SEISMIC ANALYSIS OF POUNDING IN BUILDINGS

(MAJOR PROJECT REPORT)

Submitted in partial fulfilment of the requirements
for the award of the degree of

MASTER OF TECHNOLOGY
in
CIVIL ENGINEERING
(Structural Engineering)

Submitted by

HIMANSHU GAUTAM
ROLL NO. 2K13/STE/08

under the guidance of

Dr. ASHOK KUMAR GUPTA
(Professor)

Department of Civil Engineering
DELHI TECHNOLOGICAL UNIVERSITY
SHAHBAD DAULATPUR, BAWANA ROAD
DELHI-110042, INDIA

JULY 2015

Department of Civil Engineering
Delhi Technological University
Delhi-110042 (India)

CERTIFICATE

This is to declare that the final year project **"SEISMIC ANALYSIS OF POUNDING IN BUILDINGS"** is a bonafide record of work done by me for the partial fulfilment of the requirement of the Degree of Master of Technology in Civil Engineering(Structural Engineering) from Delhi Technological University, Delhi.
This project has been carried out under the supervision of Dr. Ashok Kumar Gupta Professor Civil Engineering Department, Delhi Technological University.
I have not submitted the matter embodied in this report for award of any other degree.

Date:

Himanshu Gautam
(2K13/STE/08)

Certificate

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Dr.Ashok Kumar Gupta
Professor
Department of Civil Engineering
Delhi Technological University

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my project guide **Dr. Ashok Kumar Gupta** for giving me the opportunity to work on this topic. It would never be possible for me to complete this project without his precious guidance and his relentless support and encouragement.

I would also like to present my sincere regards to my Head of Civil Engineering Department and faculty members, for their support and encouragement throughout the program.

The successful compilation of major project depends on the knowledge and attitude inculcated in the total length of course. So I want to express my sincere gratitude to all the faculties who taught us during M.Tech.

I am also thankful to all my classmates for the support and motivation during this work. Last but not least, I specially thank all the people who are active in this field.

HIMANSHU GAUTAM

(2K13/STE/08)

ABSTRACT

Major seismic events during the past decade have continued to demonstrate the destructive power of earthquakes, with destruction of engineered buildings, bridges, industrial and port facilities as well as giving rise to great economic losses. In urban/metropolitan cities buildings are constructed very close to each other because of high land value. Because of the insufficient gap, which is provided between adjacent buildings or adjacent units of same building are most vulnerable to seismic damage due to **Pounding.** Adjacent buildings may have different functional requirements such as one is for residential and another is for public/commercials buildings based on the owner interests, so they may have different configurations and dynamic properties (Time period and frequency etc.). During an earthquake these adjacent buildings may vibrate out of phase leads to slight architectural damage to severe structural damages.

In this paper Nonlinear Time History analysis is done for different cases of building positions and their floor levels are mentioned below.Two adjacent buildings are constructed with (1) '**Buildings with Same Height and Same Floor'**, (2) **'Buildings with Same Height but Different Floor'**.(3) '**Buildings with Different Height and Same Floor Levels'**, (4) **'Buildings with Different Heights and Different Floor Levels (Floor-Mid Column)'**. The adjacent buildings are modeled in Sap 2000 v 17 and analysis is carried out to find the Seismic response (Impact force) of buildings with connecting two floor levels of adjacent buildings by 'Gap Element model' when subjected to Different ground motions**.** In this paper also considered four adjacent buildings are constructed in a row with **'Different Height but Same Floor Levels'** and **'Different Height and Different Floor Level (Floor-Mid Column)'.**

When the two buildings are placed at different heights the impact force is more than buildings with the same heights. Also when buildings are in a row exterior building suffers more pounding damage than the interior building.

TABLE OF CONTENTS

DESCRIPTION	PAGE NO
TITLE	i
CERTIFICATE	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
TABLE OF CONTENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	ix

Chapter 1

INTRODUCTION	**1-5**
1.1 CAUSES OF SEISMIC POUNDING DAMAGE	2
1.2 PROVISION OF SEISMIC GAP AS PER IS 4326	3
1.3 OBJECTIVE OF THE STUDY	5
1.4 ORGANIZATION OF THE REPORT	5

Chapter 2

LITERATURE REVIEW **6-12**

2.1 PAST RECORDS OF POUNDING DAMAGE 6

2.1.1 Worldwide observations 6

2.1.2 Indian observations 8

Chapter 3

METHODOLOGY OF THE STUDY **12-23**

3.1 INTRODUCTION 12

3.2 BUILDING GEOMETRY 12

3.3 SEISMIC BASE SHEAR 16

3.4 CALCULATION OF DESIGN SEISMIC FORCE BY LATERAL FORCE METHOD 17

3.5 GAP ELEMENT MODEL 23

Chapter 4

POUNDING ANALYSIS OF BUILDINGS **24-48**

4.1 POUNDING ANALYSIS OF BUILDINGS WITH EQUAL HEIGHTS 24

4.1.1 Buildings with same height and same floor levels 24

4.1.2 Buildings with same height but different floor levels 32

4.2 POUNDING ANALYSIS OF BUILDINGS WITH DIFFERENT HEIGHT 35

4.2.1. Buildings with different height and same floor levels 35

4.2.2 Buildings with different heights and different floor levels (floor-mid column): 41

4.3 POUNDING ANALYSIS OF SERIES OF BUILDINGS 44

4.3.1 Pounding analysis of row of buildings with different height but same floor levels 44

4.3.2 Pounding analysis of series of buildings with different height and different floor level (floor-mid column) 46

Chapter 5

RESULTS AND DISCUSSIONS 49-52

5.1 RESULTS AND DISCUSSIONS 49

Chapter 6

CONCLUSIONS AND FUTURE SCOPE 53-55

6.1 CONCLUSIONS 53

6.2 FUTURE SCOPE OF STUDY 55

REFERENCES 56

LIST OF TABLES

Table No	TITLE	Page No
1.1	Gap width for adjoining structures	4
3.1	Load Combinations as per IS 1893 (part 1): 2002 Load Combination and Load Factors	14
3.2	Zone factor for seismic zones	15
3.3	Percentage of imposed load to be considered for seismic weight calculation	16
3.4	Lateral load distribution with height of the building	21
4.1	Details of ground motions	24
5.1	Impact force of different cases of adjacent buildings subjected to Petrolia ground motion	48
5.2	Impact force of different cases of adjacent buildings subjected to Northridge ground motion	49
5.3	Impact force of different cases of adjacent buildings subjected to Elcento ground motion	49
5.4	Impact force of different cases of adjacent buildings subjected to Lomaprieta ground motion	50
5.5	Impact force of different cases of adjacent buildings subjected to Park field ground motion	50
5.6	Comparison of impact force for different cases of buildings subjected to all ground motions.	51

LIST OF FIGURES

FIG. NO	TITLE	PAGE NO.
1.1	Different configuration of adjacent buildings.	2
2.1	Pounding damage in Santiago due to2010 Chile earthquake (photo by S.Brzev).	6
2.2	Pounding damage caused by different heights (photo by Gregory Cole)	7
2.3	Pounding damage in URM minor damage (left),major damage(right)(photo by G.Cole)	7
2.4	Pounding damage at expansion joint in 5-storey building of SMIMS boy's hostel(photo by AlpaSheth)	8
3.1	Elevation of considered building	13
3.2	Lumped mass at different storey levels of the building	18
3.3	Design seismic force along both X and Y direction	21
3.4	Gap element model from SAP2000	22
4.1	Different types of ground motion acceleration graphs	25
4.2	Elevation of buildings with same height and same floor levels	27
4.3	Displacement responses of two buildings after collision due to Northridge	28
4.4	Impact force between buildings due to different ground motions	29

4.5	Elevation buildings with same height and different floor levels	31
4.6	Impact force between buildings due to different ground motions	32
4.7	Elevation of buildings with different height and same floor levels	34
4.8	Different types of ground motion acceleration graphs	35
4.9	Displacement response of two buildings during collision due to Elcentro ground motion.	37
4.10	Impact force between buildings due to different ground motions	38
4.11	Elevation view of buildings with different height and different floor levels	40
4.12	Impact force between buildings due to different ground motions	41
4.13	Elevation of buildings in a row of different height but same floor level	43
4.14(a)	Impact force between the left exterior buildings	44
4.14(b)	Impact force between the interior buildings.	44
4.15	Elevation of buildings with different height and different floor levels in a row	45
4.16(a)	Impact force between left exterior buildings.	46
4.16(b)	Impact force between interior buildings.	46
4.16(c)	Impact force between right exterior buildings.	46

CHAPTER 1

INTRODUCTION

In urban/metropolitan cities buildings are constructed very adjacent to each other for proper connectivity between them and proper usage of high valuable land. Adjacent buildings may have different functional requirements such as one is for residential and another is for public/commercials buildings based on the owner interests, so they may have different floor levels (heights) and masses that leads to different dynamic properties. In some cases the expansion joints are used to connect same building with longer span at regular locations, improper connection of different units of same building may also have a chance to pounding between each of adjacent units during high magnitude of earthquakes.

Due to closeness of adjacent structures, they collide with each other and vibrate out of phase when subjected to strong ground motion or any other vibration. The collision of adjacent buildings or different units of same building during any vibration is called pounding which may cause either architectural and structural damage or collapse of whole structure.

In all over the world most of the countries such as Australia, Canada, Egypt, Ethiopia, Greece, India, Mexico , Peru, Serbia, Taiwan have their own code specifications for providing seismic gap to avoid pounding between adjacent buildings. Even though the building codes specify the separation gap between adjacent buildings, many of the land owners are not come forward to follow those regulations. This leads to minor architectural failure to major structural damages during strong ground motion or by any other vibrations like bomb blast near to building site.

1.1 CAUSES OF SEISMIC POUNDING DAMAGE

Seismic pounding damages will occur due to the following cases: (1) Adjacent buildings are built with same heights and same floor levels having different dynamic properties. (2) Adjacent buildings with same heights and different floor levels. (3) Adjacent buildings with different heights and same floor levels. (4) Adjacent buildings with different heights and different floor levels. (5) Buildings are in row having different heights and same floor levels. (5) Adjacent buildings are in row having different heights and different floor levels. (6) Adjacent units of same building which are connected by improper expansion joints.

Pounding is one of the main severe building damages due to the collision of adjacent buildings, nonstructural damage involves in pounding or movement across separation joints between them. The following factors which are influencing the seismic pounding between two adjacent buildings:

- During strong earthquake ground motion.
- Different Dynamic Configurations of the Buildings.
- When Buildings vibrate out of phase.
- Provided seismic gap is insufficient.

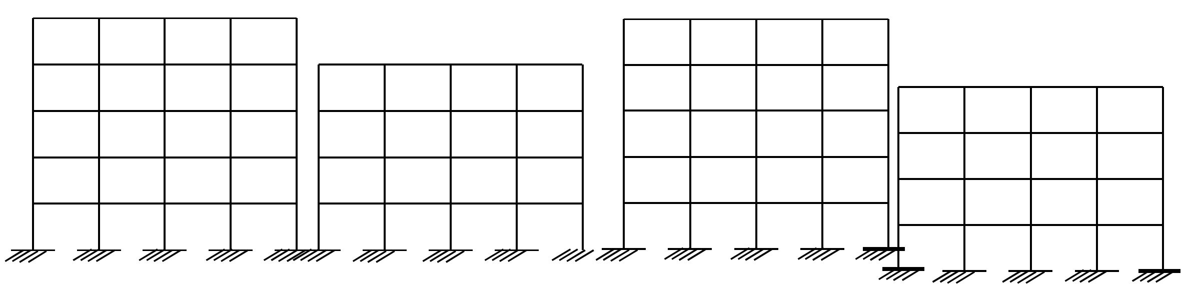


Fig 1 .1 Different Configuration of Adjacent Buildings.

1.2 PROVISION OF SEISMIC GAP AS PER IS 4326:

The seismic pounding occurs when seismic separation distance is not large enough to accommodate the relative motions of the adjacent buildings during an earthquake. Seismic codes and regulations specify the minimum separation distance required between the adjacent buildings in worldwide to preclude seismic pounding. This is obviously equal to the relative displacement demand of two potentially colliding structural systems. According to latest edition of International Building code and in many seismic design codes and regulations worldwide, the minimum separation distances are given by Absolute Sum (ABS) or Square Root of Sum of Squares (SRSS) as follows.

The Separation distance

$$S = U_a + U_b \quad \text{for ABS}$$

$$S = \sqrt{(Ua^2 + Ub^2)} \quad \text{for SRSS}$$

Where S = Separation distance.

U_a = Peak displacement response of building A.

U_b = Peak displacement response of building B.

Bureau of Indian Standards clearly mentioned in its code IS 4326 that a Separation Section is to be provided between the adjacent buildings. Separation Section is defined as "A gap of specified width between adjacent buildings or parts of the same building, either left uncovered or covered suitably to permit movement in order to avoid hammering due to earthquake".

Further it states that "For buildings of height greater than 40 meters, it will be desirable to carry out model or dynamic analysis of the structures in order to compute the drift at each storey, and the gap width structures shall not be less than the sum of their dynamic deflections at any level."

Table 1.1 Gap width for adjoining structures

SL. No.	Type of Constructions	Gap width/storey ,in mm for Design Seismic Coefficient αh=0.12
1	Box system or frames with shear walls	15.0
2	Moment resistant reinforced concrete frame	20.0
3	Moment resistant steel frame	30.0

(NOTE- Generally provides more than 25 mm seismic gap.)

Thus it is advised to provide adequate gap between adjacent buildings greater than the sum of bending of both of the buildings at their top, so that they have enough space to have vibrate. The pounding damage is severe when the adjacent buildings have in different heights than they are in same heights. To avoid collision of adjacent buildings, the minimum width of separation gap is specified in **Indian Code Is 1893-2002** as follows.

IS 1893 (part 1):2002 "Indian standard Criteria for Earthquake Resistant Design Of Structures, part 1 General Provisions and buildings,(Fifth Revision)" states that "two adjacent buildings or two adjacent units of same building which are separated by the distance equal to R times of the sum of the story displacements to avoid colliding when they are deflect towards each other, when floor levels of two adjacent units of same building or buildings are at the same floor levels factor R in this requirement may replace by R/2.

1.3 OBJECTIVE OF THE STUDY

The past earthquake ground motions such as Parkfield(1996) , Northridge(1994) , Lomaprieta(1989) , Elcentro(1940) , Petrolia(1992) have been taken as a input for the different cases of adjacent buildings to find top floor displacements of each building and impact force between them. The positions of floor levels and different heights of adjacent buildings are considered as follows: (1) Two adjacent buildings with same heights and same floor levels. (2) Two adjacent buildings with same heights and different floor levels. (3) Two adjacent buildings with different heights and same floor levels. (4) Two adjacent buildings with different heights and different floor levels. (5)Four adjacent buildings are in row (series) with different heights and same floor levels. (6)Four adjacent buildings are in row (series) with different heights and different floor levels . By using SAP 2000v17 Time History Analysis we find impact forces and top floor displacements of above mentioned different cases of adjacent buildings for each above mentioned ground motion.

1.4 ORGANIZATION OF THE DISSERTATION:

The dissertation work is arranged in five chapters.

Chapter (1) deals the introduction and causes of seismic pounding, provision of seismic gap, objective of the dissertation also included.

