# TABLE OF CONTENTS

**SECTION 1** INTRODUCTION ............................................................................................................ 1

**SECTION 2** PRINCIPLES OF OPERATION AND MODELING OF FLUIDIC SELF-CENTERING DEVICES ............................................................................................................. 9

- 2.1 Introduction.................................................................................................................................. 9
- 2.2 Principles of Operation ............................................................................................................... 9
- 2.3 Mathematical Modeling ............................................................................................................. 15

**SECTION 3** BEHAVIOR OF FLUIDIC SELF-CENTERING DEVICE AND MODEL VALIDATION ................................................................................................................ 19

- 3.1 Introduction.................................................................................................................................. 19
- 3.2 Small Size Device ....................................................................................................................... 19
- 3.3 Large Size Device ..................................................................................................................... 27

**SECTION 4** SEISMIC RESPONSE OF SINGLE-DEGREE-OF-FREEDOM SYSTEM WITH FLUIDIC SELF-CENTERING DEVICES .................................................................. 37

- 4.1 Introduction.................................................................................................................................. 37
- 4.2 Selection and Scaling of Earthquake Ground Motions .............................................................. 38
- 4.3 Analyzed Single-Degree-of-Freedom Systems .......................................................................... 43
- 4.4 Results on Peak Response of Primary Structural System ......................................................... 48
- 4.4.1 Structural System without Fluidic Self-Centering Devices .................................................. 49
- 4.4.2 Structural System with Fluidic Self-Centering Devices ......................................................... 53
- 4.5 Non-Structural Response .......................................................................................................... 62
- 4.6 Effect of Stiffness of Fluidic Self-Centering Device on Response ............................................ 66
- 4.7 Conclusions............................................................................................................................... 68

**SECTION 5** EVALUATION OF SIMPLIFIED METHOD OF ANALYSIS OF YIELDING SINGLE-DEGREE-OF-FREEDOM SYSTEMS WITH FLUIDIC SELF-CENTERING DEVICES ......................................................................................... 71

- 5.1 Introduction.................................................................................................................................. 71
- 5.2 Analyzed System ....................................................................................................................... 71
# TABLE OF CONTENTS (CONT’D)

5.3  Simplified Method of Analysis ............................................................... 73
5.4  Comparison of Results of Simplified Analysis to Results of Response History Analysis 76
5.5  Conclusions ......................................................................................... 89

## SECTION 6
DEVELOPMENT OF EQUIVALENT LATERAL FORCE AND RESPONSE SPECTRUM ANALYSIS PROCEDURES FOR NEW BUILDINGS WITH FLUIDIC SELF-CENTERING DEVICES ................................................. 91
6.1  Introduction ......................................................................................... 91
6.2  Minimum Allowable Base Shear, Minimum Preload and Minimum Damping .......... 92
6.3  Simplified Analysis of Elastic Buildings with Fluidic Self-centering Devices .......... 95
6.4  Effective Period and Effective Damping of Yielding Buildings with Self-centering Devices ......................................................................................... 101
6.5  Step-by Step Design and Analysis Procedures ........................................... 105

## SECTION 7
EVALUATION OF METHODS OF ANALYSIS AND DESIGN OF BUILDINGS WITH FLUIDIC SELF-CENTERING DEVICES ................................................................. 113
7.1  Introduction ........................................................................................ 113
7.2  Design of 3-Story and 6-Story Reference Frames ....................................... 113
7.3  Design of 3-Story and 6-Story Frames with Fluidic Self-Centering Devices .......... 114
7.4  Analytical Modeling of Buildings with Fluidic Self-Centering Devices ............... 116
7.5  Nonlinear Response History Analysis ...................................................... 118
7.6  Results of Nonlinear Response History Analysis and Comparison to Results of ELF and RSA Procedures ................................................................. 118
7.7  Conclusions ......................................................................................... 126

## SECTION 8
ADDITIONAL RESULTS AND COMPARISON OF RESPONSE OF CONVENTIONAL BUILDINGS AND BUILDINGS WITH FLUIDIC SELF-CENTERING DEVICES ............................................................................ 127
8.1  Introduction ......................................................................................... 127
8.2  Comparison of Response ....................................................................... 127
### TABLE OF CONTENTS (CONT’D)

8.3 Additional Results for 3-story and 6-story Buildings with Fluidic Self-Centering System ............................................................................................................................. 128

8.4 Conclusions ..................................................................................................................... 130

**SECTION 9  COLLAPSE PERFORMANCE EVALUATION OF BUILDINGS WITH FLUIDIC SELF-CENTERING DEVICES .............................. 145**

9.1 Introduction ..................................................................................................................... 145

9.2 Modeling the Behavior of Structural Components for Collapse Resistance Assessment ................................................................................................................................................. 147

9.3 Properties of 3-story Buildings with and without Fluidic Self-Centering Devices .... 150

9.4 Properties of 6-story Buildings with and without Fluidic Self-Centering Devices .... 156

9.5 Selection and Scaling of Input Ground Motions ........................................................................................................ 159

9.6 Collapse Fragility ............................................................................................................ 160

9.6.1 Definition of Collapse Criteria........................................................................................ 160

9.6.2 Fragility Analysis Results ............................................................................................... 161

9.7 Effect of Fluidic Self-Centering System Design on Collapse Fragility of 3-Story Structure ................................................................................................................................................. 167

9.7.1 Effect of Ultimate Characteristics of Fluidic Self-Centering System on Collapse Fragility ................................................................................................................................................. 167

9.7.2 Effect of Displacement Capacity of Fluidic Self-Centering System on Collapse Fragility ................................................................................................................................................. 169

9.7.3 Effect of Damping Provided by the Fluidic Self-centering System on Collapse Fragility ................................................................................................................................................. 170

9.7.4 Effect of Preload Provided by the Fluidic Self-centering System on Collapse Fragility 173

9.7.5 Effect of Stiffness of the Fluidic Self-Centering System on Collapse Fragility .......... 174

9.7.6 Effect of Increased Strength of Frame on Collapse Fragility ......................................... 175

9.8 Effect of Fluidic Self-Centering System Design on Collapse Fragility of 6-story Structure ................................................................................................................................................. 179

9.9 Summary ......................................................................................................................... 180
# TABLE OF CONTENTS (CONT’D)

## SECTION 10  RESIDUAL DRIFT PERFORMANCE EVALUATION OF BUILDINGS WITH FLUIDIC SELF-CENTERING DEVICES

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>Introduction</td>
<td>185</td>
</tr>
<tr>
<td>10.2</td>
<td>Residual Drift Performance Evaluation Results</td>
<td>186</td>
</tr>
<tr>
<td>10.3</td>
<td>Summary</td>
<td>191</td>
</tr>
</tbody>
</table>

## SECTION 11  ASSESSMENT OF COLLAPSE RISK AND RESIDUAL DRIFT RISK FOR BUILDINGS WITH FLUIDIC SELF-CENTERING DEVICES

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>Introduction</td>
<td>193</td>
</tr>
<tr>
<td>11.2</td>
<td>Calculated Mean Annual Frequencies and Related Probabilities in 50 years</td>
<td>197</td>
</tr>
</tbody>
</table>

