BEHAVIOURAL FACTORS EFFECT ON DRIFT DEMAND FOR TALL REINFORCED CONCRETE BUILDINGS SUBJECTED TO REPEATED FAR-FIELD EARTHQUAKES

by

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KESAN FAKTOR KELAKUAN TERHADAP KEPERLUAN HANYUTAN UNTUK BANGUNAN TINGGI KONKRIT BERTETULANG BERDASARKAN KEPADA GEMPA BUMI JARAK JAUH BERULANG

oleh

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LIST OF ABBREVIATIONS

2D	:	2 dimension
3D	:	3 dimension
CP	:	Collapse Prevention
EC8	:	Eurocode 8 (European Code Design)
EC2	:	Eurocode 2 (European Code Design)
EDP	:	Engineering Demand Parameter
FEM	:	Finite Element Model
FFE	:	Far-field Earthquake
GM	:	ground motion
ID	:	Interstorey Drift
IDA	:	Incremental Dynamic Analysis
IDR	:	Interstorey Drift Ratio
IO	:	Immediate Occupancy
LS	:	Life Safety
M-P-V	:	Moment-Axial Load-Shear Force
MDOF	:	Multi-Degree-of-Freedom system
MRFs	:	Moment resisting frames
NFE	:	Near-field Earthquake
NTHA	:	Nonlinear Time History Analysis
O	:	Operational
PBA	:	Performance Based Assessment

PBD	:	Performance Based Design
PBEE	:	Performance Based Earthquake Engineering
PGA	:	Peak Ground Acceleration
POA	:	Pushover Analysis
RC	:	Reinforced Concrete
RIDR	:	Residual Interstorey Drift Ratio
RSA	:	Response Spectrum Acceleration
SBWC	:	Strong-Beam-Weak-Column
SCWB	:	Strong-Column-Weak-Beam
SDOF	:	Single-Degree-of-Freedom system
SSI	:	Soil Structure Interaction
USGS-NEIC	:	United State Geological Survey – National Information Earthquake Center

LIST OF SYMBOLS

$A_{g,max}$	: maximum acceleration of the ground motion
a_g	: peak ground acceleration
β	: torsional demand
c_u	: undrained shear strength of soil
D	: source distance
E	: Young modulus of elasticity
F_b	: base shear force
F_e	: elastic force
F_i	: storey lateral load which is horizontal force acting on storey i
F_m	: modal force
F_y	: yield force
g	: gravitational acceleration
H_i	: individual storey height
I	: Moment of Inertia (second moment of area) of section
I_b	: moment of inertia for beam
I_c	: moment of inertia for column
km	: kilometer
K_o	: elastic rotation stiffness (initial stiffness)
K_{storey}	: storey stiffness
k_1	: elastic stiffness during loading state
k_2	: stiffness degradation during unloading state

k_3 : stiffness degradation during reloading state

L_b : length of beam

L_c : length of column

m : total mass of the building

m_i, m_j : storey masses associated with all gravity loads

M_1 : Fixed-end moment at End 1

M_2 : Fixed-end moment at End 2

M_c : capping moment

M_s : magnitude

M_w : moment magnitude

M_y : yield moment

max ID : maximum Interstorey Drift

$(\text{max ID})_i$: maximum Interstorey Drift at individual storey

$(\text{max ID})_{mean}$: mean of maximum Interstorey Drift

max IDR : maximum Interstorey Drift Ratio

$(\text{max IDR})_{avg}$: average along the height of maximum Interstorey Drift Ratio for different ground motions

N : number of storey of MDOF models

N_{SPT} : Standard Penetration Test blow-count

q_o : behavioural factor

r : bi-factor

R : Force Reduction Factor, Response Modification Factor, Force Modification Factor

R_S, Ω_d : overstrength factor

R_μ	: ductility reduction factor
R_R	: redundancy factor
Rε	: damping factor
s	: second
$S_d(T_1)$	: ordinate design spectrum of EC8 Type 1 at period T_1
$S_a(T_1)/g$	: ground motion intensity
S_dT_1	: Response spectra acceleration (RSA) for T_1
s_i, s_j	: displacements of masses m_i, m_j in the fundamental mode shape
T_1	: fundamental period of the building for lateral motion in the direction considered
T_c	: upper limit of the period of the constant elastic spectral acceleration region
T_p	: pulse period
V_d	: design lateral force
V_s	: shear velocity
$v_{s,30}$	: Average value of propagation velocity of S waves in the upper 30 m of the soil profile at shear strain of 10^{-5} or less.
W	: weight of the structure
z	: storey level
z/H	: Reduction stiffness along the height.
α_u	: Multiplier of horizontal seismic design action at formation of global plastic mechanism.
α_1	: Multiplier of horizontal design seismic action at formation of first plastic hinge in the system.
α_u / α_1	: overstrength factor
α_o	: dimensionless parameter

δ : Ratio of the lateral stiffness at the top to the base of the structure model.

θ_c : capping rotation capacity

θ_p : plastic hinge rotation capacity

θ_{pc} : post-capping plastic-rotation capacity

θ_y : yield rotation capacity

ρ : Ratio of the stiffness of all beams at the mid-height storey of the frame to the sum of the stiffness of all columns at the same storey.

$\rho_{M\&T}$: Empirical ratio of stiffness beam and column at mid-height of structures.

μ : displacement ductility factor

$\mu_{\theta,c}$: ductility of plastic rotation capacity

$\mu_{s,max}$: maximum storey ductility demand

μ_{SDOF} : target ductility ratio of the first mode SDOF system

λ : Dimensionless parameter that controls the variation of lateral stiffness along the height of the structure (the correction factor)

