SEISMIC VULNERABILITY ASSESSMENT OF AN RC-FRAME BUILDING EXPOSED TO DIFFERENT DIRECTION COMPONENTS OF GROUND MOTIONS USING NONLINEAR DYNAMIC ANALYSIS AND FRAGILITY FUNCTION

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UNIVERSITI SAINS MALAYSIA
2022

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By

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This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)

(CIVIL ENGINEERING)

School of Civil Engineering,
Universiti Sains Malaysia

JULY 2022

Appendix A8

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING ACADEMIC SESSION 2021/2022

FINAL YEAR PROJECT EAA492/6 DISSERTATION ENDORSEMENT FORM

Title **SEISMIC VULNERABILITY ASSESSMENT OF AN RC-FRAME BUILDING EXPOSED TO DIFFERENT DIRECTION COMPONENTS OF GROUND MOTIONS USING NONLINEAR DYNAMIC ANALYSIS AND FRAGILITY FUNCTION**

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Date: 11th AUGUST 2022

ACKNOWLEDGEMENT

The completion of this study will not be completed and succeeded to the utmost satisfaction without the assistance of others. Therefore, I would like to use this precious opportunity to express my heartfelt gratitude to all of the people and organizations who contributed to this study.

First and foremost, I would like to express my utmost gratitude and appreciation to my supervisor, Assoc. Prof. Ir. Dr. Fadzli Mohamed Nazri, for guiding me step by step through the accomplishment of this study. Furthermore, Dr. Fadzli is generous in sharing his knowledge with his students and is always available to back me up when I run into difficulties throughout this study. I would not have completed my study successfully on time without Dr. Fadzli's guidance and help.

Besides that, I want to express a thousand thanks to Dr. Moustafa Moufid Kassem and Mr Ahmad for assisting me through the analyses step by step. They were eager to sacrifice valuable time to educate me how to use the software and to help me with the issues I encountered during the software. Despite the fact that Dr. Moustafa has a very packed research schedule, he is willing to make time for me to review the results of my analyses

In addition, I would like to show my thankfulness to the lecturers from the School of Civil Engineering, University Sains Malaysia (USM) for providing us with a lecture on the Final Year Project (FYP). I would not have accomplished my FYP to the expectation and satisfaction without the lectures delivered by the lecturers.

Last but not least, I would like to express my thanks to my dearest family, loved ones and roommates for their moral support throughout my study. This entire study will be very difficult without their support on my back.

ABSTRAK

Bangunan rangka konkrit bertetulang sangat terdedah kepada kerosakan akibat rangsangan seismik terutamanya pengaruh komponen berlainan arah gempa bumi. Dalam kajian ini, penilaian kelemahan seismik bagi bangunan rangka konkrit bertetulang terpilih yang terletak di Kota Padang, Indonesia yang terdedah kepada komponen pergerakan tanah berlainan arah telah dijalankan. Matlamat kajian ini adalah untuk menilai prestasi seismik bangunan menggunakan fungsi kerentanan sambil mempertimbangkan sudut berlainan arah gempa bumi yang ditentukan masing-masing dalam arah X, Arah Membujur (E-W) dan Y, Arah Melintang (N-S), bermula dari 0° hingga Sudut 60° dengan kenaikan sudut sebanyak 15°. Dengan menggunakan perisian ETABS 19, analisis dinamik progresif (IDA) dan fungsi kerapuhan telah dilakukan untuk menilai prestasi seismik bangunan yang tertakluk kepada rangsangan tiga set gerakan tanah dengan julat magnitud dari 6 hingga 7. Lengkung IDA dibina dan kemudian digunakan untuk menjana lengkung kerapuhan. Selaras dengan FEMA 356, lengkung IDA dibandingkan berdasarkan tiga tahap prestasi fasa operasi (IO), keselamatan hayat (LS) and pencegahan runtuh (CP). Keputusan daripada lengkung IDA mendedahkan bahawa dalam arah X, sudut kejadian yang semakin meningkat memerlukan PGA yang lebih rendah untuk menghasilkan kerosakan struktur. Dalam arah Y, sudut 60˚ memberikan nilai PGA terendah pada tahap prestasi LS dan CP, manakala sudut 45 memberikan nilai PGA terendah pada tahap IO. Lengkung kerapuhan menunjukkan sudut 60˚ menyebabkan kebarangkalian kerosakan tertinggi kepada bangunan dalam arah X dan Y, masing-masing. Akibatnya, ini mendedahkan bahawa semakin tinggi sudut tuju daripada paksi utama bangunan, semakin tinggi kerosakan struktur yang disebabkan. Dalam kajian ini, rangsangan gempa bumi yang datang dari sudut 60˚ dalam arah X dan Y, masing-masing adalah lebih merosakkan dan berbahaya.

ABSTRACT

RC frame buildings are highly vulnerable to damage from seismic excitation, especially the influence of different earthquake direction components. In this study, the seismic vulnerability assessment of the selected RC-frame building located in Padang City, Indonesia that is exposed to different direction components of ground motions was carried out. This study aims to evaluate the seismic performance of the building using vulnerability functions while considering earthquake different direction angles that are specified respectively in both X, Longitudinal Direction (E-W) and Y, Transverse Direction (N-S), starting from 0° to 60° angle with 15° angle increments. By using ETABS 19 software, Incremental Dynamic Analysis (IDA) and fragility function are performed to evaluate the seismic performance of the building subjected to three sets of ground motion excitations with magnitudes ranging from 6 to 7. The IDA curves are constructed and then applied to generate the fragility curves. With accordance with FEMA 356, the IDA curves are compared based on three performance levels: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The results from the IDA curves reveals that in the X-direction, an increasing incidence angle requires a lower PGA to produce structural damage. In the Y-direction, 60˚ angle provides the lowest PGA value at the LS and CP performance levels, while an angle of 45 provides the lowest PGA value at the IO level. Fragility curves show the 60˚ angle caused highest damage probability to the building in both X and Y-direction, respectively. As a result, this reveals that the higher the angle of incidence from building main axes, the higher the structural damage caused. In this case, the earthquake excitation coming from 60˚ angle in X and Y-direction, respectively is more damaging and dangerous.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
CP	Collapse Prevention
DM	Damage Measure
FE	Finite Element
EDP	Engineering Demand Parameter
FEMA	Federal Emergency Management Agency
IDA	Incremental Dynamic Analysis
IM	Intensity Measure
IO	Immediate Occupancy
ISDR	Inter-Storey Drift Ratio
LS	Life Safety
MDOF	Multiple Degree of Freedom
NL-THA	Nonlinear Time History Analysis
PBEE	Performance-Based Earthquake Engineering
PGA	Peak Ground Acceleration
SA	Spectral Acceleration
SDOF	Single Degree of Freedom
SHM	Structural Health Monitoring

