

Wavelet Based Detection of Seismic Pounding in Adjacent Buildings and its Mitigating Measures

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ABSTRACT: Major seismic events such as those that have occurred in Northridge, Imperial Valley (May 18, 1940), California (1994), Japan (1995), Taiwan (1999) and Bhuj, Central Western India (2001) have continued to demonstrate the destructive power of earthquakes, with the collapse of uncountable engineered buildings, bridges, industrial and port facilities as well as giving rise to great economic losses. It has been observed that seismic induced pounding is one of the major causes of these structural damages. As a result, a parametric study on buildings' pounding response as well as proper seismic hazard mitigation practice for adjacent buildings has been carried out in this paper. Seismic pounding between adjacent buildings can cause severe damage to the structures under earthquakes due to their different dynamic characteristics. During earthquake, the buildings vibrate out of phase and at rest separation is insufficient to accommodate their relative motions leading to severe collisions. This deadly phenomenon can be prevented by providing safe separation distances between structures which will allow enough space for the lateral movements of the buildings during earthquake jolts. Sometimes provision of required safe separations is not possible in metropolitan areas due to high land value and limited availability of land space. In such cases, there should be some secure and economic methods to prevent structural pounding between adjacent buildings. Within the limited scope of this paper an attempt has been made to detect the time instant of pounding with the help of wavelet transform which is has an advantage over FFT plot as it gives information about both time and frequency content of the input signal. A comparative study of different prevention techniques such as shear walls, bracing, dampers and isolators has also been carried out to find out the best mitigating measure both in terms of their efficacy and cost effectiveness.

KEYWORDS: Wavelet transform, Damper, Isolator, Phase movement, Pounding, Shear wall

I. INTRODUCTION

The highly congested buildings of the metropolitan cities constitute a major concern for seismic pounding damage. The simplest and an effective way for pounding mitigation and reducing damage due to pounding is to provide sufficient separation gap between structures. But it is sometimes difficult to be implemented in metropolitan areas considering its limited space and high cost of land. Moreover, there is no definite guideline given to preclude pounding in the past seismic codes, because of which there are many buildings worldwide which are already built in contact or extremely close to another that could suffer pounding damage in future earthquakes. Thus an alternative to the seismic separation gap provision in the structure design is to minimize the effect of pounding through decreasing lateral motion which can be achieved by joining adjacent structures at critical locations so that their motion could be in-phase with one another or by increasing the buildings' damping capacity by means of passive structural control of energy dissipation system or by seismic retrofitting.

The focus of this paper is the development of an analytical model and methodology for the formulation of the adjacent building-pounding problem based on the time-history analysis and an investigation through parametric study to the most effective and economical mitigation measure for preventing the damage caused by pounding. The acceleration data have also been analysed to obtain the time frequency plots to locate the time instant of occurrence of the dominant frequency to overcome the limitations of the FFT plot which only gives information of the dominant frequency and its amplitude but not its time instant of occurrence. The main objective and scope are to evaluate the effects of structural

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pounding on the global response of building structures by provision of shear wall, cross bracings, isolators and dampers considered one at a time and provide the engineers with practical analytical tools for predicting pounding response and mitigating damage. A realistic pounding model is used for studying the response of structural system under the condition of structural pounding subjected to Elcentro earthquake for medium soil condition at seismic zone IV. Two adjacent buildings are considered as a representative structure for potential pounding problem. Time-history analysis is carried out on the structures to observe displacement, acceleration and number of poundings of the buildings due to earthquake excitation. The acceleration data obtained from the analysis is used as input signal for continuous wavelet transform in MATLAB to obtain the occurrence of the dominant frequency. Different cases are considered to find out the most effective mitigating measure for reducing the effect of structural pounding both before and after the construction of the buildings.

For the purpose of this study, high end finite element software SAP2000 has been used for analysis. Creation and modification of the model, execution of the analysis, and checking and optimization of the design are all done with the help of SAP 2000. Graphical displays of the results, including real-time animations of time-history displacements and acceleration obtained from the analysis are compared to find out the most effective preventive measure.

II. LITERATURE SURVEY

A series of integrated analytical and experimental studies has been conducted to investigate the seismic gap between adjacent buildings located in seismically active areas. When a building experiences earthquake jolts its foundation moves back and forth with the ground. These vibrations can be quite intense, creating stresses and deformation throughout the structure making the upper edges of the building sway from a few millimeters to many inches depending on their height, mass and size. This is applicable for buildings of all heights, whether single storied or multi-storied in high-risk earthquake zones. Pounding effect produces acceleration and shear at various story levels that are greater than those obtained from the no pounding case.

Mohammed Jameel, A.B.M. Saiful Islam and et.al (2013) [1] studied on the seismic pounding between neighbouring multi-storey structures by non-linear FEM analysis. The results were obtained in the form of pounding force, point displacement, storey shear, storey drift and acceleration. They concluded that the acceleration at pounding level increases considerably during collision of building thereby generating extra pounding force which may cause severe damage to the structural members. Pounding produces shear at various story levels, which are much greater than those obtained from no pounding case. Tall buildings suffer greater damage than shorter ones when pounding occurs. Increasing gap distance between the buildings tends to reduce story shear in consistent manner.

Chetan J Chitte ,Anand S Jadhav and Hemraj R Kumavat (2014) [2] studied about the seismic pounding between the adjacent buildings subjected to near field and far field earthquakes. Two models of G+5 storied building, one with live load 1.5KN/m², other with 2 KN/m² and a model of G+8 storied building with live load 1.5 KN/m² were modelled in which all other properties were almost kept the same. Time history analysis of building structures were done to examine the nonlinear behaviour of the building structures using the finite element software SAP2000. Newmark's direct integration method was adopted and the mass and stiffness proportional coefficients were calculated according to the frequency of the structure in two consecutive modes in same direction and it was concluded that the displacement for near source is much greater than the far source ground motion.

M Phani Kumar and J D Chaitanya Kumar (2015) [3] studied on seismic pounding of the adjacent buildings with different heights by linear and nonlinear dynamic analysis using ETABS (Non Linear) computer program. It is based on a detailed parametric study which is carried out to investigate the effect of various parameters on the structural pounding by Response Spectrum (Linear Dynamic) Analysis for medium soil at zone V and Time History (Non-Linear Dynamic) Analysis for Bhuj earthquake recorded excitation on different models with varying separation distances. Pounding forces can be calculated using the commercial software ETABS where nonlinear gap elements between the adjacent building floors are used to calculate pounding forces. It is concluded that it is necessary to carry out non-linear dynamic analysis to find out the actual response of the structure.

