

**Dynamic Testing of In-Situ Composite Floors and
Evaluation of Vibration Serviceability Using the Finite Element Method**

By

Anthony R. Barrett

Dissertation submitted to the Faculty of
Virginia Polytechnic Institute and State University
in partial fulfillment for the requirements of the degree of
Doctor of Philosophy
in
Civil Engineering

Thomas M. Murray, Chair

Finley A. Charney

W. Samuel Easterling

Raymond H. Plaut

Mehdi Setareh

Alfred L. Wicks

21 August 2006

Blacksburg, VA

Keywords: vibration, floor, serviceability, walking, modal analysis, fundamental frequency, mode shape, resonance, damping, acceleration response, finite element

**Dynamic Testing of In-Situ Composite Floors and
Evaluation of Vibration Serviceability Using the Finite Element Method**

Anthony R. Barrett

Dr. Thomas M. Murray, Chairman

Civil Engineering

(ABSTRACT)

The presented research examined three areas: best practices in high quality dynamic testing of in-situ floor systems, extensive dynamic testing of three bare (non-fit out) in-situ multi-bay steel composite floors to estimate their dynamic parameters/response and to identify trends in dynamic behavior, and development of a set of fundamental finite element (FE) modeling techniques to adequately represent the dynamic response of steel composite floors for the purpose of evaluating vibration serviceability. The measurement, analysis, and computation of a floor's accelerance frequency response function (FRF) is the core premise linking all areas of the presented research.

The burst chirp signal using an electrodynamic shaker is recommended as the most accurate and consistent source of excitation for acquiring high quality measurements suitable for use in parameter estimation, operating deflection shape animation, and calibration/validation of FE models. A reduced mid-bay testing scheme is recommended as a time-saving alternative to modal testing over a full coverage area, provided the only desired estimated parameters are frequencies, damping, and mid-bay acceleration response.

Accelerance FRFs were measured with an electrodynamic shaker located within 23 unique bays on the three tested floors. Dominant frequencies ranged from 4.85 Hz to 9 Hz and measured estimates of damping varied considerably, ranging from 0.44% to 2.4% of critical (0.5%-1.15% was typical). Testing showed several mode shapes were localized to just a few bays and not all modes were adequately excited by forcing at a single location. The quality of the estimated mode shapes was significantly improved using multi-reference modal testing.

FE models for the tested floors were developed based on high quality measured data and were shown to provide adequate representations of measured floor behavior. Fundamental techniques are presented for modeling mass, stiffness, boundary conditions, and performing dynamic analysis. A method of evaluating vibration serviceability was proposed using the FE model's computed accelerance FRF for comparison with a *design accelerance curve* that represents an acceleration response threshold in the frequency domain. An example design accelerance curve is presented based on current serviceability guidelines for acceleration tolerance and effective harmonic forces due to human activities such as walking.

DISCLAIMER: The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

ACKNOWLEDGEMENTS

I would like to sincerely thank my advisor and chair of my committee, Dr. Murray, for introducing me to the subject of floor vibrations leading me through my research endeavors. Never mind that I received a B- in structural dynamics at Illinois and the graduate school wouldn't accept the transferred credit hours, your valuable mentorship allowed me to make up for a little lost ground. Thank you for all of the once-in-a-lifetime opportunities and adventures that took us from the Verrazano-Narrows Bridge in New York to the Arizona Cardinals Stadium in Phoenix to the vineyards of Bordeaux, France. I came to Virginia Tech to work with you, and I could not have made a better choice that will forever guide my future.

I would also like to thank my committee members Dr. Setareh and Dr. Wicks for providing me such a strong foundation in modal testing that was invaluable to my research. I appreciate all the guidance and encouragement from the other members of my committee: Dr. Charney, Dr. Easterling, and Dr. Plaut. It was a pleasure working with you and I learned a tremendous amount from your classes.

I would like to thank members of Lefrak (Nick and Scott) and Branch (Pat) for granting access to test such outstanding buildings and their great support on site.

Thanks to my friends John Ryan and Troy Twesme, who were great wing-men as we traveled together through the trials and tribulations of a Ph.D. program. I'd also like to thank all the folks at the Structures and Materials Lab: Clark Brown for his mastery of the sorcery and witchcraft involved with electronics; Brett Farmer and Dennis Huffman for their help, great company, and motivational questions such as "Tell us again why you have an office out here?" Thanks to other friends that also supported me in my studies: Onur Avci, David Martin, Chuck Newhouse, Craig Favor, Devin Harris, Kirsten Baldwin-Metzger, and Brad Davis. You all rock.

