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INFLUENCE OF FORCE REDUCTION FACTOR ON THE INTERSTOREY DRIFT OF RC BUILDING UNDER REPEATED NEAR-FIELD EARTHQUAKE

by

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PENGARUH FAKTOR PENGURANGAN DAYA KE ATAS ANJAKAN ANTARA TINGKAT BANGUNAN KONKRIT BERTETULANG TERHADAP GEMPA BUMI BERULANG JARAK DEKAT

oleh

MOHD IRWAN BIN ADIYANTO

Tesis yang diserahkan untuk

memenuhi keperluan bagi

Ijazah Sarjana Sains

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LIST OF ABBREVIATIONS

$(\text{max IDR})_{mean}$	Mean of maximum interstorey drift ratio
2D	Two-dimensional
3D	Three-dimensional
CP	Collapse prevention
DM	Damage measure
EDP	Engineering demand parameter
FFE	Far-field earthquake
IDA	Incremental dynamic analysis
IDR	Interstorey drift ratio
IM	Intensity measure
IO	Immediate occupancy
LS	Life safety
MDOF	Multi degree of freedom
NFE	Near-field earthquake
OL	Operational level
PBD	Performance based design
PBEE	Performance based earthquake engineering
PEER	Pacific Earthquake Research Center
PGA	Peak ground acceleration
PGV	Peak ground velocity
RC	Reinforced concrete
RDR	Roof drift ratio
SCWB	Strong column weak beam

SDOF	Single degree of freedom
USGS	United States Geological Survey
WCSB	Weak column strong beam

LIST OF SYMBOLS

($Sa(T_1$,5%))	5% damped Spectral Acceleration at the fundamental period of building
(z/H)	Normalized storey height
Δ_y	Yield displacement
∞	Infinity
$A_{g.max}$	Maximum peak ground acceleration
g	Acceleration due to gravity, m/s^2
I_b	Moment of inertia of beam
I_c	Moment of inertia of column
K_0	Elastic rotation stiffness
L_b	Length of beam
L_c	Height of column
L_{xi}	Length of structural member along x-axis
L_{yi}	Length of structural member along y-axis
M_c	Capping moment
Mw	Magnitude of earthquake intensity
M_y	Yield moment
N	Number of storey
q_0	Behaviour factor
T_1	Fundamental period of building at first mode
T_p	Pulse period of wave
V_d	Design lateral force of the structure
W	Total weight of building

α_0	dimensionless parameter to control the degree of participation of overall flexural and overall shear deformations in a simplified model of multi-story structure
α_u/α_1	Overstrength factor
β_2	Ratio of maximum interstorey drift to roof drift
γ	Ratio of base shear strength to the weight of the structure
δ	ratio of lateral stiffness at the top of the structure to the lateral stiffness at the base
θ_c	Capping rotation
θ_p	Plastic hinge rotation capacity
θ_{pc}	Post-capping rotation
θ_u	Deformation at which the strength drop to zero
θ_y	Yield rotation
λ	Dimensionless parameter that controls the shape of stiffness distribution along the height of the structure
$\mu_{\theta,c}$	Ductility of plastic rotation capacity
ξ	Damping ratio
ρ	Ratio of the stiffness of all beams at the mid-height story of the frame to the sum of the stiffness of all columns at the same story

LIST OF PUBLICATIONS

Mohd Irwan Adiyanto and Taksiah A. Majid (2011), Seismic Response of Low and High Rise RC Building Subjected to Repeated Earthquake, *Proceeding of 2nd Civil Engineering Colloquium (CEC' 2011), 23 – 24 March 2011, Penang, Malaysia.*

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PENGARUH FAKTOR PENGURANGAN DAYA KE ATAS ANJAKAN ANTARA TINGKAT BANGUNAN KONKRIT BERTETULANG TERHADAP GEMPA BUMI BERULANG JARAK DEKAT

Abstrak

Amalan semasa dalam kejuruteraan gempa bumi hanya mengaplikasikan gerakan gempa bumi tunggal ke atas struktur bangunan semasa permodelan dan analisis. Walaubagaimanapun, dalam kejadian gempa bumi yang sebenar, gegaran berlaku secara berulang sehingga 2 atau 3 kali selepas gegaran yang pertama. Fenomena ini boleh mempengaruhi kekakuan dan kekuatan sistem struktur. Oleh kerana kekurangan masa sebarang kerja baik pulik adalah tidak praktikal. Maka, bangunan mungkin mengalami kerosakan yang lebih besar akibat gegaran yang berulang. Tesis ini membentangkan prestasi seismik untuk 3 dan 18 tingkat bangunan konkrit bertetulang yang dikenakan gempa bumi tunggal dan berulang. Analisis ‘pushover’ dan ‘time history’ tidak lelurus telah dijalankan dengan mengambil kira pelbagai tahap faktor pengurangan daya, R. Tindak balas seismik, dalam bentuk nisbah anjakan antara tingkat telah dibentangkan untuk kedua-dua model. Keputusan daripada analisis menunjukkan bahawa faktor pengurangan daya, R sangat kuat dalam mempengaruhi agihan nisbah anjakan antara tingkat di sepanjang tinggi bangunan. Magnitud nisbah anjakan antara tingkat meningkat dalam lingkungan 3.6% sehingga 4951% dengan peningkatan faktor pengurangan daya, R. Berkenaan dengan fenomena gempa bumi berulang, keputusan analisis menunjukkan bahawa gempa bumi berulang memerlukan anjakan antara tingkat yang lebih besar dalam lingkungan antara 22% sehingga 130% lebih tinggi dibandingkan dengan gempa

