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Research Article

Moderating the soft storey impact in multi-storey buildings: A comparative seismic investigation

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ABSTRACT

A storey with lateral stiffness less than 70% of the storey above or less than 80% of the average stiffness of the three storeys above is considered a soft storey. Ground-floor open-air buildings are frequently used for parking, particularly in metropolitan settings with considerable space limits. Soft-story buildings with irregular stiffness tend to collapse more than conventional buildings. The study's main goal was to understand better the soft storey effect in multi-storey structures and how to mitigate it using strategies such as adding shear walls, bracings, viscous dampers, and stiffer columns. A G+14 storey building finite element model (FEM) has been established via ETABS software and performed Response Spectrum Analysis at three seismic zones-III, IV and V. To determine the best method for reducing the soft storey effect in buildings, an analysis is conducted taking into account many parameters, including storey shear, stiffness, storey drift, and storey displacement for the entire structure, as well as the responses at the soft storey level for different configurations. According to the findings, adding a shear wall to a soft-storey building increases storey shear while reducing maximum displacement and storey drift. The first floor of the structure (soft storey) exhibits the most significant reduction in displacement (79.29%) and storey drift (79.3%) when shear walls are incorporated at the corners. There is also a 33.11% increase in base shear at the first story level, and the structure's stiffness increases by 6.5 times compared to a soft storey building. Adding a shear wall reduces the soft storey building's maximum displacement and storey drift by 25.27% and 59.28%, respectively. The soft storey building's maximum storey shear rises by 33.38%. Regarding seismic performance, a soft-storey building with a shear wall performs better than other soft-storey mitigation techniques.

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1. INTRODUCTION

Parking is needed, particularly in cities with severe space restrictions. Under these circumstances, buildings' ground floors remain open without the addition of any infill walls to make room for parking. Buildings get stiffness irregularities as a result. The ground floor displacement moves significantly when subjected to seismic force, while the upper stories, which move as one unit, move far less. As seen in Figure 1, this produces a weak point and causes the building to fall entirely [1]. The research aims to study the soft storey effect in multi-storey structures and find ways to address it by using stiffer columns, shear walls, bracings, and viscous dampers, among other methods.

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Figure 1. Soft storey building failure during Gujarat Earthquake (2001) in India [1].

Seismic retrofitting has now become a critical problem. Retrofitting aims to improve the structure's strength, resistivity, and lifespan. Recent earthquakes in different regions have emphasized the urgency of repairing inadequate seismic structures. The review paper [2] summarized the solution to seismic strengthening. Seismic study of multi storey building with and without floating column carried out and its effects presented [3]. The wall piers were modeled using a multi-layer shell element based on the composite strength of materials, which was divided into one or more orthotropic reinforcement layers and several concrete layers with equivalent thickness according to the reinforcement situation and actual component size [4].

Shear walls withstand lateral forces like wind and seismic activity and thereby increase lateral stability and safety of the building, usually constructed from materials like reinforced concrete or steel. Shear walls enhance the stiffness of the structure and thereby decrease the displacement of the structure. The incorporation of shear wall at corners increased storey stiffness and reduced displacement, thereby effectively transforming the soft storey into a standard structure and enhancing overall structural stability [5]. Bracing systems, such as V, cross, and diagonal bracing, help to mitigate soft storey effects in multi-storey buildings, distribute seismic forces uniformly to the structure and enhance structural stability. The optimum location of bracings in a building is at the corners. Strengthening ground storey columns effectively addresses soft storey vulnerabilities by increasing stiffness and load-bearing capacity, reducing the risk of structural damage during seismic events. Viscous dampers, strategically placed within the soft storey, dissipate energy and minimize lateral movement, providing cost-effective retrofitting solutions that enhance resilience of building to seismic forces. Strengthening the columns in the ground storey of building is a highly effective strategy for addressing the soft storey issue in open ground storey structures [6-14]. Kannan (2023) evaluated the effects of a soft storey for frames with different column shapes in different earthquake zones and locations along the soft storey's axis, from the first to the top level. Analyses using X bracings and shear walls were conducted. According to findings, shear walls can be employed in seismic danger zones because they lessen lateral displacement and storey drift. For low seismic zones, steel bracing is advised [15]. The impact of a soft storey and its placement on the seismic behavior of a supporting building and non-structural components was investigated by Pesaralanka et al. [16] in 2023.