Chapter (2) deals literature review and past records of pounding damage.

Chapter (3) consists of pounding analysis of adjacent buildings with same heights, adjacent buildings with different heights, adjacent buildings in row with equal floor levels, adjacent buildings in row with different floor levels are considered.

Chapter (4) consists of results and discussions

Finally, chapter (5) consists of conclusions and scope of future work regarding thesis work are mentioned.

CHAPTER 2

LITERATURE REVIEW

2.1 PAST RECORDS OF POUNDING DAMAGE

There are many earthquakes occurred in India during the past years. Some of earthquakes having high magnitude lead to pounding damage to buildings and bridges. The following are the some of earthquakes caused pounding damage in past years.

2.1.1 Worldwide observations

A magnitude of 8.8 occurred in **Chile** on february27, 2010 with a PGA of 0.65g. It lead to many multistory reinforced buildings are severely damaged. Some of the buildings and bridges are damaged by pounding. One of building shown below is damaged from pounding damage in Santiago, (Santiago is the capital city of Chile which is highly dense with population and buildings).

Fig 2.1: Pounding damage in Santiago due to2010 Chile earthquake (photo by S.Brzev)

In 2011 an earthquake near **Christchurch** there are many buildings suffered from pounding damage. About 6% of the buildings are suffered from the severe pounding damage. As the Christchurch central business district is densely built up central city buildings are closely constructed. From reports about all masonry buildings are suffered from pounding damage and some of the newly constructed buildings are also vulnerable to pounding damage.

Fig 2.2: Pounding damage caused by different heights (photo by Gregory Cole)

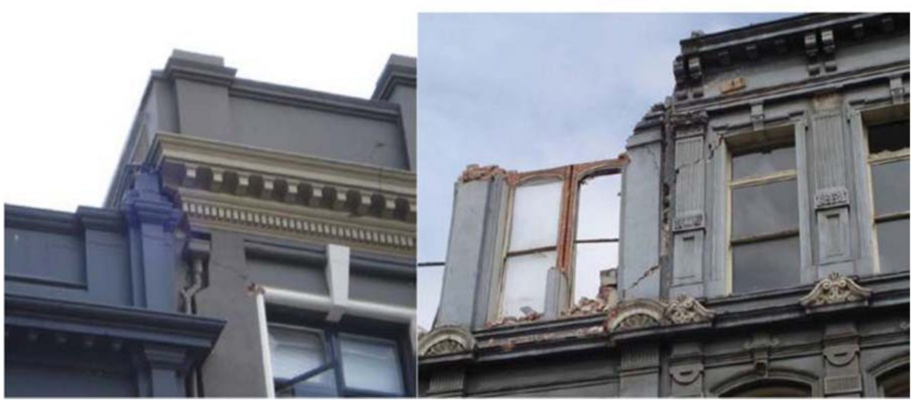


Fig 2.3: Pounding damage in URM minor damage (left), majordamage (right) (photo by G.Cole)

2.1.2 Indian observations

The following are some of the building damages occurred during the past earthquakes in India like Sikkim earthquake, Kashmir earthquake and Bhuj earthquake.

Kashmir earthquake of 2005 occurred with a magnitude of 7.6 leads severe damage to collapse of buildings about 32,000 buildings in Kashmir.

An earthquake of magnitude 6.9 is occurred near Nepal-Sikkim border on September 2011 lead to structural failures to buildings and infrastructure.

Pounding damage was noticed in adjacent buildings which are constructed with inadequately separation gap as shown in below figure. Due to pounding of adjacent building structural damages like frame-infill separation, cracking of infill walls and crackling of plaster are observed. There is a bridge namely Jawaharlal Nehru Bridge at Melli suffered pounding damage in deck slab of the bridge.

Fig 2.4: Pounding damage at expansion joint in 5-storey building of SMIMS boy's hostel (photo by AlpaSheth)

Arash Rezavani and A. S. Moghadam (2004), stated the different methods of reducing effects of buildings pounding during earthquakes, proposed that increasing the separation distance between buildings, connecting the two buildings together at different floor levels such that they move together and sue of impact absorbing materials like dampers are recommended to mitigate the pounding effect.

Shehata E. Abdel Raheem (2006), were conducted a study on pounding model of adjacent structures by giving different ground motions. They concluded that due to pounding lead to acceleration and shear forces at each floor of the building, this pounding can be controlled by providing shock absorbing materials like natural rubber shock absorbers. Which mitigate the acceleration changes due to pounding and it retards sudden change in stiffness.

Alireza M. Goltabar, R. Shamstabar and A. Ebadi (2008), have studied that various types of impacts that occur between the adjacent buildings during seismic excitation like impact of the structure on the column of an adjacent building, impact of heavier building on lighter one. The effect of pounding was studied by considering the two parameters like the distance between the adjacent buildings and the hardness of the two buildings are considered. The response of the buildings before and after collision is changes for different height buildings. They also concluded that the effect of impact is decreased by proper separation distance and by hardening the structure. They also concluded that the effect of impact depends on the characteristics of the earthquake like acceleration and directions of earthquake with repeatedly change in direction lead to more effect of pounding between adjacent buildings.

Mizam dogan and Ayten gunaydin (2009), have proposed that pounding force between the inadequately separated buildings can be reduced by placing elastic materials between the structures or providing the additional reinforcing structural systems with shear walls in proper location of a building. They also presented the importance of separation distance between adjacent buildings.

Chenna rajaram and Pradeep kumar ramancharla (2012), have proposed that the effect of pounding force between the adjacent building with different set back levels and different height levels.

They concluded that the effect is more at the floor to mid column level. And pounding force is changes with setback levels it is maximum at the extreme setback level.

Bipin Shresta (2013), presented paper on separation distance required between the adjacent buildings to avoid pounding damage by analytical method. He compared the two methods like square root of sum of squares and double difference combination methods. He concluded that DDC method is more accurate method to measure separation distance to avoid pounding.

Khaja Afroz Jamal and H.S.Vidyadhara (2013), studied that buildings with inadequate separation distances are vibrate out of phase vibrations during earthquakes led to damage/collapse of the buildings. They considered the buildings like 12 storey and 9 storey buildings and analyzed using ETABS. They have proposed that mitigation practices for seismic hazard especially for pounding, like separation distance and addition of shear wall.

They also concluded that the amount of pounding damage is inversely proportional to the separation distance, and provision of shear wall reduces the displacements in building that reduces the pounding damage that to shear wall at the outer periphery of the building gives better performance than the shear wall weight the inside of the building.

Ravindranatha, Tauseef M Honnyal, Shivananda S.M (2014), has proposed that the seismic response of adjacent structures during seismic excitation lead to pounding damage in adjacent buildings, Seismic pounding is controlled by providing passive energy devices like viscous and viscoelastic dampers. They investigated the dynamic behavior of two adjacent multi-degrees of freedom buildings connected with dampers such as viscous and viscoelastic dampers at different storey levels are studied. The effectiveness of dampers and optimal values for the distribution of viscous dampers interconnecting two adjacent buildings were also studied. They concluded that coupling of adjacent buildings with supplemental damping devices is a practical and effective approach to mitigate pounding damage. The various external damping devices like viscous dampers, viscoelastic dampers and friction dampers can be effectively used to control seismic excitations, and these dampers need not be provided through out building height, can be placed at appropriate location where displacements are maximum such that optimal number of dampers as well as displacements are reduced.

Anagnostopoulos,S.A;Spiliopoulos (1992) idealized the building as a lumped-mass model, shear beam type, multi-degree-of freedom (MDOF) with bilinear force deformations characteristics and with bases supported on Translational and rocking spring dashpots. Collision occurs between the adjacent masses at any level and is simulated by means of viscoelastic.

Impact elements .His analysis is used to find the building configuration and relative size, seismic separation distance and impact element properties by applying five real earthquake motions to study the effects of above factors. The results were found that pounding can cause high overstresses when colloidal buildings have significantly different in their heights, periods or masses. They suggests a possibility for introducing set of conditions, combined with some special measures into the codes an alternative to the seismic separation requirement .

Robert Jankowski (2004), addressed the fundamental questions regarding the application of nonlinear analysis, its feasibility and limitations in predicting the seismic gap between the buildings. In his research, elastoplastic multi-degree of freedom lumped mass models are used to simulate the seismic behaviour of structure and non-linear viscoelastic impact elements are applied to model collisions. The result of this study which proves that seismic pounding is the considerable influence on the behavior of structures .

CHAPTER 3

METHODOLOGY OF THE STUDY

3.1 INTRODUCTION

The effect of pounding between the buildings with same height is considered in this section. This situation of buildings with equal height are seen when the different units of the same building are connected by the expansion joint (or) seismic separation. When the different units of the same building are improperly connected or insufficient gap is there then the hammering between the building will occur, when earthquake of high magnitude is occurred .The two adjacent buildings are of 5-storey buildings are modeled in “SAP2000v17”.the two different cases like the two buildings are having same height and same floor levels, same height and different floor levels (mid-column).

3.2 BUILDING GEOMETRY

No. of stories of each building = 5

The Story height of each building = 3 m

Size of Beams = 0.3 m × 0.45 m

Size of Columns = 0.45 m × 0.45 m

Thickness of Slab = 0.12 m

Total heights of two buildings = 15 m

3.2.1 Material properties

Grade of concrete M25, Grade of steel Fe 415 and poisons ratio 0.2 for both adjacent buildings.

Fig 3.1 shows elevation and plan view of the considered building.

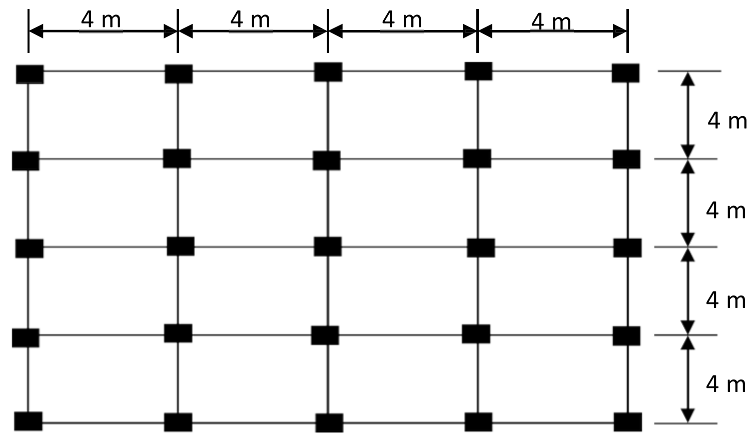


Fig: Plan view of building

`

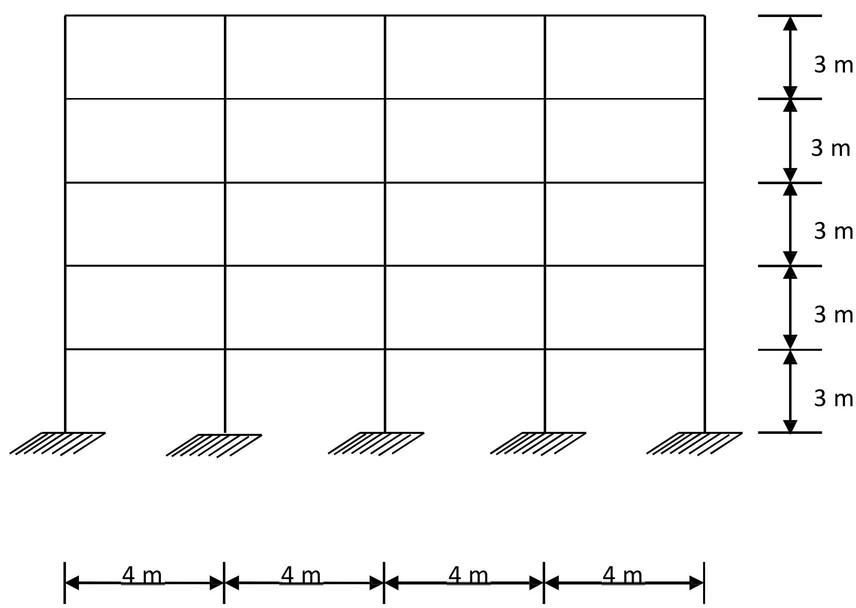


Fig 3.1: Elevation of building

3.2.2 Assigning loads:

The two adjacent buildings are modeled in "SAP2000" after that the possible load cases like gravity loads (dead load and live loads) and lateral loads (earthquake loads) are assigned to the model as per the calculations.

Defining load combinations:

As per the IS 1893 (Part I): 2002 the following load combinations are defined to the model. As per clause 6.3.2 of IS 1893 (Part I) :2002, the limit state of concrete structures shall be accounted for below load combinations.

Table 3.1: Load Combinations as per IS 1893 (part 1): 2002 Load Combination and Load Factors

Load Combination	Load Factors
Gravity Analysis	1.5 (DL + LL)
Equivalent Static Analysis	1.2 (DL + LL ± ELx) 1.2 (DL + LL ± ELy)
	1.5 (DL ± ELx) 1.5 (DL ± ELy)
	0.9 DL ± 1.5 ELx 0.9 DL ± 1.5 ELx
	1.2 (DL + LL ± RSx) 1.2 (DL + LL ± RSy)

Where DL- Dead Load

LL-Live load

EQ_x and EQ_y - Earthquake Load in x-direction and in y-direction

3.3 SEISMIC BASE SHEAR:

The total design lateral force or the design base shear force (V_b) along the principal direction (along X and Y directions) is determined as per clause 7.5.3 of IS 1893 (Part I):2002 is as follows

$V_b = A_h W$

Where A_h is the design horizontal acceleration spectral value, using the fundamental natural period T in considered direction of vibration of the building. it is determined by the expression given in clause 6.4.2 of IS 1893 (Part I):2002

$$(A_h) = \frac{ZISa}{2Rg}$$

Here Z is the zone factor is depend on the perceived maximum seismic risk characterized by maximum considered earthquake in the zone in which building is located. These values are taken from following table:

Table 3.2: Zone factor, Z

Seismic zone	II	III	IV	V
Seismic intensity	Low	Medium	Severe	Very severe
Z	0.10	0.16	0.24	0.36

Where I is the importance factor, it depends on the functional usage of the building whether it is used for residential purpose or commercial purpose like. The value of I is 1.5 for important service and community buildings and I is 1.0 for all other buildings.

Where R is Response reduction factor, it depends in the perceived seismic damage performance of the structure. The value of ratio (I/R) shall not exceed 1.0. The value of response reduction factor is taken from table 7 of IS 1893 (Part I):2002

$\frac{s\,a}{g}$ is the average response acceleration coefficient. Its value is taken from the figure 2 of IS 1893 (Part I):2002 these values are taken by assuming 5% damping in the structure. If damping is different percentage, its value should be taken with suitable correction factor given in table 3 of IS 1893 (Part I): 2002.

W is the Seismic weight of the building calculated as per clause 74 of IS 1893 (Part I) :2002, seismic weight of the whole building is the sum of the seismic weights of all the floors. The seismic weight of each floor is calculated as guidelines in the code that is sum of full dead load plus appropriate percentage of imposed loads as per table 8 of IS 1893 (PartI): 2002 .

Table 3.3: Percentage of imposed load to be considered for seismic weight calculation.

