

DAMAGE BASED RELIABILITY OF SMART INDUSTRIALISED  
BUILDING SYSTEM FOR RESIDENTIAL UNITS

WONG JING YING

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

FEBRUARY 2015

For my beloved father and mother  
and my husband, Yip Chun Chieh

## ACKNOWLEDGEMENT

The author would like to thank the almighty God for His blessing, guiding and be with her throughout the research.

In particular, the author likes to express her most sincere appreciation to her supervisor, Associate Professor Dr. Abdul Kadir Marsono for his valuable guidance, assistance, patent loan and direction to ensure the completion of this research. All the discussions and teachings especially theoretical, software knowledge and laboratory works guidance from her supervisor had guided the right way in completing this research.

Special thanks to Associate Professor Dr. Masine Md. Tap for patent loan, model development and financial support, Associate Professor Dr. Ahmad Mahir Mokhtar for patent loan, and Dr. Mohd Foad Abdul Hamid for reliability analysis part. Sincere thanks to Mr. Yip Chun Chieh and all the Structure Laboratory technicians for helping her in all laboratory works and testing of specimens. The author would like to express her gratitude to Universiti Teknologi Malaysia for providing all the facilities throughout the research.

Special thanks also to her family especially her husband for their supports, assistances and advices in carrying out this research. The author appreciates their readiness to lend their hands and become great support to her.

## ABSTRACT

SMART Industrialised Building System (IBS) is the invention of Universiti Teknologi Malaysia (UTM) researcher. The system is targeted to resist earthquakes up to 6.0 Richter scale. However, the damage based reliability of one storey SMART IBS system may become a serious concern before the product is commercialised to the countries that prone to earthquakes. In this research, scaled 1: 5 model was developed according to the Buckingham Pi Theorem and Similitude Theory. Therefore, the experimental results of scaled 1:5 model are representing the real behaviour of full scaled model and then damage based reliability of one storey of SMART IBS system on seismic performance were studied. Four types of laboratory tests with scaled 1:5 were conducted which were beam flexural test, single column pushover test, two bay frames with wall panels pushover test and vibration test of one model of residential unit. In comparison between experimental test and nonlinear finite element analysis, the results were proven to have similarities in linear and nonlinear behaviour in terms of failure modes and strength profiles. The structure was assessed based on three different performance levels that were Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). Five damage ranks ranges from 1 to 5, five damage index ranges from 0 to 1 and five damage states that were Slight, Light, Medium, Heavy and Collapse were proposed based on the damage intensities of the components. The damage based reliability procedure and equation were developed to obtain a structural damage based reliability index. The proposed damage based reliability analysis starts with the determination of weighting factor of part in a component. Then, the weighting factor was multiplied with damage ranking score to obtain the damage score. The probability of failure of a component was determined by total damage score of component in the cumulative distribution function of the damage score. The damage based reliability index was obtained by one minus the probability of failure of component. One storey SMART IBS system was proven very reliable with damage based reliability index of 1 for earthquake peak ground acceleration (PGA) ranges from 0.05g to 5.3g.

## ABSTRAK

SMART Industrialised Building System (IBS) adalah ciptaan penyelidik dari Universiti Teknologi Malaysia (UTM). Sistem ini adalah direka untuk menahan gempa bumi sehingga skala 6.0 Richter. Walau bagaimanapun, kebolehpercayaan yang berasaskan kerosakan terhadap sistem satu tingkat SMART IBS ini boleh menjadi satu kebimbangan yang serius sebelum produk itu dikomersialkan kepada negara-negara yang terdedah kepada gempa bumi. Dalam kajian ini, model berskala 1: 5 telah dibuat berdasarkan Teorem Buckingham Pi dan Teori Perumpamaan. Oleh itu, keputusan eksperimen untuk model berskala 1: 5 adalah mewakili tingkah laku sebenar model berskala penuh dan kebolehpercayaan yang berasaskan kerosakan untuk sistem bangunan bertingkat satu SMART IBS telah dikaji dari segi prestasi struktur terhadap kesan gempa bumi. Empat jenis ujian makmal yang berskala 1: 5 telah dijalankan termasuk ujian lenturan, ujian sesaran terhadap tiang tunggal, ujian sesaran terhadap dua rangka dengan dinding, dan ujian gegaran terhadap satu model rumah kediaman. Dalam perbandingan antara ujian eksperimen dan analisis unsur terhingga tak lurus, keputusan telah terbukti bahawa terdapat persamaan dalam tingkah laku lurus dan tak lurus dalam mekanisme kegagalan dan profil kekuatan. Struktur ini telah dinilai berdasarkan tiga tahap prestasi yang berbeza iaitu Penghunian Segera (IO), Keselamatan Hayat (LS) dan Pencegahan Keruntuhan (CP). Lima peringkat kerosakan yang berjulat 1 hingga 5, lima indeks kerosakan yang berjulat 0 hingga 1 dan lima keadaan kerosakan iaitu sangat sedikit, sedikit, sederhana, teruk dan runtuh telah dicadangkan berdasarkan keamatan kerosakan komponen. Prosedur kebolehpercayaan yang berasaskan kerosakan dan persamaan telah ditubuhkan untuk mendapatkan indeks kebolehpercayaan yang berasaskan kerosakan. Analisis kebolehpercayaan yang berasaskan kerosakan seperti yang dicadangkan adalah bermula dengan penentuan faktor pemberat bahagian dalam komponen. Kemudian, faktor pemberat ini didarab dengan markah peringkat kerosakan untuk mendapatkan markah kerosakan. Kebarangkalian kegagalan komponen telah ditentukan oleh jumlah markah kerosakan komponen dalam fungsi taburan terkumpul markah kerosakan. Indeks kebolehpercayaan yang berasaskan kerosakan telah diperolehi dengan satu tolak kebarangkalian kegagalan komponen. Sistem SMART IBS satu tingkat telah terbukti sangat dipercayai dengan indeks kebolehpercayaan yang berasaskan kerosakan adalah 1 untuk puncak pecutan bumi (PGA) antara 0.05g hingga 5.3g.

## TABLE OF CONTENTS

<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
	<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>	xiii
	<b>LIST OF FIGURES</b>	xv
	<b>LIST OF ABBREVIATIONS</b>	xxv
	<b>LIST OF SYMBOLS</b>	xxvi
	<b>LIST OF APPENDICES</b>	xxvii
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background of the Study	1
	1.2 Statement of the Problem	3
	1.3 Purpose of the Study	5
	1.4 Objectives of the Study	5
	1.5 Scope of the Study	5
	1.6 Significance of the Study	7
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>8</b>
	2.1 Introduction	8
	2.2 Conventional Building System versus Industrialised Building System (IBS)	9

2.2.1	Connections in Conventional Building System and Industrialised Building System	15
2.2.2	Failure of Conventional Reinforced Concrete System and Precast Structures in Seismic Events	19
2.3	Finite Element Analysis (FEA-Abaqus/CAE 6.12)	27
2.3.1	Linear and Nonlinear Analysis	28
2.3.2	Concrete Model Properties	29
2.3.2.1	Concrete Smeared Cracking Model	30
2.3.2.2	Concrete Damaged Plasticity Model	32
2.3.3	Steel Reinforcement Properties	35
2.4	Dynamic Test and Assessment	36
2.4.1	Modal Analysis	36
2.4.2	Time History Analysis	38
2.4.3	Pushover Analysis	40
2.4.3.1	Structural Displacement Ductility and Energy Dissipation	46
2.4.4	Vibration Acceleration Measurement	47
2.4.5	Signal-processing Record Software - SeismoSignal	47
2.5	Performance -Based Seismic Design	48
2.5.1	SEAOC, Vision 2000.	49
2.5.2	ATC 40	52
2.5.3	FEMA 356	54
2.5.4	Structural Damage Index	58
2.5.5	Structural Damage State	63
2.6	Reliability	70
2.6.1	Continuous Variation of Random Variable	71
2.6.2	Continuous Distribution Functions (The <i>Normal</i> Distribution)	74
2.6.3	Reliability Functions	75
2.6.4	Reliability of the System	76
2.6.4.1	Systems in Series Assembly	77
2.6.4.2	Systems in Parallel Assembly	77
2.6.4.3	Hybrid Systems	77