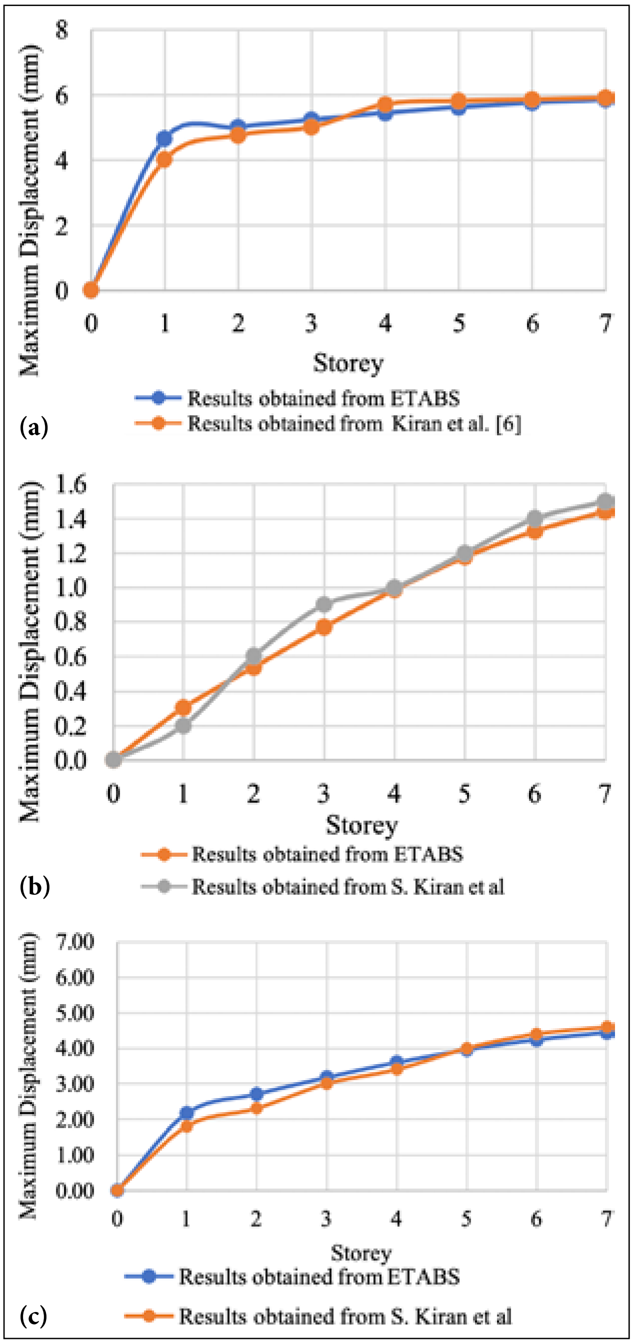

Figure 2. Comparison of displacement of **(a)** soft storey building, **(b)** soft storey building with shear wall and **(c)** soft storey building with bracings.

The models' bottom (ground), middle, and top storey levels retain the soft narrative's placement. According to the study, there is a significant vertical stiffness irregularity in the bottom soft storey, which suggests that the seismic performance of ground-level open-storied buildings has to be investigated [16]. To lessen the effect of soft storeys on the dynamic performance of the structure, Chanumolu and

Table 1. Model description

Description	Specification
No. of stories	G+14
Storey height	3.5 m
Type of soil	Medium (II)
Grade of steel	Fe415
Grade of concrete	M30
Modulus of elasticity of concrete	27386
Modulus of elasticity of steel	2 x 105 N/mm^2
Live load	3.5 kN/m^2
Floor finish	1 kN/m^2
Importance factor	1
Response reduction factor	3
Seismic zone	III, IV and V
Wind Speed	50 m/s
Terrain category	3
Column size	600 mm x 600 mm
Beam size	300 mm x 500 mm
Plinth beam size	400 mm x 600 mm
Thickness of Slab	150 mm
Thickness of brick wall	230 mm
Thickness of shear wall	230 mm
Steel section	ISMB 350
Thickness of stiffer column	600 mm x 800 mm
Viscous damper	FVD500

Anthugari (2020) arranged gap components at beam-column joints to act as a spring in either or both of the beam and column. When compared to the standard models, this aids in lowering storey displacements, inter-storey drift ratios, over-turning moments, and an increase in storey stiffness [17]. Comparative seismic response analysis of the two multi-storey reinforced concrete 3D frames under seismic loads, with and without base isolation, was carried out by Qambrani and Mirza (2023). The analysis findings demonstrate how well base isolators work in Balochistan's high-seismic-risk Zone 4 to lessen displacements, drifts, and shear in multistorey buildings. The building time period, stiffness, and energy dissipation were all successfully extended by LRB isolators [18].

The strategies above contribute to the mitigation of soft storey vulnerabilities in diverse ways, and it is necessary to determine the most effective technique for seismic retrofitting structures. This study aims to evaluate different soft storey mitigation strategies, such as stiffer columns, bracings, dampers, and shear walls, to identify the most efficient method for reducing the soft storey effect in multi-storey buildings. The study technique entails a detailed analysis utilizing ETABS software to model the behavior of structural components in connection with the soft storey effect in multi-storey structures.

2. MODELING AND ANALYSIS OF STRUCTURES

Modeling of a G+6-storey building with a symmetrical floor plan, as presented in [6], was done using ETABS software. Analyzes of a soft-storey bare-frame building with

