IDA in the figure. Also shown are results computed using the proposed equation for R_{di} and approximate results from SPO2IDA. In the figure, R_{di} overestimates the collapse capacity of the building by about 25%, while SPO2IDA provides a good approximation.

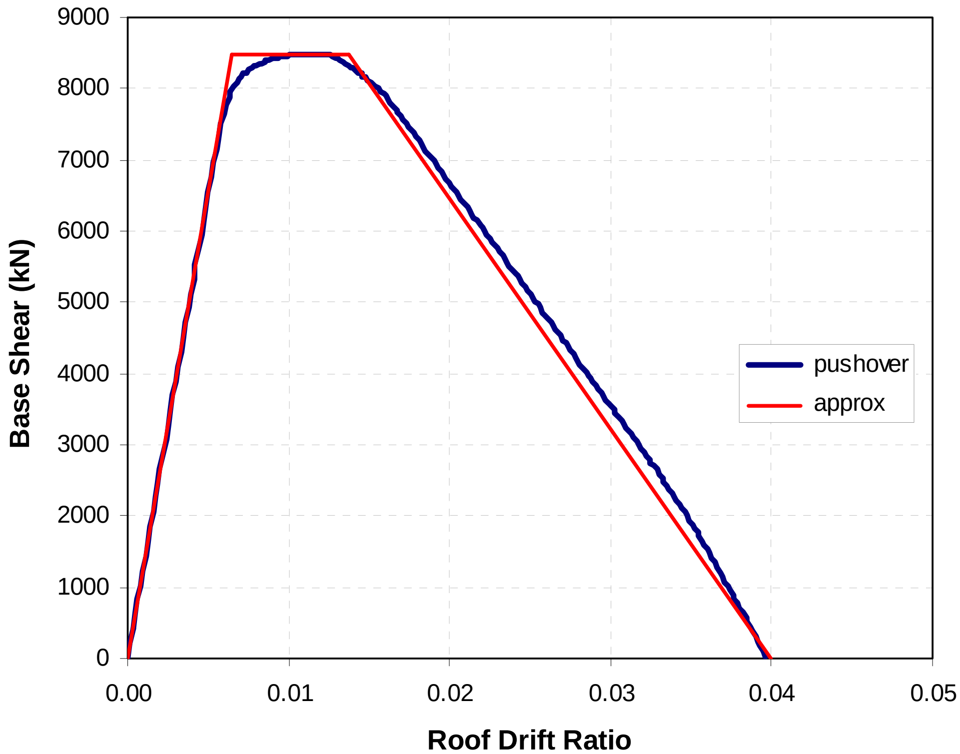

Figure G-21 Monotonic pushover force-deformation curve, and tri-linear approximation, for a twenty-story pre-Northridge steel moment frame building (adapted from Gupta and Krawinkler, 1999).

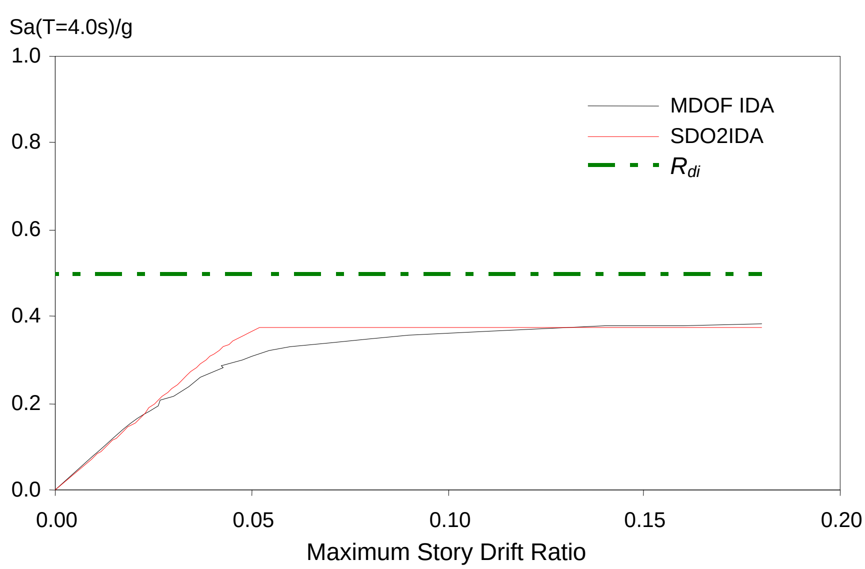

Figure G-22 Comparison of median collapse capacity for a twenty-story pre-Northridge steel moment frame building computed using incremental dynamic analysis and approximate procedures.

G.7 Summary and Recommendations

The studies documented above indicate that the application of procedures developed for SDOF systems to several representative MDOF moment frame systems produces reasonable approximations of the median intensity causing lateral dynamic instability. This was true in the case of both the proposed equation for R_{di} and simplified nonlinear dynamic analysis using SPO2IDA. These results lead to a recommendation for more thorough investigation of MDOF systems to modify, or further refine, the procedures presented here.

References and Bibliography

ACI, 2002, *Building Code Requirements for Structural Concrete (ACI 318-02)* and *Commentary (ACI 318R-02)*, American Concrete Institute, Farmington Hills, MI.

Allahabadi, R. and Powell, G. H., 1988, *DRAIN-2DX: User Guide*, Report No. UCB/EERC-88/06, Earthquake Engineering Research Center, University of California, Berkeley, California.

Anagnostopoulos, S.A., 1972, *Nonlinear Dynamic Response and Ductility Requirements of Building Structures Subjected to Earthquakes*, Report No. R72-54, Civil Engineering Dept., Massachusetts Institute of Technology, Cambridge, Massachusetts.

Archambault, M.H., Tremblay, R., and Filiatrault, A., 1995, *Etude du Comportement Sismique des Contreventements Ductiles en X avec Profiles Tubulaires en Acier*. Rapport no. EPM/GCS-1995-09, *in* Departement de Genie Civil, Ecole Polytechnique, Montreal, Canada, (in French).

