ASSESSMENT OF THE PERFORMANCE LOSS AND REPAIRABIITY OF EARTHQUAKE DAMAGED REINFORCED CONCRETE BUILDINGS UNDER REPEATED EARTHQUAKE

TAI JOON HONG

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ASSESSMENT OF THE PERFORMANCE LOSS AND REPAIRABIITY OF EARTHQUAKE DAMAGED REINFORCED CONCRETE BUILDINGS UNDER REPEATED EARTHQUAKE

By

TAI JOON HONG

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I ,____hereby declare that I have checked and revised the whole draft of dissertation as required by my supervisor.

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______________________ ______________________

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ABSTRAK

Dalam kejadian gempa-bumi Sabah pada 5th Jun 2015 dengan 6.0 magnitud, banyak bangunan di Sabah telah mengalami kerosakan struktur yang disebabkan oleh gempa bumi terutamanya bagi bangunan-bangunan konkrit bertetulang. Tahap kerosakan struktur dalam bangunan-bangunan di Sabah yang tidak diketahui dan kekurangan penjelasan dalam kriteria pembaikan bangunan telah menyebabkan seismik pemulihan dalam masyarakat Sabah perlu mengambil masa yang lebih lama. Kajian ini membentangkan cara penilaian kerosakkan bangunan konkrit bertetulang (RC) bergantung kepada keadaan kerosakan yang disebabkan oleh potensi kejutan gempa bumi. Anggaran kos untuk membaiki kerosakkan bangunan akan dinyatakan dari segi kehilangan prestasi bangunan (PL). S.M.K Ranau bangunan telah dipilih sebagai kajian kes dalam penyelidikan ini dan ia telah dimodelkan dalam perisian ETABS. Analisis dinamik tambahan (IDA) telah digunakan untuk mendapatkan maksimum kapasiti bangunan sebelum runtuh dalam pelbagai tahap kerosakan. “Residul Capacity” (REC) telah diperolehi oleh simulasi dengan gempa bumi di Sabah pada 5th Jun 2015. Didapati bahawa bangunan S.M.K Ranau telah mengalami maksimum kehanyutan 0.83% dan PL 24.96%. Kos pembaikan dicadangkan adalah RM413, 000 berdasarkan graf prestasi kehilangan (PL) degnan hubungan nisbah kerugian kos yang dihasilkan.

ABSTRACT

In Sabah earthquake on 5th June 2015 with the moment magnitude of 6.0, many buildings in Sabah have experienced the structural damage due to earthquake especially for reinforced concrete buildings. The unknown of structural damage level in various buildings in Sabah and lack of clear repair standards and criteria for re-occupancy had caused the Sabah community's seismic recovery to be taken in longer time. This study presents the results of assessment of possible variation of reinforced concrete (RC) buildings collapse vulnerability functions depending on damage state caused by potential earthquake shock. The expected building loss estimation which will be expressed in terms of performance loss (PL). S.M.K Ranau building is chosen as the case study in this research. S.M.K Ranau building was modelled in the ETABS software, and incremental dynamic analysis (IDA) was applied to develop maximum building capacity up to collapse in various damage state. Residual capacity (REC) was obtained by the simulation of seismic ground motion in Sabah on 5th June 2015, it is found that the S.M.K Ranau building experienced a drift with 0.83% and PL of 24.96%. The relatively suggested repair cost is RM413,000 based on the performance loss-cost ratio relationship graph developed.

TABLE OF CONTENTS

ACKNOWLEDGEMENT .... **II**

ABSTRAK .... **III**

ABSTRACT .... **IV**

TABLE OF CONTENTS .... **V**

LIST OF FIGURES .... **VII**

LIST OF TABLES .... **IX**

LIST OF ABBREVIATIONS .... **X**

NOMENCLATURES .... **XI**

CHAPTER 1 .... **1**

1.1 Overview 1
1.2 Problem Statement 3
1.3 Objectives 5
1.4 Scope of work 5
1.5 Research Contribution 6
1.6 Dissertation Outline 6

CHAPTER 2 .... **7**

2.1 Overview 7
2.2 Performance Loss 8
2.3 Performance Based Seismic Design 10
2.4 Incremental Dynamics Analysis 11
2.5 Fragility Curve 13
2.6 Repeated Earthquake 16
2.7 Cost Ratio ($\boldsymbol{Cr}$) 18

CHAPTER 3 .... **22**

3.1 Overview 22
3.2 Research Flow Chart 22
3.3 Application to an Existing RC Building 24
3.3.1 Study Site Selection 24
3.3.2 Description of the building structure model 24

3.3.3 Design Loads ... 28
3.4 Ground Motion used in Analysis ... 29
3.4.1 Ground Motion Selection ... 29
3.4.2 Sequencing Repeated Earthquake ... 30
3.4.3 Development of Elastic Response Spectra ... 30
3.4.4 Matching Original Earthquake and Developed Spectral ... 32
3.5 Incremental Dynamic Analysis (IDA) ... 33
3.5.1 Assessment of Intact Building ... 33
3.5.2 Assessment of Damaged Building ... 35
3.6 Fragility Curve ... 37
3.7 Performance Loss (PL) ... 38
3.7.1 Development of PL-Drift relationship graph ... 38
3.7.2 Development of PL-Cost Ratio ($\boldsymbol{Cr}$) relationship ... 39
3.7.3 Estimation of Exact Repair and/or Retrofit Cost of S.M.K Ranau ... 40

CHAPTER 4 ... 42

4.1 Overview ... 42
4.2 Finite Element Analysis ... 42
4.3 Incremental Dynamic Analysis (IDA) ... 43
4.3.1 Assessment of Intact Building ... 43
4.3.2 Assessment of Damaged Building ... 46
4.4 Fragility Curve ... 51
4.5 Performance Loss - Drift ... 53
4.6 Performance Loss – Cost Ratio (Cr) ... 55

CHAPTER 5 ... 57

5.1 Summary ... 57
5.2 Recommendation for Future Research ... 58

REFERENCES ... 59

APPENDIX A-G

LIST OF FIGURES

Figure 1.1 : Location of Malaysia and Tectonic Plate Surrounded Malaysia.................. 2

Figure 1.2 : S.M.K Ranau's building cracks after Sabah Earthquake on 5th June 2015.. 4

Figure 2.1 : IDA Curve with Interstorey Drift Ratio (IDR).. 12

Figure 2.2 : Fragility Curve with different performance level....................................... 14

Figure 2.3: Time-depend fragility (D'Aragona et al., 2015).. 15

Figure 2.4 : Ground acceleration record of the examined seismic sequences (Hatzigeorgiou and Liolios, 2010)... 18

Figure 2.5 : Building Usability Rate in drifts thresholds suggested (Polese et al., 2015) 20

