EVALUATION OF STRUCTURAL POUNDING BETWEEN ADJACENT BUILDINGS SUBJECTED TO REPEATED GROUND MOTIONS

by

MAHMOUD ALI MIARI

This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

as partial fulfillment of requirements for the degree of

MASTER OF SCIENCE

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List of Abbreviations

FEM	Finite element modeling
SDOF	Single degree of freedom
EPP	Elastic–plastic laws
RC	Reinforced concrete
IDA	Incremental dynamic analysis
DI	Damage index
IDR	Interstorey drift ratio
PGA	Peak ground acceleration
GM	Ground Motion
GMs	Ground Motions
FRP	Fiber reinforced polymer
OP	Operational performance Level
IO	Immediate occupancy performance Level
LS	Life safety performance
CP	Collapse performance Level

Abstrak

Kod semasa masih mempunyai beberapa kelemahan, di mana dua tenomena asas in tidak diambil kira: yang pertama ialah godaman struktur (keruntuhan antara struktur) yang berlaku jika jurang antara struktur tidak mencukupi dan Fenomena kedua ialah gempa bumi berulang, di mana tidak ada maklumat dalam kod yang berkaitan dengannya. Kajian ini menyiasat prestasi struktur antara bangunan bersebelahan yang mengalami godaman strutur opibilah dikenaksn pergerakan tanah yang berulang menggunakan analisis dinamik tambahan (IDA) dan kemudian menghasilkan graf kerapuhan untuk bangunan bersebelahan berdasarkan tahap prestasi yang berbeza. Bagi tujuan ini, sembilan model telah dianalisa. Setiap model mempunyai dua bingkai. Bangunan-bangunan ini dibahagikan kepada 3 gabungan: (1) dua bingkai teratur, (2) satu bingkai teratue dan satu bingkai tidak teratur dan (3) dua birgkai tidak teratur. Jurang (ruang antara struktur) juga dibahagikan kepada 3: 1 mm, 10 cm, dan 1 m bagi setiap gabungan. Dengan itu, kita mempunyai 3 kombinasi dan 3 jurang untuk setiap gabungan yang menjadikan jumlah semua model sebagai 9. Keputusan analisa membuktikan bahawa kerosakan struktur adalah berkadar terus dengan kekuatan pergerakan tanah dan ketidakteraturan struktur; sedangkan ia adalah berkadar songsang dengan jurang antara struktur. Oleh itu, 1 m ialah jurang yang terbaik untuk digunakan di kawan yang mingalami gempa bumi berulang untuk mengelakkan godaman struktur berbanding menggunakan jurang 10 cm and 1 mm. Selain itu, kerosakan utama bingkai berlaku dalam rasuk. Bagi bingkai teratur kerosakan utama berlaku pada tingkat bawah, manakala kerosakan bagi bingkai yang tidak teratur ialah di bahagian bawah dan di tingkat atas. Jadi, di kawasan-kawasan yang menglami gempa bumi yang kerap, kekukuhan yang lebih perlu diberikan kepada rasuk. Dalam kes

ini pengukuhan, kekukuhan tambahan disyorkan untuk kedua-dua bangunan. Lokasi pengukuhan tambahan perlu ditempatkan pada rasuk yang terletak sama tinggi dengan ketinggian bangunan rendah, serta di atas dan di bawah rasuk tersebut, masing-masing. Berkenaan dengan tiang, kerosakan utama berlaku di tingkat bawah. Untuk itu, tiang yang lebih kukuh digunakan di tingkat bawah , terutama sekali pada aras tanah.

