

NIST GCR 10-917-9

Applicability of Nonlinear Multiple-Degree-of-Freedom Modeling for Design

Supporting Documentation

NEHRP Consultants Joint Venture
*A Partnership of the Applied Technology Council and the
Consortium of Universities for Research in Earthquake Engineering*



Disclaimers

This report was prepared for the Building and Fire Research Laboratory of the National Institute of Standards and Technology under contract number SB134107CQ0019, Task Order 68241. The statements and conclusions contained herein are those of the authors, and do not imply recommendations or endorsements by the National Institute of Standards and Technology.

This report was produced under contract to NIST by the NEHRP Consultants Joint Venture, a joint venture of the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE). While endeavoring to provide practical and accurate information, the NEHRP Consultants Joint Venture, the authors, and the reviewers assume no liability for, nor make any expressed or implied warranty with regard to, the information contained in this report. Users of information contained in this report assume all liability arising from such use.

The policy of the National Institute of Standards and Technology is to use the International System of Units (metric units) in all of its publications. However, in North America in the construction and building materials industry, certain non-SI units are so widely used instead of SI units that it is more practical and less confusing to include measurement values for customary units only.

NIST GCR 10-917-9

Applicability of Nonlinear Multiple-Degree-of-Freedom Modeling for Design

Supporting Documentation

Prepared for
*U.S. Department of Commerce
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland*

By
NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the
Consortium of Universities for Research in Earthquake Engineering

September 2010



U.S. Department of Commerce
Gary Locke, Secretary

National Institute of Standards and Technology
Patrick D. Gallagher, Director

Participants

National Institute of Standards and Technology

John (Jack) R. Hayes, Director – National Earthquake Hazards Reduction Program
Kevin K. F. Wong, Technical Monitor

NEHRP Consultants Joint Venture

Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065
www.ATCouncil.org

Consortium of Universities for
Research in Earthquake Engineering
1301 S. 46th Street, Building 420
Richmond, California 94804
www.CUREE.org

Joint Venture Management Committee

James R. Harris
Robert Reitherman
Christopher Rojahn
Andrew Whittaker

Joint Venture Program Committee

Jon A. Heintz (Program Manager)
Michael Constantinou
C.B. Crouse
James R. Harris
William T. Holmes
Jack P. Moehle
Andrew Whittaker

Project Technical Committee

Michael Valley (Project Director)
Mark Aschheim
Craig Comartin
William T. Holmes
Helmut Krawinkler
Mark Sinclair

Project Review Panel

Michael Constantinou
Jerome F. Hajjar
Joseph Maffei
Jack P. Moehle
Farzad Naeim
Michael Willford

Working Group Members

Michalis Fragiadakis
Dimitrios Lignos
Chris Putman
Dimitrios Vamvatsikos

Preface - Supporting Documentation

The NEHRP Consultants Joint Venture is a partnership between the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE). In 2007, the National Institute of Standards and Technology (NIST) awarded the NEHRP Consultants Joint Venture a National Earthquake Hazards Reduction Program (NEHRP) “Earthquake Structural and Engineering Research” task order contract (SB1341-07-CQ-0019) to conduct a variety of tasks. In 2008, NIST initiated Task Order 68241 entitled “Improved Nonlinear Static Seismic Analysis Procedures – Multiple-Degree-of-Freedom Modeling.” The purpose of this project was to conduct further studies on multiple-degree-of-freedom effects as outlined in the Federal Emergency Management Agency (FEMA) report, FEMA 440, *Improvement of Nonlinear Static Seismic Analysis Procedures* (FEMA, 2005).

The FEMA 440 Report concluded that current nonlinear static analysis procedures, which are based on single-degree-of-freedom (SDOF) models, are limited in their ability to capture the complex behavior of structures that experience multiple-degree-of-freedom (MDOF) response, and that improved nonlinear analysis techniques to more reliably address MDOF effects were needed. In response to this need, work on this project included a detailed review of recent research on nonlinear MDOF modeling and the conduct of focused analytical studies to fill gaps in available information. The objective of this work was to improve nonlinear MDOF modeling for structural design practice by providing guidance on: (1) the minimum level of MDOF model sophistication necessary to make performance-based engineering decisions; (2) selection of appropriate nonlinear analysis methods; and (3) possible new analytical approaches. Summary findings, conclusions, and recommendations from this work are contained in the main volume report, *Applicability of Nonlinear Multiple-Degree-of-Freedom Modeling for Design*. This volume, *Supporting Documentation*, contains appendices that provide detailed reporting on the focused analytical studies, ancillary studies, and literature review activities that formed the basis of the findings.

