Comparative Study on Reducing Soft Storey Effect in RC Structures

Mostafa Mahmud*[1], Md Faiyaz Shahriar[1] and Akib Mohammad Sunny[1]

[1] Bangladesh University of Business and Technology, Dhaka 1216, Bangladesh
mahmudmostafa@bubt.edu.bd

Abstract. This study aims to assess the seismic vulnerability of soft ground stories and propose potential solutions by comparing the use of concrete shear walls and steel bracings at the ground level. In our country, soft-story buildings are commonly used, with many multistory structures leaving the ground floor open for parking, without walls. Brick infill walls are typically placed on the upper floors, a design feature that is problematic in earthquake-prone regions. The open ground floor significantly increases the seismic risk of high-rise buildings. This research focuses on analyzing a mid-rise RCC building with G+7 stories, featuring an open ground level, using ETABS V18.0.1 for pushover analysis to evaluate the structure's performance with both shear walls and steel bracings. Several structural configurations were examined, including a bare frame, soft-story frame, soft-story with shear walls, and a steel-braced frame at the ground level, to observe variations in response parameters such as storey drift ratio, lateral displacement, and ground-floor stiffness. Among these configurations, shear walls were found to perform best, followed by cross-bracings. The use of shear walls reduced storey drift and lateral displacement more effectively than steel bracings, with storey drift decreasing by 96%. Cross-bracings and inverted-V bracings lowered the drift by 70% and 64%, respectively. The first-floor stiffness with shear walls was 10.6 times higher than that of an open-ground storey, while cross-bracings and inverted-V bracings increased stiffness by 2.7 and 1.8 times, respectively. These findings can aid in designing safer buildings with open ground floors.

Keywords: Soft Storey, Pushover Analysis, Shear Wall, Steel Bracing.

1 Introduction

In response to the increasing demand for residential space in large urban centres, there has been a surge in the construction of multi-storey buildings. However, a significant proportion of these structures are being built without considering seismic effects, which poses a severe risk in earthquake-prone regions like Bangladesh. The Bangladesh National Building Code (BNBC-2020) defines a "soft storey" as a level with lateral stiffness less than 70% of the stiffness of the storey above or less than 80% of the average stiffness of the three storeys above it [1]. Soft storeys, particularly those designed with

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open ground floors, are commonly employed in urban areas to meet the demand for parking spaces. However, this structural design introduces a critical vulnerability during seismic events [2]. The reduction in stiffness in the open ground storey results in increased flexibility, leading to heightened bending moments and shear forces, which can cause catastrophic structural failure. Despite these risks, the open ground storey design remains a popular choice, particularly to address the need for parking space in congested urban areas [3,4].

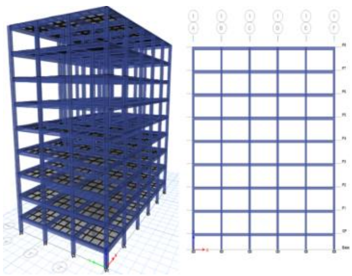
While there is substantial literature on seismic response and structural modifications to mitigate the soft storey effect, key research gaps remain. Specifically, there is limited comparative analysis on the effectiveness of different structural configurations, such as shear walls and steel bracing, in multi-storey buildings with open ground floors. Previous studies [5, 6] have primarily focused on specific structural solutions like shear walls or diagonal steel bracing but do not provide comprehensive assessments of multiple configurations within the same research scope. It is reported that adding steel bracing to RC frames significantly reduced base shear, column moments, inter-storey drift, and displacements, while increasing overall strength and stiffness [9]. The load resistance and energy dissipation capabilities of specimens with different combinations of strong and weak frames and panels along with steel bracings concluding that strong frames and panels perform better under seismic loads [10]. Both the of the research [9, 10] were limited to steel bracings. A study on the seismic behaviour of reinforced concrete structures with different bracing designs using the equivalent fixed approach which assessed diagonal, V-type, and inverted X-type bracing systems, showing how different configurations influence seismic performance [7]. The behaviour of bare frames, RC frames with struts, and RC frames with diagonal bracing in G+5 storey buildings was reported earlier [8]. The study evaluated key structural responses such as base shear, mode periods, storey acceleration, displacement, and drift, offering insights into the benefits of diagonal bracing in multi-storey structures [8]. However, these studies did not thoroughly explore the interaction between bracing systems and shear walls in mitigating soft storey vulnerabilities in varying building heights and layouts.

