SEISMIC FRAGILITY ANALYSIS ON LOW-DUCTILE REINFORCED CONCRETE FRAME WITH INADEQUATE LAP SPLICE LENGTH

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

In Malaysia, many existing buildings, particularly old buildings, are not designed for credible seismic actions. Most of the residential buildings in Malaysia which below 20 stories typically features an open space ground floor and the upper floors are featured with infill brick wall, deriving a higher lateral stiffness than the ground floor. Consequently, the safety of such buildings could be jeopardised by such uncertainties. Therefore, suitable risk management strategies such as fragility analysis should be adopted. Hence, there is a need to derive the seismic fragility curve for buildings with inadequate lap splice length in Malaysia. In this research, the seismic fragility curves for 3-, 6- and 9-story reinforced concrete frame with inadequate lap splice length were derived. All structural models were initially designed in accordance with the specification of BS 8110. The geometry orientation, material properties and reinforced detailing were also in accordance to the common practice in the construction industry of Malaysia. All structural models were subjected to 15 far-field seismic ground motion records. ETABS v2016 was used to carry out the nonlinear time-history analysis and incremental dynamic analysis to determine the inter-story drift demand and inter-story drift capacity of all the structural models. All structural models were excited by time-history data with increasing PGA from 0.05g to 0.50g with an increment of 0.05g. Three levels of seismic performance criteria were evaluated, namely immediate occupancy (IO), life safety (LS) and collapse prevention (CP) to assess the structural performance. Seismic fragility curves were plotted for all structural models. The results reveal that the nature of damage state of all structural models depends largely on the seismic wave frequency that resonate the natural frequency of the structural models. In general, the higher the building height, the lower the probability of damage exceedance induced onto the structural models. The results also show that the absence of adequate lap splice length at the both end of columns at first story could significantly increase the probability of damage exceedance for all seismic performance criteria in all structural models.

ABSTRAK

Di Malaysia, kebanyakan bangunan lama adalah tidak direka untuk menahan pengaruh pergerakan tanah seismik. Kebanyakan bangunan kediaman di Malaysia yang kurang daripada 20 tingkat lazimnya mempunyai ruang terbuka di tingkat bawah dan tingkat atas dilengkapi dengan dinding batu bata. Keadaan ini telah menghasilkan kekakuan lateral tingkat atas lebih tinggi daripada tingkat bawah. Akibatnya, keadaan ketidakpastian ini telah mengacamkan keselamatan bangunan-bangunan tersebut. Oleh itu, analisis kerapuhan perlu dijalankan untuk membentuk strategi pengurusan risiko yang sesuai. Justeru, hasilan lengkung kerapuhan seismik untuk bangunan yang diperkuat dengan pengukuhan tetuli yang tidak mencukupi adalah diperlukan di Malaysia. Dalam kajian ini, lengkung kerapuhan seismik telah dihasilkan untuk bingkai konkrit bertulang yang terdiri daripada 3-, 6- dan 9-tingkat, yang diperkuat dengan pengukuhan tetuli yang tidak mencukupi. Semua model struktur ini telah direka mengikuti spesifikasi kod BS 8110. Orientasi geometri, sifat bahan dan perincian bertetulang bingkai-bingkai tersebut juga telah direka dengan amalan umum dalam industri pembinaan Malaysia. Semua model struktur telah dikenakan 15 rekod pergerakan tanah seismik jarak jauh. ETABS v2016 telah digunakan untuk menjalankan analisis sejarah masa tidak linear dan analisa dinamik tokokan untuk menentukan permintaan drift antara tingkat dan kapasiti drift antara tingkat bagi semua model struktur. Semua model struktur teruja dengan data sejarah masa dengan peningkatan PGA dari 0.05g hingga 0.50g dengan setiap kenaikan 0.05g. Tiga tahap kriteria prestasi seismik telah dinilaikan, iaitu penghunian segera (IO), keselamatan nyawa (LS) dan pencegahan runtuhan (CP) untuk menilai prestasi struktur. Lengkung kerapuhan seismik telah dibentukkan untuk semua model struktur. Keputusan kajian ini menunjukkan bahawa keadaan kerosakan bagi semua model struktur bergantung adalah bergantung pada kekerapan gelombang seismik yang bergema pada kekerapan asli model struktur. Secara umumnya, apabila ketinggian bangunan meningkat, kebarangkalian kerosakan terhadap model struktur adalah lebih rendah. Keputusan analisis juga menunjukkan bahawa ketiadaan pengukuhan tetuli yang mencukupi pada akhiran tiang tingkat pertama akan meningkatkan kebarangkalian kerosakan terhadap semua model struktur dalam kriteria prestasi seismik masing-masing.

