

TABLE OF CONTENTS

PREFACE..... i

FOREWORD.....v

TABLE OF CONTENTS xi

CHAPTER 1: INTRODUCTION TO PASSIVE SUPPLEMENTAL DAMPING
AND SEISMIC ISOLATION.....1

1.1 FUNDAMENTAL CONCEPTS..... 1

1.2 BRIEF HISTORY OF SUPPLEMENTAL DAMPING AND SEISMIC ISOLATION
SYSTEMS..... 4

1.3 CATEGORIES OF SUPPLEMENTAL DAMPING AND SEISMIC ISOLATION
SYSTEMS..... 7

1.4 OBJECTIVES OF THE BOOK 8

CHAPTER 2: REVIEW OF SEISMIC DESIGN PHILOSOPHIES AND
ANALYSIS METHODS9

2.1 INTRODUCTION 9

2.2 FORCE-BASED SEISMIC DESIGN PROCEDURE 9

2.2.1 Principles and Objectives 9

2.2.2 Concept of Ductility 10

2.2.3 Linear Static Analysis Method 12

2.2.4 Linear Dynamic Analysis Method 14

2.2.5 Advantages and Limitations of Force-Based Seismic Design Procedures ... 15

2.3 PERFORMANCE-BASED EARTHQUAKE ENGINEERING 16

2.3.1 Background and Need for Performance-Based Earthquake Engineering ... 16

2.3.2 Current Performance-Based Seismic Design Framework..... 16

2.3.3 Explicit Consideration of Residual Deformations in Performance-Based
Earthquake Engineering..... 18

2.4	STATIC NONLINEAR (PUSHOVER AND PUSH-PULL) ANALYSIS METHODS	20
2.4.1	Need for Improved Seismic Design and Assessment Techniques	20
2.4.2	Background	20
2.4.3	Fundamentals of Nonlinear Static Analysis Methods	20
2.4.4	Capacity Spectrum Analysis Methods	22
2.5	DIRECT DISPLACEMENT-BASED SEISMIC DESIGN PROCEDURE	24
2.5.1	Fundamentals of Direct Displacement-Based Seismic Design Procedure... ..	24
2.5.2	Advantages and Disadvantages of Direct Displacement-Based Seismic Design	28
2.6	NONLINEAR DYNAMIC ANALYSES	29
2.7	INCREMENTAL DYNAMIC ANALYSES	30
2.8	NEED FOR SUPPLEMENTAL DAMPING AND SEISMIC ISOLATION SYSTEMS.....	30

CHAPTER 3: ENERGY CONCEPTS IN EARTHQUAKE ENGINEERING ...33

3.1	INTRODUCTION	33
3.2	RAIN FLOW ANALOGY	33
3.3	ENERGY BALANCE EQUATION.....	36
3.3.1	Derivation.....	36
3.3.2	Relative Input Energy and Absolute Input Energy	39
3.3.3	Discrete Energy Expressions	41
3.3.4	Using Energy Balance as a Criterion for Numerical Accuracy	42
3.3.5	Energy Spectra.....	43
3.3.6	Energy Based Design Methods.....	43
3.4	EXAMPLES OF ENERGY COMPUTATION	44
3.4.1	Scope	44
3.4.2	Structural Models	44
3.4.3	Choice of Earthquake Ground Motions	47
3.4.4	Comparison of Energy Time-Histories	48
3.5	PROBLEMS	59

CHAPTER 4: BASIC CONCEPTS AND GENERAL DESIGN REQUIREMENTS FOR STRUCTURES WITH PASSIVE ENERGY DISSIPATING SYSTEMS 61

4.1	INTRODUCTION	61
4.2	ACTIVE, SEMI-ACTIVE AND PASSIVE SYSTEMS	61
4.3	TYPES OF PASSIVE ENERGY DISSIPATING SYSTEMS	62
4.4	INFLUENCE OF PASSIVE ENERGY DISSIPATING SYSTEMS ON ENERGY BALANCE	66

4.5	GENERAL GUIDELINES FOR THE DESIGN AND ANALYSIS OF STRUCTURES WITH PASSIVE SUPPLEMENTAL DAMPING SYSTEMS	69
4.5.1	FEMA-356 Analysis Procedures	70
4.5.2	FEMA-450 Design Procedures	72
4.5.3	Testing Requirements for Supplemental Dampers.....	78
4.6	DESIGN AND ANALYSIS OF ASYMMETRIC STRUTURES INCORPORATING PASSIVE ENERGY DISSIPATING SYSTEMS.....	79