This paper attempted to address these gaps by providing a comparative analysis of various structural modifications, including shear walls, cross-bracing, and inverted V-bracing, in soft storey designs. This study aims to clarify which configurations are most effective in reducing lateral displacements, inter-storey drift, and overall building vulnerability during seismic events. Given the increasing frequency of high-rise construction in seismically active regions, it is imperative to provide a detailed understanding of these structural solutions to enhance building resilience and safety.

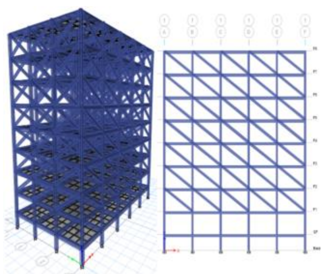
2 Methodology

The structural modeling was carried out using the standard software ETABS, which operates on the finite element method. The structure is an eight storied building consists of five spans in the x direction and three bays in the y direction where each bay is 4.5m in length. Five different structural configurations of the same model (as shown in Fig. 1) were analyzed to observe the soft story mitigation capability of concrete shear wall, inverted V and cross bracings at ground floor. For designing the building on ETABS, the site class was considered as SC and structure was considered as IMRF. Other parameters physical parameters and loads considered in ETABS are shown in the Table 1. According to BNBC-2020, Chapter-6, and Article-6.3.10.2, the section properties were considered as cracked section for all types of analysis. So, the stiffness modifiers were considered according to BNBC 2020. The Load combinations according to BNBC 2020 were considered for analysis. Table 2 shows the load combinations.

- Model-1: Bare frame structure.
- Model-2: Frame structure with a soft story.
- Model-3: Soft story frame with shear walls placed at the corners of the ground floor.
- Model-4: Soft story frame with steel cross bracing at the ground floor.
- Model-5: Soft story frame with steel inverted V-bracing at the ground floor.



(a)



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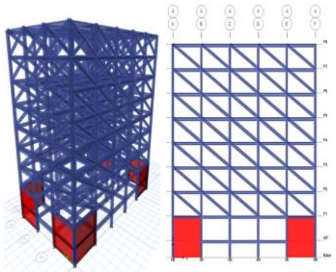

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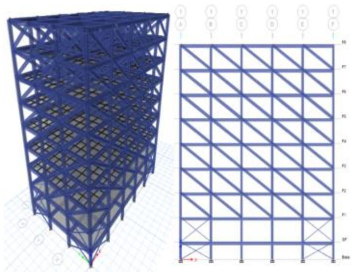

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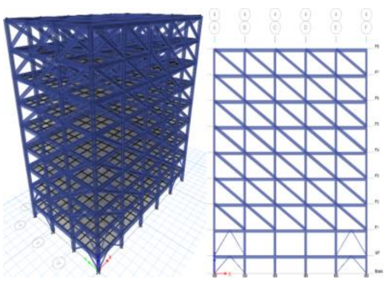

(e)

Fig. 1. 3D view of (a) Bare frame, (b) Soft story frame, (c) Soft story with provision of shear wall. (d) Soft story with provision of steel cross bracing, (e) Soft story with provision of steel Inverted-V bracing.

Table 1. Parameters of Reference for Building Models.

