

THREE DIMENSIONAL MODELING OF POUNDING BETWEEN ADJACENT BUILDINGS

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ABSTRACT

Pounding between adjacent structures is commonly observed phenomenon during earthquakes. In metropolitan areas, due to increasing population and land values buildings have been constructed very close to each other. Although seismic pounding between adjacent structures is considered in codal provisions, the practice of construction is still a problem in developing countries resulting more vulnerable during earthquakes.

To study the effect of structural pounding, a case study has been done on different setbacks and storey heights of two adjacent structures using SAP 2000. The pounding responses of two structures and collision forces are calculated. The effect of collision is more when structures are kept at extreme levels of setback. When the structures are kept at different elevation levels (setback=0), the pounding response changes significantly as the height of structure decreases.

Keywords: Pounding, Setback, SAP 2000

1. INTRODUCTION

During past earthquakes (Northridge 1994, Kobe 1995, Lomapieta 1989 (see Ref 7) and Sichuan 2008) many buildings were damaged due to failure of structural and geotechnical components. Among structural failure components, damage due to seismic pounding (i.e. collisions between adjacent structures due to earthquakes) has been frequently observed in past earthquakes. During 2007 Niigata Chuetsu-Oki Japan Earthquake (see Ref 5) pounding damage was observed to school buildings. This type of damage had occurred when slab levels of adjacent structures were located at different elevations. From figure 1 pounding occurred between two – three storey structures during Wenchuan earthquake in 2008. Due to insufficient separation distance, two storey structure was colliding with existing three storey structure having a setback of 3 m (approximately). Figure 2 illustrated that pounding occurred between an old and new buildings during L'Aquila earthquake in 2009. There would be slight damage to new structure.

Structural pounding damage in structures can arise from the following: (1) Adjacent buildings with the same heights and the same floor levels (fig 3a). (2) Same floor levels but with different heights (fig 3b). (3) Different total height and with different floor levels (fig 3c). (4) Structures are situated in a row (fig 3d). (5) Structures having different dynamic characteristics (6) Pounding occurred at the unsupported part (e.g., mid-height) of column or wall resulting in severe pounding damage. (7) Buildings having irregular lateral load resisting systems in plan rotate during an earthquake, and due to the torsional rotations, pounding occurs near the building periphery against the adjacent buildings (fig 3e). Among all the causes for structural pounding damage, the most effective way to mitigate and reduce the damage of structures from pounding is to provide minimum separation distance between the adjacent structures. So, it is essentially very important to study the pounding of buildings during earthquakes not only for safety but also to establish appropriate design guidelines.



**Fig. 1: Pounding Occurred Between Two and Three Storey Structures during 12 Dec 2008, Wenchuan Earthquake
(Photo: Khalid M Mosalam)**



Fig. 2: Pounding between New and Old Building During 6 Apr 2009, L'Aquila Earthquake