CHAPTER 5: METALLIC AND FRICTION (HYSTERETIC) DAMPERS.....81

5.1	INTRODUCTION	81
5.2	BASIC DYNAMIC RESPONSE OF STRUCTURES WITH HYSTERETIC DAMPERS	82
5.3	APPROXIMATE EQUIVALENT LINEARIZATION	84
5.4	STUDY OF A NONLINEAR MECHANICAL SYSTEM INCORPORATING HYSTERETIC DAMPERS.....	88
5.4.1	Scope	88
5.4.2	Derivation of Closed-Form Frequency Response Function.....	89
5.4.3	Closed-Form Frequency Response Analysis	94
5.4.4	Numerical Verification of Closed-Form Frequency Response Function	97
5.4.5	Summary of Study of Analogous Nonlinear Mechanical System	98
5.5	METALLIC DAMPERS.....	100
5.5.1	Hysteretic Behaviour of Yielding Steel Elements.....	100
5.5.2	Geometrical Considerations.....	102
5.5.3	Experimental Studies	104
5.5.4	Structural Implementations.....	113
5.6	FRICTION DAMPERS	113
5.6.1	Basic Principles of Solid Coulomb Friction	113
5.6.2	Stick-Slip Motion	118
5.6.3	Wear Phenomenon	118
5.6.4	Normal Load in Sliding Interfaces.....	119
5.6.5	Effects Influencing Frictional Behaviour.....	123
5.6.6	Studies on the Variation of Coefficient of Friction for Teflon-Steel Interfaces	126
5.6.7	Studies on the Variation of Coefficient of Friction for Metal-Metal Interfaces	128
5.6.8	Viscoplastic Model of Friction Process.....	129
5.6.9	Existing Friction Damping Systems	131
5.6.10	Structural Implementations	138
5.7	DESIGN OF STRUCTURES EQUIPPED WITH HYSTERETIC DAMPERS	138
5.7.1	Design Steps	138
5.7.2	Review of Different Design Procedures	140
5.7.3	Optimum Hysteretic Design Spectra.....	144
5.7.4	Design Example.....	148

5.7.5	Significance of Optimal Design	151
5.7.6	Performance-Based Design of Hysteretically Damped Structures.....	151
5.8	PROBLEMS.....	156

CHAPTER 6: VISCOUS AND VISCOELASTIC DAMPERS 159

6.1	INTRODUCTION.....	159
6.2	HYSTERETIC BEHAVIOUR OF LINEAR AND NONLINEAR VISCOUS DAMPERS.....	159
6.2.1	Linear Viscous Dampers	159
6.2.2	Nonlinear Viscous Dampers	161
6.3	HYSTERETIC BEHAVIOUR OF VISCOELASTIC DAMPERS.....	163
6.4	VARIATION OF SHEAR STORAGE AND SHEAR LOSS MODULI OF VISCOELASTIC MATERIALS	167
6.5	DYNAMIC ANALYSIS OF STRUCTURES INCORPORATING VISCOUS AND VISCOELASTIC DAMPERS	170
6.6	EXISTING VISCOUS AND VISCOELASTIC DAMPERS	173
6.7	DESIGN OF STRUCTURES EQUIPPED WITH VISCOELASTIC DAMPERS..	178
6.8	DESIGN OF STRUCTURES EQUIPPED WITH VISCOUS DAMPERS.....	179
6.8.1	Conceptual Design with Linear Viscous Dampers	179
6.8.2	Practical Design with Linear Viscous Dampers	180
6.8.3	Design Example for Linear Viscous Dampers	182
6.8.4	Additional Design Considerations for Nonlinear Viscous Dampers.....	183
6.8.5	Optimal Distribution of Viscous Dampers.....	185
6.9	GEOMETRICAL AMPLIFICATION OF DAMPING	186
6.10	STRUCTURAL IMPLEMENTATIONS.....	190
6.11	PROBLEMS	190

CHAPTER 7: SELF-CENTERING SYSTEMS..... 193

7.1	INTRODUCTION.....	193
7.2	BEHAVIOUR OF SELF-CENTERING SYSTEMS.....	195
7.3	DYNAMIC CHARACTERISTICS OF SELF-CENTERING SYSTEMS.....	196
7.3.1	Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems..	197
7.4	SEISMIC RESPONSE OF SELF-CENTERING SDOF SYSTEMS.....	213
7.4.1	Normalized Equations of Motion	213
7.4.2	Response of Flag-Shaped SDOF Hysteretic Systems	219
7.4.3	Response of Bilinear Elastoplastic Hysteretic Systems	222
7.4.4	Comparative Response of the Flag-Shaped and Elastoplastic Hysteretic Systems	223
7.4.5	Examples of Time-History Analyses	227
7.5	DYNAMIC RESPONSE OF MDOF SELF-CENTERING SYSTEMS	228