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ABSTRAK

Peristiwa gempa bumi sebenar tidak muncul dalam satu gegaran tetapi berlaku sehingga beberapa gegaran secara berturut-turut. Analisa membuktikan bahawa pergerakan dasar bumi berulang mempunyai kesan besar terhadap tindakbalas kerangka konkrit bertetulang. Kebanyakan analisa sebelum ini mengabaikan kesan gempa bumi jarak jauh berulang. Kajian dalam tesis ini melibatkan penilaian tindakbalas seismik terhadap keperluan hanyutan dua model bangunan tinggi yang didedahkan kepada gempa bumi jarak jauh normal dan berulang dengan pelbagai nilai faktor kelakuan, q_o menggunakan analisa linear dan tidak linear tidak elastik. Analisa telah dijalankan pada komponen ufukan 2-arah bangunan dengan pemodelan struktur konkrit bertetulang kepada 20 gerakan dasar bumi jarak jauh yang kuat dalam satu gerakan, gabungan dua gerakan dan gabungan tiga gerakan. Penilaian prestasi bagi kedua model bangunan tinggi dinilai berdasarkan tindakbalas seismik terhadap kekukuhan dan kekuatan model bangunan. Berdasarkan semua keputusan yang diperolehi, keperluan hanyutan meningkat secara mendadak dengan hanya 18m perbezaan tinggi antara tingkat tertinggi model bangunan 12 tingkat (N=12) dan tingkat ke-17 model bangunan 18 tingkat (N=18) dengan memiliki sifat elemen struktur yang sama. Untuk N=12, keperluan hanyutan meningkat dari tingkat bawah ke atas bangunan dengan kurang daripada 1% hanyutan dan tidak melebihi kekuatan melentur model bangunan apabila kenakan gempa bumi jarak jauh

berulang dan pelbagai faktor kelakuan, q_o (q_o = 1.0, 1.5, 2.0, 4.0 and 6.0). Untuk N=18, keperluan hanyutan meningkat secara mendadak dan hanya fokus pada tingkat bawah dan atas bangunan dengan lebih daripada 4% hanyutan melebihi kekuatan puncak model bangunan. Oleh itu, q_o tidak disyorkan pada tingkat bawah bangunan memandangkan ia akan mengurangkan kekuatan melentur dan akibatnya meningkatkan keperluan hanyutan sementara q_o ditekankan pada tingkat atas untuk meningkatkan tahap kemuluran untuk mengurangkan tindakbalas tidak elastik pada tingkat ini yang akan menyebabkan kerosakan struktur yang teruk. Gempa bumi berulang menyebabkan lebih tinggi keperluan hanyutan tetapi pada corak yang sama dengan gempa bumi normal. Gempa bumi jarak jauh penting dalam kajian tindakbalas tidak elastik struktur bangunan tinggi. Oleh itu, tesis ini menyediakan anggaran tindakbalas tidak elastik struktur dalam penilaian rekabentuk seismik struktur bangunan tinggi konkrit kerangka bertetulang apabila didedahkan kepada gempa bumi jarak jauh berulang dan cadangan nilai faktor kelakuan untuk digunakan dalam rekabentuk struktur konkrit bertetulang.

BEHAVIOURAL FACTORS EFFECT ON DRIFT DEMAND FOR TALL REINFORCED CONCRETE BUILDINGS SUBJECTED TO REPEATED FAR-FIELD EARTHQUAKES

ABSTRACT

Real earthquake event does not appear in single tremor but actually lead to appearance of several tremors consecutively. It is found that the sequences of ground motions have a significant effect on the response of reinforced concrete (RC) frames building. Previous research done mostly ignored the importance of the effect of repeated far-field earthquake (FFE) event. This thesis presents a seismic response evaluation of two tall building models in term of drift demand subjected to single and repeated FFE records at various behavioural factors, q_o using linear and nonlinear analysis. Analysis was performed in bi-directional horizontal components of the building by subjecting the RC structural model to FFE in single, double and triple of 20 strong earthquake events. The performances of both tall building models were evaluated based on seismic action towards the stiffness and strength of the building model. From all results obtained, drift demand drastically increases with 18m different in height between top floor of twelve (N=12) RC storey and 17th floor of eighteen (N=18) RC storey building models with same structural element properties. For N=12, drift demand migrates from bottom to top storey level with less than 1% drift and not exceeding yield strength of building model when subjected to repeated FFE motion and at various behavioural factors, q_o (q_o = 1.0, 1.5, 2.0, 4.0 and 6.0). For N=18, drift demand is drastically increased and is concentrated only at bottom and top storey levels with more than 4% drift

exceeding ultimate strength of building model. Therefore, q_o is not suggested at bottom storey as it will decreased yield strength and consequently increasing drift demand while q_o is forced to be used at top storey level to increase the ductility level in order to reduce inelastic performance at this storey level that will contribute to severe structural damage. Seismic sequence with double and triple events obviously contributed to higher drift demand but in similar pattern of single FFE event. FFE motion is important in study the inelastic performance of tall structural building. Hence, this study provides estimation of structural inelastic performance in evaluating structural seismic design of tall RC building subjected to repeated FFE motion and suggestion of behavioural factors value to be used in RC frame structural design.

CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia is close to areas that have experienced strong earthquakes, including Sumatra and the Andaman Sea, while Sabah and Sarawak are located close to the earthquake zone of South Philippines and North Sulawesi. Malaysia has only encountered strong vibrations and aftershocks after its neighbours were hit by strong earthquakes so far. In 2012, the Meteorological Department of Malaysia had detected eight earthquakes in the eastern part of the country, in Sabah and Sarawak which were between 2 and 4.5 on the Richter scale. Six earthquakes had occurred in Sabah (Tambunan, Kota Marudu, Kudat, Beluran, Kunak and Keningau) and two earthquakes had occurred in Belaga, Sarawak.
(*http://www.themalaysianinsider.com/malaysia/article/moderate-earthquake-can-happen-anytime-in-malaysia*)

Malaysian Peninsular is located on a stable part of the Eurasian Plate where buildings on soft soil are occasionally subjected to tremors due to far-field effects of earthquakes in Sumatra (Balendra et al., 1990). In the last few years, tremors were felt several times in tall buildings in Kuala Lumpur, the capital of Malaysia, due to large earthquakes in Sumatra. The mechanism for such tremor is illustrated in Figure 1.1 (Balendra, 1993). The seismic waves, generated from an earthquake in Sumatra, travel long distance before they reach Malaysia bedrock. The high frequency earthquake waves damped out rapidly in the propagation while the low frequency or long period waves are more robust to energy dissipation and as a result they travel long distances.