bumi tunggal. Tesis ini juga melaporkan kesan ciri-ciri denyutan dalam gempa bumi jarak dekat ke atas tindakbalas struktur. Boleh disimpulkan bahawa gempa bumi jarak dekat dengan ciri-ciri denyutan cenderung untuk memerlukan nisbah anjakan antara tingkat yang lebih besar dalam lingkungan antara 1.5% sehingga 102% lebih tinggi dibandingkan dengan gempa bumi biasa. Disebabkan oleh kesan resonan, nisbah anjakan antara tingkat secara jelasnya adalah paling tinggi bagi bangunan-bangunan yang mempunyai detik asas getaran, T_1 yang hampir sama dengan detik denyutan, T_p.

INFLUENCE OF FORCE REDUCTION FACTOR

ON THE INTERSTOREY DRIFT OF RC BUILDING

UNDER REPEATED NEAR-FIELD EARTHQUAKE

Abstract

Current practices in earthquake engineering only apply single earthquake motion on building structure during modelling and analysis. However, in real earthquake event, the tremors always occurred repeatedly until two or three times after the first tremor. This phenomenon can affect the stiffness and strength of the structural system. Due to lack of time any rehabilitation action is impractical. Thus, the building may experience greater damage due to several repeated tremors. This thesis presents the seismic performance of 3 and 18 storey generic reinforced concrete building subjected to single and repeated earthquake. The pushover and nonlinear time history analysis had been performed with consideration of various level of force reduction factor, R. Seismic response, in term of interstorey drift ratio had been presented for both models. The results from analyses demonstrate that the force reduction factor, R strongly affected the distribution of interstorey drift ratio along the height of the building. The magnitude of interstorey drift ratio increases in range of 3.6% to 4951% higher as the level of force reduction factor, R increases. Regarding to the repeated earthquake phenomenon, the results of analysis demonstrate that the repeated earthquake require larger interstorey drift demand in range of 22% to 130% higher compared to single earthquake. This thesis also reported the effect of pulse characteristic in near field earthquake on the structural response. It can be concluded that the near-field earthquake with pulse characteristic tends to require larger

interstorey drift ratio in range of 1.5% to 102% higher compared to the ordinary earthquake. Due to effect of resonance, the interstorey drift ratio is clearly large for buildings with fundamental period of vibration, T_1 close to pulse period, T_p.

CHAPTER 1

INTRODUCTION

1.1 Background

In general, the reinforced concrete (RC) moment resisting frame building was built and used widely compared to steel, timber, and masonry wall system. This type of building can be found anywhere around the world and for various type of function, from residential to working places and other public assembly. Hence, the seismic performance of RC frame buildings when subjected to earthquake loads always becomes critical issues. Malaysian people with different hierarchy, from the government leaders, local authorities, researchers, engineers and public citizen keep asking the same question on how safe the RC frame buildings subjected to earthquake load is, especially in Malaysia, where there is no provision for seismic code yet.

In earthquake engineering, the inelastic demand of structures due to earthquake loads is very important to be investigated. This parameter can be used as early description for engineers to predict how safe the structures during real earthquake event. High inelastic demand induced by seismic load will cause damage to the non-structural elements such as window frames, door frames, ceiling, electrical wiring, etc. Then, the damage will occur to the structural element, i.e. beams and columns, before the whole structure might experience collapse.

Therefore, this research gives the inelastic demand of multi degree of freedom (MDOF) system for RC building subjected to near-field earthquake (NFE) considering various level of force reduction factor, R. The inelastic demands of low and high rise RC buildings are compared among each other. Repeated earthquake phenomena are also considered in this research alongside with single earthquake.

1.2 Problem Statement

Current seismic provision such as FEMA and Eurocode 8, only consider single earthquake for designing new structures and evaluating the existing structures. Seismic responses in term of maximum interstorey drift ratio (IDR) along the height of the structure always used as the engineering demand parameter (EDP) when the building was subjected to single earthquake records. A limit of 4% of maximum IDR as stated in FEMA 356 need to be satisfied by RC frame building to avoid severe damage and collapse.

According to Krawinkler (2000), the Performance-Based Earthquake Engineering (PBEE) concept include the process of design, evaluation, construction, monitoring, and maintenance of engineered facilities whose responds in various needs and objectives under common and extreme loads. This concept is based on the idea that the performance of the structures can be predicted and evaluated. Thus, the design engineer and client jointly can make better and informed decisions based on building life-cycle considerations alongside the construction costs.

According to FEMA 356, the structural performance levels can be classified into operational level, OL immediate occupancy level, IO life safety level, LS and collapse prevention level, CP. The target building performance levels implemented in FEMA 356 considering the PBEE concept is presented in Table 1.1.

Table 1.1: Damage control and building performance levels (Table C1-2: FEMA 356)

	Target Building Performance Levels			
	Collapse Prevention (CP)	Life Safety (LS)	Immediate Occupancy (IO)	Operational (OL)
Overall Damage	Severe	Moderate	Light	Very Light
General	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	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. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	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.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional.
Non-structural Components	Extensive damage	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipment and contents are generally secure, but may not operate due to mechanical failure or lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.

