UNIVERSITI PUTRA MALAYSIA

RUBBER WALL DAMPER ELEMENT FOR REINFORCED CONCRETE AND STEEL FRAME BUILDING STRUCTURES

MOHD AZMI BIN MOHD ZAIN

FK 2017 33

RUBBER WALL DAMPER ELEMENT FOR REINFORCED CONCRETE AND STEEL FRAME BUILDING STRUCTURES

By

MOHD AZMI BIN MOHD ZAIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

January 2017

DEDICATION

Every challenging work needs self efforts as well as guidance of those who are very close to our heart. My humble effort, I dedicate to my departed and lovely father and mother, who past affection, pray of day and night make me able to get such success and honour. Alongside me is my dearest wife, who leads me through the valley of darkness with light of hope and support to see the fruit of this labour. Thank you.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

RUBBER WALL DAMPER ELEMENT FOR REINFORCED CONCRETE AND STEEL FRAME BUILDING STRUCTURES

By

MOHD AZMI BIN MOHD ZAIN

January 2017

Chairman : Farzad Hejazi, PhD
Faculty : Engineering

The application of modern control techniques to diminish the effects of dynamic loads on building structures offers an appealing alternative to traditional design approaches. Rubber Wall damper (RWD) is one of the inventive passive energy dissipation device which enhance lateral resistance capacity and damping characteristic of the structures. RWD similar to fluid infill supplemental wall dampers yet is more suited for use in far field earthquake zone and is less expensive, maintenance free and economy. Here, a RWD is fabricated using Malaysian rubber, local steel and reinforced concrete structure, to reduce dynamic load effect and preclude vibration damage of buildings.

Critical review of literature indicates no analytical model available for numerical model of RWD in building structure. Furthermore, the building frames response analysis is realistic, only if nonlinearity due to material behavior is also taken into account. Thus, nonlinear dynamic analysis is a prelude to achieving both accuracy and economy in the structural design. The analytical and constitutive model for RWD are developed for purpose of numerical modeling and finite element simulation and evaluate effect of Damper in seismic response of structures. Various types of concrete framed buildings equipped by proposed device are analyzed and efficiencies of device was assessed. Additionally, through nonlinear dynamic analysis, the possibilities of arresting plastic hinge formations in structural components were investigated. The numerical analysis results showed the maximum horizontal displacement of frames with RWD diminished from 45% range up to 92%. Generally, the maximum story displacements dropped dramatically compared to similar response of the bare frame system.

In steel frame and Reinforced Concrete frames furnished by the RWD device, the maximum failure capacity improved approximately by 256% and 244% respectively. This proved the effectiveness of developed RWD device energy dissipation option in the buildings. Besides the numerical analysis, the prototype damper device has been fabricated and experimental test has been carried out to assess the functionality and performance of the developed adaptive systems with conventional systems. Experimental test results on prototypes steel and reinforced concrete frame subjected to cyclic displacement action, verified the efficiency of the RWD device, whenever implemented in to the bare frame. The ductility behaviour and failure mechanism are enhanced in both frame systems. The results proved performance of moment resistance frame furnished by above devices has been improved noticeable and the damper device is able to increase safety of building against severe earthquakes.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

UNSUR DINDING PEREDAM GETAH BAGI BANGUNAN STRUKTUR KERANGKA KONKRIT BERTETULANG DAN KERANGKA KELULI

Oleh

MOHD AZMI BIN MOHD ZAIN

Januari 2017

Pengerusi : Farzad Hejazi, PhD
Fakulti : Kejuruteraan

Pengunaan teknik moden bagi kawalan mengurangkan kesan beban kenaan dinamik pada struktur bangunan adalah alternatif menarik berbanding kaedah kawalan secara konvensional. Peranti dinding peredam getah adalah peranti peredam tenaga pasif. yang dengan penggunaannya dapat meningkatkan kadar perendam ufuk struktur dan tingkatkan keupayaan rintangan struktur mengufuk. Peranti ini menyerupai peranti dinding peredam bendalir, namun ia lebih murah, ekonomi, bebas senggaraan dan lebih sesuai digunakan di zon lapangan gempa jarak jauh. Peranti dinding ini di rekabentuk mengunakan getah tempatan dan bagus guna dalam struktur keluli dan struktur konkrit bertetulang bagi rembatan kesan kenaan beban dinamik atas struktur itu dan seterusnya mengelakan kerosakan bangunan dari kesan gegaran.

Semakan kritikal menunjukkan ketiadaan model analitikal redaman tersedia untuk sistem paduan dinding peredam getah dalam struktur bangunan. Selain itu, tindak balas anjakan struktur berangka lebih realistik, jika ciri tak lelurus bahan melewati ciri sifat anjalan juga diambil kira. Oleh itu, analisis dinamik tak lelurus adalah metod ujian awalan untuk mencapai ketepatan dan ekonomi dalam rekabentuk struktur. Model konstitutif dinding peredam getah telah dibangunkan untuk tujuan permodelan berangka dan mensimulasi unsur terhingga dan menilai kesan penampan sebagai tindak balas seismik struktur. Pelbagai jenis struktur konkrit bertetulang yang dilengkapi oleh peranti yang dicadangkan telah dianalisis dan kecekapan peranti telah dinilai. Di samping itu, melalui analisis dinamik tak lelurus, kemungkinan memangkas pembentukan ensel plastik dalam komponen struktur telah disiasat. Angka analisis keputusan menunjukkan anjakan mendatar kerangka dengan dinding peredam getah berkurangan daripada 45% sehingga 92%. Secara umumnya, terdapat penurunan mendadak ensel berbanding kerangka tidak dipasang Peranti dinding peredam getah.

Bagi bangunan kerangka keluli dan konkrit bertetulang yang dibekalkan oleh peranti dinding peredam getah, kapasiti kegagalan telah meningkat kira-kira sebanyak 256% dan 244%. Ini membuktikan keberkesanan peranti dinding peredam getah bagi dissipasi tenaga dalam bangunan. Selain analisis berangka, prototaip dinding peredam getah telah direka dan ujian eksperimen telah dijalankan untuk menilai fungsi dan prestasi sistem peredam getah berbanding sistem konvensional. Keputusan eksperimen ujian pada prototaip rangka keluli dan konkrit bertetulang tertakluk kepada anjakan kitaran, mengesahkan kecekapan peranti dinding peredam getah, apabila dilaksanakan pada kerangka bangunan. Sifat kemuluran dan mekanisme kegagalan di sistem rangka bangunan dipertingkatkan. Keputusan membuktikan prestasi bangunan kerangka yang dibekalkan peranti telah bertambah dengan ketara dan peranti Peranti dinding peredam getah mampu meningkatkan keselamatan bangunan terhadap gempa bumi yang kuat.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Dr. Farzad Hejazi for his excellent guidance, caring, patience, and providing me with an excellent atmosphere for doing research. Besides my advisor, I would like to thank the rest of my thesis supervisory committee: Prof. Dato' Dr. Ir. Mohd Saleh Jaafar, Dr. Farah Nora Aznieta binti Abd Aziz for their insightful comments and encouragement, but also for the hard question which incensed me to widen my research from various perspectives.

My sincere thank also goes to Mr. Mohammad Haffis Hamid and Mr. Muhammad Mustaqim Mohd Dali who gave access to the structural Laboratory and research Facilities, without their precious support, it would not be possible to perform this research.

I thank my fellow lab mates in for the stimulating discussions, for the sleepless nights, we were working together before deadlines, and for all the fun we have had in the last seven years.

I would like to thank my wife, Hasnah Binti Ibrahim. She was always there cheering me up and stood by me through the good times and bad. Last but not the least; I would like to thank my family, my parents and my elder sisters for supporting me spiritually throughout writing this thesis and my life in general.

I certify that a Thesis Examination Committee has met on 16 January 2017 to conduct the final examination of Mohd Azmi bin Mohd Zain on his thesis entitled "Rubber Wall Damper Element for Reinforced Concrete and Steel Frame Building Structures" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Biswajeet Pradhan, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Faizal bin Mustapha, PhD
Associate Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Muhd Fadhil bin Nuruddin, PhD
Professor Ir.
Universiti Teknologi Petronas
Malaysia
(External Examiner)

M. Shahria Alam, PhD, PEng.
Associate Professor
University of British Columbia
Canada
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 2 June 2017

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Farzad Hejazi, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Dato' Mohd Saleh Jaafar, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Farah Nora Aznieta binti Abd Aziz, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS , PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ________________________________ Date:_________________

Name and Matric No.: Mohd Azmi Bin Mohd Zain , GS27060

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ____________________
Name of Chairman of Supervisory Committee: Dr. Farzad Hejazi

Signature: ____________________
Name of Member of Supervisory Committee: Professor Dato'Dr. Mohd Saleh Jaafar

Signature: ____________________
Name of Member of Supervisory Committee: Dr. Farah Nora Aznieta binti Abd Aziz

