ASSESSMENT OF STRUCTURE-SPECIFIC SEISMIC FRAGILITY CURVES OF BUILDINGS USING SPO2FRAG

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By

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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ABSTRAK

Malaysia berada di bawah ancaman peristiwa gempa bumi. Walaupun kelemahan dalam melawan pengujaan seismik, bangunan lembut tingkat masih memperolehi popularitinya kerana tujuan fungsi dan estetik, yang selama ini menjadi keutamaan bagi pemilik hotel dan membeli-belah kompleks. Analisis statik (Pushover) tidak linear (POA) merupakan prosedur penilaian yang menjimatkan masa dan mudah dalam Eurocode 8 (EC8), walaubagaimanapun, kebolehpercayaannya dalam mereka bentuk struktur masih dipersoalkan. Begitu juga sama untuk lengkung kerapuhan dihasilkan dengan menggunakan SPO2FRAG melalui POA. Oleh itu, Analisis dinamik bertambahan (IDA) digunakan sebagai rujukan kepada keputusan yang dihasilkan oleh POA. Kajian ini adalah untuk menilai prestasi seismik bangunan dengan menggunakan POA dalam EC8. Begitu iuga, ketepatan empirikal lengkung kerapuhan yang dihasilkan oleh POA (menggunakan SPO2FRAG) dikaji. 5- dan 11-tingkat kerangka untuk tingkat sekata dan lembut yang mendirikan empat model dengan ketinggian yang berbeza-beza telah direkabentuk mengikut Eurocode 2 (EC2) untuk saiz dan tetulang anggota struktur, manakala EC8 digunakan untuk menentukan beban gempa bumi. Perisian SAP2000 telah digunakan untuk menjalankan POA. Lengkung keupayaan yang diperolehi telah digunakan sebagai input utama dalam perisian SPO2FRAG, yang menjana lengkung kerapuhan berdasarkan keputusan POA. Kemudian, IDA dilakukan untuk menjana lengkung IDA dan lengkung kerapuhan. Pecutan puncak bumi, *PGA* telah ditukar kepada $Sa\ (T_1)$ yang bersepadan dengan menggunakan reka bentuk spektrum daripada EC8. Tahap prestasi Keselamatan Hidup (LS) dan Hampir Runtuh (NC) yang dicadangkan oleh Vision-2000 adalah minat utama dalam kajian ini. Hasil daripada POA dan IDA menunjukkan bahawa kerangka tingkat lembut ini mempunyai permintaan yang lebih tinggi daripada kerangka sekata. Lengkung kerapuhan yang dihasilkan oleh POA, menunjukkan bahawa kerangka 5-tingkat sekata boleh menangkap trend lengkung kerapuhan IDA, tetapi beberapa sisihan diperhatikan dalam struktur tingkat lembut 5-tingkat. Kesemua kerangka 11-tingkat menunjukkan perlengkapan yang tidak memuaskan untuk lengkung kerapuhan yang dihasilkan oleh POA, berbanding dengan IDA.

ABSTRACT

Malaysia is under the menace of earthquake event. Despite its weakness in resisting seismic excitation, soft storey building still gains its popularity due to the functional and aesthetic purpose, which has always been the preference for hotelier and shopping complex. Nonlinear Static (Pushover) Analysis (POA) is time saving and simple assessment procedure in Eurocode 8 (EC8), however, its reliability in designing structure remains a question. It is the same for fragility curve produced by using SPO2FRAG through POA. Therefore, Nonlinear (Incremental) Dynamic Analysis (IDA) is used as a reference for results generated POA. This study is to assess seismic performance of building using POA in EC8. Also, empirical accuracy of fragility curve generated by POA (using SPO2FRAG) is studied. Regular and soft storey of 5- and 11-storey frames that composed four models of varying height were designed according to Eurocode 2 (EC2) for sizing and reinforcement of structural member, while EC8 is used to determine earthquake loading. SAP2000 software was used to carry out POA. Capacity curve obtained is served as main input in SPO2FRAG software, which generate fragility curve based on results of POA. Then, IDA is performed to generate IDA curves and fragility curves. Peak ground acceleration, *PGA* was converted into corresponding $Sa\ (T_1)$ using design spectrum from EC8. Performance level of Life Safety (LS) and Near Collapse (NC) proposed by Vision-2000 (1995) are the main interest in this study. Results from POA and IDA shown that soft storey frame has higher demand than regular one. Fragility curve generated by POA (using SPO2FRAG), indicated that regular 5-storey frame can capture the trend of fragility curve of IDA, but some deviation is observed for soft storey structure (5-storey). All 11-storey frames shown unsatisfactory match of fragility curve from what was generated by POA, compared to IDA.

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LIST OF ABBREVIATIONS

ADRS	**A**cceleration–**D**isplacement **R**esponse **S**pectra
ASCE	**A**merican **S**ociety of **C**ivil **E**ngineers
ATC	**A**pplied **T**echnology **C**ouncil
BSI	**B**ritish **S**tandard **I**nstitute
CNA	**C**hannel **N**ews **A**sia
CSM	**C**apacity **S**pectrum **M**ethod
DAP	**D**isplacement-based **A**daptive **P**ushover
DM	**D**amage **M**easure
EC0	**E**uro**c**ode **0**
EC1	**E**uro**c**ode **1**
EC2	**E**uro**c**ode **2**
EC8	**E**uro**c**ode **8**
EDP	**E**ngineering **D**emand **P**arameter
ESDOF	**E**quivalent **S**ingle **D**egree **O**f **F**reedom
FO	**F**ully **O**perational
FAP	**F**orce-based **A**daptive **P**ushover
FEMA	**F**ederal **E**mergency **M**anagement **A**gency
IDA	Nonlinear (**I**ncremental) **D**ynamic **A**nalysis
IM	**I**ntensity **M**easure
LDP	**L**inear **D**ynamic **P**rocedure
LS	**L**ife **S**afety
MDOF	**M**ultiple **D**egree **O**f **F**reedom
MMI	**M**odified **M**ercalli **I**ntensity

