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Comparative Study of Tunnel Form and Framed Buildings by Dynamic Analysis

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Abstract— Tunnel form construction is a highly systematic, earthquake proven technique that produces monolithic structures. With a structural system composed of reinforced concrete shear walls and slabs as load bearing and transferring elements without accommodating columns and beams, tunnel form construction is observed quite appealing in the recent trend. It is a rapid construction system embracing quality, accuracy and savings in finishing works. In regions of high seismic risk, tunnel form buildings are gaining mounting popularity. In this study, performance of tunnel form building is compared to that of a beam-column framed building by linear dynamic response spectrum analysis using software package SAP2000. Generated response spectra of earthquakes are used in the response spectrum analysis which is carried out for 5-, 10-, 15-, and 20-story models. The effect of various locations of openings in shear walls is also evaluated. The variation in response is captured by examining the parameters like base shear, story displacement, interstory drift ratio etc. Tunnel form buildings experience lesser story displacement, lesser interstory drift ratio and higher base shear when compared to framed buildings. Opening locations affect the performance of tunnel form buildings under dynamic loading.

Index Terms- Tunnel form; response spectrum analysis; shear wall.

1. INTRODUCTION

With today's refinements, tunnel forming systems are well suited to repetitive cellular projects such as hotels, prisons, multi-unit housing, hostels and military housing. In this system, gravity and lateral loads are transferred to shear walls without engaging any beam or column. The number of cold-formed joints can be reduced as walls and slabs (of almost the same thickness) are cast simultaneously in a single operation. This results in monolithic structures, which provide high seismic performance and it reduces assembly time too. Non-structural components like facade walls are used as prefabricated elements. Speed of construction with a small crew and comparatively low cost is the most marketed benefits of tunnel form construction. A winning combination of speed, quality and accuracy is achieved in tunnel form construction. To roll the forms out of the structure, tunnel forming requires openings on the perimeter of the structure. This imparts restrictions on the structural plan of building and also increase susceptibility to torsional behavior in natural vibration modes which prevents from taking full advantage of the system. Adopting appropriate side dimensions and symmetrical configuration of shear walls may help to minimize torsion.

To elucidate the importance of material nonlinearity, slab-wall interaction, diaphragm flexibility, 3D behavior etc., nonlinear 3D pushover analyses were performed on finite element models using isoparametric shell element by Balkaya and Kalkan (2003). Based on 3D finite element analyses, Balkaya and Kalkan (2004) developed an equation to predict the fundamental period of tunnel form buildings. Reliability of code-based equations for fundamental period was evaluated and a consistent response reduction factor was developed. Stress flow and crack patterns around openings of 2D and 3D models were also studied along with diaphragm flexibility, behavior of transverse walls and slab-wall interaction during 3D action. An experimental study was instigated by Yuksel and Kalkan (2007) to understand the 3D behavior of tunnel-form buildings under quasi-static reversed cyclic loading. 3D nonlinear finite element models were verified through comparisons with experimental results. Influence of shear wall reinforcement ratio, boundary elements, coupling beams etc. were evaluated. Eshghi and Tavafoghi (2008, 2012) studied fundamental period by finite element analyses and executed forced vibration tests to estimate the period of mode shapes. Experiments were carried out to assess the seismic behavior of the tunnel form buildings and failure mechanisms were captured and compared to a finite element model.

This study sheds light on comparative assessment of framed building and tunnel form building in terms of story displacement, interstory

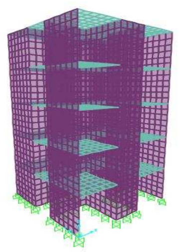


Fig.1. Tunnel form building modeled in SAP

drift ratio, base shear etc. by performing earthquake response spectrum analysis of 5-, 10-, 15- and 20-story models. It also aimed to evaluate the effect of different location of openings provided in tunnel form buildings by studying models of height varying from 15m to 60m by means of response spectrum analysis.

2. ANALYTICAL MODEL

2.1. *Tunnel form building (TFB) model*

In this work, tunnel form building of a plan/layout that avoids torsion in the fundamental response was adopted. 3D models of 5-, 10-, 15- and 20-story buildings were subjected to response spectrum analysis in SAP2000. Floor to floor height is 3m. Models comprised only of shear walls and 150mm thick slabs. Typical wall thickness for 5-, 10- and 15-story models is 150mm. In 20-story model, shear walls of 200mm thickness were used. The basic tunnel form building model has no openings and it is referred to as the control model. Door openings were provided at different locations in the basic tunnel form building model (referred as 'TFB-no door') in order to study its performance under earthquake. 5-story 'TFB-no door' modeled in SAP is shown in figure 1.

