Comparative Study on the Effectiveness Between Shear Wall and Bracing Systems on High-Rise Structures

Piash Ghosh, Saurabh Kumar Singh, Mainak Mallik, and Damodar Maity

1 Introduction

High-rise structures are often constructed throughout the metro cities due to space or architectural constraints, though the asymmetricity of the plan of some buildings cannot be avoided. This is evident that the high-rise building with asymmetric plan is highly susceptible to damage due to seismic forces and high wind pressure. The existence of the shear walls plays an important role in arresting the deformation of the adjacent parts of the buildings, by providing an ample amount of stiffness to the building. Elevator core panels are the natural location of shear walls in a building. RCC bracings can also be provided instead of providing shear walls in the panels. Shear walls and bracings both provide stiffness efficiently.

Bhojkar and Bagade [1] have found that the X type of steel bracings significantly contributes to the structural stiffness and reduces the maximum inter-storey drift of the frames of a G+9 (ten storied) building. Alashkar et al. [2] have observed that for a G+7 building shear walls reduce a significant amount of lateral displacement, bending moment, and shear forces in the frame members when the shear walls are suitably placed. Azad and Gani [3] concluded that the usage of vertical bracings is more important than the floor bracings for a symmetric G+8 building. A parametric study has been performed by Thapa and Sarkar [4] to compare the dynamic responses of frame structure with and without the shear wall.

From the above discussions, it is evident that till date, no significant studies have been performed on the performance evaluation of high-rise structures with the comparison of shear walls and RCC bracings under seismic and wind loading. In this context, this paper is an attempt to perform a comparative study between the

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effectiveness of RC shear wall and X-type of concrete bracing system of high-rise structure having an asymmetric plan. For understanding the effect of the shear wall and bracing system in the buildings having asymmetric plan in a better manner, a building having symmetric plan of the same height has also been incorporated in this study. In the present work, two different types of G+25 building of asymmetric plan and one G+25 building of symmetric plan of the same height have been modelled and analyzed using finite element software STAAD.Pro. The maximum base shear, storey drift, and maximum base moment under seismic and wind forces are calculated for the buildings with shear wall and concrete bracing systems.

2 Finite Element Formulation

2.1 Formulation for Frame

The stiffness matrix $[K]$ for a beam element may be expressed as

$$[K] = \int_0^L [B]^T EI[B]\mathrm{d}x \tag{1}$$

where E is the modulus of elasticity, I is the second moment of area and $[B]$ is the curvature displacement relationship matrix which may be expressed as

$$[B] = \left[\frac{\partial^2 N_1}{\partial x^2} \ \frac{\partial^2 N_2}{\partial x^2} \ \frac{\partial^2 N_3}{\partial x^2} \ \frac{\partial^2 N_4}{\partial x^2} \right] \tag{2}$$

The stiffness matrix for a truss element may be expressed as

$$[K] = \int_0^L [B]^T E[B]A\mathrm{d}x \tag{3}$$

where E is the modulus of elasticity, A is the area of the element and the strain–displacement matrix is

$$[B] = \left[\frac{\partial N_1}{\partial x} \ \frac{\partial N_2}{\partial x} \right] \tag{4}$$

In the present case, the structures have been analyzed as a planar frame model using two-dimensional beam element with three degrees of freedom at each node. By superimposing the stiffness matrix of a truss element corresponding to Eq. (3) and the stiffness matrix of a beam element corresponding to Eq. (1) after expanding to 6×6 stiffness matrix individually, the desired stiffness matrix can be obtained. The corresponding element stiffness matrix is

$$[K] = \begin{bmatrix} H_1 & 0 & 0 & -H_1 & 0 & 0 \\ 0 & 12H_2 & 6H_2L & 0 & -12H_2 & 6H_2L \\ 0 & 6H_2L & 4H_2L^2 & 0 & -6H_2L & 2H_2L^2 \\ -H_1 & 0 & 0 & H_1 & 0 & 0 \\ 0 & -12H_2 & -6H_2L & 0 & 12H_2 & -6H_2L \\ 0 & 6H_2L & 2H_2L^2 & 0 & -6H_2L & 4H_2L^2 \end{bmatrix} \tag{5}$$

where $H_1 = AE/L$, $H_2 = EI_z/L^3$, where I_z is the second moment of area about the z-axis, L is the length of the element, A is the cross-sectional area and E is the modulus of elasticity.