I am grateful for my family and their support, or mockery, or sometimes both. Now when they ask me, "Are you done yet?" I can say, "Yes, yes I am." A big thank you my wife, who was a "dissertation widow" for way too long and, quite frankly, is SO AWESOME!!!

I am very thankful to the Via Department of Civil and Environmental Engineering for offering such a great graduate program and for the generous Via Fellowship in my last year of studies. Lastly, I would especially like to thank the United States Air Force Academy's Department of Civil and Environmental Engineering for their confidence in my abilities and providing wonderful opportunity in all of my educational endeavors.

TABLE OF CONTENTS

ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iv
TABLE OF CONTENTS.....	v
LIST OF FIGURES.....	viii
LIST OF TABLES.....	xiv
CHAPTER 1 Introduction and Literature Survey.....	1
1.1 Introduction.....	1
1.2 Scope of Research.....	2
1.3 Literature Survey.....	4
1.3.1 Background.....	4
1.3.2 AISC/CISC Steel Design Guide Series 11: Vibrations Due to Human Activity.....	5
1.3.3 Floor Vibration Experimental Testing and Finite Element Modeling.....	10
1.4 Need for Research.....	18
CHAPTER 2 Experimental Modal Analysis of Floor Systems.....	20
2.1 Objectives.....	20
2.2 Modal Testing Theory.....	21
2.2.1 Analytical Modal Analysis.....	21
2.2.2 Digital Signal Processing.....	24
2.2.3 Parameter Estimation.....	27
2.3 Dynamic Testing Equipment.....	30
2.3.1 Electrodynamic Shaker.....	31
2.3.2 Measurement of Input Force - Force Plate.....	32
2.3.3 Measurement of Acceleration Response – Accelerometers.....	34
2.3.4 Cables.....	35
2.3.5 Multi-Channel Spectrum Analyzer.....	37
2.3.6 Single-Channel Spectrum Analyzer.....	39
2.4 Experimental Testing Methods.....	41
2.4.1 Chirp Signals.....	42
2.4.2 Instrumented Heel Drop.....	53
2.4.3 Driving Point Accelerance Frequency Response Functions.....	55

2.4.4 Sinusoidal Driving Functions	58
2.4.5 Unreferenced Measurements	62
2.4.6 Damping Estimates	65
2.4.7 Floor Test Area	74
2.4.8 Measurement Quality and Other Behavioral Investigations	76
2.4.9 Summary of Experimental Testing Methods	80
2.5 Classification of Floor Vibration Testing	83
CHAPTER 3 Dynamic Testing and Behavior of In-Situ Floor Systems	87
3.1 In-Situ Floor Systems	87
3.2 Tested Floors #1 and #2 - New Jersey Office Building, NOC VII (24 th & 18 th Floors).....	88
3.2.1 Description of Tested Floors #1 and #2	88
3.2.2 Measurement Coverage of Tested Floors #1 and #2.....	94
Tested Floor #1 (NOC VII-24) Measurement Coverage	94
Tested Floor #2 (NOC VII-18) Measurement Coverage	100
3.2.3 Measured Floor Behavior – NOC VII (Tested Floors #1 and #2)	109
Measured Floor Behavior - NOC VII 24 (Tested Floor #1)	113
Measured Floor Behavior - NOC VII-18 (Tested Floor #2).....	125
3.3 Tested Floor #3 – VT KnowledgeWorks 2 Building, VTK2 (2 nd Floor)	161
3.3.1 Description of Tested Floor #3	161
3.3.2 Measurement Coverage of Tested Floor #3	165
3.3.3 Measured Floor Behavior – VTK2 (Tested Floor #3)	174
3.4 Summary and Implications of Observed In-situ Floor Behavior	211
CHAPTER 4 Finite Element Modeling of Composite Floors for Vibration Serviceability	222
4.1 Finite Element Modeling of Composite Floors for Vibration Serviceability	222
4.1.1 Representing Mass, Stiffness, and Boundary Conditions	225
Mass & Materials	225
Stiffness.....	228
End Releases, Partial Fixity, and Boundary Conditions	232
4.1.2 Dynamic Finite Element Analysis Techniques for Floor Systems	237
Modal Analysis	237
Damping.....	240