TABLE OF CONTENTS

TITLE		PAGE
	DECLARATION	**iii**
	DEDICATION	**iv**
	ACKNOWLEDGEMENT	**v**
	ABSTRACT	**vi**
	ABSTRAK	**vii**
	TABLE OF CONTENTS	**viii**
	LIST OF TABLES	**xii**
	LIST OF FIGURES	**xiv**
	LIST OF ABBREVIATIONS	**xix**
	LIST OF SYMBOLS	**xx**
	LIST OF APPENDICES	**xxi**
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Research Background	1
1.2	Problem Statement	3
1.3	Research Objectives	4
1.4	Scope of Work	4
1.5	Significant of Study	5
1.6	Structure of Thesis	6
CHAPTER 2	**LITERATURE REVIEW**	**7**
2.1	Introduction	7
	2.1.1 Near-Fault and Far-Field Earthquakes	7
2.2	Tectonic Setting and Seismicity of Malaysia	8
	2.2.1 Seismic Hazard in Malaysia	9
	2.2.2 Seismic Ground Motion for Malaysia	11
2.3	Building Damaged by Earthquake in Malaysia	13
	2.3.1 Building Damaged by Earthquake in Taiwan	14

2.4	Seismic Performance Objectives		15
	2.4.1	Soft-Story Effect	17
	2.4.2	Equivalent Diagonal Strut	18
	2.4.3	Ductility Classes	20
		2.4.3.1 Displacement Ductility Determination of Column	21
		2.4.3.2 Shear Resistance Contributed by Concrete to RC Column	24
2.5	Seismic Analysis and Assessment Procedures		25
	2.5.1	Linear Static Procedure (LSP)	26
	2.5.2	Linear Dynamic Procedure (LDP)	27
	2.5.3	Nonlinear Static Procedure (NSP)	28
		2.5.3.1 Force-Controlled Actions and Deformation-Controlled Actions	29
		2.5.3.2 Acceptance Criteria for Nonlinear Procedures	30
		2.5.3.3 Maximum Usable Strain Limits for Concrete	32
	2.5.4	Nonlinear Dynamic Procedure (NDP)	33
	2.5.5	Incremental Dynamic Analysis	33
2.6	Seismic Fragility Analysis		35
	2.6.1	Scaling Approach in Seismic Fragility Curve	38
2.7	Past Studies on Seismic Fragility Curve of Low-Ductile Reinforced Concrete Frame		39
	2.7.1	Fragility Curve for Generic Reinforced Concrete Frame	39
	2.7.2	Fragility Curve for Low-Ductile Reinforced Concrete Building	42
	2.7.3	Fragility Curve for Reinforced Concrete Buildings in Malaysia	44
2.8	Summary of Research Gap		46
CHAPTER 3	**RESEARCH METHODOLOGY**		**49**
3.1	Introduction		49
3.2	Selection of Appropriate Plan and Number of Stories for Numerical Analysis		51

3.3 Finite Element Simulation and Design of Buildings According to Common Practice in Malaysia 56
3.3.1 Concrete Material Properties 56
3.3.2 Reinforcement Material Properties 57
3.3.3 Design Loadings 57
3.4 Selection of Appropriate Seismic Ground Motion Records 61
3.5 Nonlinear Parameters and Plastic Hinge 65
3.6 Performing Incremental Dynamic Analysis 68
3.7 Derivation of Seismic Fragility Curves 69

