

**STRUCTURAL CONTROL OF BUILDING FRAMES
SUBJECTED TO EARTHQUAKE INDUCED
EXCITATIONS USING SHAPE MEMORY ALLOYS**

VIMAL KUMAR GUPTA



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, DELHI
FEBRUARY, 2016**

**STRUCTURAL CONTROL OF BUILDING FRAMES
SUBJECTED TO EARTHQUAKE INDUCED
EXCITATIONS USING SHAPE MEMORY ALLOYS**

by

VIMAL KUMAR GUPTA

Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



**INDIAN INSTITUTE OF TECHNOLOGY, DELHI
HAUZ KHAS, NEW DELHI – 110016, INDIA**

FEBRUARY, 2016

Dedicated
to
My Parents

Certificate

This is to certify that the thesis entitled, “**Structural Control of Building Frames Subjected to Earthquake Induced Excitations using Shape Memory Alloys**”, being submitted by **Mr.Vimal Kumar Gupta**, to the Indian Institute of Technology, Delhi, for the award of ‘**DOCTOR OF PHILOSOPHY**’ in Civil Engineering is a record of the bonafide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for submission of this thesis, which to the best of my knowledge has reached the requisite standard.

The material contained in the thesis has not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

(Prof. Alok Madan)
Professor
Department of Civil Engineering
Indian Institute of Technology
New Delhi- 110016, India

Acknowledgements

It is my great pleasure and privilege to express profound gratitude to Prof. Alok Madan, my research supervisor at Indian Institute of Technology, Delhi, for his invaluable guidance, inestimable help and constructive criticism at each and every stage of this work. The idea for this work would never have taken root had it not been for his wisdom and inspiration. More than a formal guide; Prof. Madan is a 'Guru' & 'Master' to me.

I am thankful to Prof. Shashi Mathur, Prof. A.K. Jain, and Prof. S.P. Singh for their kind support during my research. Special thanks to Mr. Sairam, Research Scholar IIT Delhi and Mr. Shahid, Mr. Vikram Chand, and Mr. Rajveer Agrawal for his consistent support during entire period of research work

I am indebted to Shri P. K.Gupta, Chairman of Sharda Group of Institutions, Shri Y. K. Gupta, Vice-Chairman, Sharda Group of Institutions and Dr. R.C. Maheshwari , Advisor, Sharda Group of Institutions , Agra for their support in pursuing the research work.

My words fail to express my gratitude to my wife Anita Gupta for that entire she silently endured during the difficult times, and the way she always supported me and stood by my side.

I have no words to express my feelings to my loving mother Late Smt. Shakuntla and my father late Shri Ram Krishan Mahajan. This research is dedicated to my beloved parents.

I thank to God, the almighty, Thakur Baba, and Bhagat ji for providing me this opportunity and giving me the strength and capability to proceed successfully.

Vimal Kumar Gupta

Abstract

The Ni-Ti Shape memory alloys (SMAs) display the large ductility (Superelasticity), higher resistance to corrosion and fatigue, stable transformation temperatures and ability of shape recovery on heating i.e. Shape memory effect (SME) make them an attractive material for structural control devices and therefore their applications has been extended to semi-active control, hybrid control and smart passive control in the present study. Shape memory alloy has shown vast potential for engineering applications in the field seismic hazard mitigations of civil engineering structures. Although extensive researches have been carried out in the area of structural control, relatively less work has been reported on semi-active and hybrid control of building frames subjected to earthquake excitation using SMA devices. The superelasticity and SME are the two fundamental properties of SMAs associated with the stress-induced or thermal-induced reversible hysteretic phase transformation between austenite and martensite. These unique properties enable SMA to be used as control devices for civil engineering structure control. The SMAs can be employed as passive, semi-active or active component in structural control. The most applications of Ni-Ti SMAs in civil structural control are focused on using passive control devices which takes advantage of the damping property of super-elastic shape memory alloys.

The present study is based on the analytical investigation of the structural behavior of Ni-Ti SMA, a smart material, for potential application in vibration control of building frames subjected to the ElCentro and San Fearnando cover the aspect of far – field motion and the Kobe and Northridge cover the aspect of near-field motion.