The NEHRP Consultants Joint Venture is indebted to the leadership of Mike Valley, Project Director, and to the members of the Project Technical Committee, consisting of Mark Aschheim, Craig Comartin, William Holmes, Helmut Krawinkler, and Mark Sinclair, for their significant contributions in the development of this report and the

resulting recommendations. Focused analytical studies were led by Mark Aschheim and Helmut Krawinkler and conducted by Michalis Fragiadakis, Dimitrios Lignos, Chris Putman, and Dimitrios Vamvatsikos. Technical review and comment at key developmental stages on the project were provided by the Project Review Panel consisting of Michael Constantinou, Jerry Hajjar, Joe Maffei, Jack Moehle, Farzad Naeim, and Michael Willford. The names and affiliations of all who contributed to this project are included in the list of Project Participants at the end of this report.

NEHRP Consultants Joint Venture also gratefully acknowledges Jack Hayes (Director, NEHRP) and Kevin Wong (NIST Technical Monitor) for their input and guidance in the preparation of this report and Ayse Hortacsu and Peter N. Mork for ATC report production services.

Jon A. Heintz
Program Manager

Table of Contents - Supporting Documentation

Preface	iii
List of Figures	xi
List of Tables.....	xvii
Introduction	1-1
Appendix A: Detailed Steel Moment Frame Studies	A-1
A.1 Introduction.....	A-1
A.2 Structures Utilized in Evaluation	A-2
A.3 Nonlinear Response History Analysis	A-3
A.3.1 Component Model and Analysis Platforms	A-3
A.3.2 Analysis Model Simplification	A-4
A.3.3 Results for 2-, 4-, and 8-Story Steel Moment Frames	A-13
A.3.4 Dispersion in Seismic Input and Engineering Demand Parameters.....	A-23
A.3.5 Results for Residual Drifts.....	A-26
A.3.6 Synthesis of Nonlinear Response History Analysis Results.....	A-29
A.4 Single Mode Nonlinear Static Procedure.....	A-30
A.4.1 Nonlinear Static Analysis Options Explored	A-31
A.4.2 Results for 2-, 4-, 8-Story Steel Special Moment Frames in Pre-Capping Region.....	A-33
A.4.3 Response Predictions in Negative Tangent Stiffness Region.....	A-46
A.4.4 Synthesis of Nonlinear Static Procedure Predictions.....	A-49
A.5 Multi Mode Nonlinear Static Procedure	A-54
A.5.1 Summary Description of Procedure.....	A-54
A.5.2 Results for 4- and 8-Story Steel Moment Frames.....	A-55
A.5.3 Synthesis of Modal Pushover Analysis Predictions.....	A-61
A.6 Assessment of Elastic Response Spectrum Analysis	A-62
A.7 Load Pattern Sensitivity and Response Prediction for a Frame Structure with Severe Strength Irregularity	A-64
A.7.1 Load Pattern Sensitivity	A-64
A.7.2 Response of a 4-Story Building with Strength Irregularity ...	A-65
A.8 Incorporation of Gravity System in Analysis Model.....	A-77
A.8.1 Potential importance of Incorporating Gravity System in Analysis Model.....	A-77
A.8.2 Case Study – 4-Story Steel Moment Frame Structure	A-77

Appendix B: Detailed Reinforced Concrete Moment Frame

Studies	B-1
B.1 Ground Motions.....	B-1
B.2 Structural Systems	B-2
B.3 Nonlinear Static Procedures.....	B-4
B.3.1 ASCE/SEI 41-06 Displacement Coefficient Method	B-4
B.3.2 N2/EC8 Method.....	B-15
B.3.3 Modal Pushover Analysis	B-16
B.3.4 Consecutive Modal Pushover	B-24
B.3.5 Modal Response Spectrum Analysis	B-31
B.4 Summary and Comparison of the Analysis Methods	B-38
B.5 Correlation between Intermediate-Level and Component-Level Demand Parameters	B-48