CHAPTER 1

INTRODUCTION

1.1 Background of Study

On 30th September 2009, a major earthquake with 7.6 Magnitude struck Padang City, Indonesia. The earthquake caused severe damage to around 4000 buildings and 140,000 houses, causing loss of livelihoods of 250,000 families. The majority of the buildings damaged or collapsed in Padang city are Reinforced Concrete (RC) frame structures, with some being unreinforced masonry and a few steels building structures. The significant damage to these buildings raises questions about the effectiveness of design and construction practices, as well as the building code enforcement. In addition, there is a concern to address the seismic performance of RC frame buildings that were designed according to gravity loads only or designed according to current codes (El-Betar, 2015).

Figure 1.1: Damaged buildings in Padang City, Indonesia
(EERI, 2009)

Furthermore, the seismic loadings are different from other loads because of the high deformations and stresses conducted under earthquake effect. Seismic performance is described by designating the maximum allowable damage state for an identified earthquake ground motion. Codes require that structures possess adequate ductility to allow them to dissipate most of energy from the ground motions through inelastic deformations. This concept prevents the buildings from collapse even if it is seriously damaged because it is generally uneconomical to design most buildings to respond elastically to moderate-to-strong earthquakes.

In this study, the seismic performance of RC frame building is selected as case study in Padang City, Indonesia and is assessed according to fragility and Incremental Dynamic Analysis (IDA) capacity curves. These are important aspects of seismic investigation to determine the damage probability under different direction of ground motion components. For a given structural system, a seismic vulnerability function serves to express the relationship between the intensity of an earthquake excitation and a quantitative measure of its probable consequences on the performance of that system.

In order to precisely assess the seismic demands of the buildings, the nonlinear analysis is the method that is typically required to be used (Kassem *et al*., 2020). Its extended analytical assessment which is IDA have the capacity to develop wide diversity of non-linear material behaviour, irregularity in structures with geometric non-linearity and higher mode effects in tall buildings. Another fragility curves are analytically used to evaluate the risk of the earthquake effect on the building structure and the prediction of damage possibilities that may influence the building. Additionally, this study focuses on the directionality of seismic excitations to show that the response of structures is influenced by the different direction component of earthquakes. According to Magliulo *et al.* (2014), to better explore the seismic performance of building structures which exhibits an unusual dynamic behaviour, the influence of earthquake incidence angle i.e., different direction component is demanded. Hence, by considering the influence of different direction component of earthquakes, the study of seismic performance and capability of the selected RC frame building need to be understood.

Figure 1.2: Before and after pictures of 4-story school building in Padang City, Indonesia (EERI, 2009)

1.2 Problem Statement

Seismic performance of RC frame buildings was designed with disregard to the different direction of the earthquake excitations. Typically, most of the buildings are designed by just considering one-way analysis for each of main axes independently. However, when considering the nature of seismic events, the dynamic behaviour of the building structures is actually affected by interaction of different earthquake components. Specifically, the RC frame buildings are highly vulnerable to damage from seismic excitation especially the influence of different earthquake directions component.

Other study discusses an evaluation of the seismic performance of an existing different storey RC building but only considering the input in X and Y directions for its pushover analysis, although the input ground motion was generated from the recorded ground motion of 2009 Padang earthquake (Tanjung *et al.*, 2019). Moreover, according to Alam *et al.* (2020), due to the uncertain distribution of the internal forces under different direction seismic excitations, the assessment of critical seismic response of a building structure is complicated to estimate. The uncertainty associated with the final design direction as different seismic directions result in different seismic responses. When a comparison of the estimated seismic collapse capacity is evaluated, the results from fragility analysis indicate that the failure probabilities of buildings under the different direction excitation are significantly higher as compared to those obtained under the unidirectional excitation. (Gwalani *et al.,* 2021).

As a result, the influence of different direction earthquake components that contribute to the seismic behaviour of an RC frame building is considered in this study, among other things. It is necessary to employ nonlinear dynamic analysis in order to estimate the performance of a structure during seismic activities, and this is done by using IDA capacity curves. The findings of this study will be useful for the critical assessment of directionality influence on building structures before to making any decisions during the structural design phase to ensure that the buildings will be able to withstand future earthquake motion.

1.3 Objectives

The main objectives of this study are:

1. To estimate the seismic performance of the selected RC frame building using the IDA capacity curves according to FEMA 356 Performance Limit States.

2. To develop the fragility curves for the selected RC-frame building using different direction components of strong ground motion movement.

1.4 Scope of Work

A study of vulnerability assessment of the selected RC-frame building that is subjected to distinct different direction component of ground motions. The building model is adopted based on real building at site location. After that, the materials properties such as shear modulus, Poisson's ratio, modulus of elasticity, and steel grade are defined according to the ASTM A 992/A 992M.

Before the seismic analysis, three sets of ground motions for each model were used in this study, and the ground motions were chosen based on the magnitude range from 6 to 7. Then, the set of extracted ground motion records with different PGAs are applied in order to assure all the possible scenarios by using ETABS software.