Thus the seismic waves reaching the bedrock of Malaysian Peninsular are rich in long period waves, and are significantly amplified due to resonance when they propagate upward through the soft soil sites with a period close to the predominant period of the seismic waves. The amplified waves cause resonance in buildings with a natural period close to the period of the site, and the resulting motions of buildings are large enough to be felt by the residence. According to the historical records, the earthquakes that influence Malaysian Peninsular are originated from two earthquake faults which are Sumatran subduction zone and Sumatran fault (Balendra and Li, 2008).

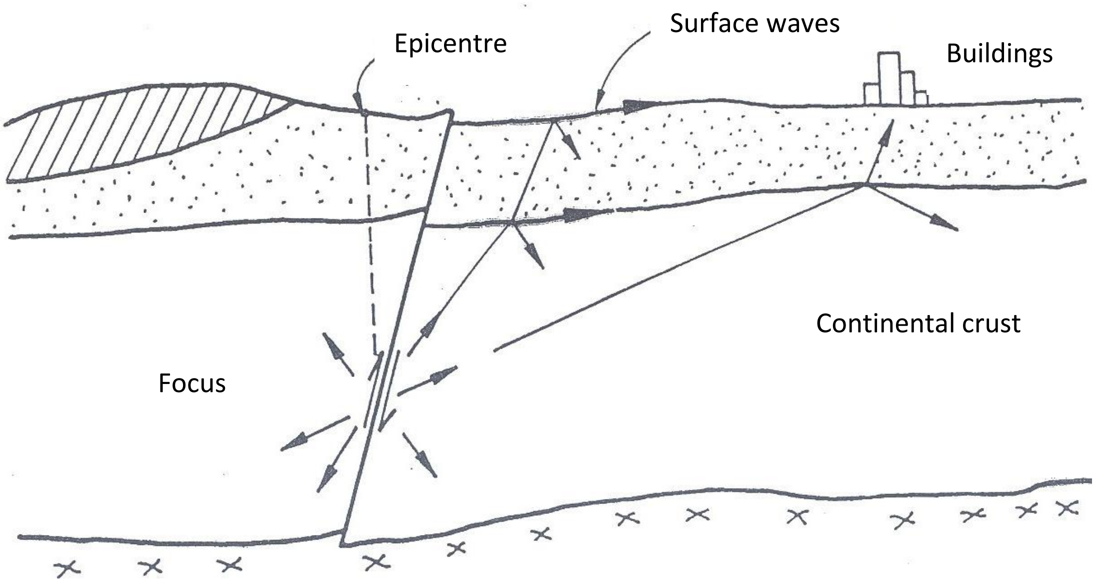


Figure 1.1 Schematic diagrams for far-field effects of earthquakes.
(Balendra and Li, 2008)

The Malaysian Peninsular is located about 350 km away from the nearest fault line in Sumatra, relatively faraway from seismic source zone. However tremors due to the Sumatra earthquakes had been reported several times. The tremors of earthquake event occurred on the 2nd November 2002 at Northern Sumatra had been felt in Penang and Port Klang and reportedly caused cracks on the buildings. Based on the Preliminary Earthquake Report from National Earthquake Information Center U.S. Geological Survey (USGS-NEIC), NS2002 was located at the longitude of 96.18E and latitude of 3.024 N. The depth of the earthquake was 33.0 km and moment magnitude, M_w, of the earthquake was 7.4. The distance of epicenter from Penang and Kuala Lumpur were approximately 523 km and 600 km, respectively. The location of the earthquake can be seen in Figure 1.2 (Adnan et al., 2002).

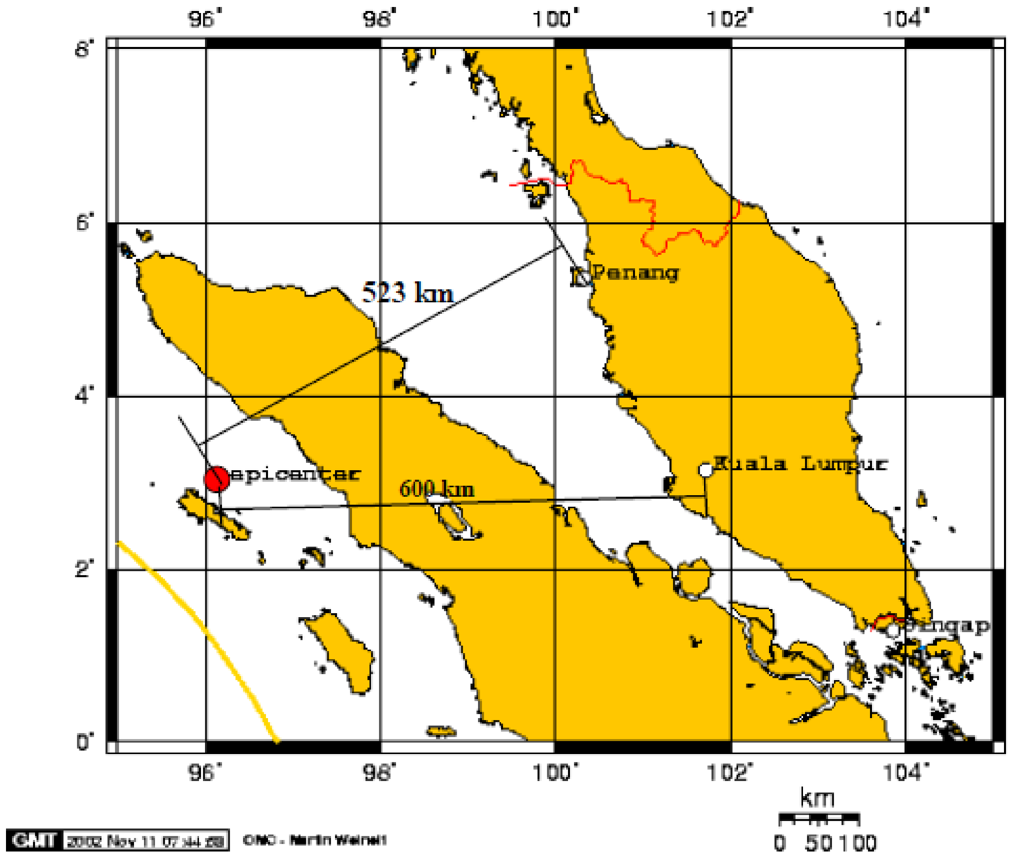


Figure 1.2: Epicentral distance of non-seismicity earthquake region in Malaysia located at Penang and Kuala Lumpur to the fault line in Sumatra seismic region (Adnan et al., 2002)

Present code procedures for seismic design cannot be rationalized sufficiently when applied to tall buildings. The traditional approach followed by the code for setting strength requirements and load distributions has strictly focused on a first mode translational response. It is well known for tall buildings that higher modes can be as important, if not more than first mode vibration, to the overall design of the building. As a result, there is a growing push in industry and academia towards a performance based earthquake engineering design approach in tall buildings. The design guidelines in codes such as the Uniform building Code (UBC) or the International Building Code (IBC) are intended for low to medium rise buildings.

