iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** V **Month of publication:** May 2026

DOI: https://doi.org/10.22214/ijraset.2026.82911

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue V May 2026- Available at www.ijraset.com

Evaluation of Horizontal and Vertical RC Jacketing Strategies for Seismic Retrofitting of Mid-Rise Frame Building

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Abstract: A considerable number of mid-rise reinforced concrete (RC) frame structures constructed prior to the adoption of modern seismic codes have critical deficiencies in ductility detailing, lateral load resistance and capacity design principles making them vulnerable structures under seismic based design ground motions. RC column jacketing is a widely adopted structural rehabilitation technique to increase the axial strength, flexural capacity, shear resistance and ductility of members by providing composite concrete casing around the existing columns. However, the effect of jacketing configuration, especially the vertical extent and the distribution of intervention across the horizontal direction on global structural performance is still not well quantified at the system level. This study presents a comparative analytical evaluation of six different RC jacketing configurations which are applied to a commercial RC moment resisting frame modelled and analyzed using Response Spectrum Analysis. Performance is evaluated in terms of PMM interaction-based demand capacity (D/C) ratio and storey response plot. Results show that the best and most consistent performance among all strategies is found in dual-floor horizontal zone strategy in terms of D/C ranging from 0.415-0.796, 46.2% reduction in first floor drift, 6.5% improvement in displacement. Vertical continuous jacketing created the largest deficiencies in D/C (1.171-1.419), indicating that vertical distribution strategies are not effective substitutes for horizontal zone-based intervention. The remaining configurations showed moderate improvement but retain residual weak points. Nonlinear time history analysis and hybrid retrofitting systems in addition to damping and bracing should be tested for future work.
Keywords: Seismic retrofitting ·RC jacketing ·Demand capacity ratio ·PMM interaction ·Storey drift ·Response spectrum analysis ·ETABS

I. INTRODUCTION

The effects of the recent earthquake on the global buildings have highlighted the urgent need forseismic testing and reinforcement of olderbuildings, especially those that were constructed before the introduction of the contemporary seismic codes. In India, the seismic hazard has a vulnerability percentage of approximate 59% stated by Zones III, IV and V with the areas of these risks accommodating the greater part of the population of more than 250 million. Several reinforced concrete (RC) buildings erected between 1960 and 2000 have severe weaknesses in their latent load endurance, ductility detailing, as well as capacity design principles which make them especially vulnerable to the earthquake induced damages(Paulay & Priestley, 1992). (Thermou et al. 2006) defined that it is the hierarchical redistribution of inelastic demand throughout the system and not the individual strength of the member that controls global seismic performance of RC buildings. As the major failure modes in non-conforming RC structures. (Christidis et al. 2016) outlined the insufficiencies of joint shear capacity, smooth bar splice failure, and the lack of hierarchy of capacity design between beams and columns. Moreover, structures built in line with the needs of modern seismic built in accordance with modern seismic codes have performed adequately in protecting human lives during design level earthquakes in recent observations of the post-earthquake(Kam et al., 2010) (Westenenk et al., 2013). Jacketing with reinforced concrete has stood out as one of the most used strengthening methods since it has been proven to be very efficient and follows simple construction with the already existing RC structures. The method entails the process of placing a reinforced concrete casing on existing columns as well as beams, and results in increase in the axial load capacity, flexural strength, shear behavior, and ductility. (Rodriguez et al. 1994) documented 40-80% improvements in ductility and lateral capacity of jacketing columns respectively and tie continuity the continuity of reinforcement was found to be the controlling post-peak detailing parameter.

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Developed a simplified analytical Campione (2013) created a simplified analytical model of RC-jacketed columns which reproduced experimental load-deformation envelopes, and which presented a convenient section-level capacity assessment instrument.

The seismic behavior of retrofitted buildings is associated critically with numerous interdependent aspects such as the distribution of increased strength elements, the vertical intervention scope, and the resultant stiffness anomalies(Rodriguez et al., 1991). (Di Sarno et al. 2012) in their full-scale tests showed that concentrating strengthening at lower storeys, without upper-storey modification, introduces stiffness discontinuity, which causes the seismic demand to shift to the first unstrengthen storey. (Thermou et al. 2006) demonstrated that retrofits with stiffening properties on the structures with extended periods on the descending spectral branch may increase the demand on seismic forces up to the extent that the jacketing capacity gains. (Priestley et al. 2007)demonstrated that the stiffness increase due to jacketing-induced stiffness causes the decrease in the yield displacement and ductility demand, though selective jacketing produces an increase in the stiffness non-uniformity, the ability of which to exert stress on un-jacketed members. Therefore, a detailed finite element–based evaluation using response spectrum analysis is essential to quantify improvements in drift control, base shear capacity, stiffness redistribution, and demand capacity ratios in retrofitted RC frame systems. Previous studies had determined the usefulness of RC jacketing in the restoration of monolithic behaviour, with proper preparation of the interface and anchorage description being undertaken(Júlio et al., 2003) (Karayannis et al., 2008). Further analytical modelling of composite flexural response showed interface slip, dowel action and shear friction that control the overall performance of jacketed seismic demand members. Bett et al. (1988) showed increased proportionality between RC jacketing and section expansion with increase in moment capacity and axial capacity, and critical bar layout geometrically symmetrical to biaxial operation. More recent literature has concerned itself with performance based retrofit solutions to regulate the inter storey drift distribution by altering stiffness along the building height(Thermou et al.,2010). (Fardis et al. 2009) determined that transition between adjacent storeys of stiffness changes is contrary to the fundamental idea of the performance-based retrofit design which demands redistribution of demand by inelasticity across the building height. It has been proven that conventional and thin RC jackets are highly effective in increasing cyclic strength, energy dissipation, ductility and that cautious detailing agrees to reduce premature debonding and hardening loss(Labdaoui et al., 2025) (Patel & Sinha, 2025). The introduction of high-performance fiber-reinforced material in recent developments has shown a significant increase in the confinement efficiency along with strengthening of the axial load at minimized jacket thickness(Labdaoui et al., 2025). (Ilki et al. 2008) demonstrated that a 15-25% increase benefit of transverse reinforcement enhancement, 0.5 to 2.0 percent, is a near-linear response to confined concrete strength with confinement effectiveness being portable between a system of FRP and RC jackets. In this study a performance based analytical methodology of the seismic retrofitting of a mid-rise reinforced concrete moment resisting frame is developed using strategically located RC column jacketing. The focus is on interaction of stiffness modification, redistribution of forces and global dynamic behavior which is analyzed with the help of response spectrum analysis. The modelling uses stiffness of the cracked sections, rigid diaphragm action, P-delta effect and PMM interaction-based capacity check as a method to model the realistic behavior. Through the study of other vertical and horizontal intervention schemes in a uniform numerical setting, the research determines a configuration-sensitive approach to the rational retrofit design of gravity designed RC buildings in moderate seismicity.

II. RESEARCH SIGNIFICANCE

Extensive experimental and analytical investigations have established reinforced concrete (RC) jacketing techniques to be an effective means of improving the axial strength of deficient columns, flexural capacity, stiffness and ductility (Júlio et al., 2003). Prior studies have been mainly concerned with interface mechanics, confinement efficiency, materials optimization and the sectional response under monotonic and cyclic loading (Thermou et al.,2010). Although substantial improvements in load-carrying capacity and deformation control have been reported, most available studies focus on strengthening at the member level and less consideration is given to the role of intervention configuration in global structural dynamics. Recent research has emphasized the significance of stiffness distribution and demand redistribution in controlling inter-storey drift concentration and soft storey mechanism (Vandoros & Dritsos, 2008). However, configuration strategies involving selectively distributed jacketing in multistorey frames remain insufficiently quantified. Accordingly, this study contributes to the current state of the art by extending from the material and section-based assessment research to the system level assessment research, in which the stiffness transition and strengthening layout are considered governingparameters in performance-based seismic retrofitting of gravity designed RC buildings.

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III. RELATED PAPERS

On established numeric and experimental research, RC jacketing leads to high improvements of the seismic behavior of insufficient RC frame structures in terms of lateral stiffness, strength as well as ductilityas shown in Table 1.