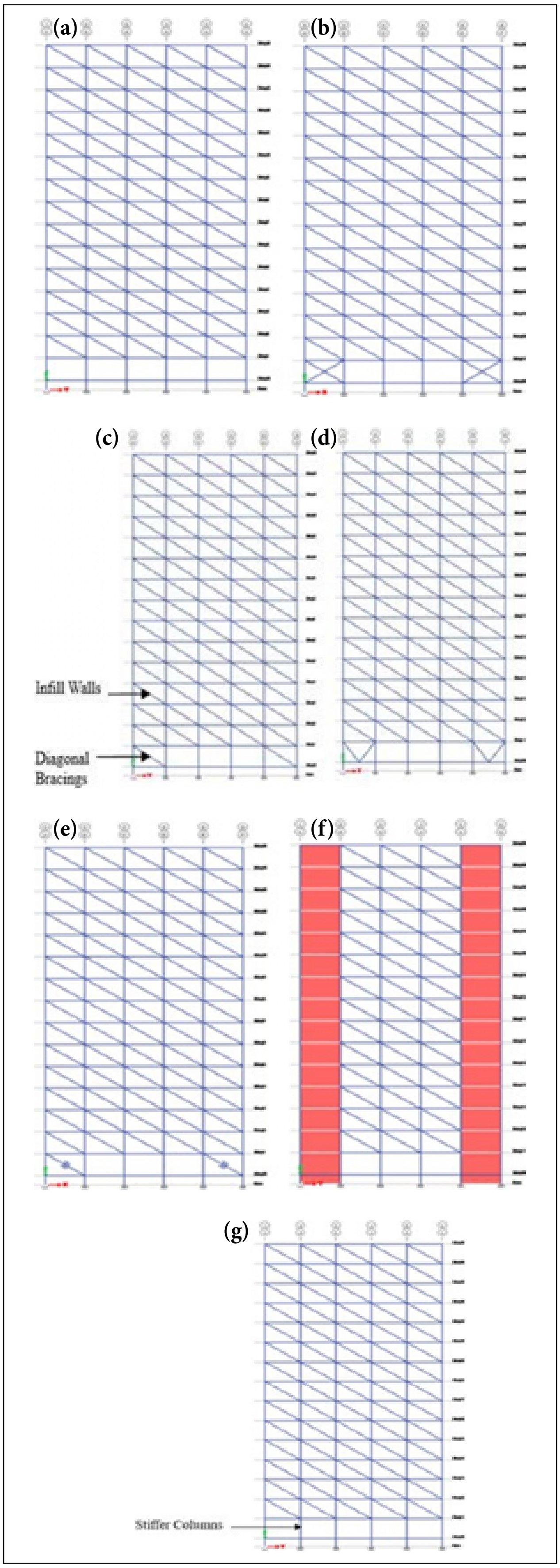

Figure 3. **(a)** Building with ground open storey, Soft storey building with **(b)** cross bracings, **(c)** diagonal bracings, **(d)** V bracings, **(e)** viscous damper, **(f)** shear wall, **(g)** stiffer columns.

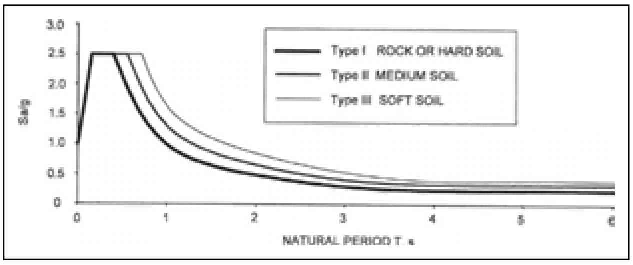

Figure 4. Spectra for response spectrum method [19].

cross bracings and a shear wall were performed, compared with the results in the literature, validating the analytical procedure. The comparison between results obtained from ETABS for the present study and the literature is shown in Figure 2.

The G+14-storey building is modeled as a bare-frame, soft-storey building using ETABS software with cross bracings, diagonal bracings, V-shaped bracings, viscous dampers, shear wall and stiffer columns using ETABS 18.0.2 standard. The beam modeling of infill walls is done using the corresponding method of diagonal bracings given in Part 1 of IS1893 2016.

The dimensions of buildings and parts are described in Table 1. Models of bare frame models, soft floor buildings with cross bracings, diagonal bracings, V- bracings, viscous dampers modeled with ETABS 18.0.2 software, shear wall, and stiffer columns are shown in Figure 3a–g.

A ground-floor open-storey building is modeled by keeping the ground floor unoccupied and adding infill walls to the higher floors, as seen in Figure 3a. According to IS1893 2016 Part 1, the masonry infill wall of the building is modeled using an equivalent diagonal strut approach.

$W_{ds}=0.175(\alpha_h)^{-0.4}L_{ds}$

where $\alpha_h=h\sqrt[4]{(E_m\, t\, sin(2\theta))/(4\, E_f I_c\, h)}$

h=Height of infill panes

Ef=Expected elastic modulus of frame material E_m= Expected elastic modulus of infill material,

E_m=550 x f_m

where f_m is the compressive strength of masonry prism (in MPa) obtained as per IS 1095 or given by expression:

fm=0.433x$f_b^{0.64}$x$f_{mo}^{0.36}$

where f_b is the compressive strength of brick in MPa and f_{mo} is the compressive strength of mortar in MPa

I_c=Moment of inertia of column

L_{ds}=Diagonal length of infill panel t=Thickness of infill panel and equivalent strut

θ=Angle whose tangent is the infill height-to-length aspect ratio

L=Length of infill wall

By substituting these values,

α^h=2.0038749 and W_{ds}=583 mm

Response Spectrum Analysis in ETABS software analyzes various models, such as bare frames, soft storey buildings with cross bracings, diagonal bracings, V bracings, viscous dampers, shear walls, and stiffer columns.