Recommended alternatives to the prescriptive guidelines that can be found in traditional codes have been published by researchers and practitioners within the earthquake engineering community for tall building design, such as Guidelines for Seismic Design of Tall Buildings (published by the Pacific Earthquake Engineering Research Center) or Next Generation Performance Based Seismic Design Guidelines (published by the US Federal Emergency Management Agency) among other publications. (*http://www.epicentreonline.com/researchproject/view/idprojects/46*)

The past four decades have seen a rapid development of knowledge in seismic analysis and design of reinforced concrete (RC) framed structures. Various rational approaches have been proposed, which are mainly based on the inelastic materials behaviour. There is a resurgence of high-rise and ultra-high rise building construction around the world.

The design of these tall buildings in seismically active regions varies dramatically from region to region. Whereas rigorous performance-based assessments are required in some countries, including Japan and China, many other countries do not require anything beyond traditional design practice that is based on fundamental mode response and force reduction factors (Willford et al., 2008).

A performance based approach to the design of tall buildings is a significant improvement over prescriptive code-based approaches that cannot accommodate the behavioural characteristics of tall buildings and that permit engineers to complete designs without a sufficient understanding of a building's likely performance. A performance based design provides the designer and the building owner with greater insight into the likely response of the building to ground shaking. If such a design is performed carefully, the resultant product is likely to be a much safer and more serviceable building (Willford et al., 2008).

It is found that the sequences of ground motions have a significant effect on the response and, hence, on the design of RC frames. Repeated earthquake effect of earthquake sequences are characterized by the reappearance of medium or strong seismic ground motions after short or long periods of time. The ductility demands of the sequential ground motions can be accurately estimated using appropriate combinations of the corresponding demands of single ground motions which are called as repeated earthquake or artificial sequential earthquake (Hatzigeorgiou and Liolios, 2010).

There are two assessment conducted in order to analyze the performance of the building response. Modal analysis is conducted for the service-level assessment because the building response must be elastic or near-elastic, and Response-History analysis is conducted for the collapse-level assessment for which inelastic response is expected in the building.

In order to perform the assessments of tall building performance, force reduction factor or behavioural factor is used to define the appropriated design intensity of the building model used in term of its ductility to recognize the suitability of the strength of the element properties of the reinforced concrete that should be used for the design criteria when subjected to far-field seismic loading. Behavioural factor (q_o) is a term of the force reduction factor in Eurocode 8 (EC8, 1994). The term of this reduction factor varies between all available seismic codes such as the term *response modification factor* (R) used in the US codes and guidelines of Uniform Building Code, UBC (FEMA 273, 1997), and the *force modification factor* (R) in the National Building Code of Canada (NBCC, 1995).

This factor is widely used in Nonlinear Inelastic analysis to lower the PGA level to the desired design PGA level as well as to increase ductility and strength of structural building; hence, application of various q_o is adopted in the study to further investigate the effect of this factor towards the buildings inelastic response behaviour in terms of its drift demand.

1.2 Problem Statement

The majority of modern seismic design codes, as for example, EC8 permit the structural nonlinearity. However, the limitation of these codes is the exclusive adoption of the isolated and rare 'design earthquake' while the influence of repeated earthquake phenomena is ignored. Despite the fact that the problem has been qualitatively acknowledged, very few studies have been reported in the literature regarding the repeated earthquake phenomena.

The influence of repeated near- or far-field earthquake phenomena on drift demands has not been systematically studied in the past. It seems impractical to only consider isolated 'design earthquakes' without taking into account the influence of repeated earthquakes phenomena on drift demands.

The repeated earthquakes effect should not be confused with the low cycle fatigue phenomenon which is referred to the importance of plastic cycling effect. This issue is associated with the energy dissipation capacity and has been proposed only for single ground motions (Hatzigeorgiou, 2010).

Hatzigeorgiou and Beskos (2009) and Hatzigeorgiou (2010) examined the influence of multiple or repeated earthquakes in numerous SDOF systems on steel structure and found that seismic sequences lead to increased displacement demands in comparison with the 'design earthquake'. However, these works are concerned with SDOF and on steel structure but not with MDOF of RC framed structures.

On the other hand, the influence of the hysteretic behaviour on seismic demands has been a topic mainly addressed through the response of SDOF systems, but fewer studies have been performed in Multi-Degree-of-Freedom (MDOF) systems that confirm observations made from SDOF analysis. Most of studies done in MDOF systems have considered only stiffness degrading hysteretic behaviour, but very little considering strength-and-stiffness degrading hysteretic models, with or without cyclic deterioration (Ruiz-Garcia and Miranda, 2005).

MDOF system is justified as a system that can represent many vibrations of systems that are too complex to be presented by only a single degree of freedom model. MDOF system is selected in the study to evaluate the modification that must be applied to strength demand parameters which being derived from simplified SDOF models in order to account for multi-mode effects in real structures. In MDOF study, it is found that the required strength for specified target ductility ratios depends strongly on the type of failure mechanism that will develop during severe earthquake compared to SDOF study that can be attempted only for ground motion with similar frequency characteristics (Nassar and Krawinkler, 1991). Hence, the MDOF system is important to study multiple mode of vibration which is being subjected to repeated earthquake motions with various frequency characteristics.

Amadio et al. (2003) examined the effect of repeated earthquake ground motions on the nonlinear response of Single-Degree-of-Freedom (SDOF) system. However, their work cannot be considered exhaustive since they examined only one natural and two artificial ground motions and only emphasized on SDOF structural systems without considering Multi-Degree-of-Freedom (MDOF) system.

