

SEISMIC PERFORMANCE OF INNOVATIVE DOUBLE LAYER SPACE SHEAR  
WALL

BEHZAD BAYAT

UNIVERSITI TEKNOLOGI MALAYSIA

SEISMIC PERFORMANCE OF INNOVATIVE DOUBLE LAYER SPACE SHEAR  
WALL

BEHZAD BAYAT

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering  
Universiti Teknologi Malaysia

JUNE 2014

## **DEDICATION**

I would like to dedicate this thesis to my beloved wife, Reihaneh, for her support and unconditional love.

## **ACKNOWLEDGEMENT**

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my supervisors, Tan Sri Prof. Ir. Dr. Mohd Zulkifli bin Tan Sri Mohd Ghazali and Prof. Dr. Ir. Mahmood Bin Md. Tahir who inspired, encouraged, supported, and advised me during past four years to accomplish my PhD study. Without their continued support and interest, this thesis would not have been the same as presented here. I also would like to thank UTM Construction Research Center for supporting me to carry out this research.

I would like to express my sincere and boundless gratitude to Prof. Daniel Aldrich for his constructive and valuable advices, Ir. Sundrarajan for his encouragement and continued supports, Ms. Dharshini, and Mr. Toong for their great assists. I also would like to thank Mr. Mehran Montazeri Shatoori for his great technical contribution and Ms. Reihaneh Montazeri for her outstanding editing and proofreading.

## ABSTRACT

Various kinds of seismic structural systems could not completely satisfy engineers due to excessive rigidity and low ductility. Then engineers innovate advanced ductile structural systems like viscous elastic dampers to dissipate earthquake forces and insulate important structural elements in safe zone; however these systems have not been pervasive in construction industry due to high production cost. Indeed, optimization of stiffness, ductility, and construction cost are the major challenges facing the engineering profession in designing a perfect lateral system. This research introduces Space Shear Wall (SpaSW), as an innovative earthquake resistant system for structures and evaluates its feasibility and seismic performance through three-dimensional linear and nonlinear-static, linear-dynamic, and finite element analysis carried out by ETABS and ANSYS program. Space shear wall is defined as a double-layer diagonal space frame structure with ball joints vertically used as infill wall. The comparative study between SpaSW and steel bracing used in typical low to high-rise structures expressed that structural drift of SpaSW is slightly higher than steel bracing. However the ductility, energy dissipation, members' stress and distribution of earthquake force in SpaSW are significantly better than typical steel bracing. In addition, failure mechanism of SpaSW were favourable due to its gradual process through many ball joints. Moreover, lightness, industrialization, maintainability and reparability, compatibility with architectural considerations, low cost, simple and fast fabrication are other realized advantages. Developing this concept would be considered in the future studies through optimization of material, grid patterns, connection, and additional dampers.

## ABSTRAK

Pelbagai jenis sistem struktur seismik tidak dapat memenuhi keperluan para jurutera dengan sepenuhnya disebabkan oleh ketegaran struktur yang berlebihan dan kemuluran yang rendah. Dengan itu jurutera telah mencipta system struktur mulur yang lebih maju seperti penyerap likat anjal yang dapat mengurangkan daya gempa bumi dan seterusnya melindungi elemen struktur utama dalam zon selamat. Namun demikian sistem ini belum lagi meluas penggunaannya dalam industri pembinaan disebabkan oleh kos pengeluaran yang tinggi. Sebenarnya, pengoptimuman ketegangan, kemuluran, dan kos pembinaan adalah cabaran utama yang dihadapi oleh bidang kejuruteraan dalam mereka bentuk sistem sisian yang sempurna. Kajian ini memperkenalkan “Space Shear Wall” (SpaSW), sebuah sistem struktur inovatif yang mempunyai daya ketahanan seismik yang dapat menilai kebolehlaksanaan dan prestasi seismik melalui analisis linear, statik bukan linear, dinamik linear dan unsur terhingga tiga-dimensi yang dilaksanakan oleh ETABS dan program ANSYS. Dinding ricih ruang ditakrifkan sebagai struktur kerangka ruang pepenjuru dua lapisan dengan sendi bola, digunakan secara menegak sebagai dinding isian. Kajian perbandingan diantara SpaSW dan keluli perambatan yang dijalankan ke atas struktur yang bertingkat rendah ke struktur yang bertingkat tinggi, membuktikan bahawa kecondongan struktur adalah sedikit tinggi berbanding dengan keluli perambatan. Walau bagaimanapun, kemuluran, pelepasan tenaga, tekanan dan taburan tenaga gempa bumi bagi SpaSW adalah jauh lebih baik daripada keluli perambatan biasa. Di samping itu, kegagalan mekanisme SpaSW lebih memihak kepada proses berperingkat melalui sendi sambungan bebola yang banyak. Selain daripada itu, keringanan, perindustrian, penyelenggaraan, pembaikan pulihan, keserasian dengan pertimbangan seni bina arkitek, kos rendah, fabrikasi mudah dan pantas adalah kelebihan lain yang realistik. Konsep yang selanjutnya akan dipertimbangkan dalam kajian pada masa hadapan melalui pengoptimuman bahan, corak grid, sambungan terperinci, dan penyerap tambahan.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xi
	<b>LIST OF FIGURES</b>	xiii
	<b>LIST OF ABBREVIATIONS</b>	xxiii
	<b>LIST OF SYMBOLS</b>	xxv
	<b>LIST OF APPENDIX</b>	xxvii
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background of the study	1
	1.2 Statement of the Problem	4
	1.3 Objectives of the Study	5
	1.4 Research Questions	5
	1.5 Significance of the Study	6
	1.6 Scope of the Study	6
	1.7 Methodology and Research Framework	6
	1.8 Definition of Terms	7
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>9</b>
	2.1 Review on Current Seismic Systems	9
	2.1.1 Steel Bracing	10

2.1.1.1	Concentrically Braced Frames (CBF)	11
2.1.1.2	Eccentrically Braced Frames (EBF)	15
2.1.1.3	Unfavourable Failure Modes of Steel Braced Frames	16
2.1.2	Steel Plate Shear Wall	19
2.1.3	Moment Resisting Frame (MRF)	24
2.1.4	Concrete Shear Wall	26
2.2	Introductory on Space Structures	30
2.3	History of Space Frame Structure	34
2.4	Expected Advantages of Space Shear Wall	39
2.4.1	High Stiffness	40
2.4.2	High Ductility, Damping, and Energy Dissipation	40
2.4.3	Lightness	43
2.4.4	Ability to Industrialize	44
2.4.5	Compatibility with architectural Consideration	45
2.4.6	Ability to maintain and repair	49
2.4.7	Ability for Retrofitting of Structures	49
2.4.8	Low cost	54
2.4.9	Simple and fast construction	54
<b>3</b>	<b>THEORETICAL BACKGROUND</b>	<b>56</b>
3.1	Introduction	56
3.2	Types of Seismic Analysis	56
3.3	An Overview on International Building Code (IBC)	61
3.4	IBC Seismic Design Procedure	62
3.4.1	IBC Seismic Design Determinant Factor	63
3.4.1.1	Occupancy Risk Category	63
3.4.1.2	Seismic Importance Factor ( $I_e$ )	65
3.4.1.3	Mapped Spectral Response Accelerations	65
3.4.1.4	Site Coefficients and Adjusted MCE Spectral Response Acceleration	67
3.4.1.5	Design Spectral Response Acceleration Parameters	68
3.4.1.6	Site Class	69
3.4.1.7	Seismic Design Category (SDC)	69
3.4.1.8	Response Modification Factor, System	



	Overstrength and Deflection Amplification	70
	3.4.1.9 Period	75
	3.4.2 Seismic Analysis Methods in Accordance to International Standards	76
	3.4.2.1 Equivalent Lateral Force Procedure	77
	3.4.2.2 Response Spectrum Analysis (RSA)	80
	3.4.2.3 Time History Analysis	87
	3.4.2.4 Quasi Cyclic Analysis (QCA)	88
	3.4.2.5 Inelastic Static Analysis (ISA) or Pushover Method	89
	3.4.2.6 Finite Element Analysis (FEA)	93
	3.4.3 Determinant Criteria for Evaluation of Seismic Resistant Structures	96
	3.4.3.1 Story Lateral Displacement and Drift	96
	3.4.3.2 Design Limits under Code's Load Combination	98
	3.4.3.3 Ductility	99
	3.4.3.4 Energy Dissipation	104
<b>4</b>	<b>METHODOLOGY</b>	<b>107</b>
	4.1 Concept of Space Shear Wall (SpaSW)	107
	4.2 Models Specifications	109
	4.3 Research Tools	114
	4.4 Procedure	114
	4.5 Data Processing and Analysis	115
	4.6 Verification and Validation	115
<b>5</b>	<b>RESULTS AND DISCUSSION</b>	<b>119</b>
	5.1 Introduction	119
	5.2 Analysing the SpaSW System via ETABS Non-linear Software	120
	5.3 Performance of SpaSW under Equivalent Earthquake Force	120
	5.3.1 Lateral Performance of SpaSW with Pinned Restrained Boundary Conditions (Model S1)	123
	5.3.2 Lateral Performance of SpaSW Surrounded by Steel Frame	125
	5.3.3 Lateral Performance of SpaSW Surrounded by	