Every ground motion data is linearly scaled to have various PGAs with a 0.05g increment until 1.5g or that corresponds to structural collapse dynamic analysis. The nonlinear dynamic time history will carry out until the 2.5% maximum ISDR according to the CP structural performance level (S-5) that stated in the FEMA 356 (FEMA, 2000).

After that, Incremental Dynamic Analysis (IDA) is performed in terms of maximum ISDR and PGA accompanied with three performance limit states which are Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). The vulnerability of the building is then determined using a fragility curve based on the three performance limit states.

1.5 Layout of Dissertation

This dissertation comprises of five chapters with each chapter describes different component of the conducted study. Introduction, literature review, methodology, results and discussion, as well as conclusion will make up the chapters of this study. Chapter 1 of this dissertation provides the background of study, problem statement, objectives, scope of work and dissertation of work.

Chapter 2 is the literature review which discusses the related review or research articles done by previous researches such as irregular RC frame building, different direction component of earthquake excitation, Intensity Measure (IM), damage measure, nonlinear dynamic analysis, fragility function and last but not least related studies of buildings vulnerability assessment in Padang City.

Chapter 3 is relating to the methodology of this study, which describes the overall flow method, modelling and design of the selected RC frame structure as well as software analysis procedures by using ETABS software. Then followed with, selection of ground motion records, intensity measure, and damage measure to develop Incremental Dynamic Analysis (IDA) curve and fragility curve.

Chapter 4 is presenting the results and discussion of this study which will cover the results obtained from the analyses. The results obtained will be thoroughly discussed based on the vulnerability functions.

Chapter 5 is the conclusion which finalizes the overall achievement of the results based on the objectives. Reviewing the original question of this study objective while considering the limitations. To finish, provide comprehensive recommendations according to the outcomes and its contributions.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this Chapter 2, past researches work that are related to this thesis topic is discussed in order to merge the conclusions and explain the overall understanding, thus laying a foundation for both the research question and primary research. An overview of the repeated earthquake sequences and structures damaged located in the case study area, Padang City, Indonesia will be focused. Furthermore, the various analyses that will be used to evaluate the vulnerability assessment of the RC frame structures under multi directional components of earthquake will be considered in this chapter.

2.2 Irregular RC-Frame Building

Shaikh and Ansari (2018) stated various types of irregularities can be divided mainly on two groups, plan irregularity and vertical irregularity. In their study, they focused on vertical irregularity by performing analysis on two G+10 multi-storey RC frame buildings having different mass irregularity but with same dimensions to study their behavior when subjected to lateral loadings. The different in irregularity is the frame 2 having heavier loads on its 3rd and 7th storey i.e., effective mass is more than 150% than the adjacent storey. The analysis shows storey displacement, drift ratio and story shear in frame 2 is higher than frame 1, hence the effect of mass irregularity on RC frame is susceptible to damage in earthquake events.

Sayyed and Rawat (2017) studied and compared G+10 multi-storey regular buildings with vertical irregular buildings in terms of stiffness irregularity and setback irregularity. Stiffness irregularity is produced by increasing the height of ground storey, fourth storey and seventh storey from 3.0m to 4.5m respectively for each building, while setback irregularity is produced by having setback at eight storey, fifth storey and second storey along X-direction respectively for each building. The response of storey displacement and storey drift of the buildings were evaluated. The storey displacement for irregular building experienced more displacement as compared to regular building and storey drift is maximum for building with stiffness irregularity at fourth storey, while sudden extreme change in storey drift for buildings with setback irregularity.