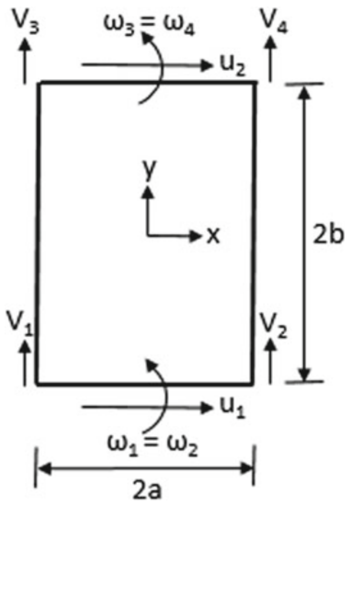
2.2 *Formulation for Shear Wall*

The finite element formulation of shear wall has been explained by Sepehrnia et al. [5]. They have presented the shear wall panel as shown in Fig. 1.

The degrees of freedom of the panel element (PE) is considered to be eight. Here, the degrees of freedom indicates the lateral and vertical movements associated with two in-plane rotational deformations, which are u_1, $-\delta u_1/\delta y$ corresponding to ω_1, v_1, v_2 and u_2, $-\delta u_2/\delta y$ corresponding to ω_3, v_3, v_4. They have been considered at the lower chord and the upper chord of the panel element, respectively. The analytical relation between strain vector $\{\varepsilon\}$, displacement vector $\{D\}$ and strain–displacement matrix $[B]$ is

$$\begin{bmatrix} \varepsilon_x & \varepsilon_y & \gamma_{xy} \end{bmatrix}^T = [B].\{D\} \tag{6}$$

Fig. 1 Panel element of shear wall



where ε_x is the horizontal strain, ε_y is flexural strain and γ_{xy} is the shear strain.

$$\{D\}_{\mathrm{PE}} = \left\{ u_1 \ \omega_1 \ v_1 \ v_2 \ u_2 \ \omega_3 \ v_3 \ v_4 \right\}^T \tag{7}$$

As per the assessment made by Taranath [6], in the modelling process of tall buildings, the horizontal strain is assumed to be negligible, for this type of element. The shear wall panel is considered to act as a deep beam and ε_y along Y-direction is considered to study the flexural behaviour of the panel. The stiffness matrix of the element is evaluated by standard expression as

$$[K] = t \int_A [B]^T [D_m][B] \mathrm{d}A \tag{8}$$

where $[D_m] = diag\left[E \ E \ G \right]$, G and E are shear and elasticity modulus, respectively, t is the thickness of the element. The element stiffness matrix (Sepehrnia et al. [5]) has been given as follows:

$$[K] = [K_{\mathrm{F}}] + [K_{\mathrm{S}}] \tag{9}$$

where $[K_{\mathrm{F}}]$ and $[K_{\mathrm{S}}]$ are flexural and shear stiffness matrices, respectively.

$$[K_{\mathrm{F}}] = \begin{bmatrix} \frac{25a^3}{21b^3} & & & S & & & & \\ -\frac{25a^3}{21b^2} & \frac{25a^3}{21b} & & & Y & & & \\ 0 & 0 & \frac{a}{3b} & & & M & & \\ 0 & 0 & \frac{a}{6b} & \frac{a}{3b} & & & M & \\ -\frac{25a^3}{21b^3} & \frac{25a^3}{21b^2} & 0 & 0 & \frac{25a^3}{21b^3} & & & \\ -\frac{25a^3}{21b^2} & \frac{25a^3}{21b} & 0 & 0 & \frac{25a^3}{21b^2} & \frac{25a^3}{21b} & & \\ 0 & 0 & -\frac{a}{3b} & -\frac{a}{6b} & 0 & 0 & \frac{a}{3b} & \\ 0 & 0 & -\frac{a}{6b} & -\frac{a}{3b} & 0 & 0 & \frac{a}{6b} & \frac{a}{3b} \end{bmatrix} \tag{10}$$

$$[K_{\mathrm{S}}] = \begin{bmatrix} 0 & & & S & & & & \\ 0 & \frac{8ab}{7} & & & Y & & & \\ 0 & \frac{4b}{7} & \frac{2b}{7a} & & & M & & \\ 0 & -\frac{4b}{7} & -\frac{2b}{7a} & \frac{2b}{7a} & & & M & \\ 0 & 0 & 0 & 0 & 0 & & & \\ 0 & \frac{6ab}{7} & \frac{3b}{7} & -\frac{3b}{7} & 0 & \frac{8ab}{7} & & \\ 0 & \frac{3b}{7} & \frac{3b}{14a} & -\frac{3b}{14a} & 0 & \frac{4b}{7} & \frac{2b}{7a} & \\ 0 & -\frac{3b}{7} & -\frac{3b}{14a} & \frac{3b}{14a} & 0 & -\frac{4b}{7} & -\frac{2b}{7a} & \frac{2b}{7a} \end{bmatrix} \tag{11}$$