Many researches done on nonlinear inelastic performance of building were focused only on low-rise buildings and concrete structures and lack of design earthquake on the influence of repeated earthquake ground motions on the nonlinear response of MDOF systems. Most case studies done for MDOF systems is very limited to capture global seismic response of buildings behaving in the fundamental vibration mode as well as lateral stiffness and strength variation along the height where typical of real framed multi-storey buildings are always neglected. Most studies done focused only on single mode vibration which is considered to be enough due to lack of past technology development.

Three dimensional (3D) RC generic frames of MDOF systems has been studied previously due to near-field earthquake (NFE) by Ade Faisal (2011), Adiyanto (2011), and Mohd Zahid (2011) and low-rise building due to far-field earthquake (FFE) has been done by Muhammad (2011), but there is no emphasis on MDOF tall building system due to FFE. Thus it is significant to study tall RC frame building performance due to seismic sequence and develop an efficient methodology for the inelastic analysis of MDOF RC framed structural systems, as to multi-storey buildings under sequential ground motions.

Stronger motion produces from NFE ground motion is due to short distance from the epicenter of fault rupture propagations compared to FFE. Hence, the dynamic characteristic behaviour or demand of building structure will be higher when subjected to NFE rather than FFE. Reviewed on tall structural building which are on the outside of fault rupture plane experiencing FFE motion is still being neglected.

Behavioural factors have proved to be very demanding in reducing peak ground acceleration of ground motion to desired design level. However, the current behaviour factor in Eurocode 8 was found by Ade Faisal (2011), Adiyanto (2011), Mohd Zahid (2011) and Muhammad (2011) to be not adequate to provide seismic safety for the RC buildings. Therefore it is important to further investigate the importance of various behavioural factors in term of medium ductility class ($0<q_o<2$) and high ductility class ($4<q_o<6$) towards drift demand of tall MDOF RC buildings subjected to repeated FFE in order to quantify the safest application of behavioral factors towards every storey levels of tall RC buildings.

FFE with tall or high-rise building is very well connected towards performing the evaluation and contribution of the earthquake effect on the building itself in order to obtain precise seismic design of newly developed high-rise or skyscrapers structural building project in either seismic prone or non seismic prone country. Thus, FFE is of interest in this research study as most of the previous studies focused more on near-field earthquake (NFE). By considering FFE induced forced on tall RC MDOF generic frame models, the effect of FFE can be further investigated to study the performance of the building models in term of drift demands.

1.3 Objectives

This study is due to the effect of real and artificial FFE ground motions with various behavioural factors, q_o on the response of tall MDOF RC frame structural buildings (square plan-shaped building models).

The main objectives of this study are as follows:

i) To determine maximum drift demand of tall MDOF RC building subjected to single and repeated far-field earthquake (FFE) motion.
ii) To evaluate the effect of behavioural factor, q_o on drift demand of tall building model due to single and repeated FFE events.
iii) To evaluate the effect of FFE repeated earthquake motion on drift demand of tall building model at various q_o.
iv) To develop the approach to quantify the drift limits associated with different damage levels for tall MDOF RC structural systems when subjected to repeated earthquake motions.

1.4 Scope of Work

The following scopes were covered to assess the relationship between the interstorey drift (ID) with other Engineering Demand Parameters (EDPs) such as artificial sequential ground motions and behavioural factors on seismic responses of fixed-based tall building; 12- and 18- storey reinforced concrete (RC) buildings.

i) The analytical models of single-bay MDOF frame system reinforced concrete squared plan building models with number of storey, N=12 with fundamental period, T_1=1.26s and N=18 with fundamental period, T_1=1.71s.
ii) Five behavioural factors (q_o = 1, 1.5, 2, 4 and 6) with some modification factors as presented by Ade Faisal (2011).

iii) Medium type of plastic hinge rotation capacity, θ_p was used in defining cyclic (stiffness and strength) deterioration from Modified-Takeda hysteresis backbone curve model.

iv) Total of 60 ground motions from 20 types of single FFE event as follows :

- Case 1 (single event: 20 single FFE)
- Case 2 (double event: 20 random combination of 2 single FFE)
- Case 3 (triple event: 20 random combination of 3 single FFE)

v) Linear Elastic Analysis by using SAP 2000 version 14 and Cumbia to obtain an accuracy of linear-elastic shaped pattern of force-displacement relationship of tall building model.

vi) Nonlinear Static Analysis (Pushover Analysis, POA) by using SAP 2000 v14 to obtain yield global displacement.

vii) Nonlinear Inelastic Time History Analysis (NTHA) by using RUAUMOKO to obtain ultimate global displacement.

12- and 18- storey models were used to define tall building models as description of tall building starts from 10-storey height. q_o were taken from 1 until 6 as most of earthquake resistant building designs using Eurocode 8 for moment resisting frame were having q_o within this range. q_o by Ade Faisal (2011) was adopted to classify the ductility class of building model as low ($1<q_o<1.5$), medium ($2<q_o<4$) and high ($4<q_o<6$) ducility class.

Medium θ_p was used to define medium rotation capacity of building member (θ_p=0.04) as referred to Zareian and Krawinkler (2009). Other option were low (θ_p=0.02) and high (θ_p=0.06) capacities. Thus, the best option to reflect rotation capacity of building member was between low and high which is medium rotation capacity. 20 ground motions were selected to represent various random combinations towards double and triple earthquake events as to obtain clearly output of the effect of repeated seismic events.

1.5 Thesis Outline

This thesis consists of five chapters. These chapters are:

Chapter 1 covers an introduction where it presents the general background of the research study of this thesis. It also comprises of problem statements, the objectives and the scope of work which will be the main outline of this thesis.

Chapter 2 covers the review of the previous studies of other researchers on the same field of analysis as references to this thesis. In this chapter, review of previous work has focused on Multi-Degree-of-Freedom system (MDOF), repeated earthquake, the effect of behavioural factors on building performance and the drift demand produced by the building models.

Chapter 3 covers the research methodology of this study which represents the sequence of how the study is carried out starting from the development of generic frame models, the generation of the repeated earthquake and the structural building analysis.