Imposed uniformity distributed floor load kN/m^2	Percentage of imposed load
Up to and including 3.0	25
Above	50

3.4 CALCULATION OF DESIGN SEISMIC FORCE BY LATERAL FORCE METHOD

Design parameters

From the building location and type of building the following are selected from IS 1893:2002

Zone factor as building is located in Zone V (Z) = 0.36

Importance factor as building is school building (I) =1.5

Response reduction factor as it is special moment resistance building(R) = 5.0

The features of the building are as mentioned above.

Seismic weight of the building (W)

As the live load on the floor slab is 3 kN/m^2 the load taken for seismic weight calculation should only 25% of the live load (as per clause 7.3.1 table 8 of IS 1893:2002 Part-I)

The live load on the roof slab should not be considered for seismic weight calculation (as per clause 7.3.2 of IS 1893 Part-I :2002)

Seismic weight on roof is

Dead weight of slab =16x16x0.12x25 =768kN

Weight of floor finishes on roof =16x16x1 =256kN

Weight of beams on one floor

= 0.3x0.45x25x {(16x5) + (16x5)} =540kN

Weight of columns (lumped at roof)

= 0.5x[0.45x0.45x3x25x25] =189.8 kN

Weight of wall at roof above as parapet wall

= 0.23x1x20x (16+16)x2 =294.4kN

Weight of wall below the roof to be lumped

= 0.5x[0.23x2.55x20x {(16x5) + (16x5)}] =938.4kN

Total seismic weight on roof (W5) = 2986.6kN

Seismic weight on each floor is

Dead weight of slab = 16x16x0.12x25 = 768kN

Weight of floor finishes on each floor is = 16x16x1 = 256kN

Weight of live load on floor slab = 16x16x0.25x3 = 192 kN

Weight of beams on floor = 540kN

Weight of columns = 379.6kN

Weight of wall on beams = {(16x5) + (16x5)} x11.73 = 1876.8 kN

Total seismic weight on floor = 4012.4kN

W1=W2=W3=W4 = 4012.4kN

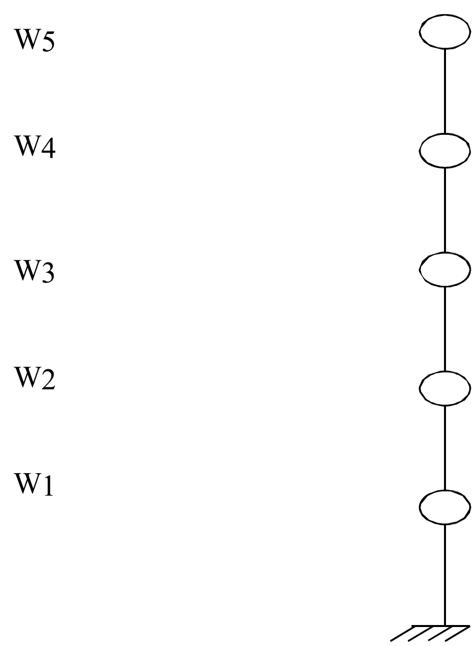


Fig 3.2: Lumped mass at Different storey levels of the Building

Time period (T):

As the building is moment resisting frame with brick infill walls the natural time period of the building as per clause 7.6.2 of IS 1893: 2002 (Part-I)

$$T_a = \frac{0.09\,h}{\sqrt{d}}$$

Where h= height of the building as per clause 7.6.1 of IS 1893:2002

d = base dimension of the building at plinth level in meters along the considered direction of lateral force.

Earthquake load in "X"-direction:

$$T_a = \frac{0.09\,h}{\sqrt{d}}$$

$$= \frac{0.09 \times 15}{\sqrt{16}} = 0.34 \text{ sec}$$

=

As the building is located in hard soil type I soil

From figure (2) of IS 1893:2002 (Part-I)

$$\frac{Sa}{g} = 2.50 \text{ as } 0.10 \leq T \leq 0.40$$

Hence design horizontal acceleration spectra (Ah) = $\frac{ZISa}{2Rg}$ (clause 6.4.2 of IS 1893:2002 part -1)

$$= \frac{0.36 \,x\, 1.5 \,x\, 2.50}{2 \,x\, 5}$$

$$= 0.135$$

Design base shear (V_B) = A_h x W (as per clause 7.5.3 of IS 1893:2002)

= 0.135 x 19036.2

= 2569.9kN

Earthquake load in "Y"-direction:

$$T_a = \frac{0.09\,h}{\sqrt{d}}$$

$$= \frac{0.09 \times 15}{\sqrt{16}} = 0.34 \text{ sec}$$

=

As the building is located in hard soil type I soil

From figure (2) of IS 1893:2002 (Part-I)

$$\frac{Sa}{g} = 2.50 \text{ as } 0.10 \leq T \leq 0.40$$

Hence design horizontal acceleration spectra (A_h) = $\frac{ZISa}{2Rg}$ (clause 6.4.2 of IS 1893:2002 part -1)

$$= \frac{0.36 \times 1.5 \times 2.50}{2 \times 5}$$

$$= 0.135$$

Design base shear (V_B) = A_h x W (as per clause 7.5.3 of IS 1893:2002)

= 0.135 x 19036.2

= 2569.9 kN

From the calculation it is evident that the building has same design seismic force along the X and Y directions.

Force distribution with building height:

As per IS 1893 clause 7.7.1 the design seismic force is to be distributed through the building height. The vertical distribution of base shear to different storey levels is as shown in below table.

Table 3.4: Lateral load distribution with height of the building

Storey level	**W_i (kN)**	**h_i (m)**	**W_i x h_i^2 (x1000)**	$\frac{W_i h_i^2}{\sum W_i h_i^2}$	**Lateral force at i^{th} level for EL load in direction**	
					X	**Y**
5	2986.6	15	671.985	0.382	982.2	982.2
4	4012.4	12	577.8	0.33	848.3	848.3
3	4012.4	9	325.044	0.185	475.63	475.63
2	4012.4	6	144.446	0.082	210.9	210.9
1	4012.4	3	36.1116	0.021	52.87	52.87
	∑		**1755.4**		**2569.9**	**2569.9**

The design seismic force is to be distributed through the building height. The vertical distribution of base shear to different storey levels is as shown in below figure.

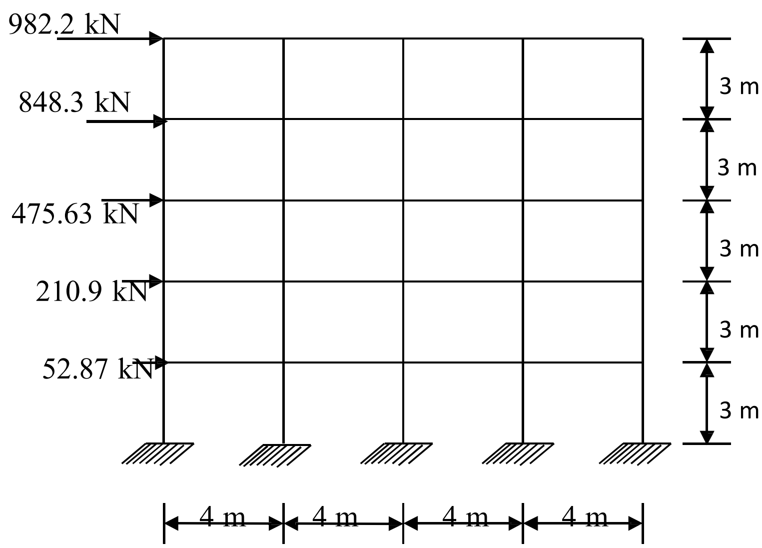


Figure 3.3: Design seismic force along both X and Y direction

3.5 GAP ELEMENT MODEL:

Gap elements are defined by two end nodes formulated in 3-D space. Only the element's axial forces are calculated for each element depending on the behavior of two nodes, only compressive or tensile forces are generated. In this analysis we use compression gap elements i.e the gap element will activate only when the new length i.e sum of displacements of two nodes (one node is positive direction and another node towards negative direction) is greater than or equal to original length i.e provided gap length.

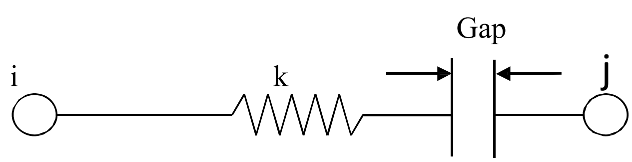


Fig 3.4: Gap element model from SAP2000.

Once the new length is greater the original length impact force (compressive force) will be generated between the two nodes. Generally the stiffness of gap element is taken 10^2 to 10^4 times of adjacent connected spring element from the literature. Here the stiffness of gap element considered 477.6x10^3kN/m (Muthukumar et al., 2004) . The linear analysis is performed based on the stiffness and damping ratio of the gap element.

The force-deformation relationship is $f = \{k\,(d+gap)$, if $(d+gap) < 0$

$\qquad\qquad 0, \qquad$ otherwise.

Where K is stiffness of gap element and d is relative displacement.

CHAPTER 4

POUNDING ANALYSIS OF ADJACENT BUILDINGS

4.1 POUNDING ANALYSIS OF BUILDINGS WITH EQUAL HEIGHTS

4.1.1 Buildings with same height and same floor levels:

For this analysis each of 5-story buildings are considered. The floor levels of two adjacent buildings kept at same level. Even though story heights and floor levels kept as same the loading on each building is different so that each building has different dynamic properties

Selection of ground motions:

The time history analysis required ground motions with suitable time step, for this we can artificial ground motions using functions or the ground motions which are already occurred. The five different ground motions are taken into consideration for analysis. The peak ground acceleration of these ground motions is ranging from 0.22g to 0.883g. The characteristics of these ground motions are as shown in below table. The effect of earthquake of suitable magnitude on building is mainly depends on the characteristics of ground motions like amplitude, frequency and duration of shaking are taking into consideration for engineering purpose.

The five types of ground accelerations such as “Petrolia”(1992), “Northridge"(1994), Elcentro(1940), Parkfield(1996), Loma Prieta(1989) have been applied to model to find response (impact force) between adjacent structures, and the above mentioned ground accelerations are shown in figures 4.1(a-e).

Table 4.1 : Details of ground motions data.

SI No.	Earthquake Name	Location	Year	Magnitude	PGA (g)	Predominant time period range,(sec)
1	Parkfield	Parkfied, California , USA	1996	6.0	0.434	0.30-1.20
2	Northridge	Northridge California, USA	1994	6.7	0.883	0.20-2.20
3	Lomaprieta	Lomaprieta California, USA	1989	6.9	0.220	0.41-1.61
4	Elcentro	Imperial valley, California , USA	1940	7.1	0.348	0.45-0.87
5	Petrolia	Cape Mendocino California , USA	1992	7.2	0.662	0.5-0.83

The ground motion record with acceleration to time step for each ground motion is as shown in below.

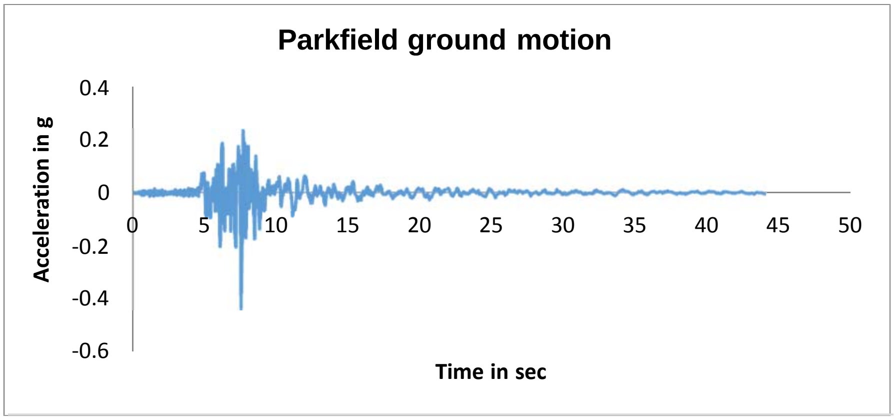


Fig 4.1 (a): Parkfield ground motion acceleration graph.

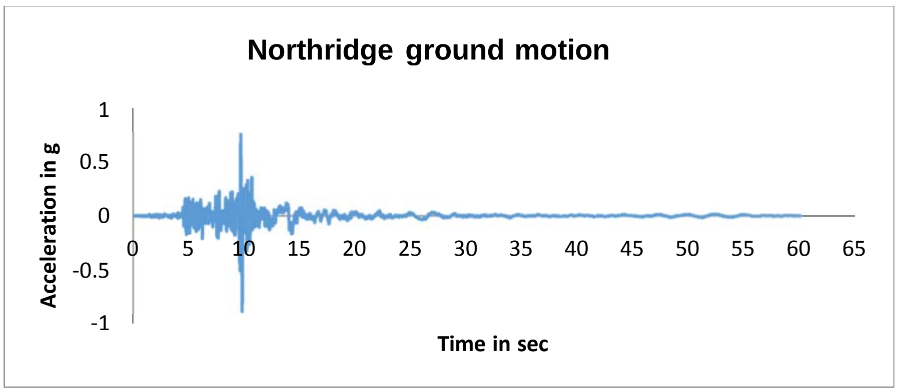


Fig 4.1 (b): Northridge ground motion acceleration graph.

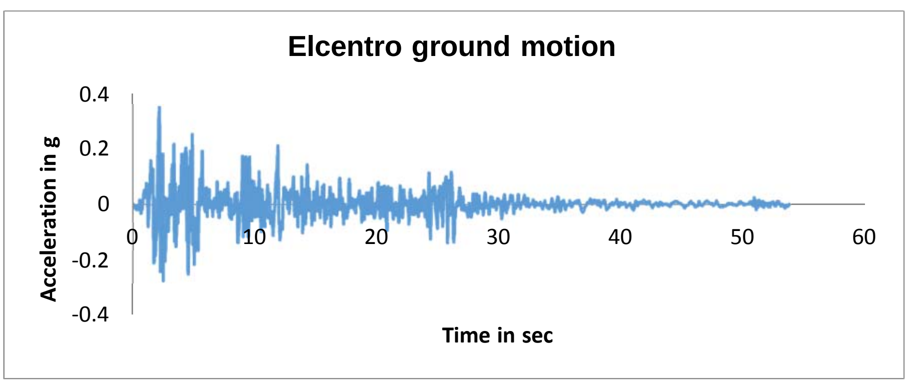


Fig 4.1 (c): Elcentro ground motion acceleration graph.

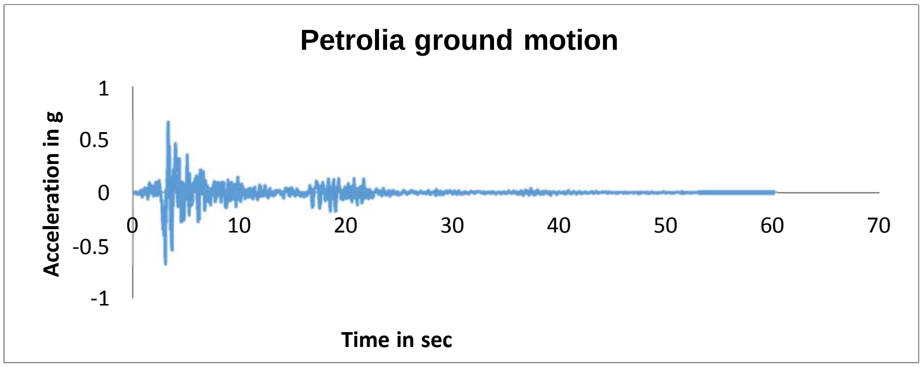


Fig 4.1 (d): Petrolia ground motion acceleration graph.