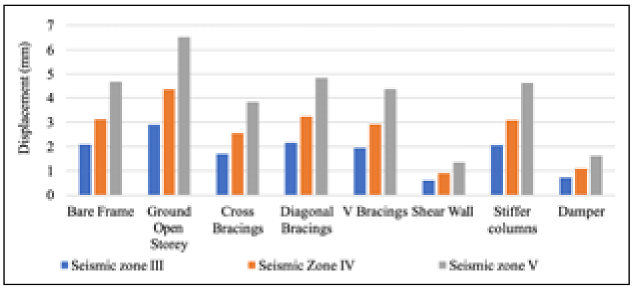

Figure 5. Comparison of displacement in first storey level for different models.

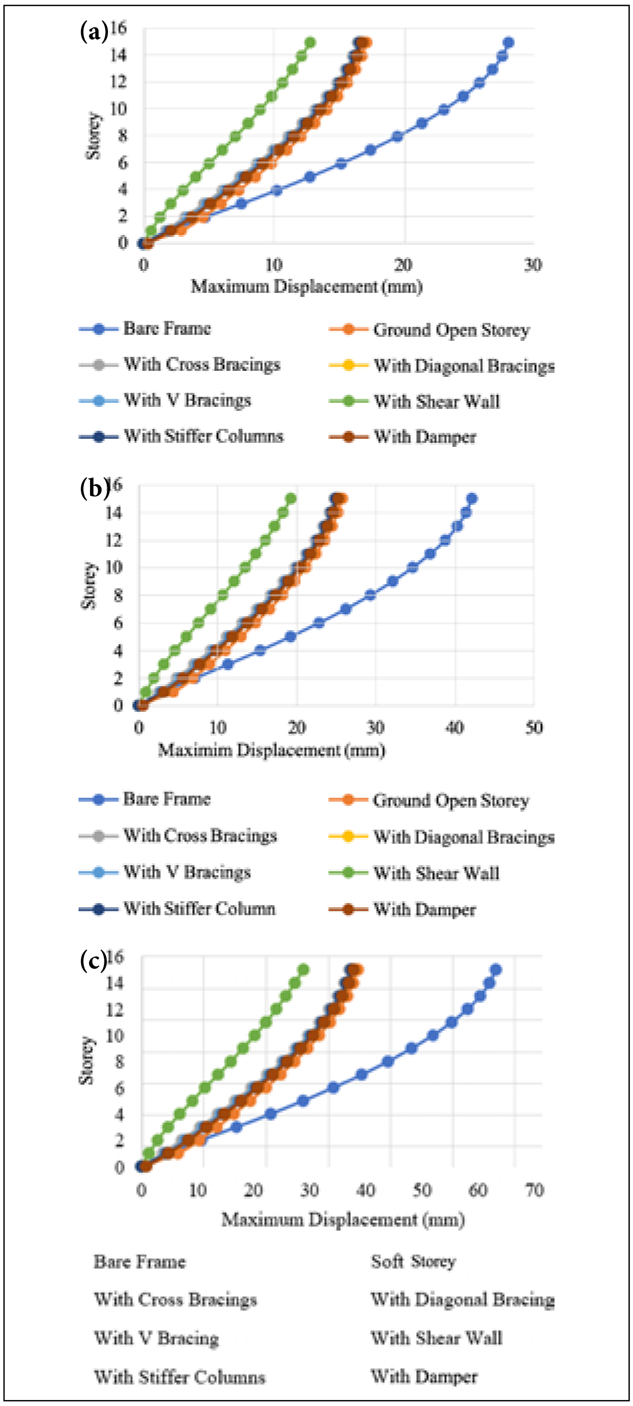

Figure 6. Comparison of different models in **(a)** seismic zoneIII, **(b)** seismic zoneIV and **(c)** seismic zone V.

Table 2. Comparison of displacement at first storey level obtained for different models

Models	Displacement at first storey level in zone III (mm)	Displacement at first storey level in zone IV (mm)	Displacement at first storey level in zone V (mm)	% reduction as compared to soft storey building
Soft storey building	2.901	4.352	6.528	–
Cross bracings	1.7	2.55	3.826	41.4
Diagonal bracings	2.153	3.229	4.843	25.8
V bracings	1.9	2.916	4.374	33.5
Shear wall	0.601	0.901	1.352	79.29
Stiffer columns	2.057	3.085	4.627	29.11
Viscous damper	0.72	1.08	1.62	75.18

Table 3. Comparison of maximum displacement obtained for different models

Models	Maximum displacement in zone III (mm)	Maximum displacement in zone IV (mm)	Maximum displacement in zone V (mm)	% reduction as compared to soft storey building
Soft storey building	17.173	25.759	38.639	–
Cross bracings	16.477	24.715	37.073	4.05
Diagonal bracings	16.838	25.257	37.886	1.95
V bracings	16.637	24.956	37.434	3.12
Shear wall	12.834	19.25	28.876	25.27
Stiffer columns	16.651	24.976	37.464	3.04
Viscous damper	16.838	25.257	37.886	1.95

Table 4. Comparison of storey drift at first storey level obtained for different models

Model	Storey drift at first storey level in seismic zone III (mm)	Storey drift at first storey level in seismic zone IV (mm)	Storey drift at first storey level in seismic zone V (mm)	% reduction as compared to soft storey building
Soft storey building	0.000727	0.000109	0.0001636	–
Cross bracings	0.000415	0.000623	0.000935	42.99
Diagonal bracings	0.000528	0.000792	0.001188	27.52
V bracings	0.000476	0.000714	0.001072	34.64
Shear wall	0.000151	0.000226	0.000339	79.30
Stiffer columns	0.000514	0.000771	0.001156	29.46
Viscous damper	0.000151	0.000227	0.00034	79.25