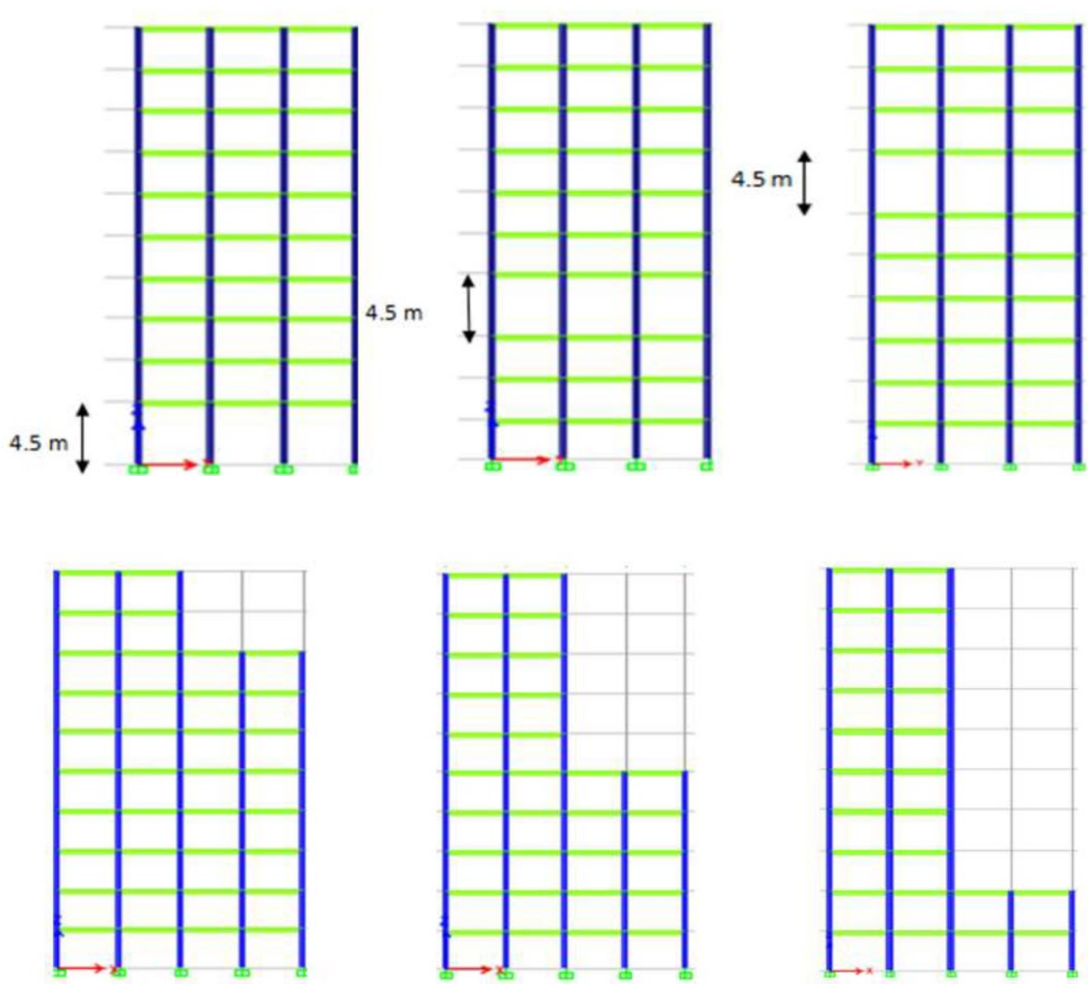

Figure 2.1: Vertical Irregularity of studied building models (Sayyed and Rawat, 2017)

Shelke and Ansari (2017) carried out Response Spectrum Analysis (RSA) on vertically irregular buildings namely mass irregularity, stiffness irregularity and vertical geometric (setback) irregularity and compared with regular building. The RSA considers the effects on the structure related to the maximum response of simple, single degree of freedom oscillators of varying earthquake shaking periods. They considered the outcome from the analysis on the basis of static and dynamic storey shear, storey displacement, storey drift and storey shear force, in X and Y direction respectively.

Joshy and Santhi (2018) performed seismic analysis on regular and plan irregular framed structure of G+9 multi-storey buildings. The irregular buildings consisting of T-shape, Z-shape, L-shape and C shape. For the evaluation of seismic response, certain critical locations in the buildings such as re-entrant and corner points are considered. From the findings, L-shape model has highest storey displacement and storey drift compared to other buildings. As the irregularity of the structure increases, storey displacement will be increased as well and the storey that has lower stiffness will have maximum displacement. They concluded that if the length of the building is longer in X-direction, it will cause the seismic response to be vulnerable in Y-direction hence, maximum column shear force and column moment can be seen at re-entrant corners of irregular buildings where there is sudden change in the stiffness along Y-direction. They concluded that if the length of the building is longer in X-direction, it will cause the seismic response to be susceptible in Y-direction hence, maximum column shear force and column moment can be seen at re-entrant corners of irregular buildings where there is sudden change in the stiffness along Y-direction.

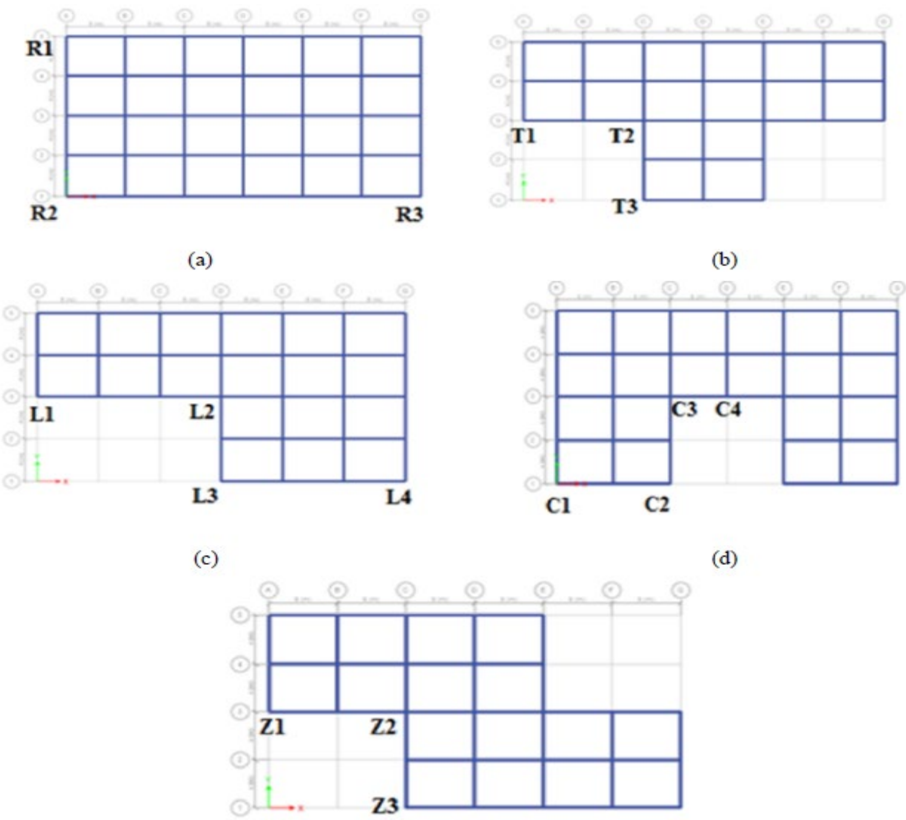

Figure 2.2: Plan Irregularity of studied building models (Joshy and Santhi, 2018)

Mouhine and Hilali (2020) studied the influence of setback location on the seismic performance of 68 RC frame buildings models with setback values vary from 0.1L to 0.5L, located at various levels. Non-linear static (pushover) analyses were conducted and analyzed using a finite element (FE) calculation code. A mathematical formula is proposed from the regression analysis of the results to express the performance point and to quantify the effect level of setback locations, along with the height of the building. The response obtained concluded that the setbacks at upper storeys of the building caused damage compared to setbacks at bottom storeys.

Babu and Jose (2018) focused on the seismic assessment of G+10 and G+20 of irregular RC frame buildings having asymmetric plan such as T-shaped, L-shaped, C-shaped and +-shaped, while also considering fixed based and base isolated for the buildings. Triple Friction Pendulum Bearing (TFPB) was chosen as base isolator which functions to minimize the force by isolating the superstructure from the substructure. B. C-Shaped building gives a lowest base shear, whereas T-shape building has longest damage exposure to earthquake excitation compared to the other models. The TFPB reduces base shear, acceleration and increases the mode period. They concluded that plan irregular building gives outstanding performance at higher seismic zone area by using the base isolators technique.