Time-History Analysis and Steady State Analysis	242
4.2 Finite Element Analysis of Tested Floors.....	252
4.2.1 New Jersey Office Building, NOC VII.....	252
4.2.2 VT KnowledgeWorks 2 Building, VTK2	269
4.3 Summary of Recommended FE Modeling Techniques for Composite Floors.....	282
4.4 Floor Vibration Serviceability Evaluation Using the Finite Element Method	285
CHAPTER 5 Conclusions and Recommendations for Future Research	296
5.1 Conclusions.....	296
5.1.1 Dynamic Testing of In-Floor Systems	297
5.1.2 Dynamic Behavior of In-Situ Floor Systems.....	298
5.1.3 Fundamental Modeling Techniques for Composite Floors	302
5.1.4 Evaluation of Vibration Serviceability of Floor Systems	304
5.2 Recommendations for Future Research	305
REFERENCES	308
APPENDIX A In-Situ Floor Framing Plans and Slab Details.....	313
APPENDIX B Design Guide 11 Analyses – FloorVibe Analysis Reports	316
APPENDIX C Single Channel Handheld Analyzer Measurements – NOC VII-24.....	332
APPENDIX D Single Channel Handheld Analyzer Measurements – VTK2.....	337
APPENDIX E Driving Point Accelerance Frequency Response Functions – NOC VII	344
APPENDIX F ME’scopeVES Modal Parameter Estimation – NOC VII.....	362
APPENDIX G Decay Measurements and Decay Curve Fit Analyses – NOC VII-18	374
APPENDIX H Driving Point Accelerance Frequency Response Functions – VTK2	387
APPENDIX I ME’scopeVES Modal Parameter Estimation – VTK2.....	402
APPENDIX J Decay Measurements and Decay Curve Fit Analyses – VTK2	411
APPENDIX K Example Composite Section Calculations	420
APPENDIX L Partial Fixity Curve for Assumed Moment-Rotation Relationship.....	425
APPENDIX M NOC VII – Composite Section Calculations & FE Model Input Values	427
APPENDIX N VTK2 – Composite Section Calculations & FE Model Input Values.....	431
VITA.....	436

LIST OF FIGURES

Figure 1.1: Recommended Peak Accelerations for Human Comfort due to Human Activities (Allen and Murray 1993; ISO 2631-2 1989)	6
Figure 2.1: Example Accelerance Frequency Response Function Plot	29
Figure 2.2: Modal Testing Schematic.....	30
Figure 2.3: Electrodynamic Shaker and Amplifier	31
Figure 2.4: Force Plate.....	32
Figure 2.5: Force Plate Calibration.....	34
Figure 2.6: PCB Model 393C Seismic Accelerometer	35
Figure 2.7: Accelerometer Cables – Coaxial (above) and Microdot (below).....	36
Figure 2.8: Model 20-42 SigLab Digital Signal Processor.....	37
Figure 2.9: Ono Sokki CF-1200 Handheld FFT Analyzer	40
Figure 2.10: Typical 4-12 Hz Continuous Chirp Force Input Signal	43
Figure 2.11: Typical 4-12 Hz Chirp Signal Acceleration Response.....	44
Figure 2.12: Typical 4-12 Hz Continuous Chirp FRF Magnitude and Coherence (0-20 Hz)	45
Figure 2.13: Typical 4-12 Hz Continuous Chirp FRF Magnitude, Phase, and Coherence.....	45
Figure 2.14: Typical 4-12 Hz Burst Chirp Force Input Signal	47
Figure 2.15: Typical 4-12 Hz Burst Chirp Acceleration Response	48
Figure 2.16: Typical 4-12 Hz Burst Chirp Magnitude and Coherence (0-20 Hz)	49
Figure 2.17: Typical 4-12 Hz Burst Chirp Magnitude, Phase, and Coherence	50
Figure 2.18: Coherence Comparison of Continuous Chirp & Burst Chirp Excitation Signals	50
Figure 2.19: Armature Acceleration and Force Plate Autospectra for 5-10 Hz Burst Chirp.....	51
Figure 2.20: Driving Point Accelerance FRF Magnitude and Phase from Different References.	52
Figure 2.21: Instrumented Heel Drop	53
Figure 2.22: Instrumented Heel Drop Time Histories and Autospectra	54
Figure 2.23: Comparison of Chirp & Instrumented Heel Drop Force Input Autospectra	55
Figure 2.24: 35 Driving Point Accelerance FRFs (Magnitude, Phase, and Coherence)	57
Figure 2.25: Example Sinusoidal Excitation Force Time History & Autospectrum	59
Figure 2.26: Example Sinusoidal Acceleration Response Time History & Autospectrum.....	60
Figure 2.27: Comparison of Force and Acceleration Time Histories.....	61
Figure 2.28: Accelerance FRF Magnitude and Phase for a Sinusoidal Measurement.....	61
Figure 2.29: Sample Acceleration Time History to Unreferenced Heel Drop Excitation.....	63
Figure 2.30: Autospectra of Unreferenced Heel Drop and Chirp Measurements.....	64