CHAPTER 4 RESULTS & DISCUSSION 71
4.1 General 71
4.2 Damage State of Studied Frame 71
4.2.1 Plastic Hinges Formation in 3-Story Frame 72
4.2.2 Plastic Hinges Formation in 6-Story Frame 75
4.2.3 Plastic Hinges Formation in 9-Story Frame 79
4.2.4 Summary of Damage State of All Studied Frames 82
4.3 Inter-Story Drift Demand 83
4.3.1 Inter-Story Drift Demand of 3-Story Frame 84
4.3.2 Inter-Story Drift Demand of 6-Story Frame 86
4.3.3 Inter-Story Drift Demand of 9-Story Frame 89
4.4 Inter-Story Drift Capacity of Structure 91
4.4.1 Inter-Story Drift Capacity of 3-Story Frame 91
4.4.2 Inter-Story Drift Capacity of 6-Story Frame 93
4.4.3 Inter-Story Drift Capacity of 9-Story Frame 95
4.5 Development of Seismic Fragility Curves 96
4.5.1 Derivation of Seismic Fragility Curves for 3-Story Frame 97
4.5.2 Derivation of Seismic Fragility Curves for 6-Story Frame 99
4.5.3 Derivation of Seismic Fragility Curves for 9-Story Frame 101

4.6 Effect of Building Height to Probability of Damage Exceedance 104
4.7 Effect of Inadequate Column Lap Splice Length 105
4.7.1 Effect on 3-Story Frame 106
4.7.2 Effect on 6-Story Frame 107
4.7.3 Effect on 9-Story Frame 108
4.7.4 Effect to Typical Buildings in Malaysia 109

CHAPTER 5 CONCLUSION & RECOMMENDATION 113
5.1 Conclusions 113
5.2 Recommendations for Future Research 115

REFERENCES 117

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Damage Control and Building Performance Levels (FEMA 356, 2000)	16
Table 2.2	Equivalent diagonal strut formulae over past decades	19
Table 2.3	Component ductility demand classification (ASCE 41, 2017)	21
Table 2.4	Modelling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures – Reinforced Concrete Columns Other Than Circular with Spiral Reinforcement or Seismic Hoops as Defined in ACI 318 (ASCE 41, 2017)	32
Table 2.5	Three Story Reinforced Concrete Frame Building Damage States with Corresponding Damage States (Tan et al., 2014)	40
Table 2.6	Drift Capacities of the Selected Structures for Each Damage State (Fazilan et al., 2018)	46
Table 3.1	Details of Frame and Design Parameters	52
Table 3.2	Concrete Properties of Reinforced Concrete Frame	56
Table 3.3	Reinforcement Properties of Reinforced Concrete Frame	57
Table 3.4	Reinforcement Properties of Reinforced Concrete Frame	59
Table 3.5	Summary of Far-Field Ground Motion Records	62
Table 4.1	Maximum Inter-Story Drift Demand of 3-Story Frame	85
Table 4.2	Maximum Inter-Story Drift Demand of 6-Story Frame	88
Table 4.3	Maximum Inter-Story Drift Demand of 9-Story Frame	90
Table 4.4	Ultimate Drift Capacity of 3-Story Frame (IDA)	92
Table 4.5	Ultimate Drift Capacity of 3-Story Frame (Pushover Analysis)	92
Table 4.6	Ultimate Drift Capacity of 6-Story Frame (IDA)	94
Table 4.7	Ultimate Drift Capacity of 6-Story Frame (Pushover Analysis)	94

Table 4.8	Ultimate Drift Capacity of 9-Story Frame (IDA)	95
Table 4.9	Ultimate Drift Capacity of 9-Story Frame (Pushover Analysis)	96
Table 4.10	Fragility Curve Computation of 3-Story Frame	98
Table 4.11	Fragility Curve Computation of 6-Story Frame	100
Table 4.12	Fragility Curve Computation of 9-Story Frame	102
Table 4.13	Soil Amplification for Peninsular Malaysia, Sabah and Sarawak due to Deep Geology Effect (MS EN 1998-1: 2017)	110
Table 4.14	PGA of Key Township under Different Soil Conditions	110