2.7	Summary	78
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>80</b>
3.1	Introduction	80
3.2	Research Instruments	80
3.3	Case Study	82
3.4	Research Framework	87
<b>4</b>	<b>EXPERIMENTAL STUDY PART I: TEST PREPARATION</b>	<b>90</b>
4.1	Introduction	90
4.2	Industrialised Building System (IBS) Components with Scale of 1:5	91
4.3	Construction of Test Specimens of Scale 1:5	92
4.3.1	Structural Reinforced Concrete Specifications	92
4.3.2	Reinforcement Details	96
4.3.3	Concrete Details	99
4.3.4	Formwork	102
4.3.5	Casting Procedure	105
4.3.6	Curing of Hardened Concrete	107
4.3.7	Concrete Surface Painting	108
4.4	Instrumentation and Testing Procedure	109
4.4.1	Module 1: Flexural test of scale of 1:5 of one bay one storey frame	109
4.4.1.1	Instrumentation	110
4.4.1.2	Loading Procedure	110
4.4.2	Module 2: Pushover test of scale of 1:5 of two single columns in x-axis and y-axis direction	111
4.4.2.1	Instrumentation	111
4.4.2.2	Loading Procedure	111
4.4.3	Module 3: Pushover pseudo-dynamic cyclic load test of scale of 1:5 of two bay one storey frames with wall panels	112



4.4.3.1	Instrumentation	112
4.4.3.2	Lateral Loading Test Procedure	114
4.4.4	Module 4: Vibration test of scale 1:5 of a complete one storey SMART IBS residential model	116
4.4.4.1	Instrumentation	116
4.4.4.2	Loading Procedure	119
4.5	Summary	119
<b>5</b>	<b>EXPERIMENTAL STUDY PART II:</b>	
	<b>RESULT AND DISCUSSION OF EXPERIMENTAL TEST</b>	<b>120</b>
5.1	Introduction	120
5.2	Module 1: Flexural Test of Scale of 1:5 of One Bay One Storey Frame	120
5.2.1	Load-displacement Relationship of SMART IBS Beam	121
5.2.2	Load-Strain Relationship of Steel Bar	123
5.2.3	Cracks Pattern and Mode of Failure	124
5.3	Module 2: Pushover Test of Scale of 1:5 of Two Single Columns in x-axis and y-axis Direction	126
5.3.1	Load-displacement Relationship of SMART IBS Column C1 and C2	127
5.3.2	Cracks Pattern and Mode of Failure	129
5.4	Module 3: Pushover Pseudo-dynamic Cyclic Load Test of Scale of 1:5 of Two bays One Storey Frames with Wall Panels	130
5.4.1	Load-Displacement Profiles for Pushover Cyclic Load Test	131
5.4.2	Cracks Pattern and Mode of Failure	133
5.4.3	Capacity Curve	143
5.4.4	Structural Stiffness Capacity	145
5.4.5	Structural Displacement Ductility and Energy Dissipation	148
5.4.6	Deformation of Steel Connections	150

5.4.7	Damage Index (DI)	151
5.5	Summary	155
<b>6</b>	<b>EXPERIMENTAL STUDY PART III: RESULT AND DISCUSSION OF STRUCTURAL VIBRATION TEST</b>	<b>159</b>
6.1	Introduction	159
6.2	Dynamic properties of One Storey SMART IBS House	159
6.3	Vibration Loadings	166
6.4	Structural Damage Assessment	169
6.5	Summary	188
<b>7</b>	<b>FINITE ELEMENT ANALYSIS - ABAQUS/CAE 6.12 and SAP 2000 v15</b>	<b>189</b>
7.1	Introduction	189
7.2	Procedures of Modelling and Analysis in Abaqus/CAE 6.12	190
7.2.1	Module 1: Parts	190
7.2.2	Module 2: Properties	193
7.2.3	Module 3: Assemblies	196
7.2.4	Module 4: Steps	198
7.2.5	Module 5: Interactions	198
7.2.6	Module 6: Loads and Boundary Conditions	199
7.2.7	Module 7: Mesh	199
7.2.8	Module 8: Job	201
7.2.9	Module 9: Visualization	201
7.3	Procedures of SAP 2000 v15	202
7.3.1	3D Frame Modelling, Materials and Section Properties	202
7.3.2	Restraints	203
7.4	Summary	203
<b>8</b>	<b>RESULT AND DISCUSSION OF FINITE ELEMENT ANALYSIS (ABAQUS/CAE 6.12 AND SAP 2000 v15)</b>	<b>204</b>
8.1	Introduction	204

8.2	Result and Discussion of Abaqus/CAE 6.12	204
8.2.1	NLFEA Load-Displacement Relationship of the Models and Comparison with Experimental Results	205
8.2.2	Cracks Patterns and Failures Modes of the Models in Comparison to the Experimental Results	207
8.3	Result and Discussion of SAP 2000 v15	218
8.3.1	Result of the Modal Analysis and Comparison with Experimental Result	219
8.3.2	Structural Natural Periods and Frequencies	219
8.3.3	Mode of Shapes	220
8.4	Summary	224
<b>9</b>	<b>SMART IBS DAMAGE BASED RELIABILITY</b>	<b>225</b>
9.1	Introduction	225
9.2	Weighting Factor of Component	226
9.3	Damage Score of the Part in Component	228
9.4	Proposed of Damage Based Reliability Index	228
9.5	Damage Based Reliability Index (DBRI) for Scale of 1:5 of Two bays One Storey Frames with Wall Panels	232
9.6	Damage Based Reliability Index (DBRI) for Scale of 1:5 of One Storey SMART IBS Residential Model (OSSIM)	241
9.7	Summary	246
<b>10</b>	<b>CONCLUSIONS AND RECOMMENDATIONS</b>	<b>248</b>
10.1	Conclusions	248
10.2	Recommendations	252
	<b>REFERENCES</b>	<b>253</b>
	Appendices A - J	260-342

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Five types of IBS (CIDB, 2003)	12
2.2	General damage descriptions for new building designs (Vision 2000)	51
2.3	ATC 40- General damage descriptions for repair and rehabilitation of buildings (After ATC,1996)	53
2.4	Earthquake probability of exceedance with its mean return period (FEMA 356)	54
2.5	Seismic performance of FEMA 356 (FEMA 356)	55
2.6	FEMA 356 Damage control and building performance levels (FEMA 356)	57
2.7	DI values and observed damaging phases for RC column under cyclic loading (Sadeghi and Nouban, 2010)	60
2.8	Categorization of damage states (Suzuki and Ibayashi, 1998)	63
2.9	Examples of existing damage scale (Okada and Takai, 2000)	64
2.10	Detailed damage pattern for structures (Okada and Takai, 2000)	66
2.11	Detailed definition of damage rank by Takashi <i>et al.</i> (2002)	67
4.1	Mechanical properties of steel	98
4.2	Admixture proportions of concrete	100
4.3	Compressive properties of concrete	101
4.4	Tensile properties of concrete	102
4.5	Load-displacement cycles	115
5.1	Summary of pushover cyclic load test	147
5.2	System displacement ductility and energy dissipated per cycle of loads	148