Mahdi Heydari and Mahdi Mousavi (2015) [4] studied the seismic effects of near-field and far-field earthquakes on relative displacement of seven-storey concrete building provided with shear wall. The characterization of near-field earthquakes and their descriptions were used to define the radically distinctive differences in the responses of the structures between near-field and far-field earthquakes. A comparative study of the associated diagrams of relative

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structural displacement has been done based on the incremental dynamic analysis of a seven-storey building with concrete structure for few near-field and far-field earthquakes. At the end, the comparison of these plots was used to denote the differences in the structural behaviours of these two types of earthquakes which showed a difference of 35.6 percent.

From the available literature it was observed that most of the studies are confined on study of 2D frames and simple 3D structures. The relative areas in which the dynamic analysis can be applied were discussed but only a limited number of published works on comparison of use of dynamic analysis to find out the most effective preventive measures have been carried out. Moreover there is no work involving the application of wavelet transform to detect the time instants of pounding and to locate the occurrence of its most dominant frequency in the time-frequency domain. Thus in this paper an attempt has been made to take the work of pounding one step ahead by using wavelet based detection of seismic pounding and to provide the most economic and efficient mitigating technique to combat it.

III. STRUCTURAL MODELLING AND ANALYSIS

In order to analyse the behaviour of buildings under seismic load with rigid floor diaphragm, two sample building were adopted, the details of which have been discussed in section III.I. Furthermore, the evaluation of the most effective mitigating method has been carried out by analysing 10 different cases as shown in section III.II.

The commercial finite element analysis software SAP2000 is utilized to create 3D model and run all analyses. The software is able to predict the geometric nonlinear behaviour of space frames under both static and dynamic loadings, taking into account both geometric nonlinearity and material inelasticity. The software accepts static loads (either forces or displacements) as well as dynamic (accelerations) actions and has the ability to analyse structures allowing the use of different energy dissipaters such as shear wall, bracings, dampers and isolators.

MATLAB is used to obtain the time frequency plot using Continuous wavelet transform (CWT) to obtain the time instant of dominant frequencies and the time instants of pounding.

III.I DETAILS OF THE MODELS FOR VERIFICATION OF THE CONDITIONS OF SEISMIC POUNDING

The models which have been adopted for study are symmetric five storey (G+4) and ten storey (G+9) buildings which have been connected with 60mm long gap elements in SAP 2000. Each building consists of 3 bays in the transverse direction and 4 bays in the longitudinal direction with a bay spacing of 3m each. The buildings consist of square columns with dimension 600mm x 600mm and all beams with dimension 400mm x 400mm. The floor slabs are taken as 150mm thick. The height of all the stories is 3m. The grade of the concrete is M 25. The modulus of elasticity and shear modulus of concrete have been taken as $E = 2.5 \times 10^7 \text{ kN/m}^2$ and $G = 1.04 \times 10^7 \text{ kN/m}^2$.

Five models have been considered for the purpose of the study.

1. Pounding of two identical adjacent building.
2. Pounding of two non-identical adjacent buildings of equal height.
3. Pounding of two identical adjacent buildings with different sectional properties.
4. Pounding of two identical adjacent buildings of unequal height.
5. Pounding of two non-identical adjacent buildings of unequal height.
6. Pounding of two identical adjacent buildings of unequal storey height.

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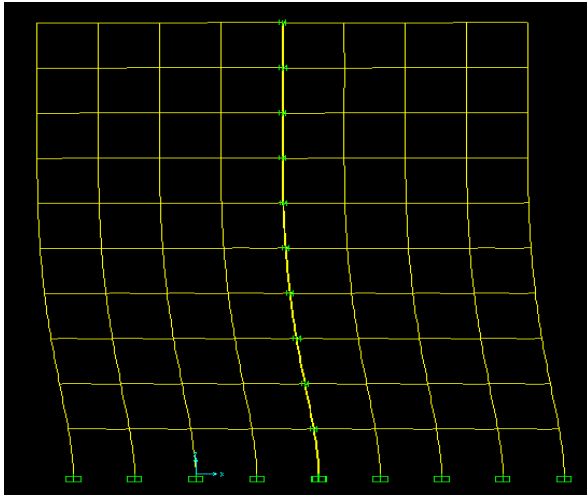


Fig 1: Pounding of two identical adjacent building.

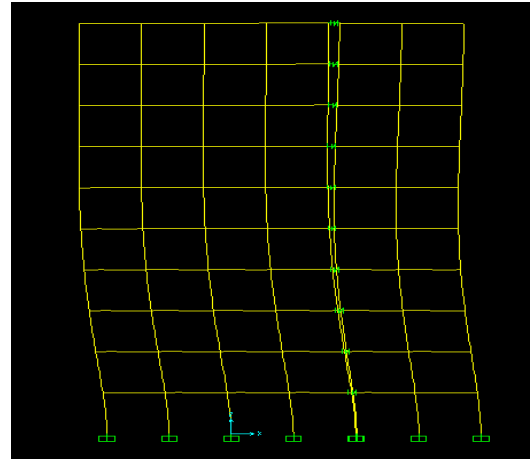


Fig 2: Pounding of two non-identical adjacent buildings of equal height.

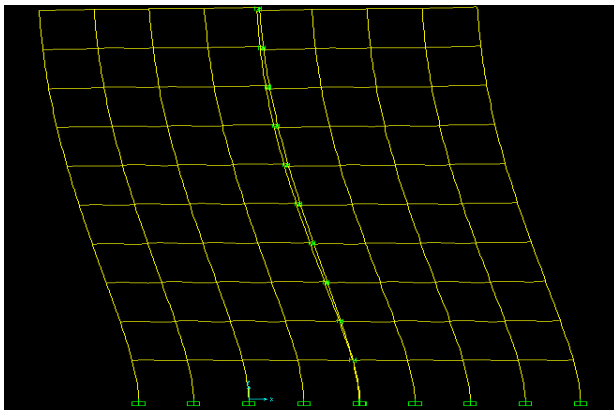


Fig 3: Pounding of two identical adjacent buildings with different sectional properties.