ASCE, 2002, *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-02, American Society of Civil Engineers, Reston, VA.

ASCE, 2003, *Seismic Evaluation of Existing Buildings*, ASCE Standard SEI/ASCE 31-03, American Society of Civil Engineers, Reston, Virginia.

ASCE, 2006a, *Minimum Design Loads for Buildings and Other Structures*, ASCE Standard ASCE/SEI 7-05, including Supplement No. 1, American Society of Civil Engineers, Reston, Virginia.

ASCE, 2006b, *Seismic Rehabilitation of Existing Buildings*, ASCE Standard ASCE/SEI 41-06, American Society of Civil Engineers, Reston, Virginia.

Astaneh-Asl, A., Goel, S.C., and Hanson, R.D., 1982, *Cyclic Behavior of Double Angle Bracing Members with End Gusset Plates*, Rep. No. UMEE 82R7, Dept. of Civil Engineering, University of Michigan, Ann Arbor, Michigan.

Astaneh-Asl, A., Goel, S.C., 1984, "Cyclic in-plane buckling of double angle braces," *Journal of Structural Engineering*, ASCE, 110(9), pp. 2036-2055.

ATC, 1992, *Guidelines for Seismic Testing of Components of Steel Structures*, ATC-24 Report, Applied Technology Council, Redwood City, California.

ATC, 1996, *Seismic Evaluation and Retrofit of Concrete Buildings*, ATC-40 Report, Volumes 1 and 2, Applied Technology Council, Redwood City, California.

ATC, 2007, *Guidelines for Seismic Performance Assessment of Buildings*, ATC-58 Report, 35% draft, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Redwood City, California.

ATC, 2008b, *Interim Guidelines on Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings*, ATC-72-1 Report, 90% Draft, prepared by the Applied Technology Council for the Pacific Earthquake Engineering Research Center, Redwood City, California.

Baber, T.T. and Wen, Y., 1981, "Random vibration hysteretic, degrading systems," *J. Eng. Mech. Div.*, 107, 6, 1069-1087

Baber, T.T., and Noori, M.N., 1985, "Random vibration of degrading, pinching systems." *J. Engrg. Mech.*, ASCE, 111(8), 1010–1026.

Baber, T.T. and Noori, M.N., 1986, "Modeling general hysteresis behavior and random vibration application," *Trans. ASME*, 108, 411-420

Berg, G.V. and Da Deppo, D.A., 1960, "Dynamic analysis of elastoplastic structures," *Proc. American Society of Civil Engineers*, Vol. 86, No. 2, pp 35-58.

Bernal, D., 1998, "Instability of buildings during seismic response," *Engineering Structures*, Vol. 20, No. 4-6, pp. 496-502.

Bernal, D., 1992, "Instability of buildings subjected to earthquakes," *Journal of Structural Engineering* , ASCE, Vol. 118, No. 8, pp. 2239-2260.

Bernal, D., 1987, "Amplification factors for inelastic dynamic P-Δ effects in earthquake analysis," *Earthquake Eng. Struct. Dyn.*, 15(5), pp. 117-144.

Black, R.G., Wenger, W.A.B. and Popov, E.P., 1980, *Inelastic Buckling of Steel Struts under Cyclic Load Reversals*, Report No. UCB/EERC-

80/40, Earthquake Engineering Research Center, University of California, Berkeley, California.

Bouc, R., 1967, “Modele mathematique d’hysteresis.” *Acustica*, France, 24(1), 16–25 (in French).

Bouc, R., 1967, “Forced vibration of mechanical systems with hysteresis,” *Proc., 4th Conf. on Nonlinear Oscillations*, Prague, Czechoslovakia

Bruneau, M. and Vian, D., 2002, “Tests to collapse of simple structures and comparison with existing codified procedures,” *Proc. 7th U.S. National Conference on Earthquake Engineering*, Boston, MA.

Bruneau, M. and Vian, D., 2002, “Experimental investigation of *P-Δ* effects to collapse during earthquakes,” *Proc. 12th European Conference on Earthquake Engineering*, London, UK.

Casciati, F., 1989, “Stochastic dynamics of hysteretic media.” *Struct. Safety*, Amsterdam, 6, 259–269.

Casciati, F., and Faravelli, L., 1985, "Nonlinear stochastic dynamics by equivalent linearization, *Proc. 2nd Int. Workshop on Stochastic Methods in Structural Mechanics*, Pavia, Italy, 571-586

Caughey, T.K., 1960a, “Sinusoidal excitation of a system with bilinear hysteresis,” *Journal of Applied Mechanics*, American Society of Mechanical Engineers 27(4), pp. 640–648.

Caughey, T.K., 1960b, “Random excitation of a system with bilinear hysteresis,” *Journal of Applied Mechanics*, American Society of Mechanical Engineers, 27(4), pp. 649–652.

Chenouda, M. and Ayoub, A., 2007,“Inelastic displacement ratios of degrading systems.” *Journal of Structural Engineering*; 134(6): 1030-1045.

Chopra, A.K., Chintanapakdee, C., 2004, “Inelastic deformation ratios for design and evaluation of structures: single-degree-of-freedom bilinear systems.” *Journal of Structural Engineering*; 130(9): 1309-1319.

Clough, R.W., 1966, *Effects of Stiffness Degradation on Earthquake Ductility Requirement*, Rep. No. 6614, Struct. and Mat. Res., University of California, Berkeley, California.

Clough, R.W., and Johnston, S.B., 1966, “Effects of stiffness degradation on earthquake ductility requirements.” *Proc. 2nd Japan Earthquake Engrg. Symp.*, 227–232.

Dolsek, M., 2002, *Seismic Response of Infilled Reinforced Concrete Frames*, Ph.D. thesis, University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia [in Slovenian].