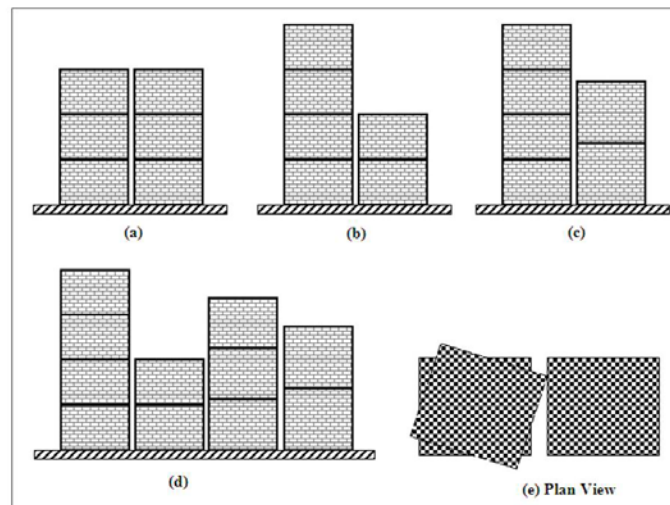


Fig. 3: Representation of Different Places Where Pounding Occurs

Large number of studies has been conducted on seismic pounding between adjacent structures to study the behavior of structures. Among them, Anagnostopoulos S A examined the case of several adjacent buildings in a row subjected to pounding (see. Ref 1). Leibovich et al. studied the effect of impact eccentricity on two sets of symmetric and asymmetric models aligned with respect to each other for several gap widths (see. Ref 8). Papadrakakis et al. developed a three-dimensional finite element model to simulate pounding between adjacent buildings (see Ref 10). Gong and Hao studied the torsional pounding between an asymmetric and a symmetric one-storey structure subjected to bi-directional ground motion (see Ref 6). Mouzakis and Papadrakakis investigated the three-dimensional pounding between two adjacent buildings based on the impulse-momentum relation (see Ref 9). Chau and Wei considered the torsional pounding between two adjacent asymmetrical single-storey structures using the nonlinear Hertz contact law (see Ref 2).

From the above observations, it is clear that torsional pounding is evident during earthquakes. Hence it is necessary to study the torsional pounding between adjacent structures. In this paper, two single storey structures are considered with different setback levels (1.5 m, 3.0 m and 6.0 m) subjected to ground motion for studying torsional pounding behavior. Also the analysis is carried out for the same structures at different height levels.

2. MODELING OF STRUCTURES

The analysis considers two single storey structures with symmetric (structure-A) and asymmetric (structure-B) configuration. Different setback levels (1.5 m, 3.0 m and 6.0 m) and structure at different height levels (at $(2/4)^{\text{th}}$ and $(3/4)^{\text{th}}$ of column height) are considered in this study. The modeling of structures has been done using SAP 2000 (see Ref 4). The total height for both structures is 3 m. The thickness of the slab is 0.12 m and the dimensions for all columns are 0.24 x 0.24 m. The slab dimensions for both structures are taken as 6 x 6 m. It is assumed that the live load acting on the structure-A is 2 kN/m². To study the torsional behavior of structures due to pounding an eccentricity is provided in both x and y directions for structure-B. The centre of mass (CM) and centre of stiffness (CS) for structure-B are (2.7 m, 3.3 m) and (3.0 m, 3.0 m) respectively. An additional load of 4 kN/m² is provided at top left corner of slab portion for structure-B. The plan and elevation view of structures are shown in fig 4.

The grade of concrete, grade of steel reinforcement and Poisson's ratio are same for both the structures. The details of material properties for the structures are as follows:

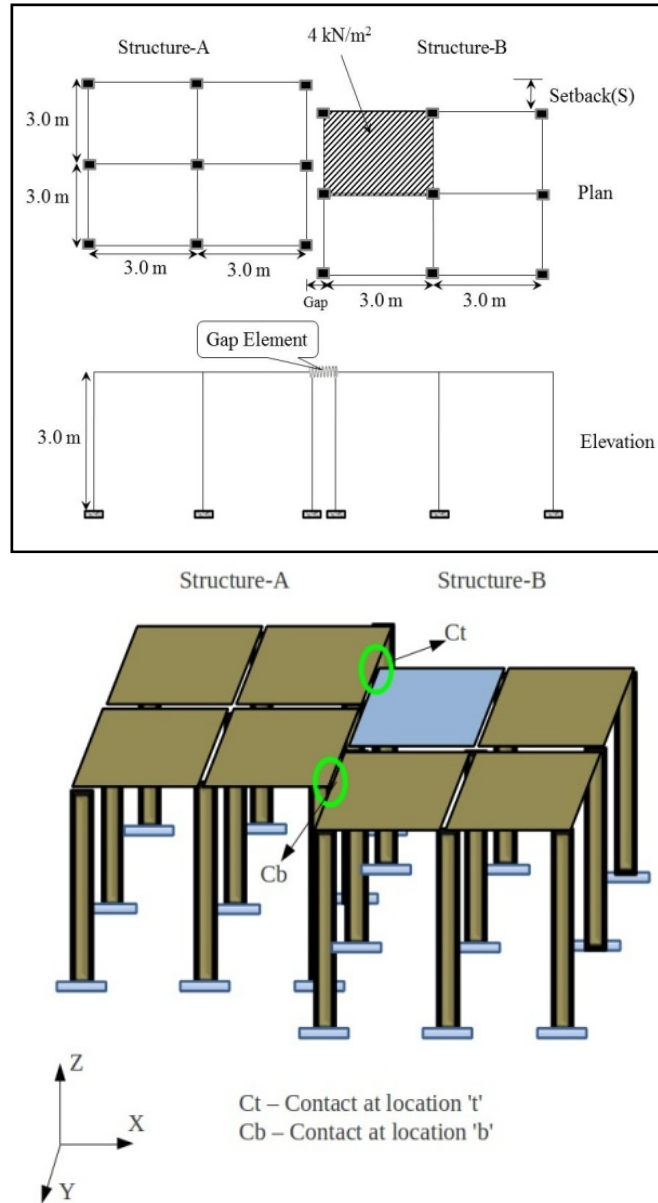


Fig. 4: Plan and Elevation Views of Single Storey Symmetric and Asymmetric Structures