Table 1 RC Column Jacketing Studies Summary

Authors	RC Jacketing Specifications						Axial Comp. Ratio (n)	Max. Drift (%)			Max. Displacement (mm)			Initial Stiffness (kN/mm)			Base Shear (kN)		
	Original Dim.	Jacketed Dim.	Jacket Thick.	Conc. Grade	Long. Reinf.	Trans. Reinf.		Before	After	Δ%	Before	After	Δ%	Before	After	Δ%	Before	After	Δ%
Ghosh & Chakraborty 2024	300×300 mm (G+6)	400×400 mm	50 mm	M25	8Ø16 mm	Ø8@100 mm	0.25	3.20%	2.10 %	-34.4% ↓	85 mm	68 mm	-20.0 % ↓	8.2	9.7	+18.3% ↑	1850	2257	+22.0% ↑
Nazri, Muda, Redzuan & Nordin 2021	230×230 mm (OGS)	330×330 mm	50 mm	M25 (S1 jacket)	8Ø12 mm	Ø8@100 mm	0.2	4.50%	2.80 %	-37.8% ↓	90 mm	56 mm	-37.8 % ↓	5.5	7.2	+30.9% ↑	1120	1456	+30.0% ↑
O. Khan et al. 2023	250×250 mm	350×350 mm	50 mm	C25	8Ø14 mm	Ø8@100 mm	0.2	6%	3.50 %	-41.7% ↓	54 mm	31.5 mm	-41.7 % ↓	4	5.8	+45.0% ↑	580	1334	+130.0% ↑
Zafar, Iqbal & Aslam 2025	300×300 mm	450×450 mm	75 mm	f'c=25 MPa	10Ø16 mm	Ø10@100 mm	0.3	3.50%	1.80 %	-48.6% ↓	105 mm	62 mm	-41.0 % ↓	9.5	14.2	+49.5% ↑	2100	2835	+35.0% ↑
Fernandez-Ruiz, Milosevic & Lavan 2018	300×300 mm (G+5 frame)	450×450 mm	75 mm	C30 (jacket)	10Ø16 mm	Ø10@100 mm	0.25	3.80%	2.20 %	-42.1% ↓	95 mm	55 mm	-42.1 % ↓	7.5	11.8	+57.3% ↑	1650	2310	+40.0% ↑

The method is effective and provides a reduced inter-storey drift and roof mass as well as enhancing the base shear capacity due to the enhanced load redistribution. It is especially advantageous to soft storey and open ground storey types of buildings and is making RC jacketing a valid and common way of seismic reinforcing an existing midrise building. Building based numerical and experimental research indicate convincing evidence in support of the effectiveness of RC concrete jacketing in the improvements in the global seismic performance of underperforming frame structures. tested a G+6 reinforced concrete frame resting on a slope and retrofitted with 50 mm RC column jackets (M25, 8Ø16 mm longitudinal reinforcement) and found that the roof of each frame was displaced by one fifth (−20.0% reduction) and the base was able to increase base shear by approximately 22% confirming that jacketing was an effective way of redistributing lateral demand in geometrical buildings that were retrofitted vaguely irregular (Dey & Chakraborty, 2024). Equally, (M. S. Khan, 2021) showed that RC jacketing of open ground storey columns as opposed to 4.5% inter storey drift reduced the drift by 2.8% (−37.8%) and enhanced an augmentation in the base lateral shear by 30%, critical jacketing columns of open ground storeys can be in averting the processes of soft storey collapses. reports drift demand drop of 6.0 to 3.5% (41.7%). In the same study,(O. Khan et al., 2025) a strengthening of base shear resistance by 130 % was observed after RC jacketing that demonstrated the beneficial nature of both enhanced ductility and strength. Incremental dynamic study of a RC building by consolidating the roof displacement decreasing by 105 mm to 62 mm (41.0%) and an increase in the lateral stiffness by 9.5 to 14.2 kN/mm (49.5%).(Criado Fernández et al., 2026)

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The system level with a G+5 frame, in which jacketing decreased drift demand by a factor of 3.8 to 2.2 (42.1%) % and increased base shear by a factor of 1650 kN to 2310 kN (+40.0%) in support of RC jacketing as a practical and cost efficient seismic retrofit approach at a structural level.

IV. METHODOLOGY

The study employs a comparative analytical analysis of various reinforced concrete column jacketing configuration shown inFig. 1 that are implemented on a mid-rise RC moment resisting frame building. The ETABS software was used to model a six-storey building representing a typical gravity designed RC structure. Response Spectrum Analysis was performed in accordance with IS 1893: 2016.Six retrofitting configurations were consideredto consist of varying vertical extents, column choices and jacket appearances to determine the impact of these designs on global structural behavior. Performance measures such as demand-capacity (D/C) ratio by PMM interaction, storey movement, inter-storey drift, base shear, and the distribution stiffness were compared systematically to measure the effectiveness of each of the retrofitting strategies.

The study takes a computational seismic analysis framework to determine the practicality of the reinforced concrete (RC) column jacketing methods on a midrise building frame structure. In ETABS, a three-dimensional numerical model of the current building created with realistic material properties, cross-section dimensions and gravity loading conditions. Seismic analysis is done using linear dynamic Response Spectrum Analysis as per the requirements of IS 1893: 2016. Several retrofitting designs were developed through varying the column size and reinforcement to see RC jacketing simulation.

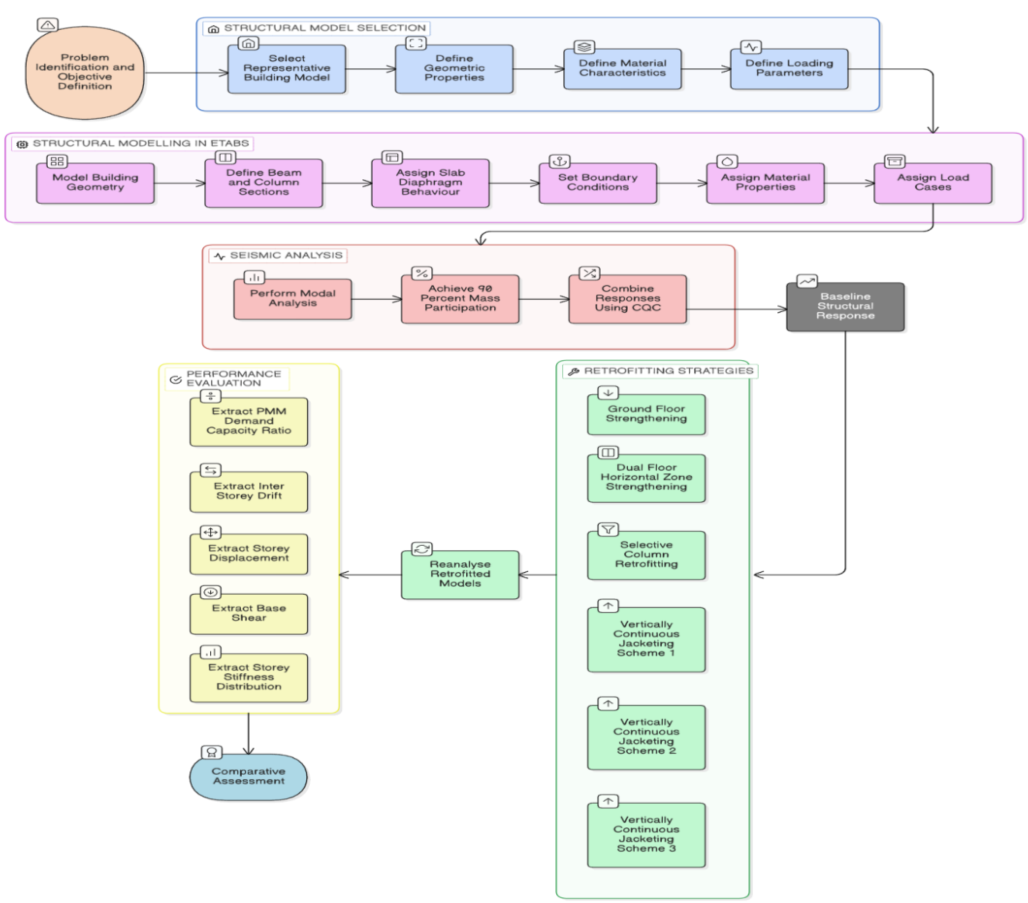

Figure 1Methodological Flowchart for Seismic Analysis and Retrofitting of RC Building

Building Description and Modelling

A six-storey reinforced concrete framed building representative of typical older construction modelled in ETABS. The structure, designed as a commercial facility (exhibition hall/gallery/showroom)as shown in Table 2.