Parameters	Value
Structure	IMRF
Floors	G.F. + 7
Ground Storey Height (mm)	3000
Typical Storey Height (mm)	3000
Depth of Foundation (mm)	1800
Span Length (mm)	4500
Bay Length (mm)	4500
Site Class	SC
Seismic Zone Coefficient	0.20
Beam Exterior (mm*mm)	350 × 400
Beam Interior (mm*mm)	350 × 450
Column Exterior (mm*mm)	350 × 350
Column Interior (mm*mm)	400 × 400
Slab Thickness (mm)	112.5
Diagonal Strut (mm*mm)	388 × 125
Floor Finish (KN/m^2)	1.437
Partition Wall (KN/m^2)	1.915
Live Load (KN/m^2)	2.873
Concrete Compressive Strength (MPa)	28
Rebar Yield Strength (MPa)	415
Specific Compressive strength of infill (MPa)	4.2
Modulus of elasticity of infill material (MPa)	3150
Thickness of Shear Wall (mm)	300

Table 2. Load combinations considered according to BNBC 2020 for analysis.

Load Combinations	
1.4D	$1.277D + L + E_y + 0.3E_x$
1.2D + 1.6L	$0.9D + 1.6W_x$
$1.2D + 0.8W_x$	$0.9D + 1.6W_y$
$1.2D + 0.8W_y$	$0.977D + E_x + 0.3E_y$
$1.277D + L + E_x + 0.3E_y$	$0.977D + E_y + 0.3E_x$

The modelling of masonry infill wall in the building is done by equivalent diagonal strut method as given in FEMA-273 [11]. A schematic diagram of infill masonry walls and the equivalent diagonal compression action parameters is presented in Fig. 2. The thickness and material properties of diagonal strut are similar to that of infill wall. According to FEMA-273, the width of diagonal strut is given by equation (1) and (2).

$$a = 0.175\times(\lambda_H h)^{-0.4}\times d_m \quad (1)$$

$$\lambda_H = \sqrt[4]{\left[\frac{E_m t \sin 2\theta}{4E_c I_c h_m}\right]} \quad (2)$$

Where, λ_H is Relative infill to frame stiffness

And,

t = Masonry wall thickness.

E_c = Elastic modulus of the concrete.

I_c = Moment of inertia of the columns.

h_m = Height of the masonry panel.

E_m = Elastic modulus of the masonry infill.

θ = Angle of the diagonal strut with the beam.

d_m = Length of the diagonal strut.

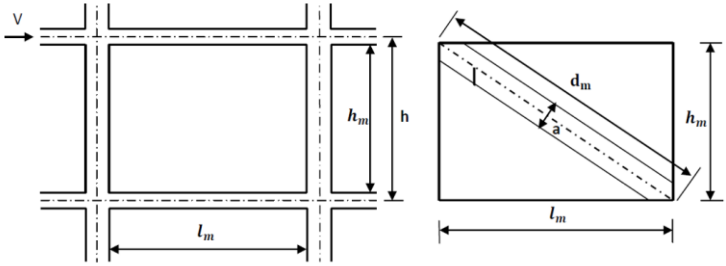

Fig. 2. Schematic diagram of infill masonry walls and the equivalent diagonal compression action parameters.

Using the equations, the λH was calculated to be 1.0042 × 10-3 and modified strut width a = 388 m. The compressive The compressive strength of masonry infill, f'_m is determined from equation (3) which is also used in an earlier study [16].

$$f'_m = \frac{f'_{cb}\left(f'_{tb}+\alpha f'_j\right)}{U_u\left(f'_{tb}+\alpha f'_{cb}\right)} \quad (3)$$

Where, f'_m = Compressive strength of masonry infill

f'_{cb} = Compression strength of brick = 6 MPa

f'_{tb} = Tension strength of brick = 2.8 MPa [18]

f'_f = Mortar compression strength =8 MPa [17]