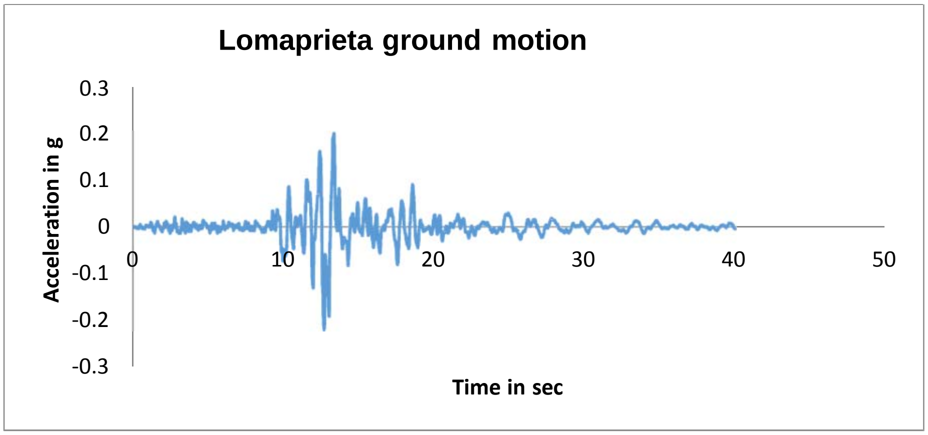


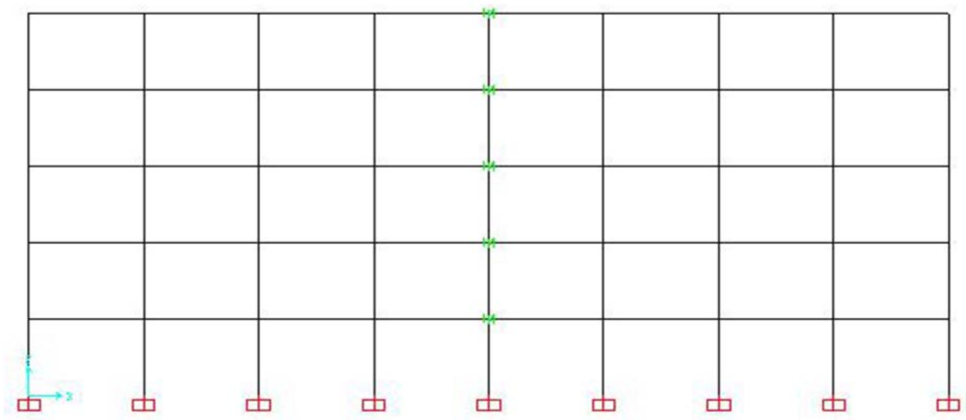
Fig 4.1 (e): Loma prieta ground motion acceleration graph

Here the two adjacent buildings are modeled in **Sap 2000v17** and the analysis is carried out using nonlinear time history analysis by giving the above mentioned ground motions, among those Northridge ground motion is applied to plot the Time vs Displacement curve for each building and remaining all are used to plot the graph between Time vs Impact force. When the ground motion is applying to the model, the two adjacent buildings collide with each other only if the dynamic properties of two buildings are different. In this case the building heights and floor levels are identical so the dynamic properties (Time period, Frequency) are same, so they don't collide with each other even though if you not provide any gap(length of gap=0) between them.

To make these two buildings collide with each other the loading condition should be different on two buildings i.e the Live load on building 2 is five times more than the building 1, so that they vibrate out of phase with different dynamic properties.

The time period of building 1 is 0.584 sec and the time period of building 2 is 0.638 sec.

The main aim of this analysis is to find the impact force between two buildings when the gap element size reducing to zero.



Building 1 Building 2

Fig 4.2: Elevation of buildings with same height and same floor levels

The displacement response of the two buildings is observed, lighter building (building 1) suffers more displacements after collision. The displacement response of the building direction is important because the building 1 displacement is 2.52cm at some time towards positive X direction at the same time building 2 displacement is more than 2.46 cm towards negative X direction there is a chance to collision between the buildings. The displacement responses of two buildings are as shown in below figure.

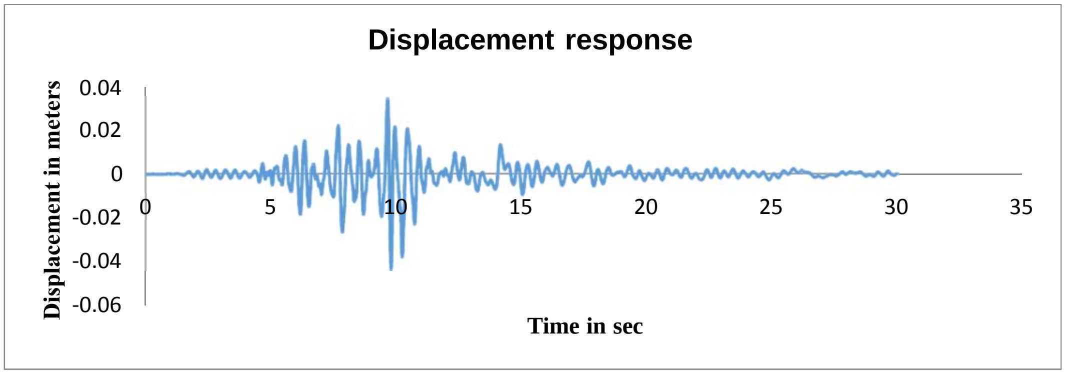


Fig 4.3 (a): Displacement response of building 1 after collision.

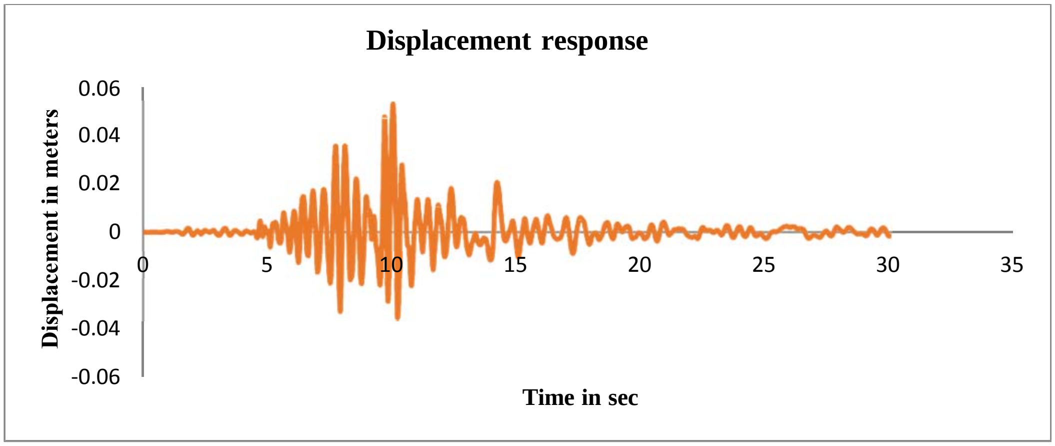


Fig 4.3 (b): Displacement response of building 2 after collision.

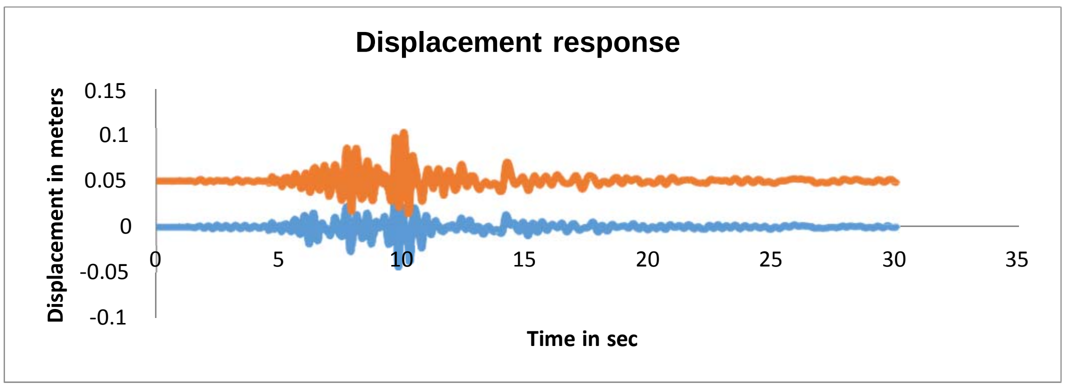


Fig 4.3 (c): Displacement responses of two buildings after collision due to Northridge.

The impact force between the buildings is known from the gap elements which are connected at each storey levels. The following figure shows the pounding force in the gap element at the roof level.

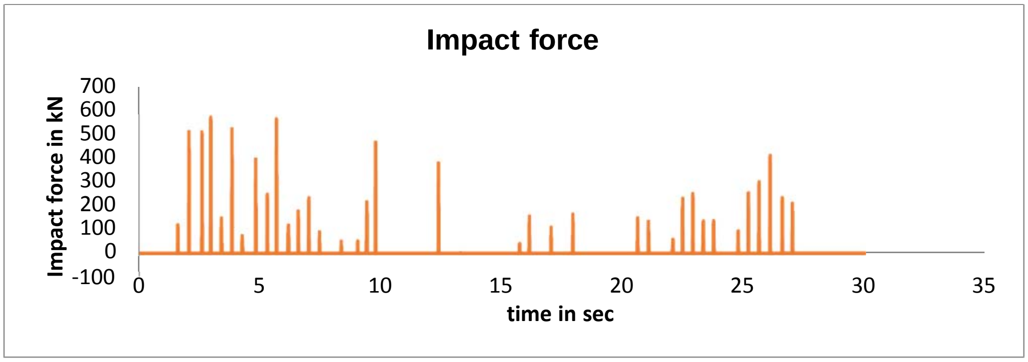


Fig 4.4 (a): Impact force between buildings due to El centro ground motion.

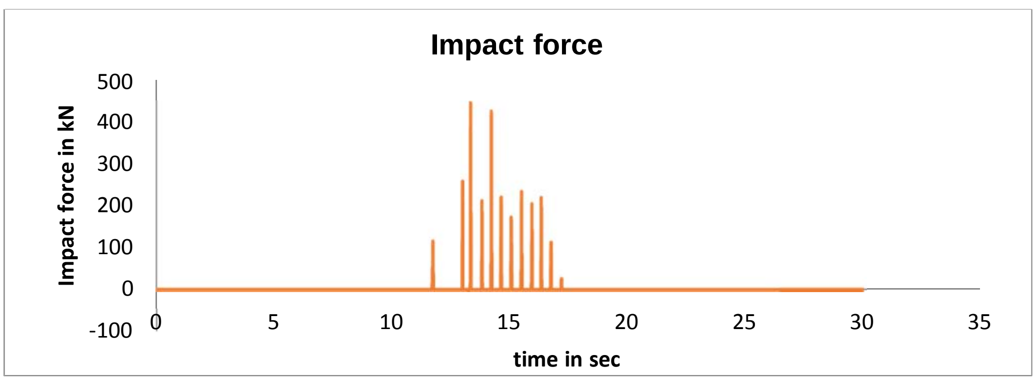


Fig 4.4(b): Impact force between buildings due to Loma prieta ground Motion

The maximum impact force between the adjacent buildings is occurred when it is subjected to Petrolia ground motion. The buildings frequency is lies in the predominant frequency of the ground motion.

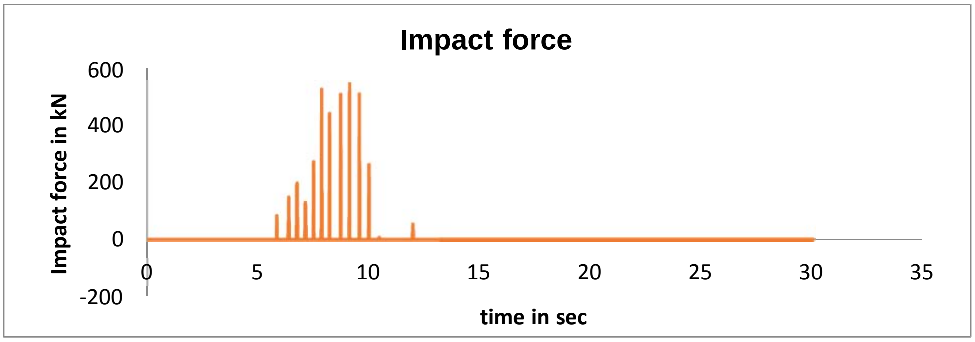


Fig 4.4 (c): Impact force between buildings due to Park field ground motion

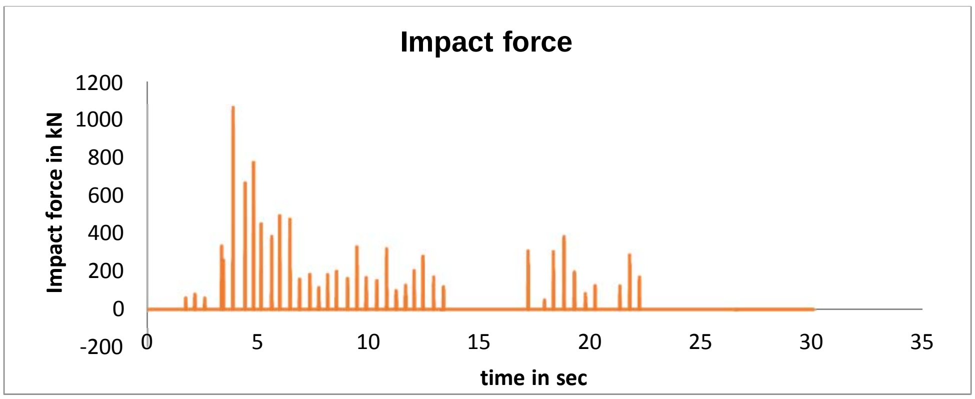


Figure 4.4 (d): Impact force between buildings due to Petrolia ground motion

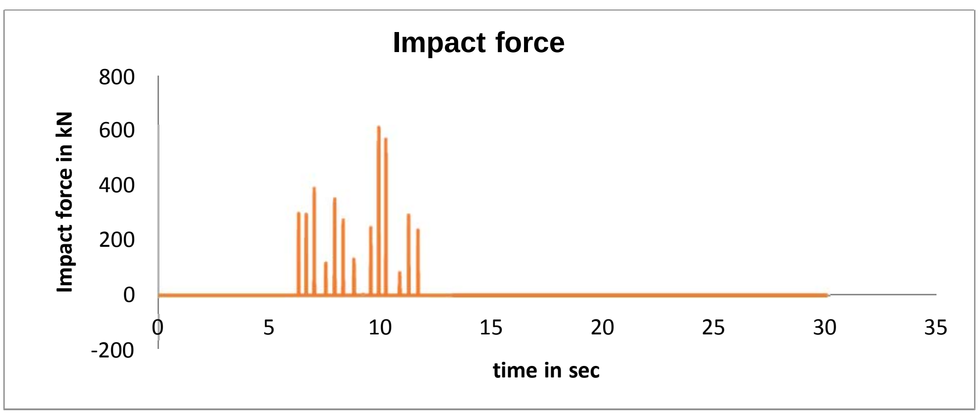
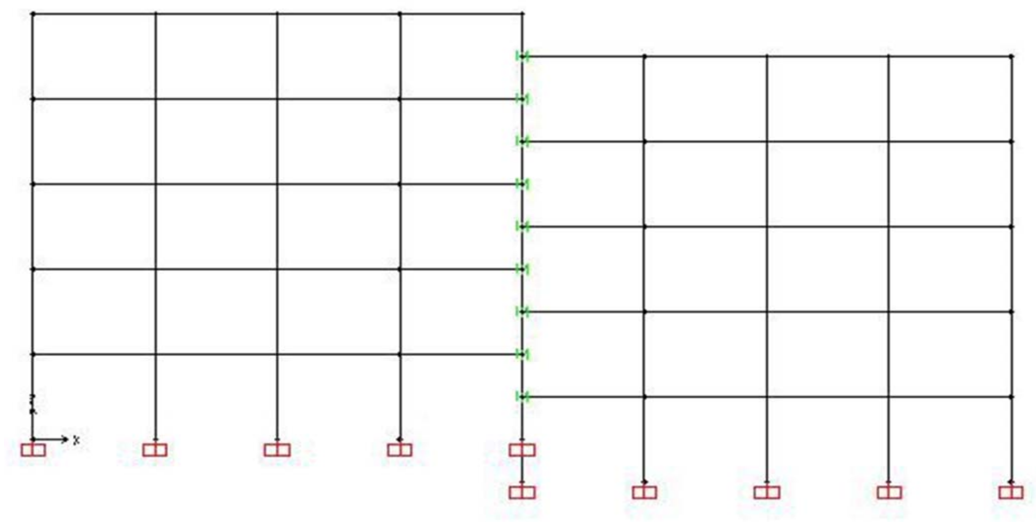


Fig 4.4 (e): Impact force between buildings due to North ridge ground motion

4.1.2 Buildings with same height but different floor levels:

In this case the two adjacent buildings heights are same but floor levels are different. Here gap element is connected between the floor levels of one building to corresponding nodes in column of adjacent building, so that the effect of mid-column pounding is studied.