	Reinforced Concrete (RC) Frame	127
5.3.4	Discussion on Lateral Performance of Models C1, C2, C3, S1, S2, and S3	128
5.4	Performance of SpaSW under Earthquake Load (Quasi Method)	132
5.4.1	Comparative Study on One Story Building using SpaSW as Lateral System under Earthquake Load	139
5.4.2	Comparative Study on Five Story Building Using SpaSW as Lateral System under Earthquake Load	145
5.4.3	Comparative Study on twenty Story Building Using SpaSW as Lateral System under Earthquake Load	149
5.4.4	Discussion on Seismic Response of SpaSW under Equivalent Static Analysis	152
5.5	Seismic Performance of SpaSW under IBC Response Spectrum Analysis (RSA)	157
5.6	Seismic Performance of SpaSW under Time-History Elastic Dynamic Analysis (EDA)	170
5.7	Seismic Performance of SpaSW under Quasi Cyclic Analysis (QCA)	187
5.8	Seismic Performance of SpaSW under Inelastic Static Analysis (ISA)	197
5.9	Finite Element Analysis (FEA)	209
<b>6</b>	<b>CONCLUSION</b>	<b>221</b>
6.1	Conclusions Based on Major Findings	222
6.2	Limitations of the Study	225
6.3	Recommendations Based on Findings	225
6.4	Recommendations for Future Research	226
	<b>REFERENCES</b>	<b>227</b>
Appendices	A - L	236-338

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Connection types with a node (Gerrits, 1996)	33
2.2	Connection types without a node (Gerrits, 1996)	34
2.3	Connection type with prefabricated units (Gerrits, 1996)	34
2.4	Famous projects using spatial structure	38
2.5	Ductility types (Gioncu and Mazzolani, 2002)	42
2.6	Specifications of the reinforcing materials	50
2.7	Results of structural design for reinforcement (Hiyama, 2004)	52
2.8	Comparison of SpaSW seismic features with common lateral systems	55
3.1	Occupancy risk category of buildings and other structures (ASCE, 2010)	64
3.2	Importance factors by risk category of buildings and other structures for earthquake loads (ASCE, 2010)	65
3.3	Spectral response acceleration for Malaysia in SI (JKR, 2007)	66
3.4	Values of Site Coefficient $F_a^a$	67
3.5	Values of site coefficient $F_v^a$	67
3.6	Site classification	69
3.7	Seismic design category based on short period response acceleration parameter (ASCE, 2010)	70
3.8	Seismic design category based on 1-S period response acceleration parameter (ASCE, 2010)	70
3.9	Design coefficients and factors for Seismic force-resisting systems (ASCE, 2010)	71
3.10	Coefficient for upper limit on calculated period	79
3.11	Values of approximate period parameters $C_t$ and $x$	79
3.12	Characteristics of the recorded ground motions (Lee et al., 2007)	82
3.13	Design spectral response acceleration against period	83

3.14	Allowable story drift, $\Delta_a$ (BSSC, 2004)	97
4.1	Specification of models investigated in research	111
4.2	Technical description of SpaSW	113
5.1	Geometric properties of single storey-single bay CB and SpaSW models	121
5.2	List of models analysed under lateral static force	122
5.3	Boundary condition of model S1 and C1 (Free=1, Fixed=0)	124
5.4	Comparison of seismic performance between models S1 and C1	124
5.5	Comparison of seismic performance between models S2 and C2	126
5.6	Comparison of seismic performance between models S3 and C3	128
5.7	Comparison of lateral performance of SpaSW and CB models with different boundary conditions under equivalent static load	129
5.8	Comparison of SBR for single story-single bay models with different boundary conditions under equivalent static load	130
5.9	Geometric and loading information for building models using SpaSW and BR	134
5.10	Comparison of seismic response of six typical buildings using SpaSW and BR	138
5.11	Modal participating mass ratios for model SP20	161
5.12	Modal participating mass ratios for model BR20	161
5.13	Estimation of RSA scale factor for models SP20 and BR20	162
5.14	Base shear force under AISC QSA for models SP20 and BR 20 in X and Y Directions	189
5.15	Properties of models S4 and C4	199
5.16	Properties of models S5 and C5	210

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Concept of cross bracing systems	2
1.2	Early concept for Space Shear Wall (SpaSW)	3
1.3	Initial natural inspiration of SpaSW	3
1.4	Early conceptual model for SpaSW	4
2.1	Gaiola construction in Lisbon after 1755 earthquake (Reitherman, 2012)	10
2.2	Distribution of damage levels (left) and damage to structural members and connections (right) with respect to structure type. Key: UFD= Unbraced frame; BF= Braced frame; H= Wide flange sections; S= Square tube sections (Di Sarno and Elnashai, 2009)	11
2.3	Examples of bracing schemes for concentrically braced frames: (a) X- braced;(b) diagonally braced; (c) alternative diagonally braced; (d) V- braced; (e) inverted V-braced; and (f ) K-braced (Booth and Key, 2006)	12
2.4	Examples of concentrically braced frames (a) Inverted V bracing (b) Combination of inverted V and V bracing (Engelhardt, 2007)	13
2.5	Failure of X-braced steel frame, Kobe, Japan, 1995 (Booth and Key, 2006)	13
2.6	Inelastic response of CBFs under earthquake loading (Engelhardt, 2007)	14
2.7	Yielded bracing members under tensile and compressive force (Engelhardt, 2007)	14
2.8	Examples of eccentrically braced frames (Nayfeh and Pai, 2008)	15
2.9	Unfavourable modes of failure for steel bracing a) Column tension fracture b) Connection fracture c) Column buckling d) In plane buckling e) Beam failure f) Brace buckling (Sabelli, 2006)	16

2.10	Failure of concentric bracing members (Seiculescu, 2006)	17
2.11	Failure of intersection connection for cross bracing system under Bam earthquake 2004	17
2.12	Failure of cross bracing connection to column under bam earthquake, 2004	18
2.13	Failure of cross bracing member at connection, Kobe earthquake 1997 (Pars Civil Technology, 2010)	18
2.14	Failure of multi-storey steel-framed buildings, Mexico City, 1985 (Booth and Key, 2006)	19
2.15	Proposed strip model for SPSW (Thorburn et al., 1983)	20
2.16	Simplified strip model (Rezai et al., 2000)	22
2.17	Propose two-way SPSW strip model (Chen and Jhang, 2006)	23
2.18	Collapsed steel MRF with partial brick infill wall, 2009 Sumatra earthquake, Padang, Indonesia (Hyland and Miller, 2009)	24
2.19	Five storey two way steel moment resisting frame collapsed under 2009 Sumatra earthquake, Padang, Indonesia (Hyland and Miller, 2009)	25
2.20	Olive view hospital, a moment-resisting frame, failure under 6.6 magnitude 1971 California earthquake (Khalili-Tehrani and Taciroglu, 2008)	25
2.21	Soft story failure mechanism (Guney and Aydin, 2012)	26
2.22	Connection collapse observed in non-ductile reinforced concrete buildings due to strong ground shaking (Khalili-Tehrani, and Taciroglu, 2008)	26
2.23	Types of shear walls: a) Simple rectangular types b) Coupled shear walls c) Rigid frame shear walls d) Framed walls with infilled frames e) Column supported shear walls f) Core type shear walls (Varghese, 2009)	27
2.24	Survival of precast panel buildings adjacent to ruined precast frame buildings, Spitak, Armenia, 1988 (Booth and Key, 2006)	28
2.25	Collapse of a reinforced concrete building using concrete shear wall, Mexico City, 1985 (Booth and Key, 2006)	28
2.26	Major failure of a multi-story reinforced concrete residential structure occurred, Chile, 2010 (Franco et al, 2010)	29
2.27	Structural vulnerabilities of existing buildings (Gould, 2007)	29

