Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings

Prepared by
APPLIED TECHNOLOGY COUNCIL
201 Redwood Shores Pkwy, Suite 240
Redwood City, California 94065
www.ATCouncil.org

in collaboration with
Building Seismic Safety Council (BSSC)
National Institute of Building Sciences (NIBS)
Federal Emergency Management Agency (FEMA)

Prepared for
PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER (PEER)
Jack P. Moehle, Principal Investigator
Stephen Mahin, Director
Yousef Bozorgnia, Executive Director

TASK 7 PROJECT CORE GROUP
James O. Malley (Technical Director)
Gregory Deierlein
Helmut Krawinkler
Joseph R. Maffei
Mehran Pourzanjani
John Wallace
Jon A. Heintz

October 2010
In October 2006, the Applied Technology Council (ATC) began work on a contract assisting the Pacific Earthquake Engineering Research Center (PEER) in developing guidelines for the seismic design of tall buildings as part of the PEER Tall Buildings Initiative. The purpose of this work was to prepare recommendations for modeling the behavior of tall building structural systems and acceptance values for use in seismic design. Shortly thereafter, ATC secured additional funding on behalf of PEER from the Federal Emergency Management Agency (FEMA), through the Building Seismic Safety Council (BSSC) of the National Institute of Building Sciences, in support of this effort.

A Workshop on Tall Building Seismic Design and Analysis Issues was conducted in January 2007. The purpose of this workshop was to identify and prioritize seismic design and analytical challenges related to tall buildings by soliciting the opinions and collective recommendations of leading practitioners, regulators, and researchers actively involved in the design, permitting, and construction of tall buildings. The outcome of this workshop is recorded in a companion report, ATC-72 Proceedings of Workshop on Tall Building Seismic Design and Analysis Issues, which includes a prioritized list of the most important tall building modeling and acceptance criteria issues needing resolution, based on the opinions of those in attendance.

Using the workshop as a starting point, this report is the result of further work under the PEER Tall Buildings Initiative to develop modeling recommendations and acceptance criteria for design and analysis of tall buildings. It is intended to serve as a resource document for the Guidelines for Seismic Design of Tall Buildings, published as a companion report by PEER (2010).

ATC is indebted to the leadership of Jim Malley, Project Technical Director, and to the members of the PEER/ATC-72 Task 7 Project Core Group, consisting of Greg Deierlein, Helmut Krawinkler, Joe Maffei, Mehran Pourzanjani, and John Wallace, for their efforts in researching and assembling the information contained herein. A group of experts on tall building design and analysis was convened to obtain feedback on the
recommendations as they were being developed, and input from this group was instrumental in shaping the final product. 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.

ATC also gratefully acknowledges Jack Moehle, Yousef Bozorgnia, and the PEER Tall Buildings Project Advisory Committee for their input and guidance in the completion of this report, Ayse Hortacsu and Peter N. Mork for ATC report production services, and Charles H. Thornton as ATC Board Contact.

Jon A. Heintz                     Christopher Rojahn
ATC Director of Projects          ATC Executive Director
# Table of Contents

Preface .............................................................................................................................. iii

List of Figures .................................................................................................................... ix

List of Tables ......................................................................................................................... xvii

1. Introduction .................................................................................................................... 1-1
   1.1 Background ............................................................................................................. 1-1
   1.2 Pacific Earthquake Engineering Research Center Tall Buildings Initiative ............... 1-2
   1.3 Workshop on Tall Building Seismic Design and Analysis Issues ........................................ 1-3
   1.4 Issues in Tall Building Design .............................................................................. 1-4
   1.5 Report Organization and Content ......................................................................... 1-5