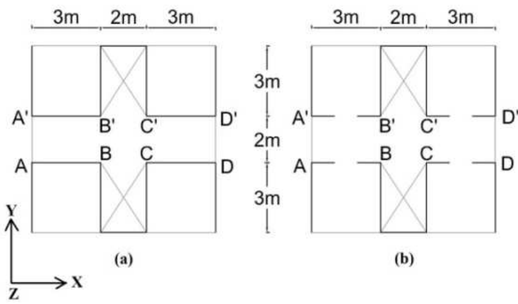


Fig. 2. Line sketch of plan
(a) TFB-no door (b) TFB-door case 1

The various door locations differentiate the basic model in to 4 cases and the models are classified as follows.

- TFB-no door
- TFB-door case 1
- TFB-door case 2
- TFB-door case 3
- TFB-door case 4

Size of door opening is 1m x 2m. Layout of the models are given in figure 2. Darker lines in plan indicate shear walls. Figure 3 shows the section along ABCD in the various models. Section is the same along ABCD and A'B'C'D'. A minimum of 0.25% steel is provided for shear walls as vertical and horizontal reinforcement in accordance with IS 456:2000. Yield strength of the steel is taken as 415 MPa. M30 grade concrete was opted throughout the height of all models. Shear walls are generally modeled by either a composition of frame elements or a mesh of shell elements. In this work, shear walls and slabs were modeled using layered shell and thin shell elements respectively. Poisson's ratio for concrete was taken as 0.20. Live load and floor finish of 1.5kN/m^2 was applied on roof and in all other floors, the corresponding values applied were 2kN/m^2 and 1kN/m^2 respectively. Mesh size of 0.5m x 0.5m was used for modeling shear walls and slabs.

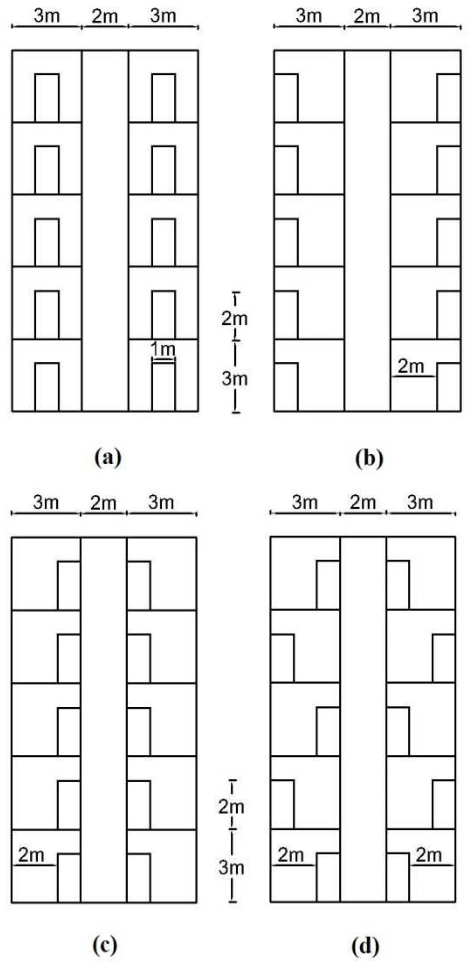


Fig. 3. Section along ABCD [XZ plane]
(a) TFB-door case 1 (b) TFB-door case 2
(c) TFB-door case 3 (d) TFB-door case 4

2.2. *Framed building model*

For the same layout of the tunnel form building model, framed building models were also defined, in order to have a comparative study of the two. Framed model consists of beams and columns as load transfer and bearing elements. Slabs are of 150mm thickness. 5-, 10-, 15- and 20-story models were considered for comparison with basic tunnel form building models. Beam dimensions: 0.23m x 0.45m. Column dimensions used are 0.3m x 0.3m for 5-story and 10-story models, 0.39m x 0.39m for 15-story model and 0.49m x 0.49m for 20-story model. Typical floor to floor height is 3m. M30 grade concrete was opted for columns and M20 grade concrete was opted for beams and slabs. 0.8% to 0.9% steel was provided for columns in accordance with IS 456:2000. Steel material property, meshing for slabs and loading condition was provided as same as that of TFB. The plan of framed model is shown in figure 5.