The spectra for the response spectrum method are shown in Figure 4. The system's maximum acceleration, velocity, and displacement values in response to time-dependent dynamic excitation are displayed graphically in the response spectrum. Maximum displacement, storey drift, storey shear, and stiffness are the basis for the analysis. The response of the entire structure and the reaction on the first floor are considered. While storey drift is the relative horizontal displacement between two neighboring floors or storeys during an earthquake, maximum displacement is the most prominent horizontal movement a specific storey within the structure experiences. In a structure, storey shear is the lateral force that external sources, such as lateral loads, act on a particular level or storey. The resistance to deformation under external loads is measured by stiffness.

3. RESULTS AND DISCUSSIONS

Comparisons are made between the displacement, storey drift, stiffness, and storey shear results for several models in seismic zones III, IV, and V.

3.1. Storey Displacement

Figure 5 compares the displacement at the first storey level for various models. Figures 6a–c show the results for the maximum displacement in the different models for seismic zones III, IV, and V, respectively. Tables 2 and 3 compare displacement at the soft storey level and the maximum displacement of various models, respectively, about the soft storey building.

It is noted that, as illustrated in Figure 5, the soft storey building with shear wall experiences the least displacement at, while the bare soft storey building experiences the high-

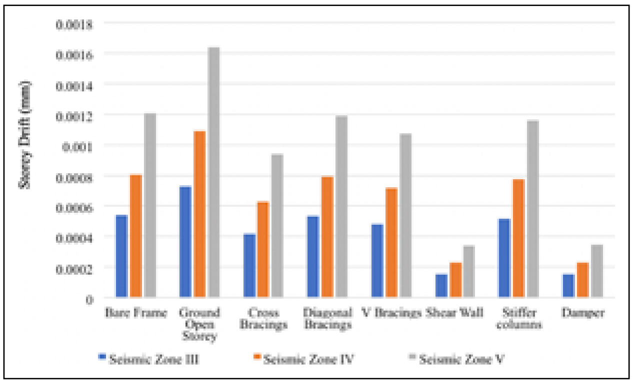

Figure 7. Comparison of storey drift in first storey level for different models.

est displacement. When a soft storey structure incorporates a shear wall, viscous damper, cross bracings, V bracings, stiffer columns, and diagonal bracing, the first storey displacement appears to reduce by 79.29%, 75.18%, 41.4%, 33.5%, 29.11%, and 25.8%, respectively, as shown in Table 2. The maximum displacement of the soft storey building decreases when shear walls, cross bracings, V bracings, stiffer columns, diagonal bracings, viscous dampers, and stiffer columns are incorporated, by amounts of 25.27%, 4.05%, 3.12%, 3.04%, 1.95%, and 1.95%, respectively, as shown in Table 3. It is also clear from Figure 6 that, as one moves into greater seismic zones, lateral displacement increases because of the stronger seismic action. Shear walls, bracings, and stiffer columns all contribute to increased stiffness, which lessens lateral sway and displacement. The addition of a damper causes energy to be absorbed and dispersed, which lowers lateral movement.

3.2. Storey Drift

Figure 7 compares the storey drift at the first storey level for several models. Figure 8a–c show the maximum storey drift for various models for seismic zones III, IV, and V, respectively. Tables 4 and 5 present a comparison of storey drift at the soft storey level and the maximum displacement of various models, respectively, in relation to the soft storey building.

The first floor storey drift is reduced by 79.3%, 79.25%, 42.99%, 34.64%, 29.46%, and 27.52 when shear wall, viscous damper, cross bracings, V-braces, stiffer columns and diagonals bracings respectively as shown in Figure 7 (Table 4). Figure 8–c it is evident that the maximum storey drift of the soft floor building is reduced by 59.28%, 40.85%, 40.3%, 34.52%, 29.29% and 27.37% when the shear wall, cross bracings, viscous dampers and V bracings, stiffer columns and diagonal braces are added, as shown in Table 5. Reduction of storey drift through soft storey mitigation measures due to reduced lateral movement.

3.3. Storey Shear

Variation of storey shear for different models in first storey level is shown in Figure 9. Storey shear for different models for seismic zone III, IV and V are illustrated in Figure 10a–c respectively. Tables 6 and 7 present a comparison