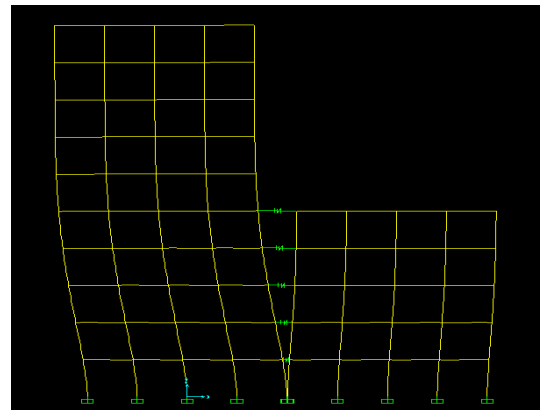


Fig 4: Pounding of two identical adjacent buildings of unequal height.

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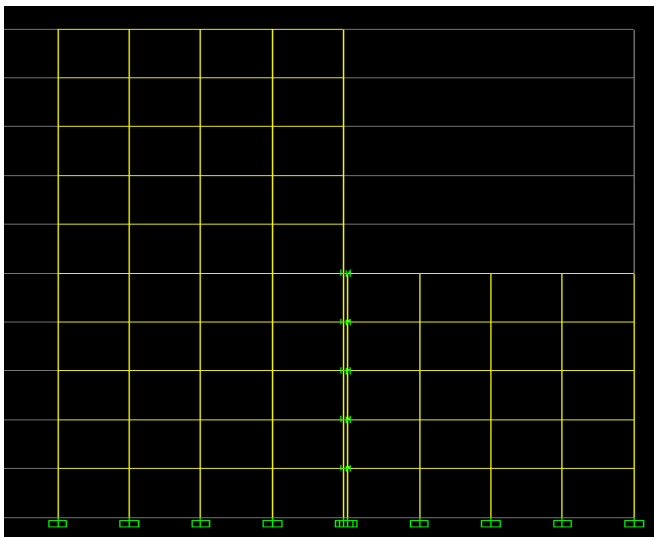
Observation-In each of the above cases, there is pounding except in the first case where both the buildings are in phase. In the third case there is negligible pounding whereas all the other cases have prominent pounding. This extent of pounding is enhanced with increase in height difference as obtained from the results of fourth and fifth case. There is also significant pounding when there is unequal geometry or unequal storey height as observed in the second and sixth case respectively. Thus it can be concluded that in highly populated areas where provision of sufficient separation gap between buildings is often difficult symmetrical buildings of similar heights should be constructed to overcome the pounding effects.

III.II. DETAILS OF MODELS FOR COMPARISON OF DIFFERENT PREVENTIVE MEASURES

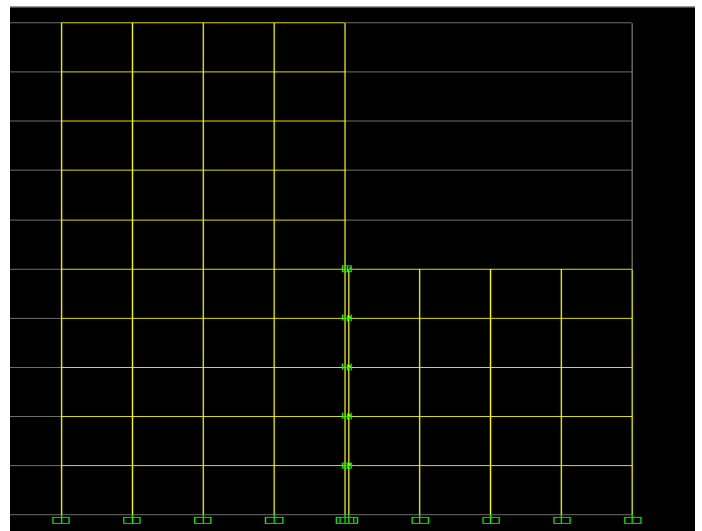
To find out the most effective preventive measure for seismic pounding time history analysis of ten models have been done using Elcentro response.

These ten models considered are as follows:

1. Bare frame
2. Building with dampers attached on the top gap elements at $Z=15\text{m}$ and bottom gap elements at $Z=3\text{m}$
3. Building with dampers attached to gap elements on the front side at $Y=0\text{m}$ and attached to gap elements on the back side at $Y=9\text{m}$.
4. Building with dampers attached to the middle gap elements at $y=3\text{m}$ and at $y=6\text{m}$
5. Building with rubber isolators attached to the taller building.
6. Building with rubber isolator attached to the shorter building.
7. Building with single angle cross bracing attached to taller building.
8. Building with single angle cross bracing attached to shorter building.
9. Building with shear wall attached to taller building.
10. Building with shear wall attached to taller building.



Model 1: Bare frame



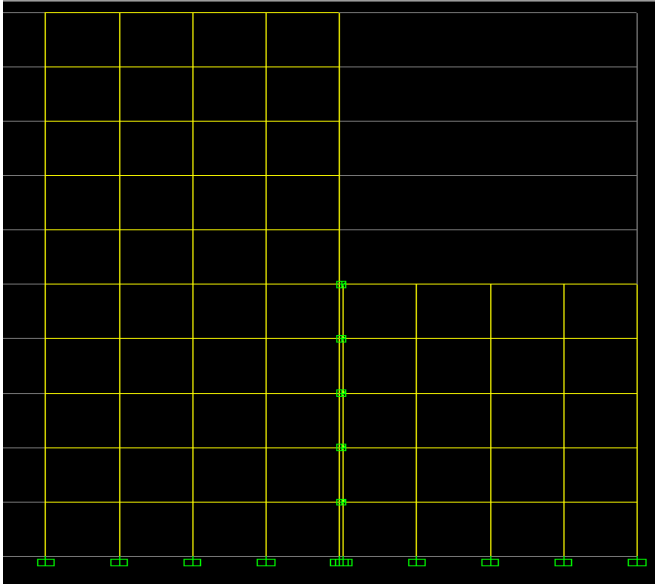
Model 2: Building with dampers attached on the top gap elements at $Z=15\text{m}$ and bottom gap elements at $z=3\text{m}$