In particular, the Nitinol (Nickel Titanium Naval Ordinance Laboratory) SMA is proposed for implementation in the form of Ni-Ti wires as the core component of the SMA based smart structural control devices for semi-active control, smart passive

control, smart base isolation, and hybrid control of building frames subjected to earthquake ground motions. The objectives of the present study may be summarized by the following tasks:

- i)** Integration and implementation of realistic and efficient hysteretic models of Ni-Ti SMA in simulated structural control systems based on available experimental data.
- ii)** Analytical modeling and simulation of semi-actively controlled building frames using Ni-Ti based SMA devices under the influence of earthquake ground motions.
- iii)** Analytical evaluation of the suitability and efficacy of SMA dampers in smart passive control of building frames.
- iv)** Analytical investigation of the feasibility of SMA based devices in seismic base isolation. The SMA base-isolation devices may be passive or semi-active in nature.
- v)** Formulation of a hybrid control method using passive SMA dampers and an active mass damper (AMD) for structural control of building frames.
- vi)** Validation of the proposed SMA based structural control systems by examining the stability of the conceptual designs using frequency domain analysis.

The semi-active control of earthquake induced vibrations in building frames based on smart stressing of building frame using shape memory alloys. Smart cables composed of (Ni-Ti) shape memory alloy (SMA) wires are proposed to be installed externally with concrete building frame elements. In principle, the cables can be designed such that the SMA wires are elongated beyond their plastic limit under the action of earthquake loads on the frame. Upon regulating electrical heating, the Ni-Ti SMA wires will undergo a martensite to austenite phase transformation resulting in large shrinkage strains. The strain energy, thus induced can be used to generate a significantly effective control force in the building frame. The concept is analytically investigated by numerical simulations of proposed semi-active control scheme in an idealized single degree of freedom and

multi degree of freedom structural frame model. Some of the important conclusions of the study are: i) the proposed semi-active control technique implementing the SMA based tendon is distinctly effective in the response reduction of the building frame; ii) position of tendons has significant effect on the control of response. The semi-active tendons at alternate floors provide the maximum control of response for all storeys; iii) the Ni-Ti Semi-active tendons are more effective in response reduction than the Ni-Ti Passive dampers.

The new concept of smart passive control of earthquake induced vibrations in building frames based on the dissipation of energy by using shape memory alloy (SMA). The proposed smart passive control scheme originates from a passive control system, based on martensite & austenite co-exist wires. In this version, the system monitors the feedback measurements and accordingly strain is adjusted continuously in the Nitinol wires for safe functioning of dampers of building frame subjected to earthquake. Some of the important conclusions of the study are: i) the smart passive control show the significant reduction of response in term of displacement, velocity & drifts; ii) the SMA based smart passive control system provides the protection for a wide range of earthquakes. Thus the adaptable nature of the smart passive control allows a structure to be protected against to all sizes of earthquake ground motions.

Base isolation strategy provides a very effective passive method of protecting buildings against earthquakes. The proposed smart base isolation system is composed of laminated rubber bearings and shape memory alloy (SMA) dampers. The smart base isolation utilizes the potential of the SMA dampers to control the responses of the base isolated building frames subjected to various ground motions. Three cases for isolation system are considered, base isolation alone, isolation with passive mode of SMA and Semi-active mode of SMA. Some of the important conclusions of the study are: i) the

semi-active SMA damper system provides the superior protection; ii) the adaptable nature of the semi-active SMA damper system allows a structure to be protected against extreme earthquakes, without sacrificing performance during mild & moderate earthquakes.

The proposed hybrid control system consists of Active mass damper and passive damper in the form of Shape memory alloy wire damper. Passive SMA Dampers are installed in the lower storey and the AMD is placed on the top of the building frame. The control algorithm is developed by considering structure AMD together. The effectiveness of the following control schemes is compared: i) only AMD, ii) only SMA dampers and iii) AMD and SMA dampers. Some of the important conclusions of the study are: i) hybrid control technique is more efficient than active control in that the smaller actuator is required; ii) it is adaptable in nature to change in ground motion; iii) the SMA based hybrid control system possesses the same response reduction capacity as SMA passive control, but it requires smaller control force than a passive control system for mild and moderate earthquakes.