U_u = Stress Non-Uniformity Coefficient =1.5

$\alpha = \frac{j}{4.1\, h_b}$

j = Mortar joint thickness = 15 mm

h_b = Height of masonry unit = 65 mm

After calculation, the compressive strength of masonry infill was found to be 4.2 MPa. In the present study, the analysis of infill frame is done by Equivalent Diagonal Strut Method. All the models are analyzed separately through Response Spectrum Analysis (RSA) and Pushover Analysis by using the software ETABS [15]. A pushover study often gives results in terms of response demand vs capacity. The structure is resilient if the intersection of the demand curve and the capacity envelope occurs within the elastic range. If the capacity curve meets the demand curve with little room to spare, it's safe to assume that the structure won't hold up well under the forced seismic excitation and will need to be strengthened before it can be used again [13]. The pushover analysis's weak zones will inform our decision between seismic retrofitting and rehabilitation. Some elements may fail in a sequential manner when subjected to loads that increase in increments. As a consequence of this, the structures go through a change in their stiffness at every occurrence, where IO, LS, and CP stand for immediate occupancy, life safety, and collapse prevention, respectively [14].

3 Results and Discussion

The analysis of the structural models resulted in the following outcomes. Fig. 3 demonstrates the maximum drift of the building frame at different storey levels in both directions. As evident from Fig. 4 that bare frame system shows the highest storey drift due to the absence of lateral load-resisting elements like shear walls or bracings. The significant drift at lower levels occurs because those levels must resist the lateral forces without reinforcement. When shear walls or bracings are added, they provide additional stiffness and improve the overall lateral load resistance. Research has shown that cross bracings, in particular, form a more rigid system compared to inverted V bracings because of the enhanced load transfer mechanism. Cross bracings resist forces in both compression and tension more efficiently [19].

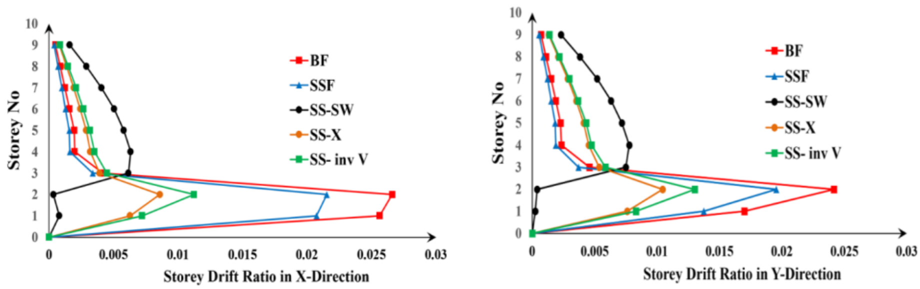

Fig. 3. Observed values of storey drift in longitudinal direction (left) and transverse direction (right).

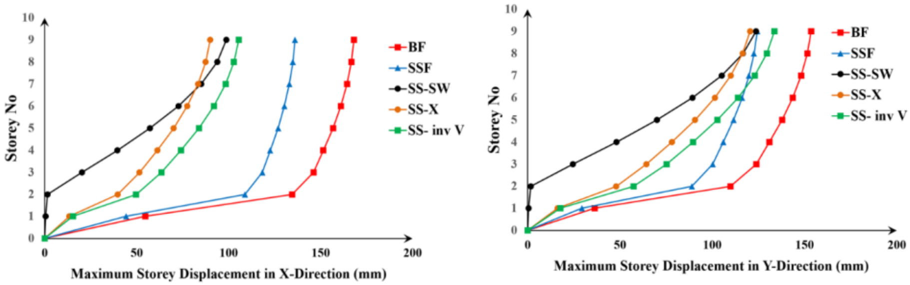

Fig. 4. Observed values of maximum storey displacement in longitudinal direction (left) and transverse direction (right).