The strain–displacement matrix $[B]$ of the proposed panel element (Sepehrnia et al. [5]) is

$$[B] = \begin{bmatrix} 0 & -\frac{5xy^3}{2b^5} & 0 \\ 0 & \frac{5xy^3}{2b^4} & \frac{y^3}{2b^3} - \frac{1}{2} \\ 0 & \frac{x}{4ab} - \frac{1}{4b} & \frac{y^3}{4ab^3} - \frac{1}{4a} \\ 0 & -\frac{x}{4ab} - \frac{1}{4b} & -\frac{y^3}{4ab^3} + \frac{1}{4a} \\ 0 & \frac{5xy^3}{2b^5} & 0 \\ 0 & \frac{5xy^3}{2b^4} & -\frac{y^3}{2b^3} - \frac{1}{2} \\ 0 & -\frac{x}{4ab} + \frac{1}{4b} & -\frac{y^3}{4ab^3} - \frac{1}{4a} \\ 0 & \frac{x}{4ab} + \frac{1}{4b} & \frac{y^3}{4ab^3} + \frac{1}{4a} \end{bmatrix}^T \tag{12}$$

3 Numerical Modelling of the Buildings

The numerical modelling and analysis of the buildings have been performed by finite element software STAAD.Pro. The model of Building 1 (B1) is shown in Fig. 2.

The specification of the model of the buildings is shown in Table 1.

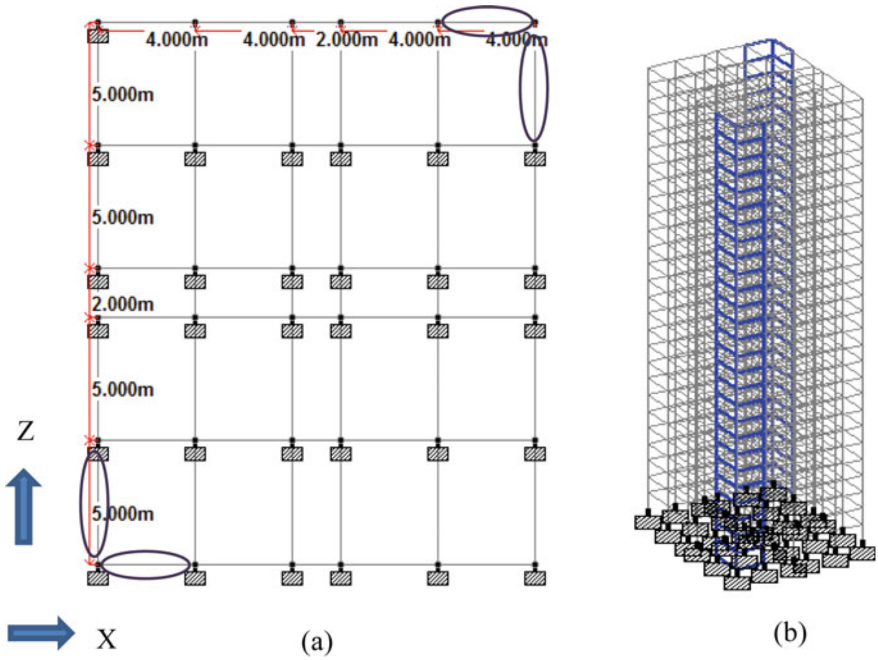


Fig. 2 **a** Top view of the model of B1 with positions indicating shear wall and bracings and **b** isometric view of B1 with bracings