Figure 3.1: Flow chart of Methodology.. 23

Figure 3.2 : S.M.K Ranau Layout Plan... 25

Figure 3.3: Column Detailing 26

Figure 3.4: Beam Detailing... 26

Figure 3.5: 3-Dimension modelling of S.M.K Ranau building in ETABS.................... 27

Figure 3.6: Pinching Material (Polese et al., 2013) 27

Figure 3.7: Ground Acceleration Records of the 29

Figure 3.8: Design Elastic Response Spectral of 0.12g.. 32

Figure 3.9: IDA Curve for Intact Builidng (Polese et al., 2013) 34

Figure 3.10: Example of Hinge Result on building.. 34

Figure 3.11: Example of two repeated earthquakes with sequencing and scaling......... 36

Figure 3.12: IDA curve with pre-fixed damage (Polese et al., 2013)............................ 36

Figure 3.13: Collapse Fragility Curve at different limit state (LS)................................ 37

Figure 3.14: Example of PL-drift Relationship Graph 38

Figure 3.15: Example of PL-Cr relationship Graph.. 40

Figure 3.16: Kota Kinabalu Earthquake Ground Motion (5 June 2015) 40

Figure 4.1: Hinge Results of Intact Building S.M.K Ranau 44

Figure 4.2: IDA Curve of Intact Structure 46

Figure 4.3: IDA Curve for damage structure at D1 49

Figure 4.4: IDA Curve for damage state at D2 49

Figure 4.5: Collapse Fragility Curve 52

Figure 4.6: Hinge result of S.M.K Ranau building during Sabah Earthquake 54

Figure 4.7: Performacnce Loss-Drift Curve 54

Figure 4.8: PL-Cr graph 56

LIST OF TABLES

Table 2.1: Building Usability Tagging (Polese et al., 2015) 19

Table 3.1: Design Assumptions based on EC 2 and EC 8 24

Table 3.2: Beam Detailing of Reinforcement 26

Table 3.3: Column Dimension and Reinforcement 26

Table 3.4: Permanent Load 28

Table 3.5: Temporary Load 28

Table 4.1: Fundamental Period and Frequency of S.M.K Ranau Building 43

Table 4.2: Maximum Displacement and Drift Result 45

Table 4.3: Repeated Ground Motion PGA at drift 2.5% 46

Table 4.4: Scaled PGA with Fixed Damage State 47

Table 4.5: Maximum Displacement and Drift Result 48

Table 4.6: Maximum Displacement and Drift Result 48

Table 4.7: Building Damage State $D1$ (PGA Up to Collapse) 50

Table 4.8: Building Damage State $D2$ (PGA Up to Collapse) 50

Table 4.9: Mean and Standard Deviation of 51

Table 4.10: Residual Capacity of S.M.K Ranau 52

Table 4.11: Performance Loss of S.M.K Ranau 53

Table 4.12: Repair Cost according to building usability tagging 56

LIST OF ABBREVIATIONS

MMD	**M**alaysia **M**eteorological **D**epartment
EC8	**E**uro**c**ode **8**
FEMA	**F**ederal **E**mergency **M**anagement **A**gency
PL	**P**erformance **L**oss
PEER	**P**acific **E**arthquake **E**ngineering **R**esearch
ETABS	**E**xtended **T**hree-dimensional **A**nalysis of **B**uilding **S**ystems
PBPF	**P**erformance-**B**ased **P**olicy **F**ramework
IDA	**I**ncremental **D**ynamic **A**nalysis
IM	**I**ntensity **M**easure
PGA	**P**eak **G**round **A**cceleration
RC	**R**einforced **C**oncrete
FS	**F**ore **S**hock
MS	**M**ain **S**hock
AS	**A**fter **S**hock

NOMENCLATURES

T_1	Building fundamental period
M_w	Moment magnitude
$\emptyset$	Standard Normal Cumulative Distribution
σ	Standard Deviation of Natural Logarithm
C_r	Cost Ratio
C_i	Repair and/or Retrofit Cost
C_d	Re-construction Cost

CHAPTER 1

INTRODUCTION

1.1 Overview

Natural disaster is a major adverse event resulting from physical phenomena processes of the Earth such as earthquake, volcanic eruptions, tsunami and other geologic processes. All the natural disaster can't be predicted or being avoid, for example an earthquake can strike anytime along the tectonic plate without any pre-warning which can cause loss of life or property damage, and it will definitely impact the economic damage, and the severity depends on the affected population's resilience, or ability to recover with the infrastructure available.

Malaysia is situated on a minor tectonic plate with specific name of Sunda Plate, stranding the equator in the eastern hemisphere on which the majority of Southern Asia is located as shown in Figure 1.1 (Otofuji et al., 2017). Malaysia is located on Sunda Plate which consider as stable part of Eurasian Plate is the sole reason that Malaysia are rare from major earthquake. However, Malaysia is not considered as completely seismic free zone as it is near to instead of located on the seismic active plate boundaries. Balendra and Tan (1990) introduced the far-field effects of earthquakes in Sumatra related to buildings on soft soil, explained the occasionally tremors of moderate and weak earthquake to either Peninsula or East Malaysia. Seismic design on buildings has not been given much emphasis until a decade ago when the Malaysia lawmakers (or Members of Parliament) were briefed by Meteorological Department (MMD) in 2002, on the distant shock waves of the 2001 Gujarat earthquake which travelled 600km from its epicentre to rock and cause devastations to many cities in India (Bendick et al. ,2001).