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Table 2 Building discription

Category	Parameter	Value
Configuration	Plan	Regular symmetric plan, G+6 storeys
Storey Data	Ground storey height (m)	5.1
	Typical storey height (m)	5
	Total height (m)	30.2
Structural System	Grid system	Regular orthogonal layout
	Floor system	100 mm rigid diaphragm
Beam Details	Primary beam (mm)	300 x 600
	Secondary beam (mm)	200 x 600
Column Details	Typical column (mm)	500 x 500
	Below ground column (mm)	600 x 600
Material	Concrete grade (general)	M25
	Concrete grade (critical columns)	M30
	Reinforcement steel	Fe 415 HYSD
Dead Load	Self-weight	Auto (ETABS)
	Floor finish (kN/m²)	1
	Waterproofing terrace (kN/m²)	2
	Brick wall load (kN/m²)	4.9
	Terrace finish (kN/m²)	1
Live Load	Typical floor (kN/m²)	4
	Terrace (kN/m²)	1.5

The definition of the seismic parameters was based on the IS 1893:2016 which defines a zone factor (Z) of 0.16 as that of Zone III, an importance factor (I) of 1.5 due to a public building, a response reduction factor (R) of 5.0 and conditions of Type II medium soils; the fundamental period of the structure was also assumed at 0.97 s. In the tradition of Response Spectrum Analysis and in accordance with the requirements of the code, seismic loads were provided, taking into consideration not only the effects of the earthquake in both directions but also vertical elements. ETABS has used a consistent set of numerical modelling assumptions in all its analytical models in order that differences in the response are attributable to a jacketing configuration. There was an assignment of column flexural stiffness of 0.70 I k and beam flexural stiffness of 0.35 I k that follows the requirements in IS 1893:2016 Cl. 6.4.3.1 on the flexural stiffness of the section under a crack. Rigid diaphragms were used to model all the floors, taking into account the 100 mm RC slab as providing sufficient in plane stiffness, and the P Delta was also used in the case, with the stability index Q less than 0.10 on all storeys and the height of the building over 12 m. Declaring the column bases as completely fixed with six degrees of freedom to Type II medium soil at Vadodara, the soil structure interaction at the postulate of the code was disregarded. All the modes were given a damping ratio of 5 % that is critical of the available structure in the form of RC and applied to the IS 1893: 2016 design spectrum of Zone III and medium soil. Dead load plus 25 % live load centroid at the floor in accordance with Cl. 7.4, and the infill walls were not modelled structurally, including only the dead load of the infill walls to represent an open plan commercial arrangement and provide a conservative bare frame base on which the effect of jacketing on frame stiffness is not confounded.

V. RESPONSE SPECTRUM ANALYSIS

Response Spectrum Analysis (RSA) conducted according to Clause 7.7 of the IS 1893:2016. Design response spectrum generated with respect to damping ratio and the type of soil. The mode analysis determined enough modes to obtain the participation of at least 90% of the mass in both horizontal directions as shown in Fig. 2.

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Modal responses summed together with Complete Quadratic Combination (CQC) to represent the closely spaced modes. Response Spectrum Analysis (RSA) is a methodology that is recommended by the IS 1893: 2016 to use when analyzing seismic effects on regular buildings and as a means of providing a definition of rational methods of applying the design seismic forces to the structure depending on their dynamic property and the intensity of the ground motions at the site (Júlio et al., 2003). The response spectrum graphically shows the highest response of multiple single degree of freedom oscillators with different natural periods to a given ground motion. RSA can be applied to the retrofitted building context by giving key information on how the structural changes by jacketing can affect the dynamic properties of the building, even the basic period of vibration, the participation of modal masses and the distribution of seismic forces at the different levels of the building(Wilson et al., 1981). RC jackets cause columns to become stiffer, decreasing the fundamental period which may escalate seismic force demands depending upon the downward step of the acceleration response spectrum.

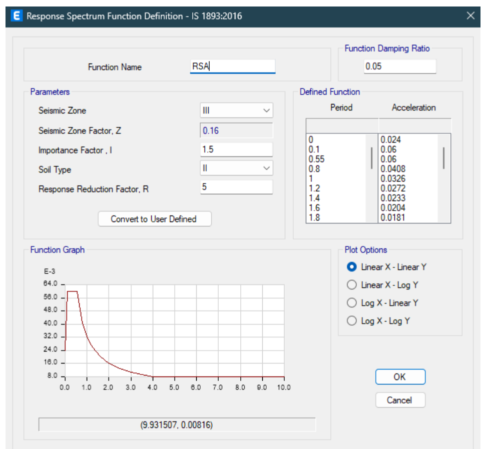

Figure 2Response Spectrum Parameters

VI. REINFORCEMENT DETAILING

The reinforced concrete columnsare constructed with M35 grade concrete jacketing. The longitudinal reinforcement is made of 12 Ø18 mm diameter bars and evenly spaced around the edge of the cross-section, to give a balanced axial and flexural performance and reduce the effects of stress concentration. The lateral ties that provide transverse confinement have dimensions 8 mm in diameter and spacing between them is 150 mm, which provides sufficient restraint against longitudinal bar buckling and enhances the ductility and capacity to dissipate energy in the member. This has all reinforcement that is defined as Fe 415 grade steel which has a characteristic yield strength of 415 Mpa. There is a minimum clear cover of 40 mm to increase durability as per applicable design provisions.

VII. MODEL FOR RC JACKETED MEMBERS

Six distinct retrofitting configurations systematically evaluated for influence of column selection, vertical extent, and jacket thickness on seismic performance. Table 3 summarizes these configurations:

Table 3 Jacketing configuration

Configuration	no. of column retrofitted	Jacket Thickness (mm)	Concrete Grade	Floor Retrofitted
GF-FULL	16	100	M35	GF
HZ-GF+FF	32	100	M35	GF,1F
GF-8C	8	100	M35	GF
SEL-8-80	16	80	M35	GF,1F
SEL-8-100	16	100	M35	GF,1F
VR-C16	16	100	M35	GF,1F,2F,3F,4F

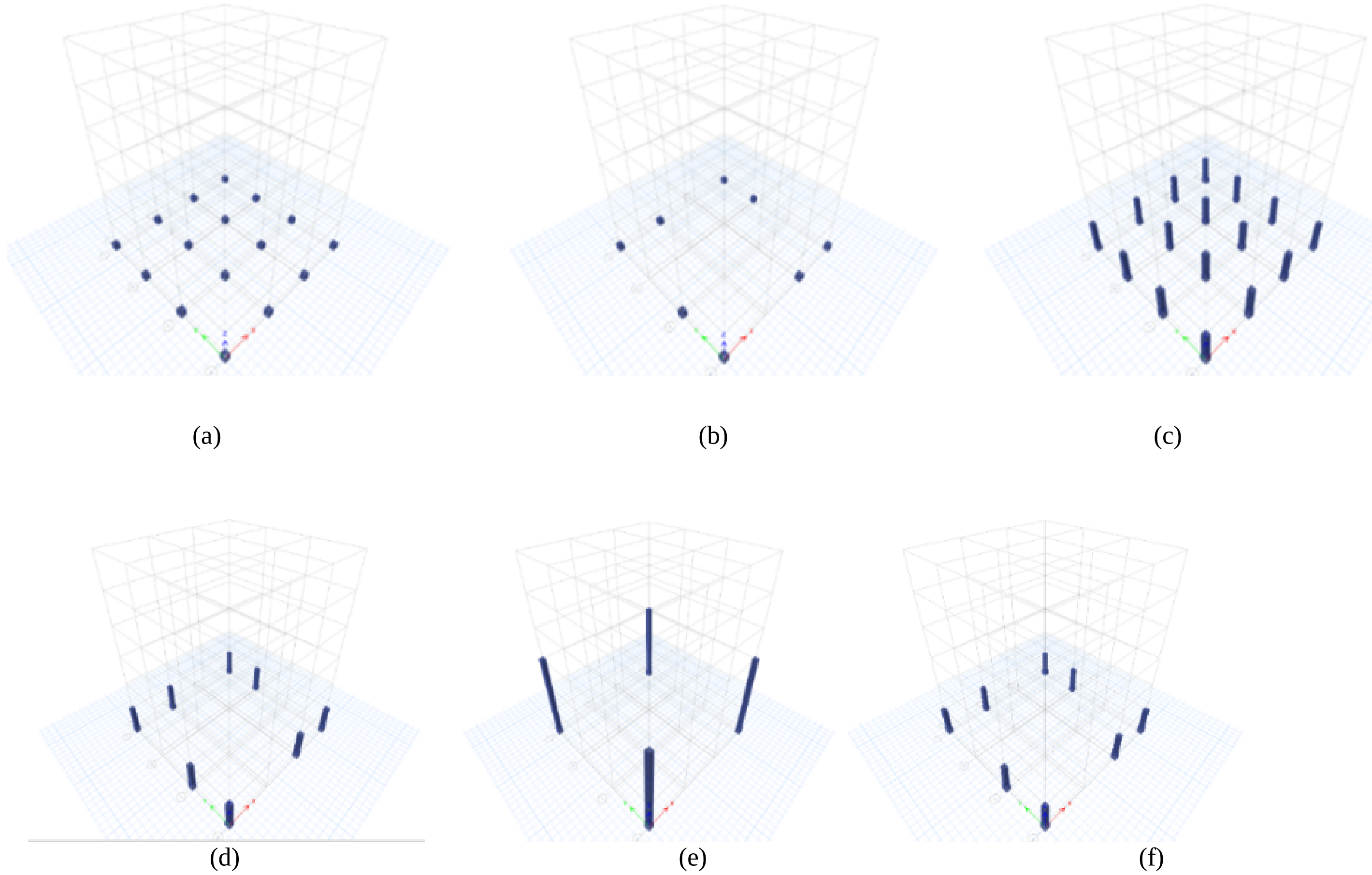

Figure 3Retrofitting configuration (a)GF-FULL (b)GF-8C (c)HZ-GF+FF (d)SEL-8-80 (e)VR-C16 (f)SEL-8-100