TABLE OF CONTENTS

		Page
ABSTRACT		i
ABSTRAK		iii
ACKNOWLEDGEMENTS		v
APPROVAL		vi
DECLARATION		viii
LIST OF TABLES		xiii
LIST OF FIGURES		xiv
LIST OF ABBREVIATIONS		xxii
CHAPTER		
1	**INTRODUCTION**	1
	1.1 General	1
	1.2 Research hypothesis	3
	1.3 Brief description of present work	4
	1.4 Motivation for the current study	5
	1.5 Statement of problem	7
	1.6 Objectives of study	8
	1.7 Scope and limitation of work scope	9
	1.8 Proposed layout of the thesis	9
2	**LITERATURE REVIEW**	10
	2.1 Introduction	10
	2.2 Earthquake energy dissipation system	10
	2.3 Rubber in damper as the energy dissipation medium	21
	2.3.1 Rubber bearings for building isolation	22
	2.3.2 Viscoelastic Solid Dampers	26
	2.3.3 Hybrid Passive Control Devices	32
	2.3.4 Wall type damper	34
	2.3.5 Classic damping models	37
	2.3.6 Geometrical modelling- Constrained Layer Beams Modelling	40
	2.3.7 Novel issue rubber wall damper contribution to structural Engineering	41
	2.4 Development of analytical model for Rubber Wall Damper(RWD)	42
	2.5 Summary	47
3	**METHODOLOGY AND MATERIALS**	48
	3.1 Introduction	48
	3.2 Development of New Rubber Wall Damper	51
	3.2.1 Configuration and development of New Rubber Wall Damper concept	51
	3.2.2 A mechanism of the RWD device energy dissipation	61

	3.2.3 Assessment of frame response equipped with rubber wall damper	64
3.3	Development of analytical model for Rubber Wall Damper	64
	3.3.1 Finite Element Model for RC frame with Rubber Wall Damper	69
3.4	Development of finite element program	72
3.5	Numerical analysis of RC frame using developed ARCS3D program	74
	3.5.1 General	74
	3.5.2 Typical section for frame	74
	3.5.3 The exciting force - earthquake (El-Centro earthquake)	75
	3.5.4 Method of analysis for RC frames	77
	3.5.5 Frame type and names	80
	3.5.6 Geometric properties of frames	84
	3.5.7 Procedure numerical analysis and evaluation process	85
3.6	Experimental test for RWD prototype	87
	3.6.1 Experimental test for portal steel frame	87
	3.6.2 Portal steel frame assembly and test set up procedure	87
3.7	Modeling Reinforced Concrete frame building	94
	3.7.1 Experimental design of reinforcement concrete frame	94
	3.7.2 Reinforced Concrete frame specimens	95
	3.7.3 Material properties of RC specimens	99
3.8	Monotonic displacement history in cyclic test	102
3.9	Summary	104
4	**EXPERIMENTAL TEST AND NUMERICAL STUDY OF MOMENT RESISTING FRAME EQUIPPED WITH RUBBER WALL DAMPER SYSTEM**	105
4.1	Introduction	105
4.2	Experimental testing	105
	4.2.1 Steel Frame subjected to cyclic load	105
	4.2.2 Failure mechanism in frame via visual inspection	106
	4.2.3 Analysis of Hysteresis results	109
	4.2.4 Comparison of the skeleton graph and hysteresis graph	114
	4.2.5 Records of strain gauges in dynamic test on steel frame	118
4.3	Experimental test for Reinforced Concrete (RC) frames	121
	4.3.1 Introduction	121
	4.3.2 Reinforced Concrete Frame subjected to cyclic load	122
	4.3.3 Failure mechanism of Reinforced Concrete frame	124
	4.3.4 Comparison of experimental results between Steel frame and Reinforced Concrete frame	130
4.4	Explore capabilities of the developed Numerical system in analysis of Frame equipped with rubber wall damper	131

		4.4.1 Introduction	131
		4.4.2 Pushover analysis to verify the developed computational model	132
		4.4.3 Verification of linear static analysis for developed software (ARCS3D)	137
	4.5	Time history analysis for assessing the response of frame structure equipped with rubber wall damper	140
		4.5.1 Planar analysis of Reinforced Concrete Frame Structure	140
		4.5.2 Single storey –one bay and a Time History analysis	140
		4.5.3 Three (3) storey – Single bay, time history analysis	144
		4.5.4 Five storey – single bay, time history analysis	150
		4.5.5 Coupled units comprises of 2 sets, three storey by two bays frame and a tower eight storey single bay analyses by time history analysis	157
		4.5.6 Coupled twin tower comprises of 2 sets, ten storey by one bays RC frame analyses by time history analysis	165
	4.6	Three Dimensional analysis of Time history analysis for assessing the response of frame structure equipped with rubber wall damper	169
		4.6.1 Five storey, one by one bay, time history analysis	169
		4.6.2 Eight storey, one by one bay, time history analysis	174
		4.6.3 Eight storey, two by two bay, time history analysis	178
		4.6.4 Three storey, three by two bay, time history analysis	182
	4.7	Summary	196
5	**CONCLUSION AND RECOMENDATION**		198
	5.1	General Conclusion	198
	5.2	Specific Conclusion	199
	5.3	Discussion of results	201
	5.4	Recommendations for future study	201
REFERENCES			203
APPENDICES			214
PATENT AND AWARD			273
BIODATA OF STUDENT			277
LIST OF PUBLICATIONS			278

LIST OF TABLES

Table		Page
3.1	Name for bare Frame System	81
3.2	Name of Frame type equipped with Rubber wall damper devices:	82
3.3	Show 86 numerical frame models were prepared for analyses.	84
3.4	RC frame geometric properties	85
3.5	Reinforced Concrete Portal detail	99
3.6	Concrete mix design (per meter cube)	101
4.1	Fitted line equation for all the skeleton graph for the various frames	116
4.2	Outcome comparison among Bare frame, Cross Braced frame and Frame equipped with RWD	118
4.3	Outcome (Area under the graph of force versus displacement) comparison between Bare RC frame and RC frame equipped with RWD	129
4.4	t-Test: Two-Sample Assuming Equal Variances	137
4.5	Top story nodes displacements and rotations in 3 directions (ARCS3D) for the frame.	138
4.6	Top story nodes displacements and rotations in 3 directions (ARCS3D) for the frame	139
4.7	Hinges formed and deformed for system under El Centro excitation	140
4.8	The results of inelastic analysis	186

LIST OF FIGURES

Figure		Page
2.1	Structural Control System *(Kurata et al. (2002))*	12
2.2	The sample force-displacement loops of hysteretic dampers and Velocity dependent damper system	13
2.3	Acceleration response spectrum	22
2.4	Laminated Elastomeric Bearing Pads	23
2.5	Schematic of Cloister Façade	24
2.6	Typical Stress-Strain relationship for HDPR	25
2.7	Typical Configurations for VE Devices	27
2.8	Force versus displacement in viscoelastic solid device	27
2.9	Viscoelastic Damper in Reinforced Concrete Frame	29
2.10	Beam-Column Connection with viscoelastic Dampers	30
2.11	Damping-Enhanced Strengthening System	31
2.12	Cylinder Type High Damping Rubber Damper	31
2.13	Combination TPEA & VE Device	32
2.14	Typical Visco-Plastic Devices	33
2.15	Typical Visco-Hyperelastic Device (VHD)	33
2.16	Viscous damping wall	35
2.17	Pure viscous behavior	36
2.18	Maxwell Element	37
2.19	Kelvin-Voigt Element	37
2.20	Generalized Maxwell Model	38
2.21	Kelvin Chain	38
2.22	The Biot Model	38

2.23	Constitutive law for rubber	42
2.24	Schematic view of RWD position in the frame bay	44
2.25	Three dimensional rubber wall damper	45
2.26	Schematic illustration of associated degrees of freedom	46
3.1	Overall schematic view of the methodology of the study	49
3.2	Detail of Rubber Wall Dampers	52
3.3	Casing without interior steel plate and plan view of Casing with interior steel plate	53
3.4	Elevation of damper fitted to portal frame	54
3.5	Detail of base plate	55
3.6	Detail of Near and Far face plate	56
3.7	Detail of Top hung T and connection to inner steel plate	57
3.8	Elevation of inner plate	58
3.9	Elevation of top hung T and summary of material used for wall damper	59
3.10	When floor drift is to right direction , the inner steel plate moves right.	62
3.11	When floor drift goes astern, drag the inner steel plate leftward	63
3.12	Modeling of beam-column section of RC building by frame element	70
3.13	Damper element for modeling of rubber wall damper system	71
3.14	Process of analysis in ARCS3	73
3.15	The beam section and details	75
3.16	The column section and details	75
3.17	Acceleration of El-centro in Up-Down Direction	76
3.18	Acceleration of Elcentro in North-South Direction	76
3.19	Acceleration of Elcentro in East-West Direction	77

3.20	Geometry of RCframe used in Time History Analysis	80
3.21	Numerical Analysis on Prototype RC frame (Bare/RWD) with ARCS3D	86
3.22	Steel frame configuration	88
3.23	Steel Frame -without and with rubber wall damper (RWD)	90
3.24	Location of strain gauges at main steel frame	93
3.25	Schematic view of test set up for RC model	93
3.26	Monotonic displacement history for RC model	94
3.27	RC bare frame (RC 1) for cyclic displacement test	95
3.28	RC frame equipped by VSB device (RC 2) for cyclic displacement test	96
3.29	Joint details and section details	97
3.30	Layout of bars in RC bare frame	98
3.31	Concrete cube test under compression test machine	100
3.32	3D perspective of out of plane fixator column	102
3.33	Location of strain gauges on steel rebar in RC model	103
3.34	Location of strain gauges on concrete surface in RC model	103
4.1	Experimental arrangement of frames under cyclic dynamic test	106
4.2	Deformed state –after test for steel bare frame	107
4.3	Deformed state –after test for steel braced frame	108
4.4	Steel frame equipped with rubber wall damper before and after cyclic load test.	109
4.5	Force displacement relation (Hysteresis graph) and skeleton form graph for steel bare frame	110
4.6	Force displacement relation (Hysteresis graph) and skeleton form graph for steel cross braced frame	112