Figure 2.31: Accelerance FRF – Driving at Point 281	69
Figure 2.32: Point 281 – Response Decay from 5.025 Hz.....	70
Figure 2.33: Point 281 – Decay Curve Fit, $\beta = 0.70\%$ at 5.025 Hz.....	70
Figure 2.34: Point 281 – Response Decay from 4.725 Hz.....	71
Figure 2.35: Accelerance FRF – Driving at Point 21	71
Figure 2.36: Point 21 – Response Decay from 4.875 Hz.....	71
Figure 2.37: Example Analytical Decay Curves with Multiple Frequencies	72
Figure 2.38: Accelerance FRF – Driving at Point 125	73
Figure 2.39: Point 125 – Response Decay from 5.05 Hz.....	73
Figure 2.40: Point 125 – Misinterpreted Curve Fit Decay.....	74
Figure 3.1: Newport Office Center (NOC) VII, Jersey City, New Jersey	88
Figure 3.2: NOC VII Floor Framing Layout (18 th and 24 th Floors).....	89
Figure 3.3: NOC VII General Layout of Tested Floors.....	90
Figure 3.4: Conditions of Tested Floor #1, NOC VII-24	91
Figure 3.5: Installation of Raised Flooring on NOC VII 24 th Floor	92
Figure 3.6: Conditions of Tested Floor #2, NOC VII-18	93
Figure 3.7: Chevron Bracing at End of Interior Core Partitions.....	93
Figure 3.8: NOC VII General Test Grid Point Numbers (Tested Floors #1 and #2).....	94
Figure 3.9: NOC VII-24 Excitation Locations	95
Figure 3.10: NOC VII-24 Shaker at Excitation Locations	96
Figure 3.11: NOC VII-24 Measurement Coverage - Shaker at Point 73.....	97
Figure 3.12: NOC VII-24 Measurement Coverage - Shaker at Point 69.....	98
Figure 3.13: NOC VII-24 Measurement Coverage - Shaker at Point 25.....	99
Figure 3.14: NOC VII-18 Excitation Locations	100
Figure 3.15: NOC VII-18 Shaker Located at Point 281	102
Figure 3.16: NOC VII-18 Burst Chirp Measurement Coverage (Forcing at Point 281)	102
Figure 3.17: NOC VII-18 Sinusoidal Measurement Coverage (Point 281 at 5.025 Hz).....	103
Figure 3.18: NOC VII-18 Shaker Located at Point 73	104
Figure 3.19: NOC VII-18 Measurement Coverage (Forcing at Point 73)	105
Figure 3.20: NOC VII-18 Burst Chirp Measurement Coverage.....	105
Figure 3.21: NOC VII-18 Shaker Located at Point 69 and Point 65	106
Figure 3.22: NOC VII-18 Reciprocal Measurement Coverage	107