Table 1 Specification of model

Specification	Building 1 (B1)	Building 2 (B2)	Building 3 (B3)
No. of storeys	G+25	G+25	G+25
Height of building in m	81.00	81.00	81.00
Size of the beam in mm × mm (width × depth)	300 × 400	300 × 400	300 × 400
Size of the column in mm × mm	800 × 800 (B+G+8th)	800 × 800 (B+G+8th)	800 × 800 (B+G+8th)
	600 × 600 (9–18th)	600 × 600 (9–18th)	600 × 600 (9–18th)
	500 × 500 (19–25th)	500 × 500 (19–25th)	500 × 500 (19–25th)
Thickness of shear wall in mm	150	150	150
Size of RCC bracings in m × m (width × depth)	0.42 × 0.42	0.43 × 0.43	0.42 × 0.42
	0.44 × 0.44	0.45 × 0.45	0.43 × 0.43
Frame configuration	Moment resisting RC frame	Moment resisting RC frame	Moment resisting RC frame
Plan type	Symmetric	Asymmetric	Asymmetric

3.1 Building Model Configuration

Bracings of different dimensions have been provided at different locations of the buildings so that the volume of concrete in the shear wall provided in each panel should be equal to the volume of concrete in bracings in each panel. The purpose of this study is to compare the effectiveness between the shear wall and bracings of each individual building only and not among the buildings. So, the comparison has been restricted to each individual building only. Models of Building 2 and Building 3 are shown in Figs. 3 and 4, respectively.

From Fig. 2, it can be seen that, the shear walls and bracing systems in the symmetric building have been provided at the diagonal positions. From the study of Thapa and Sarkar [4], it has been found that shear wall at corners (i.e. at diagonal positions of the building) reduce displacement of the building along with height significantly.

3.2 Loading Configuration

Dead Load and Live Load. Dead load and live load have been assigned as per IS 875 (Part 1) [7] and IS 875 (Part 2) [8], respectively. For the load calculation, the thickness of the wall has been considered 250 mm, the height of the parapet wall has been considered 1.20 m. The unit weight of brick masonry is 20 kN/m^3. Except

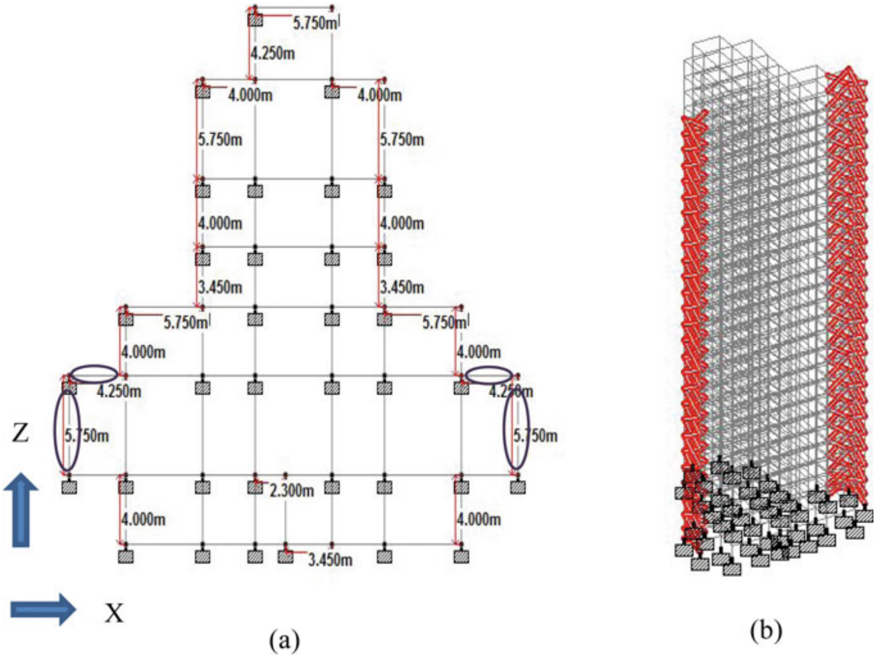


Fig. 3 **a** Top view of the model of B2 with positions indicating shear wall and bracings and **b** isometric view of B2 with shear walls

self-weight of the building, there are different loads such as dead load, live load, seismic load and wind load which are acting on the structure. The load combinations have been assigned as per IS 456-2000 [9].

Seismic Load. Seismic analysis has been performed as per IS 1893 (Part 1)-2002 [10], through STAAD.Pro. For the purpose of the analysis, building location has been considered in Patna, which is categorized under zone IV. The necessary parameters like zone factor as 0.24, response reduction factor as 5, importance factor as 1, rock and soil site factor as 1 and damping ratio as 0.05 have been considered. The natural period for Building 1 has been calculated as 1.72 and 1.55 s along X- and Z-directions, respectively, whereas the same parameter for Building 2 has been obtained as 1.25 and 1.30 s along X- and Z-directions, respectively. The natural period for Building 3 has been calculated as 1.19 and 1.40 s along X- and Z-directions, respectively.

