INFLUENCE OF EXCITATION ANGLES OF GROUND MOTION WITH FORWARD DIRECTIVITY EFFECT ON THE RESPONSE OF REGULAR AND SYMMETRIC REINFORCED CONCRETE BUILDINGS

by

HANEEN MOSBAH RATEB DEFALLAH

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LIST OF SYMBOLS

Δ_i	Drift Value of Floor (i)
A	Sectional Area
ASCE 2006	The ASCE Standards 7-05 “Minimum Design Loads for Buildings and Other Structures”, American Society of Civil Engineers – 2006
CQC	Complete Quadratic Combination Rule
DM	Damage Measure
E	Modulus of Elasticity
EDPs	Engineering Demand Parameters
Euro Code 8	Eurocode 8: Design of Structures for Earthquake Resistance. Part 1: General Rules, Seismic Actions and Rules for Buildings – 2003
FEMA 368	Building Seismic Safety Council for the Federal Emergency Management Agency – 2001
G	Modulus of Rigidity
GMC	General Model Combination
I	Effective Moment of Inertia
IBC 2000	International Building Code – 2000
IDA	Incremental Dynamic Analysis
ISO 2003	Petroleum and Fundamental Gas Industries – Specific Requirements for Offshore Structures – Part 2: Seismic Design Procedures and Criteria, International Organization for Standardization – 2003
Mw	Magnitude of Ground Motion
NZS 2004	Code and Supplement of the New Zealand Standard 1170.5 – 2004
PBEE	Performance-Based Earthquake Engineering
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity

RC	Reinforced Concrete
RHA	Response History Analysis
RSA	Response Spectrum Analysis
Sa(T1,5%)	Pseudo Spectral Acceleration at the Building Fundamental Period with 5% damping ratio
$Sa(T_{flexible})$	Spectral Acceleration of the Record Matches of the IBC at the Calculated Period of the Structure Model with Flexible-Base Condition
$Sa_{,max}$	Maximum Pseudo Spectral Acceleration as Specified by IBC (2000)
$Sa^{Y=1}$	Spectral Acceleration that Corresponds to Unit Value for Y (to failure
SPO	Static Pushover Analysis
SRSS	Square Root of the Sum of Squares
THA	Time History Analysis
UBC 1997	Uniform Building Code – 1997
Y	Critical Demand to Capacity Ratio
$\beta_{Sa}{}^{Y=1}$	Fractional Standard Deviation
$\eta_{Sa}{}^{Y=1}$	Median; or the Number in the Middle of a Set of Numbers
θ	Inter-Story Drift Ratio
θ_{00}	Maximum Inter-Story Drift Ratio of Principal Axis (Angle = 0°)
$\theta_{critical}$	Maximum Inter-Story Drift Ratio at Critical Angle
$\theta_{max.}$	Maximum Inter-Story Drift Ratio
$\bar{Y}$	Mean of Y values
n	Number of Y values
Φ	Lognormal Distribution Function
h_i	Height of Floor (i)

PENGARUH SUDUT PENGUJAAN PERGERAKAN TANAH DENGAN KESAN TERARAH KEHADAPAN TERHADAP TINDAKBALAS BANGUNAN KONKRIT BERTETULANG BIASA YANG BERSIMETRI

ABSTRAK

Prosedur sedia ada analisa seismik hanya mengatakan arah gerakan dasar bumi perlu dikenakan pada arah utama bangunan, yang berkemungkinan tidak menghasilkan tindakbalas struktur maksima. Untuk memastikan tahap analisa kebolehterimaan apabila merekabentuk bangunan, amat perlu mengenalpasti sudut pengujaan kritikal yang menghasilkan tindakbalas struktur maksima dalam terma nisbah anjakan-tingkat. Untuk mengkaji nilai nisbah anjakan-tingkat, kajian ini mengaplikasi analisa dinamik tak lelurus tak anjal terhadap bangunan konkrit bertetulang 6 tingkat dengan 4 tempoh asas yang berbeza dengan merubah nilai inersia model tanpa sebarang rekabentuk semula bangunan. Tujuh gerakan dasar bumi dikenakan pada pelbagai sudut pengujaan (dalam julat 0o hingga 170 o) ke setiap bangunan, yang mewakili kesan terarah ke hadapan dan rekod pecutan diskalakan dengan nilai tinggi dan rendah untuk mengambilkira pelbagai kesan buruk gerakan dasar bumi dari rekod yang sama. Lengkungan Analisa Tokokan Dinamik juga telah dijalankan untuk mengkaji kesan sudut pengujaan kritikal terhadap tindakbalas struktur dan mengenalpasti sudut pengujaan kritikal. Kebarangkalian struktur gagal juga dikaji menggunakan lengkok kerapuhan. Kajian dijalankan untuk mencerap bagaimana tempoh asas model memberi kesan terhadap sudut pengujaan kritikal dan kebarangkalian struktur gagal. Keputusan sudut pengujaan kritikal pada sudut 140o atau 150 o untuk komponen seismik utama dan 50o atau 60 o untuk komponen sekunder. Tindakbalas struktur maksima boleh mencapai sehingga 25% untuk komponen seismik utama dan menjangkaui 75% untuk komponen sekunder, berbanding tindakbalas yang terhasil dalam arah utama bangunan. Keputusan juga menunjukkan sudut pengujaan kritikal dipengaruhi oleh tempoh asas bangunan. Tambahan pula lengkok kerapuhan menunjukkan pecutan spektra di titik alah mempunyai nilai yang berbeza untuk setiap jenis gerakan dasar bumi pada bangunan yang sama jenis dan mempunyai nilai yang berbeza untuk tempoh asas yang berlainan. Diperhatikan juga bahawa apabila denyutan besar gerakan dasar bumi mengenai struktur lebih awal dari denyutan yang terdapat dalam rekod, kebarangkalian struktur gagal bertambah.