MPA	**M**odal **P**ushover **A**nalysis
MRCF	**M**oment **R**esisting **C**oncrete **F**rame
MSP	**M**odal **S**hear-Based **P**ushover
NC	**N**ear **C**ollapse
NDP	**N**onlinear **D**ynamic **P**rocedure
NSP	**N**onlinear **S**tatic **P**rocedure
O	**O**perational
OGS	**O**pen **G**round **S**torey
PEER	**P**acific **E**arthquake **E**ngineering **R**esearch Centre
PBSD	**P**erformance **B**ased **S**eismic **D**esign
PBSE	**P**erformance **B**ased **S**eismic **E**ngineering
POA	Nonlinear Static (**P**ush**O**ver) **A**nalysis
PGA	**P**eak **G**round **A**cceleration
SDOF	**S**ingle **D**egree **O**f **F**reedom
SPO2FRAG	**S**tatic **P**ush**O**ver **to FRAG**ility
SRSS	**S**quare **R**oot of **S**um of the **S**quares
UB	**U**pper **B**ound
UBC	**U**niform **B**uilding **C**ode

NOMENCLATURES

$A_{s,max}$	Maximum area of reinforcement
$A_{s,min}$	Minimum area of reinforcement
F_b	Design Base shear
$F_{b,\ max}$	Maximum base shear
F_i	Equivalent static force for storey level i
F_i	Horizontal force acting on level i
G_k	Permanent action
H	Building height
L_c	Length of column or storey height
L_{c1}	Height of the first storey
L_{c2}	Height of the second storey
M_{GQ}	Bending moment
M_L	Magnitude in Richter scale
Ms	Surface magnitude
M_T	Maximum bending (design) moment
M_w	Moment magnitude
N_{Ed}	Ultimate (design) axial load
$S_d\ (T_1)$	Design spectrum
$S_a\ (T_1)$	First mode spectral acceleration
T_1	First mode period of vibration
Q_k	Variable load
μ	Mean of IM
σ	Logarithmic standard deviation of IM

CHAPTER 1

INTRODUCTION

1.1 Background

The generic consensus has always been positive that Malaysia was safe and seismic free, as it is located on seismically stable Eurasian Plate and is far from Pacific Ring of Fire. There were, however, weak earthquakes that happened in Bukit Tinggi area, which is just about 50km from Kuala Lumpur (Zaini Sooria et al., 2012). Shuib (2009) suggested the earthquakes are due to fault reactivations and are believed to be the repercussion of stress build-up, due to current tectonic in South-East Asia (Sundaland).

In spite of menace from local earthquake, West Malaysia is also under the threat of long distance quake, as its position close to 1650 km long Sumatran fault (some 260km away) and Sumatran Subduction zone (some 400km away). In the event of earthquakes with considerable magnitude, tremor from the two active seismic zone has been affected buildings and felt in Malay Peninsula (Che Abas, 2001; Ramli and Adnan, 2004; Marto et al., 2013). Consequently, building in several cities had shown cracking (Che Abas, 2001; Adnan et al., 2002). Affected cities are summarized in Table 1.1. Some regional earthquake events affected Malaysia (Gill et al., 2015) are shown in Figure 1.1.

Table 1.1: Cities affected by regional earthquakes (Che Abas, 2001)

No	Earthquake event	M_w	Affected city	Building showing cracks
1	Bengkulu Earthquake (June 4th, 2000)	7.8	Johore Bahru and Klang Valley	Johore Bahru
2	Sumatra Earthquake (November 2nd, 2002)	7.4	Penang, Port Klang, Old Klang,	Penang, Port Klang,

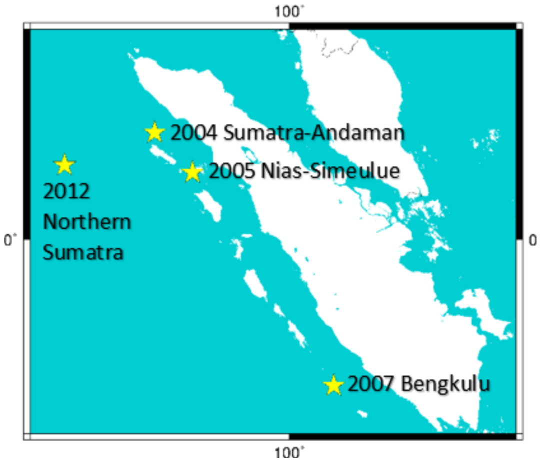


Figure 1.1: Epicenters of major earthquake affected Malaysia (Gill et al., 2015)

According to Balendra and Li (2008), high frequency (or short period) seismic waves weakened rapidly in propagation, while low frequency (or long period) waves that are resistive to energy dissipation allows them travel long distances towards bedrock of Peninsular Malaysia. As the natural period of soft soil at site close to predominant period of the said long period waves, resonance occur and results in soil (or wave) amplification, that create motion to building and the effect is significant to be felt by local inhabitant.

Rupture of Sumatran megathrusts from two major earthquake events (Acheh-Andaman earthquake, Mw 9.15 on 26 December 2004 and Nias-Simeulue earthquake, Mw 8.6 on 28 March 2005) released considerable portion of strain accumulated. Thus, there is slim chance for giant earthquakes to recur in this segment of megathrust in the near future. Despite of this, Mentawai segment of Sumatran megathrust is likely to be ruptured within next few decades (Megawati and Pan, 2009; Marto et al., 2013).

Peninsular Malaysia has been categorized as low earthquake zone. On the other hand, East Malaysia (Sarawak and Sabah) with the highest magnitude of earthquake event in the country is identified as moderate seismic zone. East Malaysia is subjected to both near- and far-field jolting. Regional sources come from Kalimantan, Sulawesi and

Southern Philippines, while local sources with some local faults and weak zones producing low-to-moderate magnitude of earthquakes (Harith et al., 2017).