In operational level, OL the structure retains its original stiffness and strength where the negligible damage occurs to non-structural components. The risk of life-threatening is very low. At immediate occupancy level, IO it is expected that very limited structural damages occur due to earthquake loads where the buildings retain nearly all of their pre-earthquake strength and stiffness. Thus, the risk of life-threatening injury is very low and minor structural repairs may be appropriate for re-occupancy.

Significant damage to some structural elements is expected in the life safety level, LS but this has not resulted in large falling debris hazards. Injuries may occur during earthquake but the overall risk of life-threatening is expected to be low. The damage is still possible to be repaired but for economic reason this may not be practical. For re-occupancy, it would be safer to implement structural repairs or install temporary bracing even the damaged structure is not an imminent collapse risk.

Collapse prevention level, CP means that the building is on the verge of partial or total collapse due to earthquake loads. At this level, severe damage has occurred to structure including significant stiffness and strength degradation, large permanent lateral deformation of the structure even the degradation in vertical load carrying capacity. The risk of injury due to falling hazards from structural debris is high. Technically, the structure may not be practical to repair. Hence, at collapse prevention level, CP the structure is not safe for re-occupancy. The aftershock activity could induce collapse.

Very recently, the effect of multi-event earthquake on the single degree of freedom (SDOF) and multi degree of freedom (MDOF) systems had been explained well by Amadio et. al (2003), Hatzgeogiou and Beskos (2009), Hatzgeogiou (2010a), and Hatzgeogiou (2010b). All researchers found that the seismic response of both SDOF and MDOF systems due to repeated earthquake is totally different compared to single earthquake. Researchers and engineers have to give attention to the aforementioned new findings above because in real earthquake event, the first tremor will be followed by 2 or more tremors after a few moments as shown by the selected real earthquakes data in Table 1.2.

Table 1.2: List of selected real repeated earthquake around the world

No	Date	Time	Mw	Longitude	Latitude	Region
1	24 Nov 2010	04:09:39	5.2	11.89 N	143.59 E	South of Mariana Islands
		06:03:03	5.1	11.96 N	143.50 E	
		11:59:40	5.2	11.96 N	143.56 E	
2	4 Dec 2010	19:02:26	4.5	53.13 N	169.48 W	Fox Islands, Alaska
		20:02:42	4.9	52.07 N	169.56 W	
		20:27:06	4.5	51.93 N	169.52 W	
3	8 Dec 2010	05:24:33	6.3	56.39 S	25.76 W	South Sandwich Islands
		05:46:09	5.1	56.35 S	25.52 W	
		05:49:52	5.3	56.40 S	25.62 W	
4	21 Feb 2011	23:51:42	6.3	43.58 S	172.70 E	South Island of New Zealand
	22 Feb 2011	01:50:29	5.6	43.59 S	172.62 E	
	22 Feb 2011	06:43:30	4.4	43.59 S	172.85 E	
5	9 Mar 2011	18:16:14	6.0	38.37 N	142.50 E	East Coast of Honshu, Japan
	11 Mar 2011	05:46:24	9.0	38.322 N	142.369 E	
	11 Mar 2011	06:25:51	7.1	38.106 N	144.553 E	

(http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/quakes_all.html,

(accessed on 15 March 2011)

The effect of repeated earthquake phenomenon can be simulated as in Figure 1.1. Based on the PBEE concept, the response of structures when subjected to multiple event of ground shaking can be predicted. In Figure 1.1, the original condition of 3 storey RC building before earthquake event is depicted and labelled as A. Then, when the first tremor hit the building, it may response elastically before exceeds the yield state and achieve the immediate occupancy level, IO. At this level (B), the building may experience minor damage such as hairline cracking on wall, damage of door and window frames, and transient drift of 1% (FEMA 356).