Figure 3.23: NOC VII-18 Reciprocal Measurement Coverage	108
Figure 3.24: NOC VII-24 ME'scope Model of Full Coverage (Forcing at Point 73)	110
Figure 3.25: NOC VII-24 Driving Point Accelerance FRFs and Coherence (Point 73)	113
Figure 3.26: NOC VII-24 Driving Point FRFs with Curve Fit Overlay (Point 73).....	114
Figure 3.27: NOC VII-24 Driving Point Accelerance FRF (Point 69).....	115
Figure 3.28: NOC VII-24 Driving Point Accelerance FRF (Point 25).....	116
Figure 3.29: NOC VII-24 ME'scope Models	118
Figure 3.30: NOC VII ME'scope 3-Bay Centerline Model.....	119
Figure 3.31: NOC VII-24 3-Bay Centerline ODSs (Forcing at Point 73)	120
Figure 3.32: NOC VII ME'scope 10-Bay Centerline Model.....	121
Figure 3.33: NOC VII-24 10-Bay Centerline ODSs (Forcing at Point 73)	122
Figure 3.34: NOC VII-24 10-Bay Centerline ODS (magnified) at 5.80 Hz.....	123
Figure 3.35: NOC VII-24 End-Bay Area ODSs (Forcing at Point 73).....	124
Figure 3.36: NOC VII-18 Driving Point Accelerance FRFs (All Excitation Points).....	125
Figure 3.37: NOC VII-18 Driving Point Accelerance FRFs (6-Bay Strip)	126
Figure 3.38: NOC VII-18 Driving Point Accelerance FRFs and Coherence (Point 281)	128
Figure 3.39: NOC VII-18 10-Bay Strip ODSs (Forcing at Point 281)	129
Figure 3.40: NOC VII-18 Exterior Bay ODSs (Forcing at Point 281)	129
Figure 3.41: NOC VII-18 10-Bay Centerline ODSs (Forcing at Point 281)	130
Figure 3.42: NOC VII-18 Stepped Sine Sweep Linearity Investigation (Point 281)	131
Figure 3.43: NOC VII-18 Chirp Accelerance FRF Linearity Investigation (Point 281).....	132
Figure 3.44: NOC VII-18 3-Bay ODS Shape Comparison (Forcing at Point 281)	134
Figure 3.45: NOC VII-18 Driving Point Accelerance FRFs (Point 73)	135
Figure 3.46: NOC VII-18 End-Bay Area ODS at 5.05 Hz (Forcing at Point 73).....	136
Figure 3.47: NOC VII-18 End-Bay Centerline ODS at 5.05 Hz (Forcing at Point 73).....	137
Figure 3.48: NOC VII-18 End-Bay ODSs (Forcing at Point 73)	138
Figure 3.49: NOC VII-18 7-Bay ODS Shape Comparison (Forcing at Point 73)	139
Figure 3.50: NOC VII-18 Driving Point Accelerance FRFs (Point 69)	140
Figure 3.51: NOC VII-24 Driving Point Accelerance FRFs (Point 69)	140
Figure 3.52: NOC VII-18 Driving Point Accelerance FRFs (Point 65)	142
Figure 3.53: NOC VII-18 3-Bay Strip Accelerance FRFs (Multiple References)	143
Figure 3.54: NOC VII-18 3-Bay Centerline ODSs (Multiple References)	144
Figure 3.55: NOC VII-18 Driving Point Accelerance FRFs (Point 25)	146

Figure 3.56: NOC VII-24 Driving Point Accelerance FRFs (Point 25)	147
Figure 3.57: NOC VII-18 Driving Point Accelerance FRFs (Point 21)	148
Figure 3.58: NOC VII-18 Driving Point Accelerance FRFs (Point 117)	149
Figure 3.59: NOC VII-18 Driving Point Accelerance FRFs (Point 125)	150
Figure 3.60: NOC VII-18 Driving Point Accelerance FRFs (Point 177)	151
Figure 3.61: NOC VII-18 Driving Point Accelerance FRFs (Point 216)	153
Figure 3.62: NOC VII-18 Partially Open Bay F/G-4/5 (Adjacent to Point 333).....	153
Figure 3.63: NOC VII-18 Driving Point Accelerance FRFs (Point 333)	154
Figure 3.64: NOC VII-18 Reciprocal Accelerance FRF Comparison (Barrett et al. 2006)	155
Figure 3.65: VT KnowledgeWorks 2 Building (VTK2), Blacksburg, Virginia	161
Figure 3.66: VTK2 Floor Framing Layout	161
Figure 3.67: VTK2 Exterior Conditions of Tested Floor	163
Figure 3.68: VTK2 Exterior Wall Framing Attached to Tested Floor and Vertical Clip.....	163
Figure 3.69: VTK2 Surface Conditions of Tested Floor	164
Figure 3.70: VTK2 Stacked Construction Materials in Bays C/D-1/3 and D/E-1/3	164
Figure 3.71: VTK2 Underside Conditions of Tested Floor	165
Figure 3.72: VTK2 B-Wall Partition Framing on Underside of Tested Floor.....	165
Figure 3.73: VTK2 Test Grid Point Numbers (Tested Floor #3)	166
Figure 3.74: VTK2 Excitation Locations.....	166
Figure 3.75: VTK2 Mid-Bay Investigations and Reciprocal Measurement Coverage.....	168
Figure 3.76: VTK2 Measurement Coverage of Modal Sweep (Forcing at Point 126).....	170
Figure 3.77: VTK2 Shaker Located at Point 126 for Modal Sweep of 9-Bay Area.....	171
Figure 3.78: VTK2 Measurement Coverage of Modal Sweep (Forcing at Point 134).....	172
Figure 3.79: VTK2 Measurement Coverage of Modal Sweep (Forcing at Point 130).....	173
Figure 3.80: VTK2 Driving Point Accelerance FRFs (All Excitation Points)	174
Figure 3.81: VTK2 Driving Point Accelerance FRFs (By Bay Type)	175
Figure 3.82: VTK2 Driving Point Accelerance FRFs (Point 21)	177
Figure 3.83: VTK2 Driving Point Accelerance FRFs (Point 25)	179
Figure 3.84: VTK2 Driving Point Accelerance FRFs (Point 74)	180
Figure 3.85: VTK2 Driving Point Accelerance FRFs (Point 78)	181
Figure 3.86: VTK2 Driving Point Accelerance FRFs (Point 82)	182
Figure 3.87: VTK2 Multiple Day Driving Point Accelerance FRFs (Point 126).....	184
Figure 3.88: VTK2 Driving Point Accelerance FRFs (Point 126 Modal Coverage)	184