INFLUENCE OF EXCITATION ANGLES OF GROUND MOTION WITH FORWARD DIRECTIVITY EFFECT ON THE RESPONSE OF REGULAR AND SYMMETRIC REINFORCED CONCRETE BUILDINGS

ABSTRACT

Existing procedure of seismic analysis was to apply ground motion components at the principal axes, which may not produce a maximum structural response. In order to ensure an acceptable level of reliability of analysis when performing a design, it is important to find the critical excitation angle that produces the maximum structural response. To investigate values of inter-story drift ratio, the current research applied nonlinear inelastic dynamic analysis to a six story RC building with four different fundamental periods, by adjusting the inertia value of the models without redesigning the building. Seven sets of ground motions were applied at various angles (ranging from 0° to 170°) to each building. These ground motions exhibiting the forward directivity effect and the acceleration records were scaled up and down to account for more or less severe ground motions from the same record. Incremental dynamic analysis (IDA) curves were formed to study the effects of different excitation angles on the structural responses and to specify the critical excitation angle. The probability of structural failure was studied with fragility curves. An investigation was carried out to observe how the fundamental period of the model affects the critical excitation angle and probability of structural failure. The critical excitation angles were found to be 140˚ or 150˚ for the main seismic component and 50˚ or 60˚ for the secondary one. The maximum structural response can be up to 25% and up to 75% larger than the response produced when the main and secondary seismic components, respectively, are applied along the principal axes. The results also showed how the critical excitation angle has different values with different fundamental building periods. Also, the fragility curves showed that the spectrum acceleration at the yield point has different values with different ground motions on the same building type, and has different values at different fundamental building periods. It is also noticed that when the large pulse of ground motion hits the structure sooner than the rest of the pulses in the record, the probability of structural failure is increased.

CHAPTER 1

INTRODUCTION

1.1 Overview

An earthquake is defined as a sudden movement in a segment of the earth's crust along fault lines and it occurs because of a sudden release of stored energy. The earth's crust consists of a number of plates which move continuously in relation to each other. When the strain becomes great enough to overcome the friction between the plates, rock masses crack and slip past each other causing an earthquake (Abas, 2007).

Strong ground motion occurs at close range, less than 50 km from the fault that caused the shaking. The strength of the shaking involved in the strong ground motion usually overwhelms a seismometer, forcing the use of accelerographs (or strong ground motion accelerometers) to record it.

Since the beginning of time, there have always been earthquakes of different strengths, at different locations, with different effects. Some of these events have changed the shape of the map; some have killed hundreds or thousands of people and destroyed their belongings, whereas in some events people have not even felt them.

The biggest measured earthquake since 1900 according to (USGS, 2009) had a magnitude of 9.5 on the Richter scale and took place in 1960 in Chile, causing more than 2,000 deaths, with 3,000 injured, two million homeless and $550 million of damage in southern Chile. The tsunamis which followed the earthquake measured as high as 25 meters close to the epicentre. They killed 61 people in Hawaii, 138 in Japan, 32 in the Philippines, and caused $500,000 worth of damage on the US west coast.

To avoid such losses in lives and reduce the damages as much as possible, the discipline of earthquake engineering was developed. Many seismic variables, analysis methods, design criteria and specifications were developed to try to reduce and control earthquake damage.

Some of these variables are building type, importance, weight, height, soil type, seismic zone, direction of ground motion e.g. horizontal and/or vertical, etc.

Applying multiple components to represent the ground motion along different directions is an option the researcher has to made. Generally, it is common to use bidirectional components; these include two horizontally perpendicular components as shown in Figure 1.1, or three directional components where a vertical component is added on top of the two bidirectional components.

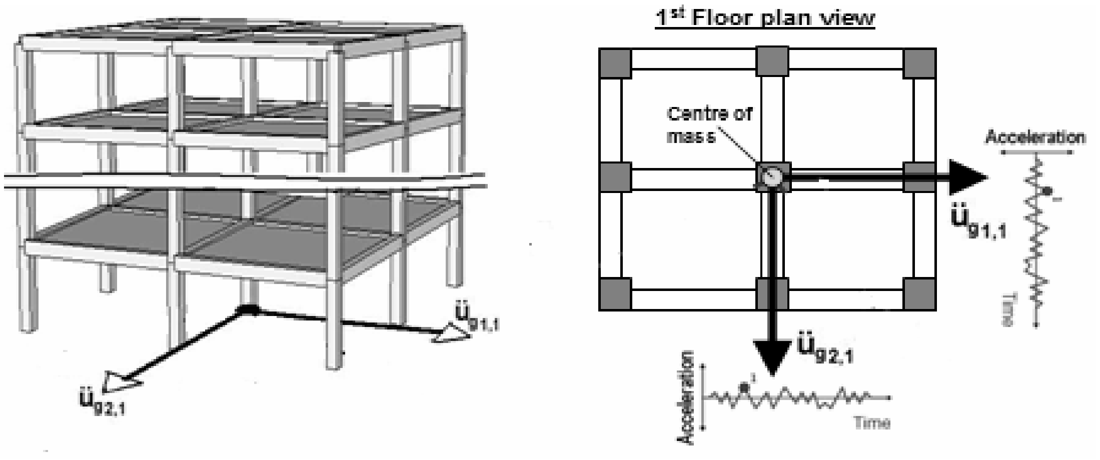


Figure 1.1: Bidirectional Components of Ground Motion Applied at the Centre of Mass of a Regular Building

Vertical component of ground motions is generally lower than the corresponding horizontal components. Most of the building codes including e.g. UBC 97 assume the vertical component of the ground motion to be ½ to ⅔ of the horizontal component. The vertical component is not of great significance to structural design of most kinds of structures, but usually it is considered for bridges (Priestley et al., 1996). Figure 1.2 shows the direction of three seismic components applied at the centre of mass of a regular building.