Grade of concrete: M_{25} ($f_{ck}=25 \text{ N/mm}^2$)

Grade of steel for reinforcement: Fe415 ($f_y=415 \text{ N/mm}^2$)

Poisson's ratio: 0.2

3. MATHEMATICAL FORMULATION

The general dynamic equation for a structure is given in equation 3.1

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \Delta f(t) - [M]\{\ddot{U}_g\} \quad (3.1)$$

Where $[M]$ is mass matrix; $[C]$ is damping matrix; $[K]$ is nonlinear stiffness matrix; $\Delta f(t)$ is incremental applied load vector ΔU and its derivatives are the incremental displacement, velocity and acceleration vectors respectively. The above equation is solved numerically using Newmark's β method (see Ref 3).

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} D^2 t \rho & & \\ & D^2 t \rho & \\ & & D^2 t \rho \end{bmatrix}$$

For mass matrix the elemental mass is assumed lumped at the joints. The mass matrix is given in equation 3.2. (3.2)

Where D is the element size; t is element thickness and ρ is the density of material. From

the above equation it is noticed that $[M_1]$, $[M_2]$ and $[M_3]$ are the masses in X, Y and Z directions. The mass matrix is a diagonal matrix. No mass moments of inertia are produced for the rotational degrees of freedom. The damping matrix is calculated from the first mode as follows:

$$C = 2\xi M \omega_n \quad (3.3)$$

Where ξ is damping ratio and ω_n is the first natural frequency of the structure.

4. GAP ELEMENT MODEL

Gap joint element is an element which connects two adjacent nodes to model the contact. This is activated when structures come closer and deactivate when they go far away. A collision force will be generated when they come closer. From figure 5, it is shown that, the gap element will activate if 'open' is equal to zero. In SAP modeling each element is assumed to be composed of six separate springs with six deformational degree of freedom (DOF). Every DOF has linear effective stiffness and damping properties. The mass contributed by the link or support element is lumped at the joints i & j and half of the mass is assigned to the three translational degrees of freedom at each of the elements joint. No inertial effects are considered within the element itself. Generally the effective stiffness value is in a range from 10^2 to 10^4 times more than the stiffness in any connected element. Larger values of effective stiffness may lead to numerical difficulties during solution. During nonlinear analysis, the nonlinear force-deformation relationships are used at all degrees of freedom for which nonlinear properties were specified. For all other degrees of freedom, the linear effective stiffnesses are used during a nonlinear analysis. The results for linear analyses are based upon linear effective stiffness and damping properties. Only the results for nonlinear analysis cases include the nonlinear behavior. The force-deformation relationship is as follows:

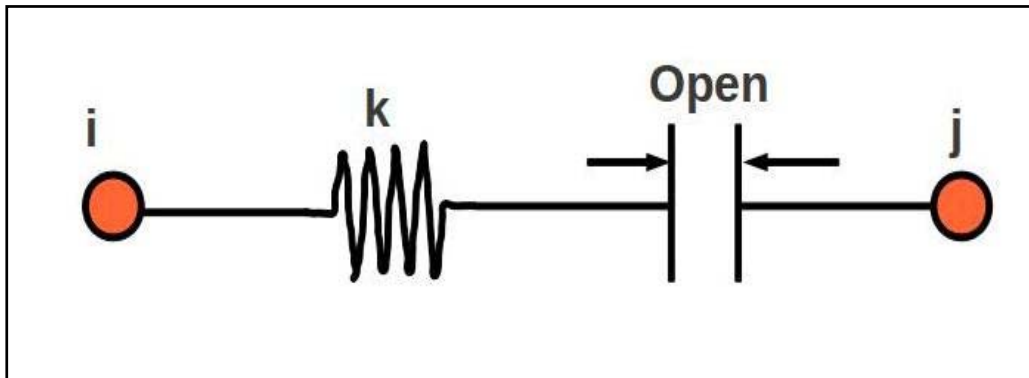


Fig. 5: Gap Joint Element Method From SAP2000

$$F = \begin{cases} k(d + open), & \text{if } (d + open) < 0 \\ 0, & \text{Otherwise} \end{cases} \quad (4.1)$$

Where, 'k' is spring constant, 'open' is the gap opening which must be positive or zero and 'd' is the relative deformation across the spring.