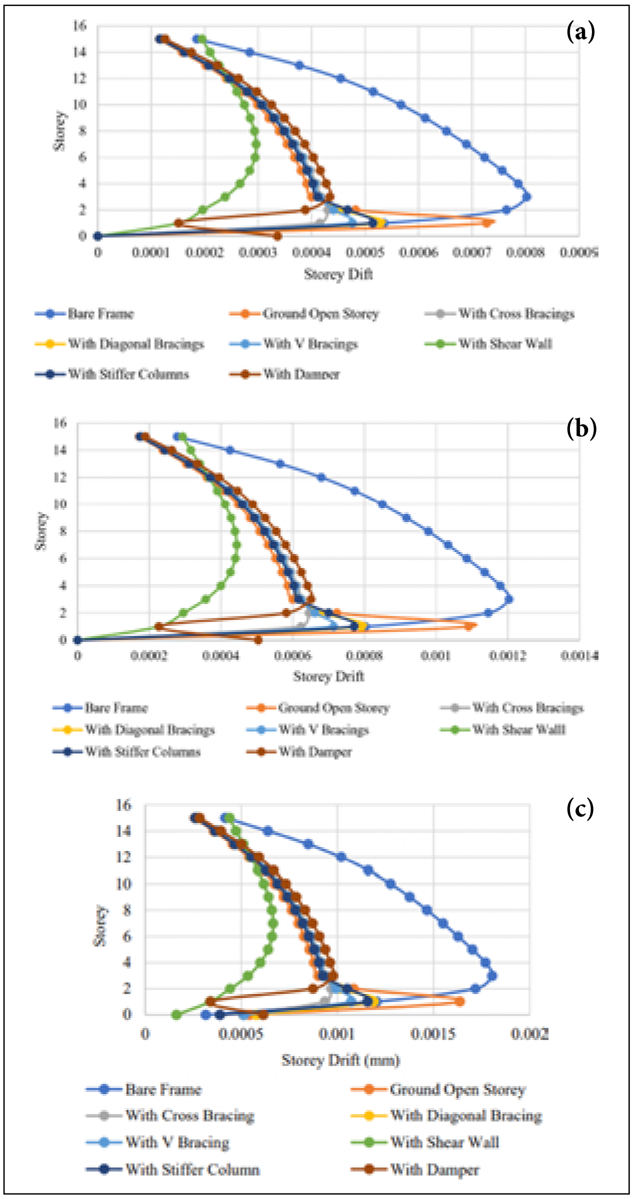

Figure 8. Comparison of storey drift for different models in **(a)** seismic zone III, **(b)** seismic zone IV and **(c)** seismic zone V.

of storey shear at the soft storey level and the maximum displacement of various models, respectively, in relation to the soft storey building.

Storey shear is highest for soft storey given with shear wall. Figure 9 demonstrates that base shear (or storey shear in first floor level) increments by 33.11%, 2.92%, 2.58%, 2.39% and 2.05%by the incorporation of shear wall, cross bracings, stiffer columns,V bracings and diagonal bracings separately as shown in Table 6. It is additionally apparent that base shear diminishes by 89.7% with the consolidation of viscos damper due to the adaptability afforded by damper which makes the building less stiffer. From Figure 10 a-c, it is appeared that maximum storey shear of the soft storey building increases by 33.38%, 2.92%,2.76%,2.4%, 2.08% and 2.07% with the addition of shear wall, cross bracings, stiffer columns, V bracings, viscos damper and diagonal bracings,

Table 5. Comparison of maximum soft drift obtained for different models

Models	Maximum storey drift in zone III (mm)	Maximum storey drift in zone IV (mm)	Maximum storey drift in zone V (mm)	% reduction as compared to soft storey building
Soft storey building	0.000727	0.00109	0.001636	–
Cross bracings	0.00043	0.00065	0.000968	40.83
Diagonal bracings	0.000528	0.00079	0.001188	27.38
V bracings	0.000476	0.00071	0.001072	34.47
Shear wall	0.000296	0.00044	0.000666	59.29
Stiffer columns	0.000514	0.00077	0.001156	29.34
Viscous damper	0.000434	0.00065	0.000977	40.28

Table 6. Comparison of base shear obtained for different models

Model	Base shear in seismic zone III (kN)	Base shear in seismic zone IV (kN)	Base shear in seismic zone V (kN)	% increase as compared to soft storey building	% decrease as compared to soft storey building
Soft storey building	2473.90	3710.84	5566.27	–	–
Cross bracings	2546.15	3819.225	5728.837	2.92	–
Diagonal bracings	2525.056	3787.584	5681.375	2.05	–
V bracings	2533.353	3800.03	5700.045	2.39	–
Shear wall	3299.58	4949.37	7424.06	33.11	–
Stiffer columns	2542.161	3813.242	5728.837	2.58	–
Viscous damper	254.76	382.14	573.22	–	88.90

Table 7. Comparison of maximum storey shear obtained for different models

Models	Maximum storey shear in zone III (mm)	Maximum storey shear in zone IV (mm)	Maximum storey shear in zone V (mm)	% reduction as compared to soft storey building
Soft storey building	2473.896	3710.844	5566.265	–
Cross bracings	2546.15	3819.225	5728.837	2.92
Diagonal bracings	2525.056	3787.584	5681.375	2.07
V bracings	2533.353	3800.03	5700.045	2.40
Shear wall	3299.581	4949.371	7424.056	33.38
Stiffer columns	2542.161	3813.242	5719.863	2.76
Viscous damper	2525.374	3788.06	5682.09	2.08

as depicted in Table 7. This trend is due to enhancement of stiffness which improves the effective distribution of lateral force within the structure and hence storey shear at each level increases.

3.4. Storey Stiffness

Variation of stiffness for different models in first storey level in shown in Figure 11. Stiffness for different models for seismic zone III, IV and V are illustrated in Figure 12–c respectively. Table 8 present a comparison of stiffness at the soft storey level of various models, respectively, in relation to the soft storey building.