2. General Nonlinear Modeling ......................................................................................... 2-1
   2.1 Overview of Modeling Issues for Nonlinear Response History Analysis .......................... 2-1
      2.1.1 Types of Nonlinear Models ............................................................................. 2-1
      2.1.2 Inelastic Component Attributes .................................................................... 2-3
      2.1.3 Energy Dissipation and Viscous damping .................................................... 2-5
      2.1.4 Gravity Load effects in Nonlinear Analysis .................................................. 2-5
      2.1.5 Acceptance Criteria ....................................................................................... 2-6
   2.2 Deterioration ............................................................................................................. 2-8
      2.2.1 Modes of Deterioration ................................................................................... 2-10
      2.2.2 Consequences of Deterioration on Structural Response .................................... 2-13
      2.2.3 Sources of Deterioration ............................................................................... 2-14
      2.2.4 Modeling of Deterioration .............................................................................. 2-15
      2.2.5 Analytical Modeling Options .......................................................................... 2-25
      2.2.6 Sensitivity of Response to Deterioration .......................................................... 2-27
      2.2.7 Summary Observations for Modeling of Deterioration .................................... 2-29
   2.3 P-delta Effects ............................................................................................................ 2-29
      2.3.1 Summary Observations for P-delta Effects ...................................................... 2-31
      2.3.2 Recommendations for Modeling P-delta Effects .............................................. 2-34
   2.4 Damping ..................................................................................................................... 2-35
      2.4.1 Physical sources of Damping ......................................................................... 2-35
      2.4.2 Survey of Damping Assumptions in Design and Assessment ............................ 2-38
      2.4.3 Measurement of Damping in Buildings ......................................................... 2-39
      2.4.4 Modeling Techniques for Damping .................................................................. 2-47
      2.4.5 Recommendations for Nonlinear Analysis and Design .................................. 2-54
   2.5 Expected Properties and Uncertainty ........................................................................ 2-56
      2.5.1 Statistical Characterization of Modeling Uncertainties .................................. 2-57
3. Modeling of Frame Components ........................................................ 3-1
   3.1 Modeling Parameters for Frame Components .......................... 3-1
   3.2 Nonlinear Modeling of Steel Beam and Column Components ........................................................ 3-1
      3.2.1 Behavioral Considerations for Steel Beams ................ 3-2
      3.2.2 Quantification of Properties for Steel Beams .............. 3-6
      3.2.3 Recommendations for Modeling of Steel Beams .......... 3-18
      3.2.4 Behavioral Considerations for Steel Columns............. 3-19
      3.2.5 Recommendations for Modeling of Steel Columns...3-21
      3.2.6 Acceptance Criteria for Steel Beams and Columns ... 3-22
   3.3 Nonlinear Modeling of Steel Panel Zones .............................. 3-23
      3.3.1 Quantification of Properties for Steel Panel Zones ... 3-24
      3.3.2 Acceptance Criteria for Steel Panel Zones ............. 3-28
   3.4 Nonlinear Modeling of Reinforced Concrete Beams, Columns, and Beam-Column Joints ....................................... 3-28
      3.4.1 Behavioral Considerations for Reinforced Concrete Frame Components ........................................................ 3-30
      3.4.2 Quantification of Properties for Reinforced Concrete Beams and Columns ........................................................ 3-32
      3.4.3 Quantification of Properties for Reinforced Concrete Beam-Column Joints ........................................................ 3-42
      3.4.4 Recommendations for Modeling of Reinforced Concrete Frame Components ........................................................ 3-43
      3.4.5 Acceptance Criteria for Reinforced Concrete Frame Components ........................................................ 3-44

4. Modeling of Shear Wall and Slab-Column Frame Systems ............... 4-1
   4.1 Modeling of Planar and Flanged Reinforced Concrete Shear Walls ......................................................................................... 4-1
      4.1.1 Beam-Column Element Models .................................. 4-1
      4.1.2 Fiber Beam-Column Models ....................................... 4-2
      4.1.3 Biaxial Fiber and Detailed Finite Element Models .... 4-3
      4.1.4 Coupled Models (Shear-Flexure Interaction) .................. 4-4
   4.2 Quantification of Properties for Planar and Flanged Walls .... 4-5
      4.2.1 Shear Behavior ....................................................... 4-5
      4.2.2 Effective Flexural Stiffness ....................................... 4-11
      4.2.3 Material Models ....................................................... 4-16
      4.2.4 Material Models in Commercially Available Software ........................................................................................................... 4-17
      4.2.5 Simulation of Tested Behavior ................................... 4-20
      4.2.6 Model Sensitivity to Material and Model Parameters ........................................................................................................... 4-26
      4.2.7 Summary Recommendations for Modeling of Planar and Flanged Walls ........................................................ 4-29
   4.3 Modeling of Coupling Beams ................................................. 4-30
      4.3.1 Effective Stiffness ................................................... 4-30
      4.3.2 Detailing Options and Force-Deformation Response ........................................................................................................... 4-32
      4.3.3 Implied Damage States .............................................. 4-35
      4.3.4 Simulation of Tested Behavior ................................... 4-37
      4.3.5 Summary Recommendations for Modeling of Coupling Beams ........................................................ 4-39
   4.4 Response and Behavior of Core Wall Systems ....................... 4-40
4.4.1 Core Wall Geometry, Configuration, and Modeling .............................................. 4-40
4.4.2 Summary Findings for Core Wall Response and Behavior ........................................ 4-48