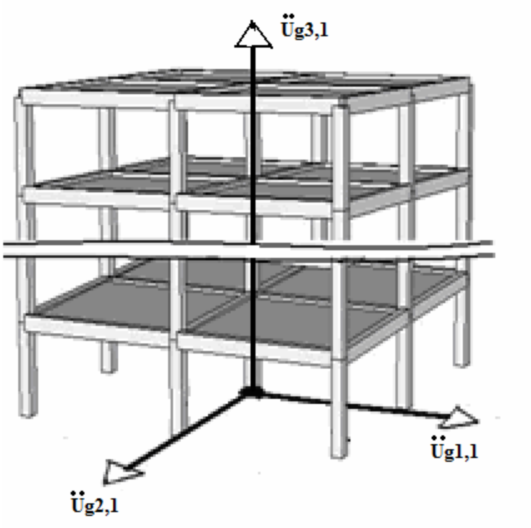


Figure 1.2: Three Seismic Components of Ground Motion Applied at the Centre of Mass of a Regular Building

There are some characteristics that could govern the ground motions; these include the forward directivity effect, fling-step effect, or just simple ground motion. Ground motions with forward directivity effect occur when the velocity of rupture is close to the velocity of shear waves in the rock mass near the source and produce pulse-type motions that differ significantly from ordinary ground motions that occur at greater distances from the causative fault (Rodriguez-Marek and Bray, 2006).

It should be mentioned that the forward directivity effect in the velocity record has the signature of a long period, short duration and high pulse amplitude in the direction of rupture (BSSC, 2003). But the fling-step effect causes a permanent ground displacement which occurs across the rupture fault. This static displacement occurs over a finite time interval of several seconds in which the fault-slip is concentrated (Agarwal and Shrikhande, 2006) and the difference between these characteristics is seen more clearly in Figures 1.3 to 1.5.

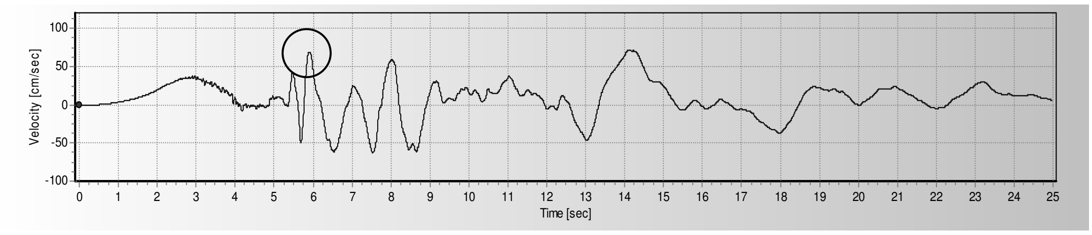


Figure 1.3: Velocity Record for Ordinary Ground Motion

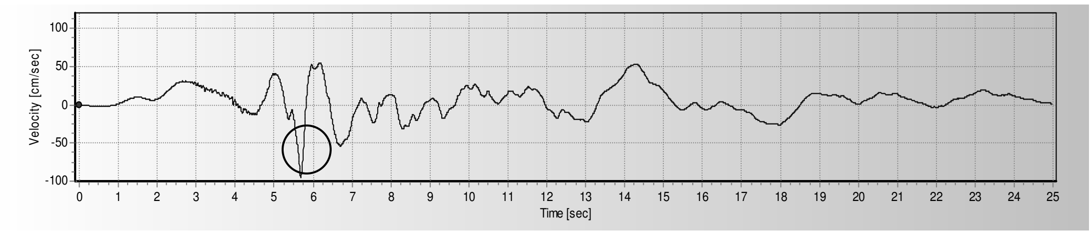


Figure 1.4: Velocity Record for Ground Motion with Forward Directivity Effect

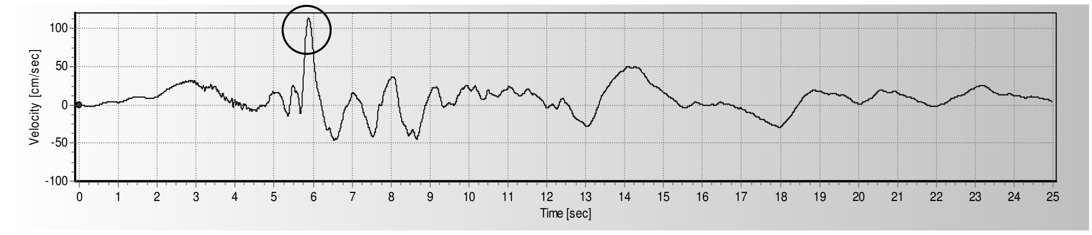


Figure 1.5: Velocity Record for Ground Motion with Fling-Step

The properties of a building influence its responses to ground motion. The most significant properties are: mass, fundamental period of structure, and damping ratio of structure. No building could resist a major earthquake without some kind of damage. Hence, it is necessary to define various kinds of damage and tolerable levels of damage. The most critical damage is the total collapse of a building, or some significant part of it. More often, there is some damage which does not result in the collapse of the building or injury to the occupants but causes the building to be unusable. Lastly, minor but undesirable damages, such as cracked plaster, jammed doors and broken window glass are known to occur. Although it is important to prevent all forms of damage, the injury of the building's occupants is the major concern. Apparently, the collapse of the structure is a major concern in order to protect the safety of occupants and prevent hazards to the surroundings of the building. Ideally designers prefer buildings which respond to earthquakes with minimal damage and with the lowest possible risk of injury or loss of life of occupants.

There are many analyses methods such as 30% rule, SRSS combination, and 20% rule, IDA method …etc. and design methods such as the ultimate strength design method.

IDA method is a parametric analysis method to estimate more thoroughly the structural performance under seismic loads. It involves subjecting a structural model to one or more ground motion records, each record being scaled to multiple levels of intensity.

There are many responses which can be obtained and studied from the analysis carried out for any structure. Such responses are: axial force, bending moment, shear force, displacement, and inter-story drift ratio.

The axial force is the resultant longitudinal internal component of force that acts perpendicular to the cross-section of a structural member and at its centroid, producing uniform stress, and is shown in Figure 1.6.

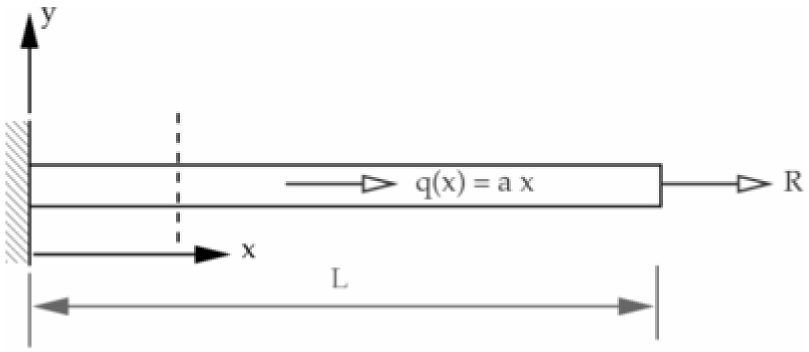


Figure 1.6: Axial Force

The bending moment can be calculated by multiplying the force by the distance between the centroid and the point of application of the force and Figure 1.7 shows an example for this force. The shear force is an external force that acts parallel to a plane as shown in Figure 1.8.