5. NON-LINEAR ANALYSIS OF POUNDING

To study torsional pounding between the structures, different setbacks are considered in this analysis. The structures which are considered in this analysis are subjected to El-centro ground motion and gap element is provided between them. The stiffness of gap element is 477.6 MN/m (see Ref 11). The fundamental natural periods of structure-A & B are 0.176 and 0.217 sec respectively which are far from predominant period (0.45-0.87 sec) of the ground motion.

5.1 Case-I: Different Setback

5.1.1 At Setback of 1.5 m

The analysis is carried out for structures with setback of 1.5 m. The structures have responses in both x and y directions, though the ground motion is restricted to x-direction. This is because of un-symmetric mass properties about X & Y axes. The pounding at top edge of structure-B is referred as location 'C_t' and the bottom edge of structure-A is referred as location 'C_b'. The maximum pounding responses at location C_t for structure-A and B are 0.0351 m and 0.043 m respectively. The pounding responses would be more if structures vibrate near to the predominant period of ground motion. In this case, both structures vibrate far from predominant period of ground motion. Resulting more response in flexible structure compared to stiff structure. During vibration, the response of structure-A in y-direction is amplified due to collision between structure-A & B. The maximum pounding responses for structure-A and B in y-direction are 0.00138 m and 0.0073 m respectively. From results, it has been clearly observed that the responses for stiffer structure get amplified due to collision between them. Also, structure-B vibrates at lesser frequency because of reduction in stiffness. The maximum pounding force between them is 53.16 kN. The displacement responses for structure-A & B and collision forces are shown from fig 6.

Due to unsymmetrical mass property of structure-B, the possible pounding may occur at C_b also. From the results, the maximum responses of structure-A & B in X and Y directions are 0.0344 m, 0.033 m, 0.00138 m and 0.0073 m respectively. It is clearly shown that the maximum pounding responses at C_t and C_b are same in Y-direction. The displacement responses for structure-A & B in x-y directions and collision forces are shown from fig 7.

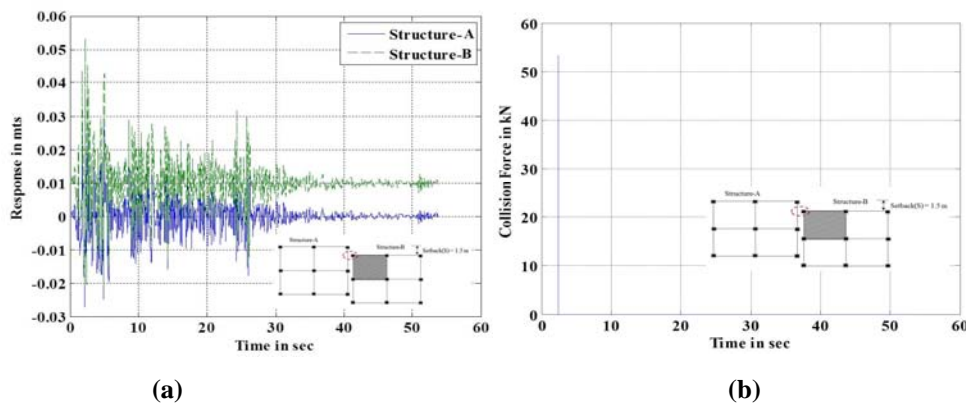


Fig. 6: (a) Response of Structures at a Location Ct and (b) Pounding Force between Structures with Setback of 1.5 m