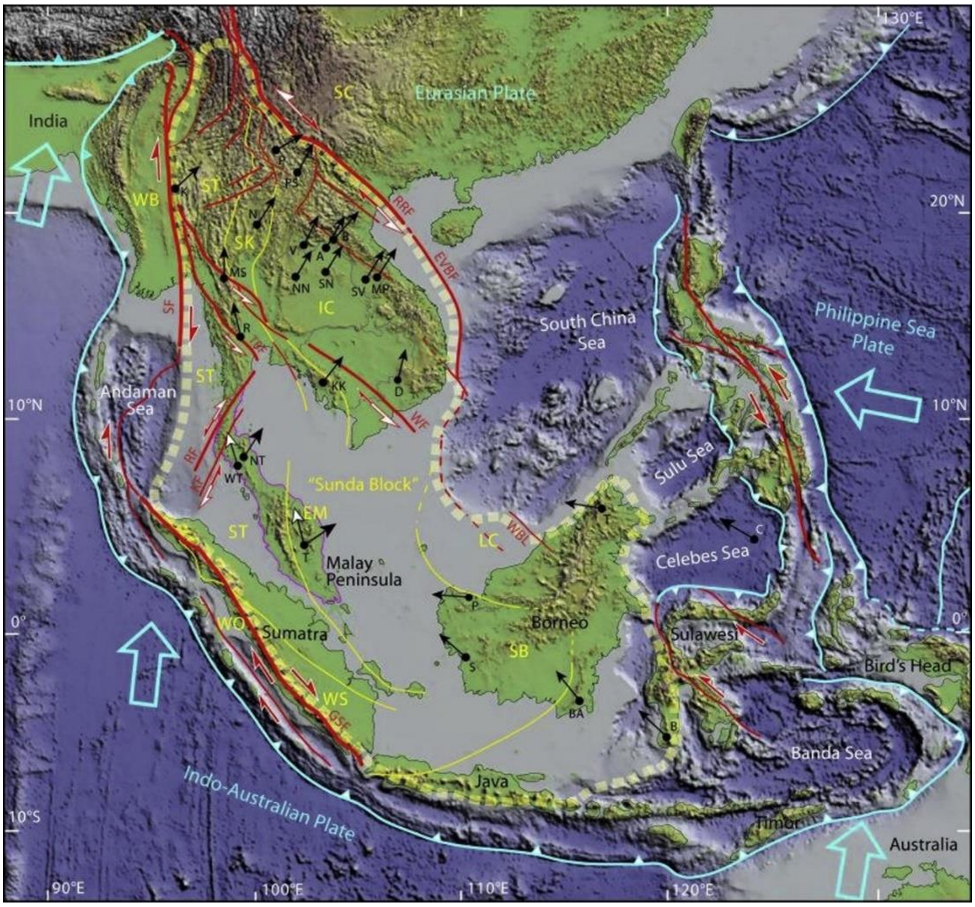

Figure 1.1 : Location of Malaysia and Tectonic Plate Surrounded Malaysia
(Otofuji et al., 2017)

Earthquake seems to be no longer a stranger term to Malaysia when the first biggest damage due to earthquake strike to Sabah, Malaysia on 5th June 2015 with the moment magnitude (M_w) scale of 6.0. Earthquake is one of the deadly natural disasters, however it doesn't kill people, but normally buildings do, especially for the damage and collapse reinforced concrete building which are life threatening. Malaysia soon realise the importance of community's seismic resilience as all the repair work was in dilemma as damaged buildings in Ranau earthquake event are lack of clear repair standards and criteria for re-occupancy. For example, the damaged building of S.M.K Ranau in Sabah was announced for the repair works only after one month of the earthquake event. The building re-occupancy is often delayed owing to pending determination of safety levels and necessary works for repair and/or retrofit. Evaluation of damaging building capacity after an earthquake normally take longer time in field investigation, hence the relative performance loss (PL) by computerized method for the damaged building is introduced as a significant indicator to any decision for the repair and retrofit works.

In this chapter, it will show the background of studies regarding the evaluation of damaging building capacity and the importance of introducing Performance Loss (PL) as an indicator for repair and/or retrofit decision. Besides the inspection of the functioning of damaged buildings, the economic loss factors for repair and/or retrofit cost is also considered in this research for the seismic resilience decisions. By developing the performance loss and cost (repair or retrofit) relationship graph, it could be used for a final decision of the possible reparability of the building with suggested repair cost to avoid huge economic loss value.

1.2 Problem Statement

Earthquake comes in with the unexpected way and often causes tragedy in any place all over the world. Performing seismic risk and loss estimation analysis is a priority to establish acceptable levels of safety, and facilitate decisions on appropriate course of action for specific buildings.

Among the basic features of an exhaustive risk and loss estimation system, seismic fragility curves (also referred to as vulnerability curves) play a critical role as they represent the probability of attaining different damage states given the ground motion intensity. In common, physical vulnerability to seismic events is considered almost as stationary in time. However, in many parts of the world, the repetition of medium – strong intensity earthquake ground motions at brief intervals of time has been observed and, after a main shock has occurred, the structure in its new ‘damaged ’ state may behave very differently from the intact one as shown in Figure 1.2. For these kind of reinforced concrete buildings, the key question in the aftermath of damaging earthquakes is not only if a damaged building should be simply repaired or also retrofitted, but often now if it is more convenient to repair and retrofit or to demolish and rebuild it. To answer that question, not only the building loss level is needed but also an estimate of the costs to repair the building to its original state, and if necessary, of retrofit costs. Therefore, it would be very useful to adopt in a performance-based assessment framework, a suitable tool to link Performance Lost (PL) to reparability convenience. In particular, clear and easy to use instruments are needed to assess the reparability of a large building that is usually at stake when strong earthquakes hit highly urbanized regions.

Figure 1.2: S.M.K Ranau's building cracks after Sabah Earthquake on 5th June 2015

1.3 Objectives

The objectives of this research are:

i. To investigate the possible variation of building collapse vulnerability functions depending on the damage state caused by a potential earthquake shock.

ii. To develop the damage-dependent vulnerability curve for buildings relating maximum story drift to the expected performance loss (PL).

1.4 Scope of work

Research scope has been set in this study as a guideline to achieve the objectives. The research scopes are:

i. Layout of school building of SMK Ranau was used and modelling in ETABS software.

ii. The Incremental dynamic analysis (IDA) was done by using ETABS software with three selected scaled ground motions which downloaded from Pacific Earthquake Engineering Research (PEER) website.

iii. The IDA curve was developed and used to identify the performance level based on performance-based policy framework.

iv. The Collapse Fragility Curve is then developed based on IDA results.

v. Performance Loss (PL) and Drift Curve is developed based on residual capacity (REC) and performance-based policy framework.

vi. Relative repair cost and retrofit cost are calculated based on the cost database suggested from (Polese et al., 2015).

vii. The foundation is fixed to the ground and soil interaction is neglected.

1.5 Research Contribution

The expected outcomes of this research are:

i. Community's seismic resilience may be enhanced by the adoption of recovery strategies to enable communities to return to levels of pre-disaster functioning (or other acceptable levels) as rapidly as possible once a damaging earthquake occurred.

ii. Prior to lack of clear repair standards and criteria for re-occupancy damage of the buildings, the relative Performance Loss (PL) for the damaged building is introduced as a significant indicator for repair and/or retrofit decisions.