5.3	Proposed limit damage indices for the proposed damage ranks	153
5.4	Damage descriptions of components for proposed damage ranking of SMART IBS	154
5.5	Classification of damage ranks of SMART IBS	157
6.1	Dynamic properties of beams	164
6.2	Dynamic properties of columns	165
6.3	PGA scaling by AC 1 from 19 Amp to 50 Amp	167
6.4	PGA at 48 Amp and 49 Amp by AC 1 and AC 3	167
6.5	Structural deformation pattern of scale 1:5 model in vibration test at PGA Level 1, Level 2, Level 3 and Level 4	171
6.6	Structural deformation pattern of scale 1:5 model in vibration test at PGA Level 5	177
6.7	Structural deformation pattern of scale 1:5 model in vibration test at PGA Level 6	181
6.8	Structural deformation pattern of scale 1:5 model in vibration test at PGA Level 7	186
8.1	Natural periods and frequencies of scale 1:5 IBS models	219
9.1	Description of importance level of the part of a component	226
9.2	Weighting factor of column based on importance level	228
9.3	Description of calculation of minimum damage score (DSc) of column	229
9.4	Description of calculation of maximum damage score (DSc) of column	230
9.5	Proposed range of Damage Based Reliability Index (DBRI)	232
9.6	Damage rank score (DRSc) of Column 1	234
9.7	Damage rank score (DRSc) of Column 2	235
9.8	Damage rank score (DRSc) of Column 3	236
9.9	Damage score (DSc) of columns of pushover pseudo-dynamic cyclic load test	237
9.10	DBRI for one storey two bay pushover frames	238
9.11	Damage rank score (DRSc) of columns for OSSIM	243
9.12	Total damage score (DSc) of components for OSSIM	243
9.13	DBRI for OSSIM	246

## LIST OF FIGURES

FIGURE NO	TITLE	PAGE
2.1	Le Corbusier Dom-ino Frame, 1914 (Curl, 2006)	10
2.2	Five major types of IBS in Malaysia (a) precast reinforced concrete frame building (FEMA 154), (b) steel formwork system (CIDB, 2003), (c) steel framing system (CIDB, 2003), (d) prefabricated timber framing system (BRE, 2005), and (e) House built with concrete interlocking blocks (Nasly and Yassin, 2009)	11
2.3	SMART Industrialised Building System (Building Assembly System, 2011)	13
2.4	SMART IBS (a) single storey terrace house, (b) shop terrace house, (c) school and government building and (d) SMART mechanical joint (Building Assembly System, 2011)	14
2.5	Monolithic rigid connections in typical conventional reinforced concrete system	16
2.6	Beam-column joints (a) intersection of beams and columns, (b) push-pull forces on joints cause compression and tension forces and (c) distortion of joint causes diagonal cracking and crushing of concrete (Murty (Eds.), 2006)	17
2.7	Failure modes of conventional building system (a) collapsed unreinforced masonry walls (URM) and nonductile concrete beam at Xingfu Primary School, (b) captive column failure at Hanwang High School, (c) column flexural failure at Mianzhu Experimental School and (d) total collapse of conventional reinforced concrete residential building (Miyamoto <i>et al.</i> , 2008)	20

2.8	Failure of poorly detailed beam-column connection in 1976 Tangshan earthquake, China (Park, 2003)	22
2.9	Collapsed of precast concrete structure Mexico City in 1985 Michoacan earthquake (a) connection failure (Gallagher, 2010) and (b) pounding against adjacent structure (Park, 2003)	23
2.10	Collapse of precast concrete buildings in 1988 Spitak earthquake in Armenia (a) under construction in Lennikan (b) composed of wall panels with connection of plain cast-in-situ concrete and hollow-core slabs and (c) built of precast and in-situ infilled frame panels (Fardis, 2003)	24
2.11	Brittle failure of beam-column pin connection at top of corner column in 1994 Northridge Earthquake (Park, 2003)	25
2.12	Precast industrial building (a) frame with short cantilevers supporting cranked beam and (b) shear failure of precast concrete column at foundation socket (Murat <i>et al.</i> , 2001)	26
2.13	Failure of connection in 1999 Kocaeli Earthquake (Murat <i>et al.</i> , 2001)	26
2.14	Interface of Abaqus/CAE 6.12	28
2.15	Yield and failure surfaces (a) in plane stress and (b) in the $(\sigma - \varepsilon)$ plane (Simulia, 2010)	30
2.16	Abaqus: Uniaxial concrete behaviour (Simulia, 2010)	31
2.17	(a) Tension stiffening model, and (b) fracture cracking energy model (Simulia, 2010)	32
2.18	Response of concrete to uniaxial loading in (a) compression and (b) tension (Simulia, 2010)	33
2.19	Uniaxial load cycle (tension-compression-tension) assuming default values for the stiffness recovery factors: $w_t = 0$ and $w_c = 1$ (Simulia, 2010)	35
2.20	Simple structural steel parametric stress-strain curve (CSI, 2008)	36
2.21	Earthquake records (a) El-Centro, (b) Northridge and (c) San Fernando (Nguyen and Kim, 2014)	39

2.22	Illustration of yielding sequence in pushover analysis (Mortezaei <i>et al.</i> , 2011)	41
2.23	Hysteresis loops of the steel frame (Vatansever and Yardimci, 2010)	41
2.24	Envelopes of the steel frame in the pushing and pulling directions (Vatansever and Yardimci, 2010)	42
2.25	Generalized force-deformation relations for concrete elements or components (FEMA 356)	43
2.26	Idealized force-displacement curve (a) positive post-yield slope and (b) negative post-yield slope (FEMA 356)	44
2.27	Components model for nonlinear analysis (FEMA 273)	45
2.28	Typical performance curve from pushover analysis (Ghobarah, 2000)	45
2.29	USB accelerometer model X16-1C	47
2.30	FAS of Northridge earthquake in 1994	48
2.31	Vision 2000 recommended seismic performance objectives for buildings (SEAOC, 1995)	50
2.32	Capacity curve (Sen, 2009)	52
2.33	Illustration of performance-based earthquake engineering (after Holmes) (Andrew, 2004)	56
2.34	Relationship between damage variable and damage index (Bozorgnia and Bertero (Eds.), 2004)	59
2.35	DI based on experimental test and numerical simulation for cyclic loading case (Sadeghi and Nouban, 2010)	59
2.36	Calculated damage index versus observed seismic damage (Park <i>et al.</i> , 1984)	63
2.37	Crack observed on column (a) flexural crack (b) shear crack and (c) negligible cracks and spalling of conventional concrete (Takashi <i>et al.</i> , 2002)	68
2.38	Damage rank of columns (column width > 40 cm) (Takashi <i>et al.</i> , 2002)	68
2.39	Damage rank of columns (column width < 40 cm) (Takashi <i>et al.</i> , 2002)	69