Malaysia has decided to adopt seismic code – Eurocode 8. The Ministry of Science, Technology and Innovation (MOSTI), together with Department of Standards Malaysia approved the development of MS EN 1998-1:2015, Eurocode 8-Part 1 on August 2015, and the development of National Annex for EC8 is expected to roll out by the year of 2018 (Bernama, 2017). EC 8 suggested 4 analytical methods as shown in Table 1.2.

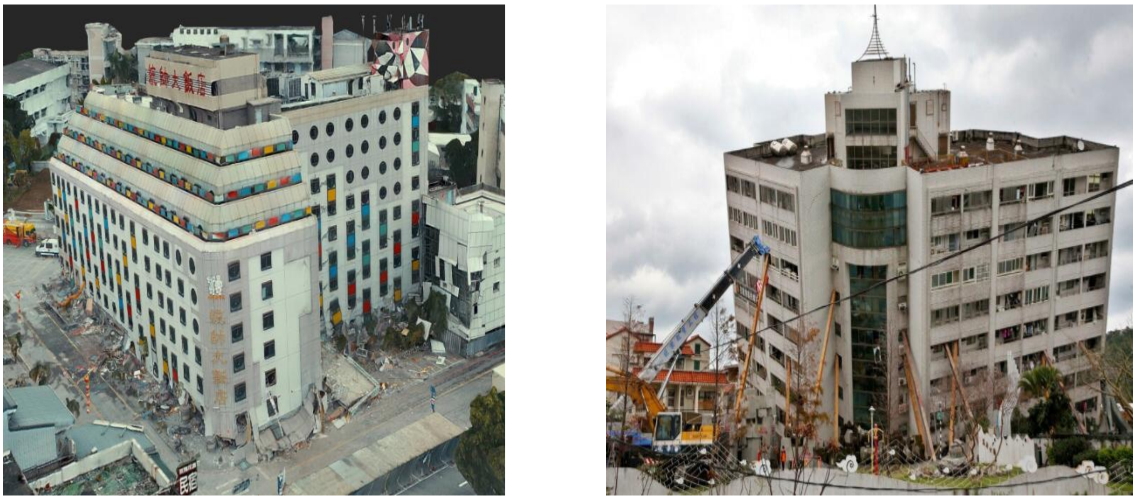
Table 1.2: Method of Analysis (BSI, 2004)

No	Method	Linear/Nonlinear	Static/Dynamic
1	Lateral force method of analysis	Linear	Static
2	Modal response spectrum analysis	Linear	Dynamic
3	Pushover analysis	Nonlinear	Static
4	Time history analysis	Nonlinear	Dynamic

The most recent 6.0 magnitude Hualien earthquake that hit Taiwan on 6 February 2018, has resulted in death toll up to 17, owing to the partial collapse of 12-storey Yun Men Tsui Ti building and collapse of three lowest storeys of 10-storey Marshal Hotel that sit on Milun fault (CNA, 2018; Lin et al., 2018). The failure could be due to flimsy floor that an engineer in general called it as a soft storey building (Jennings, 2018). Both original and collapse state of the two worst-hit buildings are shown in Figure 1.2 and Figure 1.3.

(a) Marshal Hotel (b) Yun Men Tsui Ti building

Figure 1.2: Original state of two worst-hit buildings before Hualien quake in Taiwan



(a) Marshal Hotel (b) Yun Men Tsui Ti building

Figure 1.3: Collapse state of the two worst-hit buildings in Hualien quake in Taiwan

1.2 Problem Statement

Noteworthy, soft storey building is prevailing across the globe, even in Malaysia. Example of irregular building are hotel and shopping complex, where the ground (or more) storey is often constructed with height greater than the others, for the sake of aesthetic and functioning purpose. Consequently, there is an urgent need for engineers and earthquake experts to scrutiny into the capacity of building in resisting incurred damage (demand) arise from ground movement, in the context of Performance Based Seismic Engineering (PBSE).

Malaysia is making progress to adopt seismic code – Eurocode 8 to design aseismic building. Four main procedures of analysis in EC8 are Linear Static Procedure (LSP), Linear Dynamic Procedure (LDP), Nonlinear Static Procedure (NSP) and Nonlinear Dynamic Procedure (NDP). However, current researchers and academicians regarded NDP as the most accurate analytical method in the development of structural earthquake engineering.

Despite the popularity of NDP, there are still some reservations, which are mainly related to its computational cost and selection of proper ground motion records for practical design applications (Li et al., 2017). On the other hand, the seismic demands resulting from the NDP are influenced by parameters of the modelling as well as the characteristics of the ground motions such as frequency content, intensity, magnitude and duration (Kalkan and Kunnath, 2006).

Other difficulties and drawbacks of NDP include: it requires the selection and employment of an appropriate set of ground motions; it remains computationally demanding; and it still requires the use of preliminary simpler analyses (as linear static and dynamic) to calibrate the model. Thus, there is still room and warrant for continuous development and improvement of NSP, so that these analyses can become even more reliable and applicable also for irregular structures (Belejo and Bento, 2016). It is therefore Pushover Analysis or Nonlinear Static Procedure (NSP) has become popular because of its efficiency and capability to estimate seismic demands directly from the site-specific hazard spectrum (Soleimani et al., 2017).

In the past, NDP has been sought after by researchers in assessing fragility of building. Fragility assessment associated with nonlinear capacity of building to seismic response, for the sake of economic design. Nevertheless, advancement of Performance Based Seismic Engineering (PBSE) is making establishment of fragility assessment from NSP possible, without seeking recourse to NDP.