Building1 Building 2

Fig 4.5: Elevation buildings with same height and different floor levels

The time period of building 1 is 0.584 sec and time period of building 2 is 0.638 sec as the time period are different both the buildings are having different dynamic properties. The buildings are modeled in SAP 2000 V17.the time history analysis is performed by giving the following ground motions whose PGA values ranges from 0.2 to 0.8 g the impact forces in the link elements connected at different storey levels are observed. The impact force at roof joints is maximum compared to the below storey levels. The impact force in the gap element at roof floor level node is as shown in the below figure.

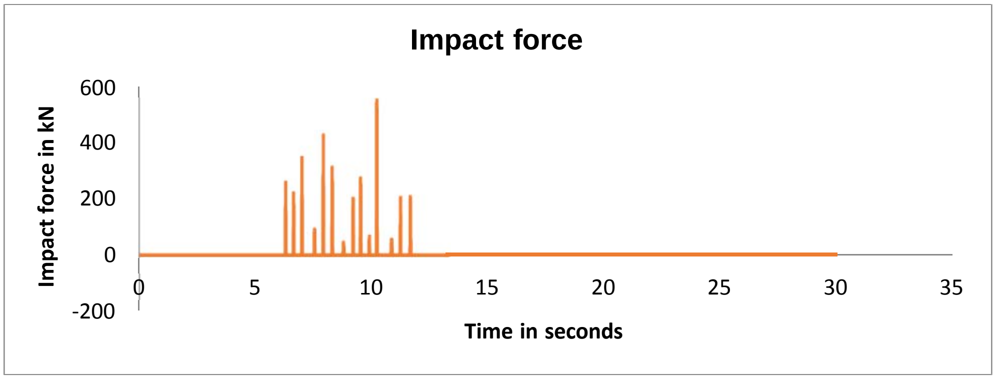


Fig 4.6 (a): Impact force between buildings due to North ridge ground motion

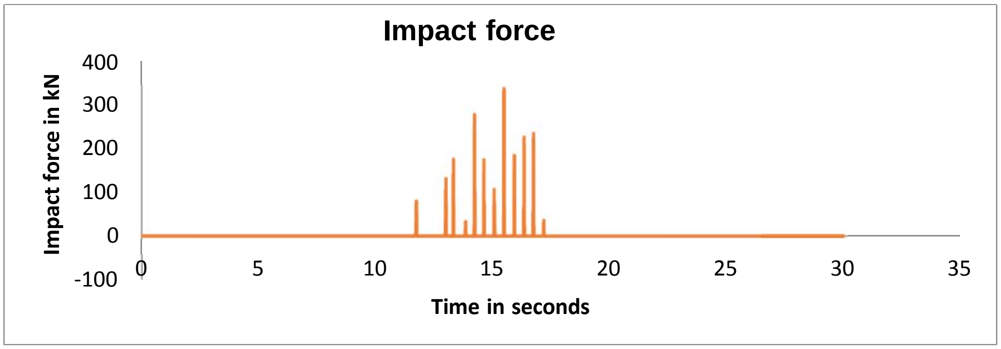


Fig 4.6 (b): Impact force between buildings due to Loma pieta ground motion

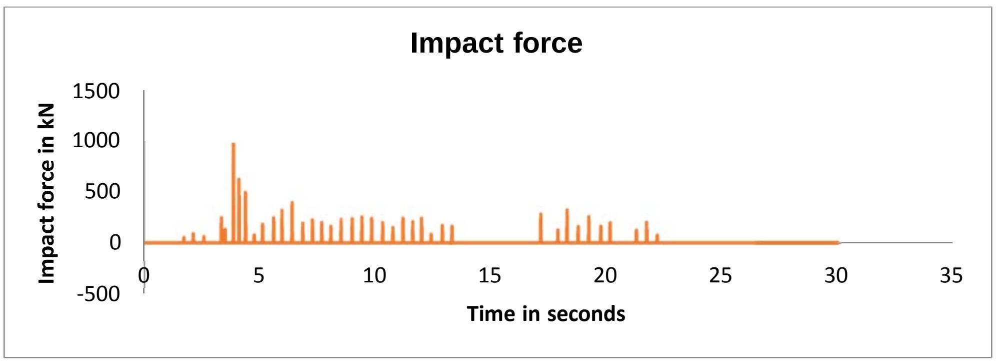


Fig 4.6 (c): Impact force between buildings due to Petrolia ground motion

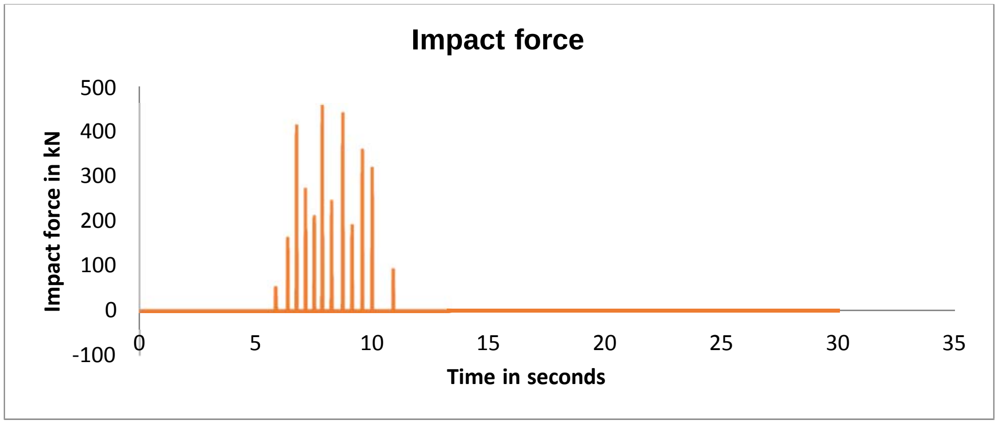


Fig 4.6 (d): Impact force between buildings due to Park field ground motion

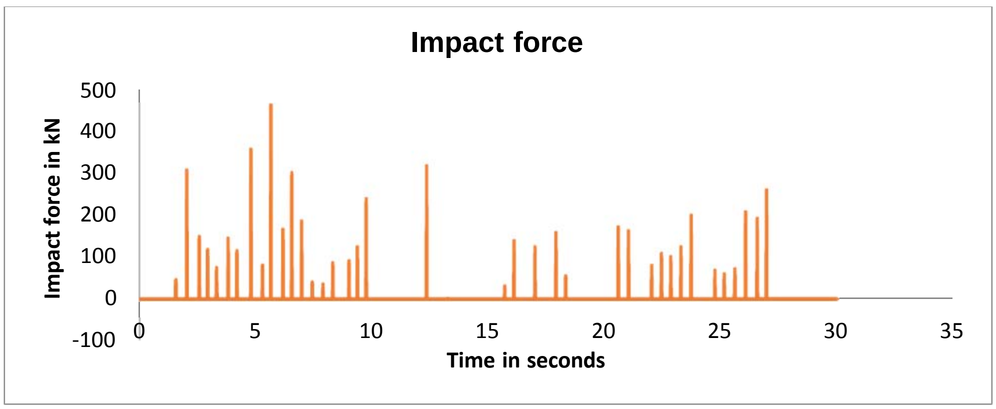


Fig 4.6 (e): Impact force between buildings due to El centro ground motion.

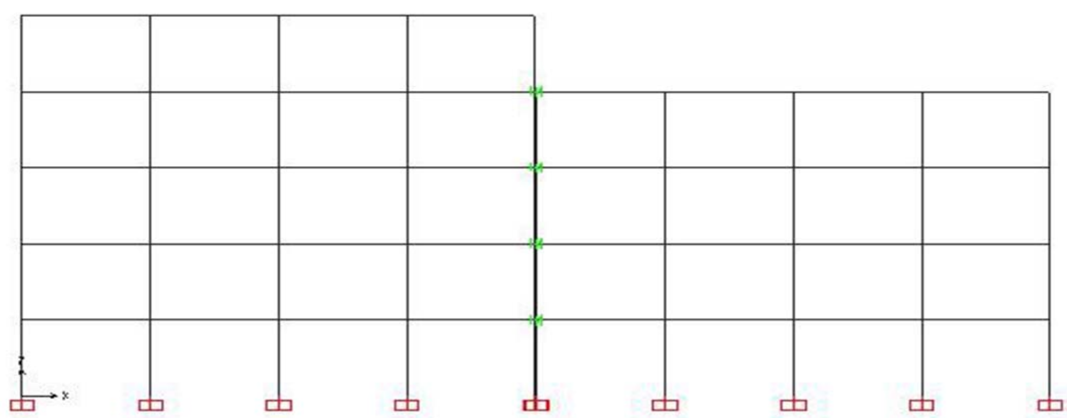
Here the impact force found by connecting the gap element between floor level of one building to corresponding node in the column of adjacent building. The pounding force is maximum at roof of building 2 and gradually it is reducing to first floor. Even though the impact force is minimum compare to buildings with same height and same floor levels, the type of pounding is leads to collapse of structure because the floor level of one building is directly affects the column of other building.

4.2 POUNDING ANALYSIS OF BUILDINGS WITH DIFFERENT HEIGHT

The impact force is studied between the adjacent buildings having different height are considered in this section. The two adjacent buildings are modeled using SAP2000.Two different cases are taken for analysis like two buildings are of different height and having the same floor levels, two buildings are of different height and having different floor levels (mid-column pounding).

4.2.1 Buildings with different height and same floor levels:

In this section two buildings are in different height and same floor levels. The left side building is 5 story and right side building is 4 story considered for this analysis to find seismic response (impact force) of two adjacent buildings under the different ground motions with connection of gap element. The seismic gap between two buildings specified above is 0.05 m. Modeling is done by using Sap 2000 v 17.



Building 1 building 2

Figure 4.7: Elevation of buildings with different height and same floor levels.

The time period of left side 5 story building is 0.681 sec and right side 4 story building is 0.465 sec.

Analysis is done using nonlinear time history under the different ground motion which are specified above. The two adjacent buildings are connected by gap contact element with 0.05 m separation gap.

The adjacent buildings with different height but same floor levels are modeled in SAP 2000 V 17.as shown in figure. The dynamic analysis is performed by time history analysis. The different ground motions are given as input for time history analysis. The ground motion records are as shown below.The ground motion record with acceleration to time step for each ground motion is as shown in below.

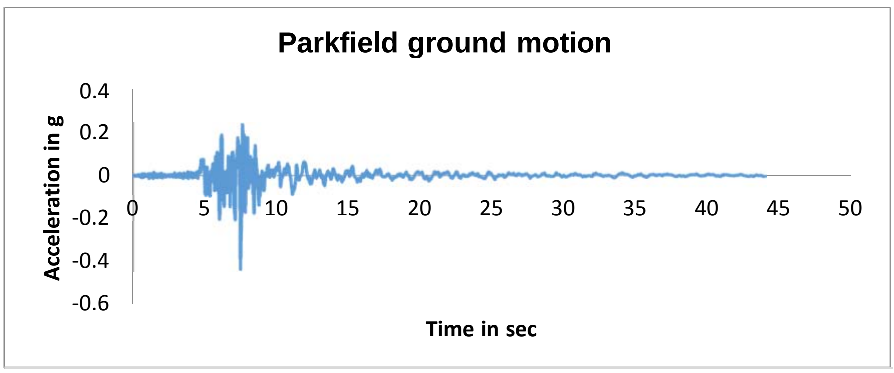


Fig 4.8 (a): Parkfield ground motion acceleration graph.

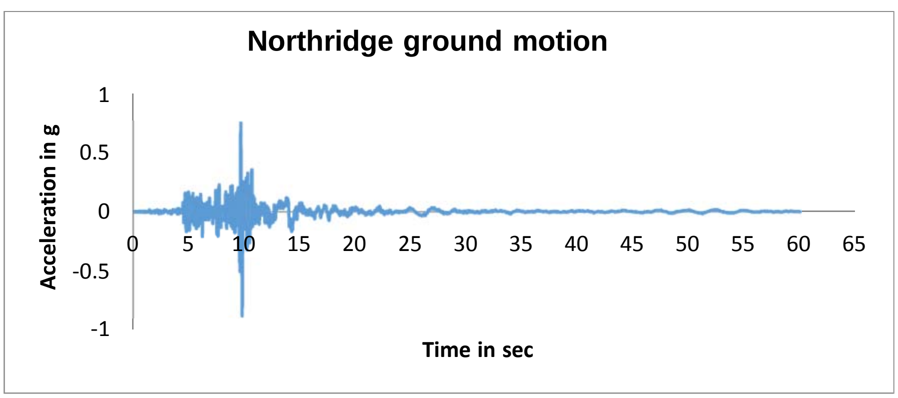


Fig 4.8 (b): Northridge ground motion acceleration graph.