Agrawal and Kalurkar (2021) presented a comparative study of a regular G+9 storey RC frame with other 9 irregular frames having different types of irregularities i.e., 1st and 2nd soft storey (frame 2), removal of 4th and 5th storeys column (frame 3), heavy loading on 3rd and 6th storeys (frame 4), heavy loading on top storey (frame 5), removal of intermediate columns on ground storey (frame 6), no corner columns and edge columns on ground storey(frame 7), no floor beams on 4th and 5th storeys (frame 8), setback of height in three bays (frame 9) and setback of height in three bays with removal of intermediate columns on ground storey (frame 10). Parameters evaluated in this study are maximum shear force, axial force, bending moment in members and storey displacement in X-direction. Highest storey displacement is recorded for frame no. 7 at top storey, making it the most fragile types of irregular frames, while base frame i.e., regular frame structure can be considered as safe structure since it recorded least storey displacement at the top storey.

2.3 Different Direction Components of Ground Motion

Vargas et al. (2021) developed a simplified method for estimating seismic risk that considers the azimuthal position of the structures with respect to the epicentre. The structure's fragility is analyzed by rotating ground motion records to various incidence angles in order to create orientation-dependent fragility functions. The variability introduced by the incidence angle on the fragility functions were quantified. Hence, rather than using random different incidence angle, one may consider adopting consistent incident angle for any given event with the relative location of the site and the rupture. The incidence angle is assumed as uncertain in the model of process due to limited data and knowledge.

Jadhav and Jaiswal (2017) described the needs to determine the seismic response of a structure for all possible orientations of the principal axes in case the epicentre's location is not available, then followed by considering the largest or critical response for the design of the structure. In their analysis, a set of values from 0 to 90 degrees with an increment of 10 degrees is used for angle of earthquake excitation.

Skoulidou and Romao (2017) focused on determining the critical angle of earthquake incidence based on the building's structural characteristics. To define the critical angle for single-story buildings and a certain class of multi-story buildings subjected to constant lateral stresses, an analytical equation was created and with the structures assumed to exhibit linear elastic behaviour.

Magliulo et al. (2014) explored the influence of earthquake direction on the seismic response of an irregular L-plan shape building, with twelve different earthquake directions considered. Three set of accelerograms from past earthquake events are selected to match with EC8 target elastic spectrum for design ground acceleration of 0.35g, 0.25g and 0.15g respectively. The earthquake directions are rotated from 0˚ to 330˚ with 30˚ increments for each analysis with respect to both orthogonal components. Response parameters of X-direction displacement, Y-direction displacement and top vectorial displacement (Square Root of the Sum of both orthogonal displacements) were evaluated. From the findings, variation of displacements is recorded larger than 35% with earthquake incidence angle taken into account.

Fontara et al. (2015) analysed the influence of seismic incident angle on the damage index of an asymmetric single storey RC frame building subjected to the recorded, the uncorrelated and completely correlated pairs of accelerograms (orientation of ground-motion reference axes). Seismic incidence angles are varied from 0˚ to 350˚, with 10˚ increments and there are four distinct seismic intensity levels included in the nonlinear time history analysis. The results prove with different pairs of accelerograms, the overall damage index produced by each seismic incident angle shows diverse pattern and peak. The use of the recorded pairs of accelerograms as seismic input for seismic incident angles 0º and 90º which shows principal axes of the structures does not always lead to the maximum damage and critical case of study.

According to Elhifnawy et al (2017), the seismic response of three RC buildings of six, ten, and twenty storeys was examined in the context of a multi-component earthquake that occurred close to the source of each structure. Four different types of earthquake analyses are taken into account for each one, including one lateral earthquake component (X-case), two lateral earthquake components (XY-case), a lateral earthquake component along with a vertical component (XZ-case), and two lateral earthquake components along with a vertical component. (XYZ-case). An evaluation of the multicomponent influence of earthquake records on the prototype structures is performed by comparing the building reactions to the four different earthquake loading instances (X, XY, XZ and XYZ). While earthquakes have a major impact on the building lateral-deformation response, their multi-component effect has little influence on the axial forces and strain ductility factors of the building columns.

On a collection of reinforced concrete structural archetypes with diverse typologies and plan regularity, Bugueno et al. (2022) used nonlinear time history analysis to analyse the seismic reaction while taking earthquake different direction angle into account. In order to determine the angle of incidence that results in the greatest displacement demands through inter-storey drift and roof displacement, an analysis is performed using previous earthquake motion observed in Chile. From 0° to 337.5°, each incidence angle is rotated by a factor of 22.5. Polar graphs were used to display the findings of both inter-storey drift and roof displacement. The angle of incidence for each typology appears to follow a consistent pattern regardless of the number of storeys in the structure being studied. Displacement and drift maxima were not all reached at the same time in our investigation, but rather at different intervals. Analysis shows that there is no clear correlation between incidence angle and roof displacement and inter-storey drift, based on the results.