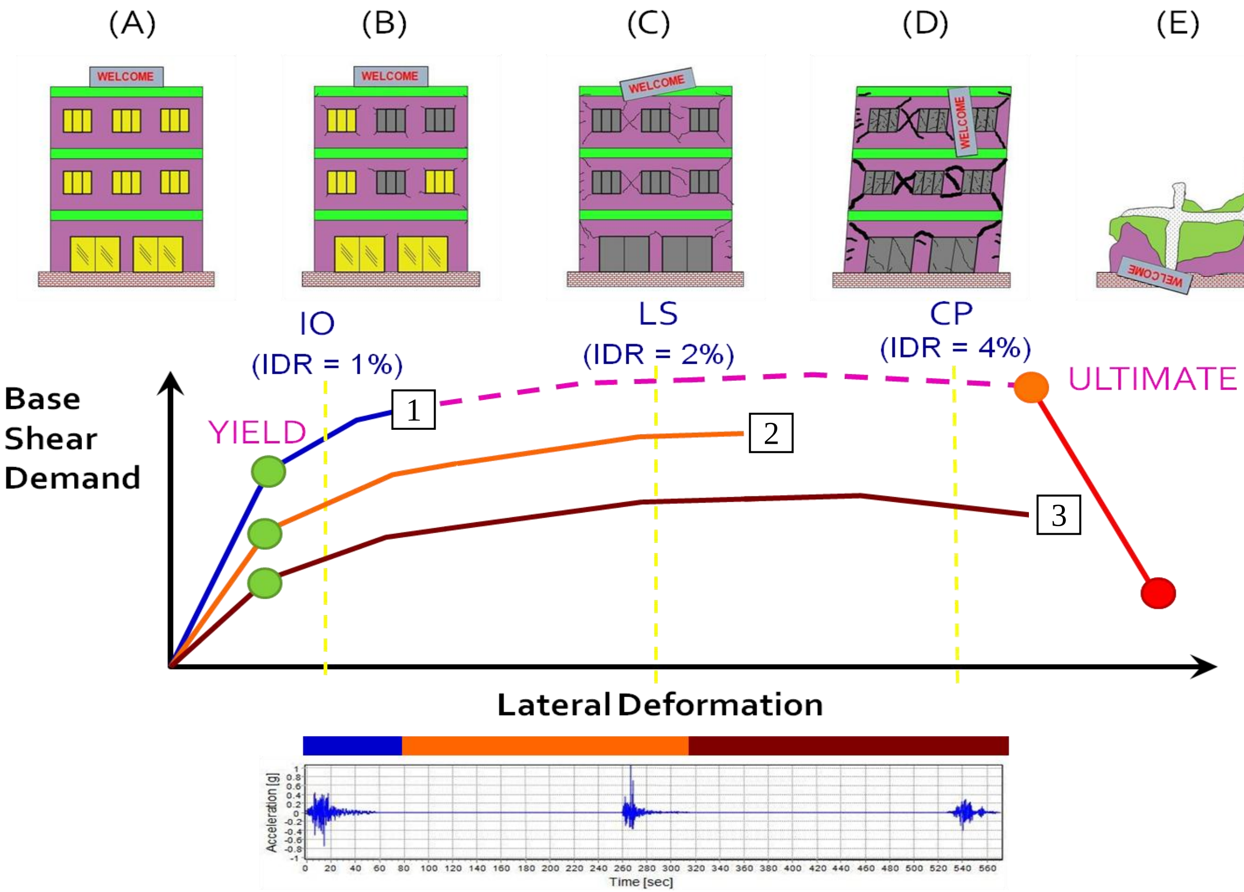
If the first tremor is strong enough to cause the building responses to higher performance level, the moderate damage can be observed. At life safety performance level, LS (building C), the earthquake loads may induce heavier vibration on the building resulting in extensive damage to beam and spalling of concrete cover, and transient drift of 2% is allowed. These may decrease the stiffness and strength of the structure.

Due to lack of time, any repairing work is impractical. The not yet repaired building may subjected to the second and third tremor just a few hours after the first one. Hence, the building may responses up to the collapse prevention performance level, CP (building D) due to action from third tremor. At this level, the building may experience severe damage such as permanent lateral drift (4%) and column buckling (FEMA 356). If the ultimate state is exceeded, the building is structurally unstable and may lead to total collapse when the structure loses its ability to resist the gravity load (building E). Therefore, this research work presents the seismic response of RC building subjected to repeated earthquake and how significant the results differ compared to the conventional single earthquake approach.

Based on Table C1-3 in FEMA 356, all damages and drift limit correspond to different structural performance levels of RC frame building are shown in Table 1.3.

Table 1.3: Damage type and structural performance levels for reinforced concrete building (Table C1-2: FEMA 356)

Element	Reinforced Concrete Frame		
Type of damage	Structural Performance Levels		
	Collapse Prevention (CP)	Life Safety (LS)	Immediate Occupancy (IO)
Primary	Extensice cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Extensive damage to beams. Spalling of cover and shear cracking (<1/18" width) for ductile columns. Minor spalling in nonductile columns. Joint cracks <1/8" wide.	Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).
Secondary	Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints <1/16" width.
Drift	4% transient or permanent	2% transient; 1% permanent	1% transient; negligible permanent



(1: Fore-shock) (2: Main-shock) (3: After-shock)

Figure 1.1: Seismic response of structures as defined by Performance-Based Earthquake Engineering concept.

1.3 Objectives

This research work study the effect of repeated earthquake on the low and high rise RC building. A square shape single bay 3 storey RC building was generated to represents the low rise structure as well as 18 storey RC building will represents the high rise structure. The main objectives of this study are as follows:

i. To determine the inelastic structural demand of RC building in term of maximum IDR, affected by force reduction factor, R when subjected to single and repeated of NFE.

ii. To determine the effect of high velocity pulse in NFE with forward directivity effect compared to ordinary earthquake.