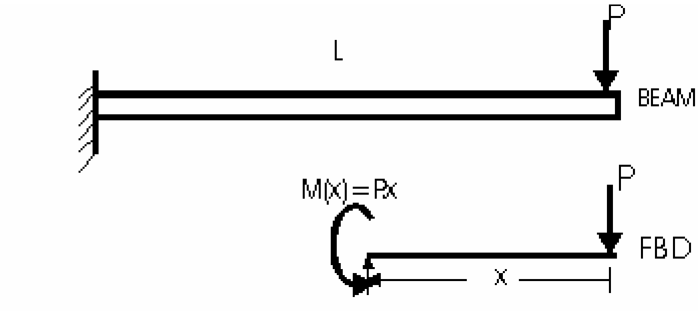


Figure 1.7: Bending Moment

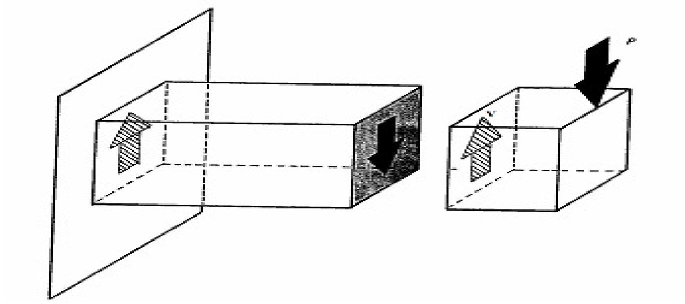


Figure 1.8: Shear Force

The displacement and inter-story drift ratio are shown in Figures 1.9 and 1.10 respectively. Many researchers (Vamvatsikos and Cornell, 2002a, Vamvatsikos and Cornell, 2002b, Vamvatsikos and Cornell, 2004, Kalkan and Kunnath, 2006) who are interested in incremental dynamic analysis and excitation angles use the inter-story drift ratio as the structural response.

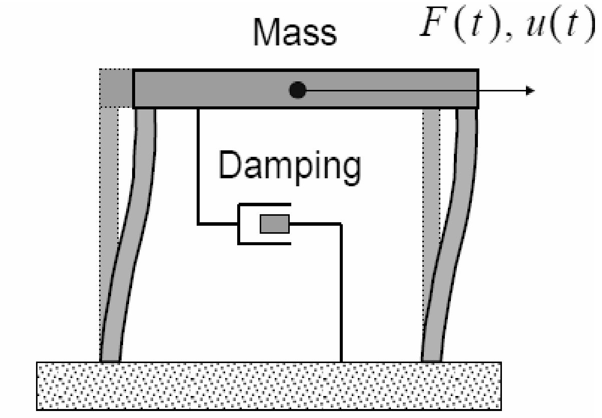
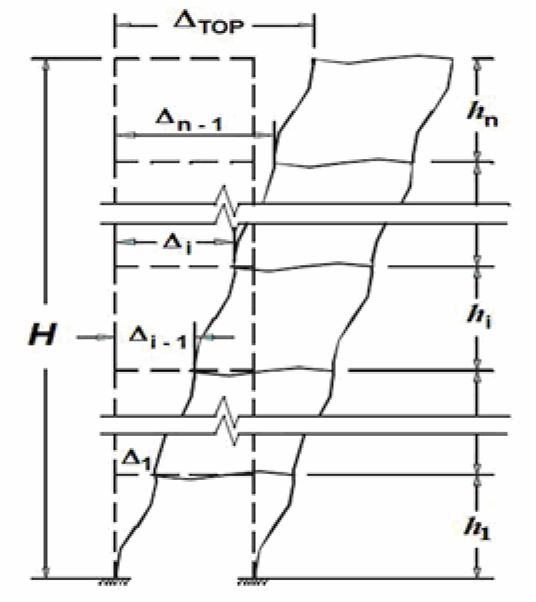


Figure 1.9: Displacement



$$\theta = (\Delta_i - \Delta_{i-1}) / h_i$$

Figure 1.10 Inter-Story Drift Ratio

One of the ways to use the above mentioned structural responses is studying the probability of failure. The probability of failure is the probability of reaching the capacity point and this probability depends on the amount of demand (Wen et al., 2003). And this probability can be extracted from the fragility curve.

1.2 Problem Statement

One issue which has been neglected by seismic codes so far is that they do not state in what direction to apply the ground motion components to get maximum structural responses (Beyer and Bommer, 2007). Structural engineers used to apply the ground motion on the principal axis to get the structural responses and design the structure according to these responses. Researchers have started to carry out investigations into critical excitation angle/s that produce critical structural responses, where the critical responses are defined as maximum and minimum structural responses for any ground motion incident angle (Marinilli and Lopez, 2008).

According to ASCE 7-05 and FEMA 368, the seismic components must be applied in the direction that will produce the worst structural response. Figure 1.11 shows the excitation angle (α) measured from the principal axis.