NSP such as Capacity Spectrum Method (CSM) proposed by Freeman (1998) can be used to generate fragility curve. It is widely used, in design code, such as the ATC-40 (1996), FEMA-356 (2000) and by researcher such as the popular N2 method (Fajfar, 1999; Fajfar, 2000). CSM involved only the capacity curve and response spectra in the acceleration–displacement response spectra (ADRS) format, which can generate fragility curve by determining the performance point, where the demand meets capacity.

Recently, SPO2FRAG software has been invented by Baltzopoulos et al. (2017). It allows the generation of fragility curve with its special features on the use of the capacity curve as the only input in the software. Other characteristics includes idealization and fitting of capacity curve into complex quadrilinear backbone capacity curve, ability to analyze both interstorey drift ratio (IDR) and roof drift ratio (RDR), managing additional sources of variability, taking into account damping effect or hysteresis pinching and inclusion of estimation uncertainty though statistical approach.

However, it is still unclear to the reliability of Lateral Force Method of Analysis (LSP) in EC8 to be used in designing base shear resistance for regular and soft storey structure. On the other hand, albeit the superiority of SPO2FRAG software that offers, which are easy to use, fast and required results (capacity curve) from a simple NSP, the reliability of the fragility curve produced by the software also leaves a question mark to earthquake engineering society.

In summary, mushrooming construction of soft storey building in urban cities continues, despite most buildings are not designed for aseismic function and question on the safety with respect to earthquake excitation remains. In terms of analysis-wise, there are uncertainties in NDP procedure such as selection & scaling of ground motion, hysteresis behaviour, damping effect and many more. Coupling with cumbersome computational effort, the astonishing cost deter the current practitioners from adopting NDP in fragility assessment of building. To overcome the abovementioned setbacks of NDP, one may employ NSP, for its simplicity and readily understandable.

1.3 Objectives

The objectives in this study are:

i. To assess the adequacy of seismic resistance of regular and soft storey buildings designed by EC8 using POA, and also IDA.
ii. To develop the fragility curve through POA (using SPO2FRAG) and make comparison with IDA.

1.4 Scope of Work

The scope of work performed in this study consists of:

i. Design 5 and 11 storey regular and vertically irregular Moment Resisting Concrete Frame (MRCF) according to EC2 and EC8.
ii. Perform Nonlinear Static (Pushover) Procedure (NSP) by using SAP 2000 Software.
iii. Development of fragility curve using Static Pushover to Fragility (SPO2FRAG) software and Nonlinear (Incremental) Dynamic Analysis and determine the

median capacity or Peak Ground Acceleration (PGA) at 50% probability of damage states.

1.5 Dissertation Outline

The dissertation is categorized into five chapters:

Chapter 1 gives a brief introduction about the background of this research. It emphasize on earthquake hazard that Malaysia is facing. This chapter also highlights the importance of this research on the issue of soft storey building and using simpler NSP for fragility assessment of building. The objectives of this research are well-defined.

Chapter 2 discusses about the previous research studies which are related to this topic. Past studies were reviewed to get more understanding on development of NSP, fragility curve and subjects in the earthquake engineering. It also includes the analysis related to the Nonlinear Static Procedure (NSP) and fragility assessment with respect to Performance Based Seismic Engineering (PBSE).

Chapter 3 explains the methodology in the study with the aid of flowchart and description stating the steps and flow of the study. It describes the code used to design the moment-resisting concrete frame (MRCF). NSP (using SPO2FRAG) and NDP are carried out to assess the seismic performance. The structural modelling is done by using SAP 2000 software.

Chapter 4 discusses the capacity curve from POA. Fractile IDA curves generated by POA (using SPO2FRAG) and IDA curves from IDA are well analyzed and presented. Comparison between fragility curve generated by SPO2FRAG and IDA is made.

Chapter 5 concludes results of this research. Several recommendations are highlighted for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter reviews the relevant literature related to the topic of this dissertation. Previous study concerning the present research is highlighted into few sections. First, Nonlinear Static Procedure (NSP) involved in this research and previous study is presented. Second is the fragility assessment that, quantify the performance level of building and some viable approaches, in the context of Performance Based Seismic Engineering (PBSE). Finally, soft storey building to be used in this study are explained.

2.2 Non-linear Static Procedure (NSP)

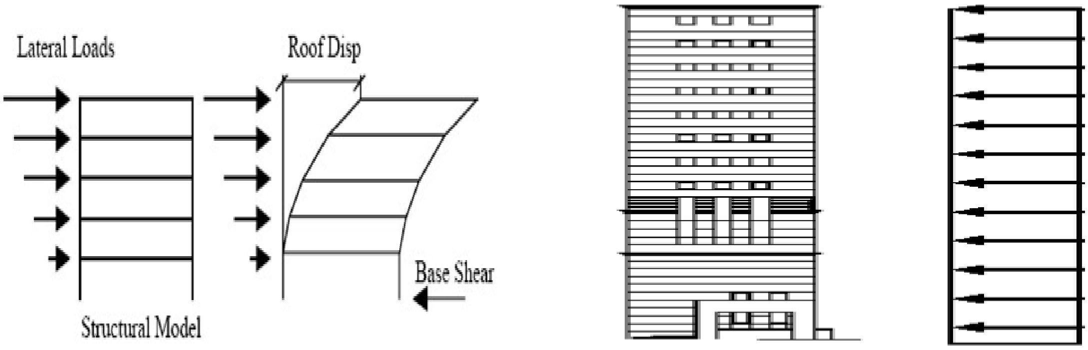
2.2.1 Inelasticity and Non-linearity

Earthquake loadings are different from other loading type due to high deformation and stresses under earthquake effect. Codes requested designed structures possess enough ductility (or beyond) to dissipate most of energy in respond to earthquake through inelastic deformations. Designing buildings to respond elastically to moderate-to-strong earthquakes is generally uneconomical, consequently, the concept of inelastic design prevents the buildings from collapse even if it is severely damaged (El-Betar, 2017).