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Location of Peninsular Malaysia on the Sunda Plate and the surrounding seismic sources (Loi et al., 2018)	8
Figure 2.2	Tectonic System of Southeast Asia (Tongkul, 2017)	9
Figure 2.3	Location of seismic recording stations and epicentres of Bukit Tinggi Earthquakes (Lat and Ibrahim, 2009)	10
Figure 2.4	Procedure of thickening and uplift of Crocker Range upper crust of Mount Kinabalu (Tongkul, 2015)	11
Figure 2.5	Elastic Response Spectrum with 0.07g at 475 years return period on rock (a) displacement and (b) acceleration for Peninsular Malaysia for Type II ordinary buildings (Lam et al., 2016)	12
Figure 2.6	Elastic Response Spectrum with 0.07g at 475 years return period on rock (a) displacement and (b) acceleration for Sarawak and South-western Sabah for Type II ordinary buildings (Lam et al., 2016)	12
Figure 2.7	Elastic Response Spectrum with 0.12g at 475 years return period on rock (a) displacement and (b) acceleration for Central and Eastern Sabah for Type II ordinary buildings (Lam et al., 2016)	13
Figure 2.8	Damaged soft-story building due to short column effect, insufficient confinement reinforcement, buckling of flexural reinforcement and concrete crushing (Masjid et al., 2017)	14
Figure 2.9	Damaged minaret and ceiling of Ranau mosque (Tongkul, 2015)	14
Figure 2.10	Ground floor of soft-story collapsed in 921 Chi-Chi Earthquake (Chiou et al., 2017)	15
Figure 2.11	Story displacement induced by ground motion for (a) a regular building; and (b) a building with soft-story irregularity (Teresa, 2012)	17
Figure 2.12	Masonry infill frame sub-assemblage (Asteris et al., 2011)	18
Figure 2.13	Ductility parameters definitions (Bae et al., 2004)	20

Figure 2.14	Description of the objective for displacement ductility determination procedure (Vielma and Mulder, 2017).	22
Figure 2.15	Lateral force-displacement behaviour of the non-ductile column under shear failure mechanism (Stirrat et al., 2014)	23
Figure 2.16	Interaction between shear strength and ductility of RC column (ATC 40, 1996)	25
Figure 2.17	Modal combination method for 1D seismic input applied to x-direction or y-direction of building.	28
Figure 2.18	Idealised Force-Displacement Curve (ASCE 41, 2017)	29
Figure 2.19	Component Force Versus Deformation Curves (ASCE 41, 2017)	30
Figure 2.20	Generalised Force-Deformation Relation for Concrete Elements or Components (ASCE 41, 2017)	31
Figure 2.21	Acceptance Criteria and Performance Level of Components or Elements (ASCE 41, 2017)	31
Figure 2.22	Thirty Ground Motion Records IDA Study on a T_1 = 1.8 sec, 5-Storey Steel Braced Frame showing (a) Maximum Interstory Drift Ratio for Thirty IDA Curves and (b) Their Summary (16%, 50% and 84%) Fractile Curves (in log-log scale) (Vamvatsikos and Cornell, 2002)	34
Figure 2.23	IDA Steps using Ground Motion Scaling (Ayala et al., 2015)	35
Figure 2.24	Workflow for the Calculation of Vulnerability Assessment with Analytical Method (Ayala et al., 2015)	37
Figure 2.25	Fragility Curves for a Three-Story RC Frame Building on Soil Profile Type C and D (Tan et al., 2014)	40
Figure 2.26	Frame Buildings with Open Ground Story Fragility Curves Designed with 1959 seismic codes (top) and 1984 seismic codes (bottom) (Tsionis and Fardis, 2014)	41
Figure 2.27	Frame Buildings with Infilled Frame Fragility Curves Designed with 1959 seismic codes (top) and 1984 seismic codes (bottom) (Tsionis and Fardis, 2014)	41
Figure 2.28	Fragility Curves for f_{ck} = 20MPa and f_y = 520MPa in x-direction for Mander's model (left) and Kent and Park's model (right) (Vinay et al., 2017)	42