2.40	Damage rank of beam-column joints (Takashi <i>et al.</i> , 2002)	69
2.41	Damage rank of beams (Takashi <i>et al.</i> , 2002)	70
2.42	Histogram illustrates the shape of distribution	71
2.43	Continuous probability distribution	72
2.44	Typical cumulative distribution function ( <i>cdf</i> )	74
2.45	The <i>Normal (Gaussian)</i> distribution	75
2.46	The relationship between the failure probability density function ( <i>pdf</i> ), reliability $R(t)$ , and failure function $F(t)$ (O'Connor and Kleyner, 2012)	76
2.47	Reliability block diagram for a series system	77
2.48	Reliability block diagram for a parallel system	77
2.49	Reliability block diagram for a series-parallel system	78
2.50	Reliability block diagram for a parallel-series system	78
3.1	Scale of 1:5 of one bay one storey frame for frame flexural test	83
3.2	Scale of 1:5 of two single columns for pushover test in x-axis and y-axis direction	83
3.3	Scale of 1:5 two bay one storey frames with wall panels for pushover pseudo-dynamic test	84
3.4	Scale of 1:5 of one storey SMART IBS residential building for vibration test	84
3.5	SMART IBS components (a) beam (b) column (c) infill and (d) steel footing	85
3.6	Procedures in Part 1 and 2 (Structural Analysis)	88
3.7	Procedure in Part 3 (Proposed Damage Based Reliability Analysis)	89
4.1	Total constructed IBS components	92
4.2	IBS model elevation view and details (Building Assembly System, 2011): (a) 3D perspective view (b) 3D wireframe view (c) 2D front view and (d) cross sections	93
4.3	Reinforcement and links for IBS components	96
4.4	Steel materials for the IBS components	96
4.5	Tensile Test (a) 1.5mm steel bar (b) 5mm steel bar (c) steel	

	plate for panel (d) steel plate for column (e) steel plate for beam and (f) tested specimens	97
4.6	Procedure to attach stain gauges on reinforcements of beam and column (a) Dunlop glue provide water resistance and (b) bitumen provide impact resistance during concrete casting	99
4.7	Cylinder samples testing (a) compressive test (b) sample after compression test (c) tensile test (d) sample after tensile test and (e) Young's modulus test	100
4.8	Stress-strain profile of concrete for Young's modulus test	102
4.9	Formworks for components (a) beam (b) column and (c) panels	104
4.10	Concrete after casting in moulds (a) beam (b) column (c) panels and (d) three cylinder samples	105
4.11	IBS products after concrete casting (a) all representative components (b) beam connection (c) column connection and (d) panel connection slots	106
4.12	Concrete cured in the curing tank	108
4.13	Concrete painting using white emulsion	108
4.14	Diagram of frame flexural test set-up	110
4.15	Diagram of column monotonic pushover test set-up (a) Column 1 in x-axis loading and (b) Column 2 in y-axis loading	111
4.16	Schematic diagram of test set-up of scale 1:5 frame	112
4.17	Diagram of pushover cyclic test set-up	113
4.18	Strain gauges attached on steel (a) connection 1 (b) connection 2 and (c) beam main reinforcement	114
4.19	Four accelerometers were installed on columns	116
4.20	Four accelerometers were placed on beams	117
4.21	Schematic diagram of scale 1:5 model for vibration test	117
4.22	Assembly of scaled of 1:5 of one storey residential unit	118
4.23	Side view of scale 1:5 one unit residential model	118
4.24	Sequence of location of accelerometers and axis of the	

	structure	119
5.1	Location of U-shaped steel plate	121
5.2	Experimental load versus vertical displacement diagram (a) all deflection points and (b) at mid-span	122
5.3	Site view profile of deflection of beam at ultimate state (13 kN	123
5.4	Load-strain relationship of steel bar	124
5.5	Experimental crack pattern of beam (a) at 3 kN and (b) at 13 kN	125
5.6	Experimental deformation pattern of beam at load 13 kN (a) front view and (b) rear view	125
5.7	Deformation of steel-concrete	126
5.8	Columns testing directions (a) C1 x-axis and (b) C2 y-axis	127
5.9	Load-displacement relationship (a) Column C1 and (b) Column C2	128
5.10	Comparison of C1 and C2 in load-displacement relationship at top column	128
5.11	Crack pattern of Column 1 in x-axis loading direction	129
5.12	Crack pattern of Column 2 in y-axis loading direction	130
5.13	Deflected shape of C1 and C2 at ultimate state	130
5.14	Identity of components	131
5.15	Hysteresis profile of frame assembly	132
5.16	Cycle 1 loading test: (a) load - horizontal displacement relationship (b) sketch of front view crack pattern (c) sketch of back view crack pattern and (d) photograph	134
5.17	Cycle 2 loading test: (a) load - horizontal displacement relationship (b) sketch of front view crack pattern (c) sketch of back view crack pattern and (d) photograph	137
5.18	Cycle 3 loading test: (a) load - horizontal displacement relationship (b) sketch of front view crack pattern (c) sketch of back view crack pattern and (d) photograph	140
5.19	Cycle 4 loading test: (a) load - horizontal displacement relationship (b) sketch of front view crack pattern (c)	

	sketch of back view crack pattern and (d) photograph	142
5.20	Capacity curve of frame	145
5.21	Elastic and effective stiffness of frame	146
5.22	Graph of load versus displacement ductility	149
5.23	Graph of load versus dissipated energy	150
5.24	Load-strain curve of column RHS at connection part	151
5.25	Ductility ratio damage index of pushover frame	152
5.26	Park and Ang's damage index of pushover frame	152
5.27	Capacity curve II of pushover frame	158
6.1	Schematic 3D grid numbering diagram	160
6.2	y-z plane @ x = A	161
6.3	y-z plane @ x = B	161
6.4	y-z plane @ x = C	162
6.5	x-z plane @ y = 1	162
6.6	x-z plane @ y = 2	162
6.7	x-z plane @ y = 3	163
6.8	x-z plane @ y = 4	163
6.9	x-z plane @ y = 5	163
6.10	x-z plane @ y = 6	163
6.11	Recorded PGA on ground by Accelerometer 1	168
6.12	Vibration loading at 48 Amp in (a) x-axis (b) y-axis and (c) z-axis	168
6.13	Scale of 1:5 of SMART IBS house model before vibration test	169
7.1	Modelling of concrete parts in Abaqus/CAE (a) beam (b) column and (c) wall panel	191
7.2	Modelling of steel parts in Abaqus/CAE (a) U-shaped steel plate for beam (b) U-shaped steel plate for connection part of wall panel (c) rectangular hollow section at the bottom of column (d) rectangular hollow section at top of column (e) bolt and nut (f) long steel connector (g) short steel connector and (h) footing	191
7.3	Modelling of main reinforcement in Abaqus/CAE (a)	

	merged beam reinforcement and (b) merged column reinforcement	193
7.4	Input stress-strain curve for concrete in nonlinear parts in Abaqus/CAE 6.12	194
7.5	Input stress-strain curve for steel main reinforcement in nonlinear parts in Abaqus/CAE 6.12	194
7.6	Input stress-strain curve for U-shaped steel plate for connection part of wall panel in nonlinear parts in Abaqus/CAE 6.12	195
7.7	Input stress-strain curve for steel rectangular hollow section of column in nonlinear parts in Abaqus/CAE 6.12	195
7.8	Input stress-strain curve for steel U-shaped steel plate for beam in nonlinear parts in Abaqus/CAE 6.12	196
7.9	Assembly of scale of 1:5 of one bay one storey frame for flexural analysis in Abaqus/CAE	197
7.10	Assembly of scale of 1:5 of two single columns for pushover analysis in Abaqus/CAE	197
7.11	Assembly of scale of 1:5 of two bay one storey frames with wall panels for pushover pseudo-dynamic cyclic load analysis in Abaqus/CAE	198
7.12	Flexural test model in Abaqus/CAE (a) meshed frame and (b) meshed IBS column-beam connection	200
7.13	Refined meshed part in Abaqus/CAE (a) U-shaped steel plate for beam and (b) rectangular hollow section for column	201
7.14	Modelling of scale 1:5 of one storey SMART IBS house in SAP 2000	202
8.1	Comparison of load-displacement relationship in flexural experimental test and NLFEA at mid span of beam	205
8.2	Comparison of load-displacement relationship in single column pushover experimental test and NLFEA at top of column C1	206
8.3	Comparison of load-displacement relationship in single	