1.6 Dissertation Outline

This dissertation consists of five chapters. Chapter 1 presents an overview, problem statement, objectives, scope of work. Chapter 2 reviews the literatures and discusses about the effect of repeated earthquake to the dynamic characteristics of reinforced concrete building. Besides, introduction to performance loss (PL) for obtaining the different damaged-state of the building are elaborated in this chapter. In Chapter 3, the process and methodology of research are outlined which include study location, procedure of data acquisition and analysis and numerical simulation. Chapter 4 reveals the results obtained from the selected damaged building based on performance-framework and nonlinear time-history analysis. Besides, the performance loss (PL) – cost relationship graph is developed for further discussion. Lastly, Chapter 5 concludes the findings in this research and the recommendations for improvement in future research are proposed. All the details of results are documented in appendices.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In the aftermath of earthquake event, a guideline or transparent policies should be established to facilitate the decisions on appropriate course of action for specific buildings. In FEMA 308 (1998) a Performance-Based Policy Framework (PBPF) was introduced for the post-earthquake damage assessment that relies on performance index of building before and after earthquake damaged state and it also relies on the relative Performance Loss (PL) as significant indicator for repair and/or retrofit decisions. However, there is no any justification of the establishment on how to choose significant PL element regard to damage acceptability. San Francisco Building Code (CCSF, 2010) is the first to propose for capacity loss and recently updated in 2012, but still there are not enough evidence to support the suggestion. Polese et al. (2015) suggested simplified tools by using Pushover Analysis to assess PL and repair costs for damaged buildings were presented. In Polese et al. (2013) a first comparison between a simplified method (Pushover based) and detailed method (Nonlinear Time-History) for evaluation of PL is performed, showing that simplified procedures might able to give approximate building capacity at damaged state. However, during the comparison, for Nonlinear Time History analysis, the local P-delta effects were not included (Polese et al., 2013). Hence, even though simplified tools were presented, there is still require a further investigation on suitable PL thresholds, and detailed studies on real cases study are needed. With several previous studies or researches showed that the significant of taking consideration of effect of damage accumulation with several sequential of ground motion (repeated earthquake) to examine the building loss capacity (Hatzigeorgiou and Liolios, 2010).

This study will also gain insights of the importance of using repeated earthquake to evaluate Performance Loss (PL) index as a key indicator of repair works decision in the aftermath of earthquake event with estimated repair cost.

2.2 Performance Loss

Evaluation of damaged-state building is significant as the post-earthquake building capacity might significantly reduce due to the spread of damage all over the building, while the probability of collapse increases. Appropriate facilitation and right decision on community's seismic resilience will definite minimize the cost for repair buildings and avoid unnecessary steps. Hazards US (Hazus) which is a geographic information system-based natural hazard analysis tool developed and freely distributed by the Federal Emergency Management Agency (FEMA). In Hazus (FEMA HAZUS99 SR2), a clear evaluation methodology is presented, where capacity curves and fragility curves are used to estimate damage from an earthquake. The use of capacity curves in conjunction to response spectra allows estimating seismic demand for buildings at assigned levels of earthquake intensity; entering the fragility curves with the relevant value of seismic demand, it is possible to evaluate the probability of reaching or exceeding selected damage states. Next, the direct economic losses (e.g. repair/replacement costs) are estimated accumulating loss contributions from all states of structural and non-structural damage (Kircher et al.,1997). Meanwhile the Hazus software is one of the complete framework for the assessment of the effects of scenario earthquakes within urban areas or across large regions, its capacity and fragility functions, as well as the loss rates used for calculation of direct economic losses, are derived for building typologies that are typical for US and do not necessarily comply to those of other areas. Examples of studies to extend the capacity curves and fragility curves database to other building typologies may be found in Erberik (2008), Lagomarsino and Giovinazzi (2006) and Lervolino et al. (2007). Other than the different building typologies,the concept of Performance Loss (PL) index also not introduced in Hazus, which may play a significant role in post-earthquake decisions.

Similar to Hazard US (Hazus), the method, which is based on a detailed approach and is developed with reference to selected building, makes use of specific sets of functions (Fragility Curves, FC) to evaluate seismic demand due to an earthquake with a spectral approach. Seismic behaviour of damaged buildings, and their relative seismic safety, is represented by their seismic capacity modified due to damage, the so-called Residual Capacity (REC) (Bazzurro et al., 2004, Polese et al., 2012). In other terms, REC can be defined as a parameter which represent the building seismic capacity (up to collapse) in terms of a spectral quantity. REC also can be interpreted as the median value of collapse fragility curves. Its variation owing to damage is a useful indication of increased building vulnerability. REC reduction, indicating the lowering of seismic safety after an earthquake which used to calculate Performance Loss (PL). PL represents an effective index for assessing the need of seismic repair/strengthening after earthquakes (Polese et al., 2012). Performance Loss (PL) index which consider the building capacity after earthquake is defined as a significant indicator for repair and/or retrofit decision. By considering variation of REC for a depending on ductility demand, PL might express as in Equation 2.1:

$$PL = 1 - \frac{REC_{Sa,i}}{REC_{Sa,0}} \tag{2.1}$$

where $REC_{Sa,i}$ refers to Residual Capacity with minimum anchoring peak ground acceleration at maximum drift displacements of roof at different damage level (global ductility) while $REC_{Sa,0}$ refers to Residual Capacity at undamaged or intact level of the building.

2.3 Performance Based Seismic Design

In Ghobarah (2001), the performance-based seismic design is defined as a general philosophy in structural design which the standards design is achieving the feature design stated performance objectives when the structure is under seismic hazard. The performance-based seismic design (PBSD) procedure has been adopted by engineers since 1994 Northridge Earthquake to produce structures with predictable seismic performance under stated levels of seismic hazard (Alhaddad et al., 2015). It was recognised that structural systems would perform better if design for seismic resistance changed from strength to performance. In Ibrahim and El-Shami (2011), performance level is defined as the expected behaviour of the building in the design earthquake which referring to the limiting levels of damage to the structural and non-structural components regarding the safety component. PBSD is intended to achieve higher performance levels than those required by current codes and to assess the performance of existing buildings. The limiting condition is described by the physical damage within the building, regard with the threat towards life safety of the building's occupants created by the damage, and related to post-earthquake serviceability of the building.

The Federal Emergency Management Act (FEMA-273) and the Structural Engineers Association of California (SEAOC Vision-2000) described the performance levels. By referring to FEMA 273 (1997) and Vision 2000 (1995), the overall performance levels are classified into four categories which are Fully Operational, Operational, Life Safety and Near Collapse which showing the life threaten level of the damaged building.

Fully Operational referring to the building performance system is still functional with no damage to the structural and non-structural. Operational referring to the post-earthquake damage state in which only very limited structural damage has occurred and structural retains a significant portion of its original stiffness and strength. Life Safety referring as the post-earthquake damage state in which significant damage to the structure has occurred, and it may have lost a significant amount of its stiffness but a substantial margin remains for additional lateral deformation before collapse occurrence. Near collapse referring to the building experienced extreme damage and if laterally deformed beyond this point, the structure will be instable and collapse. Based on Vision 2000 (1995), the permissible drifts of 0.2% for fully operational, 0.5% for operational, 1.5% for life safety, and 2.5% for near collapse.