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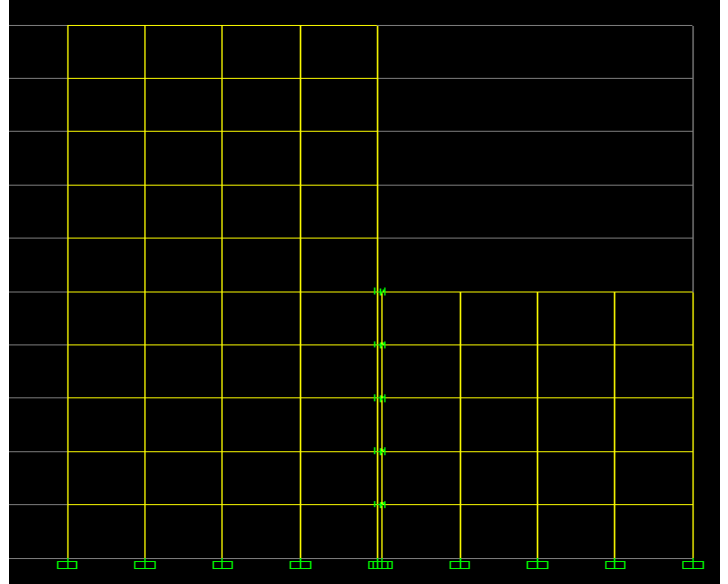
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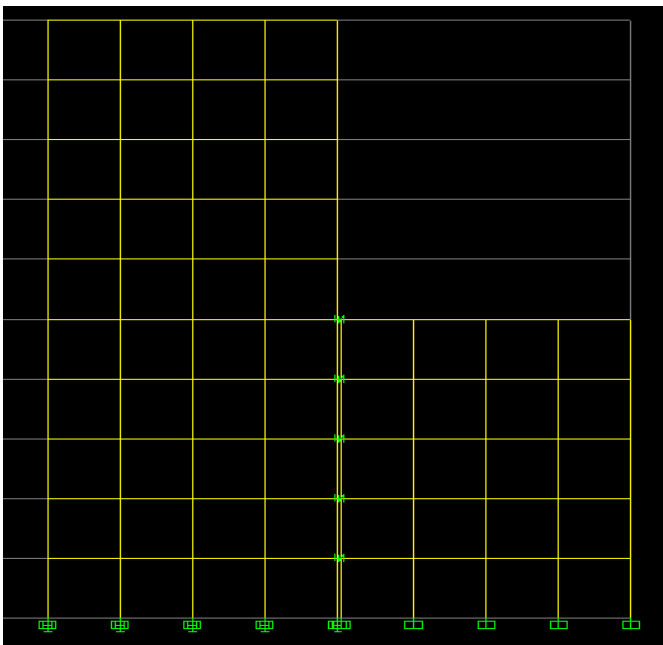
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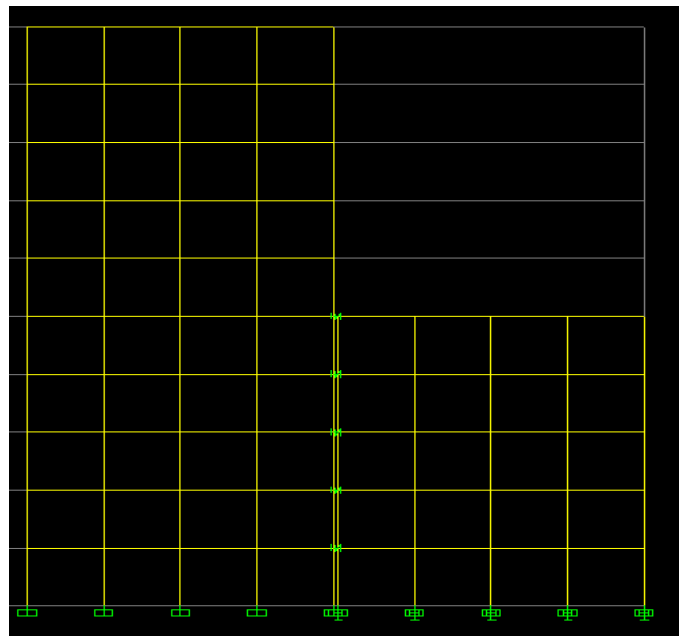
Model 3: Building with dampers attached to gap elements on the front side at $y=0m$ and attached to gap elements on the back side at $y=9m$



Model 4: Building with dampers attached to the middle gap elements at $y=3m$ and at $y=6m$



Model 5: Building with rubber isolators attached to the taller building.



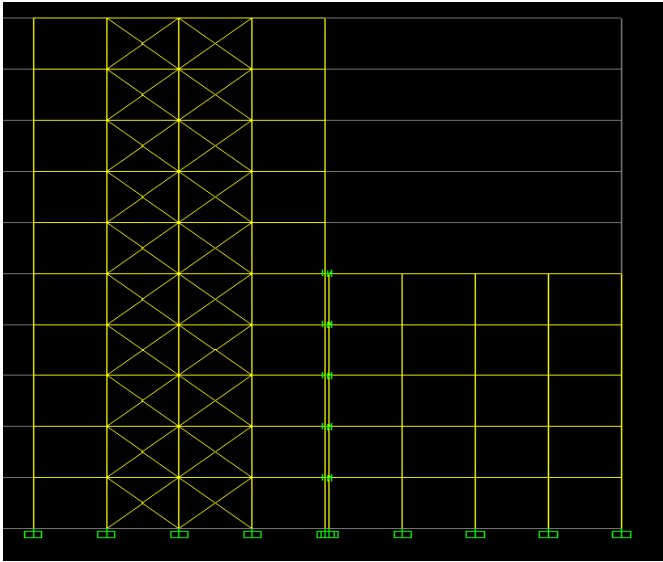
Model 6: Building with rubber isolators attached to the taller building.