Wind Load. Wind load analysis has been performed through STAAD.Pro. Wind load data has been calculated as per IS 875 (Part 3)-1987 [11]. The zone has been considered as Patna, where the basic wind speed is 47 m/s. The terrain category has been considered as 3 and building class has been considered as C.

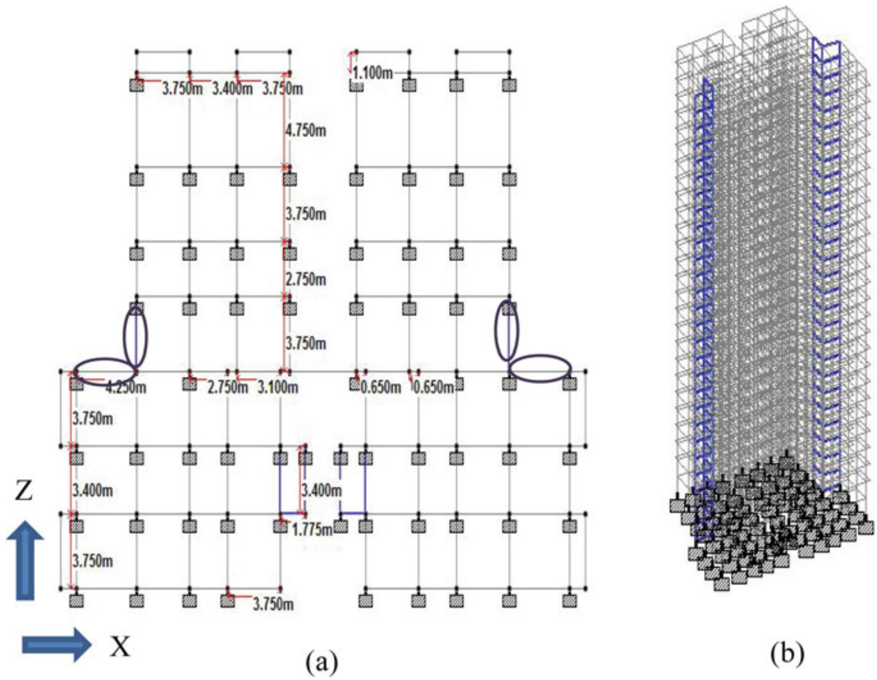


Fig. 4 **a** Top view of the model of B3 with positions indicating shear wall and bracings and **b** isometric view of B3 with shear wall

4 Results and Discussions

The frame structure buildings have been analyzed with shear wall and X-type of RCC bracings provided at suitable locations on the boundary of the buildings. Results have been compared in terms of maximum base shear, storey drift at each floor level and maximum base moment. Assuming Building 1, Building 2 and Building 3 as B1, B2 and B3, respectively.

4.1 Base Shear

The maximum expected lateral force on the base of the structure due to seismic activity is defined as base shear. The buildings have been analyzed to calculate the base shear for shear wall and bracing systems at appropriate locations of the buildings.

From Figs. 5, 6, 7, 8, 9 and 10, this is clear that the base shear will be more for the buildings with shear walls as well as for the buildings having RCC bracings because of the increase in the dead load of the buildings. The addition of new elements to