Appendix C: Detailed Reinforced Concrete Shear Wall Studies

C-1	C-1
C.1 Introduction.....	C-1
C.2 Structures Utilized in Evaluation.....	C-1
C.3 Nonlinear Response History Analysis	C-3
C.3.1 Component Models.....	C-3
C.3.2 Results for 2-, 4-, and 8-Story Reinforced Concrete Shear Wall Structure with Fiber Model.....	C-6
C.3.3 NRHA Results for 4-story Reinforced Concrete Shear Wall Structure with Simplified Spring Model.....	C-17
C.3.4 Synthesis of Nonlinear Response History Analysis Results	C-22
C.4 Single Mode Nonlinear Static Procedure.....	C-23
C.4.1 Nonlinear Static Analysis Options Explored	C-23
C.4.2 Results for 2- and 8-Story Reinforced Concrete Shear Wall Structures Utilizing FM-ASCE41.....	C-25
C.4.3 Results for 4-Story Reinforced Concrete Shear Wall Structure Utilizing Alternative Nonlinear Static Procedures	C-31
C.4.4 Synthesis of Nonlinear Static Procedure Predictions	C-38
C.5 Multi-Mode Nonlinear Static Procedure.....	C-42
C.5.1 Results for 4- and 8-Story Reinforced Concrete Shear Wall Structures	C-42
C.6 Importance of Failure Mode	C-47

Appendix D: Effect of Ground Motion Selection and Scaling on Engineering

Demand Parameter Dispersion	D-1
D.1 Effect of Intensity Measure on EDP Dispersion	D-1
D.1.1 Observations on Dispersion	D-5
D.1.2 Observations on Bias	D-15
D.2 Use of Record Subsets to Characterize EDP Distributions.....	D-26
D.2.1 Subset Selection Methods used for Estimating Median EDP Values.....	D-26
D.2.2 Subset Selection Methods used for Estimating 84% EDP Values	D-28
D.2.3 Subset Selection based on FEMA P-695 scaling.....	D-29
D.2.4 Subset Selection on S_{di} Scaling.....	D-46
D.2.5 Random Subset Selection on S_{di} Scaling.....	D-55

D.2.6	Subset Selection on S_{di} Scaling	D-57
D.2.7	Random Subset Selection on S_{di} Scaling	D-68
D.3	Characterization of Distributions of Response Quantities	D-71
D.3.1	Distribution of EDPs Obtained with S_a Scaling	D-72
D.3.2	Distribution of EDPs Obtained with S_{di} Scaling	D-81
D.4	Alternative Estimation of Dispersion Using Higher Intensity Levels	D-89
Appendix E: Direct Determination of Target Displacement		E-1
E.1	Introduction	E-1
E.2	Direct Computation of Equivalent Single-Degree-of-Freedom Response	E-1
E.3	The SPO2IDA Tool	E-6
E.4	Summary	E-10
Appendix F: Practical Implementation of Analysis Methods		F-1
F.1	Approach	F-1
F.2	General Modeling Assumptions	F-2
F.2.1	Ground Motions	F-2
F.3	Structures and Models	F-4
F.3.1	Building A	F-4
F.3.2	Building B	F-9
F.4	Analysis Methods	F-14
F.4.1	Nonlinear Response History Analysis	F-14
F.4.2	Response Spectrum Analysis	F-15
F.4.3	Nonlinear Static Procedure	F-15
F.4.4	Nonlinear Static Procedure with Elastic Higher Modes	F-16
F.4.5	Modal Pushover Analysis	F-16
F.4.6	Consecutive Modal Pushover Analysis	F-16
F.4.7	Extended Consecutive Modal Pushover Analysis	F-16
F.5	Results	F-18
F.5.1	Building A Results	F-18
F.5.2	Building B Results	F-30
F.6	Summary of Observations	F-71
F.6.1	Building A	F-71
F.6.2	Building B	F-78
F.6.3	Accuracy of Estimates of Demand Parameters	F-83
F.7	Conclusions	F-91
F.7.1	Modeling and Analysis Conclusions	F-91
F.7.2	Analysis Techniques Conclusions	F-92
F.7.3	Extended Consecutive Modal Pushover Conclusion	F-93
F.7.4	Assumptions and Limitations	F-93
Appendix G: Expanded Summaries of Relevant Codes, Standards, and Guidelines		G-1
G.1	ASCE/SEI 31-03 Seismic Evaluation of Existing Buildings	G-1
G.1.1	Scope of Application	G-1
G.1.2	Applicability of Analysis Procedures	G-2
G.1.3	Other Evaluation Requirements	G-3
G.1.4	Other Modeling Direction Provided	G-5