Abstract

The current codes still have some drawbacks, where the following two basic phenomena are not taken into account: the first is structural pounding (collapse between the structures) which occurs if the gap between the structures is insufficient; and the second phenomenon is the repeated earthquakes, where there is no information in the codes related to it. This research investigates the structural performance (peak ground acceleration (PGA), drift, plastic hinges, and interstorey drift) of adjacent buildings experiencing structural pounding under the effect of moderate repeated ground motions using incremental dynamic analysis (IDA) and then develops the fragility curves for adjacent buildings based on different performance levels. For this purpose, nine models have been analyzed. Each model consists of two frames. The buildings are divided into 3 combinations: (1) two regular frames, (2) one regular frame and one irregular frame and (3) two irregular frames. The gap (space between the structures) is divided into 3 gaps: 1 mm, 10 cm, and 1 m for each combination. Thus, there are 3 combinations and 3 gaps for each combination which means a total of 9 models. Results of analysis prove that the damage of the structure is directly proportional to the intensity of the ground motion and the irregularity of the structure; whereas it is inversely proportional to the gap between the structures. Hence, 1 m is the best spacing to be used in areas that experience repeated earthquakes to avoid structural pounding in contrast with 10 cm and 1 mm. Also, the main damage of the frames is concentrated in the beams. For regular frames, the damage is concentrated in the bottom storeys, while the damage for irregular frames is concentrated at both bottom and top storeys. Therefore, in areas that experience repeated earthquakes, more stiffness should be given to the beams. In this case, the additional

stiffness is recommended for both buildings. The location of the additional stiffness should be in the beams that corresponds to the height of the short building, the immediate above and the below beams, respectively. With respect to the columns, the damage is concentrated in the ground floor. For that, additional stiffness should be added to the columns in the bottom storeys, especially in the ground floor.

CHAPTER ONE

INTRODUCTION

1.1 Research background

Currently, each country follows a specific building and seismic design codes. Around 100 years ago, the building design codes did not take the effect of the seismic actions into consideration. The last century has witnessed a significant development in the seismic codes regarding the effect of earthquakes in order to design the building to resist seismic forces. Each country has its own unique history of the evolution of the authority for building codes. The purpose of a code is to regulate and control the design, quality of materials, construction, use and occupancy, location and maintenance of all buildings and structures in order to ensure minimum standards to safeguard life or limb, property, health, and public welfare. Earthquakes in Messina, Italy (1911), and Kanto (Tokyo) Japan (1923) led to the development for guidelines for the engineers to design buildings to resist horizontal forces of about 10% of the weight of the building. In 1927 first seismic regulations were developed as voluntary appendix in 1927 Uniform Building Code (Holmes, 2009). This development grew continuously until the development of the different modern seismic codes used nowadays. These codes have been able to give considerable protection for the buildings and providing a lot of solutions against seismic actions.

Although these modern codes ensure the safety of the building against seismic actions, these codes ignore two basic phenomena, structural pounding and repeated earthquakes.

The structural pounding is the collision of neighboring buildings under long-period ground motions due to the insufficient gap (space) between the two buildings as shown in Figures 1.1 and 1.2.

Figure 1.1: Collapse of intermediate stories due to pounding of adjacent buildings (Rai et al., 2016)

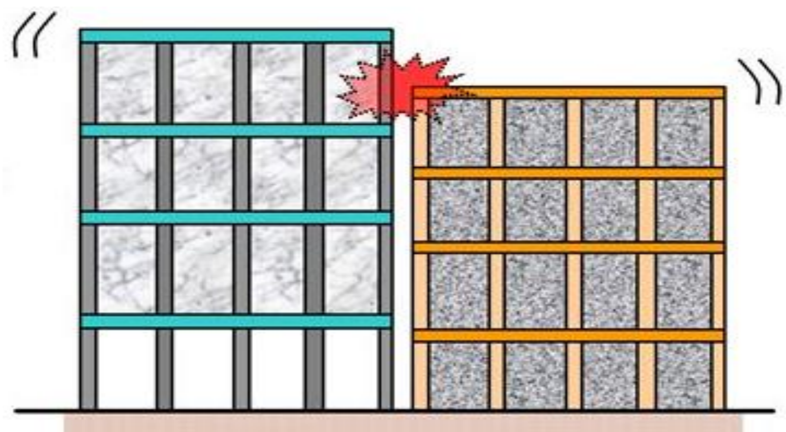

Figure 1.2: Pounding between the columns and the roof of two adjacent buildings (Murty, 2000)

The damage in the structure and the pounding phenomena are enhanced or suppressed by several factors mainly the intensity of the ground motion, the regularity/irregularity condition of the structure and the gap between the structures. Figure 1.3 shows examples of irregular structures while Figure 1.4 shows examples of the gap between the structures.