7.5.1	Structures Analyzed.....	228
7.5.2	Ground Motions Used in Analyses.....	229
7.5.3	Results from Numerical Investigation.....	229
7.6	ANCIENT APPLICATIONS OF SELF-CENTERING SYSTEMS.....	235
7.7	EARLY MODERN APPLICATIONS OF SELF-CENTERING SYSTEMS.....	235
7.8	SHAPE MEMORY ALLOYS.....	236
7.8.1	Superelasticity of Shape Memory Alloys.....	236
7.8.2	Experimental Studies Involving Shape Memory Alloys.....	238
7.8.3	Structural Implementations of Shape Memory Alloys.....	243
7.9	THE ENERGY DISSIPATING RESTRAINT (EDR)	244
7.9.1	Hysteretic Behaviour of EDR	244
7.9.2	Experimental Studies with EDR.....	245
7.10	SELF-CENTERING DAMPERS USING RING SPRINGS	246
7.10.1	Description of Ring-Spring Systems.....	246
7.10.2	Experimental Studies with Ring-Spring Dampers.....	246
7.11	POST-TENSIONED FRAME AND WALL SYSTEMS.....	254
7.11.1	Self-Centering Systems for Concrete Frames and Walls.....	254
7.11.2	Hysteretic Characteristics of Post-Tensioned Connections	257
7.11.3	Monotonic Moment-Rotation Characterization of Self-Centering Post-Tensioned Connections	259
7.11.4	Cyclic Modelling with Equivalent Nonlinear Rotational Springs.....	261
7.11.5	Extension of Model to Constrained Beams	263
7.11.6	Model of PTED Connections Accounting for Beam Depth	264
7.11.7	Further Refinements in Self-Centering Systems for Reinforced Concrete Frames and Walls	266
7.11.8	Self-Centering Systems for Confined Masonry Walls	268
7.11.9	Self-Centering Systems for Steel Structures	268
7.11.10	Self-Centering Systems for Bridge Structures.....	270
7.12	CONSIDERATIONS FOR THE SEISMIC DESIGN OF SELF-CENTERING SYSTEMS	273
7.13	PROBLEMS	274

CHAPTER 8: TUNED-MASS DAMPERS.....277

8.1	INTRODUCTION	277
8.2	THEORY OF UNDAMPED TUNED-MASS DAMPERS UNDER HARMONIC LOADING	277
8.3	THEORY OF UNDAMPED TUNED-MASS DAMPERS UNDER HARMONIC BASE MOTION	282
8.4	THEORY OF DAMPED TUNED-MASS DAMPERS UNDER HARMONIC LOADING	284
8.5	APPLICATION OF TUNED-MASS DAMPERS IN EARTHQUAKE ENGINEERING	289

8.6	ANALYSIS OF STRUCTURES WITH TUNED-MASS DAMPERS.....	291
8.7	SEISMIC RESPONSE OF INELASTIC BUILDINGS WITH TMDs.....	294
8.7.1	Building Models.....	294
8.7.2	Analysis Procedure.....	295
8.7.3	Ground Motions	296
8.7.4	Selected Analysis Results.....	296
8.8	DESIGN CONSIDERATIONS	297
8.9	PROBLEMS	298

CHAPTER 9: BASIC ANALYSIS AND DESIGN CONCEPTS FOR SEISMICALLY ISOLATED STRUCTURES 301

9.1	INTRODUCTION	301
9.2	THEORY OF LINEAR SEISMICALLY ISOLATED SYSTEMS.....	302
9.3	DESIGN CONSIDERATIONS FOR SEISMICALLY ISOLATED BUILDINGS	312
9.3.1	Design Methods	312
9.3.2	Design Based on Static Analysis	314
9.3.3	Design Based on Dynamic Analysis.....	319
9.3.4	Design Review and Testing.....	320
9.4	DESIGN CONSIDERATIONS FOR SEISMICALLY ISOLATED BRIDGES	320
9.4.1	Codified Design Methods	322
9.4.2	Design Properties of Seismic Isolation Systems	323
9.4.3	Minimum Clearances	327
9.4.4	Required Testing Program for Isolation Bearings.....	328
9.5	PROBLEMS	328