2.28	Various application of space frame structure. a) Human skeleton b) Crane tower c) Roof truss d) Lightest bicycle using space frame e) Tracker electricity generator f) Vehicle skeleton (Nooshin, 2008)	30
2.29	Common basic patterns (Nooshin, 2002)	31
2.30	Examples of double layer grids (Nooshin, 2002)	32
2.31	Early experimental space grid structure developed by Alexander Graham Bell (Chilton, 2012)	35
2.32	Details of Mero system joint and space frame (Chen and Lui, 2012)	36
2.33	Ford Rotunda building, Ford River Rouge plant, Dearborn, Michigan	36
2.34	Buckminster Fuller's geodesic dome for US pavilion at Expo '67, Montreal, Canada (Chilton, 2012)	37
2.35	Proposal detail for Milan structure (Halvorson, 2008)	39
2.36	Plan and details for Russia tower (Halvorson and Warner, 2007)	39
2.37	Manufacturing of space frame elements in factory (Xuzhou Huahai Steel Structure Co., 2012)	44
2.38	Packing the space frame elements for transportation to construction site (Xuzhou Huahai Steel Structure Co., 2012)	45
2.39	Proposed erection method for SpaSW	45
2.40	Classification of tall building structural systems by Fazlur Khan (Ali and Moon, 2007)	46
2.41	Architectural-structural integration of space grid structures a) 30 St Mary Axe, London b) Hearst tower, New York c) Almaty twin tower, Almaty d) Double-layer space structure of an un-built 150 storey project , Chicago e) Gakuen spiral tower, Nogoya f) Skytree tower, Tokyo (Nooshin, 2008)	47
2.42	A model of a three-storey section of a double-layer space structure building b) Exposed structure using exterior space frame c) Typical interior space application using the horizontal folded façade system d) Two types of balconies with open views e) An entrance for a building with internal façade f) Curved external glazing (Sutjiadi and Charleson, 2012)	48
2.43	Computer graphic drawing of existing RC buildings reinforced by SNE-Truss (Hiyama, 2004)	50
2.44	Shape and material of SNE-Truss (Hiyama, 2004)	51
2.45	Relationship of shear strength and deflection (Hiyama, 2004)	51

2.46	Example of structural design using SNE-Truss (Hiyama, 2004)	52
2.47	Simple beam loading test (Hiyama, 2004)	53
2.48	In-plane loading test (Hiyama, 2004)	53
3.1	Various types of seismic Analysis	57
3.2	Linear elastic analysis method: (a) Equivalent lateral force; (b) Mode superposition; (c) Time history (Gioncu and Mazzolani, 2002)	60
3.3	Inelastic analysis methods: (a) Plastic; (b) Pushover; (c) Time History (Gioncu and Mazzolani, 2002)	61
3.4	Peak ground acceleration (PGA) map for 500 years return period (JKR, 2007)	66
3.5	Effect of the 2/3 factor for site class D in 2003 IBC, for: (a) Los Angeles and (b) New York City (Nikolaou, 2008)	68
3.6	Vertical distribution of earthquake force in ESA method	77
3.7	Define static load case menu in ETABS	80
3.8	IBC 2006 seismic loading menu in ETABS	80
3.9	Smoothed design spectrum	81
3.10	Normalized spectral pseudo-acceleration for the six recorded ground motions computed for 3% viscous damping (Lee et al., 2007)	82
3.11	IBC design response spectrum	83
3.12	Typical elastic design spectrum indicating constant factors	83
3.13	Schematic diagram for modal response combination this study uses ETABS software RSA method through following steps	84
3.14	Define the response spectrum in ETABS	85
3.15	Define response spectrum case in ETABS	85
3.16	Define number of modes in ETABS	86
3.17	El-Centro earthquake record (Thai and Kim, 2011)	88
3.18	Cyclic loading protocol by AISC (AISC, 2002)	89
3.19	Main steps for static pushover (Napier and Powell, 2013)	89
3.20	Bilinear approximation of pushover curve (Napier and Powell, 2013)	90
3.21	Static pushover curve (Booth and Key, 2006)	92
3.22	Plastic and elastic deflection under imposed force (Booth and Key, 2006)	92
3.23	Typical force-displacement diagram indicating serviceability limit states (Abell, 2013)	93
3.24	Various types of finite elements used for FEA	94
3.25	Story drift determination (ASCE, 2010)	98



3.26	Stress-strain hysteresis curve of a steel structure under cyclic load (The European Steel Design Education Programme, 1993)	100
3.27	Force-displacement diagram for low, medium and high ductility	101
3.28	Examples of loading time history (The European Steel Design Education Programme, 1993)	102
3.29	Hysteresis loop types	103
3.30	Influence of loading history on the cycle behaviour of beams (The European Steel Design Education Programme, 1993)	103
3.31	Oscillation of pendulum	105
3.32	Hysteretic energy curve	106
4.1	Three-dimensional model of diagonal and two-way SpaSW	108
4.2	Distribution of lateral loads into the SpaSW members (C=Compression; T=Tension)	109
4.3	Perspective view of models investigated in this research	112
4.4	Specimens and loading system for in-plane shearing tests of truss wall	116
4.5	Load-deflection curve for specimen A	117
4.6	Elevation view of analytical model in ETABS	117
4.7	Deflection of analytical model under cyclic load	117
4.8	Comparison of load-deflection diagram between analytical and Okubo experimental model	118
5.1	Three-dimensional view of model S1	123
5.2	Three dimensional view of model C1	124
5.3	Three-dimensional view of model S2	125
5.4	Elevation view of model C2	126
5.5	Three-dimensional view of Model C3	127
5.6	Three-dimensional view of model S3	128
5.7	Comparison of SBR for single story-single bay models with different boundary conditions under equivalent static load	130
5.8	Typical layout plan for modelled building using SpaSW	133
5.9	Typical layout plan for modelled building using IV and CB	133
5.10	Perspective view of one story building using bracing (BR1)	134
5.11	Perspective view of five story building using bracing (BR5)	135
5.12	Perspective view of twenty story building using bracing (BR20)	135
5.13	Perspective view of one story building using SpaSW (SP1)	136
5.14	Frontal view of SpaSW in three-dimensional structure	136

5.15	Perspective view of five story building using SpaSW (SP5)	136
5.16	Perspective view of twenty story building using SpaSW (SP20)	137
5.17	Comparison between CM lateral displacement of SP1 and BR1	140
5.18	Comparison between CM drift of SP1 and BR1	140
5.19	Comparison between maximum reaction force of SP1 and BR1	141
5.20	Comparison between average reaction force of SP1 and BR1	141
5.21	Comparison between maximum brace force of SP1 and BR1	142
5.22	Comparison between average brace force of SP1 and BR1	142
5.23	Comparison between maximum brace stress ratio of SP1 and BR1	143
5.24	Comparison between average brace stress ratio of SP1 and BR1	143
5.25	Reaction force of BR1	144
5.26	Reaction force of SP1	144
5.27	Comparison between CM lateral displacement of SP5 and BR5	146
5.28	Comparison between CM drift of SP5 and BR5	146
5.29	Comparison between maximum reaction force of SP5 and BR5	147
5.30	Comparison between average reaction force of SP5 and BR5	147
5.31	Comparison between maximum brace force of SP5 and BR5	147
5.32	Comparison between average brace force of SP5 and BR5	148
5.33	Comparison between maximum brace stress ratio of SP5 and BR5	148
5.34	Comparison between average brace stress ratio of SP5 and BR5	148
5.35	Comparison between CM displacement of SP20 and BR20	150
5.36	Comparison between CM drift of SP20 and BR20	150
5.37	Comparison between maximum reaction force of SP20 and BR20	150
5.38	Comparison between average reaction force of SP20 and BR20	151
5.39	Comparison between maximum brace force of SP20 and BR20	151
5.40	Comparison between average brace force of SP20 and BR20	151
5.41	Comparison between maximum brace stress ratio of SP20 and BR20	152
5.42	Comparison between average brace stress ratio of SP20 and BR20	152
5.43	Comparison of SBR for lateral displacement of models SP and BR	153
5.44	Schematic diagram of stress-strain for a brittle and ductile structure	154
5.45	Failure of 6-story non-ductile structure under a destructive test	155
5.46	Comparison of SBR for average reaction force of models SP and BR	155
5.47	Comparison of SBR for average lateral system member's stress of models SP and BR	156
5.48	Comparison of SBR for average lateral system member's force of models SP and BR	157

5.49	IBC response spectrum considered for RSA method	158
5.50	a) Modal shapes of model SP20 under RSA b) Modal shapes of model BR20 under RSA	159
5.51	Lateral displacement of model SP20 at modes 1, 2, and 3	162
5.52	Lateral displacement of model SP20 at modes 4, 5, and 6	163
5.53	Lateral displacement of model SP20 at modes 7, 8, and 9	163
5.54	Lateral displacement of model SP20 at modes 10, 11, and 12	164
5.55	Lateral displacement of model SP20 at modes 13, 14, and 15	164
5.56	Floor's lateral displacement of models SP20 and BR20 under RSA and ESA method in X direction	165
5.57	Floors' lateral displacement of models SP20 and BR20 under RSA and ESA method in Y direction	166
5.58	Maximum lateral displacement of models SP20 and BR20 under RSA and ESA method in X and Y directions	166
5.59	Comparison of SBR factor for maximum lateral displacement under RSA and ESA methods	167
5.60	SP20 Lateral CM drift under RSA and ESA method in X and Y Directions	167
5.61	Comparison of structure period between models BR20 and SP20 based on RSA method	168
5.62	Response spectrum acceleration diagram indicating first 15 Modes of SP20 against IBC Design Response Spectrum	169
5.63	Zoning of response spectrum against period	169
5.64	Story acceleration under RSA method for models SP20 and BR20 in X and Y directions	170
5.65	Acceleration time history of El-Centro ground motion	171
5.66	Possible dynamic response to time history analysis a) Dynamically stable with exponential decay, b) Dynamically stable with sinusoidal oscillation in exponential decaying envelope, c) Neutral dynamic stability d) Dynamically unstable with sinusoidal oscillation in exponentially increasing envelope, and e) Dynamically unstable with exponential increase (CA, 1988)	173
5.67	Maximum CM displacement of SP20 and BR20 in X direction under time history of El-Centro earthquake	173
5.68	Maximum CM displacement of SP20 and BR20 in Y	