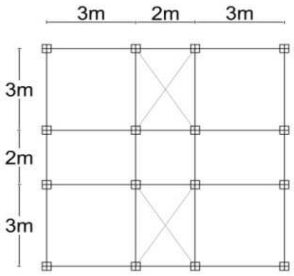


Fig. 5. Plan of framed model

Table 1. Fundamental periods of models

Model	Height of model (m)	Framed (s)	TFB-no door (s)
5 story	15	0.51	0.15
10 story	30	1.04	0.46
15 story	45	1.31	0.88
20 story	60	1.71	1.39

3. RESPONSE SPECTRUM ANALYSIS

Response spectrum analysis is a linear-dynamic analysis method which facilitates in earthquake-resistant design of structures. It helps to obtain the peak structural responses under linear range. Ground motions of Northridge, Kobe and Kocaeli earthquakes were chosen for this study. Response spectra of these earthquakes were generated using the software PRISM. The generated spectra were used for response spectrum analysis in SAP2000. The ground motion records of the three earthquakes and their corresponding response spectra are shown in figure 6 and figure 7 respectively. Modal analysis was done in SAP prior to response spectrum analysis. Fundamental periods of framed and 'TFB-no door' models obtained by ritz vector modal analysis are given in table 1. It shows that tunnel form buildings have lesser fundamental period compared to the framed buildings.