2.4 Incremental Dynamics Analysis

Incremental Dynamic Analysis (IDA) is a current dynamic response history analysis practice in Performance-Based Earthquake Engineering (PBEE), uses the same suite of ground motions at all Intensity Measure (IM) levels to estimate structural response (Lin and Baker, 2013). Structural response assessment can be categorized as static or dynamic and linear or nonlinear. The complexity in the static regime increases from linear to nonlinear to pushover, where incremental static load is applied to the structure, leading to component by component failure and eventually system failure. Similarly, there is a parallel in the dynamic regime from linear to nonlinear, with a dynamic analysis termed incremental dynamic analysis (IDA) by Vamvatsikos (2011). In Vamvatsikos (2011) it described IDA as a “dynamic pushover”, where incremental dynamic load is applied to the structure until it reaches dynamic instability. IDA is developed for seismic assessment where the dynamic load is earthquake ground motion, often scaled from lower to higher intensity and applied to the structure to obtain statistics about the structure performance, characterized by displacement and eventually collapse, under a range of earthquake excitation. The concept of IDA involves ground motions at multiple intensity levels.

Incremental Dynamic Analysis (IDA) is used to determine the probability of exceeding specified structural demand levels and the computation of fragility curve, scaled up until collapse is reached (Vamvatsikos , 2011; Mackie and Stojadinović, 2003). IDA is also known as parametric analysis method that has recently emerged in several different forms to estimate more thoroughly structural performance under seismic loads. It involves subjecting a structural model to one (or more) ground motion record(s), each scaled to multiple levels of intensity, thus producing one (or more) curve(s) of response parameterized versus intensity level. In Bazzurro et al. (2004), IDA curves is used to estimate the median peak ground acceleration (PGA) corresponding to the performance level. In Figure 2.1, the green dots at IDA curves representing the Partial Collapse performance level for intact and damaged cases from damage state 2 to 5 (DS2-DS5) expressed in terms of same reference spectral acceleration at fundamental period (T_1).

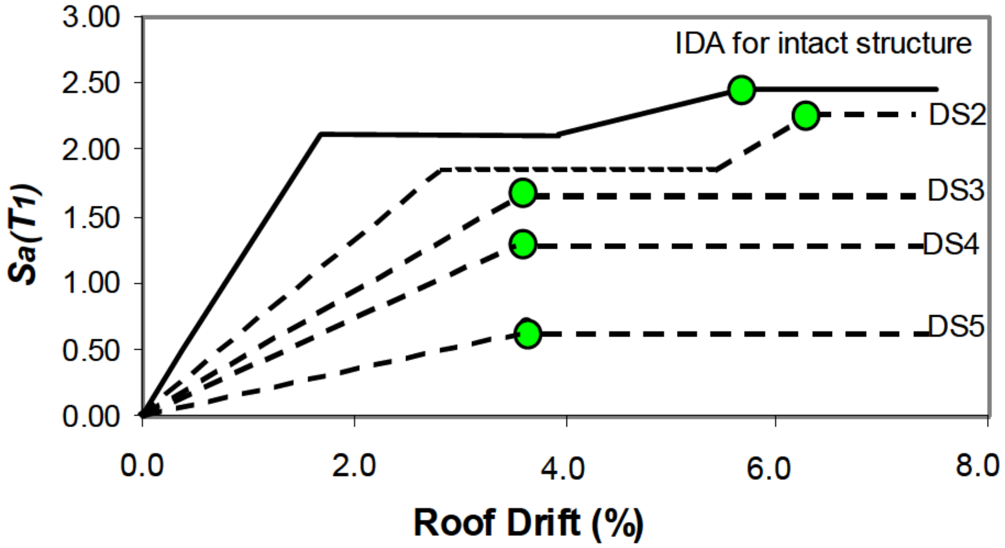

Figure 2.1 : IDA Curve with Interstorey Drift Ratio (IDR)
(Bazzurro et al., 2004)

2.5 Fragility Curve

Fragility curves epitomise the conditional probability that a response of the specified structure may exceed the performance limit at a given ground motion intensity. These curves are valuable tools for the valuation of probability of structural damage due to earthquakes as a function of ground motion indices otherwise design parameters. In Bakhshi and Asadi (2013), fragility curve is developed to assess various probability parameters such as, Peak Ground Acceleration (PGA), importance factor (I) and typical over-strength and global ductility capacity (R). These illustrations were utilized to show when a coefficient or number of parameters were used to improve the performance capacity of a structure. In Samoah (2012) the fragility performance of non-ductile RC frames in low and medium seismic zones were examined. An inelastic push-over analysis was used to study the structural capability of the while the seismic demand is investigated by inelastic time history analysis followed by evaluation of fragility curves. The modelling and analysis for the non-ductile RC frame buildings are done adequately based on the basis of their structural properties.

Fragility curve indicates the probability of exceeding a specific damage state as a function of an engineering demand parameter that represents varies with the ground motion. Figure 2.2 shows a typical fragility curve with PGA along the x-axis and probability of failure along y-axis at different performance level. A point in the curve represents the probability of exceedance of the damage parameter, which can be lateral drift, storey drift, base shear etc., over the limiting value mentioned, at a given ground motion intensity parameter. In Figure 2.2, varies fragility curves based on performance level were presented, such as operational phase (OP), immediate occupancy (IO), damage control (DC), life safety (LS) and collapse point (CP).

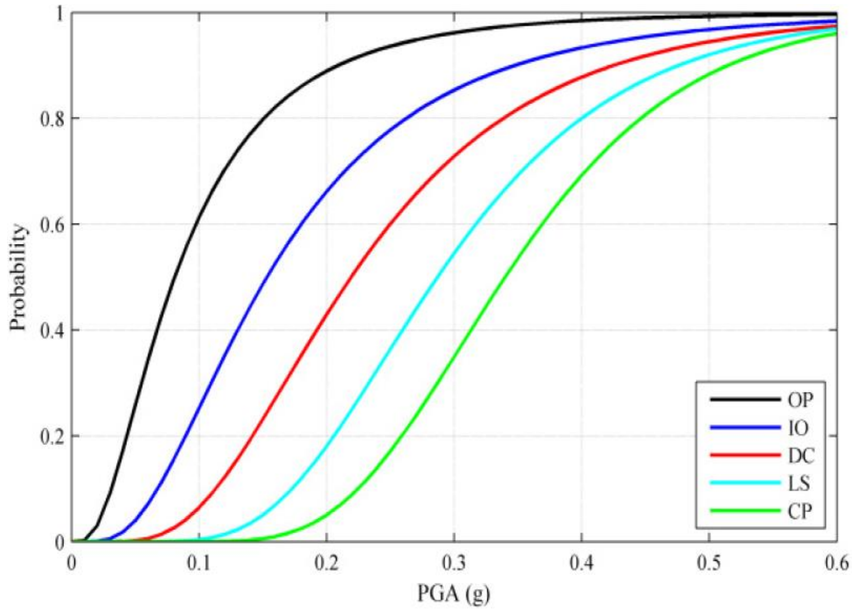

Figure 2.2 : Fragility Curve with different performance level
(Saruddin and Nazri, 2015)