	Direction under time history of El-Centro Earthquake	174
5.69	Baseline acceleration, velocity, and displacement time histories (Darragh et al., 2004)	174
5.70	Acceleration time history of models SP20 and BR20 under El-Centro earthquake in X direction	175
5.71	Acceleration time history of models SP20 and BR20 under El-Centro earthquake in Y direction	176
5.72	Base shear force time history graph in X direction	176
5.73	Base shear force time history graph in Y direction	177
5.74	Input energy curve for SP20 and BR20 based on time steps	178
5.75	Potential energy curve for SP20 and BR20 based on time steps	178
5.76	Kinetic energy curve for SP20 and BR20 based on time steps	179
5.77	Hysteresis curve for axial force-elongation of most critical SP20 lateral system's members	180
5.78	Hysteresis curve for axial force-elongation of most critical BR20 lateral system's members	180
5.79	Hysteresis curve for axial force-elongation of most critical BR20 lateral system's members	181
5.80	Hysteresis curve for acceleration-CM displacement in X direction	182
5.81	Hysteresis curve for acceleration-CM displacement in X direction	182
5.82	Radar hysteresis graph for acceleration-CM displacement in X direction for models SP20 and BR20	183
5.83	Radar Hysteresis graph for acceleration-CM displacement in Y direction for models SP20 and BR20	183
5.84	Hysteresis curve for base shear force - CM displacement in X direction for models SP20 and BR20	184
5.85	Hysteresis curve for base shear force - CM displacement in Y direction for models SP20 and BR20	184
5.86	Radar hysteresis graph for base shear force - CM displacement in X direction for models SP20 and BR20	185
5.87	Radar hysteresis graph for base shear force - CM displacement in Y direction for models SP20 and BR20	185
5.88	Maximum and minimum CM displacement under EDA method for models SP20 and BR20	186
5.89	Maximum and minimum CM displacement under EDA method for models SP20 and BR20	186

5.90	AISC cyclic loading protocol (AISC, 2002)	187
5.91	Cyclic spectral acceleration time history for models SP20 and BR20 in X direction	188
5.92	Cyclic spectral acceleration time history for models SP20 and BR20 in Y direction	188
5.93	Schematic spectral acceleration time history of buildings under a unique ground motion (Chandradhara, 2013)	189
5.94	Base shear force time history of models SP20 and BR20 under QCA in X direction	191
5.95	Base shear force time history of models SP20 and BR20 under QCA in Y direction	191
5.96	Base shear force time history of models SP20 and BR20 under QCA in Y Direction	192
5.97	Base shear force time history of models SP20 and BR20 under QCA in Y direction	192
5.98	Displacement time history of models SP20 and BR20 under QCA in X Direction	193
5.99	Displacement time history of models SP20 and BR20 under QCA in Y Direction	193
5.100	Hysteresis curve of base shear force-CM displacement for model SP20 in X direction	194
5.101	Hysteresis curve of base shear force-CM displacement for models SP20 and BR20 in X direction	195
5.102	Hysteresis curve of base shear force-CM displacement for models SP20 and BR20 in Y direction	195
5.103	Hysteresis curve of spectral acceleration-CM displacement for models SP20 and BR20 in X direction	196
5.104	Hysteresis curve of spectral acceleration-CM displacement for models SP20 and BR20 in Y direction	196
5.105	Three-dimensional view of model S4	198
5.106	Three-dimensional view of model C4	198
5.107	Capacity curve of model S4	200
5.108	Idealized capacity curve with positive post-yield slope	201
5.109	Idealized capacity curve with negative post-yield slope	201
5.110	Capacity curve for model C4	202
5.111	Capacity curve for models S4 and C4 under ISA method	203

5.112	Collapse mechanism of model S4 at steps 1, 135, 161, 179, 233, and 300 of incremental imposed displacement	205
5.113	Collapse mechanism of model S4 at steps 400, 500, 600, 800, 1000, and 1500 of incremental imposed displacement	206
5.114	Collapse mechanism of model S4 at steps 2000, 2500, 3000, 3500, and 3564 of incremental imposed displacement	207
5.115	Collapse mechanism of model C4 at steps 0, 1, 3, 8, 33, and 53 of incremental imposed displacement	208
5.116	Elevation view of model S5	209
5.117	Three-dimensional view of model S5	210
5.118	Modelled Mero ball joints in ANSYS program	211
5.119	Finite element model for model S5	211
5.120	Finite element model for Model C5	212
5.121	Non-constant amplitude load history data imposed on models S5 and C5 (AISC, 2002)	212
5.122	Static deformation of model S5 under lateral force	213
5.123	Static deformation of model S5 under lateral force	214
5.124	Static equivalent stress of model S5 under lateral force	215
5.125	Static equivalent stress of model C5 under lateral force	215
5.126	Static equivalent elastic strain of model S5 under lateral force	216
5.127	Life energy contours of model S5 under lateral force	217
5.128	Life energy contours of model C5 under lateral force	217
5.129	Hysteresis curve for models C5 and S5 based on FEA	218
5.130	Dissipated and stored force for hysteretic cycles	219

## LIST OF ABBREVIATIONS

AISC	-	American Institute of Steel Construction
ASCE	-	American Society of Civil Engineers
ATC	-	Applied Technology Council
BR	-	Bracing
CB	-	Cross Bracing
CM	-	Center of Mass
CBF	-	Concentrically Braced Frames
DCR	-	Demand-Capacity Ratio
Dspl	-	Displacement
EBF	-	Eccentrically Braced Frames
EDA	-	Elastic Dynamic Analysis
ESA	-	Equivalent Static Analysis
FEA	-	Finite Element Analysis
FEM	-	Finite Element Model
IBC	-	International Building Code
IBS	-	Industrialized Building System
ISA	-	Inelastic Static Analysis
I-V	-	Inverted-V
IDA	-	Inelastic Dynamic Analysis
JBDPA	-	Japan Building Disaster Prevention Association
MDOF	-	Multi Degree of Freedom
OECD	-	Organisation for Economic Co-operation and Development
QCA	-	Quasi-Static Cyclic Analysis
RC	-	Reinforced Concrete
SBR	-	SpaSW-Bracing Ratio
SCBF	-	Special Concentrically Braced Frames
SDOF	-	Single Degree of Freedom
SEAOC	-	Structural Engineers Association of California

SpaSW	-	Space Shear Wall
SPSW	-	Steel Plate Shear Wall
THA	-	Time History Analysis
UBC	-	Uniform Building Code
UFD	-	Unbraced frame
BF	-	Braced frame
H	-	Wide flange sections
S	-	Square tube sections



## LIST OF SYMBOLS

$I_S$	Ratio of the horizontal load
${}_R I_S$	$I_S$ after reinforcement
$\alpha$	Safety factor
$I_{SO}$	Required $I_S$
$\Delta I_S$	Increased “ $I_S$ ” by using SNE-Truss
$S_D$	Reduction factor
$T$	Period
$C$	Strength index
$F$	Ductility index
$M$	Mass
$m$	Metre
$mm$	Millimetre
$c$	Damping factor
$k$	Stiffness of structures
$u(t)$	Function of displacement
$\dot{u}(t)$	Velocity
$\ddot{u}(t)$	Acceleration
$F(t)$	Time dependent Force
$\omega_0$	Modal natural frequency
$z$	Damping ratio
$P$	Constant participating factor
$F_a$	Site coefficient
$F_v$	Site coefficient
$S_1$	Mapped maximum considered
$S_{DS}$	Design spectral response
$S_{D1}$	Design spectral response
$T$	Fundamental period of the structure
$\omega$	Angular frequency
$T_a$	Approximate fundamental period
$C_t$	Seismic factor
$h_n$	Structural height
$N$	Number of stories above the base
$V$	Seismic base shear
$C_s$	Seismic response coefficient
$W$	Effective seismic weight
$R$	Response modification factor
$I_e$	Importance factor
$T_L$	Long-period transition period
$V_x$	Seismic design story shear in any
$F_i$	Portion of the seismic base shear