## SECTION 12  FLUIDIC SELF-CENTERING DEVICES AS ELEMENTS OF SEISMIC ISOLATION SYSTEMS TO REDUCE RESIDUAL DISPLACEMENTS

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.1</td>
<td>Introduction</td>
<td>199</td>
</tr>
<tr>
<td>12.2</td>
<td>Description of Analyzed Seismically Isolated Building</td>
<td>199</td>
</tr>
<tr>
<td>12.3</td>
<td>Ground Motions Used in Analysis</td>
<td>204</td>
</tr>
<tr>
<td>12.4</td>
<td>Analysis Results for Isolated Building with Fluid Viscous Dampers</td>
<td>206</td>
</tr>
<tr>
<td>12.5</td>
<td>Analysis Results for Isolated Building with Fluidic Self-Centering Devices</td>
<td>208</td>
</tr>
<tr>
<td>12.6</td>
<td>Summary</td>
<td>214</td>
</tr>
</tbody>
</table>

## SECTION 13  SUMMARY AND CONCLUSIONS

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>215</td>
</tr>
</tbody>
</table>

## SECTION 14  REFERENCES

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>219</td>
</tr>
</tbody>
</table>

## APPENDIX A  SUPPLEMENTAL RESULTS ON SINGLE-DEGREE-OF-FREEDOM SYSTEM WITH AND WITHOUT FLUIDIC SELF-CENTERING DEVICES

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1</td>
<td>Seismic Response under Near-Fault Pulse-Like Ground Motions</td>
<td>230</td>
</tr>
<tr>
<td>A.1.1</td>
<td>Structure with Linear Viscous Damping and $K_0=0$ for Near-Fault Pulse-Like Ground Motions</td>
<td>230</td>
</tr>
<tr>
<td>A.1.2</td>
<td>Structure with Non-Linear Viscous Damping and $K_0=0$ in Near-Fault Pulse-Like Ground Motions</td>
<td>246</td>
</tr>
</tbody>
</table>
### TABLE OF CONTENTS (CONT’D)

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1.3</td>
<td>Structure with Upper-Half Viscous Damping and $K_0=0$ in Near-Fault Pulse-Like Ground Motions .......................................................... 262</td>
</tr>
<tr>
<td>A.2</td>
<td>Seismic Response under Near-Fault Non-Pulse-Like Ground Motions .......................... 278</td>
</tr>
<tr>
<td>A.2.1</td>
<td>Structure with Linear Viscous Damping and $K_0=0$ for Near-Fault Non-Pulse-Like Ground Motions .......................................................... 278</td>
</tr>
<tr>
<td>A.2.2</td>
<td>Structure with Non-Linear Viscous Damping and $K_0=0$ in Near-Fault Non-Pulse-like Ground Motions .......................................................... 294</td>
</tr>
<tr>
<td>A.2.3</td>
<td>Structure with Upper-Half Viscous Damping and $K_0=0$ in Near-Fault Non-Pulse-Like Ground Motions .......................................................... 310</td>
</tr>
<tr>
<td>A.3</td>
<td>Seismic Response under Far-Field Ground Motions ................................................. 325</td>
</tr>
<tr>
<td>A.3.1</td>
<td>Structure with Linear Viscous Damping and $K_0=0$ for Far-Field Ground Motions ...... 325</td>
</tr>
<tr>
<td>A.3.2</td>
<td>Structure with Non-Linear Viscous Damping and $K_0=0$ in Far-Field Ground Motions . 342</td>
</tr>
<tr>
<td>A.3.3</td>
<td>Structure with Upper-Half Viscous Damping and $K_0=0$ in Far-Field Ground Motions . 358</td>
</tr>
<tr>
<td>A.4</td>
<td>Structure with Linear Viscous Damping and $K_0\neq0$ in Near-Fault Pulse-Like Ground Motions .......................................................... 373</td>
</tr>
<tr>
<td>A.5</td>
<td>Structure with Linear Viscous Damping and $K_0\neq0$ in Near-Fault Non-Pulse-Like Ground Motions .......................................................... 390</td>
</tr>
<tr>
<td>A.6</td>
<td>Structure with Linear Viscous Damping and $K_0\neq0$ in Far-Field Ground Motions ...... 406</td>
</tr>
</tbody>
</table>

#### APPENDIX B DESCRIPTION OF EXAMPLE CONVENTIONAL BUILDINGS AND DESIGN OF LATERAL FORCE RESISTING SYSTEMS PER ASCE 7-2010 ........................... 423

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1</td>
<td>Introduction ........................................................................................................ 423</td>
</tr>
<tr>
<td>B.2</td>
<td>Description of 3-Story Building........................................................................ 423</td>
</tr>
<tr>
<td>B.3</td>
<td>Design of Typical 3-Story Steel Special Moment Frame .................................... 426</td>
</tr>
<tr>
<td>B.4</td>
<td>Design of 6-Story Special Steel Moment Frame ................................................ 428</td>
</tr>
</tbody>
</table>

#### APPENDIX C DESIGN AND ANALYSIS OF EXAMPLE 3-STORY BUILDING WITH FLUIDIC SELF-CENTERING DEVICES ................................................................................. 433

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.1</td>
<td>Design of Frame 3S-75 .................................................................................... 433</td>
</tr>
<tr>
<td>C.2</td>
<td>Construction of Push-Over Curve of 3S-75 based on Plastic Analysis .................. 435</td>
</tr>
<tr>
<td>C.3</td>
<td>Push-Over Analysis of 3S-75 Frame and Comparison to Results of Plastic Analysis.... 439</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS (CONT’D)

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.4</td>
<td>Design and Simplified Analysis of 3S-75 Frame with Fluidic Self-Centering Devices</td>
<td>440</td>
</tr>
<tr>
<td>C.5</td>
<td>Design of Frame 3S-85 ...................................................................................................</td>
<td>459</td>
</tr>
<tr>
<td><strong>APPENDIX D</strong></td>
<td><strong>DESIGN AND ANALYSIS OF EXAMPLE 6-STORY BUILDING WITH FLUIDIC SELF-CENTERING DEVICES</strong></td>
<td><strong>467</strong></td>
</tr>
<tr>
<td>D.1</td>
<td>Design of Frame 6S-75 ...................................................................................................</td>
<td>467</td>
</tr>
<tr>
<td>D.2</td>
<td>Construction of Push-Over Curve of 6S-75 Based on Plastic Analysis..........</td>
<td>469</td>
</tr>
<tr>
<td>D.3</td>
<td>Push-Over Analysis of 6S-75 Frame and Comparison to Results of Plastic Analysis....</td>
<td>471</td>
</tr>
<tr>
<td>D.4</td>
<td>Design and Simplified Analysis of 6S-75 Frame with Fluidic Self-Centering Devices .</td>
<td>472</td>
</tr>
<tr>
<td><strong>APPENDIX E</strong></td>
<td><strong>DETAILED COLLAPSE FRAGILITY DATA</strong> ........................................................................</td>
<td><strong>503</strong></td>
</tr>
<tr>
<td><strong>APPENDIX F</strong></td>
<td><strong>DETAILED RESIDUAL DRIFT FRAGILITY DATA</strong> ..............................................................</td>
<td><strong>553</strong></td>
</tr>
<tr>
<td><strong>APPENDIX G</strong></td>
<td><strong>DETAILED RISK ASSESSMENT DATA</strong> .............................................................................</td>
<td><strong>583</strong></td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2-1 Principle of Operation of Fluidic Self-Centering Device ............................................................... 9
Figure 2-2 Components of Force in Fluidic Self-centering Device ............................................................... 10
Figure 2-3 Schematic and View of Fluidic Self-Centering Device in Neutral Position ................................. 12
Figure 2-4 Operation of Fluidic Self-Centering Device in Compression ..................................................... 13
Figure 2-5 Operation of Fluidic Self-Centering Device in Tension ............................................................... 13
Figure 2-6 Illustration of Behavior of Device in Compression and Tension (dimensions shown are for the tested large size device of Section 3) ...................................................................................... 14
Figure 2-7 Typical Force-displacement Loops of Fluidic Self-Centering Device ............................................. 15
Figure 2-8 Definition of Terms in Model of Fluidic Self-centering Device ................................................... 17