Since stiffness is not zone-specific, the stiffness of the models is constant throughout the three zones. It is evident from Figure 11 that adding a shear wall, cross bracings, V bracings, stiffer columns, and diagonal bracings increases stiffness at the first storey level by 549.12% (6.5 times), 84.27%, 58.057%, 46.09%, and 45.06%, respectively, as shown in Table 8. This is because these structural components were able to distribute the load effectively. Because

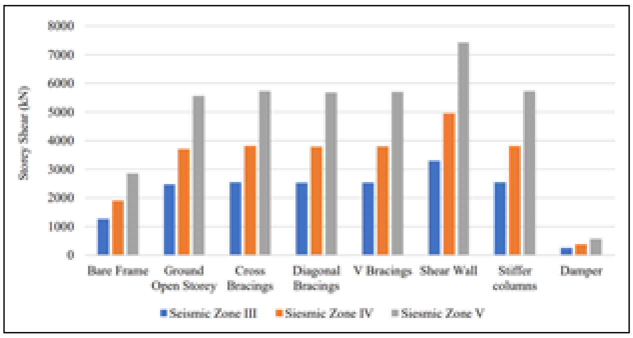

Figure 9. Comparison of storey shear in first storey level for different models.

Table 8. Comparison of stiffness obtained for different models

	Stiffness (kN/m)	% increase as compared to soft storey building	% decrease as compared to soft storey building
Soft storey building	997001.33	–	–
Cross bracings	1837228.70	84.27	–
Diagonal bracings	1446308.96	45.06	–
V bracings	1575837.85	58.057	–
Shear wall	6471766.13	549.12	–
Stiffer columns	1456597.07	46.09	–
Viscous damper	726023.72	–	27.18

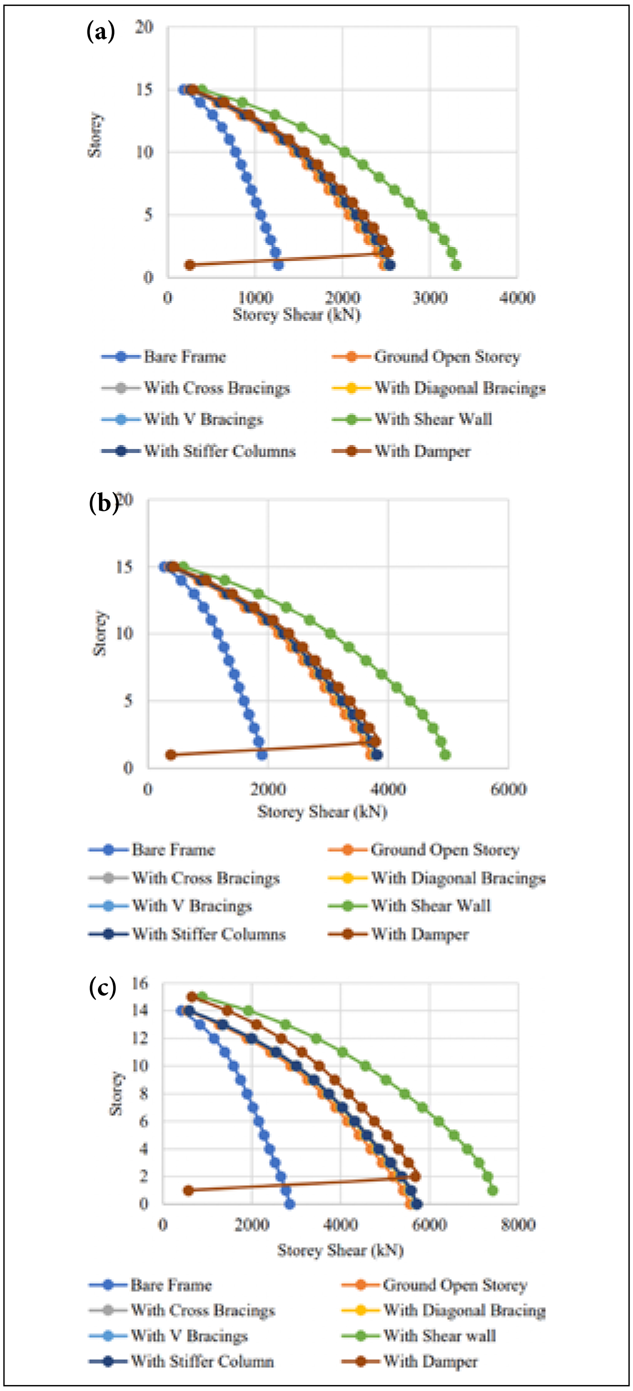

Figure 10. Comparison of storey shear for different models in **(a)** seismic zone III, **(b)** seismic zoneIV and **(c)** seismic zone V.