Chapter 4 covers the result and discussion. In this chapter, the targeted results are yield and ultimate displacement, the structural building ductility from POA, the drift demand in term of maximum Interstorey Drift (max ID), the mean of maximum ID $(\text{max ID})_{mean}$ produced and the influence of various behavioural factors (q_o) towards the building performance to both single and repeated earthquake cases.

Chapter 5 covers the conclusion of all findings from this research study and recommendations are provided for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section reviewed previous work on Multi-Degree-of-Freedom (MDOF) system of building model, repeated earthquake which is the artificial sequences of ground motion records or known as multiple earthquake generated by a random combination of real single events of far-field earthquake ground motion (FFE), the behavioural factor (q_o) which is a term denoted for a force reduction factor (R) recommended by Eurocode 8 (EC8) and the interstorey drift (ID) of a structural building under nonlinear analysis.

2.2 Multi-Degree-of-Freedom (MDOF) system models for structural analysis

Nassar and Krawinkler (1991) evaluated the modification that must be applied to strength demand parameters derived from simplified Single-Degree-of-Freedom (SDOF) models in order to account for multi-mode effects in real structures. In MDOF study, they found that the required strength for specified target ductility ratios depends strongly on the type of failure mechanism that will develop during severe earthquakes. They concluded that great strength capacities are needed to control inelastic deformations in structures with weak stories.

Seneviratna and Krawinkler (1997) evaluated the inelastic MDOF effect for seismic design. They developed procedures to quantify seismic demands on MDOF systems for use in conceptual design using response spectral representations of input ground motions. They used a statistical evaluation of the results of inelastic dynamic analysis as the basis to derive empirical rules as MDOF modifications that permit the estimation of seismic demands on MDOF systems using elastic or inelastic spectral values for SDOF system with a period equal to the first mode period of MDOF system. They concluded that except for short period structures, the maximum storey ductility demand ($\mu_{s,max}$) for MDOF frame models is higher than the target ductility ratio (μ_{SDOF}) of the first mode SDOF system. This amplification ($\mu_{s,max}$ / μ_{SDOF}) increases with period of models as illustrated in Figure 2.1, illustrating the importance of higher mode effects.

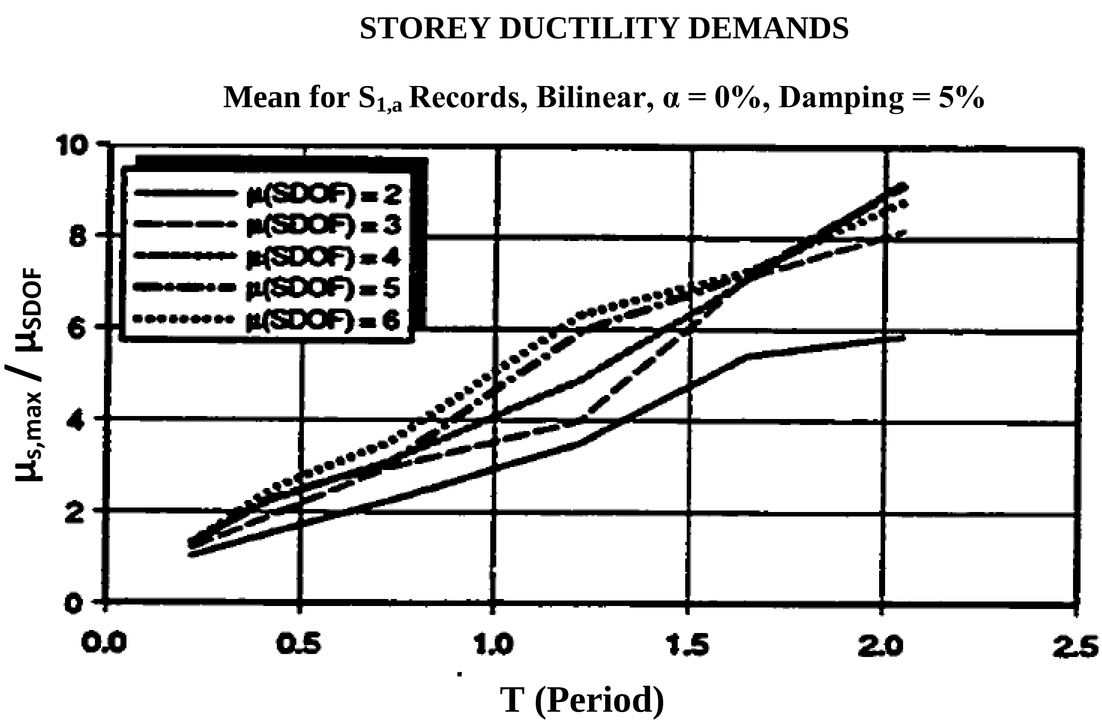


Figure 2.1: Mean amplification of maximum storey ductility demand with 0% strain hardening-$S_{1,a}$ records (Seneviratna and Krawinkler, 1997)

However, their study is still lack of information on MDOF system due to the limited number of building study cases. Therefore, Ruiz-Garcia and Miranda (2005) provided statistical studies to evaluate central tendency and dispersion of residual deformation demands in MDOF system subjected to earthquake ground motion representative of the seismic hazard in California. They have investigated various Engineering Demand Parameters (EDPs) in estimating maximum and residual displacement demands accounting for the uncertainty in the structural response of ground motion hazards for both SDOF and MDOF systems. They found that member stiffness degrading hysteretic behaviour leads to significant reduction of median residual interstorey drift ratio (RIDR) along the height.

Ibarra and Krawinkler (2005) examined the global collapse of frame structure under seismic excitation for both SDOF and MDOF structures. They observed that the variation of a particular parameter generally has a large influence on SDOF systems than on MDOF structures in which the elements yield at different times and some of them may never reach the inelastic range. The estimation of the MDOF collapse capacity obtained was still conservative where the actual collapse capacity is still underestimated.

Ade Faisal (2011) examined the ductility demand of MDOF frame structures. He found that there is still lack of findings with similar studies due to element properties. His research study was mainly focused on ductility demand of various height of RC structural building subjected to repeated earthquake motion.

Adiyanto (2011) and Mohd Zahid (2011) studied the drift and ductility demands of MDOF frame structures due to NFE, while Muhammad (2011) studied the ductility demands of MDOF frame structures due to FFE but only focused on low-rise buildings. Hence, the estimation of drift demands of tall MDOF frame structures due to FFE is importance to be further investigated.