Figure 2.29	Fragility Curves for Two-Story Building (Lumantarna et al., 2018)	42
Figure 2.30	Fragility Curves for Five-Story Building (Lumantarna et al., 2018)	43
Figure 2.31	Fragility Curves for Nine-Story Building (Lumantarna et al., 2018)	43
Figure 2.32	Fragility Curves for 3-Story Models under (a) Shear Failure and (b) First Axial Failure (Azadi Kakavand and KhanMohammadi, 2018)	44
Figure 2.33	Fragility Curves for 5-Story Models under (a) Shear Failure and (b) First Axial Failure (Azadi Kakavand and KhanMohammadi, 2018)	44
Figure 2.34	Fragility Curves for 3-Story (left) and 6-Story (right) Reinforced Concrete Moment Frame in Malaysia (Aqilah and Nazri, 2015)	45
Figure 2.35	Seismic Fragility Curves for 25-Story Tall Building with 3 Levels of Parking (left) and 5 levels of Parking (right) (Aisyah et al., 2019)	46
Figure 3.1	Flow Chart of Research Methodology	50
Figure 3.2	Plan View of Studied Reinforced Concrete Frame	53
Figure 3.3	Elevation View of 3-Story Reinforced Concrete Frame with Open Space Ground Floor	53
Figure 3.4	Elevation View of 6-Story Reinforced Concrete Frame with Open Space Ground Floor	54
Figure 3.5	Elevation View of 9-Story Reinforced Concrete Frame with Open Space Ground Floor	55
Figure 3.6	Distributed Superimposed Dead Loads from Slab using Yield Line Method	58
Figure 3.7	Distributed Superimposed Live Loads from Slab using Yield Line Method	58
Figure 3.8	Longitudinal Reinforcement Required for 3-Story Frame	60
Figure 3.9	Longitudinal Reinforcement Required for 6-Story Frame	60
Figure 3.10	Longitudinal Reinforcement Required for 9-Story Frame	61
Figure 3.11	Far-Field Earthquake Time-History Data	63

Figure 3.12	Far-Field Earthquake Time-History Data (Cont'd)	64
Figure 3.13	Far-Field Earthquake Time-History Data (Cont'd)	65
Figure 3.14	Plastic Hinges Assignment in 6-Story Frame	66
Figure 3.15	Moment Rotation Data for PMM of a Column	67
Figure 3.16	Hinge Property for Major Moment of a Beam	67
Figure 3.17	Hinge Property of Brick Wall under Force-Controlled Action	68
Figure 4.1	Formation of Plastic Hinges in 3-Story Frame Subjected to TH2 with PGA 0.15g at 3.62s	72
Figure 4.2	Formation of Plastic Hinges in 3-Story Frame Subjected to TH5 with PGA 0.20g at 9.18s	74
Figure 4.3	Formation of Plastic Hinges in 3-Story Frame Subjected to TH13 with PGA 0.20g at 16.20s	75
Figure 4.4	Formation of Plastic Hinges in 6-Story Frame Subjected to TH2 with PGA 0.25g at 14.42s	76
Figure 4.5	Formation of Plastic Hinges in 6-Story Frame Subjected to TH5 with PGA 0.40g at 18.10s	77
Figure 4.6	Formation of Plastic Hinges in 6-Story Frame Subjected to TH13 with PGA 0.35g at 22.56s	78
Figure 4.7	Formation of Plastic Hinges in 9-Story Frame Subjected to TH2 with PGA 0.40g at 16.36s	79
Figure 4.8	Formation of Plastic Hinges in 9-Story Frame Subjected to TH5 with PGA 0.45g at 25s	81
Figure 4.9	Formation of Plastic Hinges in 9-Story Frame Subjected to TH13 with PGA 0.50g at 35s	82
Figure 4.10	Maximum Inter-Story Drift Demand of 3-Story Frame	84
Figure 4.11	Maximum Inter-Story Drift Demand of 6-Story Frame	87
Figure 4.12	Maximum Inter-Story Drift Demand of 9-Story Frame	89
Figure 4.13	Median of Inter-Story Drift Demand of 3-Story Frame	97
Figure 4.14	Fragility Curve of 3-Story RC Frame with Inadequate Lap Splice Length	99
Figure 4.15	Median of Inter-Story Drift Demand of 6-Story Frame	100
Figure 4.16	Fragility Curve of 6-Story RC Frame with Inadequate Lap Splice Length	101