Figure 3-1 Tested Small Size Fluidic Self-Centering Device (manufactured in 1992) ..................................... 20
Figure 3-2 S-3 Viking Aircraft during Landing (arresting hook with centering spring-damper is visible) (http://www.navy.mil/view_image.asp?id=7171) .................................................................................. 20
Figure 3-3 Test Set-up for Small Size Device ................................................................................................. 22
Figure 3-4 Recorded Force-Displacement Loops of Devices No. 1 and 2 ..................................................... 23
Figure 3-5 Comparison of Force-Displacement Loops of Devices No. 1 and 2 Tested in 2014 and Device Tested in 1992 ......................................................................................................................... 25
Figure 3-6 Effect of Temperature on Behavior of Device No. 1 ................................................................. 27
Figure 3-7 Tested Large Size Fluidic Self-Centering Device ....................................................................... 28
Figure 3-8 Effect of Temperature on Force-Displacement Loops of Large Size Fluidic Self-Centering Device under Quasi-static Conditions ......................................................................................... 29
Figure 3-9 Recorded Force-Displacement Loops of Device at Initial Pressure of 29MPa ............................. 31
Figure 3-10 Recorded Force-Displacement Loops of Device at Initial Pressure of 72.5MPa ...................... 32
Figure 3-11 Recorded Force-Displacement Loops of Device at Initial Pressure of 116MPa ........................ 34
Figure 3-12 Recorded Histories of Imposed Displacement and Velocity in Test of Device at Pressure of 116MPa and Frequency of 2Hz ............................................................................................... 34

Figure 4-1 MCER and DE Response Spectra (5-% damped) Considered in Study ....................................... 38
Figure 4-2 Comparison of Response Spectra of Scaled Near-Fault Pulse-Like Motions and Target Spectrum .............................................................................................................................................. 40
LIST OF FIGURES (CONT’D)

Figure 4-3 Comparison of Response Spectra of Scaled Near-Fault Non-Pulse-Like Motions and Target Spectrum ..................................................................................................................................................... 40
Figure 4-4 Comparison of Response Spectra of Scaled Far-Field Motions and Target Spectrum ................. 41
Figure 4-5 Histories of Acceleration of Scaled Near-Fault Motions ................................................................. 41
Figure 4-6 Histories of Acceleration of Scaled Far-Field Motions ...................................................................... 42
Figure 4-7 Force-displacement Relation of Primary Structural System ................................................................. 44
Figure 4-8 Force-displacement Relation of System with Added Fluidic Self-centering Device ..................... 44
Figure 4-9 Forms of Viscous Damping Force Considered .............................................................................. 46
Figure 4-10 Peak Response of System without Self-Centering Devices for Near-Fault Pulse-Like Motions ................................................................................................................................................................. 50
Figure 4-11 Peak Response of System without Self-Centering Devices for Near-Fault Non-Pulse-Like Motions .................................................................................................................................................................... 51
Figure 4-12 Peak Response of System without Self-Centering Devices for Far-Field Motions ....................... 52
Figure 4-13 Comparison of Response of Structure with and without a Self-Centering System for Near-Fault Pulse-Like Motions, Linear Viscous Damping with $\beta_v=0.10$ and $F_0/F_y=0.20$ ................................................................. 54
Figure 4-14 Effect of Ground Motion Type on Maximum and Residual Displacements in MCE for Case of Linear Viscous Damping with $\beta_v=0.10$, $R_p=2$ and 5 and $F_0/F_y=0.20$ .......................................................................................... 55
Figure 4-15 Effect of Type of Damping and Damping Value ($\beta_v=0.10$ and 0.20) on Peak Response in MCE Level Pulse-Like, Near-Fault Motions for $F_0/F_y=0.20$ and $R_p=2$ ....................................................................................... 56
Figure 4-16 Comparison of Peak Response of System with Linear and Lower Half Damping both with $\beta_v=0.10$ in MCE Level Pulse-Like, Near-Fault Motions for $F_0/F_y=0.2$ ................................................................. 57
Figure 4-17 Effect of Preload on the Residual Displacement in Pulse-Like, Near-Fault Motions for $R_p=2$ and Three Types of Useful Damping with $\beta_v=0.10$ .............................................................................................. 58
Figure 4-18 Effect of Amount and Type of Damping on the Residual Displacement of System in Pulse-Like, Near-Fault Motions for $R_p=2$ and $F_0/F_y=0.2$ .................................................................................................................. 59
Figure 4-19 Comparison of Peak Responses in Near-Fault Pulse-Like Motions of Structure without and with Fluidic Self-Centering System with $F_0/F_y=0.2$ and Upper Half Damping with $\beta_v=0.1$ ......................................................... 61
Figure 4-20 Comparisons of Floor Spectra of Structures without and with Self-Centering Devices for $F_0/F_y=0.20$, Linear Damping with $\beta_v=0.1$ and $T_e=1.0sec$ in Near-Fault Pulse-Like Motions ......................... 62
Figure 4-21 Comparisons of Floor Spectra of Structures without and with Self-Centering Devices for $F_0/F_y=0.20$, Linear Damping with $\beta_v=0.1$ and $T_e=0.5sec$ in Near-Fault Pulse-Like Motions ......................... 63
LIST OF FIGURES (CONT’D)

Figure 4-22 Effect of Ground Motion Type on Floor Spectra of Structures with Self-Centering Devices for $F_0/F_y=0.20$, Linear Damping with $\beta=0.1$ and $T_e=1.0$ sec ................................................................. 63
Figure 4-23 Effect of Damping Type on Floor Spectra of Structures with Self-Centering Devices for $F_0/F_y=0.20$, $\beta=0.1$ and $T_e=1.0$ sec in Near-Fault Pulse-Like Motions .......................................................... 64
Figure 4-24 Effect of Preload on Floor Spectra of Structures with Self-Centering Devices for Linear Damping with $\beta=0.1$ and $T_e=1.0$sec in Near-Fault Pulse-Like Motions .............................................. 65
Figure 4-25 Effect of Amount of Linear Viscous Damping on Floor Spectra of Structures with Self-Centering Devices for $F_0/F_y=0.20$, $T_e=1.0$sec in Near-Fault Pulse-Like Motions ....................................................... 65
Figure 4-26 Inclusion of Stiffness in Model of Fluidic Self-Centering Device ............................................................................................................................. 66
Figure 4-27 Comparison of Peak Responses in Near-Fault Pulse-Like Motions of Structure with Self-Centering System of Stiffness $K_0 = 0$ or $K_0 \neq 0$, $F_0/F_y=0.2$ and Linear Damping with $\beta=0.1$ ............. 67
Figure 4-28 Comparison of Response of Structure with and without a Self-Centering System with $K_0\neq0$ for Near-Fault Pulse-Like Motions, Linear Viscous Damping with $\beta_c=0.10$ and $F_0/F_y=0.20$ ................. 69
Figure 4-29 Effect of Stiffness of Device ($K_0=0$ or $K_0\neq0$) on Floor Spectra of Structures with Self-Centering Devices for Linear Damping with $\beta=0.1$ and $T_e=1.0$sec in Near-Fault Pulse-Like Motions .................... 70
Figure 4-30 Comparisons of Floor Spectra of Structure without and with a Fluidic Self-Centering Device having $F_0/F_y=0.2$, Linear Damping with $\beta_c=0.1$, $T_e=1.0$sec and $K_0\neq0$ in Near-Fault, Pulse-Like Motions 70