4.5 Modeling of Slab-Column Frame Components and Behavior ............................................ 4-49
  4.5.1 Quantification of Properties for Slab-Column Frames ............................................... 4-49
  4.5.2 Application to Core Wall Systems ................................................................. 4-53
  4.5.3 Summary Recommendations for Modeling of Slab-Column Frames .......................... 4-57

4.6 Performance of Post-Tensioned Slab-Wall Connections ............................................. 4-57

A. Modeling of Podium Diaphragms, Collectors, and Backstay Effects ............................... A-1
  A.1 Podium and Backstay Effects .................................................................................. A-1
    A.1.1 Structural Elements of the Podium ................................................................. A-3
    A.1.2 Seismic-Force-Resisting Elements of the Tower ............................................ A-5
    A.1.3 Consideration of Backstay Effects ................................................................... A-5
    A.1.4 Impact of Structural System Type and Configuration on Backstay Effects ................. A-5
  A.2 Effects of Other Structural Configurations .................................................................. A-6
    A.2.1 Buildings Without Backstay Effects .................................................................. A-6
    A.2.2 Setback or Step-Back Effects .......................................................................... A-6
    A.2.3 Multiple Towers on a Common Base ............................................................ A-7
    A.2.4 Buildings on Sloping Sites ............................................................................... A-9
  A.3 Nonlinear Seismic Response and Capacity Design ..................................................... A-9
    A.3.1 Capacity Design ............................................................................................ A-9
    A.3.2 Two-Stage Design Process ........................................................................... A-11
  A.4 Modeling of Structural Elements .............................................................................. A-12
    A.4.1 Bracketing of Stiffness Properties ................................................................... A-12
  A.5 Collectors and Diaphragm Segments .......................................................................... A-13
    A.5.1 Role of Collectors ............................................................................................ A-13
    A.5.2 Design for System Overstrength .................................................................... A-13
    A.5.3 Collector Eccentricity and Diaphragm Segments ............................................. A-14
  A.6 Diaphragm Flexibility .............................................................................................. A-15
    A.6.1 Relative Stiffness of Diaphragms and Vertical Elements ..................................... A-17
    A.6.2 Building Code Requirements ......................................................................... A-17
  A.7 Semi-Rigid Diaphragm Modeling ............................................................................... A-18
    A.7.1 Linear versus Nonlinear Analysis .................................................................... A-19
  A.8 Design of Diaphragms and Collectors ........................................................................ A-19
    A.8.1 Diaphragm In-Plane Shear ............................................................................. A-19
    A.8.2 Strut-and-Tie Models ..................................................................................... A-19
    A.8.3 Diaphragm In-Plane Flexure .......................................................................... A-20
    A.8.4 Distribution of Collector Forces ....................................................................... A-20
    A.8.5 Slab Reinforcement for Gravity and Seismic Forces ........................................ A-21
  A.9 Recommended Stiffness Properties for Modeling of Backstay Effects .......................... A-23
    A.9.1 Lateral Stiffness for Passive Soil Resistance .................................................. A-25
Glossary.................................................................................................................. B-1
References ............................................................................................................. C-1
Project Participants............................................................................................. D-1
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Comparison of nonlinear component model types</td>
<td>2-2</td>
</tr>
<tr>
<td>2-2</td>
<td>Illustration of modeling components for a reinforced concrete beam-column: (a) inelastic hinge model; (b) initial (monotonic) backbone curve; and (c) cyclic response model</td>
<td>2-4</td>
</tr>
<tr>
<td>2-3</td>
<td>Plots showing different rates of deterioration: (a) slow deterioration; and (b) rapid deterioration</td>
<td>2-9</td>
</tr>
<tr>
<td>2-4</td>
<td>Monotonic and cyclic experimental response of a steel beam</td>
<td>2-10</td>
</tr>
<tr>
<td>2-5</td>
<td>Hysteretic response of identical steel beam specimens under different loading histories</td>
<td>2-11</td>
</tr>
<tr>
<td>2-6</td>
<td>Hysteretic response of identical reinforced concrete column specimens under different loading histories</td>
<td>2-12</td>
</tr>
<tr>
<td>2-7</td>
<td>Incremental dynamic analysis (IDA) curves for a moment-resisting frame example using non-deteriorating and deteriorating component models</td>
<td>2-13</td>
</tr>
<tr>
<td>2-8</td>
<td>Parameters of the initial (monotonic) backbone curve of the Ibarra-Krawinkler model</td>
<td>2-18</td>
</tr>
<tr>
<td>2-9</td>
<td>Basic options for stable hysteresis characteristics: (a) bilinear; (b) peak oriented; and (c) pinching</td>
<td>2-19</td>
</tr>
<tr>
<td>2-10</td>
<td>Simulations obtained with a modified Bouc-Wen model</td>
<td>2-19</td>
</tr>
<tr>
<td>2-11</td>
<td>Ramberg-Osgood Model</td>
<td>2-20</td>
</tr>
<tr>
<td>2-12</td>
<td>Individual deterioration modes illustrated for a peak-oriented model</td>
<td>2-21</td>
</tr>
<tr>
<td>2-13</td>
<td>Ibarra-Krawinkler model calibration examples: (a) steel beam; and (b) reinforced concrete beam</td>
<td>2-22</td>
</tr>
<tr>
<td>2-14</td>
<td>Example of a simulation using the Sivalsevan-Reinhorn model showing: (a) experimental results; and (b) calibrated simulation</td>
<td>2-22</td>
</tr>
</tbody>
</table>
Figure 2-15  Song-Pincheira model: (a) backbone curve; (b) hysteresis rules for cycles of increasing deflection amplitude; (c) hysteresis rules for small amplitude or internal cycles................................................................. 2-23