$S_a$	A
$T_0$	Initial Period
$R_j$	Maximum modal response
$R_k$	Maximum modal response
$C_{jk}$	Modal coupling factor
$g$	Acceleration due to gravity
$I g / R$	Response spectrum scale factor
$\delta_x$	Deflection $\delta_x$ at level x
$C_d$	Deflection amplification factor
$\delta_{xe}$	Deflection at the location required
E	Seismic load effect
$E_h$	Effects of horizontal seismic forces
$E_v$	Effects of vertical seismic forces
D	Dead load
E	Earthquake load
H	Load due to lateral earth pressure
L	Live load
$L_r$	Roof live load
R	Rain load
S	Snow load
W	Wind load
SDS	Design spectral response
QE	Effect of horizontal seismic forces
$\rho$	Redundancy factor
$\mu_\varepsilon$	Material ductility
$\mu_\theta$	Structural element or joint ductility
$\mu_\delta$	Structural ductility
$\varepsilon_o$	Maximum deformation
$\varepsilon_\psi$	Yield deformation
$V_g$	Gravitational potential energy
W	Constant weight
$h$	Constant gravitational field of
$v$	Velocity
$V_k$	Kinetic energy
$E_h$	Hysteresis ductility
$E_{h,tot}$	Total dissipated energy
$E_h^+$	Area of hysteresis curve above the
$E_h^-$	Hysteresis curve below the strain
SBR	SpaSW over bracing ratio
$F_a$	Force
$K_a$	Stiffness
$d$	Displacement
t	Time
$u(t)$	Time dependent Displacement
$c$	Damping
$k$	Stiffness
E	Young's modulus
A	Cross section area
L	Length of bracing
K	Stiffness of bracing

**LIST OF APPENDIX**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Verification of ETABS output with Manual Calculation for a single bracing	236
B	Analysis output of model C2	240
C	Analysis output of model C3	242
D	Analysis output of model S1	244
E	Analysis output of model S2	246
F	Analysis output of model S3	248
G	Analysis output of model BR1	252
H	Analysis output of model BR5	259
I	Analysis output of model BR20	269
J	Analysis Output Of Model SP1	290
K	Analysis Output Of Model SP5	333
L	Analysis output of model SP20	335

## CHAPTER 1

### INTRODUCTION

#### 1.1 Background of the Study

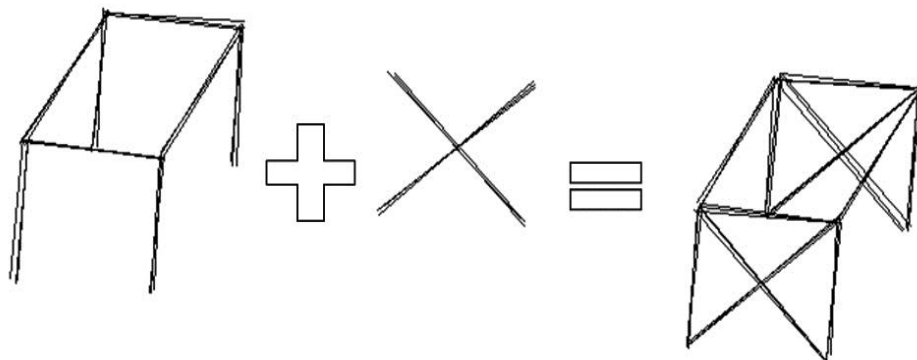
Over the past decades, earthquake and wind hazards have seriously influenced structural engineering principles. In this respect, major advances in earthquake engineering have occurred in both understanding and practice of seismic force-resisting systems. Therefore, various kinds of seismic systems were created to protect buildings from natural disasters but most of these systems could not completely satisfy engineers. Critics of current seismic systems believe that common rigid systems absorb the earthquake energy and transfer it to the structural elements. Hence engineers introduced ductile seismic systems to dissipate dynamic forces and insulate important structural elements in safe zone.

A ductile seismic system under earthquake loading dissipate earthquake forces and insulate important structural elements in safe zone like a fuse box in an electrical board, which is an essential safety device that cut off the flow of electricity if a fault occurs and protect the individual circuits that convey electricity to the various applications. However, the use of ductile systems has resulted in invention of many advanced systems like viscous elastic dampers, but these high-tech systems have not commonly been used due to their high costs and complicated fabrication. Indeed, optimisation of stiffness, ductility, and construction cost are the major challenges facing the engineering profession in designing a perfect lateral system, which is a ductile structural system with adequate stiffness that efficiently functions to resist lateral loads from wind or earthquake.

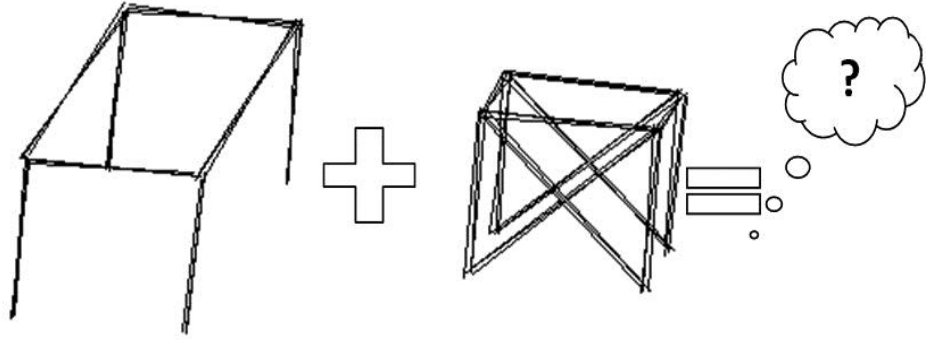
Space structure is a three dimensional truss with high stiffness and ductility due to its numerous members and flexible joints. Space structure is used where there is a need to carry vertical loads across long spans due to its high stiffness. A huge number of large scale and complex civil structures such as high-rise buildings and large-span structures have been constructed in the form of space structures. .

This study investigates the seismic performance of an innovative lateral system called Space Shear Wall (SpaSW). This name is inspired by spatial form of space structure and its application as infill wall surrounded by columns and beams to resist the shear force generated by earthquake activities. The preliminary literature researches by author show that SpaSW is an innovative application of space structure to enhance the lateral stability of structures.

Integration of a typical two dimensional lateral system like steel cross bracing with structural frame makes a stable structure, as shown in Figure 1.1. Since most of the common seismic systems such as steel bracing and concrete shear wall mainly perform under in-plane loads, a new concept could be discovered through integration of spatial seismic systems with structural frames, as demonstrated in Figure 1.2. This concept has originally been inspired by a special tree with diagonally long extended roots towards the ground's surface to protect the tree against wind loads as per Figure 1.3. This natural example points out that lateral stability of any structure might be enhanced by struts distributed spatially. Figure 1.4 illustrates the preliminary proposal for Space shear wall that is a double-layer two-way space structure surrounded in a R.C. frame.



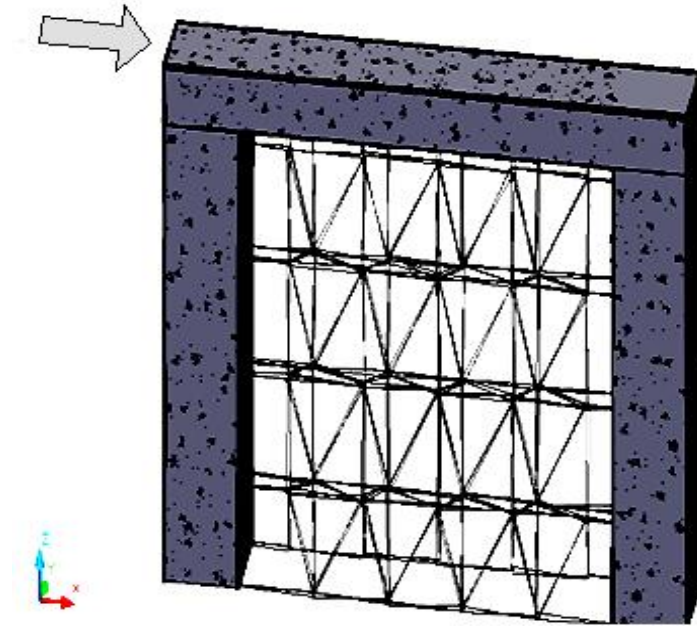
**Figure 1.1** : Concept of cross bracing systems



**Figure 1.2 :** Early concept for Space Shear Wall (SpaSW)



**Figure 1.3 :** Initial natural inspiration of SpaSW



**Figure 1.4** : Early conceptual model for SpaSW

## 1.2 Statement of the Problem

The world has been inflicted with heavy damages due to the common occurrence of natural hazards. A recent study (Leoni et al., 2011) revealed that close to 2.4 billion people were affected and a million people lost their lives by disasters during the past decades. In this regard, different kinds of seismic protection systems were designed to optimize buildings performance and increase the reliability in the wake of natural disasters. However, most of these structural systems have not effectively mitigated damages due to the inefficient integration of ductility, stiffness, and structural performance. For example, steel cross bracing that is commonly used in building structures has poor ductility due to its brittle connections. Recent earthquakes e.g. 1994 Northridge, 1995 Kobe, and 1999 Chi-Chi have shown that brittle fractures in connections of brace-to-column and beam-to-column affect the whole ductile response and energy dissipation capacity of structures under seismic loads (Di Sarno and Elnashai, 2009).