Figure 5-1 Element Combination for Fluidic Self-Centering Device ................................................................................................................................. 72
Figure 5-2 Behavior of Primary Structural System ............................................................................................................................ 73
Figure 5-3 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_c = 0.1$ and $F_0/F_y = 0.2$. Distinction by Type of Motion (DE and MCE, Pulse-like, Non-Pulse-like, Far-field) ................................................................................................................................. 77
Figure 5-4 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_c = 0.1$ and $F_0/F_y = 0.2$. Distinction by Value of Elastic Period (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ................................................................................................................................. 78
Figure 5-5 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_c = 0.1$ and $F_0/F_y = 0.2$. Distinction by Value of $R_{\mu}$ (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ................................................................................................................................. 79
LIST OF FIGURES (CONT’D)

Figure 5-6 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_k = 0.1$ and $F_0/F_y = 0.1$. Distinction by Type of Motion (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ........................................................................................................ 80

Figure 5-7 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_k = 0.1$ and $F_0/F_y = 0.1$. Distinction by Value of Elastic Period (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ............................................................................................... 81

Figure 5-8 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_k = 0.1$ and $F_0/F_y = 0.1$. Distinction by Value of $R\mu$ (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ................................................................................................................... 82

Figure 5-9 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_k = 0.2$ and $F_0/F_y = 0.2$. Distinction by Type of Motion (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ......................................................................................................... 83

Figure 5-10 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_k = 0.2$ and $F_0/F_y = 0.2$. Distinction by Value of Elastic Period (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ........................................................................................ 84

Figure 5-11 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Linear Viscous Damping, $\beta_k = 0.2$ and $F_0/F_y = 0.2$. Distinction by Value of $R\mu$ (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ................................................................................................................... 85

Figure 5-12 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Nonlinear Viscous Damping, $\beta_k = 0.1$ and $F_0/F_y = 0.2$. Distinction by Type of Motion (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ........................................................................................................ 86

Figure 5-13 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Nonlinear Viscous Damping, $\beta_k = 0.1$ and $F_0/F_y = 0.2$. Distinction by Value of Elastic Period (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ......................................................................................................... 87

Figure 5-14 Comparison of Response History Analysis Results to Simplified Analysis Results for all Cases with Nonlinear Viscous Damping, $\beta_k = 0.1$ and $F_0/F_y = 0.2$. Distinction by Value of $R\mu$ (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ................................................................................................................... 88

Figure 5-15 Comparison of Peak Velocity Calculated by Response History and Simplified Analysis for all Cases and using Average Values of $CFV$. Distinction by Type of Motion (DE and MCE, Pulse-like, Non-pulse-like, Far-field) ......................................................................................................... 90
LIST OF FIGURES (CONT’D)

Figure 6-1 Force-displacement Relations, Demand Curves and Structural Response Parameters ................. 93
Figure 6-2 Definition of Effective Stiffness of Fluidic Self-Centering Device for Calculation of Period $T_i$, Inclusive of the Self-Centering System Effect .......................................................... 95
Figure 6-3 Transformation of Force-Displacement Relation to Spectral Capacity Relation ......................... 101
Figure 6-4 Force-Displacement Relations of Building with Fluidic Self-Centering System ......................... 102
Figure 6-5 Calculation of Peak Force in Fluidic Self-Centering Device ...................................................... 110

Figure 7-1 3-Story Frame 3S-75 with Fluidic Self-Centering Devices ....................................................... 115
Figure 7-2 6-Story Frame 6S-75 with Fluidic Self-Centering Devices ....................................................... 115
Figure 7-3 Bilinear Moment-Curvature Relation for Plastic Hinges ......................................................... 116
Figure 7-4 Modeling of Fluidic Self-Centering Device and its Brace in OpenSees ....................................... 117
Figure 7-5 Representative Force-Displacement Relation of Element of Fluidic Self-Centering Device Obtained in OpenSees .......................................................... 117
Figure 7-6 Model of Analysis for 3-story Frame in Program OpenSees Illustrating Mass and Seismic Weight Distribution and the use of a Leaning Column (bracing omitted for clarity) .......................................................... 118
Figure 7-7 Story Shear Force versus Story Drift Relations for Frame 3S-75 (calculated by pushover analysis using a pattern of loads in proportion to prescribed loads in ASCE 7) and Average Drift in DE and MCE Calculated for Far-Field Motions in Response History Analysis .......................................................... 124
Figure 7-8 Formation of Plastic Hinges in Frame 3S-75 in Scaled Far-field Ground Motion Kocaeli, Duzce Station in the DE ...................................................................................................................... 125
Figure 7-9 Formation of Plastic Hinges in Frame 3S-75 in Scaled Far-field Ground Motion Kocaeli, Duzce Station in the MCE ...................................................................................................................... 125
Figure 7-10 Pushover Curves of 3-story Frame 3S-75 Exclusive of the Fluidic Self-centering System Obtained by Various Patterns of Lateral Load .................................................................................. 125
Figure 7-11 Pushover Curves of 6-story Frame 6S-75 Exclusive of the Fluidic Self-Centering System Obtained by Various Patterns of Lateral Load .................................................................................. 126

Figure 8-1 Floor Acceleration Spectra (5%-damped) of 3-story Frame 3S-75 with Fluidic Self-Centering System and Conventional Frame 3S-Reference for Near-Fault Pulse-like Motions in DE .......... 141
Figure 8-2 Floor Acceleration Spectra (5%-damped) of 3-story Frame 3S-75 with Fluidic Self-Centering System and Conventional Frame 3S-Reference for Near-Fault Pulse-like Motions in MCE .......... 141
LIST OF FIGURES (CONT’D)

Figure 8-3 Floor Acceleration Spectra (5%-damped) of 6-story Frame 6S-75 with Fluidic Self-Centering System and Conventional Frame 6S-Reference for Near-Fault Pulse-like Motions in DE ..................... 142
Figure 8-4 Floor Acceleration Spectra (5%-damped) of 6-story Frame 6S-75 with Fluidic Self-Centering System and Conventional Frame 6S-Reference for Near-Fault Pulse-like Motions in MCE ............... 142
Figure 8-5 Floor Acceleration Spectra (5%-damped) of 6-story Frame 6S-75 with Fluidic Self-Centering System in Two Cases of Damping for Near-Fault Pulse-like Motions in DE (left figure is for linear viscous damping with $\beta_1=0.10$; right figure is for nonlinear viscous damping with $\beta_1=0.15$ in the DE) ............. 143
Figure 8-6 Floor Acceleration Spectra (5%-damped) of 6-story Frame 6S-75 with Fluidic Self-Centering System in Two Cases of Damping for Near-Fault Pulse-like Motions in MCE (left figure is for linear viscous damping with $\beta_1=0.10$; right figure is for nonlinear viscous damping with $\beta_1=0.15$ in the DE) ................................................................................................................................................ 143