Dolsek, M. and Fajfar, P., 2004, "Inelastic spectra for infilled reinforced concrete frames," *Earthquake Engineering and Structural Dynamics*, Vol. 33, 1395–1416.

Dolsek ,M. and Fajfar, P., 2005, "Simplified nonlinear seismic analysis of infilled reinforced concrete frames," *Earthquake Engineering and Structural Dynamics*, Vol. 34, 49–66.

Dotiwala, F.S., 1996, *A Nonlinear Flexural-Shear Model for RC Columns Subjected to Earthquake Loads*, MS thesis, Department of Civil and Environmental Engineering, University of Wisconsin-Madison.

EERI, 2006, *New Information on the Seismic Performance of Existing Concrete Buildings*, EERI Technical Seminar developed by PEER and funded by FEMA, video download @ www.eeri.org.

EERI, 2008, *World Housing Encyclopedia*, www.world-housing.net,

El-Bahy, A., Kunnath, S.K., Stone, W.C. and Taylor, A.W., 1999, "Cumulative seismic damage of circular bridge columns: variable amplitude tests," *ACI Structural Journal*, Vol. 96, No.5, 711-719.

El-Tawil, S., 1996, *Inelastic Dynamic Analysis of Mixed Steel-Concrete Space Frames*, Ph.D. Dissertation, Cornell University, Ithaca, NY.

Elwood, K.J., 2002, *Shake Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames*, Ph.D. Dissertation, University of California, Berkeley, California.

Elwood, K.J., and Moehle, J.P., 2003, *Shake-Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames*, PEER Report 2003/01, Pacific Earthquake Engineering Research Center, University of California, Berkeley, California.

Elwood, K.J., 2004, "Modeling failures in existing reinforced concrete columns," *Can. J. Civ. Eng*. 31: 846–859.

Elwood, K.J., and Moehle, J.P., 2005, "Drift capacity of reinforced concrete columns with light transverse reinforcement," *Earthquake Spectra*, Volume 21, No. 1, pp. 71–89.

Elwood, K.J. and Moehle, J.P., 2006, "Idealized backbone model for existing reinforced concrete columns and comparisons with FEMA 356 criteria," *The Struct. Design of Tall Spec. Buildings*, 15, 553–569

Elwood, K.J., Matamoros, A.B., Wallace, J.W., Lehman, D.E., Heintz, J.A., Mitchell, A.D., Moore, M.A., Valley, M.T., Lowes, L.N., Comartin, C.D., Moehle, J.P., 2007, "Update to ASCE/SEI 41 concrete provisions," *Earthquake Spectra*, Earthquake Engineering Research Institute, Oakland, California.

FEMA, 1997, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, FEMA 273 Report, prepared by the Building Seismic Safety Council and the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 1998, *Handbook for the Seismic Evaluation of Buildings – A Prestandard*, FEMA 310 Report, prepared by the American Society of Civil Engineers for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2000, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, FEMA 356 Report, prepared by the American Society of Civil Engineers for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2004a, *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Part 1: Provisions*, FEMA 450-1, 2003 Edition, Federal Emergency Management Agency, Washington, D.C.

FEMA, 2004b, *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Part 2: Commentary*, FEMA 450-2, 2003 Edition, Federal Emergency Management Agency, Washington, D.C.

FEMA, 2005, *Improvement of Nonlinear Static Seismic Analysis Procedures*, FEMA 440 Report, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2009, *Quantification of Building Seismic Performance Factors*, FEMA P695 Report, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

Foutch, D.A. and Shi, S., 1998, "Effects of hysteresis type on the seismic response of buildings," *Proc. 6th U.S. National Conference on Earthquake Engineering*, Seattle, Washington; Earthquake Engineering Research Institute, Oakland, California.

Goel, SC., El-Tayem A., 1986, "Cyclic load behavior of angle X-bracing," *Journal of Structural Engineering*, ASCE, 112(11), pp. 2528-2539.

Goel, S.C., and Stojadinovic, B., 1999, University of Michigan, Ann Arbor, Michigan.

Gugerli, H., and Goel, S.C., 1982, *Inelastic Cyclic Behavior of Steel Bracing Members*, Rep. No. UMEE 82R1, Dept. of Civil Engineering, University of Michigan, Ann Arbor, Michigan.

Gupta, A., and Krawinkler, H., 1998, "Effect of stiffness degradation on deformation demands for SDOF and MDOF structures," *Proc. Sixth U.S. National Conference on Earthquake Engineering*, Seattle, Washington.

Gupta, A., and Krawinkler, H., 1999, *Seismic Demands for Performance Evaluation of Steel Moment-Resisting Frame Structures*. Rep. No. 132, John A. Blume Earthquake Engineering Center, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, California.

Gupta, B., and Kunnath, S., 1998, "Effect of hysteretic model parameters on inelastic seismic demands," *Proc*., *6th Nat. Conf. Earthq. Engrg*., Seattle, Washington.

Haselton, C.B., 2006, *Assessing Seismic Collapse Safety of Modern Reinforced Concrete Moment Frame Buildings*, Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University.

Haselton, C., Liel, A., Taylor Lange, S., and Deierlein, G.G., 2007, *Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of RC Frame Buildings* (In Preparation). Pacific Earthquake Engineering Research Center 2007/03, University of California, Berkeley, California.

Hassan, O.F. and Goel, S.C., 1991, *Modeling of Bracing Members and Seismic Behavior of Concentrically Braced Steel Structures,* Research Report UMCE 91-1, Department of Civil Engineering, University of Michigan, Ann Arbor, Michigan,

Higginbotham, A.B. and Hanson, R.D., 1976, "Axial hysteretic behavior of steel members," *J. Struct. Div.*, ASCE, 102, pp. 1365-81.

Hisada, T., Nakagawa, K., and Izumi, M., 1962, "Earthquake response of structures having various restoring force characteristics," *Proc. Japan National Conference on Earthquake Engineering*, pp. 63-68.