4.7 Force displacement relation (Hysteresis graph) and skeleton form graph for steel frame equipped with rubber wall damper device 113

4.8 Comparison skeleton curves of frame with and without RWD and braced frame. 115

4.9 Comparison skeleton curves of bare frame, braced frame, frame with RWD 115

4.10 Comparison of force displacement graph among bare, X-brace and frame with RWD. 117

4.11 Comparison of peak strain among the test frames; Bare frame, Cross braced frame and frame equipped with RWD 119

4.12 Comparison of peak strain between the test frames; (a) Bare frame and frame equipped with RWD ,(b) Bare frame and cross braced frame 120

4.13 Assembly of the sets of Reinforced Concrete Bare frame and RC frame equipped with RWD in cyclic movement 122

4.14 Crack line on RC Bare Frame after it underwent cyclic movement test 123

4.15 The Crack line of RC frame with RWD device under cyclic movement. 123

4.16 The force-displacement relation and skeleton curve of RC bare frame 125

4.17 Force displacement relation and skeleton graph of RC frame fitted by RWD device 127

4.18 A comparison of skeleton curve of bare RC frame and RC frame with RWD device 129

4.19 A comparison between energy dissipation per cyclic movement between bare RC frame and RC frame with RWD device 130

4.20 Hysteresis graph and skeleton graph for RC frame equipped with RWD and subjected to cyclic load 133

4.21 The skeleton graph and the trend line function for RC frame equipped with RWD 134

4.22 Numerical method outcome of force displacement for RC frame equipped with RWD and applied with Pushover force 135

4.23	Result compared among analysis by Numerical Method and experimental method for RC frame equipped with RWD	136
4.24	A 3bay by 5story planar RC frame with section details analyses by two numerical method, one using SAP2000 and second using ARCS3D	138
4.25	Output graphic of node 21 analyses using SAP2000	139
4.26	Single storey –one bay RC frame configuration	141
4.27	A typical time history response of single storey frame tip deflection.	142
4.28	A typical time history response of frame top right node deflection	143
4.29	3SSB –one bay RC frame configuration with and without RWD	145
4.30	Horizontal and Vertical displacements for the top node (8)	146
4.31	Response damper devices effectively reduced horizontal displacement	147
4.32	Comparative displacements Horizontal for the top node (8)	148
4.33	Comparative displacements (Vertical) for the top node (8)	148
4.34	The damping coefficient (C) effects on maximum displacements of three storey frame	149
4.35	Frame type 5SSB and the location of hinges on the frame	150
4.36	Position of Rubber Wall Damper devices in five(5) storey, one bay frame	151
4.37	Locations of plastic hinges according to varying type of 5 storey frame equipped with rubber wall damper.	153
4.38	Plastic hinges formed – ARCS3D's analysis output for five storey, single bay and without Damper moment resisting frame structure.	154
4.39	Occurrence of total plastic hinges against damping coefficients	155
4.40	Horizontal displacement of the top node-five storey, single bay frame	155

4.41 Vertical displacement of the top node-five storey, single bay frame 155

4.42 Horizontal and vertical displacement for 5SSB and 5SSB with vary RWD 156

4.43 Coupled units comprises of 2 sets, three storey by two bays RC frame 157

4.44 Displacement response when frame underwent El Centro excitation (Response of node 12 – top, right , 3 storey by 2 bay RC frame) 158

4.45 Tower unit comprises of one, eight storey by one bays RC frame 159

4.46 Displacement response when frame underwent El Centro excitation (Response of node 18 – top, right , 8 storey by 1 bay RC frame) 160

4.47 First tier couples of the building –RWD at podium and hinges location 161

4.48 Response of node 42 – top, right , 8 storey by 1 bay RC frame coupled 2 units 3 storey by 2 bay RC frame) 161

4.49 Second tier couples of the building –RWD at podium and tower 162

4.50 (Response of node 42 – top, right , 8 storey by 1 bay RC frame coupled 2 units 3 storey by 2 bay RC frame) 163

4.51 Comparison of Horizontal displacement and hinges elimination using RWD 165

4.52 Rubber wall Damper is effective to suppress formation of hinges. 166

4.53 Comparison of response for variety type dampers on couple tower 168

4.54 Comparison of response reduction and hinges suppression between frames 169

4.55 Comparison of response in term of hinges and horizontal displacement for variety frame type 171

4.56 Comparison of response in term of horizontal displacement for variety frame type 172

4.57 Comparison of response in term of hinges and peak horizontal displacement for variety frame type 173

4.58 Eight storey bare frame: 8S1X1BRCF and frame response hinges location 174

4.59 Comparison of displacement at top most node under El Centro action 175

4. 60 Comparison of peak displacement under EL Centro action for various type of frame. 175

4.61 Bare frame 8S1X1BRCF and 8S1X1BRCF with RWD location 176

4.62 Comparison of horizontal displacement at top most node under El Centro action 177

4.63 Comparison of displacement and hinges formation at top most node under El Centro act 178

4.64 The eight storey bare frame -8S2X2RCF and fitted location of RWD 179

4.65 Response of the frame types when all beams are loaded case by case 10kN/m, 20kN/m, 30kN/m, 40kN/m and 50kN/m, then excited by El Centro action 180

4.66 Comparison of peak amplitude and hinges for variety frame type 181

4.67 Response of horizontal displacement for the variety frame types 182

4.68 Three storey bare frame -3D2X3SSB 183

4.69 3D, 3 storey, 2 by 3 bay reinforced concrete structure 183

4.70 Hinges reduction and Peak displacement for variety frame type 184

4.71 Comparison of horizontal displacement for the variety frame types 185

4.72 (a) till (j) showing the progressive reduce of hinges when frame equipped with RWD with increasing thickness of rubber 189

4.73 Comparison of plastic hinge occurring in beam and column sections 190

4.74 The peak displacements of the selected nodes in the horizontal dimensions 191

4.75	Time history displacement of the top node in horizontal directions during earthquake excitation	193
4.76	The peak displacements of the selected nodes in the horizontal dimensions	194
4.77	Displacement against cycle time for variety of frame type	194
4.78	Peak horizontal displacement for variety frame type	195
4.79	Reduction of horizontal displacement in percent	195

LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
1S1B	A two dimensional, portal RC frame
3SSB.	A two dimensional, single bay, three story RC frame
5SSB.	A two dimensional, single bay , five storey RC frame
3SSB_8SSB	A coupled two dimensional RC frame consist of two(2) unsymmetrical , two bay, three storey RC frames and a single bay, 8 storey RC frame
Twin_10SSB	A two dimensional, twin single bay, 10 storey RC
3D5SSB	A three dimensional, one by one bay, five story RC frame
3D8S2X2B	A three dimensional, two by two bays, 8 storey RC frame
3D3S2X3B.	A three dimensional, three by two bay, three storey, RC frame
ADF	Anelastic Displacement Field
ARCS3D	Nonlinear Analysis of Reinforced Concrete Structures Equipped with Earthquake Energy Dissipation Subjected to Dynamic Excitation
ATC	The Applied Technology Council (ATC) protocol for cyclic seismic testing of components of steel structures
DOF	Degree of freedom
ETP	The Energy Technology Partnership
FEMA	The Federal Emergency Management Agency
GHM	Golla-Hughes-McTavish
GMM	Generalized Maxwell Model
HDPR	High Damping Performance Rubber
IDARC	Inelastic Damage Analysis of Reinforced Concrete frame shear-wall structures

LVDT	Linear Voltages Displacement Transducers
MRF	Moment Resisting Frame
MPD	Mass Proportional Damping
NCEER	the National Center for Earthquake Engineering Research
NEHRP	National Earthquake Hazards Reduction Program
PH	Plastic Hinge
RC	Reinforced Concrete
RWD	Rubber Wall Damper
SAP2000	Structural Analysis Programs series 2000.
USA	United State of America
VE	Viscoelastic

CHAPTER 1

INTRODUCTION

1.1 General

One of the most feared natural disasters that happen in almost all continents is earthquake. An earthquake is caused by a sudden slip on a fault. The tectonic plates are always slowly moving, but they get stuck at their edges due to friction. When the stress on the edge overcomes the friction, there is an earthquake and that releases energy in waves that travel through the earth's crust and creates seismic waves that we feel. There are a wide variety of earthquake effects - these might include a chasm opening up or a land drop of many meters across a fault line. Therefore, to design an earthquake proof building which is guaranteed to resist all possible earthquakes poses a huge challenge to building engineers. Notwithstanding, it is possible during the design and the construction process to build in, a number of earthquake resistant devices, and along with applying advance earthquake engineering analysis techniques, an engineer could provide safe building and would increase enormously the chances of survival of both buildings and their occupants. The application of earthquake resistant devices as the modern control techniques to diminish the effects of earthquake excitation (dynamic loads) and tsunami wave on building structures offers an appealing alternative to traditional design approaches.

There are many techniques introduced to enhance lateral resistance of structures and energy dissipation capabilities such as Active mass driver damper, Active tendon damper, Controllable fluid damper, Variable friction damper, Oil damper, Hysteretic damper, Visco-elastic damper , Viscous damper, shear wall and Base isolation systems. Collectively these control involved the adding of anti-seismic devices into the building structure to mitigate vibration in building or dissipate vibration energy off the system. The base isolation , for instance, the functions of a base isolation/dissipation system are generally one or a combination of the following: supporting gravity loads and providing for lateral flexibility (period shift), restoring force and energy dissipation (either of hysteretic, in the case of displacement activated dampers, or viscous nature, in the case of velocity activated dampers)(D J Wagg, S A Neild , (2010)). Despite the role performed by the base isolation, some filtered energy do get to the structure and here, supplementary energy dissipation devices are used to mitigate the effect of this energy to the building.