Fig. 5 shows the storey drift ratio and Fig. 6 shows the storey displacement in both directions. It illustrates that as building height increases, lateral displacement tends to increase due to the taller structure being more flexible, especially under wind or seismic loads. Bare frames, without infill or shear walls, experience significant displacements because they rely solely on the columns and beams for lateral resistance. Shear walls act as vertical cantilevers, stiffening the structure and significantly reducing the displacement. Cross-steel bracings also contribute by adding stiffness and controlling the swaying of the building under lateral forces [20]. Table 3 presents the lateral forces at various floor levels in both the transverse and longitudinal directions. The soft storey effect occurs due to an abrupt reduction in stiffness at the ground level, often due to the absence of infill walls. In soft storey configurations, lateral forces concentrate at the ground level, leading to increased vulnerability during seismic events. The addition of a shear wall at the ground level mitigates this issue by distributing lateral loads more effectively, thus reducing the risk of collapse. Studies show that braced frames, especially with cross-bracings, distribute lateral loads more uniformly across the height of the building [21]. The provision of shear walls results in a 96% reduction in storey drift due to the increased rigidity they provide. Cross-bracings reduce the drift by 70% because they introduce lateral stiffness that helps to resist horizontal displacements. Inverted-V bracings also improve drift performance but are less effective than cross-bracings due to less uniform distribution of forces [22].

Table 3. Comparisons of Lateral Forces (KN) in Transverse Direction (Left) and Longitudinal Direction (Right).

Lateral Load in Transverse Direction	Lateral Load in Longitudinal Direction

Bare Frame	Soft Story Frame	Soft story with Shear Wall	Soft story with Steel Cross Bracing	Soft story with Steel In-verted v Bracing	Story No.	Bare Frame	Soft Story Frame	Soft story with Shear Wall	Soft story with Steel Cross Bracing	Soft story with Steel In-verted v Bracing	Story No.
(KN)	(KN)	(KN)	(KN)	(KN)		(KN)	(KN)	(KN)	(KN)	(KN)	
822	1090	1256	1145	1134	9	831	1102	1382	1243	1232	9
762	1058	1092	1076	1067	8	754	1034	1302	1104	1132	8
634	942	1023	1011	1005	7	588	972	1182	1092	1039	7
512	872	992	985	980	6	421	866	1043	1019	986	6
456	845	945	939	933	5	377	854	945	932	912	5
412	812	894	886	880	4	294	812	923	892	862	4
388	797	865	860	855	3	256	790	889	821	816	3
301	770	782	778	773	2	190	759	840	742	735	2
74	346	458	389	367	1	64	242	368	295	282	1

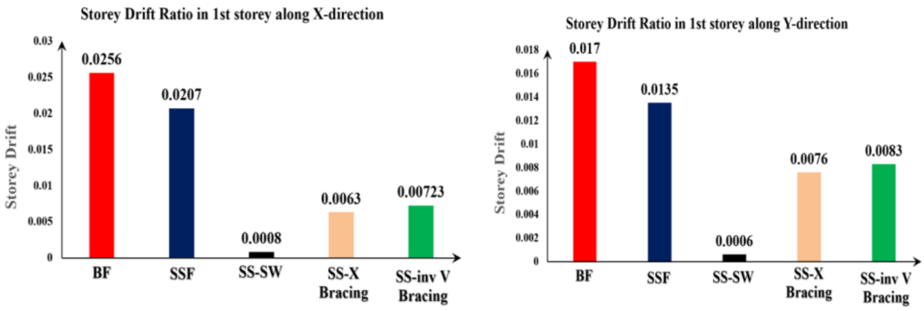

Fig. 5. Storey drift ratio at 1st storey in X-direction (Left), Y-Direction (Right).

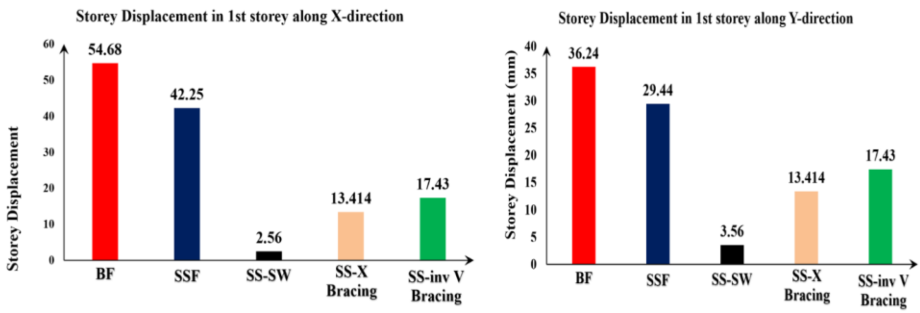

Fig. 6. Storey displacement at 1st storey in X-direction (Left), Y-Direction (Right).