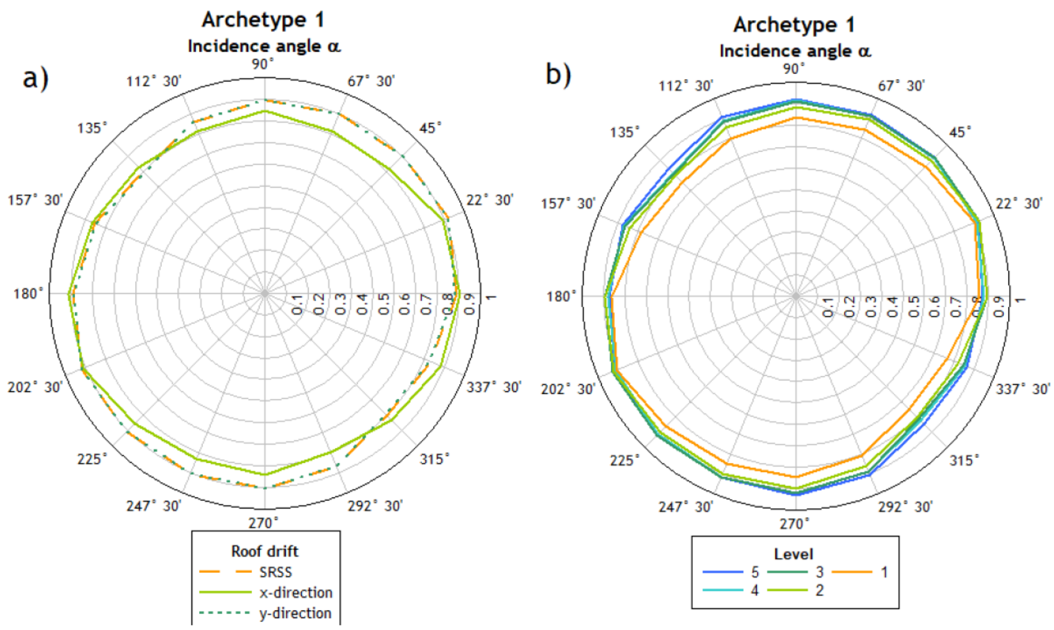

Figure 2.3: Mean Inter-storey drift and Mean roof displacement for Archetype with respect to incidence angle (Bugueno et al., 2022)

2.4 Vulnerability Assessment

RC frame buildings are highly vulnerable to damage from seismic excitation especially the influence of different earthquake directions component. To quantify the level of damages to structural elements or the whole structural system, a multi-analysis approach to seismic vulnerability assessment of RC frame buildings subjected to seismic excitation is needed. Therefore, vulnerability assessments of RC frame buildings should be discussed and reflect on the engineering demand parameters (EDP) of earthquakes excitation such as intensity measure (IM), Damage Measure (DM), nonlinear dynamic analysis and lastly fragility curve.

2.4.1 Intensity Measure

The event of ground motion potential due to earthquake excitation can be characterized by a parameter namely ground motion intensity measure (IM). Adam et al. (2017) defined the IM as a parameter associated with ground motion records, that quantifies the severity of a seismic event and characterizes the uncertainty related to earthquake excitation. Various approaches are used in defining the intensity of an earthquake record, currently the parameters that are commonly used as IMs are the peak ground acceleration (PGA), peak ground velocity (PGV) and the 5% damped spectral acceleration (SA) at first mode of vibration, $S_a(T_1)$, particularly, $S_a(T_1)$ is used in most of seismic design guidelines and for earthquake hazard evaluations especially for low rise structures.

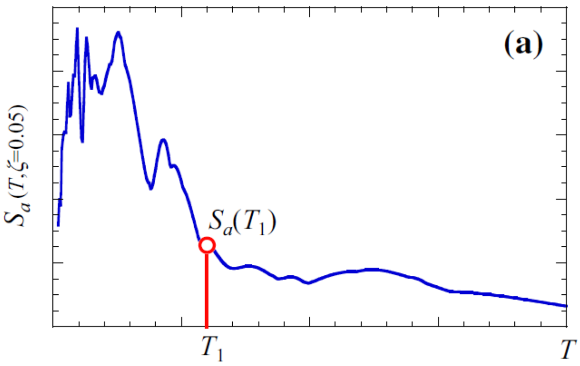

Figure 2.4: Ground motion record of spectral acceleration at the fundamental mode, T_1

For elastic single-degree-of-freedom systems (SDOF) and elastic multi-degree-of-freedom (MDOF) structures, the spectral acceleration at the first mode of vibration (Sa(T1)) is an appropriate intensity measure because of its high efficiency in forecasting seismic response. It isn't suitable for structures dominated by higher mode effects, such as tall buildings under near-source ground motion data, thus the usage of IM in this scenario is enhanced by superimposing the spectral values of the first n higher modes on top of each other.

Bojorquez and Iervolino proposed the I_{Np} spectral shape parameter in 2011 that takes into consideration the structure's nonlinear behaviour by adding numerous points on a response spectrum. Because nonlinear behaviour has a significant impact on structural response prediction, they proposed using Sa(T1) and Np to derive a new scalar ground motion intensity measure:

$$\mathrm{IN_p} = Sa(T_1) \cdot N_p\hat{}\alpha \quad (2.1)$$

where I_{Np} is a scalar ground motion intensity measure, $Sa(T_1)$ is the commonly known intensity measure, *Np* is the spectral shape parameter, and the α value must be calibrated according to the structure and the selected seismic demand parameter. Further researches have demonstrated the great potential of the I_{NP} intensity measure.

The relationships between engineering demand parameters (EDP) and the nonlinear performance of the case study structures were identified by Minas and Galasso (2019). A total of six different ground motion IMs, including standard PGA, PGV, and PGD peak responses, spectral acceleration at the first period, Sa(T1), for 5% damping and advanced scalar ground motion IMs that account for spectral shape information, are investigated. The efficiency, sufficiency-relative sufficiency, and hazard computability are the three primary criteria used to assess the suitability of any candidate IM. The selection of these criteria is critical to the development of analytical vulnerability curves that can be used to quantify the seismic losses of a building class.

When it came to depicting ground motion uncertainty, Jalayer et al. (2012) looked at the adequacy of the adopted IMs they used. We will use Sa(T1) as a baseline for comparing other IMs' appropriateness for a case study building's maximum inter-storey drift ratio by comparing their relative sufficiency to that of Sa(T1). It is important to select an IM that can take into account performance requirements with the minimum dispersion and provide considerable information about other ground-motion aspects when developing fragility functions for buildings. When the building's dynamic response is not collapsed, the reference IM, Sa(T1), performs well in evaluating the maximum inter-storey drift ratio.