In the frequency domain approach, the transient response performance is specified in terms of the phase margin, gain margin and resonant peak amplitude. In this study the one of the frequency domain approach, bode plot is used. The advantage of frequency response analysis is that the stability of a closed loop system can be determined from the frequency response of an open loop system. The performance of the control methods is investigated for a single story building frame and an eight story building frame connected with shape memory devices. Some of the important conclusions of the study are : i) the transfer function is stable and bode plots support the low response at higher frequency input and the peak of transfer function is observed at the natural frequency of the structure; ii) the H_2 control performed a better response at a smaller control force.

Contents

	Page No.
CERTIFICATE	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iv
CONTENTS	viii
LIST OF FIGURES	xiv
LIST OF TABLES	xxii
CHAPTER 1: INTRODUCTION	1-10
1.1 GENERAL	1
1.2 NEED FOR THE PRESENT STUDY	6
1.3 SCOPE AND OBJECTIVES OF THE STUDY	7
1.4 ORGANIZATION OF THE THESIS	8
CHAPTER 2: LITERATURE REVIEW	11-37
2.1 INTRODUCTION	11
2.2 STRUCTURAL CONTROL DEVICES	13
2.3 STATE-OF-THE-ART ON STRUCTURAL CONTROL	17
2.3.1 Passive Control	20
2.3.2 Active Control	21
2.3.3 Semi-active Control	24
2.3.4 Hybrid Control	29
2.3.5 Shape Memory Alloy Devices	33

2.4 CONCLUDING REMARKS	36
CHAPTER 3: SHAPE MEMORY ALLOY AND ITS MODELS	39-54
3.1 INTRODUCTION	39
3.2 SHAPE MEMORY EFFECT	39
3.3 Ni-Ti SMA SHAPE MEMORY ALLOY BEHAVIOR	41
3.4 PROPERTIES OF Ni-Ti SHAPE MEMORY ALLOY	44
3.5 HYSTERITIC MODEL	45
3.6 CYCLIC RESPONSE OF Ni-Ti SMA	48
3.7 CONCLUDING REMARKS	53
CHAPTER 4: SEMI-ACTIVE CONTROL OF BUILDING FRAMES	55-90
USING SMART CABLES OF SHAPE MEMORY	
ALLOYS	
4.1 INTRODUCTION	55
4.2 PROPERTIES OF NITINOL SHAPE MEMORY ALLOY	57
4.2.1 STRESS-STRAIN TEMPERATURE CURVE OF Ni-Ti	57
SMA	
4.2.2 HYSTERETIC MODELING OF Ni-Ti SMA	58
4.2.3 TIME DELAY COMPENSATION	59
4.2.4 TEMPERATURE DEPENDENCY OF CONSTITUTIVE LAW	60
4.2.5 TYPICAL MATERIAL PROPERTIES OF Ni-Ti SMA	61
4.3 SEMI-ACTIVE CONTROL OF BUILDING FRAMES	65
4.3.1 DESIGN CONSIDERATIONS FOR SEMI-ACTIVE TENDONS	65
4.3.2 CONTROL ALGORITHM	66

4.4 PRACTICAL IMPLEMENTATION ISSUES AND HARDWARE REQUIREMENTS FOR PROPOSED STRUCTURAL CONTROL TECHNOLOGY USING SHAPEMEMORY ALLOYS	69
4.5 CASE STUDIES FOR NUMERICAL SIMULATION OF SMA BASED SEMI-ACTIVE CONTROL	71
4.6 RESULTS OF SIMULATED CASE STUDIES	74
4.7 CONCLUSIONS	89
CHAPTER 5: SMART PASSIVE CONTROL OF CONCRETE BUILDING FRAMES USING SHAPE MEMORY ALLOY DAMPERS	91-109
5.1 INTRODUCTION	91
5.2 THEORETICAL DEVELOPMENT OF SMART PASSIVE CONTROL SCHEME	92
5.2.1 SMART PASSIVE SMA WIRE DAMPER	93
5.2.2 CONTROL SCHEME	94
5.3 SMART PASSIVE CONTROL OF BUILDING FRAME	96
5.4 EARTHQUAKE GROUND MOTIONS	96
5.5 RESPONSE ANALYSIS	97
5.6 RESULTS OF RESPONSE ANALYSIS	100
5.7 CONCLUSIONS	108
CHAPTER 6: SMART BASE ISOLATION SYSTEM OF BUILDING FRAMES USING SHAPE MEMORY ALLOY DAMPER	111-133