According to their performance, the anti-seismic devices can be grouped as :- rigid connection devices (e.g. lock-up devices), linear devices, non linear devices, viscous dampers devices, isolators devices (e.g, rubber bearings). Common types of anti-seismic devices are: Elastomeric bearings: Natural Laminated, Lead and High Damping Performance Rubber (HDPR) Bearings; Sliding devices; Friction Dampers; Metallic Dampers, Yielding steel systems, lead extrusion devices; Viscous and Viscous-elastic Damper; Self-centring Dampers: Shape Memory Alloys.

Researchers are now looking at the effectiveness of using rubber dampers within the building frame, to enhance the structural performances against lateral forces. HDPR as the damping medium in a passive damper is providing much interest among researcher. HDPR material is a damping medium in the solid visco-elastic wall damper devices. These dampers generally consist of solid elastomeric plates bonded to steel plates. The elastomeric plates exhibit both viscosity and elasticity and their mechanical properties depend on loading frequency, deformation amplitude and temperature.

The use of HDPR in energy dissipating devices in structural systems is a very promising idea in term of controlling the response under dynamic actions like wind or earthquake. The use of HDPR does, however, entail some problems because its dynamic behaviour is not completely understood and the few HDPR models that exist are not completely satisfactory for seismic analysis of structures equipped with HDPR based dissipation devices. More experimental tests need to be performed to obtain more accurate information about the behaviour of the material under cyclic shear paths with different strain rate and strain amplitude.

The issue is ; previous studies about seismic response of building with supplemental wall dampers equipped in the building; consider only the performance in one element with single degree of freedom and with much limitation. So, there is lacking of knowledge on behaviour of structure in 3D (3D) formed and is equipped with Rubber Wall Damper (RWD) . Furthermore via literature review, no information is available on 3D nonlinear, formulations of framed structures, equipped with nonlinear RWD element. Adding that, proper physical and material modelling of RC frame building equipped with RWD is not seen. There is no report on nonlinear RWD element compatible with frame structures, hence the interest for this study. The aim of this study is to explore capability of RWD in diminish response and damage of structures under dynamic excitation and vibration. For this purpose, the formulation and constitutive model of RWD will be investigate and proper numerical and finite element model for framed structures with supplemental RWD will be establish. So, nonlinear time history dynamic analysis of structure under dynamic load excitation will be performed and effect of RWD in reduction of structural response in terms of structural movement and occurring plastic hinges in structural members will be evaluated. Result of numerical analysis will be verified through experimental test which will carry out for frame structure with supplemental RWD under cyclic loads. Eventually through numerical and experimental result, potential of RWD for implementation in design of structures under dynamic loads and retrofitting and rehabilitation of existing buildings will assess with consider of costing. RWD designs comes with approaches of analysis and design, will be the physical industrial product realized from this study which will be widened the list of improved rubber product in Malaysia.

1.2 Research hypothesis

Energy dissipation cover any component used to reduced the movement of structure under dynamic excitation (by wind, earthquake alike). Passive energy dissipation method attempts to reduce the demand on the structure rather than the usual approach of adding capacity, hence the aim is provides Capacity greater than Demand. Within the passive anti seismic devices, four main categories of devices used are: 1. the yielding metal devices energy dissipated through hysteresis yielding, 2. the friction devices energy dissipated through frictional hysteresis, 3. viscous dampers energy dissipated through fluid viscosity and 4. Visco-elastic damper-energy dissipated through material viscosity. This study focus on the last category of the damper type .From the literature review it is further observe that little or no information is available on 3D and nonlinear formulations of framed structures, equipped with nonlinear RWD element. Furthermore, proper physical and material modelling of RC frame building equipped with RWD is not seen. Additionally there is no report on nonlinear, 3D RWD element compatible with frame structures and the literature indicated lack of investigation on damage detection of RWD device during earthquake which play important role in structure safety. Notwithstanding It is noted that there are some study about seismic response of building with supplemental wall dampers but the study do mostly consider the performance of one element in single degree of freedom with many limitation. So, there is lacking of knowledge on behaviour of structure equipped with passive , non linear, 3D RWD compatible with frame structure. The aim of this study is to explore the capability of RWD in diminish response and damage of structures under dynamic excitation and vibration. For this purpose, the constitutive model of rubber will be investigated and proper numerical and finite element model for framed structures with supplemental RWD will be establish. The study hypothesis is the supplementary RWD fitted in the moment resisting frame structure will dissipated dynamic excitation energy through damping action of rubber within structural frame system. The developed mathematical models of RWD are presented in this study. The assessment procedure of frames' response equipped by RWD subjected to dynamic load, are divided in two general phases include experimental test and numerical analyses. So, nonlinear time history dynamic analysis of structure under dynamic load excitation will be performed and effect of RWD in reduction of structural response in terms of structural movement and occurring plastic hinges in structural members will be evaluated. To begin, a structural control device, the RWD is developed. The device is a non gravity load carrier, fixed to the main structural frame and it provides supplemental damping to the structural frame. The following shall be elaborated later in the chapter. In RWD device, rubber sheets sandwiched between steel plates play crucial roles in system dampers, so, the damper formulation has been developed with reference on the steel plate rubber sandwiches layer concept. The industrial design and fabrication of RWD devices based on reasonable specifications have been proposed. The mathematical models of RWD devices with considering the attached connection is formulated and is implemented into specific finite element program developed by prior studies by Thanoon (1993) and Hejazi et al. (2013). Parametric study has been conducted on RWD's geometry specification and materials by aid of 3D nonlinear time history dynamic analyses for dissimilar models. In addition to that, experimental section consists of cyclic test. Cyclic test conducted is based on displacement control approach in steel and RC frames. Three steel and two RC frame specimens subjected to cyclic displacement history on their top nodes. These models included of frames with and without attached RWD devices and conventional Cross braced steel frames. The impacts of RWD applications in steel frames are compared with bare and brace frames in terms of ductility characteristics, maximum capacity and the same impact in RC frame is compared with bare RC frame. Finally, the results from experimental and numerical test has been compared and verified.

In the proposed model, a frame building with earthquake energy dissipation system is idealized as an assemblage of columns, beams, damper devices appropriately connected. The use of this model facilitates the establishment of a global structural behaviour especially in two dimensional (2D) and 3D non linear static and seismic/dynamic analysis. Then a special finite element program code is developed for analysis of RC building furnished by viscous damper under dynamic load excitations. A mathematical model for RC frame members with supplemental viscous damper element is presented here. To get the true behaviour of a building under different types of loading and earthquake energy dissipation system, all types of the elements in a building are to be carefully model. The ideal starting point in establishing an analytical model for nonlinear analysis of a building would be to take the individual members and assign material behaviour characteristics in the form of stress-strain laws. The stress-strain relationship would then be used in conjunction with the basic member geometry and basic assumptions of the nature of the deformations, to establish the structural behaviour.

1.3 Brief description of present work

In the present work, the new effective RWD have been designed and developed with the use of local materials -Malaysian rubber , steel, bolts and nuts along with advance technology and techniques available “analysis of RC structure in 3D (ARCS3D)”, to analyze dynamic load effect and preclude vibration damage of buildings. These developed dampers is composed of two layers of HDPR sandwiched between steel plates. The supplemental HDPR wall device installed in the buildings structural system is expected to absorb energy to effectively reduce vibrations caused by earthquakes and wind. Based on literature, there is lacking of knowledge on behaviour of structure equipped with RWD especially for RC structures which are the common type of structures in Malaysia. The RWD component can be implemented to any structure which is subjected to vibration and it can be assumed to assure the serviceability and safety design criteria. Mathematical model of RWD are developed for numerical modeling and finite element method simulation. The study of building frames response, would be more realistic, only if nonlinearity due to material behavior is also taken into account. Thus, nonlinear dynamic analysis is a prelude to achieving both accuracy and economy in the structural design. The performance of RWD is evaluated by aid of dynamic analysis with considering the effect of RWD element. The results reveal the efficiency of wall damper system to diminish and dissipate the energy compared with conventional system. On the other hand the replacement of rubber as damping material in wall dampers compared with viscous substance, in terms of fabrication cost and maintenance fee is more desirable and cost effective. An analytical model of wall damper will be formulated based on Rubber constitutive law and a finite element algorithm for the analysis of RC framed structures with supplemental RWD will be developed. A nonlinear time history dynamic analysis of structure under dynamic load excitation will be performed and the effect of RWD in reducing the structural response in terms of structural movement and occurring plastic hinges in structural members will be evaluated. Then based on numerical model, prototype of RWD will be fabricated and result of numerical analysis will be verified through experimental test which will be carried out for frame structure with supplemental RWD under cyclic loads. Eventually through numerical and experimental result, potential of RWD for implementation in design of structures under dynamic loads and retrofitting and rehabilitation of existing buildings will be assessed with consider of costing. RWD comes with approaches of analysis and design, will be the physical industrial product realized from this study

1.4 Motivation for the current study

Malaysia has enjoyed a relatively free event from earthquake but during the past two decades, Malaysia's fate has changed. In the west coast of peninsula Malaysia, report of tremor in major towns – Kuala Lumpur, Butterworth, Johor Baru have always being aired in the local news and media. Janda Baik in Pahang had experience of intermittent shake (rithcher-3.6) and at Tawau in Sabah, similar shake had also been reported. In 2015, the first casualty from earthquake occurred on the Mount Kinabalu. Many houses were also damaged in the aftermath of the Sabah earthquake (rithcher-6.0). Shake was also reported happened in the vicinity of Kuala Berang , besides the Kenyir Dam in Terengganu – West coast of the peninsula Malaysia. The events above showed Malaysia now, share effect of the wave from earthquake and Malaysians must live the experience of shake from earthquake originated from Indonesia or at Sabah and at Janda Baik. This poses new threat to existing old house, institutional building and infrastructure. Most existing buildings were of RC frame structure and during those years, buildings were constructed to detail using CP110/BS8110-part 1. The detailing then falls short of meeting prescriptive seismic detailing requirement observed in codes and standards for new buildings in seismic active zone. Further, local engineers are now facing a challenge for evaluation and retrofit using code based elastic analysis methods. Elastic analysis approach is now, no longer feasible.