Figure 2-16  Monotonic and cyclic responses of identical specimens, and skeleton curve fit to cyclic response for: (a) steel beam (Tremblay et al., 1997); and (b) plywood shear wall panel ................................................. 2-24

Figure 2-17  Illustration of four options for analytical component modeling................................................................. 2-27

Figure 2-18  Effects of deterioration parameters on median collapse capacity of generic 8-story moment-resisting frame (MRF) and shear wall (SW) structures.............................. 2-28

Figure 2-19  Response history of a single degree of freedom system incorporating P-Delta effects ............................................ 2-30

Figure 2-20  Pushover deflection profiles for an 18-story frame structure at different roof drifts with P-Delta excluded (thin line), and P-Delta included (thick line) ................................. 2-31

Figure 2-21  Effects of P-Delta on median collapse capacity ($S_a/g$) of: (a) 8-story moment-resisting frame; and (b) shear wall structure deforming in a flexural mode .................... 2-32

Figure 2-22  Base shear versus roof displacement pushover curves for the SAC 20-story Los Angeles structure ............................................. 2-32

Figure 2-23  Dynamic response of SAC 20-story Los Angeles structure using four different analytical models shown as: (a) response histories; and (b) incremental dynamic analyses ...................................................... 2-33

Figure 2-24  Damping and drift demand data from buildings excited by strong ground motions......................................................... 2-41

Figure 2-25  Measured damping from buildings in Japan .................... 2-43

Figure 2-26  Illustration of amplitude dependence of measured damping under wind loading............................................................... 2-44

Figure 2-27  Variation in percent of critical damping for mass, stiffness, and Rayleigh proportional damping with $\zeta = 2\%$ at $T_1 = 5$ seconds................................................................. 2-48

Figure 2-28  Suggested target limits on damping........................................ 2-56

Figure 3-1  Hysteretic response of a steel beam with composite slab ............................................................................. 3-6
Figure 3-2  Plot showing comparison of deterioration model to experimental results ........................................................... 3-8

Figure 3-3  Cumulative distribution functions for pre-capping plastic rotation, \( \theta_p \), for: (a) full data sets; and (b) beam depths, \( d \geq 21 \) in ........................................................... 3-9

Figure 3-4  Cumulative distribution functions for post-capping rotation, \( \theta_{pc} \), for: (a) full data sets; and (b) beam depths, \( d \geq 21 \) in ................................................ 3-10