6.1 INTRODUCTION	111
6.2 THEORETICAL DEVELOPMENT OF PASSIVE CONTROL SCHEME	113
6.2.1 CONTROL ALGORITHM	113
6.2.2 PASSIVE SHAPE MEMORY ALLOY DAMPER	114
6.2.3 WORKING OF PASSIVE SHAPE MEMORY ALLOY DAMPER	115
6.2.4 SIMULINK MODEL FOR PASSIVE CONTROL	115
6.3 THEORETICAL DEVELOPMENT OF SEMI-ACTIVE CONTROL SCHEME	116
6.3.1 CONTROL ALGORITHM	116
6.3.2 SEMI-ACTIVE SHAPE MEMORY ALLOY DAMPER	117
6.3.3 WORKING OF SEMI-ACTIVE SHAPE MEMORY ALLOY DAMPER	118
6.3.4 SIMULINK MODEL FOR SEMI-ACTIVE CONTROL	118
6.4 EARTHQUAKE GROUND MOTION	119
6.5 RESPONSE ANALYSIS	119
6.6 RESULTS AND DISCUSSIONS	122
6.7 CONCLUSIONS	132
CHAPTER 7: HYBRID CONTROL SYSTEM OF BUILDING FRAMES USING SHAPE MEMORY ALLOY DAMPERS	135-160
7.1 INTRODUCTION	135
7.2 THEORETICAL DEVELOPMENT OF HYBRID CONTROL	139

7.2.1 CONTROL ALGORITHM	139
7.2.2 CONTROL STRATEGY	140
7.3 DESCRIPTION OF CONTROL FORCE DEVICES	141
7.4 NUMERICAL SIMULATION OF HYBRID SYSTEM	142
7.5 RESULTS AND DISCUSSIONS	143
7.6 CONCLUSIONS	159
 CHAPTER 8: FREQUENCY DOMAIN ANALYSIS OF CONTROL SYSTEMS	 161-186
8.1 INTRODUCTION	161
8.2 H_2 CONTROL	162
8.3 CONTROL STRATEGY	163
8.4 PROBLEM FORMULATION	165
8.5 STRUCTURAL PROPERTIES OF BUILDINGS	166
8.6 RESPONSE ANALYSIS OF BUILDING FRAMES	167
8.6.1 NUMERICAL SIMULATION USING LINEAR QUADRATIC REGULATOR	167
8.6.2 NUMERICAL SIMULATION USING H_2 OPTIMAL CONTROL	171
8.7 RESULTS	174
8.8 CONCLUSIONS	186
 CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK	 187-191
9.1 CONCLUSIONS	187

9.2 RECOMMENDATIONS FOR FUTURE WORK	191
APPENDIX A	193
APPENDIX B	201
APPENDIX C	211
APPENDIX D	217
APPENDIX E	229
APPENDIX F	233
APPENDIX G	237
REFERENCES	255
BIODATA	273

List of Figures

Figure No.	Title	Page No
Fig.3.1	Shape memory effect	42
Fig.3.2	Stress-Strain curve of a Shape Memory Alloy	42
Fig.3.3	Hysteresis Loops in Shape Memory Alloys	43
Fig.3.4	Stress – Strain – Temperature curve of Nitinol (Ni - Ti)	44
Fig.3.5	Hysteresis behavior of Nitinol (Ni-Ti) SMA	48
Fig.3.6	Superelastic behavior of Nitinol (Ni-Ti) SMA	49
Fig.3.7	Stress-Strain relation of the extended hysteretic model of Ni-Ti SMA	51
Fig.3.8	Superelastic behavior of Ni-Ti SMA up to $\epsilon_m = 0.08$ in martensite	52
Fig.3.9	Force- Displacement Curve of a SMA Wire	52
Fig.3.10	Force- Displacement Curve of a SMA Wire (Superelastic)	53
Fig.4.1	Stress-Strain behavior of Ni-Ti SMA wire a) 8% strain cycle, b) 4% strain cycle, and c) 2% strain cycle	62
Fig.4.2	Force- Displacement behavior of Ni-Ti SMA wire (a) 8% strain cycle, (b) 4% strain cycle, and (c) 2% strain cycle	63
Fig.4.3	Schematic diagram of idealized Structural control system for a single story frame using Semi-active Tendons constituted of Nitinol sma wires	64
Fig.4.4	Free body diagram of the idealized structural control system	64
Fig.4.5	Configuration of digital control of tendons	70
Fig.4.6	El Centro Earthquake Ground motion	72
Fig.4.7	Flow Chart using Block Diagram Approach for simulation of Structural Control System	73