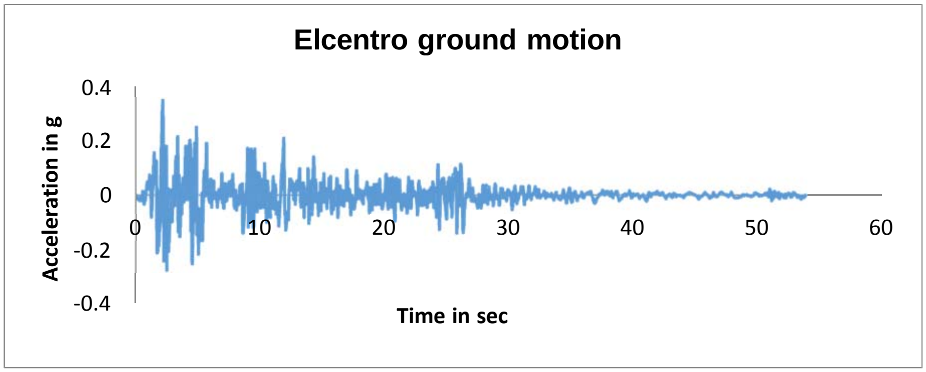


Fig 4.8 (c): Elcentro ground motions acceleration graph.

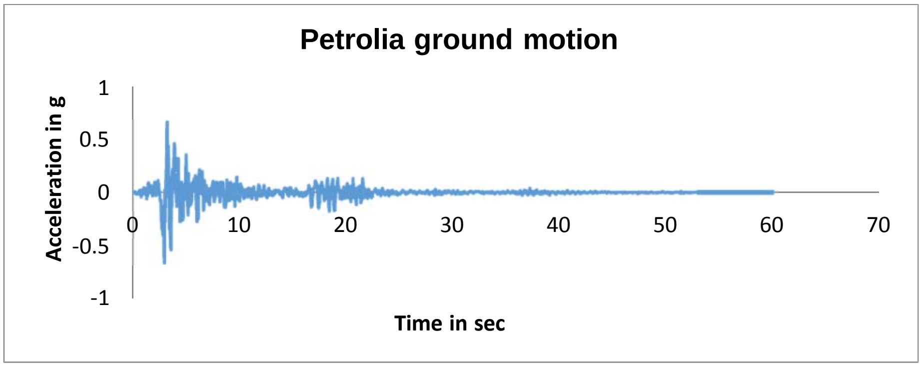


Fig 4.8 (d): Petrolia ground motion acceleration graph.

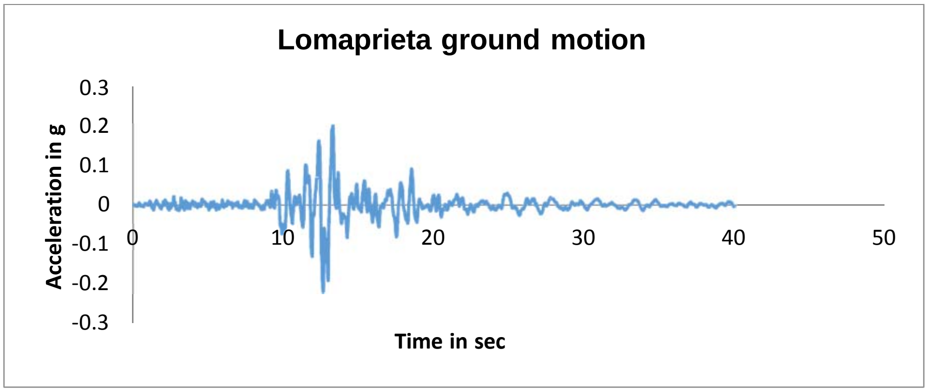


Fig 4.8 (e): Loma prieta ground motion acceleration graph

The displacement response of two adjacent buildings after collision when El-Centro ground given as input for time history analysis is as shown below.

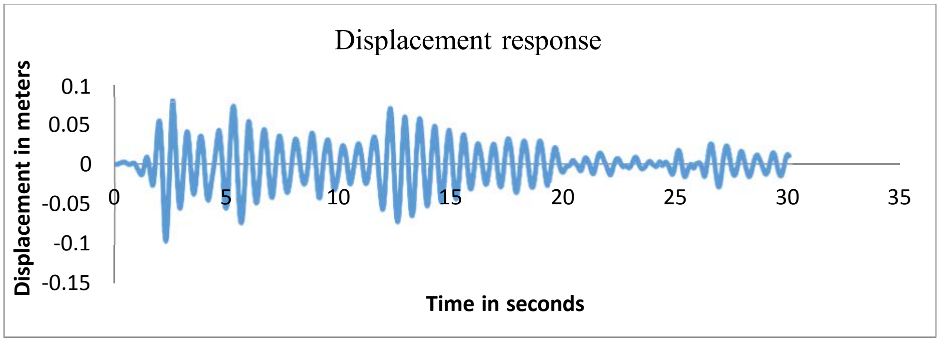


Fig 4.9 (a) displacement response of building 1

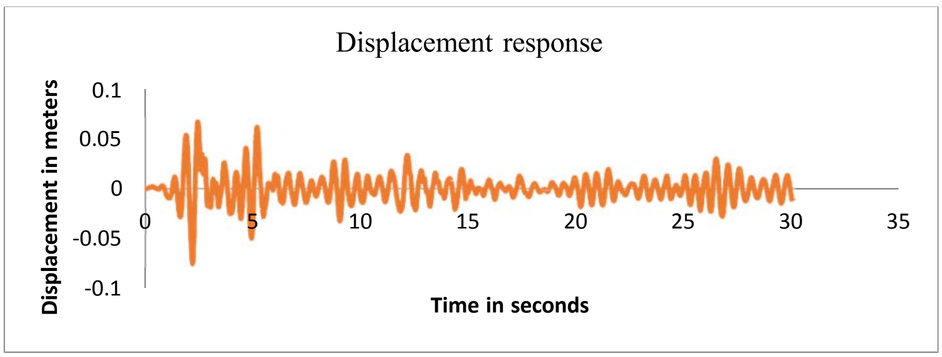


Fig 4.9 (b) Displacement response of building 2

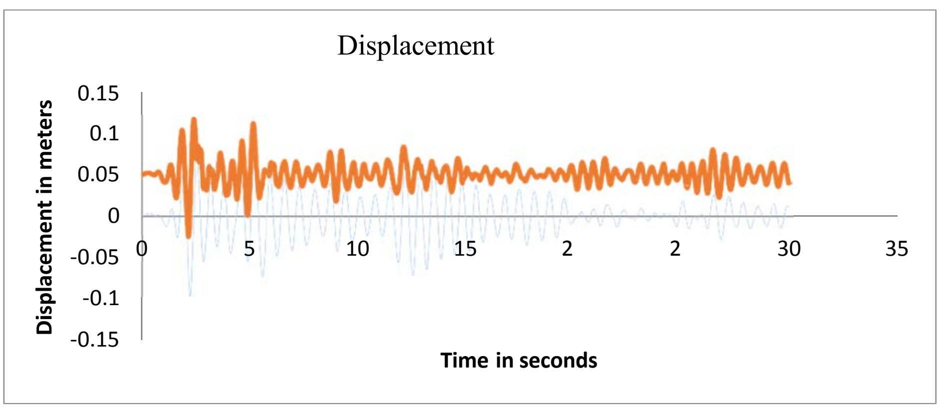


Fig 4.9 (c) Displacement response of two buildings during collision.

The impact force in the gap element at roof floor level node is as shown in the below figure

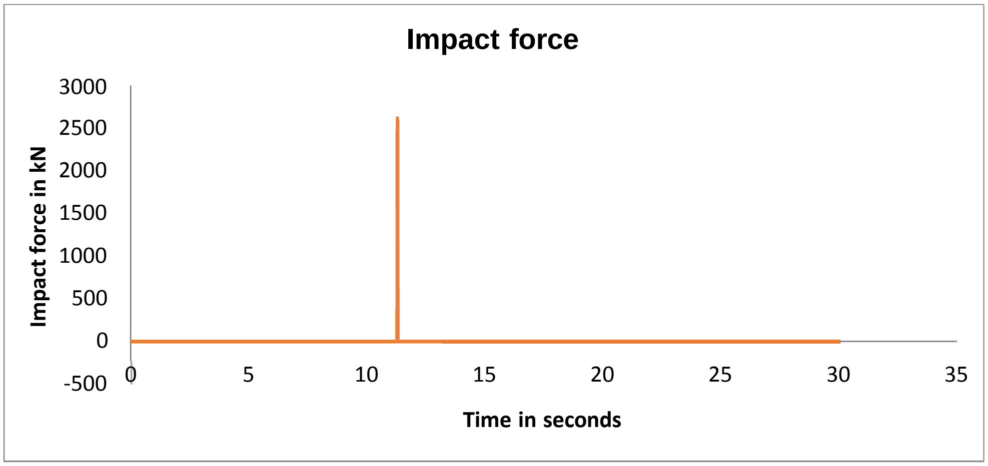


Fig 4.10 (a): Impact force between buildings due to Northridge ground motion.

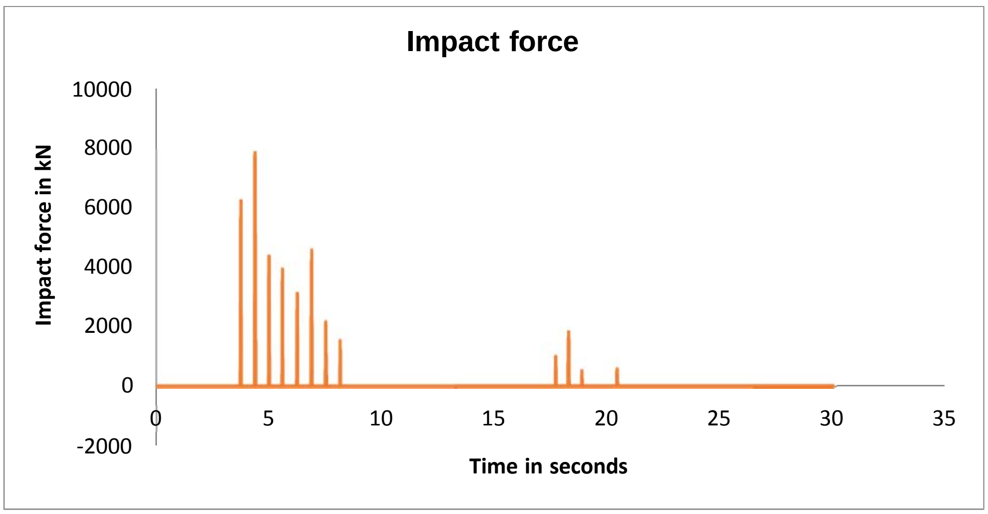


Fig 4.10 (b): Impact force between buildings due to Petrolia ground motion

.

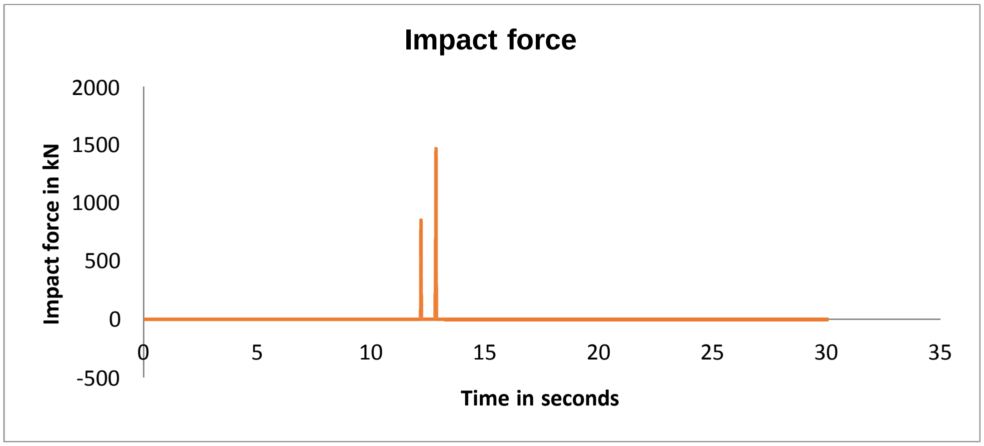


Fig 4.10 (c): Impact force between buildings due to Loma prieta ground motion.

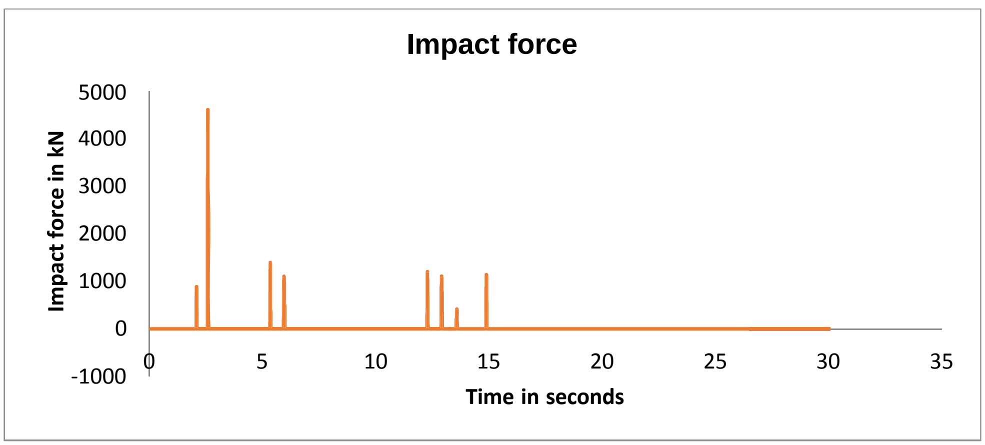
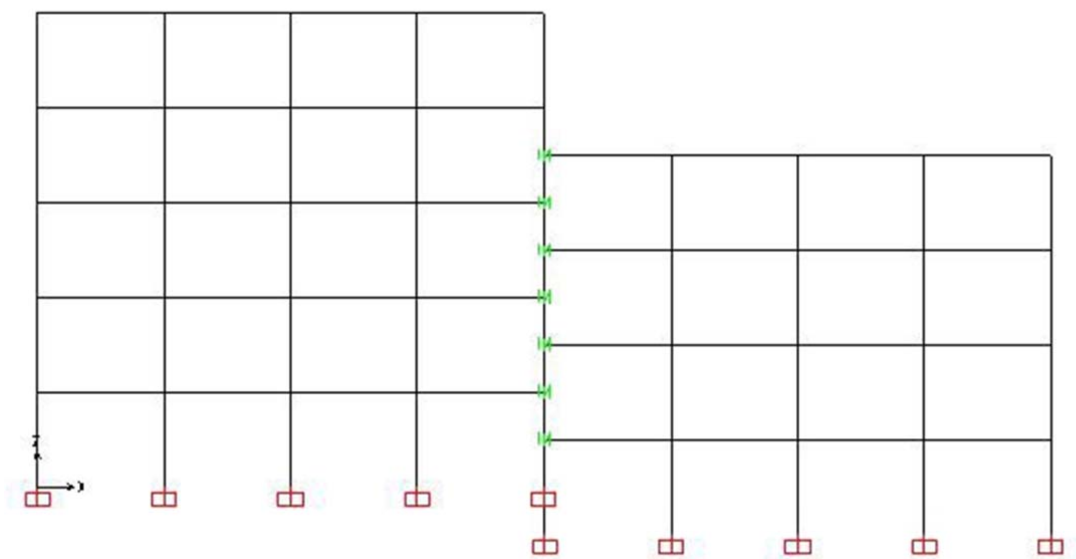


Fig 4.10 (d): Impact force between buildings due to El-centro ground motion.

The impact force value is peak where the maximum displacement will occur. In this analysis the maximum impact force 4615 kN occurred at the top floor of the 4 story building. The displacement response of two adjacent buildings is shown above figure under the **Elcentro** ground motion before and after collision with each other.