Figure 3.89: VTK2 Driving Point Accelerance FRFs (Point 126 Modal Coverage)	186
Figure 3.90: VTK2 Driving Point Accelerance FRFs (Point 130)	187
Figure 3.91: VTK2 Driving Point Accelerance FRFs (Point 134)	188
Figure 3.92: VTK2 Driving Point Accelerance FRFs (Point 178)	189
Figure 3.93: VTK2 Driving Point Accelerance FRFs (Point 182)	190
Figure 3.94: VTK2 Driving Point Accelerance FRFs (Point 186)	191
Figure 3.95: VTK2 Driving Point Accelerance FRFs (Point 230)	192
Figure 3.96: VTK2 9-Bay Area Multi-Reference FRFs (Forcing at Points 126 and 134)	194
Figure 3.97: VTK2 9-Bay Area ODSs from Forcing at Points 126 and 134.....	195
Figure 3.98: VTK2 9-Bay Area Curve Fit Mode Shapes	198
Figure 3.99: VTK2 Comparison of ODS at Strong Reference to Curve Fit Mode Shapes	199
Figure 3.100: VTK2 3-Bay Strip Multi-Reference FRFs (Points 126, 130 and 134).....	201
Figure 3.101: VTK2 3-Bay Strip ODS at 7.95 Hz (Forcing at Point 130)	201
Figure 3.102: VTK2 3-Bay Strip Curve Fit Mode Shapes	202
Figure 3.103: VTK2 Comparison of Reference Specific ODS & Curve Fit Mode Shapes.....	203
Figure 3.104: Comparison of Tested Bay's Driving Point FRFs (NOC VII-18 and VTK2).....	212
Figure 3.105: VTK2 Mid-Bay Accelerance FRFs (Forcing at Point 78)	219
Figure 3.106: VTK2 Example Shape Evaluation Using Mid-Bay Accelerance FRFs	220
Figure 3.107: VTK2 Curve Fit Mode Shape at 7.97 Hz (Max Response at Point 78)	220
Figure 4.1: 8-Bay Floor Model Example – Framing Member Layout	225
Figure 4.2: 8-Bay Floor Model Example – Plate Area Element Layout and Mesh.....	228
Figure 4.3: Representations of Composite Slab and Framing Members	229
Figure 4.4: 8-Bay Floor Model Example – End-Release and Partial Fixity	234
Figure 4.5: 8-Bay Floor Model Example – Pinned Supports Representing Interior Restraints .	236
Figure 4.6: 8-Bay Floor Example – Computed Frequencies and Mode Shapes	238
Figure 4.7: 8-Bay Floor Example – Applied Unit Load (1 lb) for Forced Response Analysis ..	243
Figure 4.8: 8-Bay Floor Example – Time History Response to Sinusoidal Load	245
Figure 4.9: 8-Bay Floor Example – Driving Point Accelerance FRF (Real and Imaginary)	247
Figure 4.10: 8-Bay Floor Example – Driving Point Accelerance FRF and Phase	248
Figure 4.11: 8-Bay Floor Example – Other Representations of Response	249
Figure 4.12: 8-Bay Floor Example – Examples Using Interpolated Hysteretic Damping	250
Figure 4.13: NOC VII – Floor Layout and Full Floor FE Model	253