At present, seismic rehabilitation of existing buildings uses the notion of performance-based limit states and FEMA, 2005 and ASCE/SEI 41-06 provided the first comprehensive guidance on the use of nonlinear analysis in design. As a result, seismic evaluation and retrofit of existing buildings has been one of the primary drivers for the use of energy dissipation devices and the seismic-rehabilitation required nonlinear analysis in engineering practice. Linear analyses are no longer sufficient to provide detailing needs for building to be constructed. Non linear analysis took its place, which indicates that structural behaviour under dynamic load are analyzed with respect to three dimension displacement, rotation and plastic hinge formations in the building. To extend the service life of the presence building, retrofitting is seen as a reasonable solution. For this purposes, passive devices are more appropriate for field applications since they are a cheaper option yet effective to check the seismic performance of the structure under various earthquake scenarios(Chen et al. (2010)). Building structure do need approximately 15–25% of additional damping as a desirable range in the damper designed buildings(Lee and Taylor (2001)). Viscous damper devices is a favorate choice in upgrading the building damper. Uetani et al. (2003) proposed a practical method for optimum structural design of building frames with viscous dampers. The method firstly addresses issue on the stiffness design of a reduced shear-building model equipped with viscous dampers. Then an optimum design for building frames was performed under static design loads. A drawback in this method is that the viscous fluid is expansive and the devices used are therefore expansive. Hence a cheaper material option is therefore sought after. Another drawback is viscous damper is still a relatively new building technology yet to be further developed and studied (Ying Zhou et al (2012)). Ibrahim et al. (2007) proposed a new elasto-plastic device that consists of a block of a HDPR sandwiched between steel plates which are allowed to yield to provide additional energy dissipation. Karavasilis et al.(2011) experimentally evaluated the hysteretic behaviour of a new innovative compressed elastomer damper developed by Sweeney and Michael and used the design procedure of Lee et al. to design steel moment resisting frame (MRF) with compressed elastomer dampers. A sequential asymptote formulation to model the cyclic behaviour of ultra HDPR dampers was developed by Sause et al. (2011). Many researchers have performed individual visco-elastic damper tests and developed models to predict damper behaviour under earthquake loading. Tsai and Lee (2001) and Kasai et al.(1998) studied the effect of loading rate and temperature on visco-elastic materials and proposed fractional derivative models to predict damper behaviour. Lee (2001) studied the behavior of elastomeric dampers made of ultra HDPR and found from characterization tests the behavior of these dampers to be less sensitive to frequency and ambient temperature compared to conventional viscoelastic dampers. Fu and Kasai (1998) presented a simplified theory to design viscoelastic dampers for a given Moment Resisting Frame. Lee et al. (2001) presented a simplified design procedure for buildings with viscoelastic or high-damping elastomeric dampers. The design procedure has been used recently to study the effect of the variation in steel MRF properties and damper design criteria on the design of steel MRF with elastomeric dampers .

The use of HDPR provides cheaper alternative to viscous fluid and those researcher above had conducted study on the material, yet those studies centres on seeking the characteristic behaviour of rubber as a damping medium. The piece of rubber that was tested was basically a small sheet size. Notwithstanding, the result from the test have shown that rubber do posses the elastic properties and able to provide supplementary damping on a moment resisting frame structure. As Malaysia is a rubber producing state, this option to study RWD is feasible and if positive result is obtained, the product could be implemented on existing building in this country as a retrofit damper device and to mitigate the damaged of the house from the oncoming shake of the ground in the event of new earthquake**.** A 3D , non linear analysis is necessary to provide the manner of fitting the rubber wall devices to the moment resisting frame. Hence a non-linear analysis method is also seek to aid fitment of the damper device into the building frame.

Furthermore, Sadeck et al. (2006) identified some limitations in the FEMA 273 [17] procedures for the design of structures with velocity-dependent passive energy dissipation devices based on the analysis of single-degree-of-freedom structures. One of the major limitations includes a non-conservative estimation of peak response and base shear when using a constant reduction factor to obtain displacement response of short-period structures and assuming a harmonic response to compute the peak velocity, story and base shear.

Thus, this study observed, there is no report on nonlinear 3D RWD element compatible with frame structures. There are no commercially available finite element code which utilize column, beam and nonlinear RWD element for dynamic inelastic analyses of frame and be capable to optimize the structural control system based on non linear response of framed building. The assessment, retrofitting and rehabilitation techniques of frame buildings with passive control device such as RWD are not addressed and need further studies.

1.5 Statement of problem

From the brief review of literature of earlier works it is observed that:

Most buildings previously constructed from year 1970 till 2010 in Malaysia are of RC and are still serving the public, yet, are prone to the dynamic action accrued from earthquake, tsunami and traffic movement via underground passage. It has been observed these buildings were analyzed by static action to ultimate limit state and designed likewise, but, checks on service limit state, yet in her life span, the material deteriorates, drop in modulus of elasticity. For retrofitting, static analysis no longer work, the servicing action is dynamic in nature and has two additional generated action –inertia and inherent damping action which changes the former static equilibrium into a dynamic equilibrium. Hence 3D nonlinear, formulations of framed structures is needed to handle the present analysis needs. Yet again computational complexities and long time analysis process burdens the engineers and accordingly simplification, alternative calculation is soughed, only to realise that building still crumbles down during earthquake. This is a tell-tale, showing the previous analysis has it shortfall and not pin pointing at the source of the problem which is matching the dynamic action against material response and subsequent responding in mode variance resisting against the action that is in the way of cyclical transformation between strain stiffness energy , inertia (mass) energy, damping energy and beyond the yield limit of the material.

Based on the extensive review of literature it was found that: Supplementary damper devices (passive , active) placed important function to provide effective damping in a structural frame system as the structure inherent damping has time and again been observed not suffice to release unwanted energy and this caused the reinforced frame section to rupture. The event of collapse buildings near column head and foot testify this event. The element of cost to retrofitting old frame RC building is a mind boggling issue too. Cheap option is greatly appreciated, yet, the prevailing method and material use is rather expansive. Even for new RC frame structure, adding supplementary damper should not increase in the present construction cost and should be provided at the same cost if not lower.

This call for the need of performing on 3D nonlinear numerical time history analysis on structure and cheap option of supplementary damper for the safety of the common public building dweller or consumer.So far little or no information is available on 3D nonlinear, formulations of framed structures, equipped with nonlinear RWD element. Furthermore, proper physical and material modeling of RC frame building equipped with RWD is not seen. There is no report on nonlinear 3D RWD element compatible with frame structures.

Review of the literature also indicated lack of investigation on damage detection of RWD device during earthquake which play important role in structure safety.In depth study on multi support excitation effects on RC framed structures equipped with RWD are not seen. There no commercially available finite element code which utilize column, beam and nonlinear RWD element for dynamic inelastic analyses of frame and be capable to optimize the structural control system based on nonlinear response of framed building. The implementation of nonlinear RWD device in unsymmetrical 3D nonlinear frame structure under multi direction ground excitation is not well investigated and little information on 3-D effects i.e. torsion and irregular issues is available. The optimization of RWD element as energy dissipation device is not available in the literature. Hence the aim of this study is to pursue " The development of a general analytical model of RWD element which will be proposed for reinforced concrete and steel frame building structures ".

1.6 Objectives of study

The development of a general analytical model of rubber wall damper which will be proposed for placement in a non linear frame structure is the main goal of this study. Other detailed objectives which see the realization of the above aims includes the following:

(1) To develop an effective passive damper from a high damping performance rubber and can be applied in frame structures which will be subjected to some earthquake excitation in its service lifespan
(2) To develop and appraise capability of the developed numerical system of a passive rubber wall damper element from a high damping performance rubber comes along with the formulation of a suitable element constitutive model. This element numerical model shall be used as structural component for framed structures.
(3) To develop a finite element method , verify the developed numerical model by performing experimental test on the passive rubber wall damper and computational procedure for nonlinear dynamic analysis of 3D frame structures equipped with rubber wall damper subjected to dynamic excitation.

1.7 Limitation of the present work Scope:

Limitations of the present works include:

(i) Effects of soil-structure interaction are not considered.
(ii) Effects of concrete confinements are not considered
(iii) Rubber is a high damping performance material and here, it behaves within the elastic ranges material. The whole damper operates at a regular environment and temperature ranges of the equatorial country.

1.8 Proposed layout of the thesis

This thesis comes in five(5) chapters. The research hypothesis and the motivation for the current studies on the chosen problem is highlighted in Chapter 1.Other matters highlighted are the definition of the problem, a determinative statement on the problem, the study objectives along with the scope and the limits of the study.