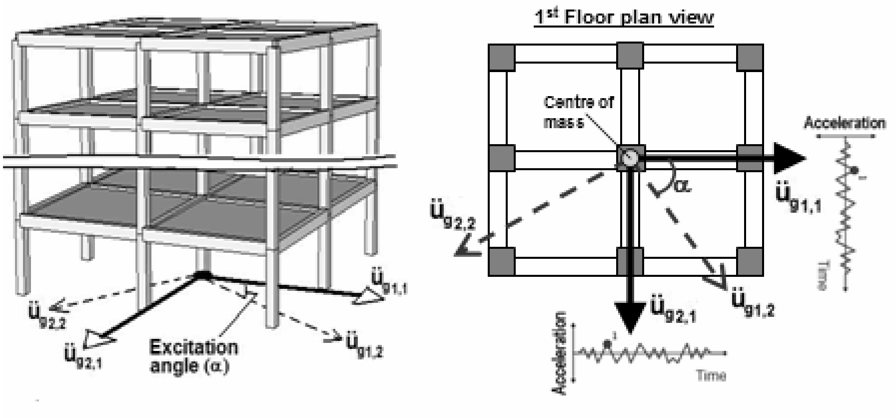


Figure 1.11 Bidirectional Ground Motion Components Applied at the Excitation Angle (α)

Several combination rules such as the 30–100% rule shown in Figure 1.12, 40–100% rule and other methods were used to distribute the combinations of ground motions along orthogonal directions. In this way, the analysis was based primarily on the horizontal components of ground motion applied along the principal axes of the buildings.

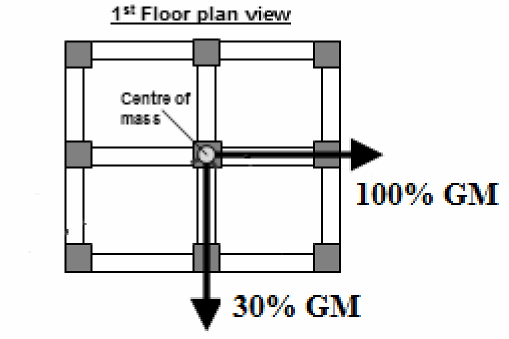


Figure 1.12: Ground Motion Components According to the 30–100% Combination

However these rules have various disadvantages. For example, they do not always produce conservative results and are limited to elastic analysis although it is widely believed that structures can be expected to behave inelastically during major earthquake events (Wilson and Suharwardy, 1995). Such studies primarily considered the elastic behaviour of structures (Wilson and Button, 1982); (Wilson and Suharwardy, 1995); Fernandez-Davila et al., 2000; Athanatopoulou, 2004).

In order to determine collapse prevention and immediate occupancy according to FEMA 368, elastic analysis is not sufficient and inelastic analysis must be carried out. Although (Alavi and Krawinkler, 2004; MacRae and Mattheis, 2000; Rigato and Medina, 2007) have carried out studies using inelastic analysis, none of them apply it on multi story RC building.

1.3 Objectives

The main objectives of this research study are:

i) To investigate the inter-story drift ratio for six stories RC buildings by nonlinear inelastic analysis, with each building having a different fundamental period and using various excitation angles to apply the seismic ground motions.

ii) To investigate incremental dynamic analysis curves to find the critical angle/s and to investigate the probability of failure with fragility curves.

iii) To investigate how changing the fundamental period of the model affects the critical excitation angle/s and probability of failure.

1.4 Significance of the Study

In this research, a group of seismic variables and structural properties were chosen to study the performance of multi-story RC buildings affected by ground motions with forward directivity effect and these variables have not been applied before in any previous study. This group of variables includes:

i. seven ground motions with forward directivity effect, each of different magnitude,

ii. bidirectional horizontal ground motion components,

iii. various excitation angles,

iv. four symmetrical RC buildings with different fundamental periods,

v. nonlinear inelastic time history analysis based on the Incremental Dynamic Analysis (IDA) method.

From the results, the critical angle/s can be determined, the angle that should be applied to the components of ground motion in seeking the maximum structural responses to a seismic event. Also, it shows whether or not the maximum responses can be achieved when the seismic forces are applied along principal axes, and whether changing the fundamental period of the building affects the results.

1.5 Scope of the Study

As mentioned in the previous section, there are many seismic variables and structural properties that affect the behaviour of a building during an earthquake. The focus of the study is as follows:

i) Ground motion with forward directivity effect.

ii) Nonlinearity of materials is considered but not the geometrical nonlinearity effect (P-delta effect) since it is usually used for slenderer buildings which can undergo large deformations.

iii) Since the building is symmetrical and the seismic components were applied at the centre of mass of the building, the torsional effect is not taken into consideration.

1.6 Thesis Layout

This thesis is organised into five chapters as follows:

Chapte 1 include introduction for the basic concepts in earthquake engineering.

Chapter 2 presents an overview as well as highlights of previous work that has been carried out in this field of research.

Chapter 3 presents the methodology adopted in the study.

Chapter 4 validates the programs used to run the analysis by regenerating a previous study and comparing the results. It then shows the results of the current study and discusses them in detail.

Chapter 5 contains the conclusion of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Studying ground motions started with studying the codes around the world, and how these codes specify the number of ground motions needed to be used through performing seismic analysis. The next step researchers start to concentrate on modifying ground motions and finding a guide line to select them. Afterwards researchers studied scaling and quantifying ground motion records and the largest pulse in these records.

To study excitation angle some studies compared between the responses of existing combinations and rules, then a coparison between the responses obtained from these combinations and rules and the responses obtained by applying ground motion along the principal axes. Other studies established formulae for determining the critical excitation angle and associated critical responses.

To see the effect of using a different number of components on the structural responses, comparison was made by some researchers.

Most of the previous research studies until 2007 have employed elastic and linear analysis. However, during severe seismic events, the building is likely to behave in a nonlinear inelastic way. After that some research studies were performed to study nonlinear inelastic behaviour on buildings with different heights and materials.

Some researchers concentrated on finding a guidelines for selecting the magnitude of the response spectrum and investigating a complete quadratic. In 2008, a comparison between both methods of analysis (RSA and THA) was made to show which methods gives better accuracy in results. Studies on how near fault ground motion with different characteristics such as the forward directivity effect or fling step affect buildings with different heights were also carried out.

Describing IDA method and how to handle the rich data from it in numerous analyses and extract useful conclusions was done after 2002.

The seismic design needs to ensure that, during seismic events, the structural performance will not reach specific limits. Researchers have tried to calculate such values in a probabilistic way. The next step in the research study is to use the value of the probability of reaching a specific point to evaluate the damage.

2.2 Earthquake Ground Motions

The effects of ground motions on the crust of the earth include: fault rupture, ground shaking, landslides, liquefaction, and tsunami. But the severity of these effects depends on several factors like the magnitude of the earthquake, where and when the earthquake occurs, the geological characteristics in the area between the source and site, soil conditions at the site, and the population density in the area (BSSC, 2003).