Figure 4.17	Median of Inter-Story Drift Demand of 9-Story Frame	102
Figure 4.18	Fragility Curve of 9-Story RC Frame with Inadequate Lap Splice Length	103
Figure 4.19	Effect of Building Height to Probability of Damage Exceedance	105
Figure 4.20	Effect of Inadequate Lap Splice Length for 3-Story Frame	107
Figure 4.21	Effect of Inadequate Lap Splice Length for 6-Story Frame	108
Figure 4.22	Effect of Inadequate Lap Splice Length for 9-Story Frame	109

LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
ASCE	-	American Society of Civil Engineers
ATC	-	Applied Technology Council
BS	-	British Standard
CDF	-	Cumulative Distribution Function
CP	-	Collapse Prevention
CQC	-	Complete Quadratic Combination
DCR	-	Demand Capacity Ratio
ELF	-	Equivalent Lateral Force
ETABS	-	Extended Three-Dimensional Analysis of Building Systems
FEMA	-	Federal Emergency Management Agency
IDA	-	Incremental Dynamic Analysis
IO	-	Immediate Occupancy
LDP	-	Linear Dynamic Procedure
LS	-	Life Safety
LSP	-	Linear Static Procedure
MS	-	Malaysian Standard
NDP	-	Nonlinear Dynamic Procedure
NSP	-	Nonlinear Static Procedure
NZSEE	-	New Zealand Society for Earthquake Engineering
PGA	-	Peak Ground Acceleration
PGV	-	Peak Ground Velocity
RC	-	Reinforced Concrete
SDOF	-	Single Degree of Freedom
SRSS	-	Square Root of Sum of Square
TH	-	Time-History
USGS	-	United States Geological Survey
UTM	-	Universiti Teknologi Malaysia

LIST OF SYMBOLS

α_L	-	Coefficient of Thermal Expansion
β_{CL}	-	Drift Capacity Uncertainty
$\beta_{D\|GMI}$	-	Demand Uncertainty = $\sqrt{\ln 1 + s^2}$, where s^2 is the standard error of the demand drift data
β_M	-	Modelling Uncertainty
d_m	-	Diagonal Length of Masonry Infill
f_{cu}	-	Concrete Cube Compressive Strength
f_u	-	Reinforcement Tensile Stress
f_y	-	Bending and Shear Reinforcement Yield Stress
E_c	-	Short Term Modulus of Elasticity of Concrete
E_s	-	Modulus of Elasticity of Steel
λ_{CL}	-	ln (median of drift capacity for a particular limit state)
$\lambda_{D\|GMI}$	-	ln (calculated median demand drift given the ground motion intensity from the fitted power law equation)
S_a	-	Response Spectrum Acceleration
v	-	Poisson's Ratio
w	-	Width of Equivalent Diagonal Strut
γ_c	-	Specific Weight Density of Concrete
γ_s	-	Specific Weight Density of Steel
Φ	-	Standard Normal Cumulative Distribution Function

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Damage State of 3-Story Frame	123
Appendix B	Damage State of 6-Story Frame	138
Appendix C	Damage State of 9-Story Frame	153

CHAPTER 1

INTRODUCTION

1.1 Research Background

Earthquake poses devastating effect which can cause catastrophic damage to the building structures, especially the buildings which possessing soft-story feature. Most of the residential buildings in Malaysia which below 20 stories typically features an open space ground floor to allow flexible use of space. In contrast, non-structural infill brick walls are commonly featured at the upper floors, deriving a higher lateral stiffness than the ground floor. In seismic event, the ground floor of soft-story building is expected to displace greatly while the superstructure remains as rigid block relatively to the horizontal motion. Therefore, the seismic performance of soft-story building depends immensely on the performance of the columns supporting the superstructure.