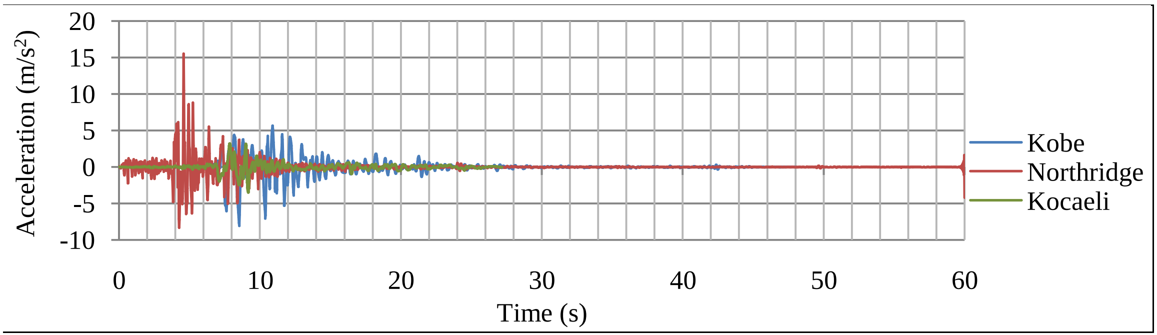


Fig. 6. Ground motion of earthquakes: Kobe, Northridge, Kocaeli

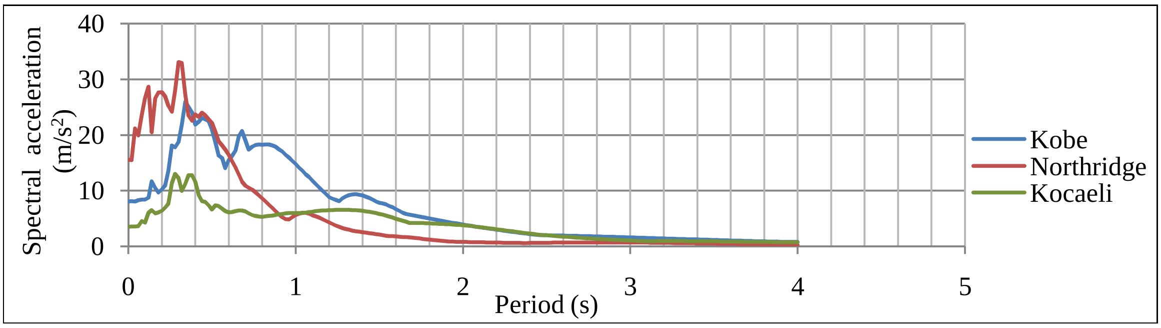


Fig. 7. Spectral acceleration: Kobe, Northridge, Kocaeli

4. RESULTS AND DISCUSSION

4.1. *Location of openings in TFB*

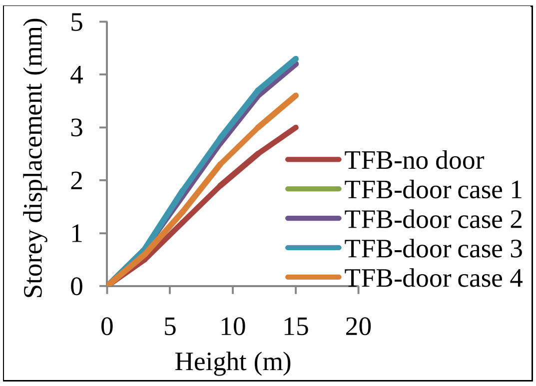
Response spectrum analysis was performed for 5-, 10-, 15-, and 20-story models with different door opening locations. The displacements at each story level were examined and plotted against the story height for each case. The results for Kobe response spectra for various door locations are shown in figure 8. The plot hit upon a trend of comparatively higher displacements for 'TFB-door case 2'. Lowest displacement values are observed for 'TFB-no door' with no opening. Among the models with openings, 'TFB-door case 4' has lower displacement. Also, the graphical representation of story displacement evidently shows that as height of the model increases, the top story displacement is increasing significantly. For 20-story models, opening location is not having much pronounced influence on the story displacement.

4.2. *Comparison of framed and TFB - story displacement*

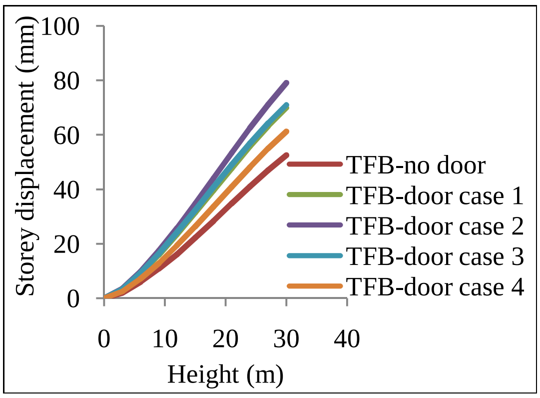
Framed and 'TFB-no door' models were subjected to response spectrum analysis for Kobe, Northridge and Kocaeli earthquakes. The results illustrate ample disparity in storey displacements of tunnel form and framed model. Figure 9 shows the plot of story displacement against height for Kobe earthquake. In tunnel form models, story displacement exhibits a consistent and identical pattern for 5-, 10-, 15- and 20-storey. For low-rise buildings, if a particular story level is considered, the displacement is too high for framed model when compared with that of a TFB model. But this difference reduces as the height of building increases. Similar results were obtained for Northridge and Kocaeli earthquakes.

4.3. *Comparison of framed and TFB - interstory drift ratio*

Interstory drift ratio is the ratio of difference of adjacent story displacements and the story height. Plots of interstory drift ratio with respect to height are shown in figure 10, figure 11 and figure 12.



(a)



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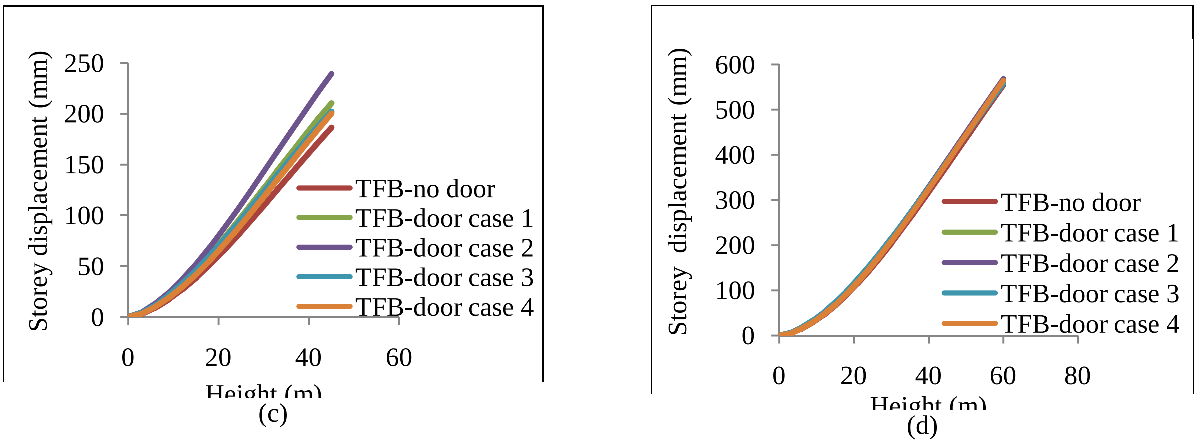