Fig. 5 Maximum base shear of B1 in X-direction

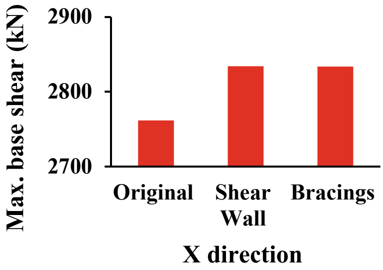


Fig. 6 Maximum base shear of B1 in Z-direction

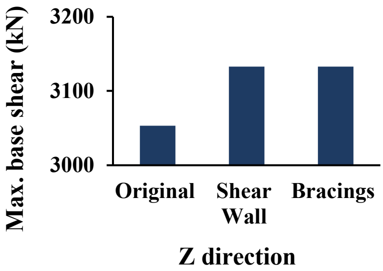


Fig. 7 Maximum base shear of B2 in X-direction

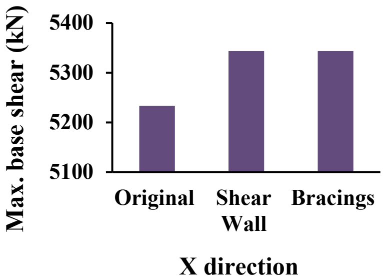
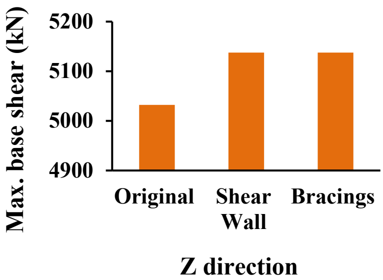


Fig. 8 Maximum base shear of B2 in Z-direction



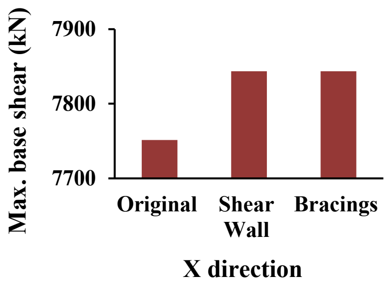


Fig. 9 Maximum base shear of B3 in X-direction

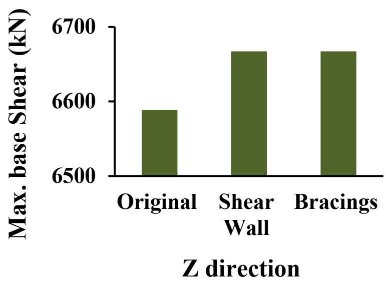


Fig. 10 Maximum base shear of B3 in Z-direction

the original building increases its dead load, which results in an increase in the base shear.

4.2 Storey Drift

Storey drift is defined as the lateral displacement of one storey with respect to the adjacent storey below. Generally, it is caused by lateral loads such as seismic and wind loads. In the figures below storey drift effect on original buildings (ORG), buildings with the shear wall (SW) and buildings with RCC bracings (BR) are shown.

From Figs. 11, 12, 13, 14, 15 and 16, buildings with shear walls show slightly lesser storey drift as compared to the buildings with RCC bracings.

The picture of the storey drift will be clearer, if the drift ratio of the buildings in each direction are observed. The drift ratio of the buildings are shown in Table 2.

From Table 2, it is clearly visible that, the original buildings are under the highest drift, while in the case of the other buildings, the drift is getting lowered with increasing resistance provided by the RCC bracings and shear walls.