Figure 3-5  Cumulative distribution functions for reference cumulative plastic rotation, \( \Lambda \), for: (a) full data sets; and (b) beam depths, \( d \geq 21 \) in...................................................... 3-10

Figure 3-6  Dependence of pre-capping plastic rotation, \( \theta_p \), on beam depth, \( d \), for non-RBS connections, full data set... 3-11

Figure 3-7  Dependence of pre-capping plastic rotation, \( \theta_p \), on shear span to depth ratio, \( L/d \), for non-RBS connections, full data set .................................................. 3-11

Figure 3-8  Dependence of modeling parameters on \( h/t_w \), for beam depths \( d \geq 21 \) in., and RBS and non-RBS connections ................................................................. 3-13

Figure 3-9  Procedure for obtaining the modified backbone curve for modeling Option 3, and the ultimate rotation, \( \theta_u \), for modeling Option 4............................................................................. 3-19

Figure 3-10  Strong column factor, \( R_{cm} \), required to avoid plastic hinging in columns for a 9-story moment-resisting frame structure ................................................................. 3-20

Figure 3-11  Representative results from tests on W14x176 column sections subjected to an axial load and cyclic bending moment: (a) moment versus story drift response for \( P/P_y = 0.35 \); and (b) peak moment versus story drift for \( P/P_y = 0.75 \) ................................................................. 3-21

Figure 3-12  Analytical predictions of flexural cyclic response of: (a) W27x146 columns for \( P/P_y = 0.35 \); and (b) W27x194 columns for \( P/P_y = 0.55 \) .................................................. 3-22

Figure 3-13  Analytical model for panel zone..................................................... 3-24

Figure 3-14  Cyclic shear behavior of weak panel zone.............................. 3-24

Figure 3-15  Trilinear shear force and shear distortion relationship for panel zone............................................................................. 3-27
Figure 3-16 Moment and shear forces at a connection due to lateral loads ................................................................. 3-27
Figure 3-17 Use of two springs to model trilinear behavior .......... 3-27
Figure 3-18 Shear force-distortion response for a typical panel zone ........................................................................ 3-27
Figure 3-19 Reinforced concrete flexural member: (a) idealized flexural element; (b) monotonic backbone curve and hysteretic response; and (c) monotonic and modified backbone curves. ................................................................. 3-29
Figure 3-20 Idealization of reinforced concrete beam-column joint ........................................................................ 3-30
Figure 3-21 Definitions of secant elastic stiffness ....................... 3-33
Figure 3-22 Comparison of effective stiffness values of reinforced beam-columns ................................................................. 3-34
Figure 3-23 Modified force-deformation response curve .......... 3-39
Figure 3-24 Comparison of plastic rotation parameters for modeling Option 3 versus ASCE/SEI 41-06 Supplement No. 1 for: (a) pre-capping rotation capacity; and (b) post-capping rotation capacity ................................................................. 3-40
Figure 3-25 Comparison of ultimate plastic rotation versus ASCE/SEI 41-06 Supplement No. 1 acceptance criteria at the Collapse Prevention performance level for: (a) Option 4; and (b) Option 3 ................................................................. 3-42
Figure 3-26 Recommended rigid end zone offsets for reinforced concrete beam column joints based on relative column and beam strengths ......................................................................... 3-43
Figure 4-1 Equivalent beam-column element representation of a reinforced concrete shear wall ................................................................. 4-2
Figure 4-2 Fiber element representation of a reinforced concrete shear wall. ........................................................................ 4-2
Figure 4-3 Biaxial fiber model for bending in two-dimensions ........ 4-4
Figure 4-4 Coupled model and results for a low-aspect ratio wall ...... 4-5
Figure 4-5 Shear force-deformation curves based on: (a) FEMA 356; and (b) ASCE/SEI 41-06 Supplement No. 1 ................................................................. 4-6
Figure 4-6 ASCE/SEI 41-06 variation in column shear strength versus ductility demand ................................................................. 4-9
Figure 4-7 Shear force-deformation results for lightly reinforced wall piers ................................................................. 4-11

Figure 4-8 Roof displacement response correlation studies for:
(a) 10-story walls; and (b) 7-story walls .......................... 4-12

Figure 4-9 Upper-bound and lower-bound wall flexural stiffness versus: (a) axial load ratio; and (b) displacement ratio .... 4-13