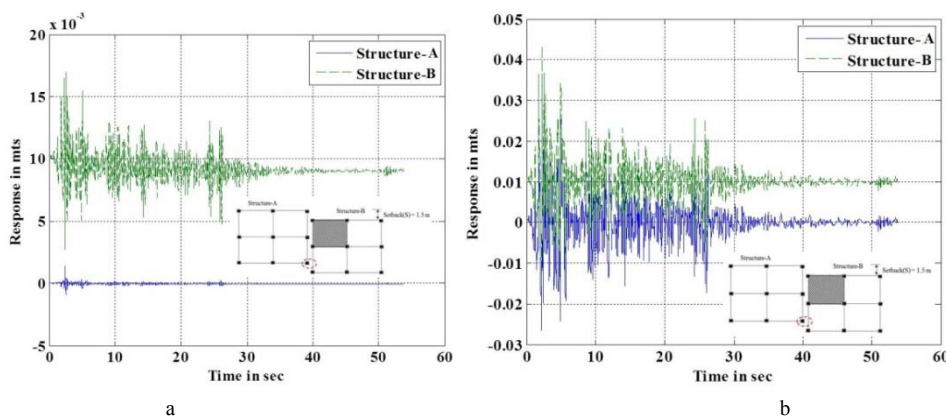


Fig. 7: (a) Response of Structures in X-Direction at a Location Cb and (b) Response of Structures in X-Direction at a Location Cb with Setback of 1.5 m

5.1.2 At Setback f 3.0m

The similar analysis is carried out for structures with setback of 3.0 m. The maximum pounding responses at location C_t for structure-A and B are 0.0347 m and 0.0432 m respectively. The response of flexible structure is more compared to stiff structure, because of non-dominant period of ground motion. In the earlier case, more response is observed at location C_t than at C_b. This is due to eccentricity in mass distribution resulting torsion

induced in the system. This torsion in structure-B initiates the collision to structure-A with a magnitude of 73.7 kN. The maximum pounding responses for structure-A and B in y-direction are 0.00428 m and 0.0090 m respectively. The collision force increases as the setback level increases. The displacement responses for structure-A & B and collision forces are shown from fig 8

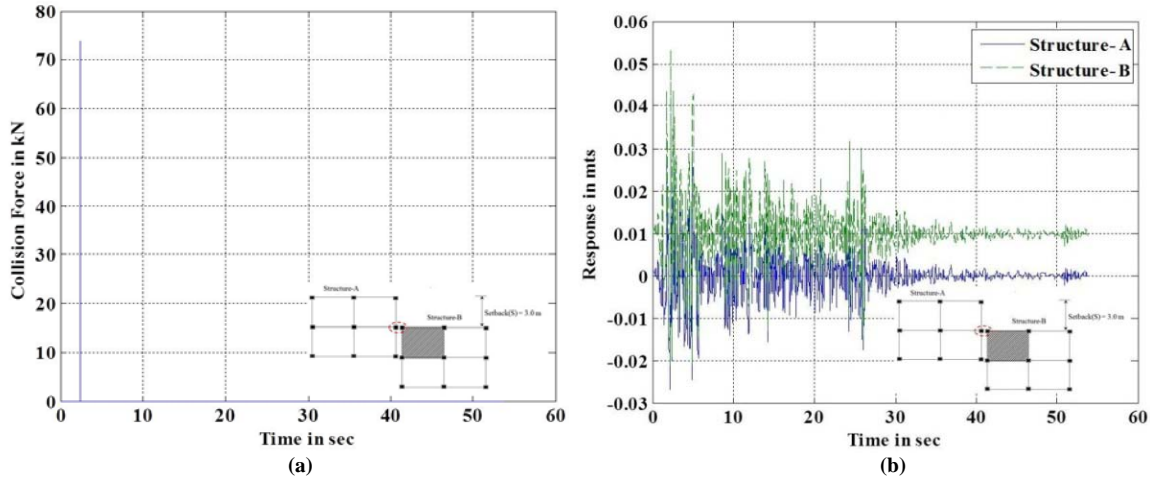


Fig 8: (a) Response of Structures at a Location Ct and (b) Pounding Force Between Structures with Setback of 3.0 m

The pounding occurred at location C_b also. From the results, the responses at location C_b are less compared at location C_t because of uneven distribution of mass for structure-B. The responses are similar at location C_t and C_b in Y-direction. The maximum pounding responses for structure-A and B in x-direction are 0.0344 m and 0.0376 m respectively.