Ibarra, L., Medina, R., Krawinkler, H., 2002, "Collapse assessment of deteriorating SDOF systems," *Proc. 12th European Conference on*

Earthquake Engineering, London, UK, Paper 665, Elsevier Science Ltd.

Ibarra, L.F., and Krawinkler, H., 2005, *Global Collapse of Frame Structures under Seismic Excitations*, Report No. 152, John A. Blume Earthquake Engineering Research Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, California.

Ibarra, L., Medina, R., and Krawinkler, H., 2005, “Hysteretic models that incorporate strength and stiffness deterioration, *Earthquake Engineering and Structural Dynamics*, Vol. 34, no. 12, pp. 1489-1511

ICBO, 1994, *Uniform Building Code*, International Conference of Building Officials, Whittier, California.

ICC, 2003, *International Building Code*, International Code Council, Washington, D.C.

Ikeda, K., Mahin, S.A., and Dermitzakis, S.N., 1984, *Phenomenological Modeling of Steel Braces under Cyclic Loading*, Rep. No. UCB/EERC-84/09, Earthquake Engineering Research Center, University of California, Berkeley, California.

Ikeda, K., and Mahin, S.A., 1984, *A Refined Physical Theory Model for Predicting the Behavior of Braced Steel Frames*, Rep. No. UCB/EERC-84/12, Earthquake Engineering Research Center, University of California, Berkeley, California.

Ikeda, K., and Mahin, S.A., 1986, “Cyclic response of steel braces.” *J. Struct. Eng.*, 112(2), 342–361.

Ingham J.M., Liddell D. and Davidson B., 2001, Influence of loading history on the response of a reinforced concrete beam, *Bulletin of the New Zealand Society of Earthquake Engineering*, 34(2), 107-124

Iwan, W.D., 1961, *The Dynamic Response of Bilinear Hysteretic Systems*, Ph.D. Thesis, California Institute of Technology, Pasadena, California.

Iwan, W.D., 1966, “A distributed-element model for hysteresis and its steady-state dynamic response.” *J. Appl. Mech.*, 33(42), 893–900.

Iwan, W.D., 1967, “On a class of models for the yielding behavior of continuous and composite systems,” *J. Appl. Mech.*, 34, 612–617.

Iwan, W.D., 1973, “A model for the dynamic analysis of deteriorating structures,” *Proc. Fifth World Conference on Earthquake Engineering*, Rome, Italy, pp. 1782-1791.

Iwan, W.D., 1977, “The response of simple stiffness degrading structures,” *Proc. Sixth World Conference on Earthquake Engineering*, pp. 1094-1099.

Iwan, W.D., 1978, “The earthquake response of strongly deteriorating systems including gravity effects”, *Proc. Sixth European Conference on Earthquake Engineering*; pp. 23-30, 1978.

Iwan, W.D., and Gates, N.C., 1979a, “Estimating earthquake response of simple hysteretic structures.” *J. Eng. Mech. Div.*, ASCE, 105(3), 391–405.

Iwan, W.D., and Gates, N.C., 1979b, “The effective period and damping of a class of hysteretic structures,” *Earthquake Engineering and Structural Dynamics*. Vol. 7, no. 3, pp. 199-211.

Iwan, W.D., 1980, “Estimating inelastic response spectra from elastic spectra,” *Earthquake Engineering and Structural Dynamics*. Vol. 8, no. 4, pp. 375-388.

Jacobsen, L.S., 1958, "Behavioristic models representing hysteresis in structural joints," *Proc. Festskrift in Honor of Prof. Anker Engelund's seventieth birthday*, Technical University of Denmark

Jain, A.K., Goel, S.C., and Hanson, R.D., 1978a, *Hysteresis Behavior of Bracing Members and Seismic Response of Braced Frames with Different Proportions*, Rep. No. UMEE 78R3, Dept. of Civil Engineering, University of Michigan, Ann Arbor, Michigan.

Jain, A.K., Goel, S.C., and Hanson, R.D., 1978b, "Inelastic response of restrained steel tubes." *Journal of Structural Division*, ASCE, 104(6), pp. 897-910.

Jain, A.K. and Goel, S.C., 1978, *Hysteresis Models for Steel Members Subjected to Cyclic Buckling or Cyclic End Moments and Buckling*, (User's Guide for DRAIN-2D: EL9 and EL10), Report UMEE 78R6, Department of Civil Engineering, University of Michigan, Ann Arbor, Michigan.

Jain, A.K., Goel, S.C., and Hanson, R.D., 1980, "Hysteretic cycles of axially loaded steel members." *Journal of Structural Division*, ASCE, 106(ST8), pp. 1777-1795.

Jennings, P.C., 1963, *Response of Simple Yielding Structures to Earthquake Excitation*, Ph.D. Thesis, California Institute of Technology, Pasadena, California.

Jun Jin and Sherif El-Tawil, 2003, “Inelastic cyclic model for steel braces,” *J. Engrg. Mech.*, 129(5), 548-557.

Kanvinde, A.M., 2003, “Methods to evaluate the dynamic stability of structures – shake table tests and nonlinear dynamic analyses,” EERI Annual Student Paper Competition, *Proceedings of 2003 EERI Annual Meeting*, Portland.

Kaul, R., 2004, *Object-Oriented Development of Strength and Stiffness Degrading Models for Reinforced Concrete Structures*, Ph.D. Thesis, Department of Civil and Environmental Engineering, Stanford University, Stanford, California.

Kawashima, K., MacRae, G.A., Hoshikuma, J., and Nagaya K., 1998, “Residual displacement response spectrum.” *Journal of Structural Engineering*; 124(5), pp. 523-530.

Khatib, I. and Mahin, S., 1987, “Dynamic inelastic behavior of chevron-braced steel frames”, *Fifth Canadian Conference on Earthquake Engineering*, Balkema, Rotterdam.