A linear relationship suggested strain is directly proportional to stress with a constant rigidity (Aguirre and Irikura, 1997). On the other hand, a nonlinear relationship means stress and strain are not related linearly, which allows nonlinear elastic and nonlinear inelastic behaviour.

2.2.2 Conventional Non-linear Static (Pushover) Procedure

Lately, NSP has been considered as a sought-after method to predict seismic force and deformation demands for performance evaluation of the structures. However, this evaluation tool is restricted to low-rise and regular buildings in which the fundamental vibration mode dominates the structural behavior (Vafaee and Saffari, 2017). The conventional NSP with a triangular, as shown in Figure 2.1(a) (Shreyasvi, 2015) or a uniform load distribution shown in Figure 2.1(b) can accurately estimate the seismic demands at the lower storey of tall buildings, in which the higher mode effect is significant (Poursha and Samarin, 2015).



(a) Triangular load distribution (Shreyasvi, 2015)

(b) Uniform load distribution (Kim et al., 2004)

Figure 2.1: Static approximations in the pushover analysis

Compare to linear procedures, NSP is generally a more reliable approach to characterizing the performance of a structure (FEMA-356, 2000). However, it is not exact, and cannot accurately account for changes in dynamic response as the structure degrades in stiffness or account for higher mode effects. When the NSP is utilized on a structure that has significant higher mode response, the Linear Dynamic Procedure (LDP) is also employed to verify the adequacy of the design. The dynamic analysis is required for regular structure over 240 feet (72.0 m) in height, while for irregular structure over 65 feet (19.5 m) in height (UBC, 1997).

To be adequately interpret results obtained by NSP, the analyst should have solid background knowledge and understand some basic assumptions involved (Astriana et al., 2017). However, one should pay attention that, the NSP assumed the nonlinear responses of a structure can be related to the response of an equivalent single degree of freedom (ESDOF) system and neglects ground motion duration and cyclic effects (Li et al., 2017).

In the framework of vulnerability assessment, the most popular methodology of analysis related to Nonlinear Static Procedure (NSP), which can provide information on some important response characteristics that are unavailable from linear analyses and, at the same time, it is comparatively easier than Nonlinear Dynamic Procedure (NDP). Without considering difficulties related to collect the original documentation, carry out materials investigation, simulation of the real structural behavior and applicability of nonlinear analysis, NSP can be used to replace a full NDP, for its simple and fast application that reduce computational effort (Uva et al., 2018).

2.2.3 Other NSPs

Capacity Spectrum Method, CSM (Fajfar, 1999) assumed that the maximum lateral story drifts describe efficiently the seismic building response and maximum lateral story drifts are dominated by deformations of the fundamental mode of the originally elastic system (Peter and Badoux, 2000). The method appraised the expected seismic performance of structures by comparing, in acceleration–displacement response spectra (ADRS) format, the adequately reduced spectral coordinates of seismic capacity with the seismic demand, on behalf of taking inelastic behaviour into consideration (Barbat et al., 2008).

Eurocode 8 (EC8) (BSI, 2004) adopted N2 method developed by Fajfar and Gašperšič (1996) that provides reasonable results for planar frames. This method is not always applicable for the case of in-plane irregular structures, and is restricted to low-rise and regular buildings in which the fundamental vibration mode dominates the structural behaviour. Main disadvantage concealed under this method is the lack of accuracy in the estimation of displacement and drift of the stiff edge (Vafaee and Saffari, 2017).

To overcome this deficiency, the Extended N2 (EN2) method (Kreslin and Fajfar, 2011) was developed. This method could significantly improve N2 method, in predicting floor displacement and story drifts of the stiff side of the building (using correction factors). The extension is based on assumption that the structure remains in the elastic range while vibrating in higher modes. Results in the upper parts of building dictated by elastic modal analysis and responses from pushover analysis were adopted for the lower parts in this method (Kreslin and Fajfar, 2012)

Balendra et al. (2004) suggested Modified Pushover Analysis in his study. By using Australian code, a force and moment are applied to the master node at each level of a 16-storey asymmetrical concrete frame-wall structure. Finding had shown that failure and load displacement behaviour closely resembled to that of NDP.

Lin and Tsai (2007) in their study has proposed 2DMPA (2 degrees of freedom Modal Pushover Analysis), in which every mode shape of the structure is represented by a 2DOF (2 Degrees of Freedom) modal stick (an independent mass and spring system). This modal stick simultaneously models the modal translation and modal rotation, and can simulate the non-proportionality of the non-linear translational and non-linear torsional behaviour of an asymmetric structure because it includes the torsional moment-rotation relation in addition to the base shear-displacement relation (Birzhandi and Halabian, 2017).

Finding of Birzhandi and Halabian (2017) indicated the maximum relative difference in the median of Intensity Measure (IM) values of fragility functions for the 2DMPA-based and exact method is found to be varied between +5.0% (overestimate) and −5.2% (underestimate). They also concluded the good estimation shows that the 2DMPA-based method is a useful approach for the fast probabilistic collapse assessment of asymmetric structures.

Vafaee and Saffari (2017) studied modal shear-based pushover procedure (MSP). Responses obtained from each NSP are compared with those of rigorous non-linear response history analysis (NL-RHA, or NDP). Results demonstrated the efficiency of the proposed method in accurate prediction of the seismic demands of high-rise buildings. In predicting seismic demand of tall buildings (up to 96m with 30 storeys), the EN2, MPA and MSP had acceptable accuracy in comparison with other considered NSPs, such as Upper Bound (UBC) method, Force-based Adaptive Pushover (FAP) and Displacement-based Adaptive Pushover (DAP). They concluded that MSP is able to provide more accurate drift ratios for symmetric and asymmetric-plan buildings for both stiff and flexible edges.