Figure 4-10 Impact of wall flexural strength on effective stiffness..... 4-14

Figure 4-11 Comparison between predicted and tested effective stiffness values for: (a) rectangular walls; and
(b) T-shaped walls ............................................................... 4-14

Figure 4-12 Comparison of modeled and tested moment versus curvature relations for: (a) slender wall; and
(b) bridge column ............................................................. 4-15

Figure 4-13 Uniaxial material models commonly used in fiber models ................................................................. 4-16

Figure 4-14 Material models in commercially available software ..... 4-18

Figure 4-15 Comparison of wall tests versus model results generated by commercially available software ..................... 4-19

Figure 4-16 Behavior of a rectangular wall section subjected to constant axial load and reverse cyclic loading............. 4-20

Figure 4-17 Comparison of model and test results for a rectangular wall section .......................................................... 4-21

Figure 4-18 Comparison of simulated results using two different concrete constitutive models ................................. 4-21

Figure 4-19 Comparison of measured versus modeled average strain in a rectangular wall section ............................. 4-22

Figure 4-20 Curvature profiles for a rectangular wall section at three levels of drift ........................................................ 4-22

Figure 4-21 Behavior of a flanged (T-shaped) wall section subjected to constant axial load and reverse cyclic loading......... 4-23

Figure 4-22 Comparison of model and test results for a T-shaped wall ........................................................................ 4-24

Figure 4-23 Distribution of concrete strains in the flange of a T-shaped wall .............................................................. 4-24

Figure 4-24 Distribution of reinforcing steel strains in the flange of a T-shaped wall ........................................................ 4-25
Figure 4-25  Distribution of concrete strains in the flange of a T-shaped wall.................................................................4-25

Figure 4-26  Influence of reinforcing steel stress-strain relation on force-deformation response for: (a) elastic-perfectly-plastic; and (b) strain hardening behavior ......................4-27

Figure 4-27  Influence of mesh size on force-deformation response for: (a) 91 elements; and (b) six elements ..................4-27

Figure 4-28  Influence of mesh size on wall strain distribution............4-28

Figure 4-29  Coupling beam effective flexural stiffness ratios..........4-32

Figure 4-30  Coupling beam reinforcement detailing for: (a) prior ACI 318 provisions; and (b) current ACI 318 provisions .................................................................4-32

Figure 4-31  Coupling beam reinforcement detailing.................4-33

Figure 4-32  Coupling beam load-deformation relations for specimens B1, B2, B3, and B4 ..........................................................4-34

Figure 4-33  Comparison of: (a) effective stiffness; and (b) backbone relations for coupling beam test results .............4-34

Figure 4-34  Crack patterns in a coupling beam with an aspect ratio of \( l_n/h=3.33 \) at different drift levels.................................4-36

Figure 4-35  Schematic coupling beam models: (a) moment hinge; and (b) shear-displacement hinge..............................4-37

Figure 4-36  Rigid plastic rotational springs for moment-hinge model (half-scale test specimens).................................4-37

Figure 4-37  Load-deformation relations for moment- and shear-hinge models .................................................................4-38

Figure 4-38  Configuration and plan section of tall core wall building system used in parametric studies .................4-40

Figure 4-39  Variation in shear force over height in the: (a) north-south direction; and (b) east-west direction, for each case of relative stiffness ..................................................4-42

Figure 4-40  Variation in moment over height in the east-west direction, for each case of relative stiffness .................4-43

Figure 4-41  Comparison of shear force distribution over height for fiber-hinge and fiber-all models..........................4-44

Figure 4-42  Comparison of moment distribution over height for fiber-hinge and fiber-all models............................4-44
Figure 4-43  Comparison of shear force distribution over height for fiber-hinge and fiber-all models, for each case of relative stiffness ............................................................... 4-45

Figure 4-44  Comparison of moment distribution over height for fiber-hinge and fiber-all models, for each case of relative stiffness. .............................................................. 4-45

Figure 4-45  Distribution of maximum compression and tension strains over height for elements along the north wall of the core. ................................................................. 4-46

Figure 4-46  Distribution of maximum compression and tension strains over height for elements along the east wall of the core ................................................................. 4-47

Figure 4-47  Comparison of shear and moment distributions over height for the 100% Steel and Reduced Steel models .... 4-48