Most of the residential soft-story buildings in Malaysia are comparatively old and were constructed before the first Malaysia Seismic Standard (MS EN 1998-1: 2015) and Malaysia National Annex to Eurocode 8 (MS EN 1998-1: 2017) were introduced in year 2015 and year 2017 respectively. Moreover, most of the buildings in Malaysia prior to year 2015 were designed according to British Standard (BS 8110-1: 1997). Based on the design philosophy of British Standard, seismic provision and ductile design are not included in the building design prior to year 2015. Therefore, the columns in the residential soft-story building are expected to be poorly-confined, lightly-reinforced and inadequate lap-spliced length provided. In addition, the spacing of the shear reinforcement in these columns could be minimal according to BS 8110 provision. According to ASCE 41 (2017), these columns could be classified as flexural and shear critical and deemed unsafe.

Fragility functions can be used to denote the vulnerable condition of a structure and provide the probability of exceeding limit states of damage for a broad range of peak ground acceleration. The risk of building structures from potential earthquakes and the losses of economical revenue can be forecasted by seismic fragility curves. Government agencies often refers to seismic fragility curve for disaster planning, while insurance companies adopt seismic fragility curve to predict the overall expenditure after post-earthquake event. In the recent practice, bank also started to refer seismic fragility curve for asset management.

Most of the buildings in Malaysia which built before seismic code, have an inherent lateral strength resistance to lateral load such as notional load and wind load, can provide certain degree of safety factor to seismic event. However, the damage intensity of those buildings under seismic event is remain unknown until further assessment. This is because the damage level of the building under seismic event is greatly dependent on the importance of the building, functional use of building and specific requirements of the owner. Due to the complexity of seismic performance investigation on new building structure, seismic fragility study herein to provide the vulnerability conditions of generic types of building construction. Simplified structural models with different properties can be adopted to study the uncertainties in structural parameters for all representative building types. By adopting this concept, seismic fragility analysis of low-ductile reinforced concrete frame with inadequate lap splice length at different building height, under different seismic sources, can be investigated effectively.

According to European Commission Syner-G Reference Report 4 (2013), there are four different methods to derive seismic fragility function, namely: i) empirical methods; ii) analytical methods; iii) expert judgement; and iv) hybrid methods. The availability of structural damage data after post-earthquake event or analytical simulation is one of the main precedents for the selection of fragility function (Kwon and Elnashai, 2006). Analytical method, expert judgement or the combination of both methods are commonly used to produce the seismic fragility curve of structural frame system and the assessment of potential economy losses of post-earthquake event.

Seismic fragility function for reinforced concrete with low-ductile frame with inadequate column lap splice length which the initial provision is in accordance to BS 8110 can be established to evaluate the vulnerability of the structure. Therefore, this research is important for the vulnerability assessment of buildings under seismic ground motion to predict the potential damage and economy loss after seismic event.

1.2 Problem Statement

Earthquake is destructive natural phenomena that seismic waves along the direction of propagation are responsible for the transmission of the destructive energy as it can propagates via solid state and liquid state. However, beyond the tremendous destruction of life that earthquake caused, it also caused massive physical damage to building structure type which more susceptible to seismic induced damage. In Malaysia, most of the buildings are not designed to resist seismic loading because almost all buildings are not mandatory to design to resist earthquake. Based on the Malaysia National to Eurocode 8 (MS EN 1998-1: 2017), the seismic hazard map shows that Malaysia is in the range of low to moderate seismicity. Therefore, seismic detailing in building is vital, especially for buildings built at moderate seismicity zone.