	column pushover experimental test and NLFEA at top of column C2	206
8.4	Comparison of load-displacement relationship in two bay frames pushover pseudo-dynamic experimental test and NLFEA	207
8.5	Deformation pattern for beam flexural analysis (a) overall deformation and (b) deformation at beam-column connection	208
8.6	AC yield of concrete beam	208
8.7	Principle stresses of concrete only for beam flexural analysis (a) maximum and (b) minimum	209
8.8	Maximum principle stresses of concrete beam	209
8.9	Minimum principle stresses of concrete beam	210
8.10	Principle stresses of concrete only at connection (a) maximum and (b) minimum	210
8.11	Stress distribution of IBS components (a) RHS of column (b) bolt and nut and (c) U-shaped steel plate of beam	211
8.12	AC yield of main reinforcements	212
8.13	Stress distribution of main reinforcement in beam	212
8.14	Deformation pattern of single column pushover analysis (a) C1 and (b) C2	213
8.15	Maximum principle stresses of column concrete (a) C1 and (b) C2	213
8.16	Minimum principle stresses of column concrete (a) C1 and (b) C2	214
8.17	Stress distribution of main reinforcement in column (a) C1 and (b) C2	215
8.18	Stress distribution of RHS (a) C1 and (b) C2	215
8.19	Deformed shape in AC yield for one storey two bay frames in FEA pushover pseudo-dynamic analysis	216
8.20	Principle stresses of concrete only for two bay frames pushover pseudo-dynamic analysis (a) maximum and (b) minimum	216

8.21	Stress distribution of steel connection (a) front view of top connection (b) top view of top connection and (c) front view of bottom connection (RHS)	217
8.22	Model 1: Modes of shapes	220
8.23	Model 2: Modes of shapes	222
9.1	Probability density function of damage score (DSc)	230
9.2	Cumulative density function of damage score (DSc)	231
9.3	Division part of the components for one storey two bay pushover frames	233
9.4	Reliability block diagram for one storey two bay pushover frames	238
9.5	System DBRI for pushover frame	240
9.6	Probability of failure of the system for pushover frame	240
9.7	Plan View of OSSIM	242
9.8	Block work diagram of <i>serial-parallel</i> OSSIM	244

**LIST OF ABBREVIATIONS**

AC	-	Accelerometer
ACI	-	American Concrete Institute
ASCE	-	American Society Civil Engineers
ATC	-	Applied Technology Council
B	-	Beam
BS	-	British Standard
BSI	-	British Standard Institute
C	-	Column
CIDB	-	Construction Industry Development Board
CP	-	Collapse Prevention
CSI	-	Computers & Structures, Inc.
DBRI	-	Damage Based Reliability Index
DI	-	Damage Index
DR	-	Damage Rank
DRSc	-	Damage Rank Score
DS	-	Damage State
DSc	-	Damage Score
EC	-	European Code
FEMA	-	Federal Emergency Management Agency
IBS	-	Industrialised Building System
IO	-	Immediate Occupancy
LS	-	Life Safety
LVDT	-	Linear Variable Displacement Transducer
NLFEA	-	Nonlinear Finite Element Analysis
OSSIM	-	One Storey SMART IBS Model
PCI	-	Prestressed/Precast Concrete Institute
PGA	-	Peak Ground Acceleration
RHS	-	Rectangular Hollow Section
SEAOC	-	Structural Engineers Association of California
SMART	-	Specific, Manufacturable, Available, Reliable, Testable/Transportable



## LIST OF SYMBOLS

$\sigma_{c0}$	-	initial yield
$\sigma_{cu}$	-	ultimate stress
$\varepsilon_i^{\sim ck}$	-	cracking strain
$\omega$	-	circular frequency
$\omega^2$	-	eigenvalue
$\mu$	-	displacement ductility
$\Delta_y$	-	lateral displacement of system at ultimate capacity
$\Delta_n$	-	lateral displacement of system at yielding.
$\mu_0$	-	maximum displacement ductility capacity under monotonic loading.
$\mu_{max}$	-	maximum displacement ductility demand
$\Delta_s$	-	story drift
$\beta$	-	calibration parameter from experimental
$\bar{x}$	-	sample mean
$\mu$	-	mean of a distribution
$\hat{\sigma}^2$	-	estimate of population variance
$\sigma^2$	-	population variance
$\varepsilon_y$	-	yield strain of steel
$\varepsilon_u$	-	ultimate strain of steel
$f_y$	-	yield stress of steel
$f_u$	-	ultimate stress of steel
$f_{cu}$	-	compressive strength of concrete
$f_t$	-	splitting strength of concrete
$E$	-	modulus of elasticity
$W_i$	-	weighting factor
$I_i$	-	importance level
$R_s$	-	system reliability
$D_s$	-	damage score
$R_i$	-	damage rank score

## LIST OF APPENDICES

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Scale of 1: 10 Model	260
B	Steel Properties For Scale 1:5 Model	271
C	Design To European Code 2	274
D	Theoretical Calculations for Pushover Pseudo-dynamic Test	290
E	Photo of Pushover Pseudo-dynamic Cyclic Load Test Result	299
F	Inspection of Damaged Building	307
G	Damage Assessment of Components Pushover Pseudo- dynamic Cyclic Test of Two bay One Storey Frame Assembly at Load of 4.8 kN and Lateral Displacement of 48 mm	313
H	Assembly Process of Scale 1:5 One Storey SMART IBS Residential Model	327
I	Vibration Loadings in Vibration Test of Scale 1:5 of One Storey SMART IBS Residential Model	331
J	List of Publications	342

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Background of the Study**

The period between First and Second World War had witnessed a mass home destruction that leads to high demand of replacement and renewal of housing. The shortages of skilled labour and essential materials for construction were greatly affecting the built of building. Then, an industrialised building system was introduced and it became a solution for house renewal. It also provides low cost housing and an improvement of construction processes through an exploration of component size and the prefabrication of standard components. Now, precast structures have been widely accepted for residential construction in both undeveloped and developing countries to meet the rapid growth of population.

In Malaysia, the demand of housing is increasing especially provide a residential building to the low and medium income group. Industrialised buildings were chosen to fulfil the demands using an advancement of technology in construction industry to produce high quality construction products at a low cost of construction operation. The conventional construction method is not able to meet the housing demand due to the step by step of conventional built and higher activity cost.

According to Construction Industry Development Board Malaysia (CIDB), Industrialised Building System (IBS) is defined as a construction system which components are manufactured in a factory, and assembled to become a structure with minimal site work. The main reason to recommend the use of IBS in Malaysia is

the high availability of raw construction materials for IBS and to complement the shortages of unskilled labours for the construction industry.

However, the main disadvantages of IBS in Malaysia are the highly capital investment and design expert, manufacturing factory, tools and skills for the assembly of components at the construction site. Even so, the IBS still becomes the main solution engaged by the Ministry of Housing and Local Government of Malaysia to overcome the high number of demand of buildings. Nevertheless, IBS is still in early stage of use with a few or limited guidelines in design of IBS components especially when the seismic effect is to be taken into consideration.

Structural seismic performance must be known for IBS building to be built in earthquake area. Poor structural seismic performance will lead to the significant fatalities and property losses without a mandatory codes strength requirement. Previous earthquake cases in 1988 Spitak Earthquake in Armenia, 1994 Northridge Earthquake, 1995 Kobe Earthquake, 1999 Kocaeli Earthquake and 2008 Wenchuan Earthquake in China had revealed the actual performance of all the precast buildings that inflicted massive damage, tragic casualties and reputation of precast industries.

Failures of precast structures are due to several factors that are the continuity of the whole structural system, insufficient ductility of the columns to beam joints, and inadequate diaphragms action that causing a failure of primary structural elements. Due to the lack of research and precise design of precast components, the safety of seismic resistant structure is unknown and indirectly causes low confidence levels of the customers toward the precast products. Hence, many researches are needed to improve the use of precast concrete in all aspects from planning, design, manufacturing and assembly in order to compete with the conventional constructions.