To separately determine the relative effect of column selection, vertical extent and jacket thickness under the same material properties and assuming identical modelling conditions, six discrete retrofitting combinations were formulated as presented in Fig. 3. The (GF-FULL) jacketing of 100 mm thick M35 reinforced concrete over all the sixteen columns on the ground floor. The (HZ-GF +FF) configuration jacket application for 32 columns placed on the ground and first floor provided thickness of 100 mm reinforced concrete jacketing. In the GF -8C, retrofit jacketing of the ground floor columns on eight columns. (SEL-8-80) design used sixteen selected columns on the ground and first level and used a thinner jacket thickness of 80mm but SEL-8-100 kept the same for column jacketingon groundfloorandprovideda jacket thickness of 100mm on the first floor. Lastly, the VR-C16 scheme was the scheme that offered vertically continuous jacketing to sixteen columns between and including the ground floor to the fourth floor with each jacket having a thickness of 100 mm.

VIII. CRITICAL COLUMN LOCATIONS

Columns C1, C2, and C5 taken for analysis checked on the ground floor level as well as the first-floor levelas shown in Fig.4. The governing member of column C2 estimated in the initial analysis states the most severe PMM interaction demand with a combined axial loading and biaxial bending. Columns C1 on the corner of the plan and C5 on the corner of the plan were incorporated to allow regard to plan boundary effects, torsional sensitivity and biaxial moment amplification that occurs in edge columns. On the ground floor, the maximum accumulation of the axial force and the transfer of shear to the storey is measured and at the top floor, there would be less accumulation of the axial compression and increased demand of flexure.

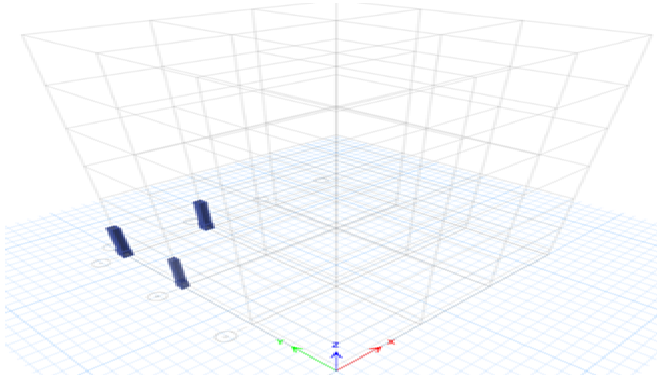

Figure 4Critical Column Locations

IX. DEMAND FOR CAPACITY RATIO ANALYSIS

Column capacity under combined axial load and biaxial bending evaluated using PMM interaction surfaces. Per IS 456:2000 given as:

$$\left(\frac{M_x}{M_{ux}}\right)^{\alpha} + \left(\frac{M_y}{M_{uy}}\right)^{\alpha} \leq 1 \qquad (1)$$

Demand to Capacity (D/C) ratio calculated as:

$$\text{D/C Ratio} = \frac{\text{Factored Demand}}{\text{Design Capacity}} \qquad (2)$$

The demand to capacity (D/C) ratios of critical columns (C1, C2, and C5) in all six configurations as critical columns based on maximum axial load and moment combinations determined in the preliminary analysis. The PMM (P, Mx and My) interaction surface is a basic three dimensional analytical model of thorough analysis of the reinforced concrete column behavior of concurrent axial loading (P) and/or the biaxial bending moment (Mx and My) that realistically defines the true loading conditions that columns are subjected to in building structures when the ground has moved as a result of an earthquake. Compared to simplified uniaxial bending analysis. This change in the interaction surface is reflected directly in the changes in safety margins that are measured in demand to capacity (D/C) ratios. A D/C ratio that is less than 1signifies sufficient capacity whereas higher ratios above 1 signify the possibility of structural deficiency that must be addressed by performing retrofitting. The axial compression in columns was checked in accordance with Clause 7.1 of IS 13920:2016 to ensure ductile seismic performance. The factored axial load acting on the column was limited by the code requirement to prevent brittle compression failure and to maintain adequate deformation capacity. The axial load ratio was evaluated using:

$$\text{Axial Load Ratio} = \frac{P_u}{f_{ck} A_g} \qquad (3)$$

where Pu is the factored axial load, fck is the characteristic compressive strength of concrete, and Ag is the gross cross-sectional area of the column. As per the code, this ratio restricted to 0.40 for columns designed for ductile detailing under seismic loading.

X. RESULTS AND DISCUSSION

A comparative seismic evaluation is conducted six RC jacketing configurations using response spectrum analysis. Structural response parameters such as storey displacement, drift, base shear, stiffness, and PMM interaction ratios are examined to determine the effectiveness of each retrofitting configuration.

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A. Ground floor

The demand to capacity (D/C) ratios of critical columns (C1, C2, and C5) in all six configurations as critical columns based on maximum axial load and moment combinations determined in the preliminary analysisas shown in Fig. 5-6.The GF-FULL (all ground floor columns retrofit) is successful in achieving ground floor D/C ratios to 0.486 up to 0.572 to key columns, and this is equivalent to 49-57% capacity utilization, and with 43-51% capacity reduction. The significance shows basic RC jacketing in increasing column capacity the column by axial and biaxial moments remains practical. The HZ-GF+FF layout has slightly higher ground floor D/C ratios (0.586-0.796) than the GF-FULL (0.486- 0.572) (8-39% improvement in the demand to capacity ratios), although both layouts utilize the same ground floor strengthening (all 16 columns jacketed).

When compared to GF FULL, approximately 8-12% period reduction by analysis. Higher stiffness of both ground and first floors cause a higher proportion of seismic base shear to lower storeys than in GM-FULL. These high demands do not indicate that the HZ-GF+FF ground floor D/C ratios are not significantly below the value of unity (maximum 0.796), indicating that there is sufficient capacity. More importantly, it is found that the HZ-GF+FF analysis has the largest gain in the performance of the first floor, where the GF-FULL fails, making HZ-GF+FF the optimal overall strategy even though it yields slightly higher ground floor demand. The highly variable ground floor performance (GF 8C, SEL 8 80, SEL 8 100) of the selective retrofitting arrangements has been shown to be highly variable based on the column location and choice of selection. The GF-8C (8 corner columns at ground floor only) provides a satisfactory D/C ratio of 0.662 at corner column C1, where jacketing was performed, but the higher D/C ratio of 0.940 at the perimeter column C5, where it was not retrofitted, is close to a failure. The basic drawback of the selective strengthening is confirmed by the 42% difference (0.940 vs 0.662) of the retrofitted perimeter columns corner against the non-retrofitted columns the targeted columns have sufficient capacity, but non-retrofitted members are still weak. The SEL-8-80and SEL-8-100 (8 chosen columns along both the ground and first floors of 80mm and 100mm jackets respectively) demonstrate that the ground floor corner C1 column severely lacks capacity at 1.067 and 1.141 and has fewer than 80mm jackets even though the building is on dual floors. Compensating the jacket thickness (100mm or 80mm), it was found that the reduction of the jacket thickness by 2mm leads to a better performance (D/C reduces by 7 %). The VR-C16 vertical retrofitting performs the least favorable regarding ground floor deficiency, with the corner column C1 D/C ratio of 1.419, which is greater than unity by 41.9 % and maximum D/C ratio of any construction at ground floor, showing that vertical strengthening strategy with focus on corner columns throughout building height does not contribute enough to capacity improvement at the ground floor (20 column locations jacketed around 5 stories). This poor performance of all the vertical intervention measures proves that horizontal zone strengthening methods are superior to the vertical jacketing, where strengthening is distributed vertically on the height, as opposed to strengthening being concentrated at levels of high demand on the floor (ground and first floor).