2.3 Far-field Earthquake (FFE) Ground Motion

There are two types of ground motion fault that always being taken into consideration when evaluating the effect on structural behaviour and investigating the structural response (seismic response) of structural building as the impact of the rupture propagation namely far-field and near-field ground motions. Far-field ground motion (FFE) have been observed as differing dramatically from near-field counterparts recorded within a few kilometer of fault rupture plane (Kalkan and Kunnath, 2006).

2.3.1 FFE Ground Motion Database

Strong FFE ground motion database is taken from the European Strong-Motion Database (Ambraseys et al., 2001). It is comprised of:-

i) Faulting mechanism

ii) Site classification of stations, peak ground acceleration (PGA), and Response Spectrum Acceleration (RSA)

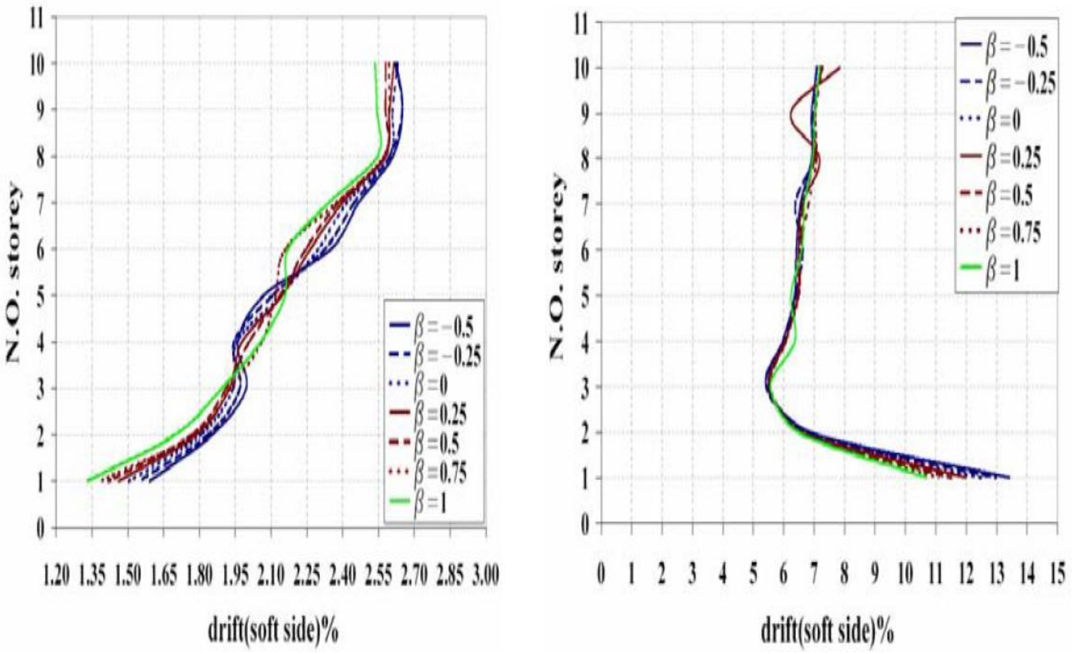
Pertinent information on the ground motion data sets including faulting mechanism, site classification of stations, peak ground acceleration (PGA) and Response Spectrum Acceleration (RSA) of FFE records of ground motions used are tabulated in Table 2.1. For pulse-type input, the maximum demand is a function of the ratio of the pulse period to the fundamental period of the structure. In this study, RSA is scaled down using scale factor appropriate to each building models fundamental period, T_1 for N=12 and N=18- storey RC building models. 20 single FFE ground motions records used in this study are presented as a list in Table 2.1 to describe the characteristics of each ground motion used in this study.

2.3.2 Characteristics and Effect of FFE on Seismic Response of Building

Kalkan and Kunnath (2006) stated that cumulative effects from increased cyclic demands are more pronounced in far-field records even though the arrival of the velocity pulse in a near-field record causes the structure to dissipate considerable input energy in relatively few plastic cycles.

Ghasemi and Shakib (2008) studied the effects of near-field and far-field motions on drift response in term of torsional demand, β in the different stories of asymmetric multi-storey buildings. They found that the storey drift demand increases from lower stories to higher stories in far-field motions and is reversed in near-field motions. Figure 2.2 (a) and (b) show the drift distribution in multi-storey building model at various stiffness eccentricities under far-field and near-field motions, respectively.

Brown and Saiidi (2008) investigated the comparison of the effect of near-field and far-field ground motions on substandard bridge bent. The results show that the force-displacement of the model have similar elastic stiffness and maintained a similar displacement response to both motions but suggest that the near-field ground motion had a greater impact with higher amplitude motions.



(a) (b)

Figure 2.2: Storey drift demand in multi-storey building under (a) Far-field motion and (b) Near-field motion (Ghasemi and Shakib, 2008)

Tavakoli et al. (2011) investigated the effect of near-field and far-field earthquake motions on the response of reinforced concrete (RC) structures considering soil structure interaction (SSI). Results based on linear time history analysis had shown that considering the soil structure interaction (SSI) increases period of structure and storey drifts and also had noticeable and significant effects on global displacement and base shear.

Table 2.1: European Strong-Motion Database (Ambraseys et al., 2001)