During the 2015 Sabah Earthquake, the aforementioned concerns on the building type with soft-story effect was damaged (Majid et al., 2017). According to the field survey reported by Majid et al. (2017), lack of confinement reinforcement, buckling of longitudinal reinforcement and crushing of concrete core were the main reasons which caused the damage to the soft-story building. The adequacy of lap splice length, especially in the column is important in seismic design to provide sufficient column flexural and shear capacity against lateral seismic loading.

To date, the seismic fragility curves for Malaysia buildings are limited. Furthermore, there is still no seismic fragility curve developed for low-ductile reinforced concrete frame with partial infilled wall that considering the columns are reinforced with inadequate lap splice length. According to ASCE 41 (2017), column with inadequate lap splice length can significantly lower the deformation capacity and thus the probability of damage to the low ductile reinforced concrete frame can be increased. On top of that, there is also limited study on the inter-story drift of low-ductile reinforced concrete frame, considering inadequate lap-splice length in Malaysia. Hence, a comprehensive study of seismic fragility analysis on low-ductile reinforced concrete frame with inadequate lap splice length should be carried out and explored promptly.

1.3 Research Objectives

The objectives of this research are listed below:

1. To determine the inter-story drift capacity of low-ductile reinforced concrete frame with inadequate lap splice length.
2. To estimate the inter-story drift demand of low-ductile reinforced concrete frame with inadequate lap splice length.
3. To derive seismic fragility curves for low-ductile reinforced concrete frame with inadequate lap splice length.
4. To estimate the probability of seismic induced damage to low-ductile reinforced concrete frame with inadequate lap splice length.

1.4 Scope of Work

This project focuses on the numerical simulation of soft-story building structure with low-ductile partially reinforced concrete frame with the height of 10m, 19m and 28m, which represent building with three-, six- and nine- stories respectively. All buildings are assumed to be regular in both plan and elevation configuration. 15 time-history data from different sources of far-field earthquake are adopted in the numerical analysis to perform Incremental Dynamic Analysis (IDA). The building structures are well designed and detailed according to BS 8110 – 1:

1997 code specification. All material properties and design loadings are in compliance with BS 8110, BS 6399 and common industrial practices in Malaysia. The preliminary design of the 3 models is performed by using ETABS v2016 finite element software. All the columns in the low-ductile reinforced concrete frame in each building type are detailed with inadequate lap splice length. The material properties such as concrete compressive strength, reinforcement yield stress and ultimate stress of reinforcement are 20 N/mm^2, 300 N/mm^2 and 420 N/mm^2 respectively. The applied superimposed dead load (comprise of floor finishes, self-weight of slab and mechanical services) at all floors and at top floor (without brick walls) on the concrete floor frame are 24.4 kN/m and 15.4 kN/m respectively. The applied live load at all floors and at top floor on concrete floor frame are 3 kN/m and 2 kN/m respectively.

1.5 Significant of Study

While many researchers have studied seismic fragility curves of reinforced concrete frame, the information on the reinforced concrete frame detailed with inadequate column lap splice length are still lacking. To date, guidelines are provided by current structural design codes for lateral loads especially notional loads and wind loads on typical building design. The establishment of national annex to Eurocode 8 will introduce additional column lap splice length to the current structural design practice in Malaysia. The introduction of seismic fragility curves of low-ductile reinforced concrete frame with inadequate lap splice length can later serves to evaluate the structural performance of existing typical residential buildings in Malaysia. This research will enhance the understanding of the impact of earthquake on existing buildings in Malaysia, as well as contribute to the local authority and development of design guideline in Malaysia for earthquake resistance building structures.

1.6 Structure of Thesis

This thesis documents the research work into five chapters. Chapter 1 presents the research background, problem statements and research objectives. Literature review and the findings of past studies on seismic fragility curves of different structural models subjected to different seismic loadings are presented in Chapter 2. Chapter 3 outlines the methodology and numerical simulation. Recorded and computed results in the numerical simulation, as well as the computation of seismic fragility curve with different seismic performance objectives are presented in Chapter 4. Chapter 5 concludes the finding of this research work and suggest recommendations for the improvement of future research work. Finally, references and appendices are attached at the ending part of this thesis.

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