Figure 4.14: NOC VII – Full Floor Model Moment End Releases and Partial Fixities	255
Figure 4.15: NOC VII – Full Floor Model Interior Restraints	255
Figure 4.16: NOC VII – Full Floor Model Computed Mode Shapes (Modes 1-12)	256
Figure 4.17: NOC VII – Full Floor Model Computed Mode Shapes (Modes 13-24)	257
Figure 4.18: NOC VII – Full Floor Model Mode Shape and ODS Comparison	258
Figure 4.19: NOC VII – Constant Damping Ratios Used in Steady State Analysis	260
Figure 4.20: NOC VII – Full Floor Accelerance FRFs (Points 21, 25, 69, 73).....	261
Figure 4.21: NOC VII – Full Floor Accelerance FRFs (Pts 65,117,125,177,216,281, & 333)..	262
Figure 4.22: NOC VII – 10-Bay Strip FE Model	263
Figure 4.23: NOC VII – 10-Bay Strip Model Computed Mode Shapes.....	265
Figure 4.24: NOC VII – 10-Bay Strip Model Mode Shape and ODS Comparison (Point 281)	265
Figure 4.25: NOC VII – 10-Bay Strip Model Mode Shape and ODS Comparison (Point 65) ..	266
Figure 4.26: NOC VII – 10-Bay Strip Model Accelerance FRFs.....	267
Figure 4.27: VTK2 – Floor Layout and FE Model.....	270
Figure 4.28: VTK2 – Moment End Releases and Partial Fixities.....	271
Figure 4.29: VTK2 – Interior Pinned Restraints.....	271
Figure 4.30: VTK2 – Computed Mode Shapes 1-7 (Tested Area of Floor).....	272
Figure 4.31: VTK2 – Computed Mode Shapes 8-20 (Tested Area of Floor)	273
Figure 4.32: VTK2 – FE Mode Shape and Curve Fit Mode Shape Comparison	274
Figure 4.33: VTK2 – Dominant Mode Shapes (Points 25, 230, 21)	275
Figure 4.34: VTK2 – Computed Modes (Non-Tested Area of Floor and Double Curvature) ...	275
Figure 4.35: VTK2 – Constant Damping Ratios Used in Steady State Analysis	276
Figure 4.36: VTK2 – Accelerance FRFs (Points 21, 25, 230).....	277
Figure 4.37: VTK2 – Accelerance FRFs (Points 74, 78, 82).....	278
Figure 4.38: VTK2 – Accelerance FRFs (Points 126, 130, 134).....	279
Figure 4.39: VTK2 – Accelerance FRFs (Points 178, 182, 186).....	280
Figure 4.40: Proposed DG11 Design Accelerance Curves for Different Reduction Factors	288
Figure 4.41: FE Serviceability Evaluation Example – Accelerance FRFs and Design Curve ...	291
Figure 4.42: FE Serviceability Evaluation Example – All Bays	293