Chapter 2, covers the review of the energy dissipation damper system, the properties of rubber, application of RWD in unsymmetrical, adjacent and parallel buildings, inelastic analysis of frame buildings developed procedure and computer program code are demonstrated and.development of optimizing RWD through genetic algorithm has been reported and optimization of structural control system. The material used and methodology of present study is presented in Chapter 3. Development of 3D nonlinear RWD element, the modelling of inelastic frame element for beams and columns and constitutive model of both elements are illustrated. Development of finite element procedure for nonlinear analysis of frame structures with RWD are also presented in this chapter. the incremental iterative procedures for computation of nonlinear response of frame structures with RWD is illustrated through step by step procedure. Then the development special computer code based on the computational scheme has been presented. The validation of developed system and program code has been reported through analysis of some example of RC portal frames and comparisons of results with experimental results are presented. Chapter 4 deals with some applications of developed system for 2D and 3D, RC frame buildings. Linear and nonlinear response of structures are investigated. The effects of RWD properties on seismic response of buildings are evaluated and the application of RWD in an example of unsymmetrical buildings is reported. Further application of the RWD for connecting the adjacent buildings and coupling of parallel structure and the effects of different arrangement of RWD position on seismic response of structures are investigated through an example are presented in chapter 4. Report on performance of RWD as an energy dissipation device are discussed here using result from the experiment outcome of the RWD devices fitted to portal frame of steel and RC.Chapter 5 deals with the major conclusions drawn from the study carried out in the thesis together with the suggestions for further research in this area.

REFERENCES

Abdi, H., Hejazi, F., Saifulnaz, R., Karim, I. A., & Jaafar, M. S. (2015). Response modification factor for steel structure equipped with viscous damper device. *International Journal of Steel Structures*, *15*(3), 605–622.

Ahn, S. ., Min, K. ., Park, J. ., Lee, S. ., Lee, D. ., Oh, J. ., … Lee, S. . (2008). Practical Issues and Solutions on Installation of Viscoelastic Dampers in a 46-Story Reinforced Concrete Building Structure. *Structural Design of Tall and Special Buildings*, *17*(1), 231–243.

Amadio, C., Clemente, I., Macorini, L., & Fragiacomo, M. (2008). Seismic Behaviour of Hybrid Systems Made of Pr Composite Frames Coupled with Dissipative Bracings. *Earthquake Engineering and Structural Dynamics*, *37*(6), 861–879.

Amran, Y. H. ., Ali, A. A. ., Rashid, R. S. ., Hejazi, F., & Safiee, N. . (2016). Structural behavior of axially loaded precast foamed concrete sandwich panels. *Construction and Building Materials*, *107*, 307–320.

Anderson, T. L. (1989). Seismic Isolation for the Los Angeles County Fire Command and Control Facility. *Structures Congress, ASCE, San Francisco.*

Andrés Jacobsen, Hitaka, T., & Nakashima, M. (2010). Online test of building frame with slit-wall dampers capable of condition assessment. *Journal of Constructional Steel Research*, (66), 1320–1329.

Brahima, Y. E., Justin, M., & Finley, A. C. (2007). A visco-plastic device for seismic protection of structures. *Journal of Constructional Steel Research*, *63*, 1515–1528.

Buckle, I. G., & Mayes, R. L. (1990). Seismic Isolation: History, Application, and Performance – a World View. *Earthquake Spectra*, *6*(2), 161–202.

Chang, K. C., Chen, S. J., & Lai, M. L. (1996). Inelastic Behavior of Steel Frames with Added Viscoelastic Dampers. *Journal of Structural Engineering*, *122*(10), 1178–1185.

Chang, K. C., & El-natur, H. A. (1993). Parametric Study of Structures with Added Viscoelastic Dampers. *Symposium on Structural Engineering in Natural Hazards Mitigation, ASCE, Irvine, CA, USA*, 724–729.

Chang, K. C., & Lin, Y. Y. (2004). Seismic Response of Full-Scale Structure with Added Viscoelastic Dampers. *Journal of Structural Engineering*, *130*(4), 600

Chang, K. C., Soong, T. T., Oh, S. T., & Lai, M. L. (1995). Seismic Behavior of Steel Frame with Added Viscoelastic Dampers. *Journal of Structural Engineering*, *121*(10), 1418–1426.

Chen, C. S., Chen, K. C., Pong, W. S., & Tsai, C. S. (2002). Parametric Study for Buildings with Combined Displacement-Dependent and Velocity-Dependent Energy Devices. *Structural Engineering and Mechanics*, *14*(1), 85–98.

Chen, X. W., Li, J. X., & Cheang, J. (2010). Seismic performance analysis of Wenchuan Hospital structure with viscous dampers. *Structural Design Tall Buildings*, *19*(4), 397–419.

Climent, A. B. (2010). A brace-type seismic damper based on yielding the walls of hollow structural sections. *Engineering Structures*, *32*, 1113–1122.

Constantinou, M. C., Soong, T. T., & Dargush, G. F. (1998). Passive Energy Dissipation Systems for Structural Design and Retrofit. *Multidisciplinary Center for Earthquake Engineering Research Center, Buffalo, NY*.

Constantinou, M. C., & Symans, M. D. (1993). Experimental Study of Seismic Response of Buildings with Supplemental Fluid Dampers. *Structural Design of Tall Buildings*, *2*(2), 93.

Constantinou, Whittaker, Ramirez, Johnson, & Chrysostomou. (2000). Equivalent lateral force and modal analysis procedures of the 2000 NEHRP Provisions for buildings with damping systems. *Earthquake Spectra*, *19*(4), 959–980.

Costantinou, M. C., Mokha, A., & Reinhorn, A. (1990). Teflon Bearings in Base Isolation. II: Modeling. *Journal of Structural Engineering*, *116*(2), 455–474.

Dall'Astaa, A., & Ragnib, L. (2006). Experimental tests and analytical model of high damping rubber dissipating devices. *Engineering Structures*, *28*, 1874–1884.

Darabi, B., & Rongong, J. A. (2012). Polymeric particle dampers under steady-State vertical vibrations. *Journal of Sound and Vibration*, *331*, 3304–3316.

De Luca, A., Mele, E., Molina, J., Verzeletti, G., & Pinto, A. V. (2001). Base Isolation for Retrofitting Historic Buildings: Evaluation of Seismic Performance through Experimental Investigation. *Earthquake Engineering and Structural Dynamics*, *30*(8), 1125–1145.

Derham, C. J., Kelly, J. M., & Thomas, A. G. (1985). Nonlinear Natural Rubber Bearings for Seismic Isolation. *Nuclear Engineering and Design*, *84*(3),417

Dinehart, D. W., Shenton, H. W., Foley, D. W., & Johnston, A. (2005). The Cyclic Performance of Viscoelastic Shearwalls. *University of Delaware Newark, USA*.

El-Attar, A. G., Saleh, A. M., & Zaghw, A. H. (2005). Conservation of a Slender Historical Mamluk- Style Minaret by Passive Control Techniques. *Structural Control and Health Monitoring*, *12*(2), 157–177.

Fateh, A., Hejazi, F., Jaafar, M. ., & Adnan, A. (2015). Dynamic analysis of variable stiffness bracing system in structure. *Applied Mechanics and Materials*, (704), 442–446.

Fateh, A., Hejazi, F., Jaafar, M. ., & Karim, I. . (2016). Numerical and experimental evaluation of a developed nonlinear curved spring element under compression force. *Journal of Constructional Steel Research*, (117), 115–125.

Fateh, A., Hejazi, F., Jaafar, M. ., Karim, I. ., & Adnan, A. (2016). Design of a variable stiffness bracing system: Mathematical modeling, fabrication, and dynamic analysis. *Soil Dynamics and Earthquake Engineering*, (80), 87–101.

Fateh, A., Hejazi, F., & Khojasteh, M. . (2014). Seismic Performance Evaluation of Steel Shear Wall by Equivalent Truss Approach Modeling. *Computing in Civil and Building Engineering, ASCE*, 1401–1408.

Fateh, A., Hejazi, F., Zabihi, A., & Behnia, A. (2013). Behavior of external column-wide beam joint with different bar arrangement and existence of joint shear link under gravity. *Caspian Journal of Applied Sciences Research*, *2*(2), 120–130.

FEMA. (1997). NEHRP Guidelines for the Seismic Rehabilitation of Buildings. *Federal Emergency Management Agency, Washington, D.C*, (273).

Fu, Y., & Kasai, K. (1998). Comparative Study of Frames Using Viscoelastic and Viscous Dampers. *Journal of Structural Engineering*, *124*(5), 513–522.

Fujita, S., Fujita, T., Furuya, O., Morikawa, S., Suizu, Y., Teramoto, T., & Kitamura, H. (1992). Development of High Damping Rubber Damper for Vibration Attenuation of High-Rise Buildings. *10th World Conference on Earthquake Engineering, A.A. Balkema, Madrid, Spain*.

Fujita, S., Furuya, O., Fujita, T., Kasahara, Y., Suizu, Y., Morikawa, S., … Kitamura, H. (1995). Research and Development of High-Damping Rubber Damper for Vibration Control of Tall Buildings. *Joint ASME/JSME Pressure Vessels and Piping Conference, ASME, New York, NY, USA, Honolulu, HI, USA*, 265–272.

Fuller, K. N., Ahmadi, H. R., & Pond, T. J. (1996). High Damping Natural Rubber Seismic Bearings: Longevity and Modelling. *1996 ASME Pressure Vessels and Piping Conference, ASME, Montreal, Canada*, 71–79.

Fuller, K. N. G., Gough, J., & Pond, T. J. (1996). High Damping Natural Rubber Compounds for Seismic Isolators: Properties and Specifications. *1st European Conference on Structural Control, Barcelona, Spain, 288*.