5.1.3 At Setback of 6.0 m

The analysis is carried out for structures with setback of 6.0 m. In this analysis, the possible pounding location is at one place only. From the results, the maximum pounding responses for structure-A and B are 0.0344 m and 0.0432 m respectively. Because of non-dominant period of ground motion, response of flexible structure is more compared to stiff structure. The maximum force generated between them is 169.4 kN. From the observation of all results, it is clearly shown that the maximum force pounding forces are increasing as the setback level increases. The number of collisions is also same for all the cases. The displacement responses for structure-A & B in x-y directions and collision forces are shown from fig 9.

From results, the response for both structures increases as the setback level increases. But this increase in response is not significant. But the collision force between them increases significantly. The number of collision occurrences is same in all the cases. It can be concluded that the effect of collision is more when structures are kept at extreme levels of setback. The response details of the above structures are illustrated in table 1.

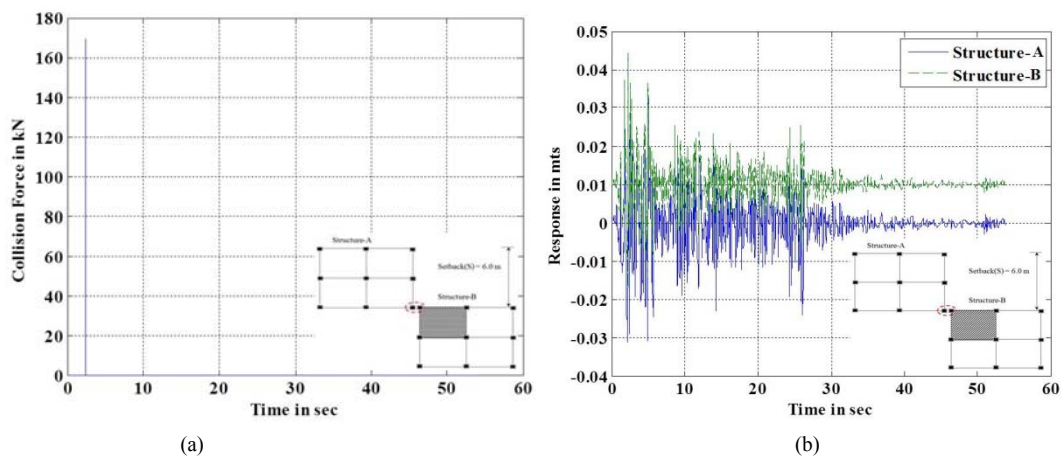


Fig. 8: (a) Response of Structures at a Location Ct and (b) Pounding Force Between Structures with Setback of 6.0 m

5.2.1 Case-I: Different Setback

5.2.1 At (3/4)th Height of Structure

Pounding analysis is carried out for structures at different elevation levels. From the analysis, the maximum pounding response of structure-A and B in X-direction are 0.21 m and 0.120 m respectively. Due to unsymmetrical mass of structure-B, they have responses in both directions. Because of non-dominant period of ground motion, the response of flexible structure is more than stiff structure. The responses of structure-A and B in Y- direction are 0.052 m and 0.025 m respectively. The maximum collision force between them is 1244 kN. The displacement responses for structure-A & B and collision forces are shown from fig 9.

The maximum pounding response of structure-A and B in X and Y direction are 0.126 m, 0.170 m, 0.016 m and 0.062 m respectively. The maximum pounding force generated between them is 777 kN. It is clearly shown that, the pounding forces are more where mass concentration is more. If we change the mass concentration to other location (top right corner of structure-B), the responses and collision forces change. The displacement responses for structure-A & B and collision forces are shown from fig 10.

5.2.2A T (2/4)th Height of Structure

The same analysis is carried out for structures at mid height of structure-A. From the analysis, the maximum pounding response of structure-A and B in X and Y direction are 0.20 m, 0.168 m, 0.0053 m and 0.02 m respectively. The response of flexible structure is more than stiff structure due to non-dominant period of ground motion. The collision force between them is 5350 kN. This force is more than the force when structures are kept at (3/4)th height. From the results it can conclude that the collision force at mid height level is more than (3/4)th height level because of more shear amplification. Depending on the response of structures, this collision force changes at different levels. The displacement responses for structure-A & B and collision forces are shown from fig 11.