Amini and Poursha (2016) utilizes some single-run conventional and enhanced pushover analyses. The enhanced lateral load distributions in the Non Adaptive Displacement-Based Pushover (NADP) procedure are calculated by algebraically adding the modal story displacements. Therefore, the sign of each modal displacement vector is preserved and the sign reversals in the lateral displacement distributions can be included. On the other hand, the signs of modal displacement vectors are suppressed in the DAP procedure due to the use of the SRSS combination rule.

2.3 Static Pushover to Fragility (SPO2FRAG) Software

SPO2FRAG (Baltzopoulos et al., 2017) is a MATLAB-coded software tool for estimating structure-specific seismic fragility curves of buildings by utilizing results of Nonlinear Static Pushover Analysis (NSP, or POA). It irritates the outcome of Incremental Dynamic Analysis (IDA, or NDP) via the Static Pushover to Incremental Dynamic Analysis (SPO2IDA) algorithm and an Equivalent Single Degree Of Freedom (ESDOF) system, thereby eschew the need of performing cumbersome dynamic analyses.

Intensity Measure (IM)-based analytical approach is used to calculate multiple limit states of fragility functions. The author concluded that, in seismic fragility estimation, SPO2FRAG that shows good agreement with analytical solution involving IDA, is able to provide expedient solution for regular, symmetric and first mode dominated frame under assumptions behind IDA.

In the past, IDA curve is generated from Nonlinear Dynamic Analysis. However, due to the inherent complexity and heavy computation load of IDA, Vamvatsikos and Cornell (2006) introduced SPO2IDA algorithm capable of reproducing 16%, 50% and 84% fractile IDA curves from relatively simple POA. Response of SDOF oscillator that has been subjected to a suite of thirty recorded ground motion records has been used, allowing simulation of complex quadrilinear backbone curve. Finally, fragility curve of $Sa\ (T_1)$ can be plotted. The software can also taking into consideration of Multi Degree of Freedom (MDOF) effect and many other uncertainties.

2.4 Nonlinear (Incremental) Dynamic Analysis

In the context of Performance Based Seismic Design (PBSD), Incremental dynamic analysis, IDA (Vamvatsikos and Cornell, 2002) radically predicted demand and capacity, in regions ranging from elasticity to global dynamic instability, by using suitably multiply-scaled ground motion records to perform a series of nonlinear dynamic analyses (Vamvatsikos and Cornell, 2005).

IDA is a parametric analysis method that estimate structural performance under seismic loads thoroughly. The analysis is done by subjecting a structural model to one (or more) ground motion record(s), each increasingly scaled to multiple levels of intensity, thus producing one (or more) curve(s) of response parameterized versus intensity level (Vamvatsikos and Cornell, 2002).

In general, typical IDA curve of the structure response, as shown in Figure 1.1is plotted in the format of damage measure (DM) against intensity measure (IM). Example for DM is peak roof drift ratio, θ_{roof} *(or* θ_{max}*)*, while for IM can be peak ground acceleration *(PGA)*, peak ground velocity *(PGV)* or the 5% damped the first mode spectral acceleration $Sa(T_1, 5\%)$.

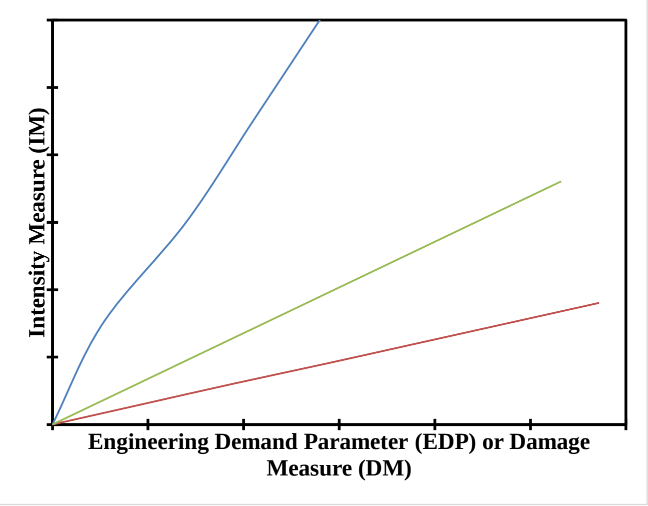


Figure 2.2: Typical IDA curve

2.5 Performance Based Seismic Engineering (PBSE)

The core of PBSE is to precisely estimate seismic demand and capacity of structures (Vamvatsikos and Cornell, 2005). It is a structural engineering paradigm that taken inherent uncertainty of ground motion, by employing probabilistic approach to evaluate structural performance in seismic area (Baltzopoulos et al., 2017). The modern approach to earthquake resistant design is an attempt to predict buildings with predictable seismic performance.

To fulfill objective of PBSE, logical elements has been advanced to discretize the performance assessment and design process. Elements of process introduced include description, definition and quantification of earthquake intensity measures, engineering demand parameters, damage measures and decision variables (Patil and Patil, 2018).

Accordingly, performance objectives (or performance levels) such as Fully Operational (FO), Operational (O), Life Safety (LS) and Near Collapse (NC) are used to define the damage state of the building following a design earthquake (Naeim et al., 2001). Several codes, such as Vision-2000 (1995), ATC-40 (1996), FEMA-273 (1997) and FEMA-356 (2000), provide performance level with corresponding drift, as shown in Table 2.1, Table 2.2 and Table 2.3.

In ATC-40 (1996), descriptions of acceptable damage at various performance levels are identical to those used in FEMA-273 (1997), and has similar concept to those proposed in Vision-2000 (1995).

In Immediate Occupancy (IO) performance level, overall damage is light and there is no permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.

Building in Life Safety (LS) performance level suffered moderate damage with some permanent drift. Some residual strength and stiffness left in all stories. Gravity-load bearing elements function. No out-of-plane failure of walls or tipping of parapets. Damage to partitions. Building may be beyond economical repair.