Structural reliability is an important tool to measure the level safety of building structures. Damage model is used to predict the reliability index based on damage intensities of IBS system. Structure with a high-risk of damage will endanger

human lives due to catastrophic failure when subjected to earthquake loads. However, until now the damage based reliability research has not been conducted in Civil Engineering field especially to SMART IBS. Thus, damage based reliability research on industrialised building should be carried out to mitigate the damages and to ensure that the designed and commercialised structure is safe for living.

## **1.2 Statement of the Problem**

Malaysia is situated at the peripheral of the Pacific Ring of Fire and it is surrounded by area that experienced earthquakes. Peninsular Malaysia is close to the Sumatra and the Andaman Sea while Sabah and Sarawak is close to the South Philippines and North Sulawesi. The earthquakes could affect Malaysia anytime soon.

The Borneo Post has reported an earthquake of 5.5 magnitude occurred in northern Sumatra, Indonesia on 14<sup>th</sup> June 2011. From the event, tremors were felt in several areas on the west coast of peninsular Malaysia such as Melaka, Selangor and south of Perak. In 2012, six earthquakes in Sabah and two earthquakes in Sarawak between 2 and 4.5 Richter scale were detected by Malaysian Meteorological Department. On 6<sup>th</sup> June 2013, earthquake of 4.9 Richter scale hit Sabah and other parts of Borneo. The Star newspaper reported that on 11<sup>th</sup> July 2013, an earthquake measuring 4.7 Richter scale rocked northern Sumatra in Indonesia and tremors were felt in several areas in Selangor, Kuala Lumpur and Putrajaya. However, 5.8 Richter scale of earthquake in Lahat Datu, Sabah in 1976 is the strongest earthquake so far felt in Malaysia.

The buildings in Malaysia are normally designed for gravity loads and hence they cannot resist the force of an earthquake. Even medium earthquakes strike is strong enough to damage a large part of buildings throughout the nation. Since IBS is taken as an alternative method to solve the housing shortage, thus its building

performance must be taken into account to prevent damages and casualties in the future.

The seismic performance of SMART IBS, a new prefabricated hybrid Industrialised Building System (IBS) with patent name as Building Assembly System PCT/MY2010/000182 PI2010003779 need to be investigated to study its structural mode of failure and its connection behaviour at the extreme maximum earthquakes lateral load capacity. The performance of SMART IBS is evaluated based on Federal Emergency Management Agency 356 (FEMA 356).

Full scale model is not prescribed as it is not practical for laboratory experiments. Therefore, the scale of 1:5 model is chosen to assess the whole house system in an earthquake experimental test. Obviously, the ultimate capacity of small model cannot be scaled up to represent exactly the performance of full scale model. However, the obtained structural performance, damages and cracks of small model can indicate the characteristics of structural performance for damage reliability assessment.

Then, the research was further explored to facilitate its performances to customers in terms of structural seismic safety index. Structural damage reliability research was conducted to assess the performance of SMART IBS building using Damage Based Reliability Index. Consequently, the procedure of damage based reliability analysis has been proposed for SMART IBS residential building. The indices give illustrations to the house owner on the level of damage at different earthquake peak ground acceleration (PGA).

Since UTM IBS house can be easily assembled and dissembled, the house owner can replace the damage component instantly after earthquakes as compared to rebuilt the conventional houses. Therefore, the research is to provide a Damage Based Reliability Index for SMART IBS residential building at different levels of earthquake PGA.

### **1.3 Purpose of the Study**

The purpose of the study is to obtain a damage based reliability index of SMART IBS residential building subjected to earthquake peak ground acceleration (PGA) ranges from 0.05g to 5.3g through experimental tests and nonlinear finite element analyses.

### **1.4 Objectives of the Study**

The objectives of the study are:

- i) To examine the modes of failures and flexural strength of scaled 1:5 beam, lateral strength of scaled 1:5 single column and lateral strength of scaled 1:5 two frames assembly through nonlinear finite element analysis and experimental tests.
- (ii) To assess the structural performance level using structural seismic demand parameters such as story drift, ductility and energy dissipation.
- (iii) To propose and assess damage ranking, damage index and performance level based on degree of damage of scaled 1:5 SMART IBS structure through various intensity of vibration test.
- (vi) To develop damage based reliability procedure and equation to obtain a structural damage based reliability index for earthquake peak ground acceleration (PGA) ranges from 0.05g to 5.3g for SMART IBS.

### **1.5 Scope of the Study**

The scope is to assess the reliability index based on damage of scale 1:5 of one storey SMART IBS residential structure using surface visual damage assessment method.

A scale of 1:5 of one frame for flexural test, two single columns for single degree of freedom pushover test, two frames assembly for pushover pseudo-dynamic cyclic load test and one storey SMART IBS residential model were built and tested to fail in laboratory. All the structural failures were recorded during the tests. The pushover two frames assembly test was assessed for a story drift, ductility and energy dissipation. The performance of the pushover frames was then evaluated using FEMA 356 and categorized by three different performance levels that was the level of Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP).

Nonlinear finite element software, Abaqus/CAE 6.12 was used to analyse one beam frame in flexural test, two single columns of a single degree of freedom of pushover tests and two frames in pushover analysis. Heavy duty finite element analysis of one-storey SMART IBS residential unit was not conducted in this research due to limited computing facilities such as high performance computer. The obtained data from Abaqus/CAE were compared with the experimental result for conformance. The obtained data were the ultimate capacity and maximum displacement. The locations of concrete crack and crush were detected via maximum and minimum principal stresses while the deformation of steel connections was assessed as a von Mises stress.

SAP 2000 v15 was used to perform modal analysis on scaled of 1:5 of one storey residential unit in order to obtain its mode of shape, natural frequencies and natural periods.

Vibration test was performed for a scale of 1:5 of a complete one storey of residential building on vibrating table in Structure Laboratory, UTM. The procedure of damage based reliability analysis was then proposed for SMART IBS residential building. The individual damage ranking score for each component of IBS was recorded to calculate the probability of failure of the whole house system. From there, the damage based reliability index (DBRI) was calculated.



## **1.6 Significance of the Study**

The findings of research are important to provide reliability index for scaled of 1:5 of one storey SMART IBS residential unit when subjected to earthquake peak ground acceleration (PGA) ranges from 0.05g to 5.3g using damaged values of the structure. The probability of failure of the system is then calculated to further improve the design of the failed components so that the structure will achieve better quality and performance in the future as well as minimize the casualties rate and loss of properties. This research provides supportive evidences on SMART IBS performances to give a pre-engineered building for the future. With the evidence on hand, owners or stakeholders are more confidence in decision making for adopting IBS for mass housing construction.

## REFERENCES

- Abdul Hamid, M. F., Haron, A. and Ahmad, J. (2012). Application of Probability and Statistics in Constructing Likelihood of Failure Bands for RBI Approach in Structural Integrity Management. *Managing & Challenges in Asset Integrity Management Implementation*. 19<sup>th</sup> January 2012, Kuala Lumpur, Malaysia.
- Agus, M. R. (1997). Urban Development and Housing Policy in Malaysia. *International Journal For Housing Science and Its Application*. 21(2), 97–106.
- Akira, M. and Shinpei, T. (2004). Damage Index Sensor for Smart Structures. *Structural Engineering and Mechanics* 17, 331-346.
- Alarcón, E., Recuero, A., Perera, R., López, C., Gutiérrez, J. P. and De Diego, A. (2001). A Repairability Index for Reinforced Concrete Members based on Fracture Mechanics. *Engineering Structures*. 23(6), 687–97.
- American Concrete Institute (2001). *ACI ITG/T1.1-01*. Farmington Hills, Michigan: American Concrete Institute
- Andrew, W. (2004). *ATC-58 Project Task Report -Engineering Demand Parameters For Structural Framing Systems*. New York.
- Anthugari, V. and Ramancharla, P. K. (2012). Displacement Based Damage Estimation of RC Bare Frame Subjected to Earthquake Loads: A Case Study on 4 Storey Building. *15th World Conference on Earthquake Engineering*. Lisbon, Portugal.
- Applied Technology Council (1996). *ATC 40*. California: Applied Technology Council.
- American Society Civil Engineers (2006). *ASCE 7-05*. Reston, Virginia: American Society Civil Engineers.
- American Society for Testing and Materials (2004). *ASTM C496*. USA: American Society for Testing and Materials.