It is apparent from Fig. 7 that provision of shear wall is the most effective technique for reducing the lateral displacement. Shear walls are highly efficient in reducing lateral displacement, achieving up to a 94% reduction as compared to an open ground storey. This efficiency is due to the large increase in lateral stiffness provided by the walls.

Cross-bracings, while less effective than shear walls, still provide significant reductions in displacement by creating a truss action within the frame [23]. It can be seen from the above figures that the extreme increase in stiffness with shear wall provision is due to the inherent structural form of the wall, which resists lateral loads very effectively by acting like a deep vertical cantilever. Bracings, particularly cross-bracings, also increase stiffness but to a lesser extent because their load paths are more flexible than the solid form of a shear wall. Inverted V bracings provide less stiffness than cross bracings because the load is concentrated at the apex of the V, reducing overall lateral stiffness [24].

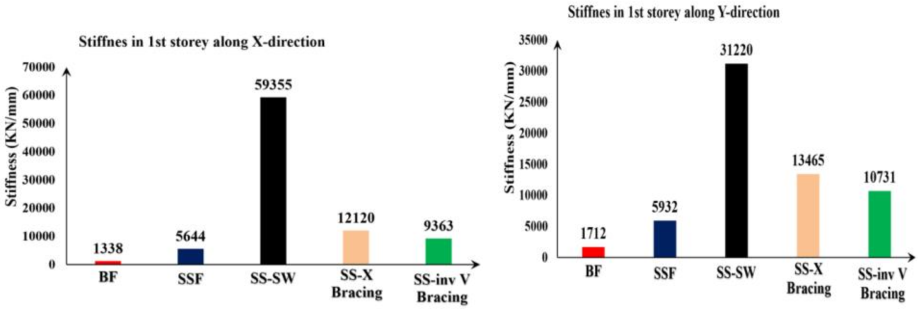

Fig. 7. Stiffness at 1st story in X-direction (Left), Y-Direction (Right).

4 Conclusion

This study investigates the impact of soft story designs in buildings and evaluates the effectiveness of different structural configurations—such as shear walls, diagonal steel bracing, and cross-steel bracing—in mitigating these effects. The key conclusions from the study are summarized below:

1. Shear walls are the most effective solution for mitigating the soft storey effect in reinforced concrete (RC) structures. With a reduction of storey drift by 96% compared to an open ground storey configuration, shear walls significantly improve the structural integrity of buildings, particularly in earthquake-prone regions. Their capacity to act as vertical cantilevers provides a high level of stiffness and reduces lateral displacements effectively.
2. Among the steel bracing configurations, cross bracings were found to be more efficient than Inverted-V bracings. Cross bracings achieved a 70% reduction in storey drift, compared to the 64% reduction achieved by Inverted-V bracings. This makes cross bracings the second-best option after shear walls, offering both stiffness and a more uniform load distribution under seismic forces.
3. The inclusion of shear walls led to a 94% reduction in lateral displacement, further emphasizing their superiority. Cross bracings also demonstrated significant displacement control, contributing to enhanced structural stability. In terms of stiffness, the shear walls increased first-floor stiffness by 10.6 times, whereas cross and Inverted-V bracings improved it by 2.7 and 1.8 times, respectively.

4. Based on the results, incorporating shear walls at the ground level of RC structures with open ground storeys is highly recommended to enhance seismic performance. Where shear walls are not feasible, cross bracings provide a viable alternative for improving stiffness and reducing lateral drift.

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