Figure 4-48  Normalized effective stiffness factors for interior slab-column frames based on Equations 4-10 through 4-12... 4-51

Figure 4-49  Model of slab-column connection ......................... 4-51

Figure 4-50  Unbalanced moment transferred between the slab and column in a torsional connection element................. 4-52

Figure 4-51  ASCE/SEI 41-06 Supplement No. 1 modeling parameter \( a \) for reinforced concrete and post-tensioned slab-column connections .............................................. 4-53

Figure 4-52  Floor plan and simplified model of the combined slab-column frame and core wall system ................................. 4-54

Figure 4-53  Application of effective width model to core wall ....... 4-54

Figure 4-54  Schematic of the slab model ................................................ 4-55

Figure 4-55  Comparison of story drifts in the north-south and east-west directions for the core wall model and coupled core-slab model .................................................. 4-56

Figure 4-56  Comparison of column axial stress in the north-south and east-west directions for the core wall model and coupled core-slab model .................................................. 4-56

Figure 4-57  Slab-to-wall connection details for Specimen 1 (left) and Specimen 2 (right) ........................................................... 4-58

Figure 4-58  Overall test specimen geometry ................................................ 4-58

Figure 4-59  Force-displacement relations for slab-wall connection Specimens 1 and 2 ........................................................... 4-59
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-60</td>
<td>Observed cracking at 2.5% drift in Specimen 1 (left) and Specimen 2 (right)</td>
</tr>
<tr>
<td>A-1</td>
<td>Example of a tall building structural system with a concrete core wall superstructure and below-grade perimeter retaining walls forming a podium</td>
</tr>
<tr>
<td>A-2</td>
<td>Construction of a concrete core and below-grade levels of a high-rise building</td>
</tr>
<tr>
<td>A-3</td>
<td>Construction of concrete walls for a high-rise apartment building. The structural system has two individual walls, at left, and a concrete core, at right</td>
</tr>
<tr>
<td>A-4</td>
<td>Example of a setback in a concrete core wall building in which an additional concrete wall extends above the lower podium, but not the full height of the building</td>
</tr>
<tr>
<td>A-5</td>
<td>Example of two towers on a common base</td>
</tr>
<tr>
<td>A-6</td>
<td>Desirable nonlinear mechanisms for: (a) cantilever wall; and (b) coupled wall</td>
</tr>
<tr>
<td>A-7</td>
<td>Example location of a collector (shown hatched)</td>
</tr>
<tr>
<td>A-8</td>
<td>Eccentric collector and reinforcement into, and alongside, a shear wall</td>
</tr>
<tr>
<td>A-9</td>
<td>Relative stiffness assumptions associated with diaphragm flexibility models</td>
</tr>
</tbody>
</table>
# List of Tables

| Table 2-1 | Selected Results of Measured Damping in Tall Buildings under Wind-Induced Vibration | 2-45 |
| Table 2-2 | Measured Damping versus Level of Damage from Shaking Table Tests | 2-46 |
| Table 2-3 | Comparison ofEffective Damping with Inelastic Softening and Period Elongation | 2-52 |
| Table 3-1 | Modeling Parameters for Various Beam Sizes (non-RBS connections) Based on Regression Equations with Assumed Beam Shear Span $L=150$ in., $L_b/r_y=50$, and Expected Yield Strength, $F_y=55$ ksi | 3-16 |
| Table 3-2 | Modeling Parameters for Various Beam Sizes (with RBS connections) Based on Regression Equations with Assumed Beam Shear Span $L=150$ in., $L_b/r_y=50$, and Expected Yield Strength, $F_y=55$ ksi | 3-16 |
| Table 3-3 | Empirical Plastic Rotation Values, $\theta_p$ and $\theta_{pc}$, for a Representative Column Section | 3-37 |
| Table 4-1 | New Zealand Standard 3101 Coupling Beam Coefficients | 4-31 |
| Table 4-2 | Parametric Variation in Stiffness Parameters | 4-41 |
| Table A-1 | Diaphragm Flexibility and Applicability of Modeling Assumptions | A-15 |
| Table A-2 | Recommended Stiffness Assumptions for Structural Elements of a Podium and Foundation | A-24 |
| Table A-3 | Recommended Stiffness Assumptions for Structural Elements of a Tower and Foundation | A-24 |