Fragility curve can be developed by using mean and standard deviation of Peak Ground Acceleration (PGA) at different performance level (Ibrahim and El-Shami ,2011). Equation 2.2 was used to developed the fragility curve shown in Figure 2.2.

$$P[D / a_g] = \phi[\frac{In(a_g) - \mu}{\sigma}] \tag{2.2}$$

where,

D = Performance Level

a_g = Peak Ground Acceleration

$\emptyset$ = Standard Normal Cumulative Distribution

μ = Mean

σ = Standard Deviation of Natural Logarithm of a_g

Time-dependent fragility curve is the fragility curve where the performance level of a structure that depends on the period or duration after the construction. It is commonly considered to be affected by two categories of phenomena which may determine time-dependency: (1) continuous deterioration of material characteristics or ageing, and (2) cumulating damage because of repeated overloading due to shocks in short period of time (Sanchez-Silva et al., 2011). There are number of interesting studies investigating on the variation of seismic risk after material degradation (e.g. Ghosh and Padgett (2010) for bridges or Celarec et al. (2011) for buildings). For example, return period of an earthquake can be considered in fragility curve to determine the building performance level at certain period (D'Aragona et al., 2015) as shown in Figure 2.3.

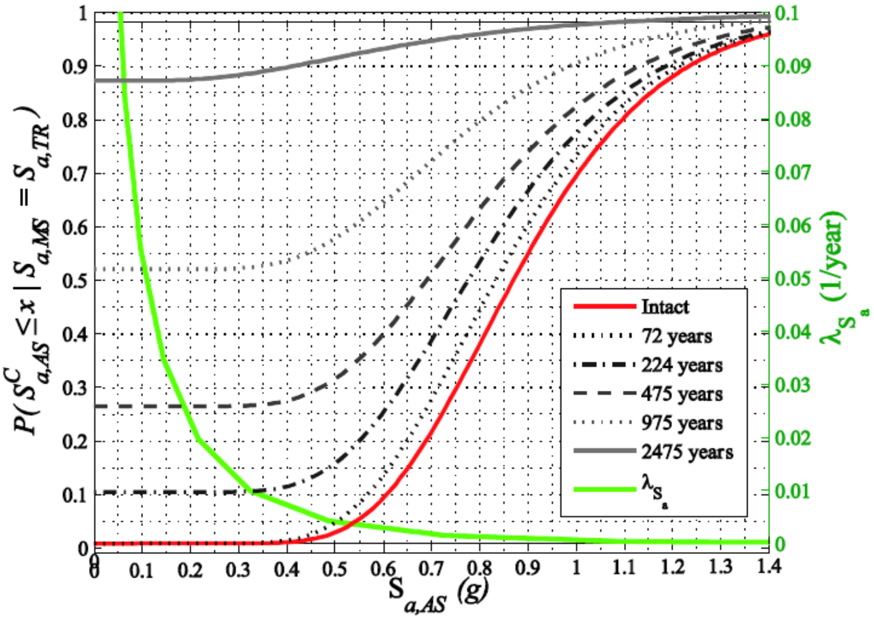

Figure 2.3: Time-depend fragility (D'Aragona et al., 2015)

The red curve represents the behavior of the intact building. As the return period increases, due to the increasing building damage for Main Shock (MS) application, the fragility curve shift left and up. A comprehensive indicator of the structural safety that involves considering both the hazard curve at the site and the collapse fragility curves is the probability of collapse over *t* years.

Under the hypothesis of the occurrence of earthquakes in times, the time-dependent fragility curve is developed by using Poisson process (D'Aragona, 2015). The probability of performance level over t years can be computed as Equation 2.3:

$$P_c(t) = 1 - \exp(-\lambda_c t) \tag{2.3}$$

with λc the mean annual frequency of collapse.

2.6 Repeated Earthquake

Repeated Earthquake is the repetition of medium-strong ground motions at short time interval, which may also refer to a few seismic sequences (foreshock, main shock and aftershock) come in same direction and in a short period time. In such cases, there is a significant damage accumulation as result of multiplicity of earthquakes, and due to lack of time, any rehabilitation action is impractical (Hatzigeorgiou and Liolios, 2010). Large shallow earthquakes are followed by an increase in seismic activity, defined as an aftershock sequence (AS). It is also well known that large earthquakes are sometimes preceded by an unusually large activity rate, defined as a foreshock (FS) sequence. There are huge fluctuations of the foreshock seismicity rate, if any, from one sequence of earthquakes to another one preceding a main-shock (MS). Moreover, the number of foreshocks per main-shock is usually quite smaller than the number of aftershocks (Helmstetter, 2003).

In general, building seismic design is based on the building seismic capacity that withstand the mainshock of the earthquake. However, recent works Réveillere et al. (2012) and Raghunandan et al. (2014) are addressed the possibility of aftershock collapse due to vulnerability of Reinforce Concrete (RC) damaged buildings which indicate the importance to examine repeated earthquake on the effect of RC building. Those studies allow the evaluation of safety variation based on the maximum transient or residual drift.

In Fragiacomo et al. (2004), the effects of repeated earthquake ground motions were first being examined on the response of single-degree-of-freedom (SDOF) systems with different hysteretic models. Other researchers have found that significant effect of repeated earthquakes phenomenon on the inelastic displacement ratio of SDOF systems (Hatzigeorgiou and Beskos, 2009). In Hatzigeorgiou and Liolios (2010), a research has been carry out to continue to examine the effect of repetition ground motions on nonlinear behaviour of reinforced concrete (RC) frames. Five of the strong ground motion with the real seismic sequences were used in their studies, which have been recorded during a short period of time, by the same station, in the same x-y direction, and almost closer at the fault distance. The strong ground motions are named as Mammoth Lakes (May 1980–5 events), Chalfant Valley (July 1986–2 events), Coalinga (July 1983–2 events), Imperial Valley (October 1979–2 events) and Whittier Narrows (October 1987–2 events) earthquakes shown in Figure 2.4. A typical time gap of 100 seconds is applied between two consecutive seismic events to allow the creasing vibration and stop the moving of any structure due to damping. The significant of damaged accumulated due to multiplicity of earthquakes and in short period of time, as the building is proved to be not able to rehabilitate (Hatzigeorgiou et. al, 2010).