In addition, concrete shear wall as another widely used system in most parts of the world, is inconvenient in terms of its industrialization's difficulties. Moreover, the new ductile systems, like viscous elastic dampers, are very expensive due to limited availability of knowledge and technology for design and fabrication (Kelly, 2007 )

Therefore, this study proposes space shear wall as an innovative individual seismic resistant structural system to enhance the lateral stability of structures and resist the forces of earthquake. This system uses a double layer spatial truss with interconnected members and flexible joints absorbing hazardous energy from earthquake. This system effectively transmits the imposed lateral and vertical loads into tensile and compressive force to be carried by SpaSW designed structural elements and reduce lateral movements.

It is high time that engineering society take serious effort in creating effective seismic systems to improve the structural performance and minimize damages from earthquake. This research comparatively investigates seismic performance of SpaSW that is introduced as an innovative seismic resistant structural system.

### **1.3 Objectives of the Study**

The main objective of this research is to explore an innovative seismic structural system using available technologies to improve the seismic performance of buildings. The specific research objectives are:

- i. To propose an innovative seismic structural system (double layer SpaSW) to enhance the lateral stability of structure under lateral force
- ii. To assess the seismic performance of SpaSW in terms of ductility level, and failure mechanism via elastic-static, inelastic-static, and elastic dynamic analysis
- iii. To verify the proposed system on multi-story frame with comparative study with a typical steel cross bracing

### **1.4 Research Questions**

This research shall respond to the following questions:

- i. How SpaSW is determined as an effective seismic system to increase the lateral stiffness of structures?
- ii. How the current concerns of integration of stiffness, ductility, and industrialization are addressed in SpaSW system?



- iii. How is the seismic performance of SpaSW under various types of seismic analysis?
- iv. What is the difference between the SpaSW and the steel bracing which is a common lateral system?

## **1.5 Significance of the Study**

Although currently there are various kinds of seismic structural systems, most of them could not efficiently reduce earthquake damages, as shown in Chapter 2. The findings of this study are important to help the engineering society to find out effective seismic systems to improve the performance of complex structural systems and minimise hazardous effects of earthquake.

## **1.6 Scope of the Study**

Considering the successful performance of space structures in sustaining the lateral loads, it is anticipated that the SpaSW would efficiently enhance the stability of structures under wind and earthquake forces. This study is mainly dedicated to implement, and evaluate the seismic performance of innovative SpaSW system. This assessment is delimited to static analysis to determine the seismic performance of SpaSW through lateral drift, reaction force, and member stress factors.

## **1.7 Methodology and Research Framework**

This section briefly discusses the methodology of the research. The evaluation performance of the innovative seismic system includes four basic steps: modeling, analysis, design, and validation of the results. Firstly, the new concepts of the seismic system were simulated using three-dimensional software, 3D MAX and AutoCAD, to visualise and assess the viability of proposed concept. Then, the conceptual model was analysed under static and dynamic loads via ETABS program to monitor the seismic

performance of SpaSW. In this research, lateral drift, reaction force, and member stress ratio were the major criteria to realize seismic behaviour. In the third step, the constituent members of SpaSW were designed to verify the feasibility of SpaSW model. Finally, the analytical results were validated with an experimental study and verified through a comparative study between SpaSW and steel bracing.

## **1.8 Definition of Terms**

### **Seismic Performance:**

Seismic performance is the structural response of a building to earthquake forces which is evaluated by strength, deformation demands, ductility level, and failure mechanism of structural systems.

The seismic performance factors could be used in the context of linear analysis and response to equivalent static forces (SEAOC, 1995; ASCE, 2010 and IBC, 2011). This research focuses on deformation and strength of structures using SpaSW under equivalent static, response spectrum, pushover, time history, and finite element analysis to assess the seismic performance of SpaSW system.

### **Innovative System:**

According to the Oslo Manual, the foremost international guideline on innovation activities, “a technological product innovation is the implementation or commercialization of a product with improved performance characteristics such as to deliver objectively new or improved services to the consumer.”(OECD, 2005). There is an important distinction between the innovation and invention. “Invention is the first occurrence of an idea for a new product or process while innovation is the first attempt to carry it out into practice.” Innovation vs. invention: Knowing the difference makes a difference (Gurel, 2007). This study investigates on an innovative seismic system integrating the others’ invention of space structures and Mero joints.

**Space Shear Wall (SpaSW):**

Space shear wall is an innovative application of space structures performing as seismic system to resist the lateral earthquake force. This system involves the tubular members with ball joint system connected to the surrounding frames.

## REFERENCE

- Abbassi S. K. (2009). *The Weight Efficiency of Steel Framed Buildings with Various Wind Bracing Systems*. Eastern Mediterranean University: Master Thesis.
- Abell, M. and Habib, F. (2012). How is the Response-spectrum Scale Specified? *American Society of Civil Engineers*. Retrieved December 10, 2013, from <https://wiki.csiamerica.com/display/etabs/Scale+factor+in+RSA>.
- AISC (American Institute of Steel Construction). (2002). *Seismic Provisions for Structural Steel Buildings*. Chicago, Illinois: American Institute of Steel Construction.
- Ali, M. M. and Moon, K. S. (2007). Structural Developments in Tall Buildings: Current Trends and Future Prospects. *Architectural Science Review*. 50(3): 205-223.
- Alinia, M. M. and Dastfan, M. (2006). Behaviour of Thin Steel Plate Shear Walls Regarding Frame Members. *Journal of Constructional Steel Research*. 62(7): 730-738.
- ASCE (American Society of Civil Engineers). (2007). *Seismic Rehabilitation of Existing Buildings*. Reston, Virginia: American Society of Civil Engineers.
- Anderson, J. C. and Naeim, F. *Basic Structural Dynamics*. Hoboken, N.J.: John Wiley & Sons, Inc. 2012.
- ASCE (American Society of Civil Engineers). (2010). *Minimum Design Loads for Buildings and Other Structures*. Reston, Virginia: American Society of Civil Engineers.
- Ashraf Habibullah, S. and Stephen Pyle, S. (1998). Practical Three Dimensional Nonlinear Static Pushover Analysis. *Structure Magazine*, Winter.
- Astaneh-Asl, A. (2001). Seismic Behavior and Design of Steel Shear Walls. *2001 SEOANC Seminar, Structural Engineers Assoc. of Northern California Structural*. 7 November. San Francisco.
- Awkar, J. C. and Lui, E. M. (1999). Seismic Analysis and Response of Multistory Semirigid Frames. *Engineering Structures*. 21(5): 425-441.
- Bansal, R. (2011). *Pushover Analysis of Reinforced Concrete Frame*. Thapar University: Master Thesis.

- Barbato, M. (2007). *Finite Element Response Sensitivity, Probabilistic Response and Reliability Analyses of Structural Systems with Applications to Earthquake Engineering*. University of California, San Diego: Doctor of Philosophy Thesis.
- Bathe, K. J. *Finite Element Procedures*. United States of America: Prentice Hall. 2006.
- Becker, R. (1996). *Seismic Design of Special Concentrically Braced Steel Frames*. Moraga, California: Structural Steel Educational Council.
- Behbahanifard, M. R., Grondin, G. Y. and Elwi, A. E. (2003). *Experimental and Numerical Investigation of Steel Plate Shear Walls*. Structural Engineering Report. University of Alberta.
- Bommer, J. J. and Acevedo, A. B. (2008). The Use of Real Earthquake Accelerograms As Input to Dynamic Analysis. *Journal of Earthquake Engineering*. 8: 43-92.
- Booth, E. D. and Key, D. *Earthquake Design Practice for Buildings*. 2<sup>nd</sup> ed. London: Thomas Telford. 2006.
- Borrego, M., Douglas, E. P. and Amelink, C. T. (2009). Quantitative, Qualitative, and Mixed Research Methods in Engineering Education. *Journal of Engineering Education*. 98 (1): 53-66.
- Blandon U, C. A. 2004. Equivalent Viscous Damping Equations for Direct Displacement Based Design. Master, Università degli Studi di Pavia.
- Bozorgnia, Y. and Bertero, V. V. (2001). Improved Shaking and Damage Parameters for Post-earthquake Applications. *Proceedings of the SMIP01 Seminar on Utilization of Strong-Motion Data*. Los Angeles. 1-22.
- BSSC (Building Seismic Safety Council). (2004). NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. Washington, D.C.: Building Seismic Safety Council.
- USAF Test Pilot School Edwards AFB CA (1988). *Flying Qualities Phase: Dynamics*. California: United States Air Force Test Pilot School.
- Caccese, V., Elgaaly, M. and Chen, R. (1993). Experimental Study of Thin Steel-plate Shear Walls Under Cyclic Load. *Journal of Structural Engineering*. 119(2): 573-587.
- Caltrans (2013). *Caltrans Seismic Design Criteria, Version 1.7*. California, USA: California Department of Transportation.
- Chandradhara, G. (2013). *Structural and Architectural Aspects of Earthquake Resistant Design*. Mysore.
- Chen, S. J. and Jhang, C. (2006). Cyclic Behavior of Low Yield Point Steel Shear Walls. *Thin-Walled Structures*. 44(7): 730-738.