Severe damage and large permanent drift left a building categorized as Collapse Prevention (CP). The structure retained little residual stiffness and strength, but load bearing columns and walls function. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.

Table 2.1: Definition of performance levels from Vision-2000 (1995)

Performance level	Performance description	Story Drift (%)
Fully Operational (FO)	Continuous service, negligible damage	< 0.2
Operational (O)	Safe for occupancy, light damage, repairs for Non-essential operation	< 0.5
Life Safety (LS)	Moderate damage, life safety protection, repair may be possible but impractical	< 1.5
Near Collapse (NC)	Severe damage, collapse prevented, falling Non-structural elements	<2.5
Collapse (C)	-	>2.5

Table 2.2: Performance level and drift from ATC-40 (1996)

Interstorey Drift Limit	Performance level			
	Immediate Occupancy	Damage Control	Life Safety	Structural Stability
Maximum total drift	0.01	0.01-0.02	0.02	$0.33\frac{Vi}{Pi}$
Maximum inelastic drift	0.005	0.005-0.0015	No limit	No limit

where,

Vi is the total calculated lateral shear force in story, and

Pi is the total gravity load (i.e. dead plus likely live load) at story i.

Table 2.3: Structural Performance Levels and Damage —Vertical Elements (FEMA-273, 1997; FEMA-356, 2000)

Elements	Type	Structural Performance Levels		
		Immediate Occupancy	Life Safety	Collapse Prevention
Concrete Frames	Drift	1% transient; negligible permanent	2% transient; 1% permanent	4% transient or permanent

2.5.1 Ground Motion Intensity Measure (IM)

Spectral acceleration (Sa), spectral velocity (Sv) and the spectral displacement (Sd) describe the maximum response of single-degree-of-freedom (SDOF) system to a certain input motion as a function of the natural period and damping ratio of the SDOF. Spectrum values from the response of the SDOF system circuitously reflect strong ground motion characteristics. Spectral values depend on amplitude, frequency content, and less dependent on the earthquake duration (Pejovic and Jankovic, 2015). In this study, Sa is employed as the only IM, as SPO2FRAG software gives results of fractile IDA curves and fragility curve using Sa only.

2.5.2 Fragility Assessment

By definition, fragility curves express continuous relationships between the probabilities associated to a given asset (e.g. a class of buildings) of exceeding predefined damage states (or performance levels) for a range of earthquake ground motion intensities. The curve is useful in establishing structure's capacity of sustaining certain level of seismic load, including its behaviour in the non-linear or inelastic range.

Modern analytical method in deriving fragility function, relies on advanced numerical model of structure subjected to NDP, such as Incremental Dynamic Analysis (IDA, or NDP) by Vamvatsikos and Cornell (2002). Heavy computational burden involved to model non-linear behaviour of structure, is however time consuming, has deterred engineering industry from employing NDP but making recourse to NSP instead.

NSP has been gaining recognition cumulatively, as an effective tools in seismic design and vulnerability assessment, that provide information on structure's strength and ductility, without losing the simplicity of static analysis (Bocciarelli and Barbieri, 2017). Static Pushover to Fragility (SPO2FRAG) software is a good example of fragility assessment that make use of NSP as cornerstone in deriving fragility function.

2.5.3 Fragility Curve

Type of material, plan and vertical configuration, structural system, structural damping often contributes to the natural frequency of building. Coupling with inherent uncertainties in ground motion such as duration of excitation, record-to-record variability and distance from source, the response of structure is affected, thereby give rise to structure-specific seismic fragility curves.

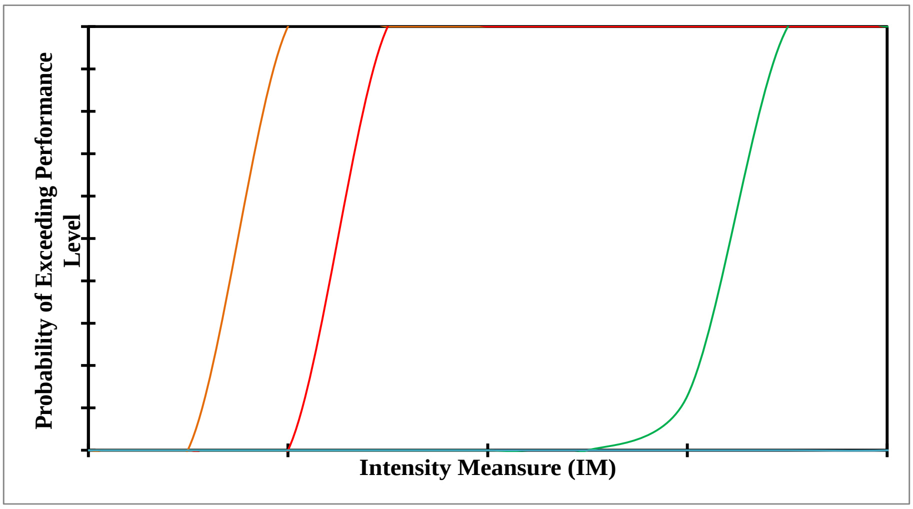


Figure 2.3: Typical fragility curve

In the development analytical fragility curve, various approaches are available to estimate the seismic demand. They are Elastic Response Spectrum Analysis (RSA), Nonlinear Static (Pushover) Analysis (POA), Nonlinear Response History Analysis (NRHA), and Incremental Dynamic Analysis (IDA).

POA is gaining its popularity. POA can generate fragility curve as per HAZUS (HAZUS, 1997) manual. These curves take into account the variability and uncertainty associated with capacity curve properties, damage states and ground shaking, and has been used by Vazurkar and Chaudhari (2016) in his study on bridge.

Capacity Spectrum Method (CSM) proposed by Freeman (1998) has been widely used in generating fragility curve. CSM proposed in the past, such as the ATC-40 (1996) approach, the coefficient method in FEMA-356 (2000) and the N2 method (Fajfar, 1999; Fajfar, 2000), are code-based procedure that would normally require a standardized design spectrum and the use of a corner period to identify acceleration- and displacement-sensitive segments of the demand spectrum.