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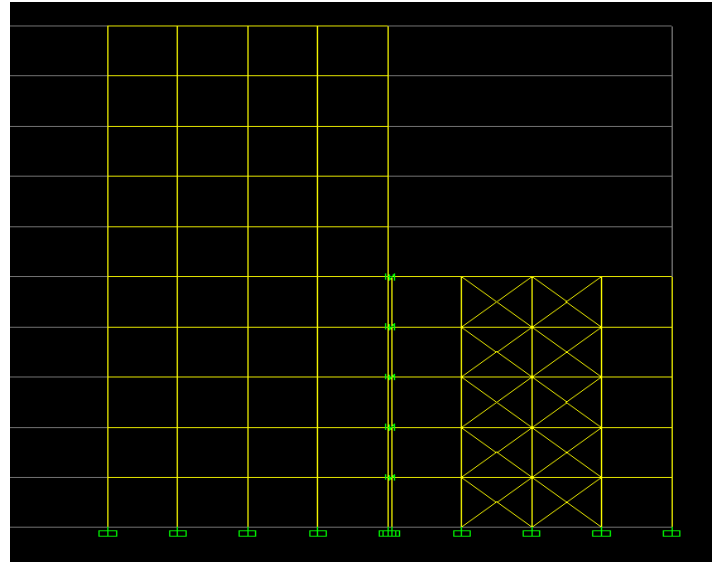
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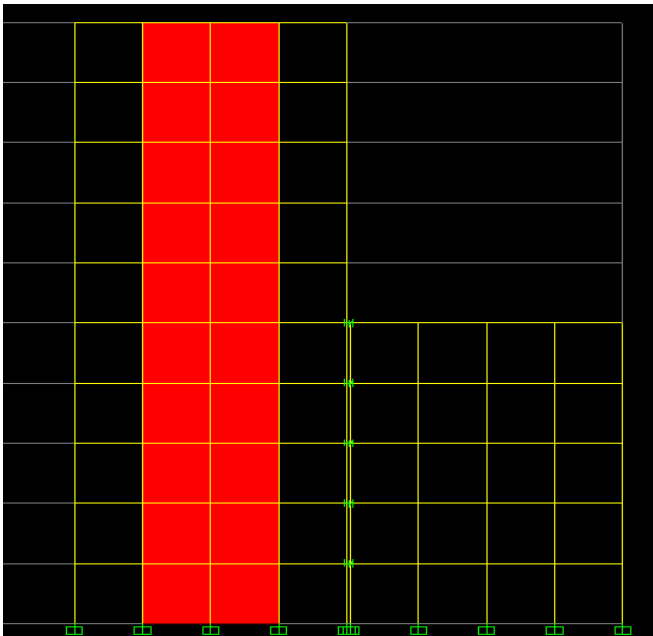
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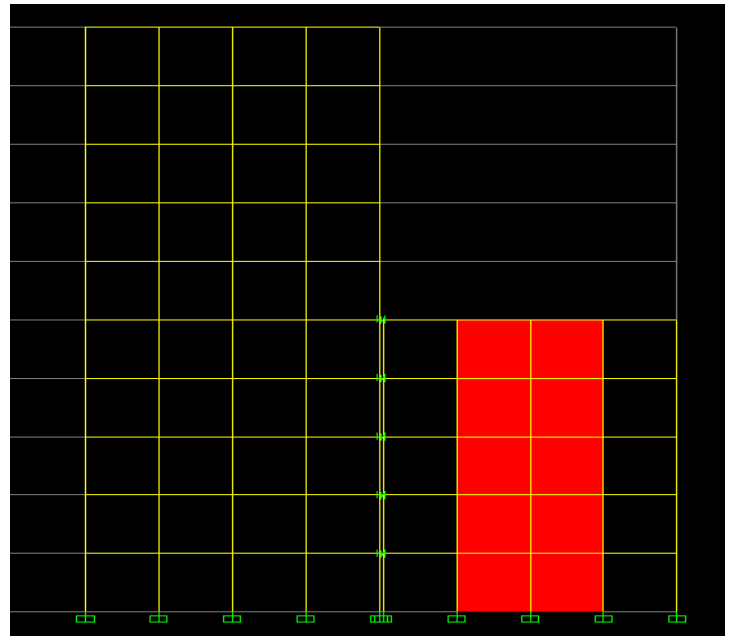
Model 7: Building with single angle cross bracing attached to taller building.



Model 8: Building with single angle cross bracing attached to shorter building.



Model 9: Building with shear wall attached to taller building.



Model 10: Building with shear wall attached to taller building.

In each of these cases, one ten-storey and one five-storey building of identical plan, geometric properties and material properties have been considered which have a spacing of 120mm between them. These two structures have been joined by a gap element whose stiffness is taken as 1000kN/m. The storey height is 3m for all the buildings. The plan and of the buildings are shown in Fig 7 .

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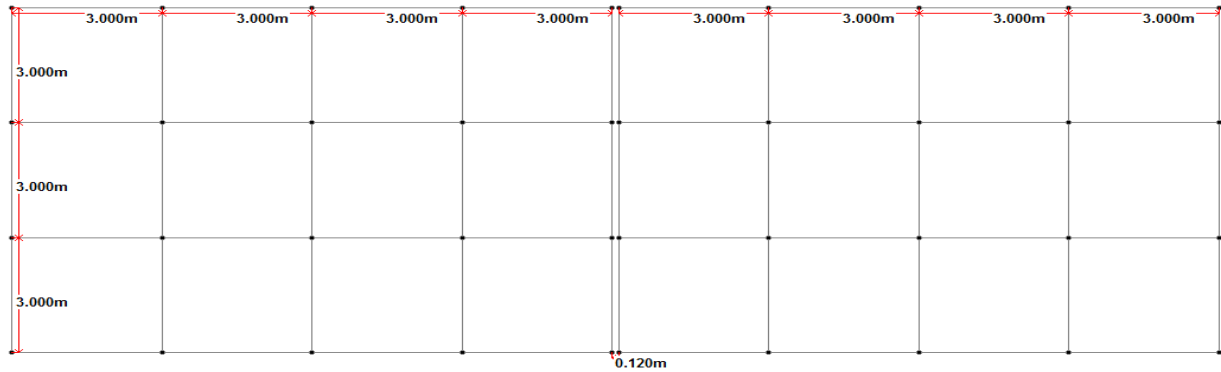


Fig 7: Plan of the buildings

The other parameters of the buildings have been provided in Table 1. The required material properties like mass, weight density, modulus of elasticity, shear modulus and design values of the material used can be modified as per requirements or default values can be accepted.

Grade of concrete	M25
Modulus of elasticity	$2.5 \times 10^7 \text{ kN/mm}^2$
Shear Modulus	$1.04 \times 10^7 \text{ kN/m}^2$
Column size	600 mm x 600 mm
Beam size	400 mm x 400 mm
Slab thickness	150mm
Floor finish	1kN/m
Height Parapet Wall	1.5m
Live load	3kN/m
Thickness of brick wall	250mm
Unit weight of bricks	20 kN/m^3
Unit weight of concrete	25 kN/m^3
Weight of the brick wall	15kN/m
Weight of parapet wall	7.5kN/m
Thickness of the shear wall	300mm
Size of bracings	100mm x 100mm x 10 mm (single angle cross bracing)

Table 1: Different parameters of the models considered

Beams and column members have been defined as ‘frame elements’ with the appropriate dimensions. Soil structure interaction has not been considered and the columns have been restrained in all six degrees of freedom at the base. Slabs are defined as area elements having the properties of shell elements with the required thickness and have been modelled as rigid diaphragms.