Figure 9-1 Modified Ibarra-Krawinkler used for Beams (left monotonic, right cyclic) .................... 148
Figure 9-2 Ultimate Behavior of Self-Centering Fluidic Device-Brace System ........................................... 149
Figure 9-3 Post-failure Behavior of Fluidic Self-Centering Device-Brace System .............................. 149
Figure 9-4 Force-displacement Relations of Fluidic Self-Centering Device-Brace System with and without Consideration of Ultimate Behavior ............................................................ 150
Figure 9-5 Frames (a) 3S-75 and (b) 3S-Reference ................................................................................. 151
Figure 9-6 Push-Over Curves of 3S-Reference and 3S-75 Frames ......................................................... 153
Figure 9-7 Self-Centering Device Configurations Analyzed .............................................................. 154
Figure 9-8 Pushover Curves of 3-Story Frame 3S-75 with Balanced Self-centering Devices per Configurations of Figure 9-7 (FEMA P695 distribution of load) ................................................................. 154
Figure 9-9 Pushover Curves of 3-story Frame 3S-75 with Unbalanced Self-Centering Devices per Configurations of Figure 9-7 (FEMA P695 distribution of load) ................................................................. 154
Figure 9-10 Frames (a) 6S-75 and (b) 6S-Reference ................................................................. 157
Figure 9-11 Push-Over Curves of 6S-Reference and 6S-75 Frames ..................................................... 158
Figure 9-12 Example of $S_a$-Component Scaling ............................................................................. 159
Figure 9-13 Example of PGV Normalization Scaling ......................................................................... 160
Figure 9-14 IDA Curves for 3S-75 and 3S-Reference Frames for Motions based on $S_a$-Component Scaling ......................................................................................................................... 161
LIST OF FIGURES (CONT’D)

Figure 9-15 Collapse Fragility (or cumulative distribution function) for 3S-75 and 3S-Reference Frames for Motions based on $S_a$-Component Scaling ......................................................................................................................... 162
Figure 9-16 IDA Curves for 3S-75 and 3S-Reference Frames for Motions based on PGV Normalization Scaling ................................................................................................................................. 162
Figure 9-17 Collapse Fragility (or cumulative distribution function) for 3S-75 and 3S-Reference Frames for Motions based on $PGV$ Normalization Scaling .............................................................................................. 163
Figure 9-18 IDA Curves for 6S-75 and 6S-Reference Frames for Motions based on $S_a$-Component Scaling .............................................................................................................................................. 163
Figure 9-19 Collapse Fragility (or cumulative distribution function) for 6S-75 and 6S-Reference Frames for Motions based on $S_a$-Component Scaling ........................................................................................................ 164
Figure 9-20 IDA Curves for 6S-75 and 6S-Reference Frames for Motions based on PGV Normalization Scaling .............................................................................................................................................. 164
Figure 9-21 Collapse Fragility (or cumulative distribution function) for 6S-75 and 6S-Reference Frames for Motions based on $PGV$ Normalization Scaling .............................................................................................. 164
Figure 9-22 IDA Curves for 3S-75 in Unbalanced Configuration for Motions based on $S_a$-Component Scaling .............................................................................................................................................. 168
Figure 9-23 Collapse Fragility for 3S-75 Frame in Balanced and Un-Balanced Configurations and for 3S-Reference Frame for $S_a$-Component Scaled Motions ........................................... 168
Figure 9-24 Collapse Fragility for 3S-75 Frame in Balanced (capacity 1.3 times the peak force) and Increased Capacity (2 times the peak force) Configurations and for 3S-Reference Frame for $S_a$-Component Scaled Motions ......................................................................................................................... 169
Figure 9-25 Collapse Fragility for 3S-75 Frame in Balanced Configurations with Displacement Capacity of 165mm and 215mm and for 3S-Reference Frame for $S_a$-Component Scaled Motions ......................................................................................................................... 170
Figure 9-26 Collapse Fragility for 3S-75 Frame in Balanced Configurations with Linear Viscous Damping Ratio of 0.10 ($C_{N}=1140$kN-$s/m$) and 0.15 ($C_{N}=1710$kN-$s/m$), and for 3S-Reference Frame for $S_a$-Component Scaled Motions ......................................................................................................................... 171
Figure 9-27 Collapse Fragility for 3S-75 Frame in Balanced Configuration with Nonlinear Effective Viscous Damping Ratio of 0.10 in the DE ($C_{N}= 551.3$ kN-(sec/m)$^{1/2}$), Linear Viscous Damping Ratio of 0.10 ($C_{N}=1140$ kN-sec/m), and for 3S-Reference Frame for $S_a$-Component Scaled Motions ......................................................................................................................... 172
LIST OF FIGURES (CONT’D)

Figure 9-28 Collapse Fragility for 3S-75 Frame in Balanced Configuration with Nonlinear Effective Viscous Damping Ratio of 0.15 in the DE \((C_N= 666.4 \text{ kN-(sec/m)}^{1/2})\), Linear Viscous Damping Ratio of 0.15 \((C=1710 \text{ kN-sec/m})\), and for 3S-Reference Frames for \(S_r\)-Component Scaled Motions .................................................. 172

Figure 9-29 Collapse Fragility for 3S-75 Frame with Nonlinear Effective Viscous Damping Ratio of 0.15 in the DE \((C_N= 666.4 \text{ kN-(sec/m)}^{1/2})\) in Balanced Configuration (ultimate capacity about 1.3 of force in MCE) and in Increased Ultimate Capacity (about twice of force in MCE), and for 3S-Reference Frames for \(S_r\)-Component Scaled Motions ............................................................................................................ 173

Figure 9-30 Collapse Fragility of 3S-75 Frame with Increased Preload \((F_{0,1}=F_{0,2}=390\text{kN}, F_{0,3}=160\text{kN})\), Frame 3S-75 in Balanced Configuration (preload of \(F_{0,1}=F_{0,2}=390\text{kN}, F_{0,3}=125\text{kN}\)) and 3S-Reference Frame for \(S_r\)-Component Scaled Motions .................................................................................................................................. 174

Figure 9-31 Collapse Fragility of 3S-75 Frame with High and with Low Fluidic Device Stiffness and with Nonlinear Effective Viscous Damping Ratio of 0.15 in the DE \((\alpha=0.5, C_N= 666.4 \text{ kN-(sec/m)}^{1/2})\), and for 3S-Reference Frame for \(S_r\)-Component Scaled Motions .................................................................................................................................. 175

Figure 9-32 Collapse Fragility for 3S-85 Frame with the Comparisons to other Frames for \(S_r\)-Component Scaled Motions .................................................................................................................................. 176

Figure 9-33 Collapse Fragility for 6S-75 Frame in Configurations with Ultimate Capacity of 1.3 times the Peak Device Force and Increased Capacity (2 times the peak force) and for 6S-Reference Frame for \(S_r\)-Component Scaled Motions .................................................................................................................................. 179

Figure 9-34 Collapse Fragility for 6S-75 Frame in Configurations with Ultimate Capacity of 1.3 times the Peak Device Force, with Nonlinear Effective Viscous Damping Ratio of 0.15 in the DE or Linear Viscous Damping Ratio of 0.10 and for 3S-Reference Frame for \(S_r\)-Component Scaled Motions .......................................................... 180

Figure 10-1 IDA Curves for 3-Story Frame 3S-75, Linear Viscous Damping \(\beta_v=0.1\) and Device-Brace System Capacity Equal to 1.3\(F_{MCE}\) .................................................................................................................................. 186

Figure 10-2 Residual Drift Fragility (or cumulative distribution function) for 3S-75 Frame, Linear Viscous Damping \(\beta_v=0.1\), Device-Brace System Capacity Equal to 1.3\(F_{MCE}\) and \(S_r\)-Component Scaled Motions 188

Figure 10-3 Residual Drift Fragility (or cumulative distribution function) for 3S-75 Frame, Increased Preload, Linear Viscous Damping \(\beta_v=0.1\), Device-Brace System Capacity Equal to 1.3\(F_{MCE}\) and \(S_r\)-Component Scaled Motions .................................................................................................................................. 188