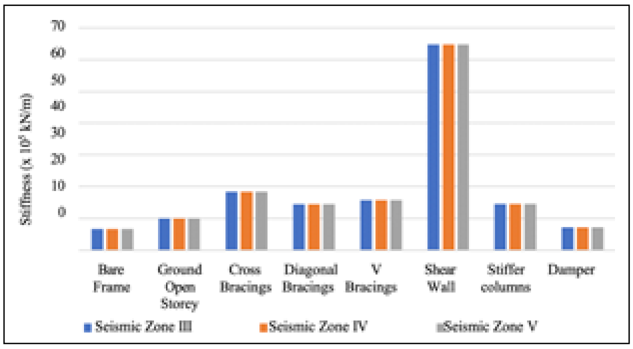

Figure 11. Comparison of stiffness in first storey level for different models.

of the flexibility that the viscous damper adds to the level, the structure's stiffness at the first storey level decreases by a factor of 27.19% when incorporated. Three seismic zones' worth of variations in stiffness for various models are depicted in Figures 12a–c. The percentage increase in the overall stiffness of soft storey buildings resulting from including viscous damper, cross bracings, stiffer columns, and the shear wall is 16.05%, 7.56%, and 1.18%. Including V and diagonal bracings reduces stiffness by 0.14% and 0.05%, respectively.

4. CONCLUSIONS

Because of their irregular stiffness, soft-storey buildings are more likely to collapse after an earthquake. Therefore, buildings must minimize the impact of their soft stories. Comparative seismic analysis is researched to lessen the soft storey impact on structures. Shear walls, cross bracings, diagonal bracings, V bracings, stiffer columns, and viscous dampers approaches are used in the present study to know their effect. The following are the study's main conclusions:

- The addition of different soft storey mitigation techniques improved the seismic performance of the soft storey building.
- The structure's first floor exhibits the most significant reduction in displacement (79.29%) and storey drift (79.3%) when shear walls are incorporated at the corners. There is also a 33.11% increase in base shear, and the structure's stiffness increases by 6.5 times compared to a soft storey building.

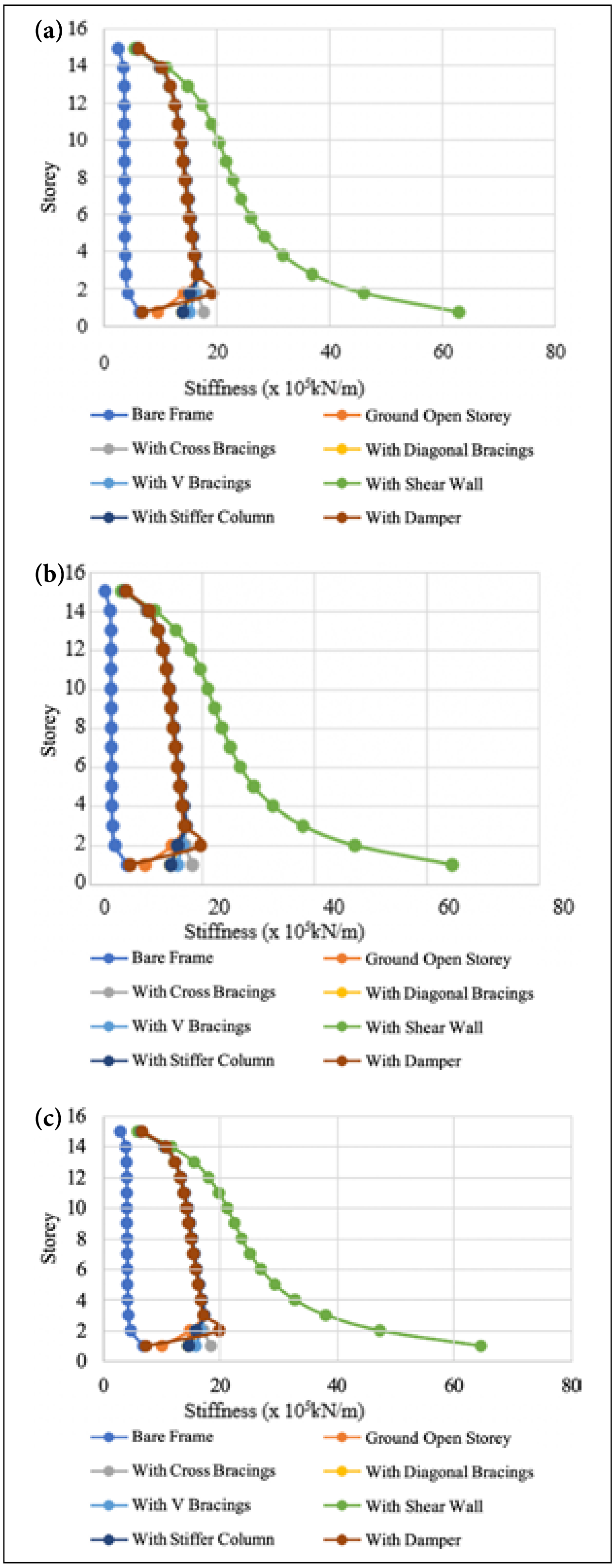

Figure 12. Comparison of stiffness for different models in **(a)** seismic zone III, **(b)** seismic zone IV, and **(c)** seismic zone Vb.

- Adding a shear wall reduces the soft storey building's maximum displacement and storey drift by 25.27% and 59.28%, respectively. The soft storey building's maximum storey shear rises by 33.38%.
- Compared to other soft storey mitigation techniques, the seismic performance of soft-storey buildings with shear walls positioned at corners is superior.

Future research can assess how well these configurations work together to reduce the soft storey effect in buildings. The most cost-effective way to mitigate the soft storey effect in buildings can also be determined by performing a cost analysis of structures integrated with various strategies.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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USE OF AI FOR WRITING ASSISTANCE

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PEER-REVIEW

Externally peer-reviewed.

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