Fig. 8. Story displacement for various door opening cases, for Kobe earthquake: (a) 5-story (b) 10-story (c) 15-story (d) 20-story

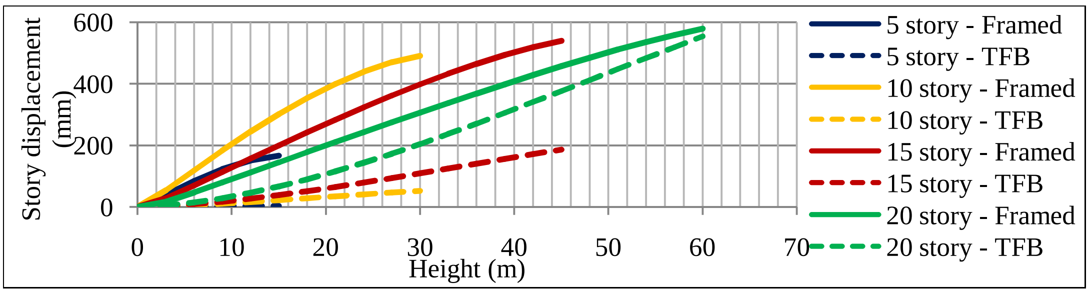

Fig. 9. Story displacements of framed and TFB models for Kobe earthquake

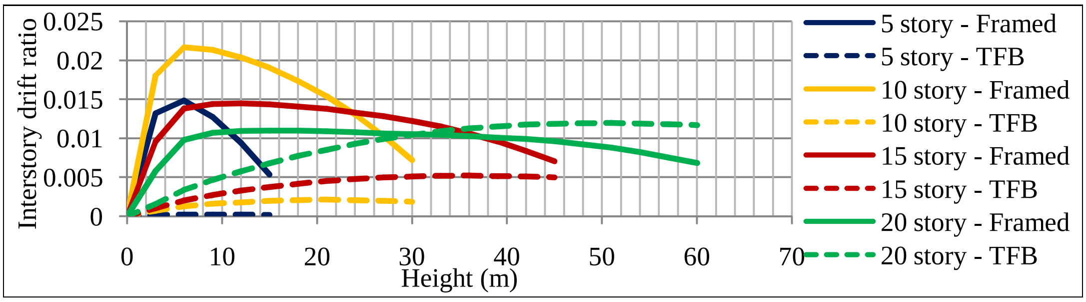

Fig. 10. Interstory drift ratio of framed and TFB models for Kobe earthquake

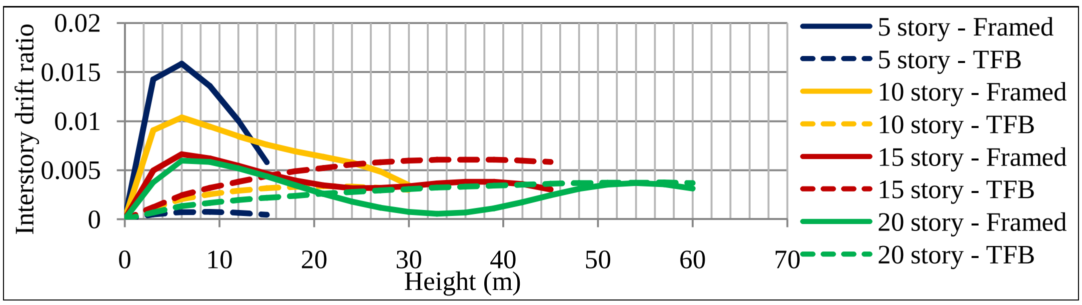

Fig. 11. Interstory drift ratio of framed and TFB models for Northridge earthquake