- Chen, W. F. and Lui, E. M. (2010). *Handbook of Structural Engineering*. 2<sup>nd</sup> ed. Boca Raton, FL: Taylor & Francis Group.
- Chen, W. F. and Lui, E. M. (2012). *Handbook of Structural Engineering*, 2<sup>nd</sup> ed. Boca Raton, FL: Taylor & Francis Group.
- Chenaghlou, M. R. (1997). *Semi-rigidity of Connections in Space Structures*. University of Surrey, Guildford, United Kingdom: Doctor of Philosophy Thesis.
- Chilton, J. *Space Grid Structures*. UK: Architectural Press. 2000.
- Chopra, A. K. *Dynamics of Structures*. 4<sup>th</sup> ed. Upper Saddle River, N.J.: Pearson Education, Inc. 2012.
- Cullen, G. W. and Korkolis, Y. P. (2013). Ductility of 304 Stainless Steel Under Pulsed Uniaxial Loading. *International Journal of Solids and Structures*. 50(10): 1621-1633.
- Dahal, P. P. (2013). *Nonlinear Pushover Analysis of Steel Frame Structure*. Southern Illinois University, Carbondale, Illinois, USA.
- Dhakal, R.P. 2011. Structural Design for Earthquake Resistance – Past, Present and Future of Seismic Design. Canterbury Earthquakes Royal Commission.
- Darragh, B., Silva, W. and Gregor, N. (2004). Strong Motion Record Processing for the PEER Center. *Proceedings of COSMOS Invited Workshop on Strong-Motion Record Processing*. Richmond, CA, USA, 26-27.
- Di Sarno, L. and Elnashai, A. S. (2009). Bracing Systems for Seismic Retrofitting of Steel Frames. *Journal of Constructional Steel Research*. 65(2): 452-465.
- Eekhout, M. (1989). *Architecture in Space Structure*. Rotterdam: Uitgeverij 010 Publishers.
- Eghtesadi, S., Nourzadeh, D. and Bargi, K. (2011). Comparative Study on Different Types of Bracing Systems in Steel Structures. *World Academy of Science, Engineering and Technology*. 25-27 January. United Arab Emirates.
- Engelhardt, M.D. 2007. Buckling Restrained Braced Frames. University of Texas, Austin.
- Environment Canada. (2013). History of the Biosphère. *Environment Canada*. Retrieved October 12, 2013, from <https://www.ec.gc.ca/biosphere/default.asp?lang=En&n=7DD2D209-1>
- Fadaee, M. J. and Bayat, B. (2007). Effects of Using Low Yield Point Steel Instead of Normal Steel in Steel Shear Walls. *Proceedings of the Eleventh International Conference on Civil, Structural and Environmental Engineering Computing*. Stirlingshire, Scotland, UK: Civil-Comp Press.

- Filiatrault, A. (2013). *Elements of Earthquake Engineering and Structural Dynamics*. 2<sup>nd</sup> ed. Canada: Polytechnic international Press. 2002.
- Franco, G., Leiva, G. and Lai, T. (2010). Post-Disaster Survey Findings from the M8.8 Chile Earthquake. *AIR Worldwide*. Retrieved December 12, 2013, from <http://www.air-worldwide.com/Publications/AIR-Currents/2010/Post-Disaster-Survey-Findings-from-the-M8-8-Chile-Earthquake/>
- Gerrits, J. M. (1996). The Architectural Impact of Space Frame Systems. *Proceedings of the Asia-Pacific Conference on Shell and Spatial Structures*. Beijing, China.
- Ghali, A., Neville, A. M. and Brown, T. G. *Structural Analysis: A Unified Classical and Matrix Approach*. 5<sup>th</sup> ed. London: Spon Press. 2003.
- Ghosh, S. K. and Fanella, D. A. *Seismic and Wind Design of Concrete Buildings: (2000 IBC, ASCE 7-98, ACI 318-99)*. USA: International Code Council. 2003.
- Gioncu, V. and Mazzolani, F. M. *Earthquake Engineering for Structural Design*. UK: Taylor & Francis. 2010.
- Gioncu, V. and Mazzolani, F. M. *Ductility of Seismic Resistant Steel Structures*. USA: Spon Press. 2002.
- Girgin, K. and Darilmaz, K. (2002). Seismic Response of Infilled Framed Buildings Using Pushover Analysis. *ARI Bulletin of the Istanbul Technical University*. 54(5):1-17.
- Gould, N. C. (2007). *Seismic Risk for Structures*. ABS Consulting Earthquake Engineering Research Institute: ABS Consulting.
- Green, J. M. (1996). Peer Reviewed: A Practical Guide to Analytical Method Validation. *Analytical Chemistry*. 68(9): 305A-309A.
- Green, R. A., Gunberg, K., Parrish, K. and Munger, T. (2007). A Simple Uniform Hazard Design Spectral Shape for Rock Sites. *Seismological Research Letters*. 78(2): 323-343.
- Guney, D. and Aydin, E. 2012. The Nonlinear Effect of Infill Walls Stiffness to Prevent Soft Story Collapse of RC Structures. *The Open Construction and Building Technology Journal*, 6, 74-80.
- Gurel, O. (2007). Innovation vs. Invention: Knowing the Difference Makes a Difference. *WTN News*. Retrieved November 2, 2012, from <http://wtnews.com/articles/4184/>
- Haldar, A. and Salazar, A. R. (1996). Ductility Evaluation of Steel Frames with PR Connections. *Eleventh World Conference on Earthquake Engineering (11WCEE)*. Elsevier Sciece Ltd.

- Halvorson, R. (2008). Structural Design Innovation: Russia Tower and Other Tall Collaborations. *CTBUH 8th World Congress*. Dubai, UAE: CTBUH 8th World Congress.
- Halvorson, R. and Warner, C. (2007). Structural Design Innovation: Russia Tower. *The Structural Design of Tall and Special Buildings*. 16(4): 377–399.
- Hiyama, Y. (2005). *Recent Development of Seismic Retrofit Methods in Japan*. Japan: Japan Building Disaster Prevention Association.
- Hyland, C. and Miller, S. (2009). Steel Performance in Padang Earthquake. *Hyland Consultants Ltd*. Retrieved October 9, 2013, from <http://www.hylandconsultants.com/50/>
- ICC (International Code Council). (2012). *International Building Code*. Illinois: International Code Council. 2011.
- JBDPA. (2001). *Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings*. Japan: Japan Building Disaster Prevention Association.
- JKR. (2007). *Seismic Design Guideline for Concrete Buildings in Malaysia*. Malaysia: Jabatan Kerja Raya.
- Karni, E. 1996. Plastic cladding for bar, joint and cladding structures physical properties and performance. *Materials and Structures*, 29, 241-249.
- Kalny, O. (2013). ETABS. *Computers and Structures, Inc*. Retrieved December 15, 2013, from <https://wiki.csiberkeley.com/display/etabs/Home>
- Kalny, O. and Abell, M. (2012). Hinge. *Atlassian Confluence*. Retrieved October 5, 2013, from <https://wiki.csiamerica.com/wiki-staging/display/kb/Hinge>
- Kamar, K., Alshawi, M. and Hamid, Z. (2009). Barriers to Industrialized Building System (IBS): The Case of Malaysia. *Proceedings of the 9th International Postgraduate Research Conference (IPGRC)*. 29-30 January. Salford, United Kingdom.
- Kasslimali, A. and Badiy, M. (1984). Nonlinear Behavior and Stability of Latticed Domes Under Combined Loading. *Proceedings of the Southeastern Conference on Theoretical and Applied Mechanics (SECTAM XII)*. 114-119.
- Kelly, T. E. (2008) Improving Seismic Performance: Add Stiffness or Damping? *2007 NZSEE Annual Conference in Palmerston North*. Bulletin of the New Zealand Society for Earthquake Engineering. 41(1): 24-30.
- Khalili-Tehrani, P. and Taciroglu, E. 2008. M7.8 Southern San Andreas Fault Earthquake Scenario: Non-ductile Reinforced Concrete Building Stock. University of California, Los Angeles.