- Aviram, A., Mackie, K. R. and Stojadinović, B. (2008). *Guidelines for Nonlinear Analysis of Bridge Structures in California*. Pacific Earthquake Engineering Research Center. University of California, Berkeley, California.
- Badir, Y. F. and Razali, A. (1998). Theory of classification: Its application and Badir Razali Building Systems Classification. *Journal of the Institute of Engineering*, Malaysia.
- Bournas, D. A., Negro, P. and Taucer, F. (2013). The Emilia Earthquakes: Report and Analysis on the Behavior of Precast Industrial Buildings from a Field Mission. *4<sup>th</sup> ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*. 12–14 June. Kos Island, Greece.
- Bozorgnia, Y. and Bertero, V. V. (Eds.) (2004). *Earthquake Engineering-From Engineering Seismology to Performance-Based Engineering*. London: CRC Press.
- BRE (2005). BRE Digest 496 - *Timber frame buildings: A Guide to the Construction Process*. [Brochure]. Garston, BRE.
- British Standard Institution (2004). *BS EN 1998-1: 2004* (Eurocode 8). London: British Standard Institution.
- British Standard Institution (2004). *BS EN 1992: 2004* (Eurocode 2). London: British Standard Institution.
- British Standard Institution (2009). *BS EN 12390-5: 2009*. London: British Standard Institution.
- Building Assembly System (2011). *International Patent No: PCT/MY2011/000182 PI2010003779*. Dr. Abdul Kadir Marsono, Dr. Ahmad Mahir Makhtar and Dr. Masine Md. Tap.
- Buckingham, E. (1914). On Physically Similar Systems: Illustrations of the Use of Dimensional Equations. *Physical Review*. 4(4), 345-376
- Bungale, S. T. (2005). *Wind And Earthquake Resistant Buildings*. New York: Marcel Dekker.
- Chai, Y. H., Romstad K. M. and Bird, S. M. (1995). Energy-based Linear Damage Model for High Intensity Seismic Loading. *J Struct Eng, ASCE* 121(5), 857–64.
- Choi, H. K., Choi, Y. C. and Choi, C. S. (2013). Development and Testing of Precast Concrete Beam-To-Column Connections. *Engineering Structures* 56, 1820–1835.

- Choi, S. K., Grandhi, R. V. and Canfield, R. A. (2007). *Reliability-based Structural Design*. London: Springer.
- CIDB (2003). *Industrialised Building System (IBS) Roadmap 2003-2010*. In CIDB. Malaysia (Ed.). Kuala Lumpur: CIDB.
- Cosenza, E., Manfredi, G. and Ramasco, R. (1993). The Use of Damage Functionals in Earthquake Engineering: A Comparison between Different Methods. *Earthquake Engineering & Structural Dynamics*. 22, 855-868.
- CSI Analysis Reference Manual: For SAP2000®, ETABS®, SAFE® and CSiBridge® (2013). Computers and Structures, Inc. Berkeley, California, USA
- Curl, J. S. (2006). *The Oxford Dictionary of Architecture and Landscape Architecture* (2<sup>nd</sup> ed.) U.K.: Oxford University Press.
- Datta, T. K. (2010). *Seismic Analysis of Structures*. Singapore: John Wiley & Sons (Asia) Pte. Ltd.
- Death Toll Rises in Armenian Earthquake. (1988, December 10). *BBC News*.
- DeFranco, S. and O'Connor, P. (1999). Development of a Risk Based Underwater Inspection (RBUI) Process for Prioritizing Inspections of Large Numbers of Platforms. *1999 Offshore Technology Conference*. 3–6 May 1999. Houston, Texas.
- Building Research Establishment (1997). *Design of Normal Concrete Mixes*. London: Building Research Establishment.
- Devore, J. L. (2009). *Probability and Statistics for Engineering and the Sciences*. Canada: Nelson Education, Ltd.
- Durmisevic, E. (2006). *Transformable Building Structures: Design for Disassembly as a Way to Introduce Sustainable Engineering to Building Design & Construction*. Netherlands: Cedris M&CC.
- Elliott, K. S. and Jolly, C. K. (2013). *Multi Storey Precast Concrete Framed Structures* (2<sup>nd</sup> ed.) U. K.: Wiley-Blackwell.
- Fardis, M. (2003). *Seismic Assessment And Retrofit Of Reinforced Concrete Buildings*. Switzerland: International Federation For Structural Concrete.
- Federal Emergency Management Agency (2002). *FEMA 154* (Second ed.). California: Applied Technology Council.
- Federal Emergency Management Agency (2000). *FEMA 356*. Washington: American Society of Civil Engineers.

- Federal Emergency Management Agency (1997). *FEMA 273*. Washington : Applied Technology Council.
- Gallagher, P. D. (2010). Program Plan for the Development of Collapse Assessment and Mitigation Strategies for Existing Reinforced Concrete Buildings. *National Institute of Standards and Technology (NIST) GCR 10, 917-7*.
- Garcia, A. L. (2008). *Probability, Statistics and Random Processes for Electrical Engineering*. Upper Saddle River, NJ: Pearson/Prentice-Hall.
- Ghobarah, A. (2000). Seismic Assessment of Existing RC structures. *Prog. Struct. Engng Mater* 2, 60–71.
- Girty, G. H. (2009). *Perilous Earth: Understanding Processes Behind Natural Disasters*. Department of Geological Sciences, San Diego State University.
- Gong, M. S., Xie, L. L. and Ou, J. P. (2008). Modal Parameter Identification of Structure Model using Shaking Table Test Data. *The 14<sup>th</sup> World Conference on Earthquake Engineering*. 12-17 October. Beijing, China.
- Grigoriu, M. (1987). *Damage Models for Seismic Analysis. Technical Report 87-4*. Cornell University.
- Housner, G. W. and He, D. X. (2002). *Report on The Great Tangshan Earthquake of 1976*. California Institute of Technology. Pasadena, California.
- Hu, H. T and Schnobrich, W. C. (1990). Nonlinear Analysis of Cracked Reinforced Concrete. *ACI Structural Journal*, 199-207.
- Kunnath S. K., Reinhorn, A. M. and R. F. (1992). Lobo *IDARC Version 3.0: A Program for the Inelastic Damage Analysis of Reinforced Concrete Structures, Technical Report NCEER-92-0022*, National Center for Earthquake Engineering Research, Buffalo, NY.
- Lew, H. S., Cooper, J., Hays, W. and Mahoney, M. (1994). The January 17, 1994, Northridge Earthquake California. *National Institute of Standards and Technology (NIST) SP 871*, 375-426.
- Loring, A. W. (1992). Analysis of the Collapsed Armenian Precast Concrete Frame Buildings-*Proceedings Of The Tenth World Conference On Earthquake Engineering*. Madrid, Spain.
- Marsono, A. K. and Khoshnoud, H. R. (2010). Evaluating Equivalent Static Analysis of Iranian Code with Nonlinear Static Pushover Analysis. *Proceeding of the First Makassar International Conference on Civil Engineering (MICCE2010)*. Makassar, Indonesia.