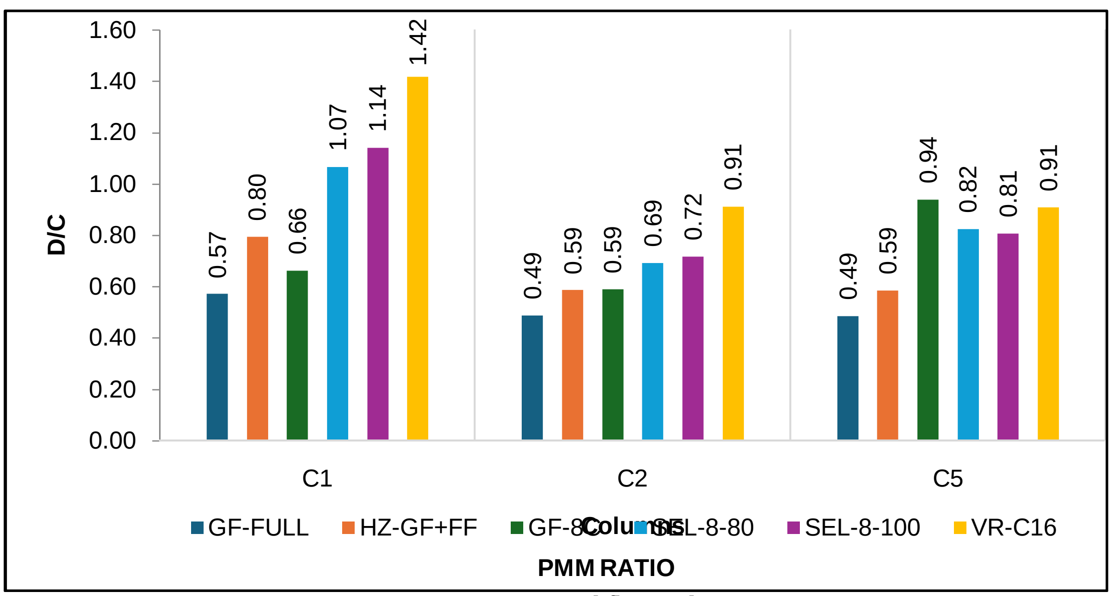

Figure 5 Ground floor column PMM ratio

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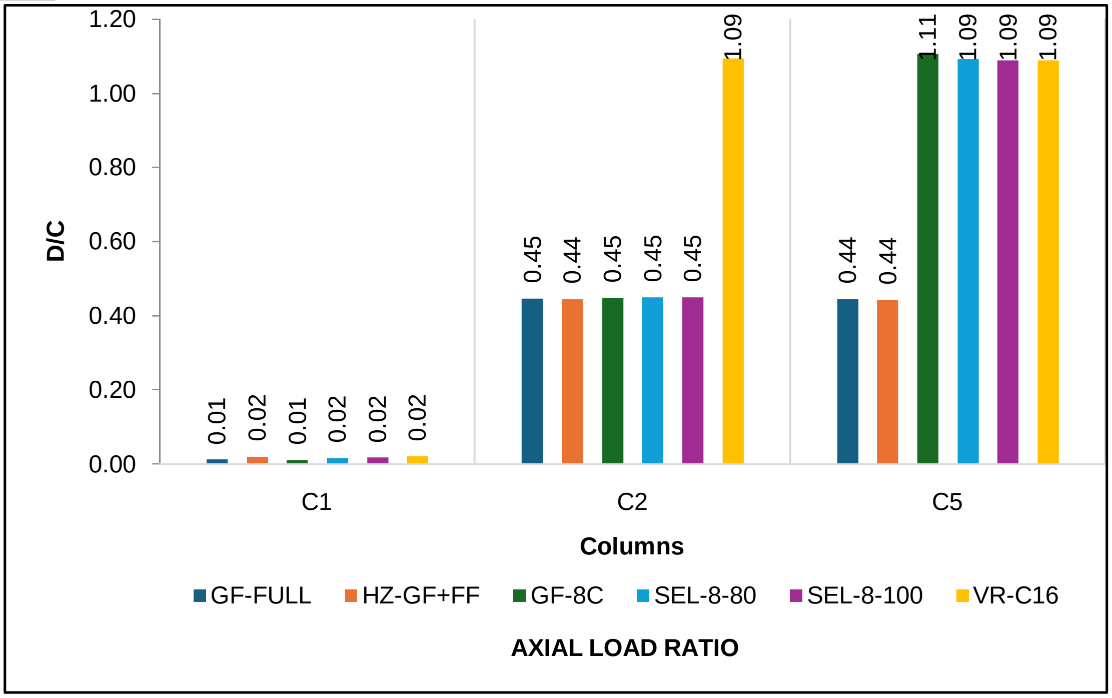

Figure 6 Ground Floor Column axial load compression ratio

B. First floor

Critical Analysis First Floor D/C Ratios the first-floor demand to capacity ratios provides even more drastic performance differences and essential shortcomings of several retrofitting approaches as shown in Fig. 7-8.The GF-FULL design has a grossly inadequate performance of the first floor with D/C ratios ranging between 1.258 and1.356 that exceed unity by 26-36% showing insufficiency in the capacity despite successful ground floor reinforcement. Such deficit shows structural weakness that will induce collapse in the case of design level earthquakes.HZ-GF+FF combination provides transformative performance improvement of the first floor with D/C ratios decreasing to 0.586 0.730, which is 54-78% enhanced compared to GF-FULL (1.258-1.356) and indicates the essential role of extending jacketing to the first floor.

It is sudden change from parametric to deficient conditions (D/C > 1.25) to highly adequate conditions (D/C < 0.75): dual floor strengthening is marginally superior to single floor strengthening and acceptable in seismic performance. The 0.586 0.730 ranges of D/C give comfortable safety margins of 27-41% at the first-floor level, which provides strong performance during design level earthquakes. The selective configurations SEL-8-80 and SEL-8-100 are of mixed first floor performance with D/C ratios of 0.940-1.061 (just less than unity) configurations are effective in reinforcing the selected columns to reasonable parameters (C1 and C2 with D/C close to 0.94), other columns on the first floor, such as C5 have D/C of 1.061-1.033, greater than unity by 3-6% suggesting inadequate capacity. This states that selective 8 column strengthening does not benefit in terms of comprehensive capability of delivering comprehensive development, as there are numerous weak points that may trigger the process of progressive failure. The low variation in performance between 80mm (SEL-8-80) and 100mm (SEL-8-100) jacket thickness (maximum 2.7% D/C variation) indicates that in selective retrofitting strategies, the jacket thickness is secondary to the column choice and to the consideration of the vertical length. Nevertheless, both selective arrangements are still unfavorable than HZ-GF+FF strategy, which provides the capacity of all columns to be sufficiently high and without weak spots. The VR-C16 vertical retrofitting plan has extremely poor first floor performance with D/C ratios of 1.171-1.189, which is more than unity by 17-19% even when the corner columns are continuously strengthened vertically between the first and fourth floor. This failure shows that vertical strategies do not effectively lead to the first-floor capacity, even with the strengthening of corner columns. The D/C ratios that are close to 1.19 are evidence of about 19 % of capacity deficit that generates severe seismic vulnerability and risks some seismic collapse under the level of design capacity earthquakes.