Khatib, I.F., Mahin, S.A., and Pister, K.S., 1988, *Seismic Behavior of Concentrically Braced Steel Frames*, Report UCB/EERC-88/01, Earthquake Engineering Research Center, University of California. Berkeley, California.

Kunnath, S.K., Reinhorn, A.M. and Park, Y.J., 1990, “Analytical modeling of inelastic seismic response of RC structures,” *Journal of Structural Engineering*, ASCE, 116, 996–1017.

Kunnath S.K., Mander J.B. and Fang L., 1997, “Parameter identification for degrading and pinched hysteretic structural-concrete systems,” *Engineering Structures*, 19(3), 224-232.

Lee, L.H, Han, S.W., and Oh, Y.H., 1999, “Determination of ductility factor considering different hysteretic models,” *Earthquake Engineering and Structural Dynamics*, Vol. 28, 957–977.

Lignos, D.G., (2008), *Sidesway Collapse of Deteriorating Structural Systems under Seismic Excitations*, Ph.D. Thesis, Department of Civil and Environmental Engineering, Stanford University, Stanford, California.

Lin, M.L., Weng, Y.T., Tsai, K.C., Hsiao, P.C., Chen, C.H. and Lai, J.W., 2004, Pseudo-dynamic test of a full-scale CFTBRB frame: Part 3 - Analysis and performance evaluation. *Proc. 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, Paper No. 2173, August 1-6.

Liu, J. and Astaneh-Asl, A., 2004, "Moment-rotation parameters for composite shear-tab connections," *Journal of Structural Engineering*, ASCE, Vol. 130, No. 9, 1371-1380.

MacRae, G.A., and Kawashima, K., 1997, "Post-earthquake residual displacements of bilinear oscillators," *Earthquake Engineering and Structural Dynamics* 26, pp. 701-716.

Mahin, S.A. and Bertero, V.V., 1972, *Rate of Loading Effect on Uncracked and Repaired Reinforced Concrete Members*, Report EERC 73/6, Earthquake Engineering Research Center, University of California, Berkeley, California

Mahin, S.A. and Lin, J., 1983, *Construction of inelastic response spectra for single-degree-of-freedom systems: computer program and applications*, Report No. UCB/EERC-84/09, Earthquake Engineering Research Center, University of California, Berkeley, California.

Maison, B.F., and Popov, E.P., 1980, "Cyclic response prediction for braced steel frames," *J. Struct. Div.*, ASCE, 106(7), 1401–1416.

Masing, G., 1926, "Eigenspannungen und verfestigung beim messing." *Proc., 2nd Int. Cong. Appl. Mech.*, 332–335.

McKenna, F.T., 1997, *Object-Oriented Finite Element Programming: Framework for Analysis, Algorithms, and Parallel Computing*, Ph.D. Dissertation, University of California, Berkeley, California.

Medina, R., 2002, *Seismic Demands for Nondeteriorating Frame Structures and their Dependence on Ground Motions*, Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University.

Medina, R. and Krawinkler, H., 2004, "Influence of hysteretic behavior on the nonlinear response of frame structures," *Proc. 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

Mehanny, S.S.F., and Deierlein, G.G., 2001, "Seismic collapse assessment of composite RCS moment frames," *Journal of Structural Engineering*, ASCE, Vol. 127(9).

Menegotto, M., and Pinto, P., 1973, "Method of analysis for cyclically loaded RC plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending." *Proc., Symp. Resistance and Ultimate Deformability of Struct. Acted on by Well-Defined Repeated Loads*, IABSE Reports, Vol. 13. 2557–2573.

Miranda, E., 1993, "Evaluation of site-dependent inelastic seismic design spectra," *Journal of Structural Engineering*, ASCE, 119(5), pp. 1319-1338.

Miranda, E., 2000, "Inelastic displacement ratios for structures on firm sites," *Journal of Structural Engineering*, ASCE, 126(10), pp. 1150-1159.

Miranda, E. and Akkar, S.D., 2003, "Dynamic instability of simple structural systems," *Journal of Structural Engineering*, ASCE, 129(12), pp 1722-1727.

Miranda, E. and Ruiz-Garcia, J., 2002, "Influence of stiffness degradation on strength demands of structures built on soft soil sites," *Engineering Structures*, Vol. 24, No. 10, pp. 1271-1281.

Mostaghel, N., 1998, *Analytical description of pinching, degrading hysteretic systems*, Rep. No. UT-CE/ST-98-102, Dept. of Civ. Engrg., University of Toledo, Toledo, Ohio.

Mostaghel, N., 1999, "Analytical description of pinching, degrading, hysteretic systems," *J. Engrg. Mech.*, ASCE, 125(2), 216–224.

Mostaghel, N. and Byrd, R.A., 2002, "Inversion of Ramberg-Osgood equation and description of hysteresis loops," *International Journal of Non-Linear Mechanics*. Vol. 37, no. 8, pp. 1319-1335.

Nakashima, M. and Wakabayashi, M., 1992, "Analysis and design of steel braces and braced frames in building structures," *in* Fukumoto Y, Lee GC, editors, *Stability and Ductility of Steel Structures under Cyclic Loading*, Boca Raton, FL: CRC Press; p. 309-21.

Nassar, A.A. and Krawinkler, H., 1991, *Seismic Demands for SDOF and MDOF Systems*, Report No. 95, John A. Blume Earthquake Engineering Center, Stanford University, Stanford, California, 204 pages.

Nielsen, N.N. and Imbeault, F.A., 1970, "Validity of various hysteretic systems," *Proc. Third Japan Earthquake Engineering Symposium*, Tokyo, Japan, pp. 707-714.

Nonaka, T., 1973, “An elastic-plastic analysis of a bar under repeated axial loading,” *Int. J. Solids Struct.*, 9, 569–580.

Nonaka, T., 1977, “Approximation of yield condition for the hysteretic behavior of a bar under repeated axial loading,” *Int. J. Solids Struct.*,13, 637–643.