IV. RESULTS AND DISCUSSIONS

Fig 8 shows the comparison of displacements of all the ten models. It is observed from the graph that displacement is maximum in case of bare frame. Displacement is arrested the most when damper is added to the middle gap elements. Isolators, bracings and shear wall when added to shorter building causes lesser sway than when they are added to taller building.

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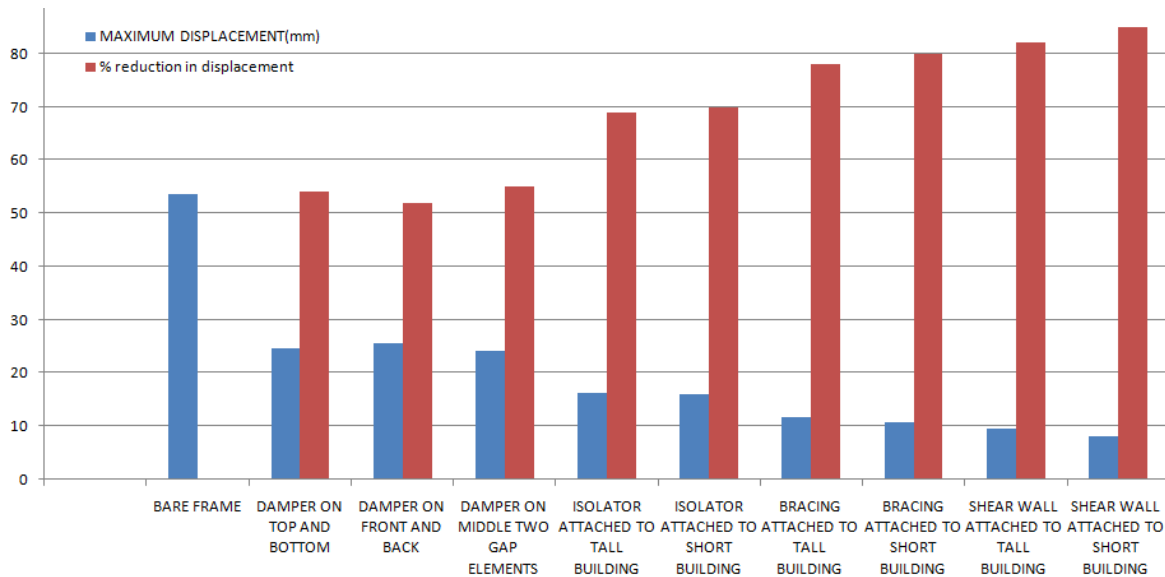


Fig 8: Comparison of displacements of all the ten models

From the graphical representation of the above time history response shown in Fig 9 it is found that sway in building with bare frame > Damper > Isolator > bracing > Shear wall. Therefore it can be safely concluded that shear wall is the best preventive measure

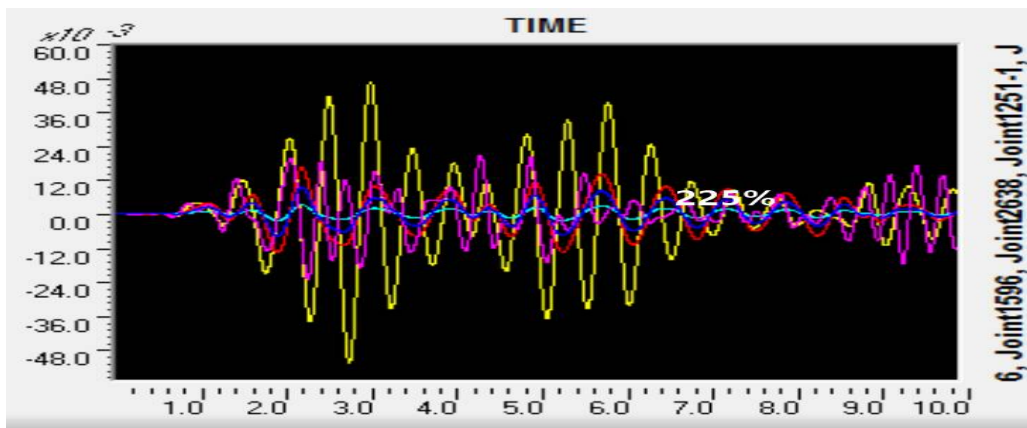


Fig 9: Time-displacement graphs of bare frame and the best cases of the damper, isolator and shear wall (i.e. case1, case 4, case 6, case 8 and case 10) as obtained from SAP analysis

The bar chart in Fig 10 shows the comparison of displacements of all the ten models. It is observed that acceleration is maximum in case of bare frame and is least when shear wall is attached to the shorter building. Thus in case of tight budget, only provision of shear wall to the shorter building will help in resisting the pounding effect to a great extent.

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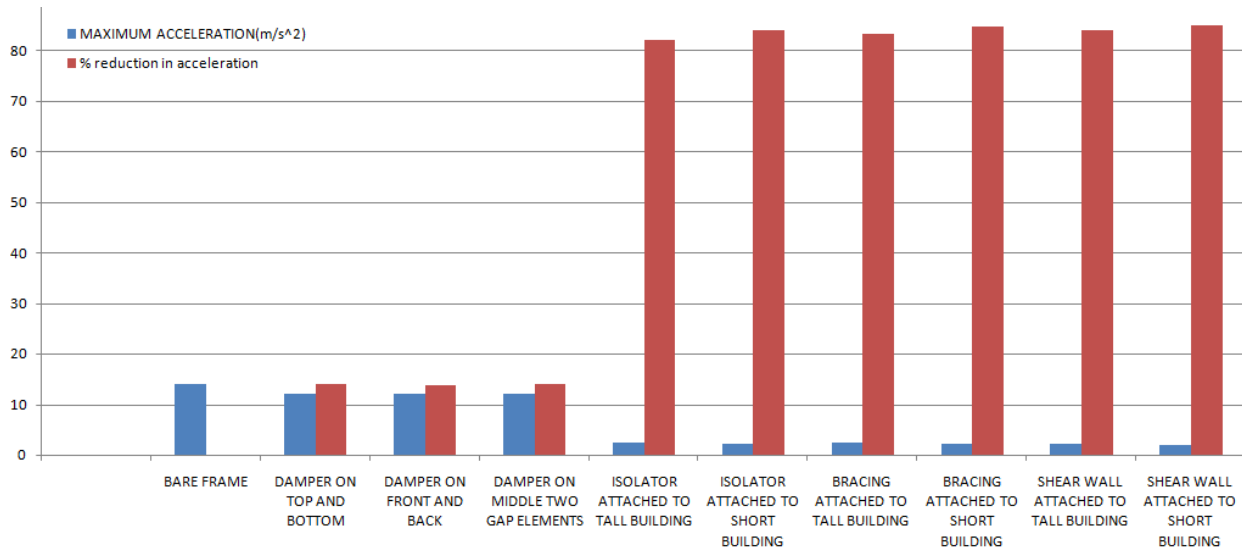