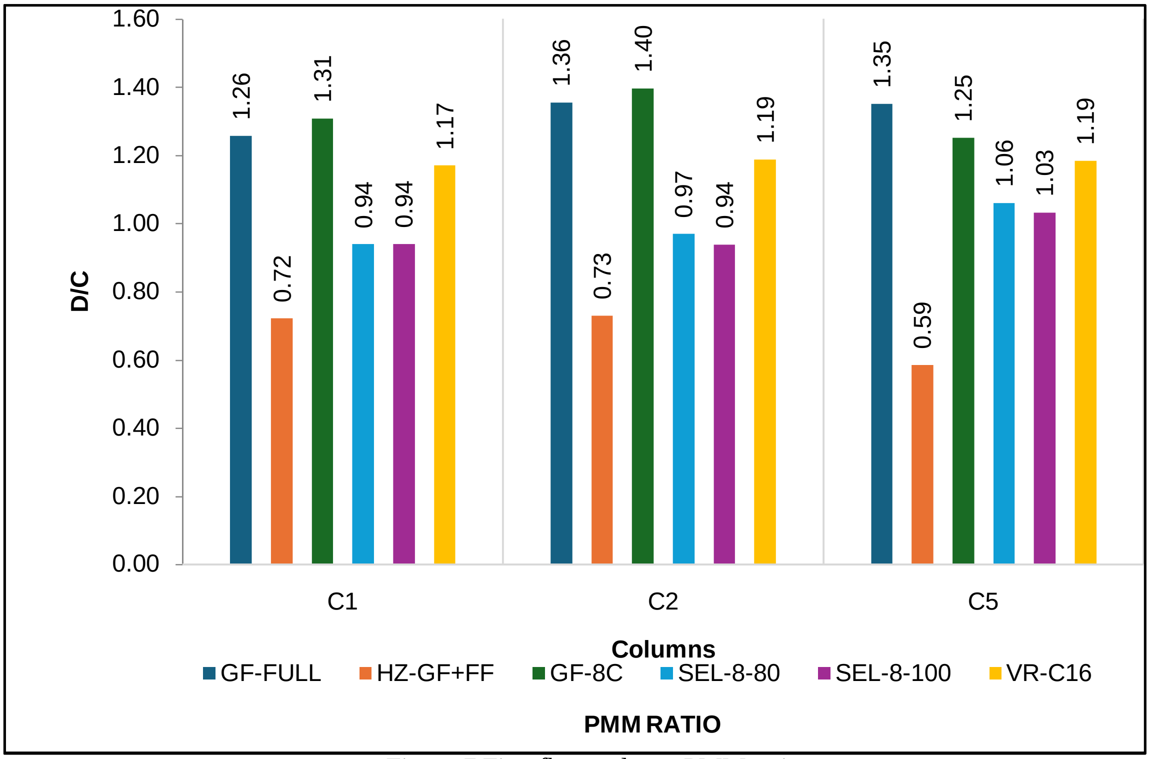

Figure 7 First floor column PMM ratio

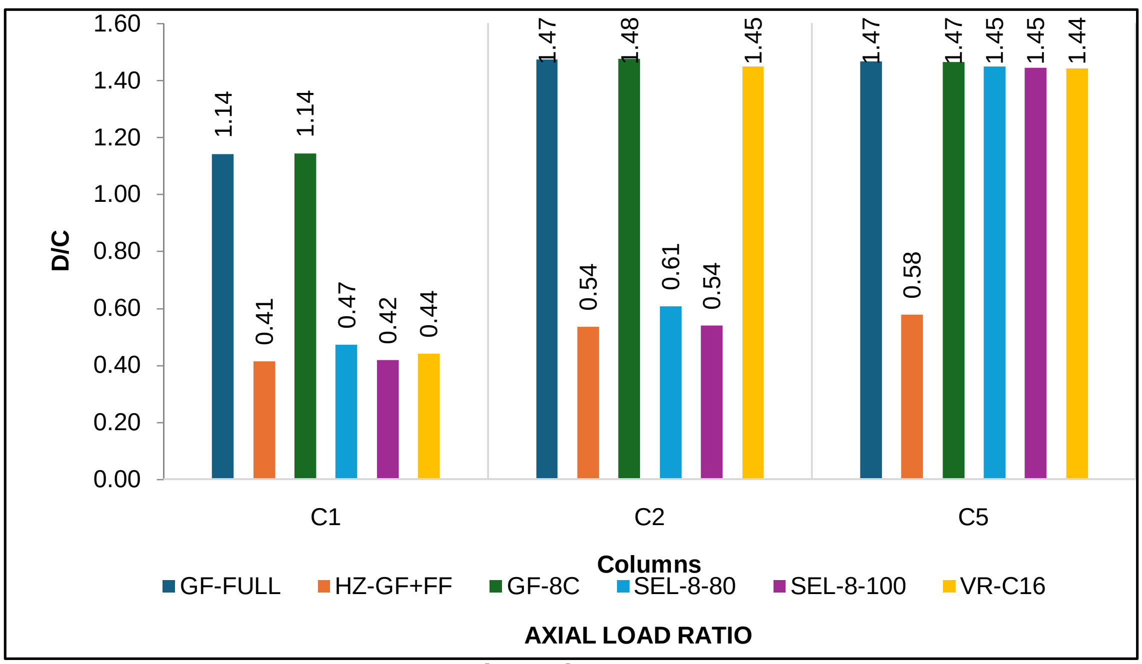

Figure 8 First Floor Column Capacity Assessment

C. Max storey displacement

Fig.9 shows the maximum storey displacements in the direction of the primary seismic direction (RX direction) on all the floors of each configuration. Displacement profiles provide information on overall structural elasticity and general deformation trends. Detailed jackets reduce lateral displacements by 20–35% compared to unreinforced specimens.

HZ-GF+FF setting is capable of a better amount of displacement control with the least roof displacement of 35.872 mm, which is a decrease of 6.5 % and 7.1 % compared to GF-FULL (38.377 mm) and Compared (38.63 mm).

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue V May 2026- Available at www.ijraset.com

The change is nominal, but the decrease implies increased global stiffness without causing much rigidity that would increase the demands of the internal forces. The profiles of the displacement have smooth, monotonic behavior with the height of a building in all the configurations, proving the absence of sudden stiffness irregularities, which may cause weak storey mechanisms or inelastic demands. With selective configurations (SEL-8-80, SEL-8-100), intermediate displacement reduction (36.732-37.042 mm) indicates that with some simplified forms of retrofitting, it is possible to make the selection actively controlled, although only half of the columns are used, implying that selective intervention can be optimized in situations where the overall retrofitting costs are economically limited. VR-C16 vertical strategy produces a 37.238 mm displacement of the roof, which shows that vertical distribution of strengthening offers little global displacement control compared to horizontal zone concentration of the critical floors.

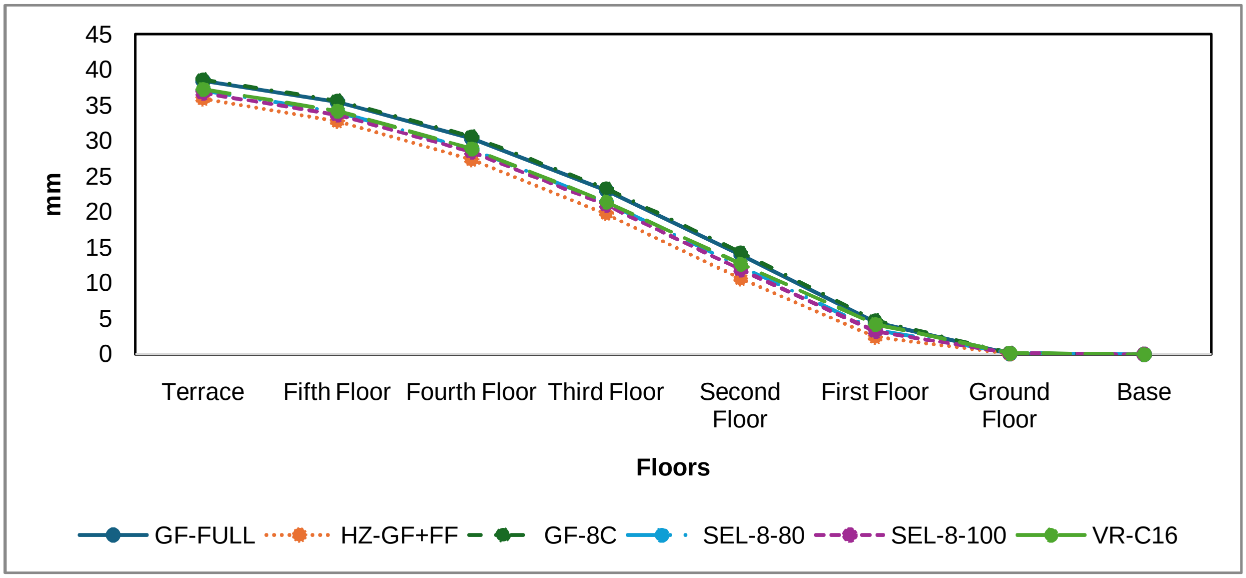

Figure 9Floor-wise Max storey displacement

D. Max storey drift

Inter-storey drift ratios are determined as relative displacement between two adjacent storeys divided by storey height as given in Fig. 8. Inter storey drift ratios are determined as the relative displacement between two adjacent storeys divided by storey height, as in Fig. 8. Drift with respect to IS 1893:2016 drift ratios are restricted to a maximum of 0.004 with relation to RC frame buildings. All the configurations meet the IS 1893:2016 drift limit value of 0.004 with some highest limits of 0.001649 (HZ-GF+FF at second floor) to 0.001924 (GF-FULL at second floor), which indicate safety margin of 59-52% against code limits. The HZ-GF+FF design shows superior levels of drift control at the first floor, which is in the critical location with a value of 0.000575 (46.2% lower than the effectively high concentration of stiffness at the ground floor in compared with the GF-FULL value of 0.001069), thereby reducing the soft storey vulnerability observed generally when a ground floor is strengthened excessively. The drift distribution shows that the highest values consistently occur at second floor across most configurations (0.001649-0.001924), showing such height as the critical zone of the ductility demand concentration, which is a typical non uniform redistribution of deformation demands to rely on non-retrofit immediately fined adjacent floors in the medium rise frame constructions.