Rossetto et al. (2016) proposed Fragility through Capacity Spectrum (FRACAS) assessment, which is originally proposed by Rossetto and Elnashai (2005). It allows idealization of capacity curve (through fitting) and model, while directly uses acceleration time histories from which both elastic and inelastic spectra are computed and used to find the performance point. This ability has provided an advantage to effectively capture the variability of earthquake ground motions while deriving fragility curves from the analysis of a specific structure or a population of frames.

Papadrakakis et al. (2017) carried out Finite Element Modelling (FEM) to simulate dam structure and adopted Enhanced Monte Carlo simulation to generate fragility curve. The method is claimed to be particularly suitable in estimating small failure probabilities accurately without need for more simulation runs, and have increased efficiency by applying an extrapolation technique.

It should be noted that, in this study, relatively simple and user friendly SPO2FRAG software was used to develop the fragility curves and verified by IDA.

Baltzopoulos et al. (2017) presented general definition of fragility function from Jalayer and Cornell (2003) and a simplified version has been exercised by Ibrahim and El-Shami (2011). Typical fragility curve is shown in Figure 2.3. By referring to the three previous studies, the conditional probability of a structure, P to reach or exceed a specific damage state, D, given the Sa, expressed in Equation (2.1) is used in this study.

$$P\left[D / Sa(T_1)\right] = \Phi\left[\frac{\ln\left[Sa(T_1)\right] - \mu}{\sigma}\right] \tag{2.1}$$

where,

Φ = standard normal cumulative distribution function

μ = mean of the natural logarithm of spectral acceleration, $Sa\ (T_1)$

σ = standard deviation (or dispersion) of the natural logarithm of spectral acceleration, $Sa\ (T_1)$

2.5.4 Ground Motion Intensity Measure (IM)

Spectral acceleration (Sa), spectral velocity (Sv) and the spectral displacement (Sd) describe the maximum response of single-degree-of-freedom (SDOF) system to a certain input motion as a function of the natural period and damping ratio of the SDOF. Spectrum values from the response of the SDOF system circuitously reflect strong ground motion characteristics. Spectral values depend on amplitude, frequency content, and less dependent on the earthquake duration.

Notably, in this study, fundamental mode spectral acceleration, $Sa\ (T_1)$ is employed as the only IM, but not Peak Ground Acceleration *(PGA)*, due to the limitation of SPO2FRAG software that could give results of fractile IDA curves and fragility curves expressed in $Sa\ (T_1)$ only.

2.6 Building's Elevation Irregularity (Soft and weak storey)

Massive construction of irregular buildings significantly contribute to the inventory of modern urban infrastructure. The irregularity lead to building structures with irregular assignment of their mass, stiffness and strength along the height of building. In an earthquake resistant system, sudden change in strength or stiffness of the structure is undesirable.

Low strength for the lateral load system elements such as weak stories is one of most categories of seismic deficiencies (El-Betar, 2016). Discontinuity in the rigidity of structure, at the soft story level, can be attributed to lack of infill walls or variation in floor height. It is the discontinuity that render structural failure of multi storey buildings when subjecting to earthquake load (Ghalimath and Hatti, 2015). Gautham and Gopi Krishna (2017) in their study concluded collapse probability is higher for a soft storey building which is an indication of the lack of lateral stiffness of the ground storey which results in a soft storey irregularity.

Normative documents such as UBC (1997) and ASCE (2010), defined both soft and weak storey cases. Soft storey is one in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above. Weak storey is one in which the story strength is less than 80% of that in the storey above. The storey (lateral) strength is the total strength of all seismic-resisting elements sharing the story shear for the direction under consideration.

Additional information of elevation irregularity has been provided by ASCE (2010). Extreme soft storey irregularity defined as a storey in which the lateral stiffness is less than 60% of that in the storey above or less than 70% of the average stiffness of the three storeys above. Discontinuity in lateral strength of extreme weak storey irregularity is defined to exist where the storey lateral strength is less than 65% of that in the storey above.

However, Eurocode 8 (BSI, 2004) does not thoroughly illuminate both soft and weak storey. Instead, a generic definition was given as in Clause 4.2.3.3 Criteria for regularity in elevation, that, both the lateral stiffness and the mass of the individual storeys shall remain constant or reduce gradually, without abrupt changes, from the base to the top of a particular building.

2.7 Summary

This chapter expanded discussion on details of previous study, including Nonlinear Static (Pushover) Analysis (POA), SPO2FRAG software, Nonlinear (Incremental) Dynamic Analysis (IDA), IDA curve, Performance Based Seismic Engineering (PBSE), fragility curves, ground motion intensity measure (IM) and building’s elevation irregularity.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

This chapter described the methodology employed in this study with the aid of flow chart and step by step explanation. 5- and 11-storeys of regular frame of regular and soft storey cases that constituted to four models are designed according to Eurocode 2 (CEN, 1992) and Eurocode 8 (BSI, 2004). EC 2 provides the design guideline for Moment Resisting Concrete Frame (MRCF) while the EC 8 provides the general requirements for earthquake-resistance design. The four models in this research is analysed using SAP2000 software (CSI, 2010).

Nonlinear Static (Pushover) Analysis, POA and Nonlinear (Incremental) Dynamic Analysis, IDA suggested in the document of EC8 are selected as method of analysis. Fractile IDA curves from SPO2FRAG and IDA curve from IDA are presented. Finally, fragility curves from SPO2FRAG and IDA are generated. Performance Based Seismic Design (PBSD) proposed by Vision-2000 (1995) indicating Life Safety (LS) and Near Collapse (NC), is used in this study. The sequence of this study is summarized in a flowchart, as shown in Figure 3.1.