Otani, S. and Sozen, M.A., 1972, *Behavior of Multistory Reinforced Concrete Frames during Earthquakes*, Civil Engineering Studies, SRS No. 392, University of Illinois at Urbana, 551 pages.

Otani, S., 1981, “Hysteresis model of reinforced concrete for earthquake response analysis,” *Journal*, *Fac. of Eng.*, University of Tokyo, Series B, Vol. XXXVI-11, 2, 407-441.

Ozdemir, H., 1976, *Nonlinear Transient Dynamic Analysis of Yielding Structures*, Ph.D. Dissertation, University of California, Berkeley, California.

Pampanin, S, Christopoulos, C, and Priestley, M.J.N., 2002, *Residual Deformations in the Performance-Seismic Assessment of Frame Structures*, Research Report No. ROSE-2002/02, European School for Advanced Studies in Reduction of Seismic Risk, Pavia, Italy.

Park, Y.J., and Ang, A., 1985, “Mechanistic seismic damage model for reinforced concrete,” *Journal of Structural Engineering*, ASCE, 111-4, pp. 722-739.

Park, Y. J., Reinhorn, A.M., and Kunnath, S.K., 1987, *IDARC: inelastic damage analysis of reinforced concrete frame, shear-wall, structures*, Tech. Rep. NCEER-87-0008, State University of New York at Buffalo, Buffalo, New York.

PEER, 2005, *Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment*, PEER Report 2005/11, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.

PEER, 2006, *PEER NGA Database*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, California, http://peer.berkeley.edu/nga/

Penzien, J., 1960a, “Elastoplastic response of idealized multistory structures subjected to a strong-motion earthquake, *Proc. Second World Conf. on Earthquake Engineering*, Vol. II, Tokyo and Kyoto, Japan.

Penzien, J., 1960b, “Dynamic response of elastoplastic frames,” *Proc. American Society of Civil Engineers*, Vol. 86, No. 7, pp 81-94.

Pincheira, J.A., and Dotiwala, F.S., 1996, "Modeling of nonductile RC columns subjected to earthquake loading," *Proc. 11th World Conf. on Earthquake Engineering*, Paper No. 316, Acapulco, Mexico.

Pincheira, J.A, Dotiwala, F.S., and D'Souza, J.T., 1999, "Spectral displacement demands of stiffness- and strength-degrading systems," *Earthquake Spectra*, 15(2), 245–272.

Pinto, P. E. and Giuffre, A., 1970, "Behavior of reinforced concrete sections under cyclic loading of high intensity," *Giornale del Genio Civile*, No. 5, (in Italian).

Popov, E.P. and Black, G.R., 1981, "Steel struts under severe cyclic loadings," *Journal of Structural Engineering*, ASCE, 107(9), pp. 1857-1881

Popov, E.P., Zayas, V.A., and Mahin, S.A., 1979, "Cyclic inelastic buckling of thin tubular columns." *J. Struct. Div.*, ASCE, 105(11), pp. 2261–2277.

Powell, G.H., and Row, D.G., 1976, *Influence of Analysis and Design Assumptions on Computed Inelastic Response of Moderately Tall Frames*, Report No. UCB/EERC-76/11, Earthquake Engineering Research Center, University of California at Berkeley, Berkeley, California.

Prathuangsit, D., Goel, S.C. and Hanson, R.D., 1978, "Axial hysteresis behavior with end restraints," *J. Struct. Div.*, ASCE, 104, 883-95.

Rahnama, M, and Krawinkler, H., 1993, *Effects of Soft Soil and Hysteretic Models on Seismic Demands*, Report No. 108, John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, California, 258 pages.

Rai, D.C., Goel, S.C., and Firmansjah, J., 1996, *User's Guide Structural Nonlinear Analysis Program (SNAP)*, Department of Civil and Environmental Engineering; University of Michigan; College of Engineering, Ann Arbor, Michigan.

Ramberg, W., and Osgood, W.R., 1943, *Description of Stress-Strain Curves by Three Parameters*, Tech. Note 902, National Advisory Committee on Aeronautics.

Remennikov, A.M. and Walpole, W.R., 1997a, "Analytical prediction of seismic behavior for concentrically-braces steel systems," *Earthquake Eng. Struct. Dyn.*, 26, 859–874.

Remennikov, A.M. and Walpole, W.R., 1997b, "Modeling the inelastic cyclic behavior of a bracing member for work-hardening material," *Int. J. Solids Struct.*, 34, 3491–3515.

Riddell, R. and Newmark, N.M., 1979, *Statistical Analysis of the Response of Nonlinear Systems Subjected to Earthquakes*, Rep. No. UILI-ENG79-2016, Structural Research Series, Dept. of Civil Engineering, University of Illinois, Urbana.

Riddell, R. and Newmark, N.M., 1979, "Force-deformation models for nonlinear analyses," *J. Struct. Div.*, ASCE, 105, pp. 2773–2778.

Ruiz-Garcia, J. and Miranda, E., 2003, "Inelastic displacement ratio for evaluation of existing structures," *Earthquake Engineering and Structural Dynamics*, 32(8), 1237-1258, 2003.

Ruiz-Garcia, J. and Miranda, E., 2004, "Inelastic displacement ratios for structures built on soft soil sites", *Journal of Structural Engineering*, Vol. 130, No. 12, December 2004, pp. 2051-2061

Ruiz-Garcia, J. and Miranda, E., 2005, *Performance-Based Assessment of Existing Structures Accounting for Residual Displacements*, Report No. 153, John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, California, 444 pages.

Ruiz-Garcia, J. and Miranda, E., 2006a, "Residual displacement ratios for the evaluation of existing structures," *Earthquake Engineering and Structural Dynamics*, Vol. 35, pp. 315-336, 2006.

Ruiz-Garcia, J. and Miranda, E., 2006b, "Inelastic displacement ratios for evaluation of structures built on soft soil sites," *Earthquake Engineering and Structural Dynamics*, Vol. 35(6), pp.679–94.