CHAPTER 10: SEISMIC ISOLATION SYSTEMS 331

10.1	INTRODUCTION	331
10.2	LAMINATED-RUBBER BEARINGS.....	331
10.2.1	Gravity Load Carrying Capacity of Laminated-Rubber Bearings.....	332
10.2.2	Lateral Stiffness of Laminated-Rubber Bearings.....	334
10.2.3	Natural Period of Vibration of Laminated-Rubber Bearings Supporting a Rigid Structure.....	334
10.2.4	Damping Provided by Laminated-Rubber Bearings.....	335
10.2.5	Vertical Stiffness of Laminated-Rubber Bearings	335
10.2.6	Allowable Lateral Displacement of Laminated-Rubber Bearings.....	335
10.3	LEAD-RUBBER BEARINGS.....	336
10.3.1	Properties of Lead-Rubber Bearings	336
10.3.2	Modelling of Lead-Rubber Bearings	337
10.4	FRICTION PENDULUM SYSTEM	339
10.4.1	General Description.....	339
10.4.2	Properties of Frictionless Pendulum System	339

10.4.3	Properties of Pendulum System Including Friction	340
10.4.4	Double Curvature Friction Pendulum Systems	341
10.5	OTHER SEISMIC ISOLATION SYSTEMS	343
10.5.1	Seismic Isolation Systems Incorporating Metallic Dampers	343
10.6	EFFECT OF AXIAL LOAD VARIATION ON THE RESPONSE OF LAMINATED AND LEAD-RUBBER BEARINGS	348
10.7	PROBLEMS	349
CHAPTER 11:	SAMPLE SEISMIC RETROFIT PROJECTS	355
11.1	INTRODUCTION	355
11.2	PERFORMANCE INDICES	356
11.3	SEISMIC HAZARD	356
11.4	SAMPLE PROJECT 1: RETROFIT OF A MOMENT-RESISTING STEEL FRAMED BUILDING	358
11.4.1	PHASE 1: Building Identification	359
11.4.2	PHASE 2: Characterization of Design Ground Motions	362
11.4.3	PHASE 3: Performance Evaluation of Original Building Structure	363
11.4.4	PHASE 4: Retrofit of Building Structure with Hysteretic Dampers	364
11.4.5	PHASE 5: Retrofit of Building Structure with Viscous Dampers	366
11.4.6	PHASE 6: Retrofit of Building Structure with a Tuned-Mass Damper	367
11.4.7	PHASE 7: Retrofit of Building Structure with a Lead-Rubber Seismic Isolation System	369
11.4.8	PHASE 8: Performance Assessment of Optimum Retrofit Strategies Under the 2% in 50 Years Ground Motions and Near-Field Ground Motions	371
11.4.9	PHASE 9: Summary of Results and Comparison of Retrofit Strategies	372
11.5	SAMPLE PROJECT 2: RETROFIT OF A CABLE-STAYED BRIDGE	372
11.5.1	PHASE 1: Identification of Bridge Structure	373
11.5.2	PHASE 2: Characterization of Design Ground Motions	378
11.5.3	PHASE 3: Performance Evaluation of Original Bridge Structure	379
11.5.4	PHASE 4: Retrofit of Bridge Structure with Hysteretic Dampers	380
11.5.5	PHASE 5: Retrofit of Bridge Structure with Viscous Dampers	382
11.5.6	PHASE 6: Retrofit of Bridge Structure with Tuned-Mass Dampers	383
11.5.7	PHASE 7: Design of Bridge Structure with Friction Pendulum Seismic Isolators	385
11.5.8	PHASE 8: Performance Assessment of Optimum Retrofit Strategies Under the 2% in 50 Years Ground Motions and Near-Field Ground Motions	386
11.5.9	PHASE 9: Summary of Results and Comparison of Retrofit Strategies	387
REFERENCES		389

APPENDIX A: Implementation of Metallic Dampers in Structures. [N]: New Construction, [R]: Retrofit 411

APPENDIX B: Implementation of Friction Dampers in Structures. [N]: New Construction, [R]: Retrofit 413

APPENDIX C: Implementation of Viscoelastic and Viscous Dampers in Structures. [N]: New Construction, [R]: Retrofit..... 417

APPENDIX D: Implementation of Base Isolation Systems in Buildings and Bridges. [N]: New Construction, [R]: Retrofit..... 421

LIST OF SYMBOLS.....447

ANSWERS TO PROBLEMS467

INDEX..... 471