Fig 10: Comparison of displacements of all the ten models

From the graphical representation of the time history response given in Fig 11 it is found that acceleration in building with Damper> Isolator> bracing>Shear wall. Therefore it can be concluded that shear wall is the better preventive measure compared to the other three.

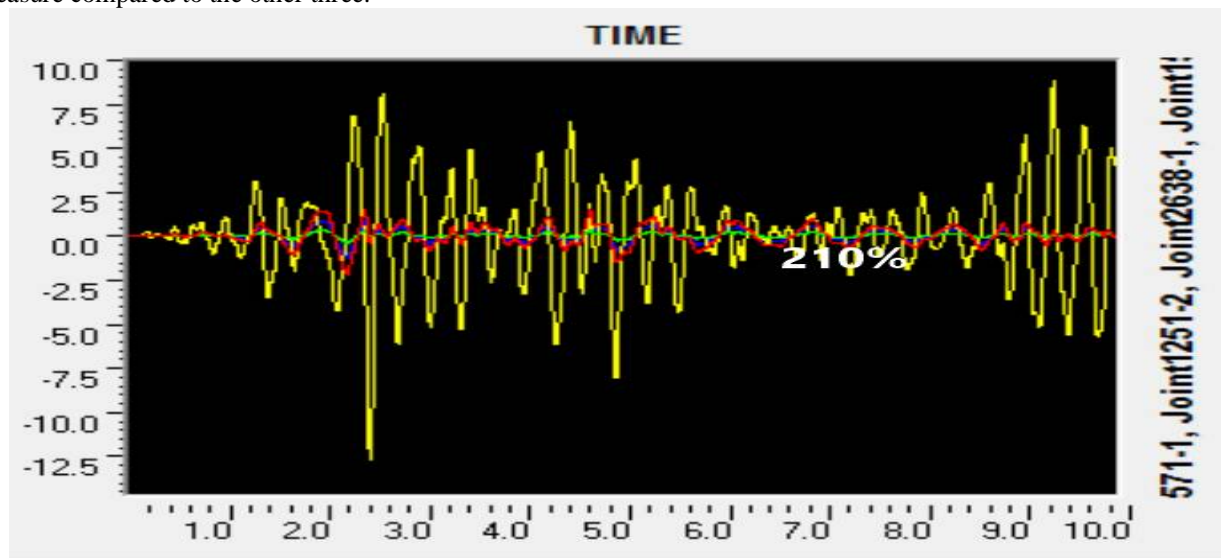


Fig 11: Time-acceleration graphs of the best cases of the damper, isolator, bracing and shear wall (i.e. case1, case 4, case 6, case 8 and case 10) as obtained from SAP analysis

It is evident from Fig 12 that in the short span of 20 seconds, the structure has maximum number of pounding in the first case (i.e. Bare Frame) where the number of pounding is equal to 14. Among the different arrangements of damper in the second, third and fourth case, the number of pounding is comparatively lesser i.e. 12 than the second case where the structure pounds 13 times. Isolators, bracings and shear wall added to the shorted building gives lesser number of pounding compared to isolators, dampers and shear walls added to the taller building respectively.

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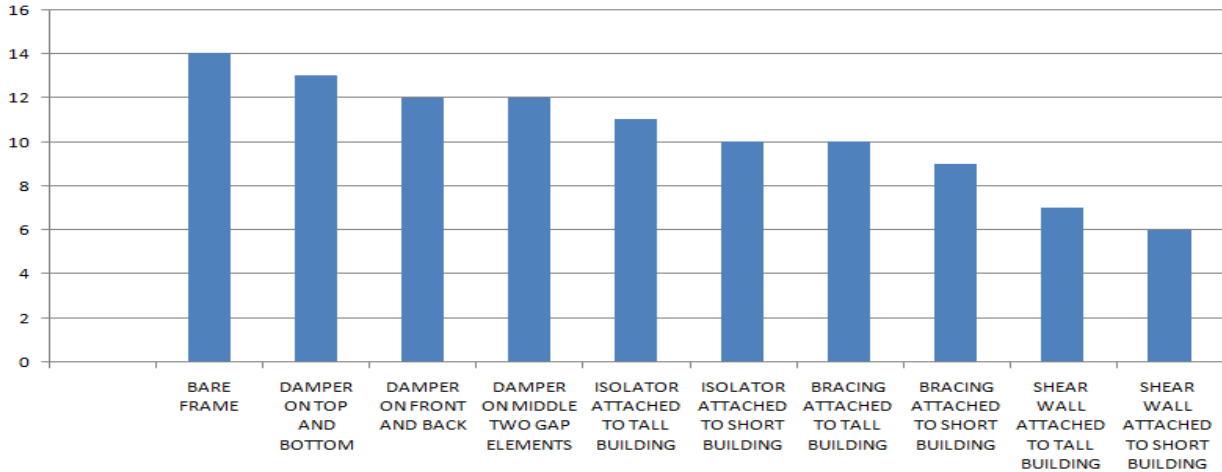


Fig 12: Comparison of the number of pounding in a span of twenty seconds for all the ten models.

It has been found that lateral movement of buildings is better arrested when bracing is attached to the shorter building than when it is attached to the taller building. Fig 13 shows the time-frequency-amplitude plot of the wavelet transform of the acceleration response of the critical node when bracing is attached to the shorter building. In the plot x axis represents time, the y axis represents frequency of the wavelet coefficients and z axis represents the amplitude of the wavelet coefficients.