1.4 Scope of Works

This research considers the following scope of works:

i. Only 2 types of number of storey, N = 3 and 18 to represent the low and high rise RC building with fundamental period, T_1 = 0.45 sec and 1.71 sec, respectively.

ii. Only consider the NFE with forward directivity effect in performing the nonlinear time history analysis since the latter require higher demands than the far-field earthquake (FFE) as reported by Kalkan and Kunnath (2006).

iii. 5 levels of force reduction factor, R was selected equal to 1, 1.5, 2, 4, and 6 as recommended by Ruiz-Garcia and Miranda (2006) with some modification as presented by Ade Faisal (2011).

iv. The Modified-Takeda hysteresis model (medium type of rotation capacity) is used to represents the cyclic behaviour of concrete members. The aforementioned hysteresis model considers the strength deterioration.

v. A total number of 3 cases of earthquake (consist of 20 motions for each cases) as used by Hatzigeorgiou (2010b) were adopted in this research.

vi. The RUAUMOKO-3D program (Carr, 2008) was used to perform the nonlinear time history analysis on both 3D generic frames. SAP 2000 computer program was used to perform pushover analysis to determine the building's capacity against lateral load.

vii. Only 2 orthogonal direction of earthquake load considered in this research. The effect of excitation angle is neglected.

viii. Both 3D generic frames are not considering the existence of infill wall. The effect of soil-structure interaction also neglected since fix support is applied at the base of the structure.

ix. Since the square shape building is used as model, this research only considers the maximum IDR as EDP to be investigated.

1.5 Thesis Outline

This thesis consists of five chapters namely as Introduction, Literature Review, Research Methodology, Result and Discussion, and Conclusion. Chapter 1 presents the general background of the study, problem statement, objectives, and scope of works.

Chapter 2 discusses the previous researches presented by previous researchers related to this study work. This chapter shares several researches on the effect of repeated earthquake on SDOF and MDOF system which were used as major reference in this study. Researches relate on how the force reduction factor, R affecting the seismic response of structure also taken into account. The effects of NFE with forward directivity effect on building’s response also discussed in this chapter.

The research methodology of this work is discussed in detail in chapter 3. The 3D generic frame models, alongside with all list of NFE used in this study are presented clearly. In this chapter, the process of generating the artificial repeated earthquake and performing the nonlinear time history analysis using RUAUMOKO program also discussed. The implementation of pushover analysis on both models also include in this chapter.

In chapter 4, the result and discussion obtained from this research work will be highlighted. By employing the maximum IDR as the EDP, this chapter presents the effect of force reduction factor, R and repeated earthquake on the low and high rise RC generic frame models. The pattern of maximum IDR distribution along the height for both models also can be investigated. In this chapter, the nonlinear behaviour of structural system is presented via incremental dynamic analysis (IDA) curve and the effect of pulse in NFE also discussed.

Finally, chapter 5 concludes all findings obtained from this study. This part also includes some recommendations for future research works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter consist of several main sections. The first section presents the effect of various level of force reduction factor, R (denoted as R-factor afterward) on the seismic response of structural system. From previous researches, it is found that the R-factor is strongly affecting the building's performance due to lateral load such as earthquake. Various level of R-factor tends to create variation in magnitude of lateral displacement and distribution of interstorey drift along the height. As the level of R-factor increases, the interstorey drift ratio (IDR) will increase.

General review for past researches that focus on displacement and drift demand of the structure when subjected to earthquake load is presented in the second section. The correlation between several parameters such as the number of stories, N number of mode of vibration, lateral stiffness ratio, α_0 and its distribution along the height, δ on the structural response (roof drift ratio and maximum interstorey drift ratio) are briefly discussed.

The third section in this chapter reviews several past researches regarding the effect of repeated earthquake phenomenon on the structural system. Recently, it is found that the repeated earthquake phenomenon require higher ductility demand compared to the single earthquake counterpart. Furthermore, process of generating the artificial repeated earthquake also discussed in this section based on several scientific works done by other researchers.

Then, the review on other studies such as the effect of near-field earthquake (NFE) on structural response and the application of static pushover and incremental dynamic analysis (IDA) are described in further section.

2.2 Effect of Various Level of Force Reduction Factor, R on Seismic Response.

The evaluation of the R-factor on medium rise reinforced concrete (RC) buildings was presented by Mwafy and Elnashai (2002). Three types of RC building namely as irregular (8 storey), regular (12 storey), and frame wall (8 storey) were used in their study with various design ground acceleration and ductility level. The static pushover and dynamic collapse analysis using eight single earthquakes (including 4 artificial motions) had been performed to all structures with R-factor varies in range of 1.75 to 5.00. Furthermore, upper limit of IDR equal to 3% was adopted as global failure criteria. From their investigation, the authors concluded that due to higher ductility level, yield occur at lower level of ground motion intensity for the structure which assigned higher R-factor. For regular medium rise RC frame, the IDR at collapse occurs at middle storey reflecting the contribution of higher modes of vibration.

Medina and Krawinkler (2003) conducted an analytical study to evaluate the seismic demand patterns as a function of the properties of moment resisting frames and ground motions. They used typical model with various numbers of stories, N ranging from 3 to 18 (3 storey increment). Two types of fundamental period of building at first mode, T_1 = 0.1N and T_1 = 0.2N were employed to each model to represent the RC and steel frame structures, respectively. A total of 80 set of ground motions from Californian earthquake, which compatible with Soil type D (stiff soil) in FEMA 368 were used in their analyses. The variation of R-factor was investigated by various relative ground motion intensity ranging from 0.25g to 15g (increment of 0.25g). They concluded that the dynamic response of short period structures is mostly dominated by the first mode. Thus, the distribution over the height of drift and ductility demands is rather uniform. Except for short period systems, the maximum storey drift angle demands concentrate at the top storey for elastic and relatively low levels of relative ground motion intensity. Furthermore, as the level of relative intensity increases, maximum storey drift angle demands migrate towards the bottom stories. Although employed Strong Column Weak Beam (SCWB) concept and considering the P-Delta effect in structural modelling, they only used single earthquake in their analyses.