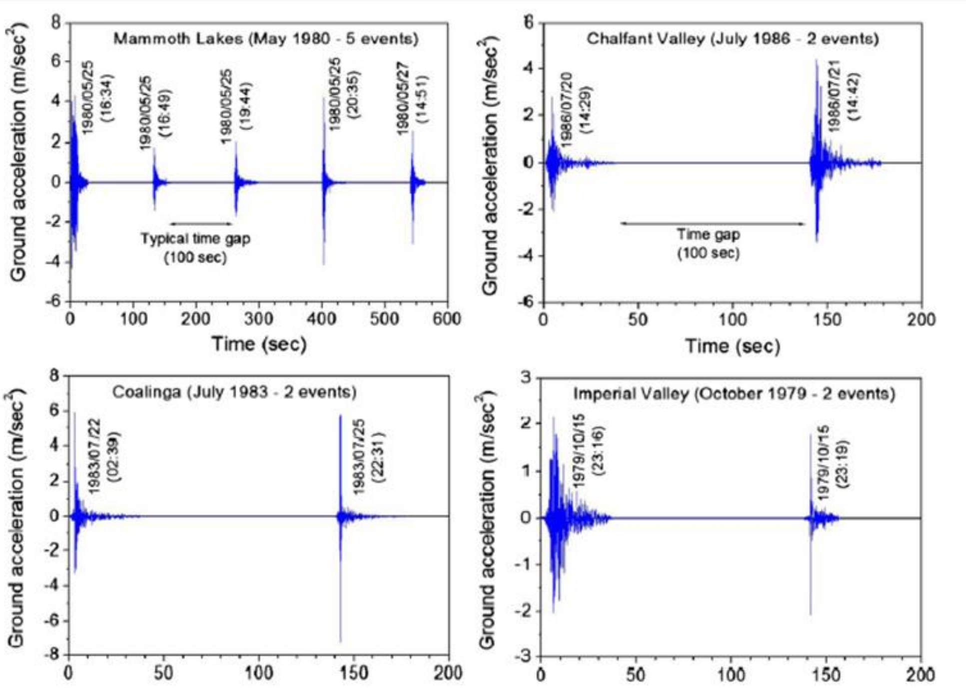

Figure 2.4 : Ground acceleration record of the examined seismic sequences (Hatzigeorgiou and Liolios, 2010)

2.7 Cost Ratio (C_r)

Cost ratio (C_r) is referring to the cost ratio obtained as ratio between the repair costs related to building structure and dwellings and the average building demolition and re-construction cost (Polese et al., 2015) as shown in Equation 2.4.

$$C_r = \frac{C_i}{C_d} \tag{2.4}$$

where C_i = Repair and/or Retrofit Cost

C_d = Re-construction Cost

Due to the lack of repair and retrofit cost for seismic damage in buildings in Malaysia. The estimation cost of repair and retrofit in Polese et al. (2015) had adopted even though the different building typologies. The building usability tagging is developed from the cost database for RC buildings damaged after the 2009 L'Aquila Earthquake under the coordination of the Italian Civil Protection Department which considering the post-earthquake damaged buildings can be classify into four categories as shown in Table 2.1.

Table 2.1: Building Usability Tagging (Polese et al., 2015)

Building Usability Rate	**Characteristic**
A	Usable building (slightly damaged, can keep on housing the functions to which it was dedicated)
B	The building is usable only after short term countermeasure (buildings with limited or no structural damage but with severe non-structural damage)
C	Partially Usable Building (buildings with limited or no structural damage but with severe non-structural damage located in a part of the building)
D	The building is to be re-inspected (because of a typical damage scenario, a specific but still visual investigation is required)
E	unusable building (high structural or non-structural risk, high external or geotechnical risk)
F	unusable building for external risk only

The RC building classes representative of existing European–Mediterranean constructions. The estimated cost for repair and/or retrofit interventions based on the building usability rate of damaged building is established as follow (Polese at al., 2014;2015): i) RM675/m^2 (150€/ m^2) of the overall building gross surface) for the local strengthening (of critical structural and non-structural members) of buildings with rate B or C; ii) RM1125/m^2 (250€/ m^2) the local strengthening of buildings with rate E but with light or no structural damage (named E-B buildings in the reconstruction approval process); iii) RM1800/m^2 (400€/ m^2) for the seismic retrofit of severely damaged buildings (usability rate E); iv) for buildings with usability rate E, demolition and reconstruction was also allowed, if economically suitable. According to usability tagging and considering the post-earthquake ordinances (Baggio et al., 2007), the buildings can be grouped into four categories (B-C, E-B, E and Edem) as shown in Figure 2.5. In Polese et al. (2015), building usability rate have been classified based on base-shear coefficient (Cb) at constant PGA with varies reinforced concrete building and story drift (d') relationship curve as shown in the Figure 2.5.

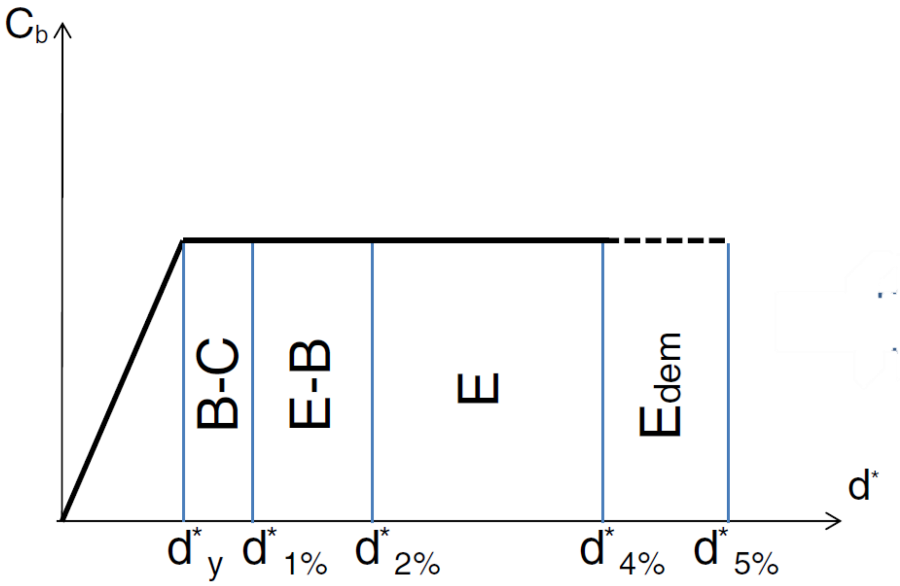

Figure 2.5 : Building Usability Rate in drifts thresholds suggested (Polese et al., 2015)