Figure 10-4 Residual Drift Fragility (or cumulative distribution function) for 3S-75 Frame, Linear Viscous Damping \(\beta_v=0.1\), Device-Brace System Capacity Equal to 2.0\(F_{MCE}\) and \(S_r\)-Component Scaled Motions 189
LIST OF FIGURES (CONT’D)

Figure 10-5 Residual Drift Fragility (or cumulative distribution function) for 3S-75 Frame, Nonlinear Viscous Damping $\beta=0.15$ in DE, Device-Brace System Capacity Equal to $1.3F_{MCE}$ and $S_a$-Component Scaled Motions.................................................................................................................................189

Figure 10-6 Residual Drift Fragility (or cumulative distribution function) for 3S-Reference Frame in $S_a$-Component Scaled Motions.................................................................................................................................189

Figure 10-7 Residual Drift Fragility (or cumulative distribution function) for 3S-85 Frame, Linear Viscous Damping $\beta=0.1$, Device-Brace System Capacity Equal to $1.3F_{MCE}$ and $S_a$-Component Scaled Motions 190

Figure 10-8 Residual Drift Fragility (or cumulative distribution function) for 6S-75 Frame, Linear Viscous Damping $\beta=0.1$, Device-Brace System Capacity Equal to $1.3F_{MCE}$ and $S_a$-Component Scaled Motions 190

Figure 10-9 Residual Drift Fragility (or cumulative distribution function) for 6S-75 Frame, Nonlinear Viscous Damping $\beta=0.15$ in DE, Device-Brace System Capacity Equal to $1.3F_{MCE}$ and $S_a$-Component Scaled Motions.................................................................................................................................190

Figure 10-10 Residual Drift Fragility (or cumulative distribution function) for 6S-75 Frame, Linear Viscous Damping $\beta=0.1$, Device-Brace System Capacity Equal to $2.0F_{MCE}$ and $S_a$-Component Scaled Motions 191

Figure 10-11 Residual Drift Fragility (or cumulative distribution function) for 6S-Reference Frame in $S_a$-Component Scaled Motions.................................................................................................................................191

Figure 11-1 Seismic Hazard Curves at Site of Latitude 37.8814°N and Longitude 122.08°W, Site Class D for Periods of 1.0, 2.0 and 3.0 second (source USGS)..................................................................................................................194

Figure 11-2 Seismic Hazard Curves at Site of Latitude 37.8814°N and Longitude 122.08°W, Site Class D for Periods of 1.07, 1.23, 1.28, 1.31, 1.90 and 2.06 second obtained by Linear Interpolation in Logarithmic Space of Data of Figure 11-1 ..............................................................................................................................................195

Figure 11-3 Example of Calculation of Mean Annual Frequency of Collapse for Frame 3S-75, Case of Linear Viscous Damping $\beta_{d1}=0.10$ and Ultimate Brace Force equal to $1.3F_{MCE}$. Top Graph is the Collapse Fragility Curve, Middle Graph is the Slope of the Seismic Hazard Curve and Bottom Curve is the Product of the Two........................................................................................................................................196

Figure 12-1 Three-Dimensional View of Analysis Model of Isolated Building in SAP2000 ...............200

Figure 12-2 Elevation of Building and Plan of Isolation System ..........................................................201

Figure 12-3 Section of Triple FP Isolator .............................................................................................202

Figure 12-4 Plan View of Viscous Damping Device.............................................................................202
LIST OF FIGURES (CONT’D)

Figure 12-5 Site-Specific Spectra and Average Spectra of Fault Normal and Fault Parallel Scaled Motions .................................................................................................................................................................. 205

Figure 12-6 Force-Displacement Components for Fluidic Self-Centering Device ................................................. 209

Figure A-1 Acceleration in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 230

Figure A-2 Displacement in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 232

Figure A-3 Residual Displacement in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 234

Figure A-4 Ductility Ratio in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 236

Figure A-5 Acceleration in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 238

Figure A-6 Displacement in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 240

Figure A-7 Residual Displacement in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 242

Figure A-8 Ductility Ratio in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 244

Figure A-9 Acceleration in DE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping ......................... 246

Figure A-10 Displacement in DE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 248

Figure A-11 Residual Displacement in DE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 250

Figure A-12 Ductility Ratio in DE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 252

Figure A-13 Acceleration in MCE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 254

Figure A-14 Displacement in MCE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_p=1$, 2 and 5 ............................................................................................................................................. 256
LIST OF FIGURES (CONT’D)

Figure A-15 Residual Displacement in MCE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 258

Figure A-16 Ductility Ratio in MCE, Near-Fault Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 260

Figure A-17 Acceleration in DE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 262

Figure A-18 Displacement in DE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 264

Figure A-19 Residual Displacement in DE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 266

Figure A-20 Ductility Ratio in DE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 268

Figure A-21 Acceleration in MCE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 270

Figure A-22 Displacement in MCE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 272

Figure A-23 Residual Displacement in MCE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 274

Figure A-24 Ductility Ratio in MCE, Near-Fault Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 276

Figure A-25 Acceleration in DE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 278

Figure A-26 Displacement in DE, Near-Fault Non-pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 280

Figure A-27 Residual Displacement in DE, Near-Fault Non-pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 282

Figure A-28 Ductility Ratio in DE, Near-Fault Non-pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 284

Figure A-29 Acceleration in MCE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0$, $R_{\mu}=1$, 2 and 5 ................................................................. 286
LIST OF FIGURES (CONT’D)

Figure A-30 Displacement in MCE, Near-Fault Non-Pulse-Like Motions, Linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 288
Figure A-31 Residual Displacement in MCE, Near-Fault Non-Pulse-Like Motions, Linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................... 290
Figure A-32 Ductility Ratio in MCE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 292
Figure A-33 Acceleration in DE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 294
Figure A-34 Displacement in DE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 296
Figure A-35 Residual Displacement in DE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................... 298
Figure A-36 Ductility Ratio in DE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 300
Figure A-37 Acceleration in MCE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 302
Figure A-38 Displacement in MCE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 304
Figure A-39 Residual Displacement in MCE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 306
Figure A-40 Ductility Ratio in MCE, Near-Fault Non-Pulse-like Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 308
Figure A-41 Acceleration in DE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 310
Figure A-42 Displacement in DE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 312
Figure A-43 Residual Displacement in DE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 314
Figure A-44 Ductility Ratio in DE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_u=1, 2$ and 5 ................................................................................................................... 316
LIST OF FIGURES (CONT’D)

Figure A-45 Acceleration in MCE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 318
Figure A-46 Displacement in MCE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 320
Figure A-47 Residual Displacement in MCE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 322
Figure A-48 Ductility Ratio in MCE, Near-Fault Non-Pulse-like Motions, Upper-half Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 324
Figure A-49 Acceleration in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 326
Figure A-50 Displacement in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 328
Figure A-51 Residual Displacement in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 330
Figure A-52 Ductility Ratio in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 332
Figure A-53 Acceleration in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 334
Figure A-54 Displacement in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 336
Figure A-55 Residual Displacement in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 338
Figure A-56 Ductility Ratio in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 340
Figure A-57 Acceleration in DE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 342
Figure A-58 Displacement in DE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 344
Figure A-59 Residual Displacement in DE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0, R_\mu=1, 2$ and 5 ............................................................................................................................. 346
LIST OF FIGURES (CONT’D)

Figure A-60 Ductility Ratio in DE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5....................................................................................................................................................... 348