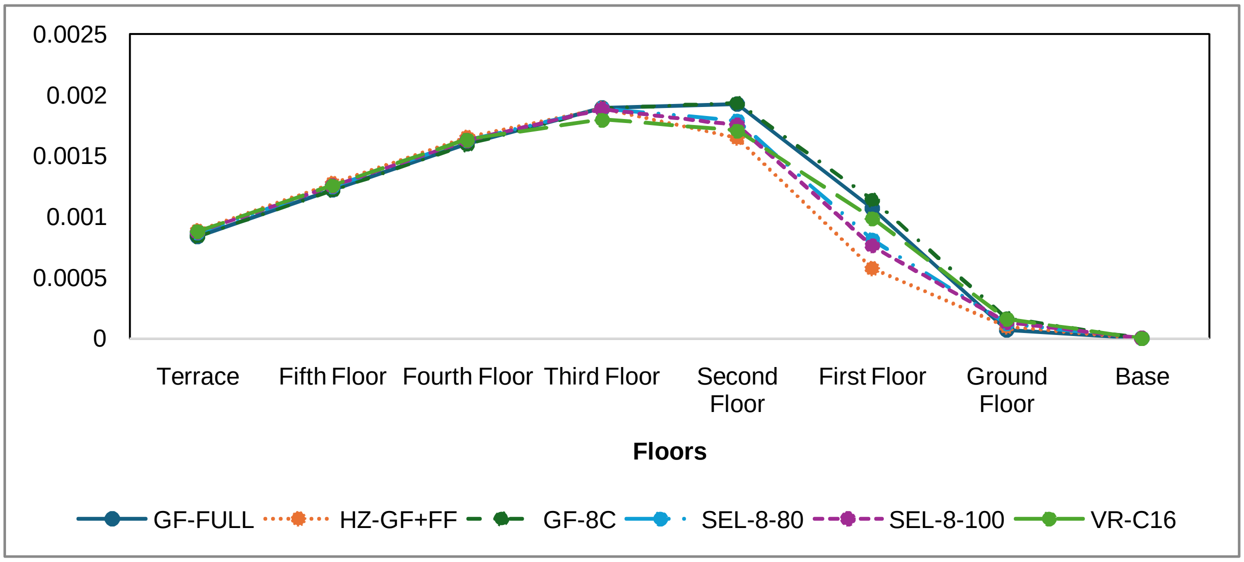

Figure 10 Floor-wise Max storey drift

E. Storey shear

Base shear and storey shear distributions fundamental indicators of seismic demand and load transfer mechanisms. Fig.11shothese values across configurations. Storey shear distribution is governed by fundamental mode shape for regular low to medium rise buildings.HZ-GF+FF indicates the largest base shear capacity of 362.017 kN, which is 8.8 % higher than that of GF-FULL (332.663 kN) and 11.3 % higher than that of GF-8C (325.38 kN). Although this enhancement of shear at the base, being veneer on the surface, creates an image of augmented seismic pressure, this is essentially a valuable gain that points to heightened structural hardness and enhanced attraction strength. High base shear will reflect successful involvement of global participation in lateral resistance, where the strength is more evenly spread throughout the strengthened structural system and not simply located in a few weak areas that may fail prematurely. More importantly, concomitant reduction of base shear ratio (stiffness improvement) with reduction in demand to capacity ratios (capacity sufficiency) attests to structural sufficiency in the HZ-GF+FF setup. These storey shear profiles have progressive, evenly declining profiles with respect to the elevation in all constructions and conform to the anticipated triangular distribution patterns in structures with fundamental mode predominance, thus confirming the lack of substantially higher mode significantly contributing to the mechanisms of force transfer.

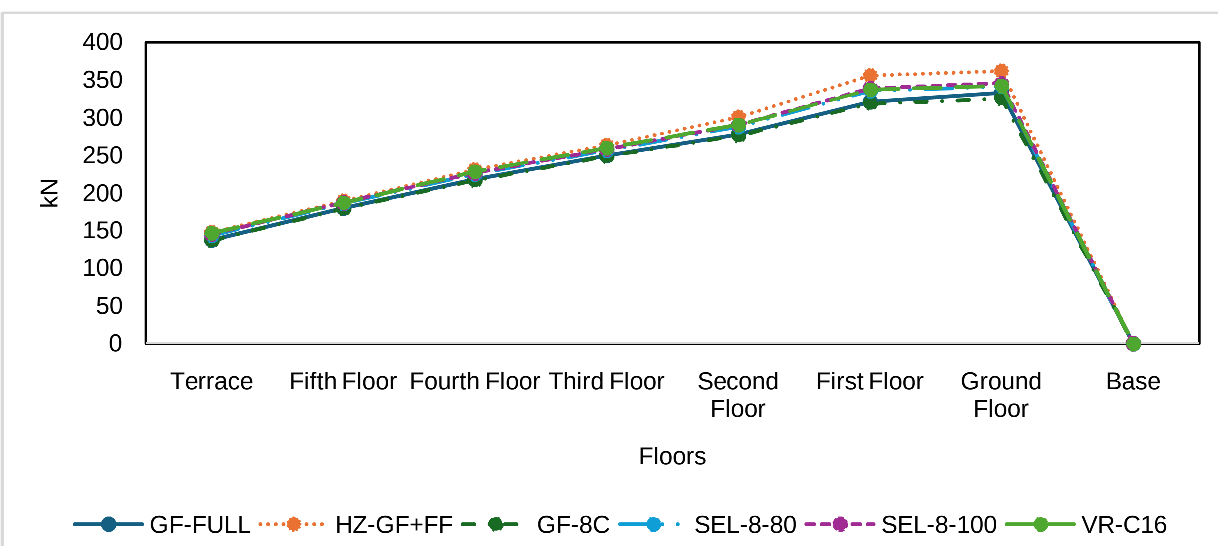

Figure 11Floor-wise storey shear

F. Storey stiffness

Storey stiffness, calculated as the ratio of storey shear to inter storey drift, provides insight into structural rigidity distribution as shown in Fig. 12-13. Selective strengthening of critical storeys is an economically viable compromise, provided stiffness enhancement is moderate and extends over at least two consecutive storeys. Abrupt stiffness variations between adjacent floors can induce soft storey behaviour and concentration of plastic deformations. Fig. 10 presents these values. Characteristic orders of magnitude concentration at ground floor (2,007,828-4,555,862 kN/m) due to the fixity of foundations of all boundary conditions but gradually reducing with storey numbers (26,436 33,461 kN/m at typical storeys) was seen in the stiffness distribution profiles. More importantly, the HZ-GF+FF arrangement displays a better ground to first floor gradation of stiffness reduction, with compared (3,480,074 to 151,015 kN/m) lower than GF-FULL (4,555,862 to 73,273 kN/m). This controlled stiffness change is an inherent benefit, in effect reducing the possibility of its soft storey forming at the first storey by distributing the stiffness increase over both levels of vital significance, instead of concentrating the excess rigidity on the ground surface [5]. The extreme stiffness irregularity occurs in the GF-8C configuration (2,536,060 kN/m to 69,127 kN/m) as evidence of the weakness of localised minimal intervention strategies. On the other hand, the selective dual floor types (SEL-8-80, SEL-8-100) have shown intermediate stiffness changes (25.0-26.5% reductions), capable of optimizing selective retrofitting that trades off higher vertical regularity with resource constrained construction.

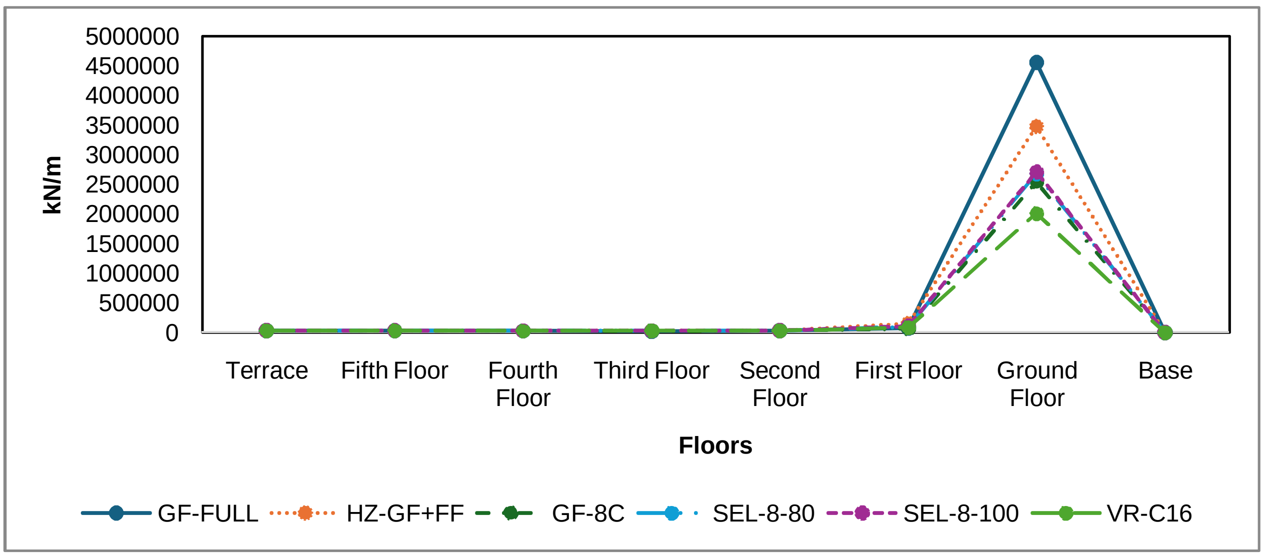

Figure 12 Storey Stiffness (base- terrace)