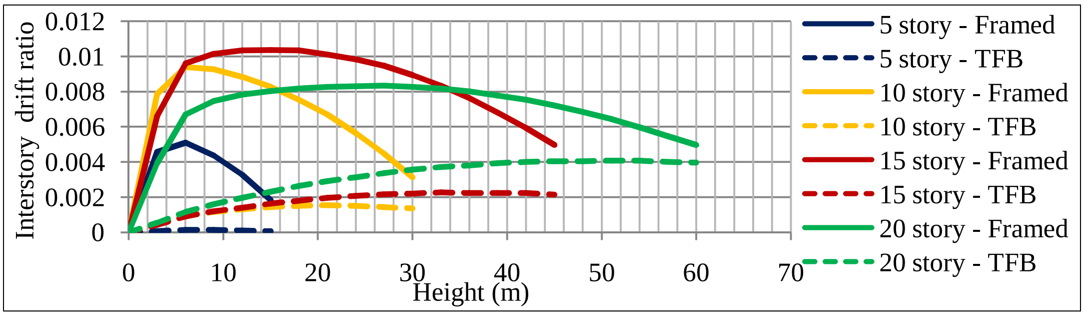

Fig. 12. Interstory drift ratio of framed and TFB models for Kocaeli earthquake

In TFB, maximum interstory drift ratio is observed in the upper floors and this remains constant for few upper floors. The lower floors experience lesser drift. In framed models, the lower floors experience the highest drift and it reduces for the upper floors in general. Also, the pattern of drift followed in TFB is gradual and of uniform nature unlike framed type. Framed building models are experiencing higher drifts than tunnel form building models. Maximum interstory drift ratio is also higher in the framed models when compared to TFB models.

4.4. *Comparison of framed and TFB - base shear*

Base shear experienced by framed and tunnel form models of height 15m, 30m, 45m and 60m is sketched in figure 13. Base shear in TFB system is higher than that in framed system for the three earthquakes. Shear walls in tunnel form building attract more force at the base which causes higher base shear in them. Shear walls make the building stiffer. For Kobe earthquake, base shear of framed and TFB increases with the height of model.

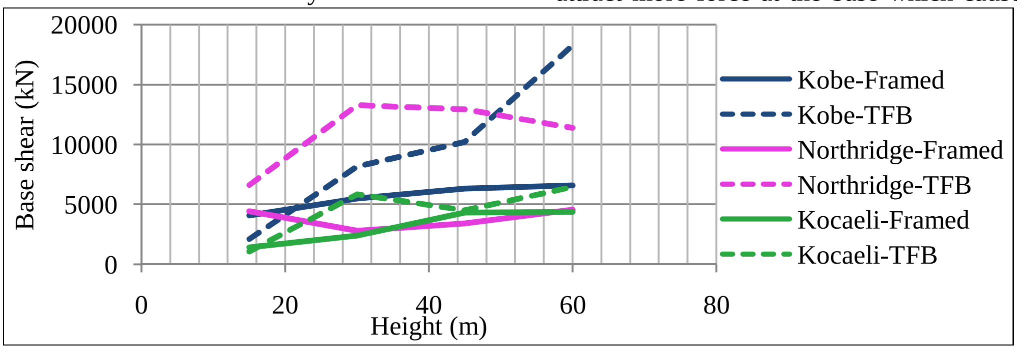

Fig. 13. Base shear of framed and TFB models

5. CONCLUSIONS

Earthquake response spectrum analysis was carried out for tunnel form building models and beam-column framed building models. The study was conducted on 5-, 10-, 15- and 20-story models of both framed and tunnel form buildings using software SAP2000. In tunnel form building type, a few models were fixed based on locations of openings and the analyses were carried out for them too. Results led to the following conclusions.

- Tunnel form buildings have lesser story displacements than framed buildings when subjected to dynamic loads. Story displacement pattern along height of model is of gradually increasing nature for 5-, 10-, 15- and 20-story TFB models.
- Interstory drift is gradual in tunnel form buildings and higher for the top stories. For framed building, the drift is observed to be highest in the lower floors and it gradually reduces towards the upper floors. Maximum interstory drift ratio is higher in framed buildings than tunnel form buildings.
- Base shear experienced by the tunnel form building is comparatively higher than that in framed building. Presence of shear walls makes the tunnel form building stiffer and it attracts more force at the base.
- Openings of same dimensions when arranged in different locations in shear wall affects the story displacements under dynamic loading.

Staggered arrangement of openings shows lesser displacement among all.

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