Fig.4.8	Eight Story Building frame model with semi-active tendons composed of Nitinol based SMA	75
Fig.4.9	Time History of Displacement	77
Fig.4.10	Number of wires actuated to induce the computed control force	77
Fig.4.11	Time histories of control forces computed for actuation in the Semi-active tendons at alternate floors 1,3,5 and 7	78
Fig.4.12	Number of wires actuated to induce the computed control force at alternate floors 1,3,5, and 7	79
Fig.4.13	Time histories of displacements at eighth floor of the frame model with various control schemes	79
Fig.4.14	San Ferandado Ground motion	80
Fig.4.15	Kobe ground motion	80
Fig.4.16	Northridge ground motion	81
Fig.4.17	Displacement –Time history under El Centro ground motion at First Floor	81
Fig.4.18	Displacement –Time history under El Centro ground motion at Eighth Floor	82
Fig.4.19	Displacement –Time history under Kobe ground motion at First Floor	82
Fig.4.20	Displacement –Time history under Kobe ground motion at Eighth Floor	83
Fig.4.21	Displacement –Time history under Northridge ground motion at First Floor	83
Fig.4.22	Displacement –Time history under Northridge ground motion at Eighth Floor	84
Fig.4.23	Displacement –Time history under San Fernandos ground motion at First Floor	84
Fig.4.24	Displacement –Time history under San Fernandos ground motion at Eighth Floor	85
Fig.4.25	Displacement time history of Semi-active vs. Passive control under El-Centro ground motion at First Floor	85

Fig.4.26	Displacement time history of Semi-active vs. Passive control under El-Centro ground motion at Eighth Floor	86
Fig.4.27	Displacement time history of Semi-active vs. Passive control under Kobe ground motion at First Floor	86
Fig.4.28	Displacement time history of Semi-active vs. Passive control under Kobe ground motion at Eighth Floor	87
Fig.4.29	Displacement time history of Semi-active vs. Passive control under Northridge ground motion at First Floor	87
Fig.4.30	Displacement time history of Semi-active vs. Passive control under Northridge ground motion at Eighth Floor	88
Fig.4.31	Displacement time history of Semi-active vs. Passive control under San Fernandos ground motion at First Floor	88
Fig.4.32	Displacement time history of Semi-active vs. Passive control under San Fernandos ground motion at Eighth Floor	89
Fig.5.1	Functional scheme of the passive and the smart passive systems	95
Fig.5.2	Single Story building frame equipped with SMAWD	95
Fig.5.3	Eight story building frame equipped with SMAWD	97
Fig.5.4	Schematic diagram of smart passive control of building frame	99
Fig.5.5	Displacement time history of single story building frame	100
Fig.5.6	Control force time history of single story building frame	101
Fig.5.7	Displacement time history at eighth floor	102
Fig.5.8	Velocity time history at eighth floor	103
Fig.5.9	Control force time history of eight story building frame	103
Fig.5.10	Displacement –Time history under El Centro ground motion at First Floor	104
Fig.5.11	Displacement –Time history under El Centro ground motion at Eighth Floor	105
Fig.5.12	Displacement –Time history under Kobe ground motion at First Floor	105

Fig.5.13	Displacement –Time history under Kobe ground motion at Eighth Floor	106
Fig.5.14	Displacement –Time history under Northridge ground motion at First Floor	106
Fig.5.15	Displacement –Time history under Northridge ground motion at Eighth Floor	107
Fig.5.16	Displacement –Time history under San Fernandos ground motion at First Floor	107
Fig.5.17	Displacement –Time history under San Fernandos ground motion at Eighth Floor	108
Fig.6.1	Flow Chart using Block Diagram Approach for passive base isolation	116
Fig.6.2	Flow chart using Block Diagram Approach for semi active base isolation	119
Fig.6.3	Two degrees of freedom model	121
Fig.6.4	Six degrees of freedom model	121
Fig.6.5	Displacement time history of SDOF	124
Fig.6.6	Control force time history of SDOF	125
Fig.6.7	Control force in base isolation with Passive SMA	128
Fig.6.8	Control force in base isolation with semi-active SMA	129
Fig.6.9	Comparison of displacement time history at top floor	129
Fig.6.10	Acceleration time history at the base level in various base isolation schemes	130
Fig.6.11	Comparison of Displacements at base isolation under El Centro	130
Fig.6.12	Comparison of Displacements at base isolation under Kobe	131
Fig.6.13	Comparison of Displacements at base isolation under Northridge	131
Fig.6.14	Comparison of Displacements at base isolation under San Fernandos	132
Fig.7.1	Hybrid Control building model of AMD and SMAWD	147