(a) Maxis tower (b) Mitraland tuilding

Figure 1.3: Irregular structures

Figure 1.4: Contact and spaced structures

The surveys on damage during past earthquakes show that interactions (structural pounding) between insufficiently separated buildings or bridge segments may cause substantial damage or even lead to total structural collapse. For example, due to the earthquake that struck Mexico City in 1985, which was approximately 400 km away from the epicenter (Figure 1.5), 40% of the 330 collapsed or severely damaged buildings have experienced structural pounding while 15% of the 330 collapsed or severely damaged structures was caused by structural pounding (Rosenblueth and Meli, 1986; S. A. Anagnostopoulos and Anagnostopoulos, 1996). This considerable damage is mainly due to the insufficient spacing between the structures. Because of that, seismic pounding phenomena have become a significant issue in a lot of countries like Japan.

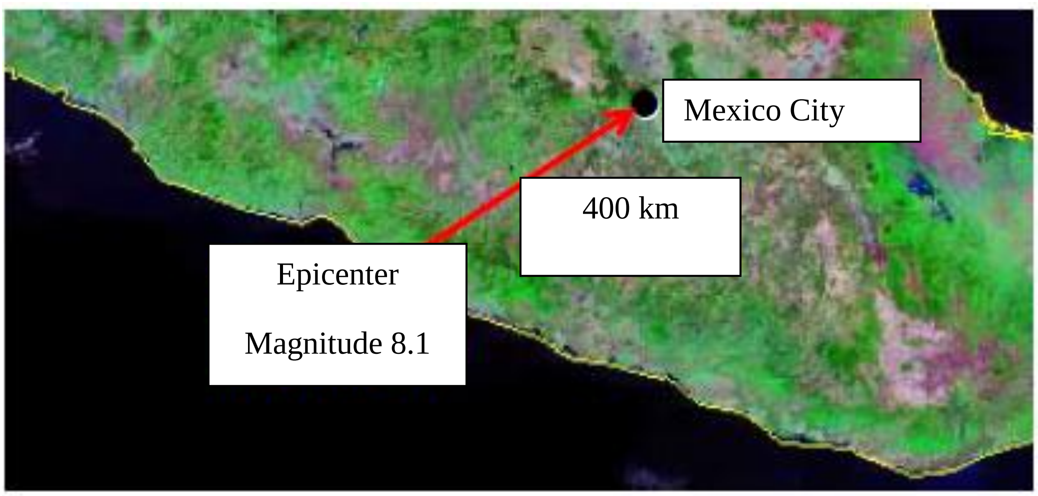

Figure 1.5: Epicenter of the 1985 Mexican earthquake (Isobe, 2012)

Regarding the effect of regularity of the structure, the most used type of the irregular structures is setback irregularity. The previous earthquakes show that irregular structures (with setback) have higher damages compared to regular structures (Varadharajan et al., 2015).

Several researches have been performed studying structural pounding phenomena. For the case of earthquake-induced pounding between RC structures, the pertinent literature can be divided into two main categories, experimental research which provides us with a small number of papers and computational investigations, performed mainly with the use of FEM, where numerous investigations have been reported.

However, the effect of repeated earthquakes is totally ignored by the codes in which nothing is mentioned in these codes. All these codes design the buildings to resist only one single earthquake. Few studies have been reported in the literature regarding the multiple earthquake phenomena, for both single degree of freedom and multi-degree of freedom systems.

1.2 Problem statement

The magnitude of the ground motion is a crucial issue since it is one of the most factors that can affect the performance of the structure. With respect to Malaysia, the earthquakes affecting the area are either low or moderate. Because of that, the buildings are designed to resist moderate and low seismicity earthquakes because the design against high earthquakes is considered as over design. The last important seismic event that affected Malaysia was in Ranau, Sabah on 5th of June 2015 at 7.15 am. This earthquake was a moderate earthquake of 6.0 Richter scale. The considerable damage that occurred reveals that of the effect of earthquakes should be given more importance.