204 near-fault pulse-type data were used by Cao and Ronagh (2014) to perform time history and damage evaluations on a 3-storey RC frame simulating low-rise reinforced concrete structures. A damage index and the maximum inter-story drift were measured and compared in this study to determine and evaluate many accessible IMs that have high associations with the structural damage measured by a damage index. Velocity Spectrum Intensity, Housner Intensity, Spectral Acceleration, and Spectral Displacement were all shown to have the best association with Velocity Spectrum Intensity. Structural

damage did not correlate well with the commonly used metric of PGA. Despite the fact that this study did not contain an energy-based parameter, it provided important insights into the association of damage in low-rise structures with any intensity measure.

2.4.2 Damage Measure

The measure on the damage, such as cracks, displacements, and drifts, is examined in order to look for significant damages that will lead to the collapse of the studied structure while the performance of the structure is being evaluated against the seismic excitation.

Strukar et al. (2019) conducted efficient damage measure assessment for selected earthquake records based on spectral matching of reinforced concrete bare frames. By referring to Ghobarah (2004) that stated the value of Inter-storey Drift Ratio (IDR) defined the damage measure for every structural performance level and the description of damage condition is required to comprehend the physical state of the structure for the end user. IDR as the main damage measure were presented in order to make comparison with defined performance levels of reinforced concrete bare frames. In order to facilitate comparison with predetermined performance levels of reinforced concrete bare frames, the IDR was used as the primary damage measure were presented. The damage levels are set by four maximum IDR values, and the mean IDRs for each target spectrum were mutually compared. The table below compares IDR based on structural performance levels and equivalent structure type according to (Ghobarah 2004), (FEMA 356, 2000), and (SEAOC 1995).

	Structural performance level	RC frames IDR (%)		
		(Ghobarah 2004)	(FEMA 356 2000)	(SEAOC 1995)
	Slight damage	IDR<0.20	IDR<1.0	IDR<0.50
	Moderate damage	0.20<IDR <1.0	1.0<IDR <2.0	0.50<IDR <1.50
	Extensive damage	1.0<IDR <3.0	2.0<IDR <4.0	1.50< IDR <2.50
	Near collapse	IDR>3.0	IDR>4.0	IDR>2.50

Figure 2.5: Comparison of IDR (%) according to structural performance levels and structure type (Strukar et al., 2019)

Skolnik and Wallace (2019) described IDR as the relative translational displacement between two successive floors divided by the story height, and it is a significant engineering response quantity and indication of structural performance. Several parts of structural engineering might benefit greatly from reliable IDR measurements, particularly for structures subjected to inelastic deformations. Limits on IDR are utilized in design to maintain structural performance at acceptable deformation levels by minimizing p-delta effects and non-structural component damage. Accurate IDR measurements may be utilized to improve design performance metrics such as amplification factors and drift limitations, and they may also play a part in innovative Structural Health Monitoring (SHM) approaches allowed by damage detection derived from developing Performance-Based Earthquake Engineering (PBEE) tools such as fragility functions.

Displacement is described using a variety of terms, each of which has a different meaning. The following definitions will aid in the comprehension of the context. u stands for global displacements in a Single Degree of Freedom system that describes the structure in the same way. The lateral shifts in the structure's roof in relation to the foundation are referred to as "roof displacement." In certain circles, this is referred as the "u_{roof}." Storey drift is the horizontal displacement between two adjacent storeys that are next to the storey. The I is used to signify the value at level i. Inter-storey drift is divided by the height of each floor to arrive at a drift ratio of i/h_i, where h_i is the vertical distance between the floors. Using the average roof displacement as a proportion of structural height, figure 2.6 depicts the average drift (FIB, 2003).

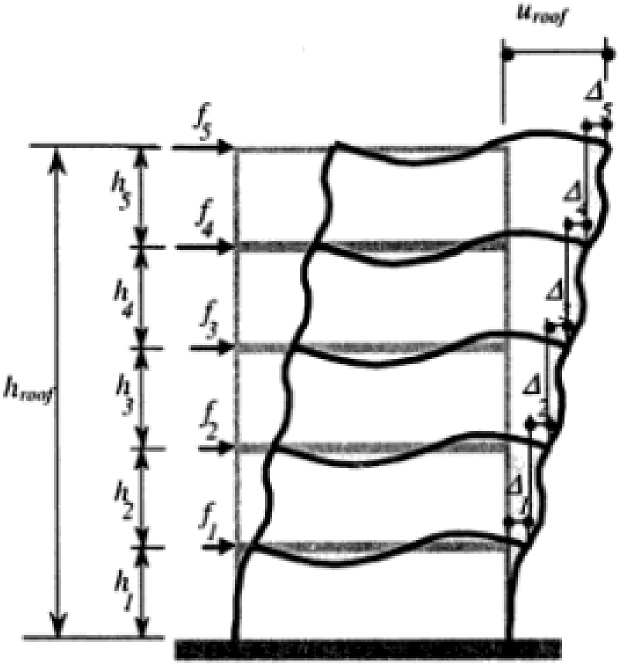

Figure 2.6: Storey Drift Definition (FIB, 2003)

As the height of a structure increases, the forces of nature start to become more dominant in the structural system and take on a more important role in the building's overarching structural system. The research and design of tall buildings are impacted by lateral loads, namely the drift or sway that these loads generate. The amount of sideways movement that occurs at the top of the structure in comparison to its foundation is referred to as drift or sway (Rahman et al., 2012).

2.4.3 Nonlinear Dynamic Analysis

Nonlinear Dynamic Analysis or Time History Analysis (NL-THA) is the widely accepted approach for demonstrating the performance of structures and aiming to adequately portray the seismic response of buildings in the absence of these significant assumptions' simplification (Patil and Kumbhar, 2013).

When deciding on a nonlinear analytic tool, keeping in mind the tool's limits is critical. The structure's NL-THA may be accurately analysed with this instrument (Farsangi et al., 2014). Nonlinear dynamic analysis, or NL-THA, takes into account geometric nonlinearity and material inelasticity in order to estimate the displacement behaviour and collapse load. In addition, ground motion is required for this strategy. There must be an adequate ground motion established to ensure the validity of the fragility curves Ground motion set adequacy, on the other hand, is a critical consideration (Billah and Alam, 2014).