Figure A-61 Acceleration in MCE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5....................................................................................................................................................... 350

Figure A-62 Displacement in MCE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5....................................................................................................................................................... 352

Figure A-63 Residual Displacement in MCE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5 .................................................................................................................................. 354

Figure A-64 Ductility Ratio in MCE, Far-Field Motions, Non-linear Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5 ............................................................................................................................................. 356

Figure A-65 Acceleration in DE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5....................................................................................................................................................... 358

Figure A-66 Displacement in DE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5....................................................................................................................................................... 360

Figure A-67 Residual Displacement in DE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5 .................................................................................................................................. 362

Figure A-68 Ductility Ratio in DE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5 ............................................................................................................................................. 364

Figure A-69 Acceleration in MCE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5............................................................................................................................................. 366

Figure A-70 Displacement in MCE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5............................................................................................................................................. 368

Figure A-71 Residual Displacement in MCE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5 .................................................................................................................................. 370

Figure A-72 Ductility Ratio in MCE, Far-Field Motions, Upper-half Viscous Damping, Stiffness $K_0=0$, $R_\mu=1$, 2 and 5 ............................................................................................................................................. 372

Figure A-73 Acceleration in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_\mu=1$, 2 and 5............................................................................................................................................. 374

Figure A-74 Displacement in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_\mu=1$, 2 and 5............................................................................................................................................. 376
LIST OF FIGURES (CONT’D)

Figure A-75 Residual Displacement in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 378
Figure A-76 Ductility Ratio in DE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 380
Figure A-77 Acceleration in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 382
Figure A-78 Displacement in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 384
Figure A-79 Residual Displacement in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 386
Figure A-80 Ductility Ratio in MCE, Near-Fault Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 388
Figure A-81 Acceleration in DE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 390
Figure A-82 Displacement in DE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 392
Figure A-83 Residual Displacement in DE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 394
Figure A-84 Ductility Ratio in DE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 396
Figure A-85 Acceleration in MCE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 398
Figure A-86 Displacement in MCE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 400
Figure A-87 Residual Displacement in MCE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 402
Figure A-88 Ductility Ratio in MCE, Near-Fault Non-Pulse-like Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 404
Figure A-89 Acceleration in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_0\neq0$, $R_p=1$, 2 and 5 .................................................................................................................... 406
LIST OF FIGURES (CONT’D)

Figure A-90 Displacement in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_{o} \neq 0$, $R_{x}=1, 2$ and 5.......................................................................................................................................................... 408
Figure A-91 Residual Displacement in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_{o} \neq 0$, $R_{x}=1, 2$ and 5............................................................................................................................................. 410
Figure A-92 Ductility Ratio in DE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_{o} \neq 0$, $R_{x}=1, 2$ and 5.......................................................................................................................................................... 412
Figure A-93 Acceleration in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_{o} \neq 0$, $R_{x}=1, 2$ and 5.......................................................................................................................................................... 414
Figure A-94 Displacement in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_{o} \neq 0$, $R_{x}=1, 2$ and 5.......................................................................................................................................................... 416
Figure A-95 Residual Displacement in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_{o} \neq 0$, $R_{x}=1, 2$ and 5............................................................................................................................................. 418
Figure A-96 Ductility Ratio in MCE, Far-Field Motions, Linear Viscous Damping, Stiffness $K_{o} \neq 0$, $R_{x}=1, 2$ and 5.......................................................................................................................................................... 420

Figure B-1 Plan and Elevation of 3-Story Building.................................................................................. 424
Figure B-2 3S-Reference Frame Geometry, Section Properties and Tributary Weights ....................... 428
Figure B-3 6-Story Special Moment Frame Designed to Meet ASCE 7-2010 Criteria without a Self-Centering Damping System (6S-Reference) ........................................................................................................... 431

Figure C-1 Frame 3S-75 Geometry, Section Properties and Tributary Weights ........................................... 434
Figure C-2 Plastic Analysis of Moment Frame for Calculation of Base Shear Strength.............................. 437
Figure C-3 Comparison of Pushover Curves of Frame 3S-75 ................................................................. 440
Figure C-4 Story Shear Force Versus Story Drift Relations for Frame 3S-75............................................. 441
Figure C-5 Frame 3S-85 Geometry, Section Properties and Tributary Weights ....................................... 460
Figure C-6 Base Shear Force versus Roof Drift Relations for Frame 3S-85 ................................................... 462
Figure C-7 Story Shear Force versus Story Drift Relations for Frame 3S-85............................................. 462

Figure D-1 Frame 6S-75 Geometry, Section Properties and Tributary Weights ........................................ 468
Figure D-2 Comparison of Pushover Curves of Frame 6S-75 ................................................................. 472
LIST OF FIGURES (CONT’D)

Figure D-3 Story Shear Force versus Story Drift Relations for Frame 6S-75 .................................473

Figure F-1 Spectral Acceleration at Exceedance of Specified Residual Drift Ratio ..........................554
# LIST OF TABLES

Table 1-1 Damage State and Residual Story Drift Ratio (FEMA, 2012) ................................................................. 2

Table 3-1 Test Matrix for Small Size Device ........................................................................................................ 21
Table 3-2 Parameters in Analytical Model of Large Size Fluidic Self-Centering Device ........................................ 35

Table 4-1 Near-Fault Pulse-Like Ground Motions (Fault Normal Components) ...................................................... 39
Table 4-2 Near-Fault Non-Pulse-Like Ground Motions (Fault Normal Components) ............................................ 39
Table 4-3 Far-Field Ground Motions (Fault Normal Components) ....................................................................... 40
Table 4-4 Values of Parameters of Primary Structural System and Fluidic Self-Centering Device .................. 48

Table 5-1 Parameters of Analyzed SDOF System with Fluidic Self-Centering Devices ......................................... 72
Table 5-2 Damping Parameter B .......................................................................................................................... 75
Table 5-3 Velocity Correction Factor $CFV$ per Ramirez et al (2001) ................................................................. 75

Table 7-1 Characteristics of Example Frames ...................................................................................................... 115
Table 7-2 Comparison of Results of ELF and RSA Procedures to Nonlinear Response History Analysis for 3S-75 Frame with Fluidic Self-Centering Device in the DE ................................................................. 121
Table 7-3 Comparison of Results of ELF and RSA Procedures to Nonlinear Response History Analysis for 3S-75 Frame with Fluidic Self-Centering Device in the MCE ................................................................. 121
Table 7-4 Comparison of Results of ELF and RSA Procedures to Nonlinear Response History Analysis for 6S-75 Frame with Fluidic Self-Centering Device in the DE ................................................................. 122
Table 7-5 Comparison of Results of ELF and RSA Procedures to Nonlinear Response History Analysis for 6S-75 Frame with Fluidic Self-Centering Device in the MCE ................................................................. 123

Table 8-1 Comparison of Response Calculated in Response History Analysis for 3-story Structure with and without Fluidic Self-Centering System in DE ............................................................................. 131
Table 8-2 Comparison of Response Calculated in Response History Analysis for 3-story Structure with and without Fluidic Self-Centering System in MCE ...................................................................... 132
Table 8-3 Comparison of Response Calculated in Response History Analysis for 6-story Structure with and without Fluidic Self-Centering System in DE ..................................................................... 133
LIST OF TABLES (CONT’D)