LIST OF TABLES

Table 1.1: Common Forcing Frequencies and Dynamic Coefficients (Murray et al. 1997)	8
Table 2.1: Digital Signal Processor Settings.....	39
Table 3.1: Summary of Test Settings and Parameters of Tested Floor #1, NOC VII-24	97
Table 3.2: Summary of Test Settings and Parameters of Tested Floor #2, NOC VII-18	101
Table 3.3: NOC VII-24 Pt 73 – Driving Point Curve Fit Estimated Frequencies & Damping ..	114
Table 3.4: NOC VII-24 Pt 69 – Driving Point Curve Fit Estimated Frequencies & Damping ..	116
Table 3.5: NOC VII-24 Pt 25 – Driving Point Curve Fit Estimated Frequencies & Damping ..	116
Table 3.6: NOC VII-24 Global Curve Fit Estimated Frequencies and Damping (Point 73).....	117
Table 3.7: NOC VII-18 Pt 281–Driving Point Curve Fit Estimated Frequencies & Damping ..	128
Table 3.8: NOC VII-18 Parameter Estimates at Various Excitation Levels (Point 281)	132
Table 3.9: NOC VII-18 Pt 73–Curve Fit Estimated Frequencies & Damping	136
Table 3.10: NOC VII-18 Pt 69–Driving Point Curve Fit Estimated Frequencies & Damping ..	141
Table 3.11: NOC VII-18 Pt 65–Driving Point Curve Fit Estimated Frequencies & Damping ..	142
Table 3.12: NOC VII-18 Multi-Reference Curve Fitting Shape Strengths	145
Table 3.13: NOC VII-18 Multi-Reference Curve Fit Estimated Frequencies and Damping	145
Table 3.14: NOC VII-18 Pt 25–Driving Point Curve Fit Estimated Frequencies & Damping ..	147
Table 3.15: NOC VII-18 Pt 21–Driving Point Curve Fit Estimated Frequencies & Damping ..	148
Table 3.16: NOC VII-18 Pt 117–Driving Point Curve Fit Estimated Frequencies & Damping ..	149
Table 3.17: NOC VII-18 Pt 125–Driving Point Curve Fit Estimated Frequencies & Damping ..	150
Table 3.18: NOC VII-18 Pt 177–Driving Point Curve Fit Estimated Frequencies & Damping ..	152
Table 3.19: NOC VII-18 Pt 216–Driving Point Curve Fit Estimated Frequencies & Damping ..	153
Table 3.20: NOC VII-18 Pt 333–Driving Point Curve Fit Estimated Frequencies & Damping ..	154
Table 3.21: NOC VII-18 Summary of Decay Curve Fit Damping Estimates	157
Table 3.22: NOC VII-18 Summary of Dominant Frequency & Damping Estimates (All Bays).....	158
Table 3.23: NOC VII - DG11 Predicted Beam/Girder/System Frequencies (Hz).....	159
Table 3.24: Summary of Test Settings and Parameters of Tested Floor #3, VTK2	167
Table 3.25: VTK2 Point 21 – Driving Point Curve Fit Estimated Frequencies and Damping... ..	178
Table 3.26: VTK2 Point 25 – Driving Point Curve Fit Estimated Frequencies and Damping... ..	179
Table 3.27: VTK2 Point 74 – Driving Point Curve Fit Estimated Frequencies and Damping... ..	181
Table 3.28: VTK2 Point 78 – Driving Point Curve Fit Estimated Frequencies and Damping... ..	182
Table 3.29: VTK2 Point 82 – Driving Point Curve Fit Estimated Frequencies and Damping... ..	183

Table 3.30: VTK2 Point 126 – Driving Point Curve Fit Estimated Frequencies and Damping.	185
Table 3.31: VTK2 Point 130 – Driving Point Curve Fit Estimated Frequencies and Damping.	187
Table 3.32: VTK2 Point 134 – Driving Point Curve Fit Estimated Frequencies and Damping.	188
Table 3.33: VTK2 Point 178 – Driving Point Curve Fit Estimated Frequencies and Damping.	190
Table 3.34: VTK2 Point 182 – Driving Point Curve Fit Estimated Frequencies and Damping.	191
Table 3.35: VTK2 Point 186 – Driving Point Curve Fit Estimated Frequencies and Damping.	192
Table 3.36: VTK2 Point 230 – Driving Point Curve Fit Estimated Frequencies and Damping.	193
Table 3.37: VTK2 9-Bay Area Multi-Reference Curve Fitting Shape Strengths and Estimated Frequencies and Damping.....	198
Table 3.38: VTK2 3-Bay Area Multi-Reference Curve Fitting Shape Strengths and Estimated Frequencies and Damping.....	202
Table 3.39: VTK2 Consolidated Summary of Curve Fit Estimated Frequency & Damping	204
Table 3.40: VTK2 Summary of Decay Curve Fit Estimates of Damping	206
Table 3.41: VTK2 Summary of Dominant Frequency and Damping Estimates – Part 1.....	207
Table 3.42: VTK2 Summary of Dominant Frequency and Damping Estimates – Part 2.....	208
Table 3.43: VTK2 - DG11 Predicted Beam/Girder/System Frequencies (Hz)	210
Table 4.1: NOC VII – Composite Slab Parameters & Slab Area Element/Material Properties.	253
Table 4.2: NOC VII – Computed Modes for Full Floor Model.....	256
Table 4.3: NOC VII – Computed Modes for 10-Bay Strip Model	264
Table 4.4: VTK2 – Composite Slab Parameters and Slab Area Element/Material Properties ...	269
Table 4.5: VTK2 – Computed Modes.....	272
Table 4.6: FE Serviceability Evaluation Example – Change in Computed Frequencies.....	290