Table 1: Response Details of Both Structures at Different Levels

Staggered Level				
	Position	Response (m)		Force (kN)
		Structure-1	Structure-2	
Level-1 (1.5 m)	Top	0.0351	0.043	53.16
	Bottom	0.0344	0.033	
Level-2 (3.0 m)	Top	0.0347	0.0432	73.7
	Bottom	0.0344	0.0376	
Level-3 (6.0 m)	Top	0.0344	0.0432	169.4

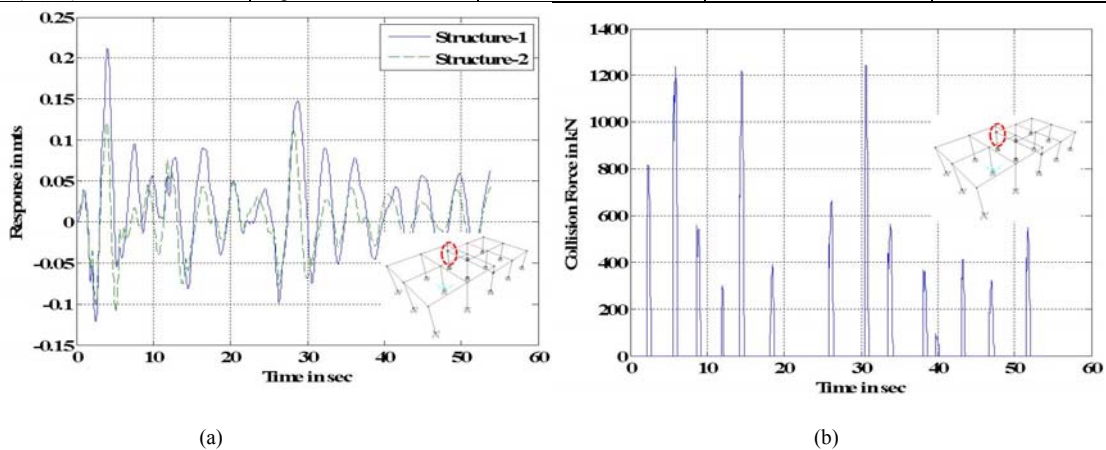


Fig. 9: (a) Response of Structures at a Location C_t and (b) Pounding Force between Structures at (3/4)th Height of Structure

The maximum pounding response of structure-A and B in X and Y direction are 0.20 m, 0.127 m, 0.005 m and 0.022 m respectively. The maximum pounding force generated between them is 3493 kN. From results, the maximum pounding force at location C_t is more than at C_b. This is because of uneven mass distribution resulting torsional effect. The displacement responses for structure-A & B and collision forces are shown from fig 12.

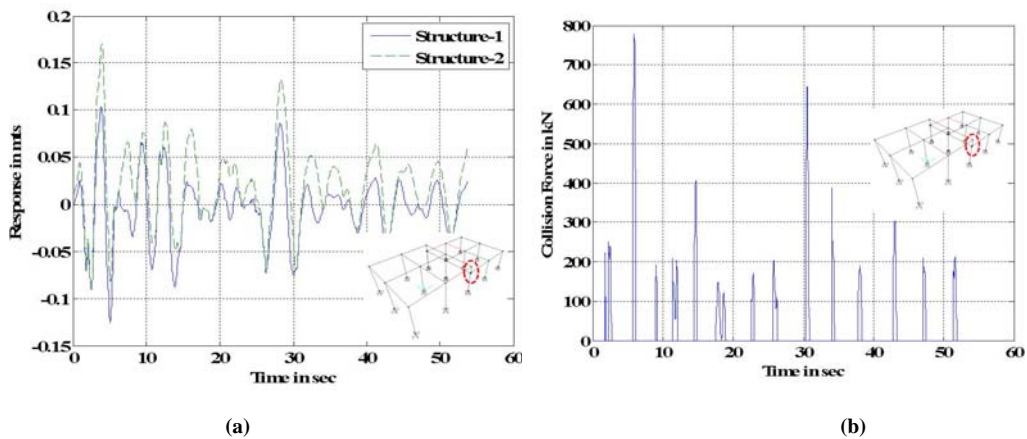


Fig. 10: (a) Response of Structures at a Location Cb and (b) Pounding Force Between Structures at $(3/4)^{th}$ Height of Structure