	G.1.5	Ground Motion Characteristics.....	G-6
	G.1.6	Discussion.....	G-6
G.2		ASCE/SEI 41-06 Seismic Rehabilitation of Existing Buildings (with Supplement No.1).....	G-6
	G.2.1	Scope of Application	G-6
	G.2.2	Applicability of Analysis Procedures	G-7
	G.2.3	Other Modeling Direction Provided	G-10
	G.2.4	Additional Analysis Requirements	G-11
	G.2.5	Ground Motion Characterization	G-12
	G.2.6	Discussion.....	G-12
G.3		ATC-40 Seismic Evaluation and Retrofit of Concrete Buildings.....	G-13
	G.3.1	Scope of Application	G-13
	G.3.2	Applicability of Analysis Procedures	G-14
	G.3.3	Other Modeling Direction Provided	G-16
	G.3.4	Additional Analysis Requirements	G-17
	G.3.5	Ground Motion Characterization	G-17
	G.3.6	Discussion.....	G-19
G.4		FEMA 440 Improvement of Nonlinear Static Seismic Analysis Procedures.....	G-20
	G.4.1	Scope of Application	G-20
	G.4.2	Applicability of Analysis Procedures	G-20
	G.4.3	Other Modeling Direction Provided	G-24
G.5		FEMA P-440A, Effects of Strength and Stiffness Degradation on Seismic Response	G-25
	G.5.1	Scope of Application	G-25
	G.5.2	Applicability of Analysis Procedures	G-26
G.6		FEMA 351 Recommended Seismic Evaluation and Upgrade Criteria and FEMA 352 Recommended Post-Earthquake Evaluation and Repair Criteria for Welded Steel Moment-Frame Buildings.....	G-27
	G.6.1	Scope of Application	G-27
	G.6.2	Applicability of Analysis Procedures	G-27
	G.6.3	Other Modeling Direction Provided	G-28
	G.6.4	Additional Analysis Requirements	G-30
	G.6.5	Ground Motion Characterization	G-31
	G.6.6	Discussion.....	G-32
G.7		ASCE/SEI 7-05 Minimum Design Loads for Buildings and Other Structures	G-32
	G.7.1	Scope of Application	G-32
	G.7.2	Applicability of Analysis Procedures	G-33
	G.7.3	Other Modeling Direction Provided	G-34
	G.7.4	Additional Analysis Requirements	G-35
	G.7.5	Ground Motion Characterization	G-36
G.8		NEHRP Recommended Seismic Provisions for New Buildings and Other Structures	G-36
	G.8.1	Scope of Application	G-36
	G.8.2	Applicability of Analysis Procedures	G-37
	G.8.3	Other Modeling Direction Provided	G-37
	G.8.4	Additional Analysis Requirements	G-38

G.9	PEER/ATC-72-1 Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings	G-40
G.9.1	Scope of Application	G-40
G.9.2	Applicability of Analysis Procedures	G-40
G.9.3	Other Modeling Direction Provided	G-49

Appendix H: Bibliography of Recent Multiple-Degree-of-Freedom Modeling

Research	H-1
H.1 Pushover Methods of Analysis	H-1
H.1.1 General Features/Observations	H-1
H.1.2 Target Displacement	H-3
H.1.3 Load Vectors and Approaches	H-6
H.1.4 P-delta Effects	H-31
H.1.5 Modeling Choices	H-32
H.1.6 Efficacy and Limitations	H-44
H.2 Dynamic Approaches	H-75
H.2.1 Incremental Dynamic Analysis and Approximations	H-75
H.2.2 Simplified Dynamic Analysis	H-82
H.2.3 Collapse Prediction	H-89
H.2.4 Sensitivity of Response to Modeling	H-91
H.2.5 Efficacy and Limitations Relative to Empirical Results	H-95
H.3 Special Configurations and Typologies	H-95
H.3.1 Torsional or Plan Irregularities	H-95
H.3.2 Weak Stories	H-118
H.3.3 Vertical Irregularities	H-119
H.3.4 Diaphragm Flexibility	H-123
H.3.5 Base-Isolated Buildings	H-126
H.3.6 Systems with High Viscous Damping	H-130
H.4 Engineering Demand Parameters	H-137
H.4.1 Estimation of EDPs Using Different Analysis Methods and Simplified Structural Models	H-137
H.4.2 Complexity of Response and Effect of Configuration on Accuracy of Estimation of EDPs	H-145
H.5 Probabilistic Treatments	H-147
H.6 Design Methods	H-154
H.7 Applications	H-166
H.7.1 Masonry	H-166
H.7.2 Wood	H-169
H.7.3 Reinforced Concrete	H-172
H.7.4 Steel Braced Frames	H-176
H.7.5 Moment Frames	H-177
References	I-1
Project Participants	J-1