According to (Bommer and Ruggeri, In Bommer and Acevedo, 2004), out of 33 current seismic codes, only eight specify that real records should be used in the dynamic analysis. As ground motions occur randomly and the calculated response can be very sensitive to the characteristics of the individual ground motion used as seismic input, the procedure of choosing one ground motion for seismic design is not reliable. The codes recommend the minimum ground motions required in the analysis and design process, as shown in Table 2.1. UBC 1997, IBC 2000 and FEMA-356 have recommended three ground motions as a minimum to give maximum responses or seven ground motions to get the mean or median response and these recommendations are listed in Euro Code 8 as well as in ASCE. NZS recommends only three ground motions be used and ISO recommends four.

Using the mean (average) or median (middle value) for the structural responses that have been carried out after applying seven ground motions is still a debatable matter; (Athanatopoulou, 2004) and (Rigato and Medina, 2007) used the mean of the responses, while (Cornell et al., 2002) and (Vamvatsikos and Cornell, 2002a) used the median response.

Table 2.1: Seismic Code Requirements for Ground Motion Records

Code	Ground Motion Record Type	Minimum No. of Records
UBC 1997	Recorded or Simulated	3 or 7
IBC 2000	Recorded or Simulated	3 or 7
Euro Code 8	Artificial, Recorded or Simulated	3 or 7
FEMA 368	Recorded or Simulated	3 or 7
ASCE 2006	Recorded or Simulated	3 or 7
NZS 2004	Recorded	3
ISO 2003	Recorded	4

In Table 2.1 recorded ground motions fit the features of the source and the soil conditions at the site. Records need to be scaled to the peak ground acceleration in the top soil layers. Artificial ground motions are records that match the code elastic response spectra. The duration of accelerograms should be consistent with the magnitude and other relevant features of the seismic event. And the simulated ground motions generated in a physical simulation of source and travel path mechanisms must comply with the requirements of recorded ground motions (Stratan and Dubina, 2008).

Mayroeidis and Papageorgiou (Mayroeidis and Papageorgiou, 2003) have presented in their research a simple and effective mathematical model to represent strong ground motions near a fault. An example is presented in Figure 2.1. In their study, 170 excitation records were selected with different fault types and magnitudes. The advantages of this model are that it can describe the quality and quantity of the pulse in the ground motion record and, from the original records, empirical observations can be reproduced analytically. The differences between pulses and non-pulses can be seen in Figures 1.3-1.5 shown previously in Chapter 1. Another simple method was presented to create realistic artificial ground motions that are suitable for seismic analysis and design.

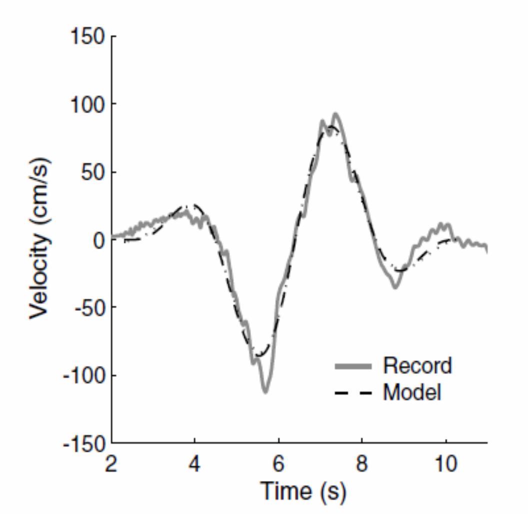


Figure 2.1: Example of a Pulse Generated by the Mathematical Method by (Mayroeidis and Papageorgiou, 2003)

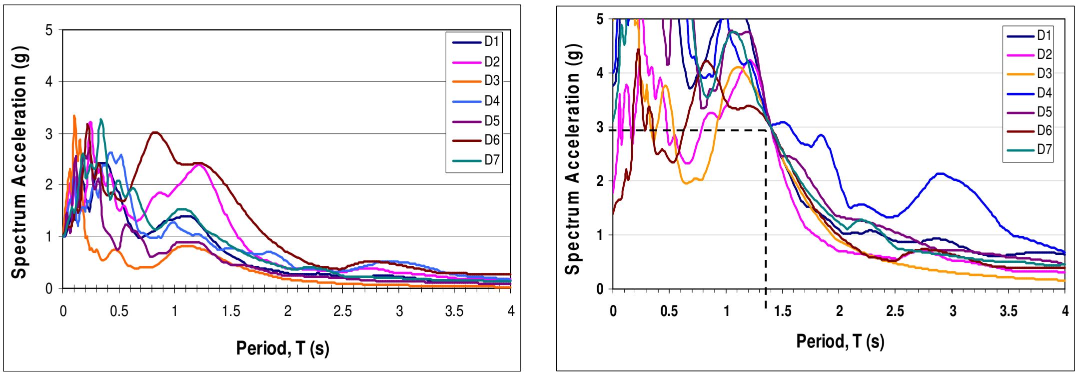
Even though (Mayroeidis and Papageorgiou, 2003) have presented a method to modify ground motion records, the engineer or the researcher still needs guidelines for selecting such records. This issue has attracted the attention of Bommer and Ruggeri (2004).

In their paper, Bommer and Ruggeri (2004) aimed to provide guidelines for selecting real records and records with response spectral ordinates. To achieve this, their paper pointed to some global databanks and internet sites which provide ground motion accelerograms. The records can be classified according to: seismological parameters (e.g. magnitude, focal depth, site classification) or ground motion parameters (e.g. peak amplitude, spectral ordinates, durations). The selection of ground motion records and the way that seismic design codes deal with this issue were discussed.

Selecting and modifying ground motion records is the first step taken by the researchers, but the next step involves scaling and quantifying these ground motion records and the largest pulse in these records.

In their paper, (Beyer and Bommer, 2007) tried to concentrate on some features related to the selection and scaling of bidirectional ground motion records. An example of the effect of scaling on ground motions is shown in Figure 2.2 and the concept of scaling is detailed later in the chapter. In the paper, a comparison between seismic codes for selecting, scaling, and applying directions to bidirectional seismic analysis was made and the individual processes were discussed. The authors presented a case study and all steps that were applied were listed in the paper.