4.2.2 Buildings with different heights and different floor levels (floor-mid column):

In this section two adjacent buildings are considered one is 5 stories (left) and another is 4 stories (right) with different building heights and different floor levels. The foundation levels of two buildings are different, and the floor of one building is level to mid-column of another building vice versa. The gap element is connected to each corresponding nodes of two buildings with length of gap element is 0.05 m. The analysis is carried out using nonlinear time history in Sap 2000 v 17.



Building 1 Building 2

Fig 4.11: Elevation view of buildings with different height and different floor levels

These buildings are subjected to different ground motions with different PGA values ranging from 0.2g to 0.8g.the dynamic analysis performed by time history analysis with the following ground motions as input.

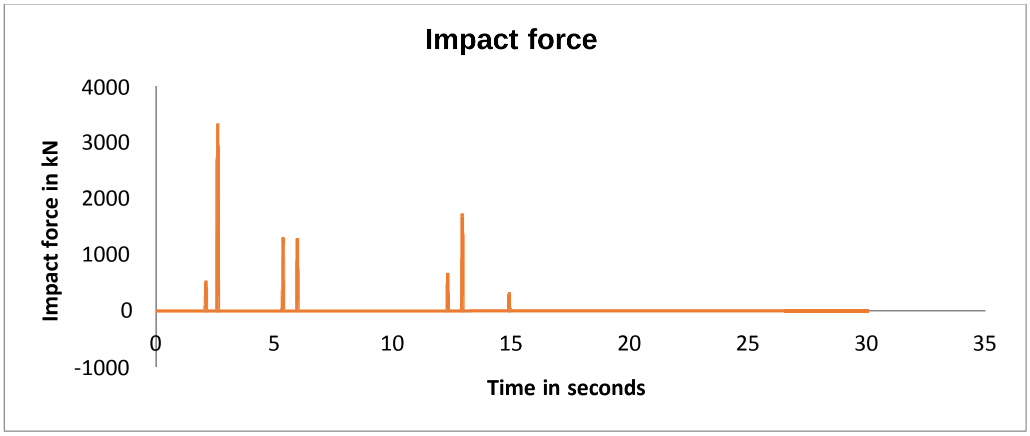


Fig 4.12 (a): Impact force in roof link due to El centro ground motion.

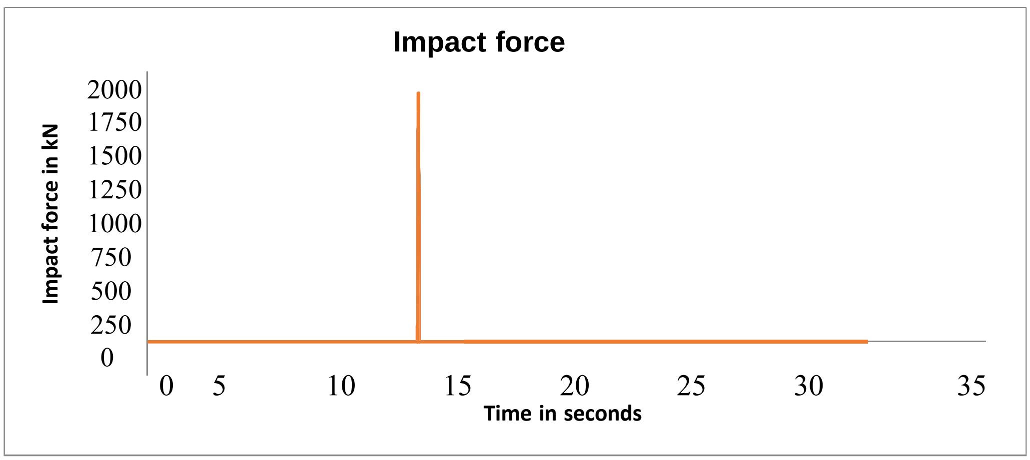


Fig 4.12(b): Impact force in roof link due to North ridge ground motion.

The impact force is maximum at the top floor of building 2 (right side) and gradually this impact force is reducing from top floor to bottom floor. This type of pounding is also leads to severe structural damages in adjacent buildings. The impact forces 3216 kN and 1825 kN occurred due to Elcentro and Northridge ground motions respectively.

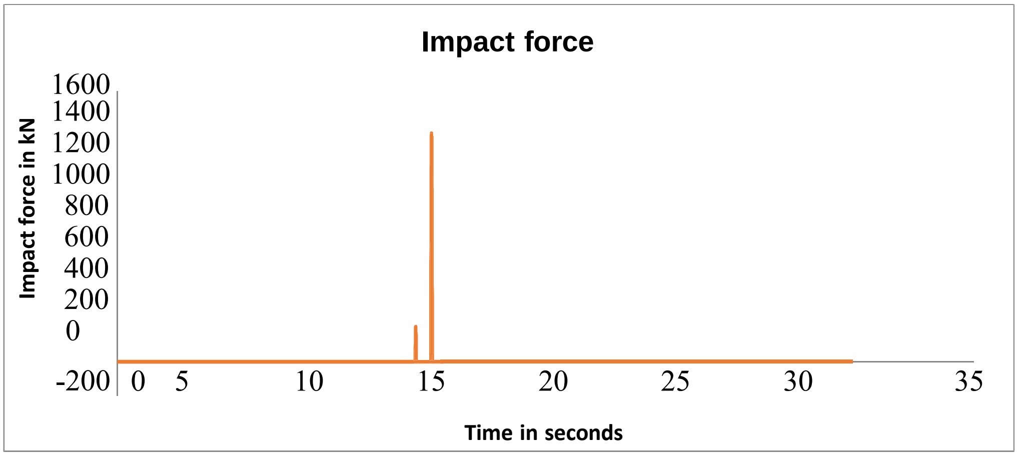


Fig 4.12(c): Impact force in roof link due to Loma Prieta ground motion.

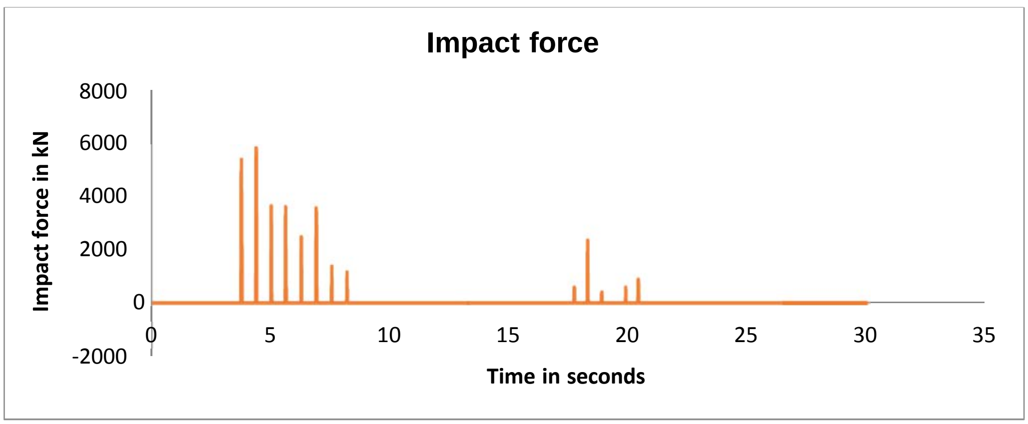


Fig 4.12(d): Impact force in roof link due to Petrolia ground motion.

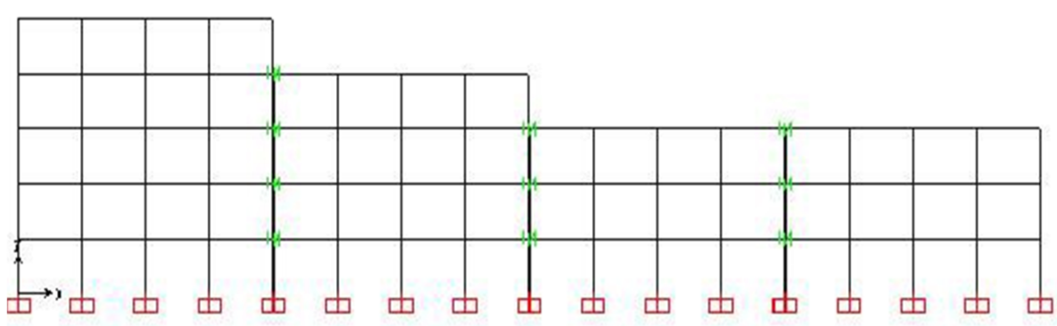
The impact force is maximum at the top floor of building 2 (right side) and gradually this impact force is reducing from top floor to bottom floor. This type of pounding is also leads to severe structural damages in adjacent buildings. The impact forces 1365 kN and 5650 kN occurred due to Loma Prieta and Petrolia ground motions respectively.

4.3 POUNDING ANALYSIS OF SERIES OF BUILDINGS

Buildings in metropolitan cities are constructed in a series with different building configurations. In this chapter 4 buildings with different height but same floor levels are considered and also the row of buildings having different height and different floor levels are analyzed.

4.3.1 Pounding analysis of row of buildings with different height but same floor levels:

Generally we find these types of buildings in metropolitan/urban areas. Here 4 adjacent buildings have been considered in a row of series with a different heights and same floor levels. First building is 5 stories, second is 4 stories, third is 3 stories and forth is also 3 stories are adjacent to each other from left to right side. Nonlinear time history analysis is using to find the seismic response (impact force) between two floor levels of adjacent buildings by connecting gap element to it's nodes at the floor levels. The above considered four adjacent buildings are modeled in sap 2000 v 17 and seismic gap between them is 0.05 m. insufficient gap between the series of buildings are vulnerable to seismic pounding during a strong earth quake ground motion. Here we considered Northridge ground motion is applying to the model to get displacements and impact force between them.



Building 1 Building 2 Building 3 Building 4

Fig 4.13: Elevation of buildings in a row of different height but same floor level.

Based on the above configuration of adjacent buildings in row during **Northridge** ground motion, the exterior buildings suffer more compare to interior buildings. The impact force of exterior buildings is more because these are experiences more displacement than interior buildings, so pounding/compressive force is more in the gap element at exterior buildings. The graphs of Time vs Displacements and Time vs Impact force are shown below.

Impact force between left exterior buildings is 1905 kN and Impact force between interior buildings is 915 kN as shown in the below figures 4.14 (a) and 4.14 (b) respectively.

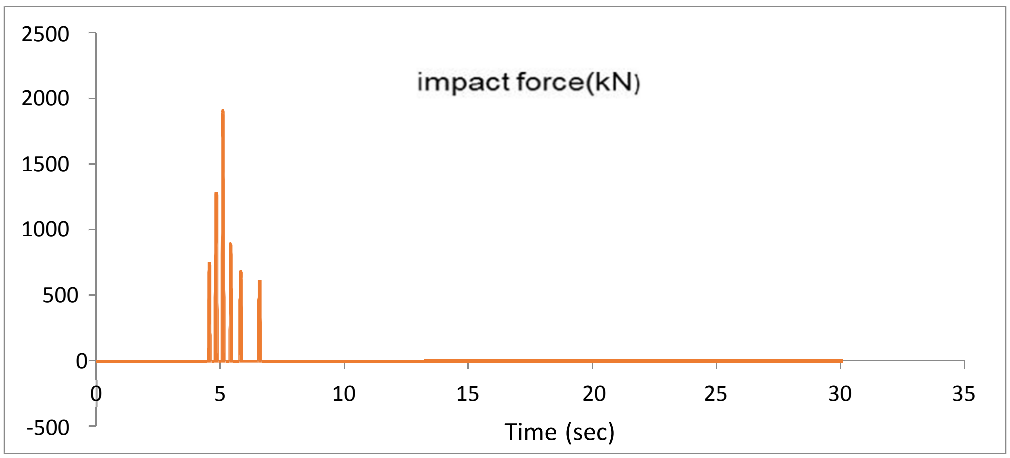


Fig 4.14(a): impact force between the left exterior buildings.

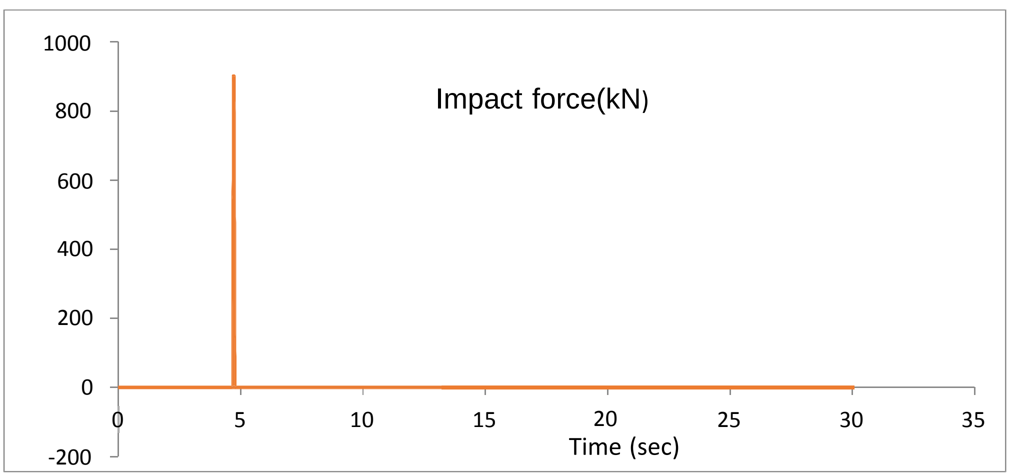
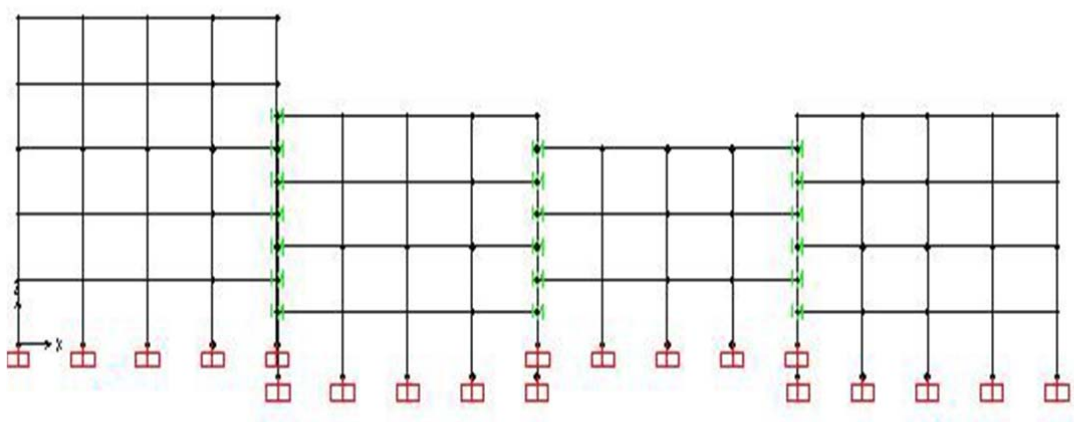


Fig 4.14 (b): impact force between the interior buildings.