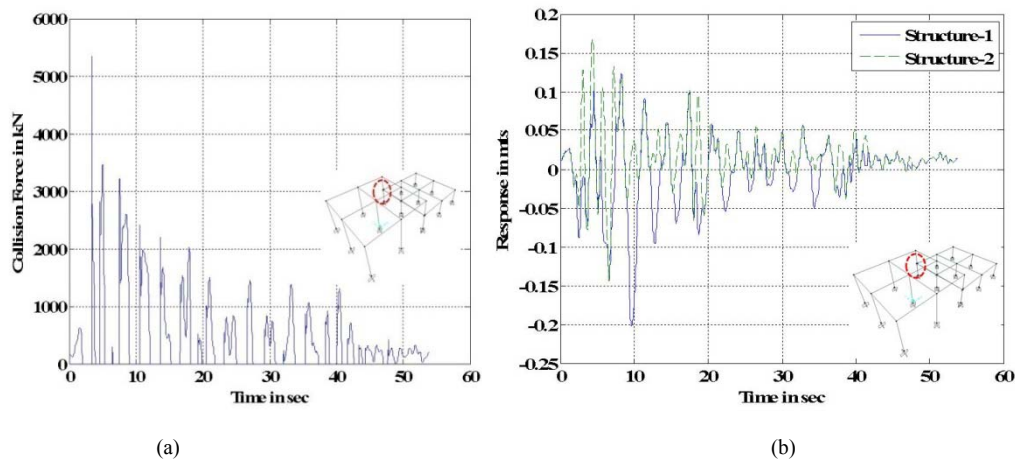


Fig. 11: (a) Response of Structures at a Location Ct and (b) Pounding Force Between Structures at $(2/4)^{th}$ Height of Structure

From the results, the pounding response changes significantly as the height of structure decreases. At $(2/4)^{th}$ height of structure, the collision force is more compared to $(3/4)^{th}$ height. It can be concluded that as the height of structure increases, the collision force decreases.

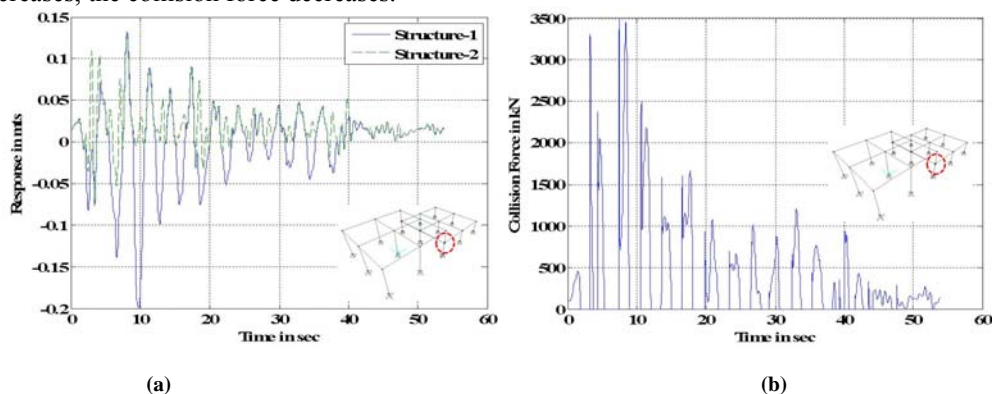


Fig. 11: (a) Response of Structures at a Location Cb and (b) Pounding Force Between Structures at $(2/4)^{th}$ Height of Structure

6. CONCLUSION

This analysis considered different setback levels for a single-single storey structure. The setback levels were 1.5 m, 3.0 m and 6.0 m. The separation distance between them is 0.01 m and they subjected to El-centro ground motion.

6.1 Setback Level

From results, the response for both structures increases as the setback level increases. But this increase in response is not significant. But the collision force between them increases significantly. The number of collision occurrences is same in all the cases. It can be concluded that the effect of collision is more when structures are kept at extreme levels of setback. The response of flexible structure is more than stiff structure when they vibrate at non-dominant period of ground motion. As the setback distance increases, the collision force between them also increases.

1.1 Height Level

From the results, the pounding response changes significantly as the height of structure decreases. At $(2/4)^{\text{th}}$ height of structure, the collision force is more compared to $(3/4)^{\text{th}}$ height because of shear amplification. It can be concluded that as the height of structure increases, the collision force decreases.

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