Furuya, O., Fujita, S., Fujita, T., Masaki, N., Kitamura, H., & Ozaki, H. (1999). Vibration Control Performance of High-Damping Rubber Damper Evaluating from Seismic Observation in Actual Building. *1999 ASME Pressure Vessels and Piping Conference, Fairfield, NJ, USA, Boston, MA, USA,* 305–310.

Gacem, H., Chevalier, Y., Dion, J. L., Soula, M., & Rezgui, B. (2009). Nonlinear dynamic behaviour of a preloaded thin sandwich plate incorporating visco-hyperelastic layers. *Journal of Sound and Vibration*, *322*, 941–953.

Gluck, N., Reinhorn, A., Gluck, J., & Levy, R. (1996). Design of supplemental dampers for control of structures. *Journal of Structural Engineering*, *122*(12), 1394–1399.

Guerreiro, L., Craveiro, A., & Branco, M. (2006). The Use of Passive Seismic Protection in Structural Rehabilitation. *Progress in Structural Engineering and Materials*, *8*(4), 121–132.

Hatami, F., Ghamari, A., & Rahai, A. (2012). Investigating the properties of steel shear walls reinforced with Carbon Fiber Polymers (CFRP). *Journal of Constructional Steel Research*, *70*, 36–40.

Hejazi, F. (2011). Development of earthquake energy dissipation system in Reinforced Concrete frame buildings. *PhD Thesis, Universiti Putra Malaysia*.

Hejazi, F., Dalili, M., Noorzaei, J., Jaafar, M. ., Ali, A. A. ., & Thanoon, W. (2010). Coupling parallel buildings by supplemental viscous damper device. *Proceedings of the International Conference on Computing.*

Hejazi, F., Dalili, M. S., Noorzaei, J., Jaafar, M. S., Ali, A. A. ., & Thanoon, W. . (2011). Seismic response evaluation of RC tower connected to short rigid buildings. *Key Engineering Materials*, *462*, 569–575.

Hejazi, F., Jilani, S., Noorzaei, J., Chieng, C. Y., Jaafar, M. S., & Ali, A. A. . (2011). Effect of soft story on structural response of high rise buildings. *IOP Conference Series: Materials Science and Engineering*, *17*(1), 12–34.

Hejazi, F., Kojouri, S. J., Noorzaei, J., Jaafar, W. S., Thanoon, W. A., & Ali, A. A. A. (2011). Inelastic seismic response of RC building with control system. *Key Engineering Materials*, *462*, 241–246.

Hejazi, F., Noorzaei, J., & Jaafar, M. S. (2010). Application of nonlinear damper in reinforced concrete structure control., Challenges, Opportunities and Solutions in Structural Engineering . *Journal of Structural Engineering*.

Hejazi, F., Noorzaei, J., Jaafar, M. S., & Ali, A. A. A. (2009). Earthquake analysis of reinforce concrete framed structures with added viscous dampers. *International Journal of Applied Science, Engineering and Technology*, *5*(4), 191.

Hejazi, F., Noorzaei, J., Jaafar, M. S., Ali, A. A. A., & Seifi, M. (2009). 3 Dimensional Damper Element for Reinforced Concrete Frames. *TCLEE : Lifeline Earthquake Engineering in a Multi Hazard Environment*, *1*, 12.

Hejazi, F., Noorzaei, J., Jaafar, M. S., Thanoon, W., & Ali, A. A. A. (2009). Optimization of active variable stiffness system for controlling structural response of a building under earthquake excitation. *Journal of Structural Engineering*, *36*(27), 235–242.

Hejazi, F., Shahpasand, M., Mirnezhad, M., Jaafar, M. ., & Ali, A. A. A. (2014). A web-based architecture for interactive finite element program. *Computing in Civil and Building Engineering*, 1393–1400.

Hejazi, F., Shoaei, M. D., Tousi, A., & Jaafar, M. S. (2015). Analytical model for viscous wall dampers. *Computer-Aided Civil and Infrastructure Engineering*.

Hejazi, F., Toloue, I., Jaafar, M. S., & Noorzaei, J. (2013). Optimization of earthquake energy dissipation system by genetic algorithm. *Computer-Aided Civil and Infrastructure Engineering*, *28*(10), 796–810.

Hejazi, F., Zabihi, A., & Jaafar, M. S. (2014). Development of elasto-plastic viscous damper finite element model for reinforced concrete frames. *Soil Dynamics and Earthquake Engineering*, *65*, 284–293.

Higgins, C., & Kasai, K. (1998). Experimental and Analytical Simulation of Wind Response for a Full- Scale Ve-Damped Steel Frame. *Journal of Wind Engineering and Industrial Aerodynamics*, *77*, 297–313.

Hussain, J., Alalkawi, M., Zainab, K., Hantoosh, Raad, H., & Majid. (2010). The Tensile And Fatigue Properties Of Vulcanized Natural Rubber Under Ambiant Temperatures. *Diyala Journal of Engineering Sciences*, *3*(2), 16–24.

Hwanga, J.-S., Chun, H. T., Wang, S.-J., & Huange, Y.-N. (2006). Experimental study of RC building structures with supplemental viscous dampers and lightly reinforced walls. *Elsevier , Engineering Structures*, *28*, 1816–1824.

Ibrahim, Y. E. (2005). A New Visco-Plastic Device for Seismic Protection of Structures. *Ph.D.Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA*.

Ibrahim, Y. E., Marshall, J. D., & Charney, F. A. (2007). A Visco-Plastic Device for Seismic Protection of Structures. *Journal of Constructional Steel Research*, *63*(11), 1515–1528.

Juan, C., Llera, D. la, Carlos, E., & Almazan, J. L. (2004). Earthquake behavior of structures with copper energy dissipators. *Earthquake Engineering Structural Dynamic*, *33*, 329–358.

Kani, N., Takayama, M., & Wada, A. (2006). Performance of Seismically Isolated Buildings in Japan. *8th US National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, San Francisco, CA*.

Kareem, A., Kijewski, T., & Tamura, Y. (1999). Mitigation of Motions of Tall Buildings with Specific Examples of Recent Applications. *Wind & Structures: An International Journal*, *2*(3), 201–251.

Kasai, K., Fu, Y., & Watanabe, A. (1998). Passive control system for seismic damage mitigation. *Journal Structural Engineering*, *124*(5), 501–512.

Kelly, J. M., Skinner, R. I., & Heine, A. J. (1972). Mechanisms of Energy Absorption in Special Devices for Use in Earthquake Resistant Structures. *Bulletin of the New Zealand Society for Earthquake Engineering*, *5*(3), 63–88.

Kim, J., Ryu, J., & Chung, L. (2006). Seismic Performance of Structures Connected by Viscoelastic Dampers. *Engineering Structures*, *28*(2), 183–195.

Kyung-Won, M., Ji-Young, S., & Jin-koo, K. (2010). Simple design procedure of a friction damper for reducing seismic responses of a single-story structure. *Elsevier, Engineering Structures*, *32*, 3539–3547.

Lai, M. L., Chang, K. C., Soong, T. T., Hao, D. S., & Yeh, Y. C. (1995). Full-Scale Viscoelastically Damped Steel Frame. *Journal of Structural Engineering*, *121*(10), 1443–1447.

Lee, D., & Taylor, D. P. (2001). Viscous damper development and future trends. *Structural Design of Tall and Special Buildings*, *10*(5), 311–320.

Lee, K. S., Sause, R., Ricles, J., Ab-Malek, K., & Lu, L. W. (2004). Non-Linear Rate-Dependent Hysteresis Model for Structural Dampers Made from Ultra-High Damping Natural Rubber. *Journal of Rubber Research*, *7*(2), 79–103.

Lin, T. K., Chang, K. C., Chang, C. Y., & Chen, C. H. (2006). Application of Viscoelastic Dampers in a Multi-Purpose Vibration Prevention System. *8th US National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, San Francisco, CA.*

Lin, Y. ., Tsai, M. ., Hwang, J. ., & Chang, K. . (2003). Direct displacement-based design for building with passive energy dissipation systems. *Engineering Structures*, *25*(1), 25–37.

Lyan, Y. L., Ging, L. L., & Ming, H. S. (2012). An experimental study on a generalized Maxwell model for nonlinear visco- elastic dampers used in seismic isolation. *Engineering Structures*, *34*, 111–123.

M.C, C., Tsopelas, P., Kasalanati, A., & Wolff, E. (1999). Property Modification Factors for Seismic Isolation Bearings. *Technical Rep. No. MCEER-99-0012, Multidisciplinary Center for Earthquake Engineering Research, State Univ. of New York at Buffalo, Buffalo, N.Y.*

Madsen, L. P. ., Thambiratnam, D. P., & Perera, N. J. (2002). Seismic response of building structures with dampers in shear walls. *Pergamon-Computers & Structure*, *81*, 239–253.

Malek, K. A., & Basir, K. B. (2001). Design and Characteristics of High Damping Natural Rubber Bearings for Base Isolation. *Earthquake Resistant Engineering Structures III, Computational Mechanics Publications, Ashurst, United Kingdom, Malaga, Spain*, 155–163.

Martelli, A. (2006). Modern Seismic Protection Systems for Civil and Industrial Structures. *SAMCO*.

Masoud, M., Amir, P. Z., Sahand, S. S., & Hamid, R. S. (2011). Numerical and experimental study of hysteretic behavior of cylindrical friction dampers. *Engineering Structures*, *33*, 3647–3656.

Mazzolani, F. M. (2001). Passive Control Technologies for Seismic-Resistant Buildings in Europe. *Progress in Structural Engineering and Materials*, *3*(3), 277–287.