Meanwhile, (Baker, 2007) provided a method for quantifying ground motions that include the forward directivity effect. This method extracts the largest velocity pulse from the ground motion by using wavelet analysis according to the size of this large pulse relative to the original ground motion which categorizes the ground motion as “pulse like”. Figure 2.3 shows an example of an extracted pulse. For further classification, two more conditions were applied: whether the pulse starts early in the record and whether the velocity pulse has large amplitude. This method was applied to over 3500 ground motions in order to extract 91 motions with large pulses. Many areas of research have profitted from this method; namely nonlinear dynamic analysis, research in probabilistic seismic hazard analysis, and ground motion prediction models.



(a) (b)

Figure 2.2: Example of the Effect of Scaling Seven Ground Motions: a) with Scale = 1, and b) with Scale = 3

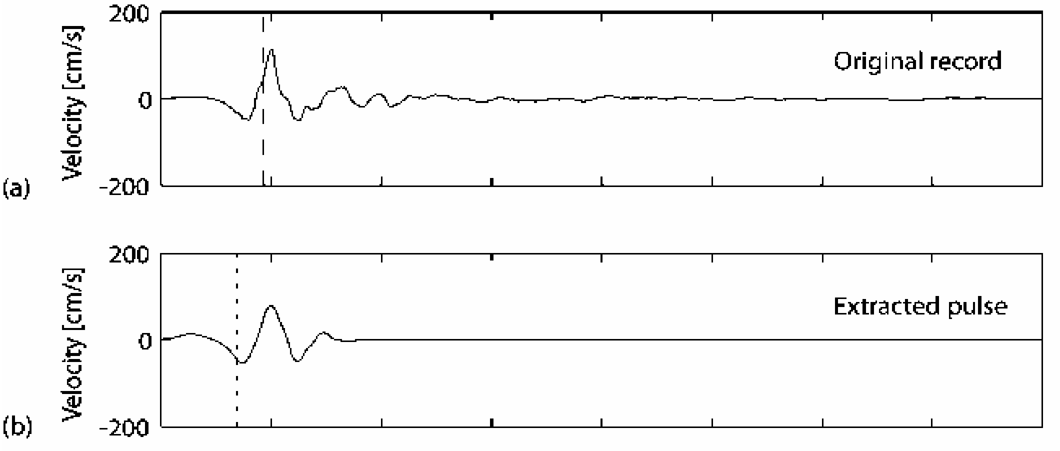


Figure 2.3: An Early-Arriving Pulse (the 1979 Imperial Valley): a) Original Ground Motion, b) Extracted Pulse (Baker, 2007)

2.3 Ground Motion Excitation Angles

In their paper, (Fernandez-Davila et al., 2000) looked at five-story RC structures which were analyzed elastically. Maximum seismic responses were presented according to different situations and combinations such as:

i. Applying the two horizontal components of the earthquake at a number of angles,
ii. Applying the largest component along each direction,
iii. 30–100% rule,
iv. Square root rule,
v. Multiplying by 20% the maximum response obtained by applying the largest component along the two directions.

Then they compared the results to find that the 30–100% and SRSS rules underestimate the structural responses by 25% compared to the exact responses.

While (Fernandez-Davila et al., 2000) studied existing combinations and rules and compared the responses obtained by applying them along the principal axes, (Athanatopoulou, 2004) established formulae for determining the critical excitation angle and associated critical responses (e.g. axial force, bending moment, shear force and displacement) due to three seismic components.

The model used by (Athanatopoulou, 2004) was a five-story asymmetric RC building. SAP2000 software, a computer program for structural analysis and design (SAP2000, 2000), was used to perform the linear analysis. The same building was analyzed at different incident angles to illustrate the maximum structural response as a function of incident angle. Figure 2.4 shows a vectorial representation of the seismic components, namely Rp and Rw in the Opwz coordinate system, the orientation of the two horizontal excitation axes (p,w) being defined by the angle α, which is the angle from the fixed coordinate axis x (which is part of the fixed structural coordinate system Oxyz) to the p axis, measured in the counter clockwise direction.

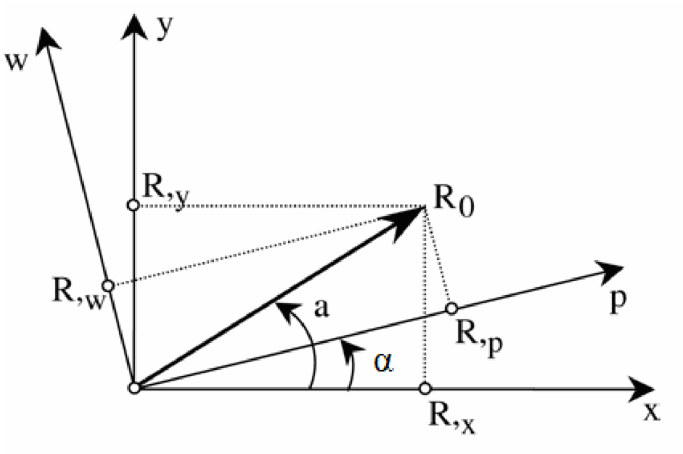


Figure 2.4: Vectorial Representation of R_p and R_w (Athanatopoulou, 2004)

From the results of the analysis by (Athanatopoulou, 2004), it was noticed that:

i. Each structural response has a different critical excitation angle when one seismic record is used,

ii. Each seismic record has different critical angles from other seismic records for the same structural response, and

iii. The maximum structural response can be up to 80% larger than the response produced when the seismic components are applied along the principal axes.

Some researchers used one, two, or three seismic components within their studies but, in order to see the effect of using a different number of components on the structural responses, a comparison must be made which was carried out by (Khoshnoudian and Poursha, 2004).

In the paper (Khoshnoudian and Poursha, 2004), the effect of one component and two horizontal components of earthquake on 14 steel buildings with five stories was analyzed linearly and three steel buildings were analyzed nonlinearly under arbitrary excitation angles. While considering the two horizontal component effects, the authors used the following methods; 30–100% rule, SRSS combination and 20% rule. The SAP2000 software was used to run the analysis.