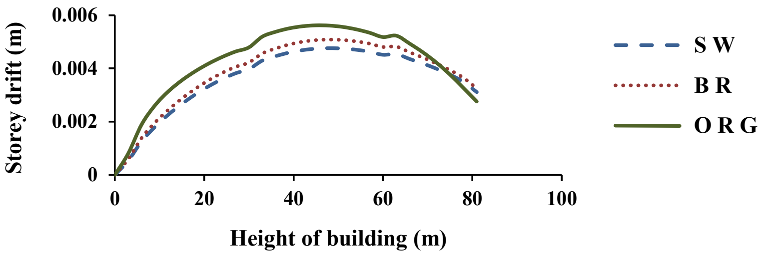


Fig. 11 Storey drift in X-direction for B1

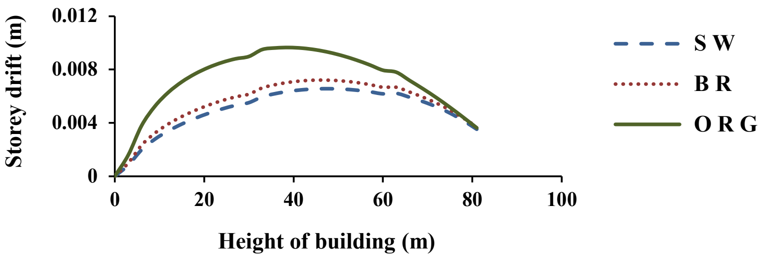


Fig. 12 Storey drift in Z-direction for B1

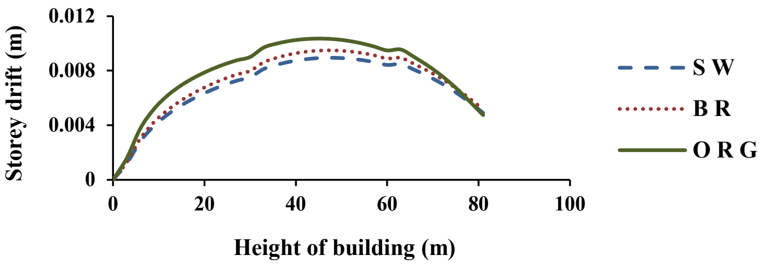


Fig. 13 Storey drift in X-direction for B2

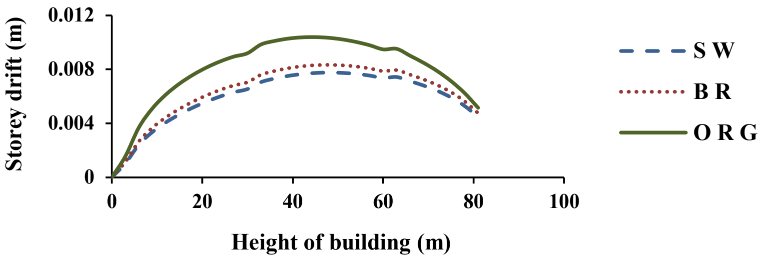


Fig. 14 Storey drift in Z-direction for B2

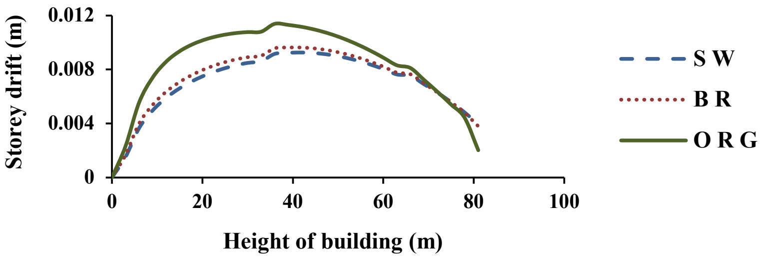


Fig. 15 Storey drift in X-direction for B3

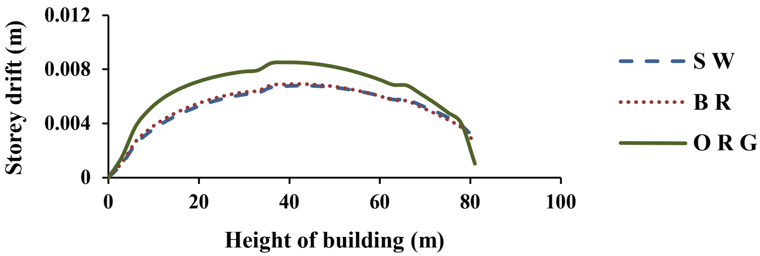


Fig. 16 Storey drift in Z-direction for B3

Table 2 Drift ratio of the buildings

Drift ratio						
Types	Original		Shear wall		Bracing	
	X	Z	X	Z	X	Z
Building 1	0.14460	0.24437	0.12325	0.16890	0.13109	0.18544
Building 2	0.26857	0.27182	0.23124	0.20245	0.24497	0.21760
Building 3	0.28632	0.21712	0.23891	0.17534	0.24801	0.17756

4.3 Base Moment

Base moment is defined as the moment produced at the base of the structure due to different loading conditions that are acting on the structure. The buildings are analysed to calculate the base moment for shear walls and bracings, which are provided at some appropriate locations on the boundary of the buildings.

From Figs. 17, 18, 19, 20, 21 and 22, this is clear that for all of the cases irrespective of direction maximum base moment is highest for the original buildings and lowest for the buildings with shear walls. Also, it is to be noted that, for all of the cases the maximum base moment of the buildings with RCC bracings is higher than the maximum base moment of the buildings with shear walls.