- Kinetics Noise Control. (2008). *Seismic Design Manual*. Dublin, Ohio, USA: Kinetics Noise Control, Inc.
- Kohoutek, R. (2000). Non-destructive and Ultimate Testing of Semi-rigid Connections. *Fourth International Workshop on Connections in Steel Structures*. University of Wollongong, Australia. 454-463.
- Krawinkler, H. and Seneviranta, G. (1998). Pros and Cons of a Pushover Analysis of Seismic Performance Evaluation. *Engineering Structures*. 20: 452-464.
- Lee, H. J., Kuchma, D. and Aschheim, M. A. (2007). Strength-based Design of Flexible Diaphragms in Low-rise Structures Subjected to Earthquake Loading. *Engineering Structures*. 29(7): 1277-1295.
- Lee, S. S. and Moon, T. S. (2002). Moment–rotation Model of Semi-rigid Connections with Angles. *Engineering Structures*. 24(2): 227-237.
- Leoni, B., Radford, T. and Schulman, M. (2011). Disaster Through a Different Lens: Behing Every Effect, there is a Cause. *A Guide for Journalists Covering Disaster Risk Reduction*. United Nations.
- Lew, M. and Naeim, F. (1996). Use Of Design Spectrum-compatible Time Histories in Analysis of Structures. *Eleventh World Conference on Earthquake Engineering (11WCEE)*. Elsevier Sciece Ltd.
- Liel, A. B. (2008). *Assessing the Collapse Risk of California's Existing Reinforced Concrete Frame Structures: Metrics for Seismic Safety Decisions*. Report No.166. Stanford University: The John A. Blume Earthquake Engineering Center.
- Longo, A., Montuori, R. and Piluso, V. (2012). Theory of Plastic Mechanism Control of Dissipative Truss Moment Frames. *Engineering Structures*. 37: 63-75.
- Lubell, A. S. (1997). *Performance of Unstiffened Steel Plate Shear Walls Under Cyclic Quasi-static Loading*. University of British Columbia: Master Thesis.
- Luco, N. (2007). Ground Motions for Design. *Thailand Seismic Hazard Workshop*. 18 January. Thailand.
- McFarlane, A. 2009. The Ford Rotunda, Available: <http://michpics.wordpress.com/2009/12/12/the-ford-rotunda/>
- Merritt, F. S. and Ricketts, J. T. (2001). *Building Design and Construction Handbook*. 6<sup>th</sup> ed. USA: McGraw-Hill.
- Nakashima, M. (1995). Strain-hardening Behavior of Shear Panels Made of Low-yield Steel. I: Test. *Journal of Structural Engineering*. 121(12): 1742-1749.
- Napier, J. and Powell, G. H. (2013). Static Pushover Methods - Explanation, Comparison and Implementation. *Computers and Structures, Inc*. Rertieved October 15, 2013,

- from <https://wiki.csiamerica.com/display/perform/Static+pushover+methods+-+explanation,+comparison+and+implementation>
- Nayfeh, A. H. and Pai, P. F. *Linear and Nonlinear Structural Mechanics*. Germany: Wiley-VCH. 2008
- Newnan, D. G. and Banks, J. H. *Civil Engineering: License Review*. 15<sup>th</sup> ed. Chicago: Kaplan AEC Education. 2004.
- Nikolaou, S. (2008). Site-Specific Seismic Studies for Optimal Structural Design. *Structure Magazine*. February. 15-19
- Nooshin, H. (2008). Introduction of Space Structure. Bahonar University of Kerman. 2008.
- Nooshin, H. (2002). What is Space Frame? Official website of Surrey University. Retrieved from [http://portal.surrey.ac.uk/portal/page?\\_pageid=822,568927&\\_dad=portal&\\_schema=PORTAL](http://portal.surrey.ac.uk/portal/page?_pageid=822,568927&_dad=portal&_schema=PORTAL)
- Nukala, P. K. V. and White, D. W. (2004). A Mixed Finite Element for Three-dimensional Nonlinear Analysis of Steel Frames. *Computer Methods in Applied Mechanics and Engineering*. 193(23): 2507-2545.
- OECD. (2005). *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data*. 3<sup>rd</sup> ed. France: Organisation for Economic Co-operation and Development and Statistical Office of the European Communities.
- Oğuz, S. (2005). *Evaluation of Pushover Analysis Procedures for Frame Structures*. Middle East Technical University: Doctor of Philosophy Thesis.
- Okubo, S., Hiyama Y., Ishikawa, K., Wendel, W. and Fischer, L. (2001). Load Capacity and Plastic Deformable Ability of Aluminum Alloy Double Layer Latticed Wall Subjected to Plane Load. *International Symposium on Theory, Design and Realization of Shell and Spatial Structures*. Nagoya, Japan.
- Pars Civil Technology. 2010. Brace Rupture, Pars Civil Technology. Available: [http://fanomran.com/education/brace\\_rupture.jpg](http://fanomran.com/education/brace_rupture.jpg)
- Pinto, P. E. (2000). Design for Low/Moderate Seismic Risk. *Proceedings of the Twelfth World Conference on Earthquake Engineering (12 WCEE)*. New Zealand.
- Quach, W. M. and Qiu, P. (2014). Strength and Ductility of Corner Materials in Cold-formed Stainless Steel Sections. *Thin-Walled Structures*.
- Reitherman, R. *Earthquakes and Engineers: An International History*. Reston, Virginia: American Society of Civil Engineers. 2012.

- Rezai, M., Ventura, C. E. and Prion, H. G. (2000). Numerical Investigation of Thin Unstiffened Steel Plate Shear Walls. *Twelfth World Conference on Earthquake Engineering (12WCEE)*.
- Rigobello, R., Breves Coda, H. and Munaiar Neto, J. (2013). Inelastic Analysis of Steel Frames with a Solid-like Finite Element. *Journal of Constructional Steel Research*. 86: 140-152.
- Sabelli, R. 2006. Seismic Braced Frames: Design Concepts and Connections. Chicago, Illinois.
- Sabouri-Ghomi, S. and Roberts, T. M. (1992). Nonlinear Dynamic Analysis of Steel Plate Shear Walls Including Shear and Bending Deformations. *Engineering Structures*. 14(5): 309-317.
- SEAOC (1995). *Steel Moment Frame Connections*. Structural Engineers Association of California.
- Seiculescu, V. (2006). *Advance Design – Bracing Members Design According to Eurocode 3*. Romania: GRAITEC.
- Sev, A. and Özgen, A. (2009). Space Efficiency in High-rise Office Buildings. *METU JFA*. 26(2): 69-89.
- Shishkin, J. J., Driver, R. G. and Grondin, G. Y. (2009). Analysis of Steel Plate Shear Walls Using the Modified Strip Model. *Journal of Structural Engineering*. 135(11): 1357-1366.
- Sutjiadi, H. Y. and Charleson, A. W. (2012). Structural-architectural Integration of Double-layer Space Structures in Tall Buildings. *Journal of Architectural Engineering*. 19(4): 219-228.
- Thai, H.T. and Kim, S. E. (2011). Nonlinear Inelastic Time-history Analysis of Truss Structures. *Journal of Constructional Steel Research*. 67(12): 1966-1972.
- The European Steel Design Education Programme. (1993). *The Cyclic Behaviour of Steel Elements and Connections*. ESDEP Lecture Note.
- Thorburn, L. J., Kulak, G. L. and Montgomery, C. J. (1983). *Analysis of Steel Plate Shear Walls*. Structural Engineering Report. University of Alberta.
- Timler, P. (1999). Economical Design of Steel Plate Shear Walls from a Consulting Engineer's Perspective. *Proceedings of the 1999 North American Steel Construction Conference (NASCC)*. American Institute of Steel Construction.
- Topkaya, C. and Atasoy, M. (2009). Lateral Stiffness of Steel Plate Shear Wall Systems. *Thin-Walled Structures*. 47(8): 827-835.

- Usami, T. and Itoh, Y. *Stability and Ductility of Steel Structures*. UK: Elsevier Science Ltd. 1998.
- Varghese, P. C. *Advanced Reinforced Concrete Design*. 2<sup>nd</sup> ed. New Delhi, India: PHI Learning Pvt. Ltd. 2006.
- Wang, F., Wang, X., Yang, F. and Li, H. B. (2010). The Influence of Joint's Stiffness on Stability of Reticulated Shell. *Eleventh International Symposium on Structural Engineering*. Guangzhou, China.
- Williams, A. *Seismic and Wind Forces: Structural Design Examples*. Illinois, USA: International Code Council. 2003.
- Williams, A. *Civil and Structural Engineering: Seismic Design of Buildings and Bridges*. 5<sup>th</sup> ed. Illinois, USA: Kaplan AEC Education. 2005.
- Wilson, E. L. *Three Dimensional Static and Dynamic Analysis of Structures: A Physical Approach with Emphasis on Earthquake Engineering*. 2<sup>nd</sup> ed. USA: Computers and Structures Inc. 1998.
- Xuzhou Huahai Steel Structure Co., Ltd. 2012. Available:  
<http://www.steelstructure.cn/pro.asp?id=12>