No.	Date	Earthquake Name	Magnitude. (Mw)	Epicentral Distance (km)	Station	PGA (g) major (x)	PGA (g) minor (z)	N=12 RSA(T_1=1.26s) in g major(x)	N=12 RSA(T_1=1.26s) in g minor(z)	N=18 RSA(T_1=1.71s) in g major(x)	N=18 RSA(T_1=1.71s) in g minor(z)
1	09/15/1976	Friuli (aftershock)	6.0	21	Breginj-Fabrika IGLI	0.505	0.474	0.069	0.128	0.034	0.052
2	09/15/1976	Friuli (aftershock)	6.0	37	Kobarid-Osn.Skola	0.142	0.106	0.021	0.013	0.012	0.012
3	04/15/1979	Montenegro	6.9	25	Petrovac-Hotel Olivia	0.454	0.306	0.306	0.100	0.119	0.062
4	04/15/1979	Montenegro	6.9	24	Ulcinj-Hotel Olimpic	0.293	0.241	0.532	0.565	0.241	0.386
5	05/24/1979	Montenegro (aftershock)	6.2	33	Bar-Skupstina Opstine	0.270	0.202	0.057	0.074	0.040	0.043
6	05/24/1979	Montenegro (aftershock)	6.2	22	Kotor-Zovod	0.152	0.118	0.022	0.026	0.022	0.033
7	11/23/1980	Campano Lucano	6.9	43	Brienza	0.227	0.174	0.090	0.075	0.048	0.042
8	11/23/1980	Campano Lucano	6.9	48	Mercato San Severino	0.139	0.108	0.075	0.062	0.038	0.031
9	03/19/1983	Heraklio	5.6	40	Heraklio-Prefecture	0.182	0.076	0.012	0.009	0.006	0.005
10	10/16/1988	Kyllini	5.9	36	Armaliada-OTE Building	0.156	0.083	0.041	0.022	0.027	0.033
11	06/15/1991	Racha (aftershock)	6.0	40	Iri	0.112	0.105	0.036	0.031	0.016	0.014
12	10/14/1997	Umbria Marche (aftershock)	5.6	24	Nocera Umbra	0.140	0.129	0.007	0.006	0.005	0.006
13	08/17/1999	Izmit	7.6	73	Goynuk-Devlet Hastanesi	0.137	0.120	0.068	0.148	0.075	0.066
14	09/07/1999	Ano Liosia	6.6	20	Athens 2 (Chalandri District)	0.161	0.110	0.062	0.026	0.050	0.020
15	06/27/1998	Adana	6.3	80	Mersin-Meteoroloji Mudurlugu	0.128	0.118	0.030	0.043	0.018	0.018
16	06/17/2000	South Iceland	6.5	21	Selsund	0.278	0.227	0.128	0.179	0.119	0.159
17	11/18/1997	Strofades	6.6	38	Zakynthos-OTE Building	0.131	0.116	0.101	0.049	0.040	0.034
18	06/21/2000	South Iceland (aftershock)	6.4	21	Hella	0.165	0.111	0.102	0.058	0.068	0.038
19	11/12/1999	Duzce 1	7.2	31	LDEO Sta. C1061	0.126	0.102	0.101	0.083	0.050	0.039
20	11/12/1999	Duzce 1	7.2	26	LDEO Sta. D0531 WF	0.157	0.125	0.055	0.101	0.025	0.047

FFE is considered in this study because in most research study, FFE is always taken lightly with emphasization is focused more on NFE seismic event. Even though it is considered as far counterpart, observation and conclusion made through all the reviewed are for some cases, FFE would trigger higher magnitude than NFE. Priority always given to the evaluation of structural building performance in seismic prone region, therefore, NFE is always being the major part in the assessment process by neglecting the effect of FFE. In some cases regarding tall or high-rise building in non seismic prone region, the effect caused by FFE is important in the evaluation of tall structural building performance. The effect of FFE can be used as a starting point or a benchmark in earthquake structural design in order to prepare the building towards subjected single and repeated earthquake motion.

2.4 Influence of Repeated (Artificial Sequences) Earthquake Ground Motion on the Seismic Demands for Inelastic Structure

Hatzigeorgiou and Beskos (2009) investigated the influence of multiple earthquakes of both near and far-field counterparts in numerous SDOF. They found that seismic sequences lead to increased demands in comparison with the case of the 'design earthquake' which is concerned with inelastic displacement ratios.

Hatzigeorgiou (2010) investigated only artificial sequences of both ground motions, where these sequences have been generated by a rational and random combination of real single events of earthquake ground motion due to lack of real seismic sequences records. He found that due to the seismic sequence effect, it is insufficient to consider only the ‘design earthquake’ hypothesis since this only leads to underestimated ductility demands and therefore to underestimated structural damage.

Hatzigeorgiou and Liolios (2010) investigated an extensive parametric study on the inelastic response of Reinforced Concrete (RC) frame structure under repeated strong NFE and FFE ground motions. They found that the sequences of ground motions have a significant effect on the response and, hence, on the design of RC frames. The ductility demands of structures appear to be increased under sequential ground motions where these demands can be controlled using appropriately reduced behaviour factors, taking into account the multiplicity effect of earthquakes. They concluded that the ductility demands of the sequential ground motions can be accurately estimated using appropriate combinations of the corresponding demands of single ground motions.

Ade Faisal (2011) has studied the influence of repeated earthquake on the ductility demand of inelastic RC frame structures. He found that the effect of repeated NFE was insignificant and can be negligible when lower behavioural factors (q < 2) is induced. He also found that the influence of repeated earthquake to the dispersion of maximum storey ductility demand is negligible. However, the significant of repeated far-field earthquake (FFE) on drift demand of precisely tall buildings is under estimated and has been neglected as well.

Mohd Zahid (2011) has studied the effect of repeated near-field earthquake (NFE) on the ductility demand of RC buildings. He stated that, in comparison to single NFE, repeated NFE causes the migration of storey ductility demand from top to bottom storey occur at stronger structure as he conducted study on 3- and 18- storey RC generic frame structures. Stronger structure considered in his study was 18-storey structures.

Adiyanto (2011) has studied the influence of behaviour factor on the ductility demand of RC building affected by repeated near-field earthquake. He concluded that repeated NFE did not affect the distribution of maximum interstorey drift ratio (max IDR) along the height of the building instead, tends to induce higher magnitude of maximum IDR compared to single NFE. Clarification was made that consideration of repeated earthquake in dynamic analysis is significant as it leads to greater damage on structures. However, this study is lack due to the effect of repeated FFE on structures.

Muhammad (2011) has studied the effect of repeated FFE on the ductility demand of low-rise RC building. Muhammad stated that repeated FFE give significant effect to the ductility demand of low-rise structural building but this study only concentrated on ductility demand of low-rise building. Hence, it is significant to further study due to the effect of repeated FFE on drift demand of high-rise structural buildings.

2.5 Force Reduction Factor, R in term of Behavioural Factor (q_o)

Miranda and Bertero (1994) have found that R are primarily influenced by the maximum tolerable displacement ductility demand, the period of the structural system and the soil conditions of the site**.** Strength reduction factor is a reduction in