For the damaged buildings, the drift thresholds suggested are light (1%), moderate (2%) and severe damage states (4%) are introduced. For buildings tagged as B-C, it is assumed that they had sustained a seismic demand causing maximum drift larger than yield limit and lower than 1% as shown in Figure 2.5; for buildings tagged E that benefited E-B funding scheme, the hypothesis is that maximum drift is between 1% and 2%; for E buildings, the interval is 2–4% while for buildings that were to be demolished, E_{dem} , an interval 4–5% is assumed. Due to the different building typologies, the re-construction cost was referring to Malaysia construction which JUBM and Langdon Seah Construction Cost Handbook in year 2015 for Sabah area had been used. In the Construction Cost Handbook, it suggested construction at the rate RM1550/m^2 per floor area in Sabah area, hence the reconstruction cost can be estimated with total floor area of S.M.K Ranau building.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, the methodology for the evaluation of damaged building capacity of the multi-storey reinforced concrete (RC) building by post-earthquake event is presented. This research was conducted to study the performance loss (PL) of damaged building after an earthquake to act as a significant indicator for repair and/or retrofit decisions. Basically, there are four phrases of conducting this research. The first phrase involves with modelling S.M.K Ranau in ETABS and selecting a few ground motions and scale up from minimum 0.1g as interval of 0.1g Peak Ground Acceleration (PGA) is being used. In the second phrase, the maximum storey drift data is computed by using Nonlinear Time-History analysis (NTH), in ETABS Software. The third phrase, Incremental dynamic analysis (IDA) curve is plotted to obtain mean and standard deviation of PGA up to building collapse, hence fragility curve is developed. Finally, the performance loss (PL) of damaged building is developed and used to evaluated PL-cost relationship graph to prevent any economic loss for the final decision to be made. In this chapter, flow chart of methodologies is presented and the procedure of data gathering and the analysis of data are discussed.

3.2 Research Flow Chart

An evaluation of building repairability methodology is adopted as shown in Figure 3.1, where relationship between performance loss and cost ratio was developed to assess the building with final decision of the building repairability.

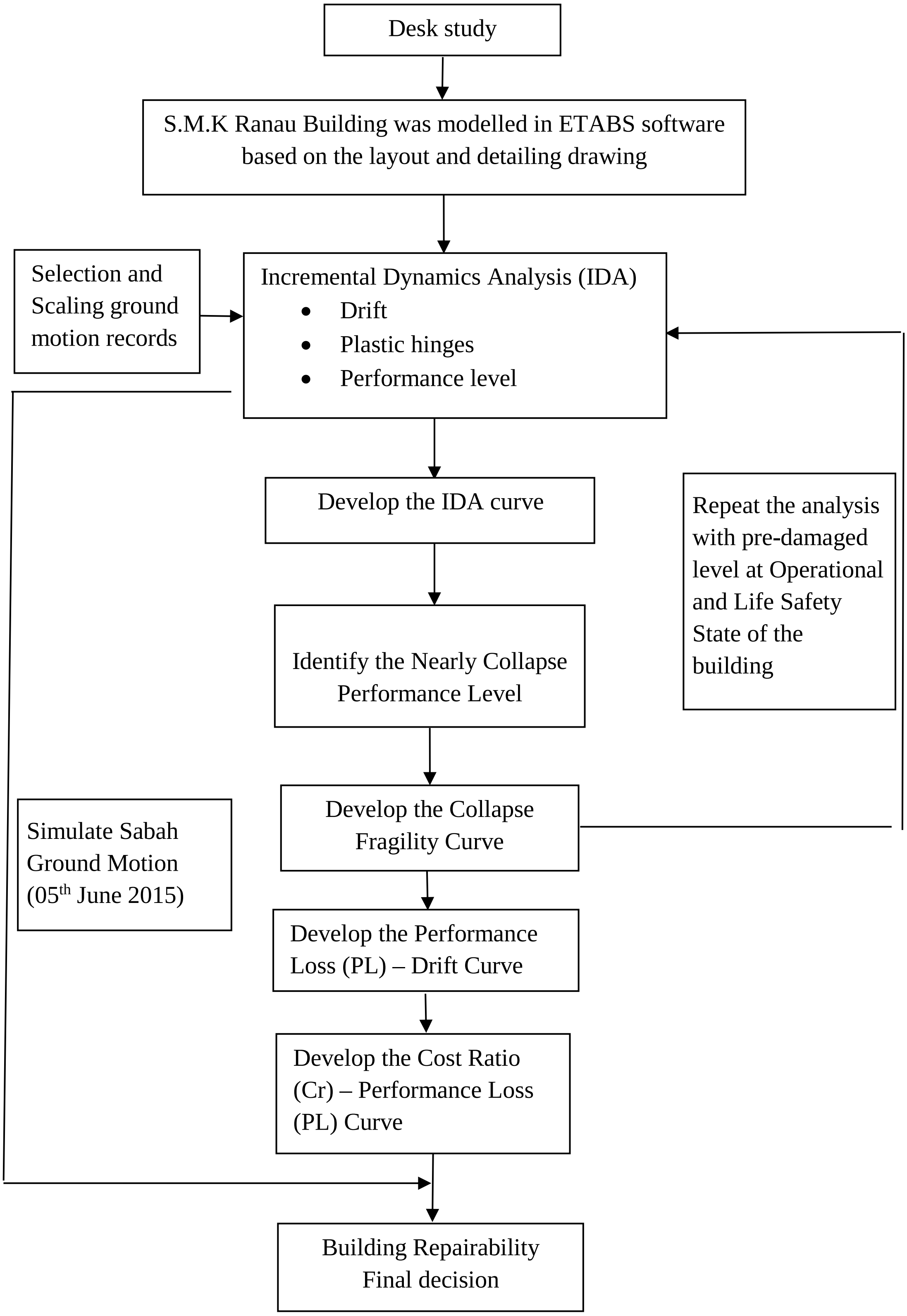

Figure 3.1: Flow chart of Methodology

3.3 Application to an Existing RC Building

3.3.1 Study Site Selection

Due to the biggest earthquake-damaged event happened in Sabah on 05th June 2015, some of the public reinforced concrete (RC) buildings suffered damage at certain degree. One of the RC damaged buildings (S.M.K Ranau building) was selected in ordered to study the Performance Loss of the damaged multi-storey RC damaged building.

3.3.2 Description of the building structure model

The model frame chosen is case study with the existing damaged building after an earthquake. School building of S.M.K Ranau is selected as it is one of the damaged Reinforce-Concrete (RC) structure reported in Ranau earthquake event. It is modelling in ETABS Software based on the layout shown in Figure 3.2. S.M.K Ranau consisted of four storey and classified as moment resisting concrete frame. It was assigned with 208 beams and 180 columns from the ground floor to the top roof. Concrete grade is assumed with C30/35 that carried characteristics strength f_{ck} of 30 MPa while the steel yield strength f_u is assumed as 500 MPa and other design assumptions have been made based on Eurocode (EC) 2 as shown in Table 3.1.

Table 3.1: Design Assumptions based on EC 2 and EC 8

Concrete Strength, f_{ck}	30N/mm^2
Steel Yield Strength, f_u	500N/mm^2
Concrete Cover	25mm
Bar Diameter	20mm /12mm
Link Diameter	10mm