Also, it is designed to resist one single earthquake since the codes ignore the multiplicity of the ground motions. Due to the lack of time between the repeated earthquakes, any rehabilitation of the affected structures is impractical. This will lead to the accumulation of the structural damage and increase in the displacement of the structures due to the reason that the buildings are designed only for one single earthquake, which lead to the pounding between the structures. Thus, the development of a methodology for the design of buildings against repeated earthquakes and structural pounding is apparent.

Architects give high attention to the aesthetic appearance of the structure. Because of that, they always like to design the building having a considerable irregularity. The most buildings are designed as regular buildings. But now the number of irregular building is increasing since the aesthetic value has become more important issue than before. Thus, the effect of the irregularity of the structure on its behavior under seismic actions should be studied and analyzed.

Moreover, the space between the structures is not the same between buildings. A lot of reasons lead to that difference such as the limitation of area and the recommendation of investors to decrease the area as much as possible in order to save more area as they can. The lack of sufficient space has leaded a lot of times to a considerable damage such as in Mexico earthquake and as in the buildings shown on Figure 1.1. So, the effect of the space between the structures on its behavior under earthquakes has been studied in this research.

To study these aspects (the effect of the gap and the regularity/irregularity of the structure) fragility curves were developed because it gives the real behavior of the structure under seismic actions. It gives the probability of damage for different performance levels. Also, incremental dynamic analysis was performed which helps to study these aspects and needed for the development on the fragility curves.

1.3 Objectives

The objectives of this research are:

1. To investigate the structural performance (PGA, drift, plastic hinges, and interstorey drift) of adjacent buildings experienced structural pounding under the effect of moderate repeated ground motions using incremental dynamic analysis (IDA)
2. To develop the fragility curves for adjacent buildings based on different performance levels in order to study the effect of the gap between the structures and its regularity/irregularity on the structural behavior under seismic actions

1.4 Scope of work

This research uses 2D moment resisting concrete frames divided into regular and irregular frames. These frames are separated by different gaps. Nine models were considered divided into 3 sets. Each model consists of two frames. The first set of models is characterized by regularity for both frames, the second set consists of one regular frame and one irregular frame, and the third set is characterized by irregularity for both frames. The distance between two buildings is 1 mm, 10 cm, and 1 m for each set of models. Thus, each set of models consists for 3 models which results in 9 models. This study is focused on the structural performance of these frames due to structural pounding under repeated earthquakes. The performance is studied under dynamic load using incremental dynamic analysis. The analysis is performed using SAP2000. Then the fragility curves is developed using a method based on Ibrahim and El-Shami equation (2011) which is discussed in Chapter two.

1.5 Outline of thesis

Chapter 1 is the introduction chapter. It gives a brief introduction about the general background of this study, the problem statement, the objectives and the scope of this research.

Chapter 2 discusses the previous researches related to the topic of this research. This review includes frame structures (regular and irregular frames), earthquake records, structural pounding, repeated earthquakes, incremental dynamic analysis, and the fragility curves.

Chapter 3 explains the overview of the methodology of this research describing the steps of this study with the aid of flowchart.

Chapter 4 shows the results of the analysis including IDA curves and the fragility curves. Then, analyses, interpretation and discussion of these results are represented.

Chapter 5 gives a conclusion of this study and recommendation for future work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

The purpose of this chapter is to provide information and give a background on the previous works related to this topic in order to understand the issues to be considered in this dissertation and reviews of the analysis approaches to emphasize the need of the present study.

2.2 Regular and irregular frames

Any structure is categorized as one of two groups: regular or irregular frames. The regular frames are characterized by no discontinuity in its parts (vertical or plan) and no considerable change in the mass or stiffness between the stories, while the irregular frames are characterized by a vertical or plan discontinuity. For that, irregular frames are two different types: vertical or plan irregularity. Common examples for the irregularity are soft stories and big opening diaphragm.

According to Varadharajan et al. (2012) study, there are four types of vertical irregularity: stiffness irregularity (soft storey), mass irregularity, vertical geometric irregularity (set-back), and in-plane discontinuity in lateral-force-resisting vertical elements as shown in Figures 2.1 and 2.2. However, plan irregularities such as translational and torsional are the result of the presence of eccentricity of the stiffness and/or mass in the structure.