Fig.7.2	Schematic diagram of hybrid control	147
Fig.7.3	Control force time history applied by AMD	148
Fig.7.4	Control force on alternate floor applied by SMAWD	148
Fig.7.5	Displacement time history in hybrid control at top floor	149
Fig.7.6	Velocity time history in hybrid system at top floor	149
Fig.7.7	Acceleration time history in hybrid system at top floor	150
Fig.7.8	Comparison of maximum displacements of various control system	150
Fig.7.9	Displacement –Time history under El Centro ground motion at First Floor	151
Fig.7.10	Displacement –Time history under El Centro ground motion at Eighth Floor	151
Fig.7.11	Displacement –Time history under Kobe ground motion at First Floor	152
Fig.7.12	Displacement –Time history under Kobe ground motion at Eighth Floor	152
Fig.7.13	Displacement –Time history under Northridge ground motion at First Floor	153
Fig.7.14	Displacement –Time history under Northridge ground motion at Eighth Floor	153
Fig.7.15	Displacement –Time history under San Fernandos ground motion at First Floor	154
Fig.7.16	Displacement –Time history under San Fernandos ground motion at Eighth Floor	154
Fig.7.17	Comparison of Hybrid control and Passive control under El Centro at First Floor	155
Fig.7.18	Comparison of Hybrid control and Passive control under El Centro at Eighth Floor	155
Fig.7.19	Comparison of Hybrid control and Passive control under Kobe at First Floor	156

Fig.7.20	Comparison of Hybrid control and Passive control under Kobe at Eighth Floor	156
Fig.7.21	Comparison of Hybrid control and Passive control under Northridge at First Floor	157
Fig.7.22	Comparison of Hybrid control and Passive control under Northridge at Eighth Floor	157
Fig.7.23	Comparison of Hybrid control and Passive control under San Fernando at First Floor	158
Fig.7.24	Comparison of Hybrid control and Passive control under San Fernando at Eighth Floor	158
Fig.8.1	Basic structure control diagram	165
Fig.8.2	Transfer function of single story (uncontrolled)	168
Fig.8.3	Transfer function of single story (LQR controlled)	168
Fig.8.4	Transfer function of top story and controller at alternate floor	169
Fig.8.5	Transfer function of top story with ADM at top floor	170
Fig.8.6	Transfer function of single story in H_2 optimal (controlled)	170
Fig.8.7	Bode plot of tf of controller with Semi-active tendons at alternate floors	172
Fig.8.8	Bode plot of tf of all floors with Semi-active tendons at alternate floors	172
Fig.8.9	Bode plot of tf of controller with AMD at top	173
Fig.8.10	Bode plot of tf of all floors with AMD at top floor	173
Fig.8.11	Response of single story frame in LQR	175
Fig.8.12	Displacement time history of single story	175
Fig.8.13	Time history of control force	176
Fig.8.14	Response reduction of Top floor with Semi-active tendons	176
Fig.8.15	Displacement Time history under El-Centro at First Floor (H2 Control)	177
Fig.8.16	Displacement Time history under El-Centro at Eighth Floor (H2 Control)	177