Michael, K., & Sean, W. (2004). An Improved Spread Plasticity Model For Inelastic Analysis Of R/C. Frames Subjected To Seismic Loading. *13th World Conference on Earthquake Engineering Vancouver, B.C., Canada*, (933).

Munshi, J. A. (1997). Effect of Viscoelastic Dampers on Hysteretic Response of Reinforced Concrete Elements. *Engineering Structures*, *19*(11), 921–935.

Murthy, K. (2005). Application of Visco-Hyperelastic Devices in Structural Response Control. *M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.*

Naeim, F. (2001). The Seismic Design Handbook (Chapter 5; Linear Static Seismic Lateral, Force Procedures). *John Wiley and Sons, Inc, New York, NY.*

Naeim, F., & Kelly, J. (1999). Design of Seismic Isolated Structures: From Theory to Practice. *John Wiley and Sons, Inc, New York, NY.*

Nikabakht, E., Rashid, K., Hejazi, F., Osman, S. A., & Mohseni, I. (2013). Nonlinear finite element analysis of PC segmental bridge columns subjected to quasi-static loading. *Int. Journal Adv. Civil Structure Environment Engineering*, *1*(1), 28–31.

Nikbakht, E., Rashid, K. A., Hejazi, F., Osman, S. A., & Mohseni, I. (2013). Seismic performance of self-centring precast post-tensioned bridge columns with SMA bars. *Int. Journal Advance Civil Structure Environment Engineering*, *1*(1), 24–27.

Nikbakht, E., Rashid, K., Hejazi, F., & Osman, S. A. (2013). A numerical study on seismic response of self-centering precast segmental columns at different post-tensioning forces. *Latin American Journal of Solids and Structures*, *11*(5), 864–883.

Officials. (1999). Guide specifications for seismic isolation design. *American Association of State Highway and Transportation Officials, Washington DC*, 76.

Oliveto, G., Calio, I., & Marletta, M. (2004). Retrofitting of Reinforced Concrete Buildings Not Designed to Withstand Seismic Action: A Case Study Using Base Isolation. *13th World Conference on Earthquake Engineering, Vancouver, Canada*.

Pradipta, B., & Avik, S. (2011). Earthquake vibration control of structures using hybrid mass liquid damper. *Engineering Structures*, *33*, 1291–1301.

Pu, J. P., Tsai, C. S., Huang, J. F., Chen, B. J., & Fang, Y. M. (2004). Analysis and Experiment on the Effect of Seismic Protection of Buildings by High Damping Rubber Bearings. *ASME Pressure Vessels and Piping Conference, American Society of Mechanical Engineers*, 237–244.

Saiful Islam, A. B. M., Jameel, M., Uddin, A. M., & Ahmad, S. I. (2011). Simplified design guidelines for seismic base isolation in multi-storey buildings for Bangladesh National Building Code (BNBC). *International Journal of the Physical Sciences*, *6*(23), 5467–5486.

Sakamoto, I., Ohashi, Y., & Fujii, Y. (1990). Seismic Behavior of Base Isolated Two-Storied Wooden Building. *International Timber Engineering Conference, Tokyo, Japan*, 938–945.

Seifi, M., Noorzaei, J., Jaafar, M. S., & Hejazi, F. (2009). Comparative Study among Conventional and Adaptive Pushover Methods. *ASCE*.

Shaopu, Y., & Yongjun, S. (2007). Recent advances in dynamics and control of hysteretic nonlinear systems. *Shijiazhuang Railway Institute, China. Chaos, Solitons and Fractals*, *40*, 1808–1822.

Shen, K. L., Soong, T. T., Chang, K. C., & Lai, M. L. (1995). Seismic Behaviour of Reinforced Concrete Frame with Added Viscoelastic Dampers. *Engineering Structures*, *17*(5), 372–380.

Tabeshpour, M. ., Azadb, A., Golafshanic, A. ., & Muallad, I. (2012). Torsion Mitigation Of Existing Asymmetric Structures Using Damper. *Asian Journal Of Civil Engineering (Building And Housing)*, *13*(6), 821–840.

Tan, X. M., Ko, J. M., Fang, E. H., & Qian, J. R. (1997). Vibration Control with Viscoelastic Dampers in a High-Rise Building. *International Modal Analysis Conference, SEM, Bethel, CT, Orlando, FL*, 935–941.

Tezcan, S. S., & Uluca, O. (2003). Reduction of Earthquake Response of Plane Frame Buildings by Viscoelastic Dampers. *Engineering Structures*, *25*(14), 1755–1761.

Thanoon, M. A. W. (1993). Inelastic dynamic analysis of concrete frames under non nuclear blast loading. *PhD Thesis, University of Roorkee, India*.

Theodore, K., James, M. R., Richard, S., & Cheng, C. (2011). Experimental evaluation of the seismic performance of steel MRFs with compressed elastomer dampers using large-scale real-time hybrid simulation. *Elsevier, Engineering Structures*, *33*, 1859–1869.

Theodore, K., Tony, B., & Martin, S. W. (2011). Development of nonlinear analytical model and seismic analyses of a steel frame with self-centering devices and viscoelastic dampers. *Computers and Structures*, *89*, 1232–1240.

Timo, V., & Anu, L. (2009). Numerical and analytical modelling of trapped gas in micromechanical squeeze-film dampers. *Journal of Sound and Vibration*, *319*, 606–621.

Toloue, I., Hejazi, F., Huan, C. C., & Jaafar, M. S. (2013). Evaluation of the effect of shear wall distribution in seismic response of precast framed structure. *International Journal of Advancements Civil Structural and Environmental*.

Trombetti, T., & Silvestri, S. (2007). Novel schemes for inserting seismic dampers in shear-type systems based upon the mass proportional component of the Rayleigh damping matrix. *Journal of Sound and Vibration*, *302*, 486–526.

Tsai, C. S., Chen, K. C., & Chen, C. S. (1998). Seismic Resistibility of High-Rise Buildings with Combined Velocity-Dependent and Velocity-Independent Devices. *1998 ASME Pressure Vessels and Piping Conference, ASME, Fairfield, NJ, San Diego, CA*, 103–110.

Tsai, C. S., Chen, W. S., Lee, G. H., & Hsu, L. . (2005). Experimental Tests of Longitudinal Added Damping and Stiffness Device. *2005 ASME Pressure Vessels and Piping Conference, American Society of Mechanical Engineers, New York, NY Denver, CO, 1*, (101–107.).

Tsai, C. S., & Lee, H. H. (1993). Applications of Viscoelastic Dampers to High-Rise Buildings. *Journal of Structural Engineering*, *119*(4), 1222–1233.

Tsai, C. S., & Tsai, K. C. (1995). Tpea Device as Seismic Damper for High-Rise Buildings. *Journal of Engineering Mechanics*, *121*(10), 1075–1081.

Uetani, K., Tsuji, M., & Takewaki, I. (2003). Application of an optimum design method to practical building frames with viscous dampers and hysteretic dampers. *Elsevier, Engineering Structures*, *25*, 579–592.

Vaghei, R., Hejazi, F., Taheri, H., Jaafar, M. S., & Ali, A. A. . (2014). Evaluate performance of precast concrete wall to wall connection. *APCBEE Procedia*, *9*, 285–290.

Vandenbroucke, A., Laurent, H., Hocine, N. A., & Rio, G. (2010). A Hyperelasto-Visco-Hysteresis model for an elastomeric behaviour: Experimental and numerical investigations. *Computational Materials Science*, (48), 495–503.

Vargas, R., & Bruneau, M. (2007). Effect of Supplemental Viscous Damping on the Seismic Response of Structural Systems with Metallic Damping. *Journal of Structural Engineering*, *133*(10), 1434–1444.

Walters, M. T., Honeck, B., & Elsesser, E. (1995). Use of Seismic Isolation in New and Retrofit Construction. *Joint ASME/JSME Pressure Vessels and Piping Conference, Seismic, Shock, and Vibration Isolation, Honolulu, HI*.

Wang, W., & Chen, G. (2006). Dynamic Behavior of a Damping-Enhanced Strengthening System for Seismic Retrofit of Rc Columns. *Structures Congress and Exposition, American Society of Civil Engineers, Reston, VA St. Louis, MO, 84*.

Whittaker, A. S., Bertero, V. V, Thompson, C. L., & Alonso, L. J. (1991). Seismic Testing of Steel Plate Energy Dissipation Devices. *Earthquake Spectra*, *7*(4), 563–604.

Xilin, L., & Zhao, B. (2004). Recent advances of passive structural control And its application in mainland china. *13th World Conference on Earthquake Engineering August Paper*.

Xu, Y. L., & Zhang, W. S. (2001). Modal Analysis and Seismic Response of Steel Frames with Connection Dampers. *Engineering Structures*, *23*(4), 385–396.

Ying, Z., Xilin, L., Dagen, W., & Ruifu, Z. (2012). A practical design method for reinforced concrete structures with viscous dampers. *Engineering Structures*, *39*, 187–198.

Yuki, T., Yukako, I., Susumu, K., Yoshihiro, O., & Fumio, W. (2008). Precast prestressed portal frames with Corrugated steel panel dampers. *Kyoto University, Kyoto. Japan ,WCEE*.

Zhang, X., & Erdman, A. G. (1999). Dynamic Responses of Flexible Linkage Mechanisms with Viscoelastic Constrained Layer Damping Treatment. *Computers and Structures*, *79*(13), 1265–1274.

Zheng-qing, C., & Zhi-hao, W. (2009). A novel passive energy dissipation system for frame-core tube structure. *Hunan University Changsha ,China ,APCWEV*.