Krawinkler et. al. (2003) presented a study regarding the evaluation of the story drift and ductility demands of moment resisting frame structure when subjected to earthquake load. Nine storey building with different fundamental period of building (T_1 = 0.9 sec and 1.8 sec) was used to represent frame structure designed according to SCWB philosophy and considering the P-delta effect. Since the strength deterioration is not incorporated in their analytical model, the limit state of collapse is out from consideration. By using dynamic analysis considering single earthquake, three types of Engineering Demand Parameter (EDP) were used to evaluate the structural response namely as maximum roof drift, average interstorey drift, and maximum interstorey drift over the height. Various level of R-factor, either by increasing the ground motion intensity, [$Sa(T_1)/g$] or by decreasing the ratio of base shear strength to the weight of the structure ($\gamma = V_d/W$) were assigned to both structures and the variation of aforementioned EDPs were presented. The authors concluded that for elastic and lightly inelastic behaviour ($[Sa(T1)/g]/\gamma \leq 2$), the maximum interstorey drift are concentrated at the top of the structure. For weaker structure or higher level of ground motion intensity, the concentration of maximum interstorey drift migrates toward the base. When subjected to ground motions without pulse characteristic, they observed that for long period structures, the ratio of maximum interstorey drift to the roof drift, β_2 is relatively high compared to short period structures.

The investigation on the response characteristics of elastic and inelastic multi degree of freedom (MDOF) frame structures subjected to NFE had been conducted by Alavi and Krawinkler (2004). Single bay 20 storey steel generic frames with damping ratio, ξ equal to 2% was used to investigate the seismic demands of MDOF structures with various fundamental period of building at first mode, T_1. Although adopted constant overstrength factor over the height, the base shear strength was varied with coefficient, γ range from 0.25 to 2.0 where higher value of γ implies higher base shear strength.

Without considering the effect of repeated earthquake phenomenon, a set of 15 NFE records with forward directivity effect which contain pulse characteristic was used by Alavi and Krawinkler (2004) in nonlinear time history analysis in order to evaluate the seismic demand of generic frame models. The pulse period, T_p in most of the NFE records is shorter than 2.0 sec. Hence, the response of MDOF structures with fundamental period, T_1 equal to 0.5 sec and 2.0 sec was compared to study the behaviour of short period and long period structures, respectively. For short period structure ($T_1 \leq T_p$) the maximum storey ductility demands occur in the bottom part of the structure regardless of strength. For long period structure ($T_1 > T_p$) counterpart, early yielding experienced by upper stories when the structure is relatively strong. For the latter, the decreasing of base shear strength tends to cause the story ductility demands stabilize in the upper portion and the maximum demands migrate toward the base. The authors also concluded that the structures with $T_1 \leq T_p$ are more vulnerable compared to those with $T_1 > T_p$.

The results of an analytical study on evaluating the amplitude and height wise distribution of residual drift demands in multi-storey moment resisting frames after earthquake excitation had been presented by Ruiz-Garcia and Miranda (2006). Although the same models were used as Medina and Krawinkler (2003), the authors only focused on steel moment resisting frame structure in their study. Two groups of fundamental period at first mode, T_1 = 0.5 to 1.8 sec and T_1 = 0.7 to 3.3 sec were employed to each model to represent the rigid and flexible structures, respectively. A total of 40 set of single earthquakes which compatible with Soil type D (stiff soil) in FEMA 356 were used alongside 6 level of R-factor which controlling the ground motion intensity (R = 0.5, 1, 2, 3, 4, 6). The results proved that the amplitudes of residual drift demands changes as the number of storey, N and the relative ground motions intensity increases. The distribution of residual drift demands along the height becomes non-uniform as the relative ground motion intensity increases and tends to concentrate at specific storey. Their study also highlighted that the secondary residual drift demands concentration tends to occur at the upper storey of tall frame due to effect of higher modes of vibration.

In addition, Zareian and Krawinkler (2009) developed a simplified Performance-Based Design (PBD) methodology that can be used for conceptual design of structural systems. Their work consists of the identification and quantification of structural parameters that permit a description of component behaviour at all levels of performance. In their study, the authors used typical model of RC moment resisting frame structure with number of storey, N equal to 4, 8, 12, and 16. Then, each model were assigned with different fundamental period at first mode, $T_1 = 0.1N$, $T_1 = 0.15N$, and $T_1 = 0.2N$. Three different level of R-factor had been investigated by using various level of ground motion intensity (0.25g, 0.67g, and 1.17g). Without considering the repeated earthquake phenomenon in analyses, the authors concluded that the profile of interstorey drift is not uniform along the height for different level of R-factor. The increasing value of R-factor tends to cause a concentration of interstorey drift at lower storey. In addition, they also mentioned that from pushover analysis, higher level of R-factor will induce lower yield strength of structural system.