Their results showed that when looking at linear and nonlinear behaviour, use of two components instead of one gives higher responses. Figure 2.5 shows the difference between one and two components. SRSS and 30-100% combinations underestimate the response of the structure relative to the maximum response to two components. The 20% method is more realistic than the other two combinations.

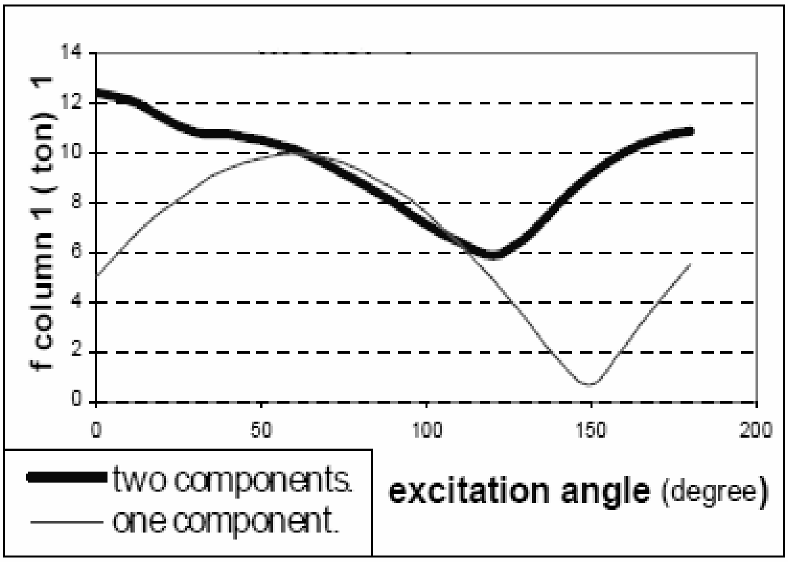


Figure 2.5: Column Axial Force Diagram (Khoshnoudian and Poursha, 2004)

Previous research has employed elastic, linear analysis. However, as mentioned earlier, during severe seismic events, the building is likely to behave in a nonlinear inelastic way. This kind of behaviour was studied in (Rigato, 2007).

In Rigato's thesis (Rigato, 2007), a number of asymmetric and symmetric models were subjected to ground motion records applied at different excitation angles to reveal Engineering Demand Parameters (EDPs). The responses found in inelastic analysis were studied and analyzed to see how they changed when the ground motion was applied along the principal axis and at other angles.

The results showed the behaviour of the mean ductility: the mean drift and slab rotations tended to vary mildly with angle of incidence and were not greatly affected by the fundamental period and the critical response was found to occur at no particular angle.

(Rigato and Medina, 2007) observed the effect that the excitation angle of ground motion had on EDPs in single story structures with varying degrees of inelasticity and different fundamental periods, subjected to bidirectional ground motions. A group of 39 ground motion pairs were discussed.

Several results were found. One result was that the critical excitation can be at any angle and this angle varies according to the degree of inelasticity and differs from the principal angle. Another result was that the maximum inelastic deformation demands are underestimated when the horizontal components of ground motion are applied along the principal axes of an inelastic structure. Also slab rotations showed that the overall torsion in a building can be reduced by increasing the degree of inelasticity for most of the models studied.

While (Rigato and Medina, 2007) applied a nonlinear inelastic analysis to a one story building, (Frenandez-Davila and Cruz, 2008) used a multi-story asymmetric building in a similar analysis. In their study, (Frenandez-Davila and Cruz, 2008) applied a number of combination rules to approximate the maximum structural responses caused by bidirectional seismic components, as well as the elastic responses to a unidirectional seismic component. The nonlinear analysis was applied to two buildings each with five stories of asymmetric plan using the ANSR-1 program – which is a computer program for static and dynamic analysis of nonlinear structures (ANSR-1, 2005). A group of 20 artificial earthquake records were chosen from real records so as to change the angle of the earthquake.

In (Frenandez-Davila and Cruz, 2008), the authors conclude from their results that it is possible to estimate the maximum structural response under bidirectional excitation and assuming nonlinear behaviour using appropriate combination rules and the elastic responses for uni-directional excitation ($\alpha = 0°; 90°$) represented by the average response spectrum.

At this stage of the research process, researchers who base their studies on response spectrum analysis still need guidelines for selecting the magnitude of the response spectrum. Investigating a complete quadratic combination is also another matter requiring study. These two issues were considered by (Pozos-Estrada et al., 2008).

In their paper, (Pozos-Estrada et al., 2008) chose one story symmetric structures and applied a numerical analysis with almost 600 ground motion records, using a damping ratio of 5%. These variables were used to investigate the accuracy of the Complete Quadratic Combination (CQC) rule for estimating the responses of structures under bidirectional horizontal seismic excitations. Their paper also included a guideline for selecting the magnitude of response spectra in the two orthogonal horizontal directions used in the extended CQC rule.

The results showed that the CQC rule gives underestimation of the maximum structural responses under bidirectional horizontal excitations. This underestimation depends on the structural characteristics and may be corrected by using scaling factors.

While some researchers still use the response spectrum analysis, others use time history analysis. One paper (Marinilli and Lopez, 2008) has given a comparison of both methods of analysis to help researchers choosing the type of analysis that best suits their research.

In their study, (Marinilli and Lopez, 2008) applied 10 horizontal far-field ground motions to rock supporting one story RC structures assumed to behave linearly with 5% damping and fundamental periods ranging from 0.1 s to 3.0 s. They evaluated the maximum structural responses and critical angles by using Response History Analysis (RHA) and/or Response Spectrum Analysis (RSA). All analyses were performed using SAP2000 software and taking into account one horizontal ground motion as major component and two minor orthogonal components.

The following result was found: RHA gives more accurate values of critical responses by using a smaller number of excitation angles than the RSA results and RHA reduces the number of numerical computations required.

2.4 Seismic Response of Structures

As outlined in this section, previous research has concentrated mainly on the effect of near fault ground motions on structural responses.

(MacRae and Mattheis, 2000) studied the effect of near fault ground motions on a three stories steel structure with one-way moment-resisting frames. A dynamic inelastic time history analysis (THA) was conducted on this structure. In this paper,