- Miyamoto, H. K., Gilani, A. S. and Wada, A. (2008). Reconnaissance Report of the 2008 Sichuan Earthquake, Damage Survey of Buildings and Retrofit Options. *The 14<sup>th</sup> World Conference on Earthquake Engineering*. 12-17 Oct. Beijing, China.
- Moghadasi, M. and Marsono, A. K. (2012). Comparative Experimental Study of Full-Scale H-Subframe using a New Industrialized Building System and Monolithic Reinforced Concrete Beam-To-Column Connection. *Struct. Design Tall Spec. Build.* Published online in Wiley Online Library.
- Mortezaei, A., Ronagh, H. R., Kheyroddin, A. and Ghodrati Amiri, G. (2011). Effectiveness of Modified Pushover Analysis Procedure for the Estimation of Seismic Demands of Buildings Subjected to Near-fault Earthquakes Having Forward Directivity. *Struct. Design Tall Spec. Build.* 20, 679–699.
- Murat, S., Denis, M., Rene, T., N. John, G., Anthony, G. G. and Ahmed, G. (2001). The August 17, 1999, Kocaeli (Turkey) Earthquake -Damage to Structures. *Canadian Journal of Civil Engineering*.
- Murty, C. V. R. (Ed.) (2006). *At Risk: The Seismic Performance of Reinforced Concrete Frame Buildings with Masonry Infills Walls*. California: Earthquake Engineering Research Institute.
- Nasly, M. A. and Yassin, A. A. M. (2009). *Sustainable Housing Using an Innovative Interlocking Block Building System*. Meniti Pembangunan Lestari dalam Kejuruteraan Awam, Pusat Pengajian Kejuruteraan Awam, Universiti Sains Malaysia.
- Negro, P. and Toniolo, G. (2012). *JRC Scientific and Policy Reports: Design Guidelines for Connections of Precast Structures under Seismic Actions*. Joint Research Centre, European Commission, Italy.
- Newmark, N. M. and Rosenblueth, E. (1971). *Fundamentals of Earthquake Engineering*. N. J: Prentice-Hall.
- Nguyen, P. C. and Kim, S. E. (2014). Nonlinear Inelastic Time History Analysis of Three-Dimensional Semi-rigid Steel Frames. *Journal of Construction Steel Research* 101, 192-206.
- O'Connor, P. D. T. and Kleyner, A. (2012). *Practical Reliability Engineering*. U. K: John Wiley & Sons, Ltd.

- Okada, S. and Takai, N. (2000). Classification of Structural Types and Damage Patterns of Buildings for Earthquake Field Investigation. *12th World Conference on Earthquake Engineering*. 30 January-4 February. Auckland, New Zealand.
- Park, R. (2003). *Seismic Design of Precast Concrete Building Structures*. Switzerland: International Federation for Structural Concrete (fib).
- Park, R. and Paulay, T. (1975). *Reinforced concrete structure*. John Wiley & Sons.
- Park, Y. J., Ang, A. H. S. and Wen, Y. K. (1984). Seismic Damage Analysis and Damage-Limiting Design Of R/C Buildings. *Structural research series report No. 516. Urbana (IL, USA)*: University of Illinois.
- Park, Y. J. and Ang A. H. S. (1985). Seismic Damage Analysis of Reinforced Concrete Buildings. *Journal of Structural Engineering, ASCE* 111 (4), 740-757.
- Park, Y. J., Ang A. H. S. and Wen, Y. K. (1987). Damage-Limiting a Seismic Design of Buildings. *Earthquake Spectra* 3, 1-25.
- Park, Y. J. and Ang, A. H. S. (1985). Mechanistic Seismic Damage Model for Reinforced Concrete. *J Struct Eng, ASCE* 111(4), 722-739.
- Powell, G. H. and Allahabadi, R. (1988). Seismic Damage Prediction by Deterministic Methods: Concepts and Procedures. *Earthquake Eng. Struct. Dyn.* 16, 719-734.
- Precast/Prestressed Concrete Institute (2010). *PCI Design Handbook Precast and Prestressed Concrete*. USA: Precast/Prestressed Concrete Institute
- Ramu, M., Prabhu Raja, V. and Thyla, P. R. (2010). Development of Structural Similitude and Scaling Laws for Elastic Models. *International Journal Manufacturing Engineering*. 9(3), 67-69.
- Raja, V. P., Ramu, M. and Thyla, P. R. (2013). Analytical and Numerical Validation of the Developed Structural Similitude for Elastic Models. *Indian Journal of Engineering & Materials Sciences*. 20, 492-496
- Sadeghi, K. and Nouban, F. (2010). A Simplified Energy Based Damage Index for Structures Subjected to Cyclic Loading. *International Journal of Academic Research* 2 (3).
- SeismoSignal (2013). SeismoSignal Documentation. Seismosoft Ltd.
- Sen, T. K. (2009). *Fundamentals of Seismic Loading on Structures, Performance Based Seismic Engineering-An Introduction*. United Kingdom: John Wiley & Son.

- Shahrul, N. (2003). *Survey on the Usage of Industrialised Building System (IBS) in Malaysian Construction Industry*. Malaysia.
- Siddharta, G., Debarati, D. and Abhinav, A. K. (2011). Estimation of the Park-Ang Damage Index for Planar Multi-Storey Frames using Equivalent Single-Degree Systems. *Engineering Structures* 33, 2509-2524.
- Simulia (2010). *Abaqus Analysis User's Manual Volume III: Materials*
- Letchford, C. and O'Rourke, M. (2014). *Full-Scale Investigation of Wind-Induced Vibrations of Mast-Arm Traffic Signal Structures*. University Transportation Research Center, USA.
- Skokan, M. J. (2000). *Reliability-Based Seismic Performance Evaluation of Steel Frame Buildings using Nonlinear Static Analysis Methods*. Doctor of Philosophy, University of California, Los Angeles.
- Suzuki, M. and Ibayashi, K. (1998). Lifetime Seismic Reliability of Reinforced Concrete Structures. *Proceeding FRAMCOS-3*. 12-16 Oct. Freiburg, Germany.
- Takashi, K., Fumitoshi, K. and Yoshiaki, N. (2002). *Quick Inspection Manual For Damaged Reinforced Concrete Buildings Due To Earthquakes: Based On Disaster Of 1999 Kocaeli Earthquake In Turkey*. National Institute of Land and Infrastructure Management.
- Tholen, P., Siddhartha, G. and Kevin, R. C. (2008). Estimation of Hysteretic Energy Demand using Concepts of Modal Pushover Analysis. *Earthquake Engineering & Structural Dynamics*. 37, 975–990.
- Thomas, T. (1998). *Seismic Design of Reinforced Concrete Structures For Controlled Inelastic Response*. Switzerland: Thomas Telford Ltd.
- van de Lindt, J. W. (2005). Damage-Based Seismic Reliability Concept for Woodframe Structures. *J Struct Eng*, ASCE 2005. 131(4), 668–75.
- Van Sien, R. C. (1968). *Small Scale Reinforced Concrete Models*. Joint Highway Research Project. Purdue University Lafayette Indiana.
- Vatansever, C. and Yardimci, N. (2010). Cyclic Behavior and Numerical Modelling of a Semi-rigid Frame. *Steel Construction* 3 (3).
- Vision 2000 (1995). *Performance Based Seismic Engineering of Buildings*. Structural Engineers Association of California. California.
- Zainal Abidin, A. R. (2007). *Simulation of Industrialised Building System Formation For Housing Construction*. Master of Science, Universiti Teknologi Malaysia, Johor, Malaysia.