Sezen, H., 2002, *Seismic response and modeling of lightly reinforced concrete building columns*, Ph.D. Dissertation, U.C. Berkeley, CA

Shi, S. and Foutch, D.A., 1997, *Evaluation of Connection Fracture and Hysteresis Type on the Seismic Response of Steel Buildings*, Report No. 617, Civil Engineering Studies, Structural Research Series, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Shibata, M., 1982, "Analysis of elastic-plastic behavior of a steel brace subjected to repeated axial force," *Int. J. Solids Struct.*, 18, 217–228.

Shing, P.B., Noland, J.L., Spaeh, H.P., Klamerus, E.W., and Schuller. M.P., 1991, "Response of Single-Story Reinforced Masonry Shear Walls to In-Plane Lateral Loads," *TCCMaR Report 3.1(a)-2*, U.S.-Japan

Coordinated Program for Masonry Building Research, University of Colorado, Boulder, Colorado.

Sivaselvan, M.V. and Reinhorn, A.M., 1999, *Hysteretic Models for Cyclic Behavior of Deteriorating Inelastic Structures*, Tech. Rep. MCEER-99-0018, Multidisciplinary Ctr. for Earthquake Engrg. Res., State University of New York at Buffalo, Buffalo, New York

Sivaselvan, M. and Reinhorn, A., 2000, "Hysteretic models for deteriorating inelastic structures," *Journal of Engineering Mechanics*, Vol. 126. No. 6., pp. 633-640.

Song J.-K., and Pincheira, J.A., 2000, "Seismic analysis of older reinforced concrete columns," *Earthquake Spectra*, 16(4), 817–851.

Takeda, T., Sozen, M.A. and Nielsen, N.N., 1970, "Reinforced concrete response to simulated earthquakes," *Journal of the Structure Division*, ASCE, ST12, pp. 2557-2573.

Takemura, H. and Kawashima, K., 1997, "Effect of loading hysteresis on ductility capacity of reinforced concrete bridge piers," *Journal of Structural Engineering*, Japan, Vol. 43A, pp. 849-858, (in Japanese).

Tang, X. and Goel, S.C., 1987, *Seismic Analysis and Design Considerations of Braced Steel Structures*, Research Report UMCE 87-4, Department of Civil Engineering, University of Michigan, Ann Arbor, Michigan.

Thyagarajan, R.S., 1989, *Modeling and Analysis of Hysteretic Structural Behavior*, Rep. No. EERL 89-03, California Institute of Technology, Pasadena, California.

Thyagarajan, R.S., and Iwan, W.D., 1990, "Performance characteristics of a widely used hysteretic model in structural dynamics." *Proc., 4th U.S. Nat. Conf. on Earthquake Engrg.*, Vol. 2, 177–186.

Tremblay, R., Tchebotarev, N. and Filiatrault, A., 1997, "Seismic performance of RBS connections for steel moment-resisting frames: influence of loading rate and floor slab", *Behavior of Steel Structures in Seismic Areas, Proceedings of the Second International Conference*, STESSA, Kyoto, August 3-8, 1997, p. 664-671.

Tremblay, R., 2002, "Inelastic seismic response of steel bracing members", *Journal of Constructional Steel Research*, 58, pp. 665-701.

Tremblay, R., Archambault, M.-H., and Filiatrault, A., 2003, "Seismic response of concentrically braced steel frames made with rectangular hollow bracing members," *Journal of Structural Engineering*, ASCE, 129(12), pp. 1626-1636.

Uang, C.M., Kent, Yu, K., and Gilton, C., 2000, *Cyclic Response of RBS Moment Connections: Loading Sequence and Lateral Bracing Effects*, Report No. SSRP 99/13, University of California, San Diego, California.

Uang, C.M. and Gatto, K., 2003, "Effects of finish materials and dynamic loading on the cyclic response of woodframe shearwalls," *Journal of Structural Engineering*, 129(10), 1394-1402

Uriz, P. and Mahin, S., 2004, "Seismic performance of concentrically braced steel frame buildings," *Proc. 13th World Conf. on Earthquake Engineering*, Vancouver, Canada.

Uriz, P., 2005, *Towards Earthquake Resistant Design of Concentrically Braced Steel Structures*, Ph.D. Thesis, University of California at Berkeley, Berkeley, California, 467 p.

Valles, R.E., Reinhorn, A.M., Kunnath, S.K., Li, C., and Madan, A., 1996, *IDARC 2D version 4.0: A program for the inelastic damage analysis of buildings*, Tech. Rep. NCEER-96-0010, Nat. Ctr. For Earthquake Engrg. Res., State University of New York at Buffalo, Buffalo, New York.

Vamvatsikos, D. and Cornell, C.A., 2002, "Incremental Dynamic Analysis," *Earthquake Engineering and Structural Dynamics*, Vol. 31, Issue 3, pp. 491-514.

Vamvatsikos, D., and Cornell, C.A., 2005, *Seismic Performance, Capacity and Reliability of Structures as seen through Incremental Dynamic Analysis*, Report No. 151, John A. Blume Earthquake Engineering Research Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, California.

Vamvatsikos, D. and Cornell, C.A., 2006, "Direct estimation of the seismic demand and capacity of oscillators with multi-linear static pushovers through Incremental Dynamic Analysis", *Earthquake Engineering and Structural Dynamics*, 35(9): 1097-1117.

Veletsos, A.S. and Newmark, N.M., 1960, "Effects of inelastic behavior on the response of simple systems to earthquake ground motions," *Proc. Second World Conf. on Earthquake Engineering*, Vol. II, Tokyo and Kyoto, Japan, pp 895-912.

Venti, M. and Engelhardt, M.D., 1999, *Brief Report of Steel Moment Connection Test, Specimen DBBW (Dog Bone, Bolted Web)*, SAC

Joint Venture - Steel Project, Internal SAC Phase 2 Background Report.

