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 lelurus, keputusan telah terbukti bahawa terdapat persamaan dalam tingkah laku lelurus dan tak lelurus 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.

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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

σ_{c0} - initial yield

σ_{cu} - ultimate stress

$\varepsilon_t^{\sim ck}$ - cracking strain

ω - circular frequency

ω^2 - eigenvalue

μ - displacement ductility

Δ_y - lateral displacement of system at ultimate capacity

Δ_n - lateral displacement of system at yielding.

μ_0 - maximum displacement ductility capacity under monotonic loading,

$\mu_{\max}$ - maximum displacement ductility demand

Δ_s - story drift

β - calibration parameter from experimental

$\bar{x}$ - sample mean

μ - mean of a distribution

$\hat{\sigma}^2$ - estimate of population variance

σ^2 - population variance

ε_y - yield strain of steel

ε_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

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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 Sumatera, Indonesia on 14th 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 6th June 2013, earthquake of 4.9 Richter scale hit Sabah and other parts of Borneo. The Star newspaper reported that on 11th 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 to be taken into assess 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.* 19th 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 Enginnering 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. *4th 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* (2nd 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* (2nd 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 14th 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 14th 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 oof 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 Siclen, 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.