4.3.2 Pounding analysis of series of buildings with different height and different floor level (floor-mid column):

Generally in urban/metropolitan cities the buildings are constructed in series with different heights and different floor levels as per their requirements. Here we observe the seismic response of adjacent buildings specified below configurations with connecting nodes by gap element at the floor of one building to column of adjacent building vice versa. North ridge ground motion is applying to model to get the Displacements and Impact forces of exterior and interior buildings. Buildings are modeled in Sap 2000 v 17



Building1 Building 2 Building 3 Building 4

Fig 4.15: Elevation of buildings with different height and different floor levels in a row

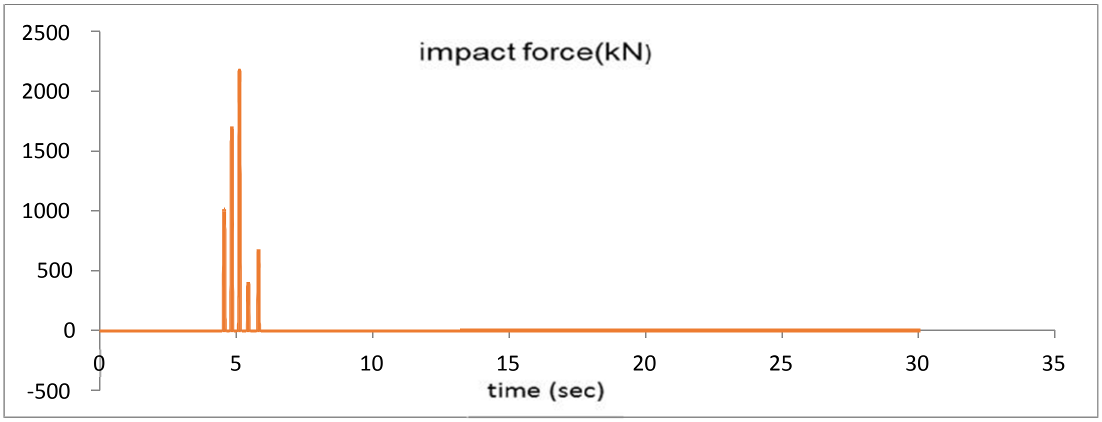


Fig 4.16(a): impact force between left exterior buildings.

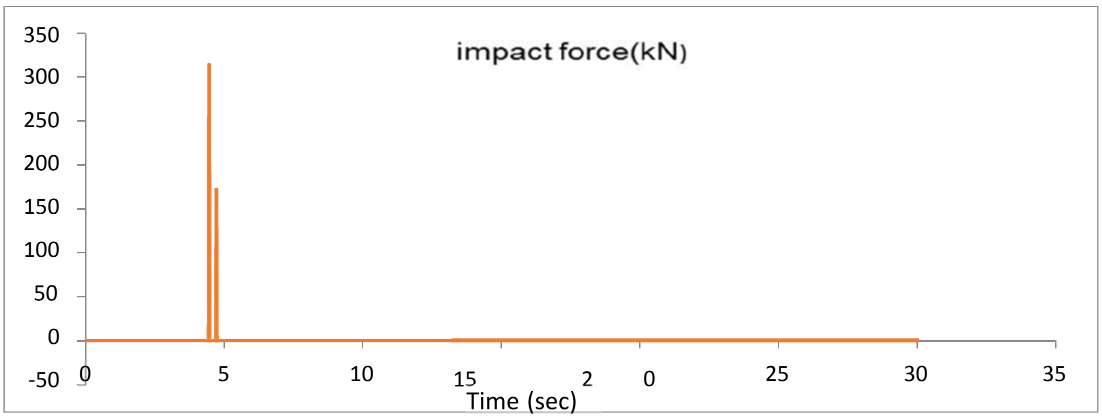


Fig 4.16(b): impact force between interior buildings.

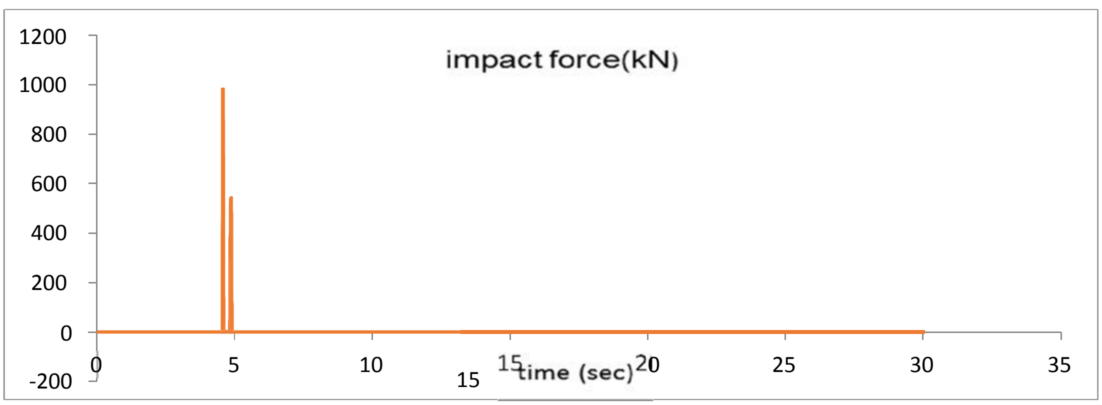


Fig 4.16(c): impact force between right exterior buildings.

The maximum impact force occurred at the left exterior buildings i.e between 5 storey building and 4 storey building that value is 2179 kN. The minimum impact force occurred at interior buildings i.e 4 storey and 3 storey buildings that value is 315 kN. The right exterior buildings have less seismic response compare to left exterior buildings because height of buildings are less at right exterior and it's value is 980 kN. This analysis concluded that pounding force is more at exterior buildings compare to interior buildings.

SUMMARY:

In this chapter, the seismic response (impact force) of adjacent buildings and series of the buildings are found based on the different types of ground motions individually. The impact force is maximum when the heights of two adjacent buildings are different compare to same height of buildings, and also proved that the impact force is maximum at exterior buildings compare to interior buildings.

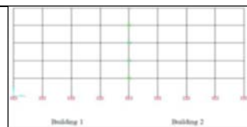
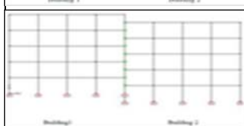
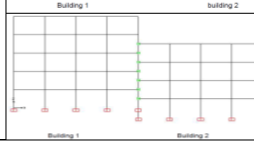
In the coming chapter comparison of impact forces for all adjacent structures when subjected to each ground motion. Among the all five ground motions Petrolia ground motion affects the buildings more in terms of impact force.

CHAPTER 5

RESULTS AND DISCUSSIONS

Impact force of different cases of adjacent buildings subjected to following ground motions in tabular form:

Table 5.1: Impact force subjected to Petrolia ground motion

Building position			Impact force
Buildings with equal height		Same height with Same floor levels	1052 kN
		Same height but different floor levels	994 kN
Buildings with different height		Different height with same floor levels	7950 kN
		Different height but different floor levels	5650 kN

Even though impact force is less when the buildings with same floor levels compare to different floor levels the seismic damage will be more in case of different floor levels, because the floor of one building is directly acting upon mid column of another building.

Table 5.2: Impact force subjected to Northridge ground motion

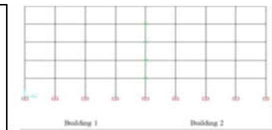
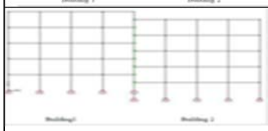
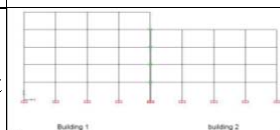
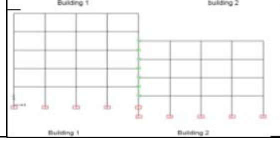
Building position			Impact force
Buildings with equal height		Same height with Same floor levels	612 kN
		Same height but different floor levels	556 kN
Buildings with different height		Different height with same floor levels	2063 kN
		Different height but different floor levels	1825 kN

Table 5.3: Impact force subjected to Elcento ground motion

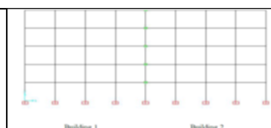
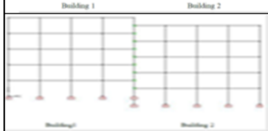
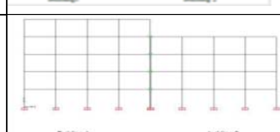
Building position			Impact force
Buildings with equal height		Same height and Same floor levels	586 kN
		Same height but different floor levels	447 kN
Buildings with different height		Different height with same floor levels	4615 kN
		Different height but different floor levels	3216 kN

Table 5.4: Impact force subjected to Loma prieta ground motion

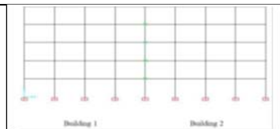
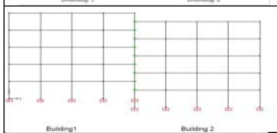
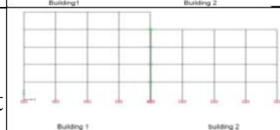
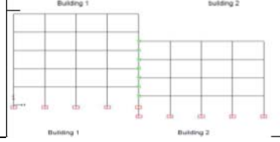
Building position			Impact force
Buildings with equal height		Same height and Same floor levels	456 kN
		Same height but different floor levels	345 kN
Buildings with different height		Different height with same floor levels	1497 kN
		Different height but different floor levels	1365 kN

Table 5.5: Impact force subjected to Park field ground motion

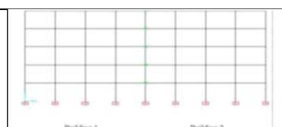
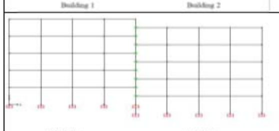
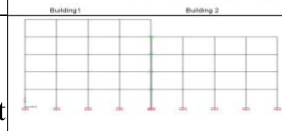
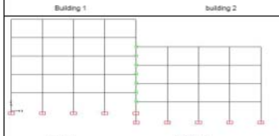
Building position			Impact force
Buildings with equal height		Same height and Same floor levels	517 kN
		Same height but different floor levels	467 kN
Buildings with different height		Different height with same floor levels	1258 kN
		Different height but different floor levels	1126 kN

Table 5.6: Comparison of impact forces for different cases of buildings subjected to all ground motions.

Building position		Impact force				
		Petrolia	Northridge	Elcentro	Lomaprieta	Park field
Buildings with equal height	Same height with Same floor levels	1052 kN	612 kN	586 kN	456 kN	517 kN
	Same height but different floor levels	994 kN	556 kN	447 kN	345 kN	467 kN
Buildings with different height	Different height with same floor levels	7950 kN	2063 kN	4615 kN	1497 kN	1258 kN
	Different height but different floor levels	5650 kN	1825 kN	3216 kN	1365 kN	1126 kN

For any ground acceleration the impact force is maximum in case of Buildings with different height compare to Buildings with same height. Among all ground accelerations Petrolia ground motion influences more i.e seismic response (impact force) is maximum.

CHAPTER 6

CONCLUSIONS

The impact force between adjacent buildings lead to local damage cracks to severe damage like failure of structural members and it is hazardous for buildings. The conclusions regarding pounding effect (Impact force) are as follows :

1. Pounding damage occurs during the strong earthquakes between the adjacent buildings or different units of the same building. Providing sufficient separation gap between adjacent buildings which are going to construct is the best mitigation measure for pounding damage.

2. Pounding damage is more when the adjacent buildings are constructed with different floor levels because the total lateral force (impact force) is directly upon column elements, so the buildings with different floor levels are undesirable compared to same floor levels.

3. It is preferable to construct adjacent buildings with same floor level and with suitable separation gap by considering dynamic analysis to avoid pounding.

4. The adjacent buildings collide with each other when they have different building configurations and dynamic properties so that they vibrate out of phase.

5. The pounding damage is severe in exterior buildings compare to interior buildings when the buildings are in series because seismic response (impact force) of exterior buildings is more.

6. Buildings which are already constructed without proper seismic separation gap are need to be coupled with supplemental damping devices is an effective method to mitigate pounding damage.

7. One of the ways to mitigate impact due to pounding of adjacent structures during seismic excitation is to harden the buildings such that the displacements and impact effects are decreased.

FUTURE SCOPE OF STUDY:

On the basis of current work, the following future scope can be performed:

1. Extension of this work needs to quantify the structural damage in terms of stiffness degradation or strength degradation.
2. Effect of complete collapsing one building is on another building and how the energy transmitted from one building to another building while occurring high magnitude of earthquake.
3. Pounding analysis of setback buildings, relation between setback and collision force need to be calculated.
4. Considering soil and brick parameters to current work.
5. Modelling the structures using expansion joints such as filler or rubber material.

REFERENCES

1. Anagnostopoulos, S.A; Spilliopoulos, K V (1992). "An Investigation of Earthquake induced Pounding between Adjacent Buildings", Earthquake Engineering & Structural Dynamics.Vol.21, No.4, and Pp.289-302.

2. Alireza M.Goltabar, R. Shamstabar kami and A. Ebadi (2008), "Analyzing the Effective Parameters in Pounding Phenomenon between Adjacent Structure due to Earthquake", The 14 th World Conference on Earthquake Engineering, pp. 12- 17, Beijing, China.

3. Arash Rezavani and A.S. Moghadam (2004), "Using Shaking Table to Study Different Methods of Reducing Effects of Buildings Pounding During Earthquake", 13th World Conference on Earthquake Engineering, Paper No. 698, Canada.

4. Beskos D.E, S. Efraimiadou & G.D.Hatzigeorjiou (2012). "Structural Pounding Between Adjacent Buildings: the effects of different structures configurations and multiple Earthquakes", 15th WCEE.

5. Bipin Shrestha (2013), "Effects of Separation Distance and Nonlinearity on Pounding Response of Adjacent Structures", International Journal of Civil and Structural Engineering, Volume 3, No 3.

6. IS 1893 (part 1):2002 "Indian standard Criteria for Earthquake Resistant Design of Structures", part 1 General Provisions and buildings, New Delhi.

7. IS 4326:1993 "Indian Standard Code of Practice for Earthquake Resistant Design and Construction of Buildings", New Delhi.

8. KabirShakya, Anil C.wijeyewickrema (2008), "Mid-Column Seismic Pounding of Reinforced Concrete Buildings in a row considering Effects of Soil", 14th WCEE.

9. Khaja Afroz Jamal, H.S.Vidyadhara (2013), "Seismic Pounding of Multistoreyed Buildings", International Journal of Research in Engineering and Technology.

10. Mizam Doğan and Ayten Günaydin (2009), "Pounding of Adjacent RC Buildings during Seismic Loads", Journal of Engineering and Architecture, Vol: XXII, No: 1.

11. Rajaram C., Pradeep Kumar R. (2012), "Study on Impact between Adjacent Buildings: comparison of Codal Provisions", 15 Th WCEE.

12. Ravindranatha, Tauseef M Honnyal, Shivananda S.M (2014), "A Study 0f Seismic Pounding between Adjacent Buildings", IJRET; 3(15) 795-799, India.

13. Robert Jankowski (2004) "Non-Linear Modelling of Earthquake Induced Pounding of Buildings" Published On ICTAM, Warsaw, Poland.

14. Shehata E. Abdel Raheem (2006), "Seismic Pounding between Adjacent Building Structures", Electronic Journal of Structural Engineering, Vol. 6, pp. 66-74.

15. S. Muthukumar and R. DesRoches (2006.), "A Hertz contact model with non-linear damping for simulation", Earthquake Eng. and Structural Dynamics, Vol. 35, pp. 811-828.