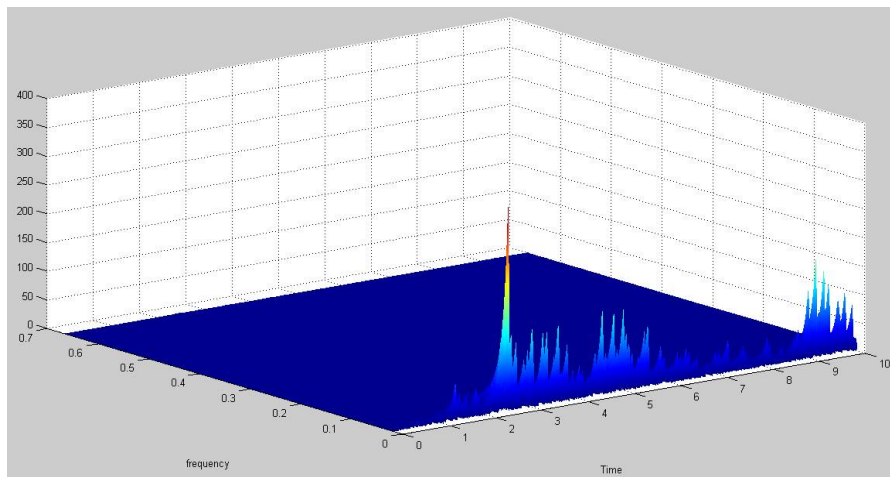


Fig 13: Time –frequency-amplitude plot when bracing is attached to shorter building

It has been found that lateral movement of buildings is better resisted when shear wall is attached to the shorter building than when it is attached to the taller building. Fig 14 shows the time-frequency-amplitude plot of the wavelet transform of the acceleration response of the critical node when shear wall is attached to the shorter building

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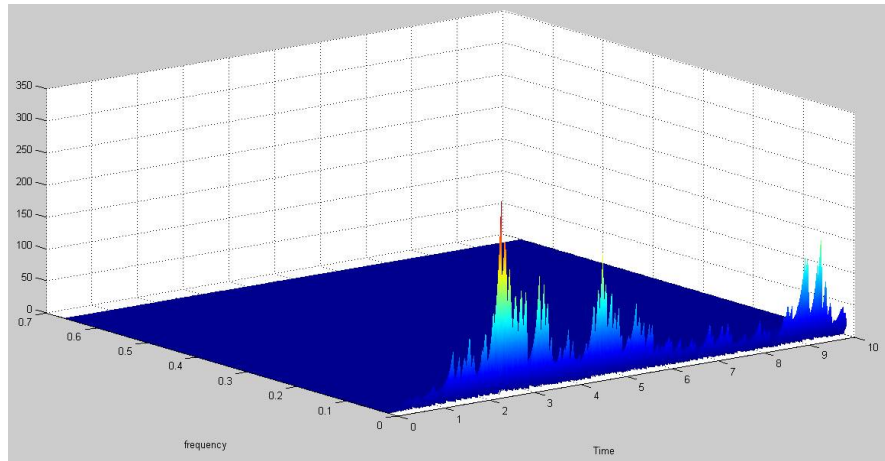


Fig 14: Time –frequency-amplitude plot when shear wall is attached to shorter building

From fig 13 and 14 it is observed that when the time acceleration data for critical node was analysed in MATLAB using continuous wavelet transform the most prominent peaks occur at 2.44 seconds and 2.42 seconds respectively which indicate the time instant of occurrence of the dominant frequencies. All the other prominent single peaks in the figures represent pounding which occur within the limited span of 10 seconds. The time instants of all the impacts can be easily obtained from the graphs. Moreover, it is seen that the amplitude of the wavelet coefficient of the dominant frequency and the number of poundings is much less in Fig 14 than Fig 13 which proves that shear walls are better energy dissipaters than bracings.

V. CONCLUSION

The main objective of this study has been to analyse the seismic pounding effects between buildings and to observe the structural behaviour under the use of various energy dissipaters and to locate the time instant of damage due to pounding. For this, the finite element software SAP2000, a linear and non-linear static and dynamic analysis and design program for three dimensional structures has been used. Dynamic analysis has been carried out to know about the displacement, accelerations and the number of poundings within a limited span of time. Two building frames, one five-storey and other ten-storey were modelled and analysed in SAP2000.

The first phase of the study involves the analysis of the behaviour of the buildings under seismic load to find out a potential solution to pounding before buildings are constructed whereas the second phase of the study involves the evaluation of most effective mitigating measure for minimizing the effect of pounding after the buildings are constructed. It also contains the use of continuous wavelet transform to identify the time instant of poundings.

The following conclusions can be drawn from the study:

1. It is clear that adjacent building with similar height and similar floor level show similar behaviour as they are in phase and hence the pounding damage is limited.
2. Out of phase movement is greater for buildings with unequal storey height compared to buildings with same floor level. So engineers are recommended to construct the adjacent buildings with same floor level.
3. All the prevention methods that are used in this study proved more or less effective to prevent pounding between adjacent buildings.
4. The most effective mitigating measure was the construction of shear wall attached to shorter building. However, constructing shear walls on both the sides for a tall building can be costly.

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5. It is preferable to leave a safe separation gap according to FEMA 273-1997, when the buildings are in early stage of design.
6. If buildings are old and are not in a stage to provide safe separation gap, then the preventive measure already discussed in the paper may be adopted.
7. From economic point of view, it is better to provide bracings or shear wall or dampers to the shorter building if provision of these mitigating measures to both the buildings is out of budget. This is because the shorter building having lesser time period is subjected to greater frequency of vibration than the taller structure leading to more damage due to pounding.
8. Wavelet transform is a very important tool to detect the time instants of poundings as well as to locate the time instant of the dominant frequency.

Though it has been found that the use of mitigating measures like shear walls, dampers, bracings and isolators reduce the displacement and acceleration produced by pounding to a great extent, there are many different measures as well. These four preventive measures can be further analysed by combining with each other and many other ways are yet to be found out which could simplify the prevention of seismic pounding with greater effectiveness. Furthermore, besides wavelet transform there are also other methods like Empirical mode decomposition, Hilbert Huang transform etc which can also be applied to get better results for detection of seismic pounding. Hence, more research work is needed in this area to evaluate the best possible way to reduce structural pounding both in terms of economy and efficacy and also to come up with better damage detection techniques.

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