Most recently, Mazza and Vulcano (2010) studied the performance of RC moment resisting frame structures designed according to the European Seismic Code (EC8). Typical symmetric residential building of 3, 6, and 12 stories were considered to study the response of low to high rise structures subjected to NFE. All models were assigned to two level of R-factor equal to 3.90 and 5.85 to represent structures with medium and high ductility, respectively. Without employing any repeated earthquake event, dynamic analyses had been performed to all models using artificial and real NFE recorded from Soil Type A (rock) and Soil Type D (soft soil) according to the European Seismic Code (EC8). In addition, the SCWB frame system was adapted to all models to prevent the formation of soft-storey mechanism. The authors concluded that the maximum IDR at lower storey of low rise building was observed to be greater than the same response observed at lower storey of high rise building. These observations are consistent with the trend of major ductility demand at lower storey. For medium ductility structures, the values of maximum IDR are relatively lower compared to the high ductility structures counterpart.

2.3 Reviews of Previous Researches on Displacement and Drift Demand.

The structural response of multi-storey buildings subjected to earthquake can be estimated by approximate method as proposed by Miranda (1999). By using simplified model of multi-storey buildings with uniform stiffness distribution along the height, the author studied the effect of number of stories, N and the lateral stiffness ratio, α_0 on roof displacement and interstorey drift demands of buildings responding primarily in the first mode of vibration. The dimensionless parameter, α_0 is used to control the lateral deflection shape of continuous model. A value of α_0 equal to zero and ∞ corresponds to a pure flexural and pure shear model, respectively. A multi-storey building that combines both shear and flexural deformations is represented by intermediate value of dimensionless α_0.

According to the Miranda (1999) it is found that the flexural-type buildings have smaller concentrations of interstorey drift than the shear-type buildings. Once the value of roof drift ratio is known, the maximum IDR can be estimated by multiply the roof drift ratio with amplification factor, β_2. The increasing of that factor is depend on three factors namely as number of stories, N, maximum storey displacement ductility ratio, and the type of mechanism. Generally, higher number of stories, N, and higher value of maximum storey displacement ductility ratio tend to give larger increase on the amplification factor, β_2. The aforementioned factor of β_2 also has larger increase in building with Weak Column Strong Beam (WCSB) mechanism.

For most of real RC buildings built around the world, the size of vertical members is usually decreases as the height of the building increases. Hence, the distribution of lateral stiffness along the height is non-uniform where the lateral stiffness at the top of the structure is relatively smaller compared to the lateral stiffness at the base. Motivated by this condition, Miranda and Reyes (2002) had extended the approximate method which was presented earlier by Miranda (1999) to cases in which the lateral stiffness is not constant along the height. By using the same continuous model as used by Miranda (1999), the authors proposed a method to distribute the lateral stiffness along the height which is strongly affected by two non-dimensional parameters, δ and λ. The ratio of lateral stiffness at the top of the structure to the lateral stiffness at the base, δ varies in range of 0.25 to 1.00 (increment of 0.25) where a value of $\delta = 1$ corresponds to uniform lateral stiffness along the height.

The variation of lateral stiffness along the height, either linear or parabolic is controlled by parameter λ which is equal to 1 or 2, respectively (Miranda and Reyes, 2002). In addition, the effect of lateral stiffness ratio, α_0 also was included in their study. According to the authors, moment resisting frame structures usually employ values of α_0 between 5 and 20. Based on comprehensive analyses using single earthquake, the authors found that reduction in lateral stiffness produce only very small increases to lateral displacement for flexural model with α_0 is smaller than 3. For shear model, the reduction in lateral stiffness (decreasing of δ) contributes to significant increases to the top lateral displacement. Hence, for the latter, the ratio of maximum IDR to the roof drift ratio, β_2 is decreased by reducing the lateral stiffness. Furthermore, the type of lateral stiffness variation, either linear or parabolic is negligible due to very small differences of lateral displacement.

Miranda and Akkar (2006) developed a drift spectrum which is useful to estimates drift demand in buildings subjected to earthquake which contain pulse characteristic. A continuous model that consist of combination of flexural and shear deflection had been used to generate the interstorey drift spectrum which considers the contribution of higher modes of vibration. By using selected single earthquake from 1994 Northridge and 1995 Kobe earthquake, the authors investigated the influence of lateral stiffness ratio, α_0 damping ratio, ξ lateral resisting system, and higher number of modes on interstorey drift demand. They found that due to stiffer characteristic and higher damping, the interstorey drift demand of RC moment resisting frame is lower than those computed on steel moment resisting frame. For structural system with fundamental period of building, $T_1 < 2.0$ sec, the drift demand is estimated to be same regardless of the number of modes considered in the analysis.

2.4 Effect of Repeated Earthquake on Seismic Response.

The effect of repeated earthquake on the response of SDOF system with non-linear behaviour was presented by Amadio et. al (2003). In dynamic analyses, the authors used SDOF system with stiffness and strength degradation hysteretic model subjected to one real and two artificial repeated earthquake records. A gap of 40 seconds was assigned between two consecutive events in artificial earthquakes for the structure to cease the vibration due to first event. The authors concluded that at low period structures (T_1 = 0.1 sec to 1.5 sec), the repeated earthquake generally require a strength increase with respect to the single earthquake event. For longer period structures (T_1 > 2.0 sec), the response under repeated earthquake excitation is very similar to the response of the same structures that only consider single earthquake. Thus, the effect of repeated earthquake phenomenon could be very important for the assessment of vulnerability and seismic risk. However, the authors had mentioned that their analyses cannot be considered as exhaustive since only 3 earthquake records were taken into account.