Vian, D. and Bruneau, M., 2001, *Experimental Investigation of P-Δ Effects to Collapse During Earthquakes*, Report MCEER-01-0001, Multidisciplinary Research for Earthquake Engineering Research Center, University at Buffalo, New York.

Vian, D. and Bruneau, M., 2003, "Tests to structural collapse of single degree of freedom frames subjected to earthquake excitations." *Journal of Structural Engineering*, ASCE, 129(12), 1676-1685.

Wen, Y.K., 1976, "Method for random vibration of hysteretic systems," *J. Engrg. Mech. Div.*, ASCE, 102(2), 249–263.

Wen, Y.K., 1989, "Methods of random vibration for inelastic structures," *Appl. Mech. Rev.*, 42(2), 39–52.

Zayas, V.A., Popov, E.P., and Mahin, S.A., 1980, *Cyclic Inelastic Buckling of Tubular Steel Braces*, Rep. No. UCB/EERC-80/16, Earthquake Engineering Research Center, University of California, Berkeley, California.

Project Participants

ATC Management and Oversight

Christopher Rojahn
Project Executive Director
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

William T. Holmes
Project Technical Monitor
Rutherford & Chekene
55 Second Street, Suite 600
San Francisco, California 94105

Jon A. Heintz
Project Quality Control Monitor
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

Federal Emergency Management Agency

Michael Mahoney
Project Officer
Federal Emergency Management Agency
500 C Street, SW
Washington, DC 20472

Robert D. Hanson
FEMA Technical Monitor
Federal Emergency Management Agency
2926 Saklan Indian Drive
Walnut Creek, California 94595

Mai (Mike) Tong
Project Monitor
Federal Emergency Management Agency
500 C Street, SW
Washington, DC 20472

Project Management Committee

Craig D. Comartin
Project Technical Director
Comartin Engineers
7683 Andrea Avenue
Stockton, California 95207

Michael Valley
Senior Advisor for Structural Engineering
Magnusson Klemencic Associates
1301 Fifth Avenue, Suite 3200
Seattle, Washington 98101

Eduardo Miranda
Senior Advisor on Strength Degradation
Stanford University
Civil & Environmental Engineering
Terman Room 293
Stanford, California 94305

Working Group

Dimitrios Vamvatsikos
University of Cyprus
75 Kallipoleos Street
P.O. Box 20537
Nicosia, 1678, Cyprus

Project Review Panel

Kenneth Elwood
University of British Columbia
Dept. of Civil Engineering
6250 Applied Science Lane, Room 2010
Vancouver, British Columbia V6T 1Z4 Canada

Subhash C. Goel
University of Michigan
Dept. of Civil and Envir. Engineering
2350 Hayward, 2340 G.G. Brown Building
Ann Arbor, Michigan 48109-2125

Farzad Naeim
John A. Martin & Associates, Inc.
1212 S. Flower Street, 4th Floor
Los Angeles, California 90015

Workshop Participants

Mark Aschheim
Santa Clara University
500 El Camino Real
Dept. of Civil Engineering
Santa Clara, California 95053

Michael Cochran
Weidlinger Associates
4551 Glencoe Avenue, Suite 350
Marina del Rey, California 90292-7927

Craig D. Comartin
Comartin Engineers
7683 Andrea Avenue
Stockton, California 95207

Anthony Court
A. B. Court & Associates
4340 Hawk Street
San Diego, California 92103

Kenneth Elwood
University of British Columbia
Department of Civil Engineering
6250 Applied Science Lane, Room 2010
Vancouver, British Columbia V6T 1Z4 Canada

Subhash C. Goel
University of Michigan
Department of Civil and Envir. Engineering
2350 Hayward, 2340 G.G. Brown Building
Ann Arbor, Michigan 48109

Robert D. Hanson
Federal Emergency Management Agency
2926 Saklan Indian Drive
Walnut Creek, California 94595

Curt Haselton
California State University, Chico
Department of Civil Engineering
Langdon 209F
Chico, California 95929

Jon A. Heintz
Applied Technology Council
201 Redwood Shores Pkwy., Suite 240
Redwood City, California 94065

YeongAe Heo
University of California at Davis
Dept. of Civil Engineering
Davis, California 95616

William T. Holmes
Rutherford & Chekene
55 Second Street, Suite 600
San Francisco, California 94105

Sashi Kunnath
University of California, Davis
Dept. of Civil & Env. Engineering
One Shields Ave., 2001 Engr III
Davis, California 95616

Joseph Maffei
Rutherford & Chekene
55 Second Street, Suite 600
San Francisco, California 94105

Stephen Mahin
University of California, Berkeley
777 Davis Hall, Dept. of Civil Engineering
Berkeley, California 94720

Michael Mahoney
Federal Emergency Management Agency
500 C Street, SW
Washington, DC 20472

Michael Mehrain
URS Corporation
915 Wilshire Blvd., Suite 700
Los Angeles, California 90017

Eduardo Miranda
Stanford University
Civil & Environmental Engineering
Terman Room 293
Stanford, California 94305

Mark Moore
ZFA Consulting
55 Second Street, Suite 600
San Francisco, California 94105

Charles Roeder
University of Washington
Department of Civil Engineering
233-B More Hall Box 2700
Seattle, Washington 98195

Mark Sinclair
Degenkolb Engineers
225 Bush Street, Suite 1000
San Francisco, California 94104

Peter Somers
Magnusson Klemencic Associates
1301 Fifth Avenue, Suite 3200
Seattle, Washington 98101

Mai (Mike) Tong
Federal Emergency Management Agency
500 C Street, SW
Washington, DC 20472

Luis Toranzo
KPFF Consulting Engineers
6080 Center Drive, Suite 300
Los Angeles, California 90045

Michael Willford
ARUP
901 Market Street, Suite 260
San Francisco, California 94103