It is practicable to utilize Nonlinear Dynamic technique for tall buildings, and many structural engineers have used the analysis to design earthquake-resistant structures using Nonlinear Dynamic Analysis. According to Powell (2006), Nonlinear Dynamic Analysis required an integration process that proceeded step-by-step and applied to nonlinear behaviour. In addition, nonlinear dynamic analysis includes the calculation of inelastic deformation, such as the rotation at a plastic hinge. According to ATC-43 (1998), a Nonlinear Dynamic Analysis needs to be carried out with at least three data sets of acceptable ground motion time histories. These time histories need to be selected and scaled from at least three different recorded occurrences.

The computational methods were advancing rapidly, and the incremental dynamic analysis (IDA) as an upgraded and expanded version of the NL-THA approach has become an effective framework for analysing the dynamic behaviour of structures subjected to ground motions. This concept is suggested by Bertero in 1977. (Kassem et al., 2020)

According to Khorami et al. (2017), as an approach for analysing the nonlinear behaviour of a structure subjected to a series of ground motions, IDA is now widely utilized. The structure will be repeatedly analysed for each motion scaled for gradually increasing the applied strong motion time-history and the appropriate damage measures (DM) are calculated and plotted against the earthquake intensity measure (IM) to generate "IDA Curves."

Zain et al. (2019) assessed the seismic vulnerability of 19 RC school buildings and presented by using IDA. Each iteration of the analysis increases the PGA at specific intended intervals with PGA range from 0.20g to 1.40g, 0.20g increments as the augmenting acceleration for each successive iteration of the analysis. This is done so that the structural response to earthquakes can be predicted. The findings of IDA are shown in the form of graphs between global drift and the selected IMs.

In general, the conventional IDA curve of the structural reaction is displayed in the format of damage measure (DM) against intensity measure (IM), as illustrated in Figure 2.7. For instance, peak roof drift ratio, θ_{roof} (or θmax), is an example of DM, whereas peak ground acceleration (PGA), peak ground velocity (PGV), or the 5% damped the first mode spectral acceleration Sa are examples of IM (T1, 5 %).

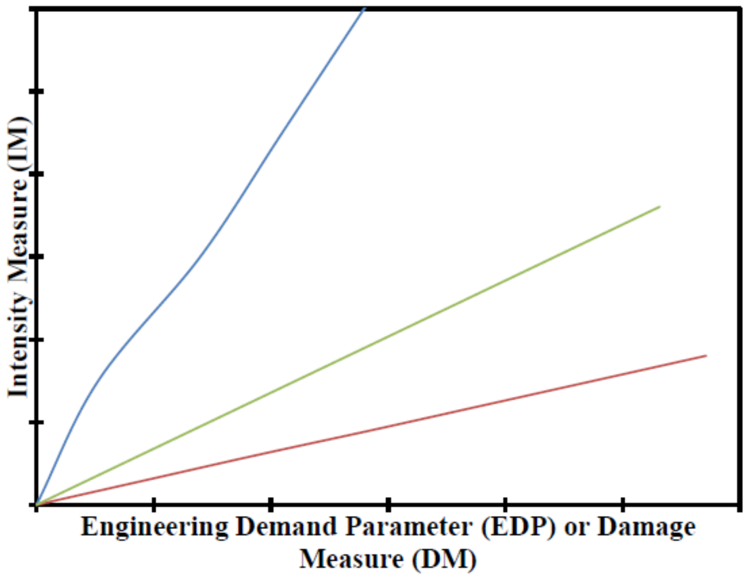

Figure 2.7: Typical IDA curve

IDA that was developed and thoroughly documented by Vamvatsikos and Cornell (2002). However, the concept of seismic load scaling was utilised in the past by a number of authors to evaluate the performance of structural frames in buildings. This was done before IDA was developed. Nevertheless, despite the fact that it has brought advantages, IDA has also caused challenges that need to be overcome. For an appropriate IDA curve, a substantial number of nonlinear time history studies are required, and the utilisation of several records is necessary for correct estimation of seismic demands. Aside from that, it is essential to the investigation that the data that were collected be subjected to post-processing, and that a suitable Intensity Measure (IM) and EDP be chosen. Understanding which aspects of a recorded ground motion are most closely correlated with the resulting structural response is becoming increasingly important as nonlinear dynamic analysis becomes a more prevalent method for evaluating the earthquake-induced load on a structure. This is because nonlinear dynamic analysis is becoming a more prevalent method for evaluating the earthquake-induced load on a structure. (Asgarian et al., 2010)

However, in other circumstances, a single IDA recording is insufficient to accurately analyse a structure's behaviour, necessitating a significant number of recordings. It is now possible to perform a variety of IDA studies on a single structural model at various acceleration rates during an earthquake using a new technique called Multi-Record Incremental Dynamic Analysis (MRIDAs). IDA has also been used by several researchers to perform tens or hundreds of IDA analyses on complex MDOF structures. There have been studies using anywhere from 10 to 200 multi-record IDA techniques, such as classic Monte Carlo with a response surface approximation to Monte Carlo with Latin hypercube sampling, and even approximate moment-estimating techniques (Liel et al., 2009; Dolsek, 2009; Vamvatsikos and Fragiadakis, 2010).

Consequently, a value should be included to quantify the impact of a record on an IM structure. In addition, after the model has been developed and the ground motion recordings have been picked, a rapid and automated method is required to do the actual dynamic analyses for IDA. This requires each record to be scaled appropriately to represent the complete spectrum of structural reaction, from elasticity to yielding to global dynamic instability. Additional studies are done at immediate IM levels to adequately frame the global collapse and improve the accuracy at lower IM levels. Concerning computational cost, it is evident that the more the number of analyses per record, the greater the accuracy and the longer the time required to finish IDA.