Hatzigeorgiou and Beskos (2009) presented a simple and effective method for the inelastic displacement ratio estimation of a structure under excitation of repeated earthquake. The authors also proposed an empirical expression of inelastic displacement ratio in terms of period of vibration, viscous damping ratio, strain-hardening ratio, and soil classes. Four types of soil classes had been considered in their study namely as A, B, C, and D represent the hard rock, soft rock, stiff soil, and soft soil, respectively according to the definition of the United States Geological Survey (USGS). A total number of 28 real earthquake records for each soil classes had been used in dynamic analyses performed on SDOF structures with various level of R-factor (R = 1 to 8) and fundamental period of building (T_1 = 0.1 sec to 3.0 sec). In their research, the authors proposed appropriate scale factors to be applied on each ground motions for purpose of generating the artificial repeated earthquake.

To cease the moving of any structure, the authors suggested a time gap equal to 3 times of duration of single event to be applied between each consecutive motion. Based on comprehensive analyses, the authors concluded that the lower the fundamental period of building ($T_1 < 0.5$ sec), the higher the inelastic displacement ratio. The local site condition (soil class) and the viscous damping ratio influence the inelastic displacement ratio slightly and can be practically ignored even for the cases of repeated earthquake. Finally, the authors explicitly mentioned that the traditional seismic design procedure which is essentially based on the isolated design earthquake (single earthquake) should be reconsidered.

Hatzigeorgiou (2010a) developed a new procedure for the ductility demands control in SDOF system under excitation of repeated NFE. Based on the well known Gutenberg-Richter law (Gutenberg and Richter, 1954) and the Joyner-Boore empirical relationship, the author explained that for every seismic event with Peak Ground Acceleration (PGA) equal to $A_{g.max}$ there will be two earthquakes with PGA equal to 0.8526 $A_{g.max}$ and three earthquakes with PGA equal to 0.7767 $A_{g.max}$. From more than 26 millions inelastic time history analyses on 8400 SDOF models excited by 3110 number of NFEs either single or repeated, the author concluded that the repeated earthquake require greater ductility demands and lead to greater structural damage. Therefore, the principles of Performance Based Design (PBD) should be reinstated since it is unpractical to examine only the isolated 'design earthquake' and ignoring the repeated earthquake phenomena.

Motivated by previous research, Hatzigeorgiou (2010b) developed the ductility demand spectra for SDOF system under repeated NFE and FFE. Using the same modelling approach as used by Hatzigeorgiou and Beskos (2009), the author used 100 single earthquakes each from far-field and near-field records to generate the artificial repeated earthquake and performing the dynamic analysis. It was observed that the NFE and FFE require different ductility demand for both single and repeated earthquake. The repeated earthquake strongly affected the ductility demand which is greater than that caused by single earthquake and can lead to greater damage. Hence, it seems impractical to only consider the isolated design earthquake without taking into account the influence of repeated earthquake phenomenon on ductility demand. Again, the traditional seismic design procedure should be generally reconsidered.

The result of an extensive parametric study on the inelastic response of eight 2D RC frames under 45 repeated earthquakes was presented by Hatzigeorgiou and Liolios (2010). The authors focused on the results of local or global structural damage, maximum displacement, maximum IDR, development of plastic hinges, and the inelastic response using incremental dynamic analysis (IDA) method. For that purposes, the 3 and 8 storey RC buildings with 3 equal bays had been selected to represent the low and medium rise buildings, respectively. Two different shapes were assigned to both structures namely as vertically regular and vertically irregular. In term of design, both structures were divided into seismic and non-seismic design approach. In order to generate the artificial repeated earthquake, the authors recommended to using a time gap of 100 seconds between two consecutive seismic events to cease the moving of any structure due to first tremor. In the end of their investigation, the authors concluded that the repeated earthquake require increased displacement demand as well as the IDR in comparison with single earthquake.

Furthermore, the development of plastic hinges are strongly affected by the repeated earthquake which can be differ than that caused by the single earthquake.

In order to investigating the effects of as-recorded repeated earthquake on the response of MDOF systems, Ruiz-Garcia and Negrete-Manriquez (2011) evaluated the performance of steel frame buildings due to mainshock and aftershock. Three different models consist of 4, 8, and 12 numbers of stories with 5 % of Rayleigh damping had been selected to represent the existing low to medium rise steel office buildings. The nonlinear time history analyses had been conducted to all models using 64 as-recorded mainshock-aftershock ground motions recorded during the 1980 Mammoth Lakes and 1994 Northridge earthquakes. According to the authors, due to aftershock activities, the IDR are increases depend on the period of vibration, number of stories, and the storey height. The authors also had proved that the near-field earthquakes induce larger IDR compared to the far-field earthquakes.

2.5 Response of Structures Subjected to Near-Field Earthquake.

Kalkan and Kunnath (2006) examined the response of typical existing moment resisting frame structures to NFE and also the demands due to FFE counterpart. In NFE, forward directivity effect exhibits the pulse-like characteristic while the fling-step associates with the permanent deformation of ground surface. On the other hand, the FFE have been observed as totally different compared to its NFE counterpart. Figure 2.1 presents the comparison in terms of velocity and displacement time history between all three types of aforementioned earthquakes.