Fig.8.17	Displacement Time history under Kobe at First Floor (H2 Control)	178
Fig.8.18	Displacement Time history under Kobe at Eighth Floor (H2 Control)	178
Fig.8.19	Displacement Time history under Northridge at First Floor (H2 Control)	179
Fig.8.20	Displacement Time history under Northridge at Eighth Floor (H2 Control)	179
Fig.8.21	Displacement Time history under San Fernandos at First Floor (H2 Control)	180
Fig.8.22	Displacement Time history under San Fernandos at Eighth Floor (H2 Control)	180
Fig.8.23	Comparison of displacement of LQR control and H2 control under El Centro at First Floor	181
Fig.8.24	Comparison of displacement of LQR control and H2 control under El Centro at Eighth Floor	181
Fig.8.25	Comparison of displacement of LQR control and H2 control under Kobe at First Floor	182
Fig.8.26	Comparison of displacement of LQR control and H2 control under Kobe at Eighth Floor	182
Fig.8.27	Comparison of displacement of LQR control and H2 control under Northridge at First Floor	183
Fig.8.28	Comparison of displacement of LQR control and H2 control under Northridge at Eighth Floor	183
Fig.8.29	Comparison of displacement of LQR control and H2 control under San Fernandos at First Floor	184
Fig.8.30	Comparison of displacement of LQR control and H2 control under San Fernandos at Eighth Floor	184
Fig.B.1	Maximum actuating force for the wires by electric heating	201
Fig.B.2	Maximum actuating force vs Current flow in the wires	201
Fig.B.3	Diameter vs. Current needed in the wires to produced maximum force	202

Fig.B.4	Experimental Setup for getting the maximum pulls forces	203
Fig.B.5	Plot of Nitinol Data	205
Fig.B.6	Simulink model of Single Story Building Frame connected with the SMA Semi-active tendon	206
Fig.B.7	Simulink model of Eight Story Building Frame connected with the SMA Semi-active tendons	209
Fig.C.1	Simulink model of Single Story Building Frame connected with the SMA damper	212
Fig.C.2	Simulink model of Eight Story Building Frame connected with the SMA dampers	215
Fig.D.1	Simulink model of smart base isolation of single story building frame using passive SMA damper	219
Fig.D.2	Simulink model of smart base isolation of single story building frame using semi-active SMA damper	222
Fig.D.3	Simulink model of smart base isolation of five story building frame using passive SMA damper	225
Fig.D.4	Simulink model of smart base isolation of five story building frame using semi-active SMA damper	228
Fig.E.1	Simulink model for hybrid system	232
Fig.F.1	Closed Loop System of H_2 control	236
Fig.G.1	Block Diagram of LQR of Single Degree of Freedom	249
Fig.G.2	Block Diagram of H_2 control of single story building frame	251
Fig.G.3	Block Diagram of H_2 control of SMA tendons at alternate floors	254

List of Tables

Table. No.	Title	Page No.
Table 3.1	Mechanical Properties of Nitinol	45
Table 4.1	Properties and parameters of Modified Wilde model	61
Table 4.2	Response reduction in single story frame model controlled with semi-active tendons composed of Nitinol SMA wires	76
Table 4.3	Comparison of dynamic response and control force parameters for the eight story frame model [Soong] with SMA based semi-active tendons	78
Table 5.1	Description Scaled Ground motion	96
Table 5.2	Peak response of Single Story Building Frame using SMA Smart passive Control and SMA Passive control	101
Table 5.3	Response of Eight Story Building Frame in smart passive control	102
Table 5.4	Peak response at top floor in Smart SMA Passive Control and SMA Passive control	104
Table 6.1	Structural Model Parameters of five degree of freedom	121
Table 6.2	Response of Single Story Building Frame (Mass level)	123
Table 6.3	Drift, Absolute accelerations and Shear at base of Single Story Building frame	124
Table 6.4	Response without control force	126
Table 6.5	Comparison of Responses under passive control and semi-active control SMA devices	127
Table 6.6	Response of Five Story Building Frame	127
Table 6.7	Drift, Absolute accelerations and Shear at base for Five Story Building frame	128
Table 7.1	System properties of eight story building frame	143
Table 7.2	Comparison of responses in various control strategies for 1.0× El Centro ground motion	145

Table 7.3	Peak response at top floor in SMA active control and SMA passive control	145
Table 7.4	Peak response at top floor in hybrid control	146
Table 7.5	Percentage response reduction & required control force for various control system	146
Table 8.1	Comparison of various Control strategies in single story frame	174
Table 8.2	Displacement and Control Force for Earthquake Excitation with H2 Control	185
Table 8.3	Comparison of various Control strategies in eight story building frame	185
Table B.1	Maximum pull force for various sizes of Wires	204
Table B.2	Data for Nine Types of Nitinol Wire	204