Table 8-4 Comparison of Response Calculated in Response History Analysis for 6-story Structure with and without Fluidic Self-Centering System in MCE ................................................................. 134
Table 8-5 Comparison of Response Calculated in Response History Analysis for 3-story Structure with Fluidic Self-Centering System in MCE and two Cases of Linear Viscous Damping ($\beta_1=0.10$ and 0.15) ................................................................................................................................. 135
Table 8-6 Comparison of Response Calculated in Response History Analysis for 3-story Structure with Fluidic Self-Centering System in MCE and two Cases of Preload (damping constant $C=1140\text{kN-s/m}$) ................................................................................................................................. 136
Table 8-7 Response Calculated in Response History Analysis for 3-story Structure with Fluidic Self-Centering System in MCE and two Cases of Nonlinear Viscous Damping ($\beta_1=0.10$ and 0.15 in DE) ................................................................................................................................. 137
Table 8-8 Comparison of Response Calculated in Response History Analysis for 3-story Structure with Fluidic Self-Centering System in MCE and Cases of Linear and Nonlinear Viscous Damping ($\beta_1=0.10$ in DE) ................................................................................................................................. 138
Table 8-9 Response Calculated in Response History Analysis for 3-story Structure with Fluidic Self-Centering System in MCE and two Cases of Fluidic Device Stiffness and Increased Nonlinear Viscous Damping ($\beta_1=0.15$ in DE) ................................................................................................................................. 139
Table 8-10 Comparison of Response Calculated in Response History Analysis for 6-story Structure with and without Fluidic Self-Centering System in MCE and Cases of Linear ($\beta_1=0.10$) and Nonlinear ($\beta_1=0.15$ in DE) Damping ................................................................................................................................. 140

Table 9-1 Parameters of Fluidic Self-Centering Device-Brace System for Frame 3S-75 in “Balanced” Configuration ................................................................................................................................. 151
Table 9-2 Lateral Force Distribution in Pushover Analysis of 3-Story Frames ................................................................................................................................. 152
Table 9-3 Parameters of Fluidic Self-Centering Fluidic Device-Brace System for Frame 3S-75 in “Unbalanced” Configuration ................................................................................................................................. 155
Table 9-4 Parameters of Fluidic Self-Centering Fluidic Device-Brace System for Frame 6S-75 ................................................................................................................................. 157
Table 9-5 Lateral Force Distribution in Pushover Analysis of 6-Story Frames ................................................................................................................................. 158
Table 9-6 Values of Fundamental Period used for Scaling Motions ................................................................................................................................. 158
Table 9-7 Collapse Margin Ratio, Probability of Collapse in the MCE and other Parameters in Case of Motions based on $S_a$-Component Scaling ................................................................................................................................. 160

xxxiv
LIST OF TABLES (CONT’D)

Table 9-8 Collapse Margin Ratio, Probability of Collapse in the MCE and other Parameters in Case of Motions based on PGV Normalization Scaling ................................................................. 166
Table 9-9 Parameters of Fluidic Self-Centering Fluidic Device-Brace System for Frames 3S-75, 3S-85 and 3S-Reference and Collapse Margin Ratio for Sₘ-Scaled Motions (parameters are the same for all stories except for the preload and stiffness; damping is linear viscous unless noted otherwise) ................................. 177
Table 9-10 Selected Response Parameters in DE and MCE (case of near-fault, pulse like motions) and Collapse Margin Ratio of Frames 3S-75, 3S-85 and 3S-Reference ........................................................................ 178
Table 9-11 Parameters of Fluidic Self-Centering Fluidic Device-Brace System for 6-Story Frame............ 181
Table 9-12 Selected Response Parameters in DE and MCE (case of near-fault, pulse like motions) and Collapse Margin Ratio of Frame 6S-75 in Various Configurations and 6S-Reference Frame .......... 182

Table 10-1 Analyzed Frames for Residual Drift Fragility, Selected Response Parameters in DE and MCE (case of near-fault, pulse like motions) and Fragility Analysis Results ................................................. 187

Table 11-1 Mean Annual Frequency of Collapse, Mean Annual Frequency of Exceeding Specified Residual Drift Limits and Related Probabilities of Exceedance in 50 Years (probabilities in %)...................... 198

Table 12-1 Properties of Triple FP Isolators .......................................................................................... 202
Table 12-2 Values of Parameters of Parallel Model of Isolators in SAP2000........................................ 204
Table 12-3 Seed Ground Motions and Recorded Characteristics ......................................................... 205
Table 12-4 Peak Isolator Displacements, Residual Displacements and Base Shear Force..................... 206
Table 12-5 Peak Damper Displacements and Forces .......................................................................... 207
Table 12-6 Peak Roof Accelerations and Story Drift Ratios ................................................................. 208
Table 12-7 Peak Isolator Displacements, Residual Displacements and Base Shear Force in Isolation System with Fluidic Self-Centering Devices ............................................................................... 210
Table 12-8 Peak Damper Displacements and Forces in Isolation System with Fluidic Self-Centering Devices .......................................................................................................................... 211
Table 12-9 Peak Roof Accelerations and Story Drift Ratios in Isolation System with Fluidic Self-Centering Devices .................................................................................................................. 212
LIST OF TABLES (CONT’D)

Table 12-10 Average Isolator Peak Displacement, Residual Displacement, Peak Device Displacement and Force, Peak Roof Acceleration and Peak Story Drift Ratio in Isolation System with Viscous Dampers and with Fluidic Self-Centering Devices of 34, 45 and 51kip Preload, Case of Upper Bound Friction ....... 213

Table A-1 Legend (Lines) ......................................................................................................................... 229
Table A-2 Legend (Markers) .................................................................................................................... 229

Table B-1 Uniform Gravity Loads on Beams of Typical Steel Special Moment Frame ...................... 426
Table B-2 Lateral Seismic Forces for 3-Story Frame ............................................................................. 427
Table B-3 Calculation of Story Drifts of 3-Story Frame ....................................................................... 428
Table B-4 Lateral Seismic Forces for 6-Story Frame ............................................................................. 429
Table B-5 Calculation of Story Drifts of 6-Story Frame ....................................................................... 430

Table C-1 Lateral Seismic Forces for 3-Story Frame 3S-75 ............................................................... 435
Table C-2 Parameters $\alpha_s, \chi, \text{ and } M_{ph}\chi_l$ ................................................................. 438
Table C-3 Calculation of $\lambda_dh_i$ ................................................................................................. 439
Table C-4 Summary of RSA and ELF Analysis Results ..................................................................... 459
Table C-5 Lateral Seismic Forces for 3-Story Frame 3S-85 ............................................................... 459
Table C-6 Parameters $\alpha_s, \chi, \text{ and } M_{ph}\chi_l$ for Frame 3S-85 ................................................... 461
Table C-7 Calculation of $\lambda_dh_i$ for Frame 3S-85 ........................................................................... 461
Table C-8 Comparison of Average Response Calculated in Response History Analysis for 3S-75 and 3S-85 in MCE ........................................................................................................... 465

Table C-9 Comparison of Average Response Calculated in Response History Analysis for 3S-85 in DE and MCE ......................................................................................................................... 466

Table D-1 Lateral Seismic Forces for 6-Story Frame 6S-75 ............................................................... 469
Table D-2 Parameters $\alpha_s, \chi, \text{ and } M_{ph}\chi_l$ ................................................................................. 470
Table D-3 Calculation of $\lambda_dh_i$ ................................................................................................. 471
Table D-4 Summary of RSA and ELF Analysis Results ................................................................. 500
Table D-5 Bracing Forces, Required Strengths and Design Strengths .................................................. 501
LIST OF TABLES (CONT’D)

Table D-5 Bracing Forces, Required Strengths and Design Strengths ................................................... 501

Table E-1 Assignment of Rank Number .................................................................................................. 504