Fig. 17 Maximum base moment of B1 along X-direction

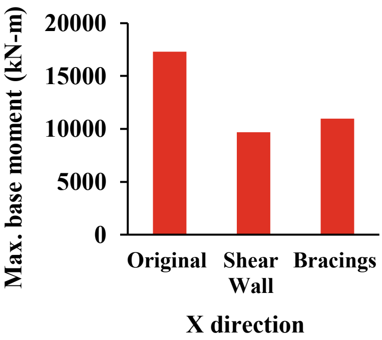


Fig. 18 Maximum base moment of B1 along Z-direction

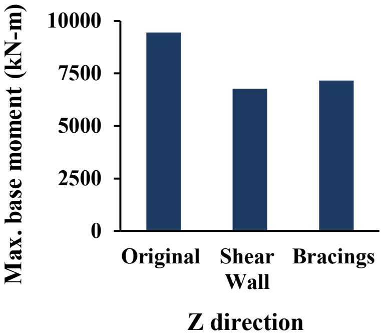
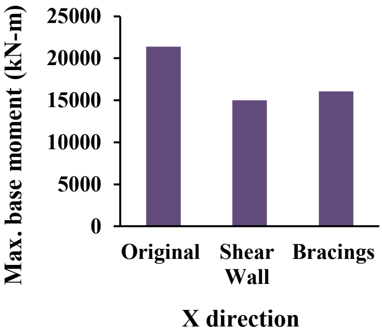


Fig. 19 Maximum base moment of B2 along X-direction



5 Conclusions

In the present work, it can be seen that the weight of the building and the lateral forces generated by seismic and wind loads play an important role to interpret the results.

(a) The buildings with shear wall and RCC bracings show higher value of maximum base shear than the original buildings irrespective of direction. This

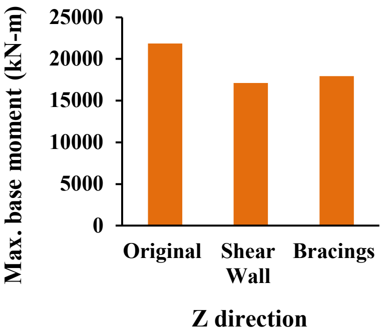


Fig. 20 Maximum base moment of B2 along Z-direction

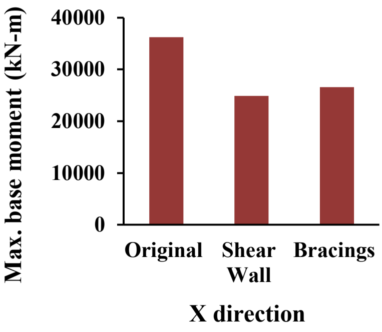


Fig. 21 Maximum base moment of B3 along X-direction

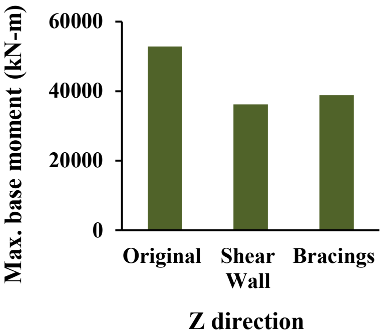


Fig. 22 Maximum base moment of B3 along Z-direction

is because; the addition of new elements to the building increases the weight factor, which in turn increases the base shear also.

(b) The value of maximum base shear is same for both the buildings, i.e. the building with shear wall and the building with bracing for a particular direction. This validates the concept of using the same volume of concrete in the shear wall as well as in the bracings.

(c) The plots of the maximum base shear show the same pattern in the asymmetric plan as well as symmetric plan buildings. So, the maximum base shear does not depend upon the asymmetricity of the plan.

(d) In the case of the storey drift, the buildings with shear walls show slightly lesser drift than the buildings with bracings and significantly lesser drift than the original buildings. The reason may be that, as shear walls connect through the circumference of the panel section, these provide very high stiffness throughout the panel, which resists the drift efficiently, whereas the bracings remain placed diagonally in the panels and are connected at the corners of panels only, due to which, the stiffness remains slightly lesser than the shear wall panels. This is true for the plan in asymmetric as well as for the plan in symmetric buildings.

(e) The maximum base moment is highest for the original buildings and lowest for the buildings with shear walls in each direction of all the cases. This result concludes that the shear walls show high resistance to the base moment.

(f) The maximum base moment of the buildings with RCC bracings are higher than the maximum base moment of the buildings with shear walls. This result accomplishes the fact that the shear walls show higher resistance to the base moment than RCC bracings. The reason may be that, the shear walls in the basement are connected to the ground, due to which, the base moment gets resisted efficiently in those buildings, which is not possible for the buildings with RCC bracings. The bracings are efficient to transfer moment, but as they are not connected to the ground directly, they show lesser efficiency than the shear walls in resisting base moment.

From the above discussion, it can be concluded that the shear walls are quite effective retrofitting elements from the point of resisting storey drift as well as base moment than the bracings. Also, the point to be noted that asymmetricity in the plan of buildings should be reduced to minimize the vulnerability of the structure.

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