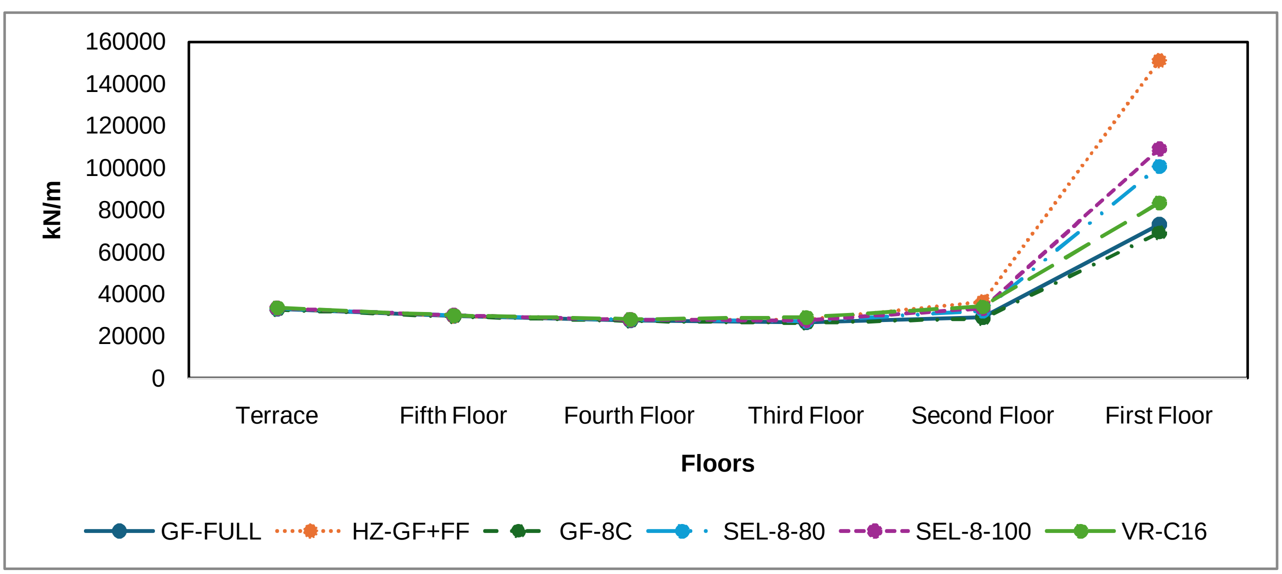

Figure 13 Storey stiffness (ground floor - terrace)

XI. FUTURE SCOPE

1) A comprehensive full-scale cost benefit analysis should be conducted with costs of materials and labour used, effects of building construction durations, quantification of occupancy disruptions, and long-term maintenance.
2) The effectiveness of hybrid retrofitting solutions that involve RC jacketing plus supplementary solutions such as shear wall addition, introduction of steel bracing and integration of damping systems to develop synergistic performance improvement should be investigated.
3) The long-term condition testing of jacketed elements when exposed to environmental exposures such as chloride-induced corrosion, freeze-thaw cycling, and alkali-aggregate reactions that might affect bond integrity and composite behaviour.

XII. RESULTS COMPARISON

The qualitative performance measurements, synthesized in demand to capacity ratios, displacement control, mitigation of drift, base shear capacity, and distribution of stiffness, exhibit different hierarchical trends of configuration efficacy. HZ-GF+FF two floor horizontal zone strengthening scheme (32 columns on ground and first floors) indicates the most effective in the entire criteria considered, registering the highest demand capacity ratios (0.415-0.796), maximum displacement reduction (6.5%), and most effective first floor drift control (46.2% reduction), a high base shear, which denotes increased lateral resistance (8.8%), and greatly enhanced regularity of vertical stiffness. In the cases of retrofitting buildings where broadly implemented strategies may be prohibited by financial factors or logistical difficulties (e.g. due to insufficient resources), the selective dual floor (SEL-8-80, SEL-8-100: 16 columns each on ground and first floors) can be considered an intermediate option. These plans of action deliver reasonable performance rates, such as demand to capacity ratios (0.419- 1.141), moderate displacement control (4.3-5.5% improvement), and a reasonable drift limit, and with just half of the columns when compared to HZ-GF+FF design, can deliver possible construction cost cuts when applied to lower criticality structures. The very low level of difference between 80mm (SEL-8-80) and 100mm (SEL-8-100) jacket thickness can conclusively suggest that optimization of the pattern of column selection and the vertical extent is much more significant than consideration of jacket thickness within rational ranges of experience (80-100mm) as to suggest strategy selection of elements is the dominant design variable rather than the magnitude of cross sectional enhancement. In the vertical retrofitting VR-C16 setup (16 corner columns through the fourth floor), although there is a huge level of vertical intervention with five floor levels of involvement, the level of performance is unsatisfactory with high demand on the capacity ratio (1.171- 1.419 at ground floor), which has shown 17-42% deficiencies in capacity. Vertical distribution strategies are not only ineffective in strengthening torsional resistance by simply continuous corner strengthening, but essentials of total seismic retrofitting of non-special frame buildings where demand is concentrated at certain floor levels that necessitate horizontal zone strengthening of all columns at the critical floor of the building. The performance of horizontal zone-based strategies (HZ-GF+FF) as compared to vertical based (VR-C16) ones highlights the necessity of alignment of retrofitting distribution with the actual patterns of seismic demand as opposed to seeking the principles of geometrical consistency or aesthetic continuity.

XIII. CONCLUSION

1) HZ-GF+FF generated the most consistent response of the structural system in the range of 0.415 to 0.796 with reduction by 6.5% on ground floor and first storey drift reduction by 46.2%.
2) The vertically continuous (VR-C16), though within five storeys (ground to fourth floor), was still insufficient at the ground level, and D/C ratios of 1.171-1.419. This ascertains that vertical continuity cannot be applied solely or suffice to the demand concentration at storey of critical height of the structure and might not be sufficient to ensure enough local capacity.
3) Inter storey drift in every arrangement was within the limit 0.004 in IS 1893:2016, with the highest value of 0.001924. The increasing base shear of 8.8% in HZ-GF +FF is associated with an increase in global stiffness and the better involvement of lateral forces as opposed to an increase in negative demand.
4) The findings indicate that prescriptive and standardized retrofitting methods are structurally inefficient. Configuration in performance differences were large (D/C: 0.415-1.476), and hence configuration specific retrofitting strategies that are demand oriented are necessary.
5) GF FULL/GF-8C strengthening at the ground floor only enhanced local capacity but resulted in concentration of stiffness leading to an initial: first floor D/C ratio of 1.258-1.398. This behavior is an indication of the need to create more intervention to at least the first floor to prevent demand transfer and create balanced seismic behavior.

6) The 16 column strengthening layout, (GF-FULL) (ground floor D/C = 0.486-0.572), provides relatively better structural adequacy based on the consistent increase of stiffness and axial-flexural strength at the critical storey of peak seismic demands; others display demand concentration based on selective column intervention (SEL-8-80 / SEL-8-100) and limited (VR-C16), where vertical continuity is insufficient to prevent peak ground-storey interactions of axial-moment demand.

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APPENDIX

Table 4 Max storey displacement

Story	Elevation m	Location	RX-Dir mm GF-FULL	RX-Dir mm HZ-GF+FF	RX-Dir mm GF-8C	RX-Dir mm SEL-8-80	RX-Dir mm SEL-8-100	RX-Dir mm VR-C16
Terrace	30.2	Top	38.377	35.872	38.63	37.042	36.732	37.238
Fifth Floor	25.2	Top	35.407	32.703	35.674	33.979	33.649	34.152
Fourth Floor	20.2	Top	30.318	27.325	30.609	28.762	28.405	28.898
Third Floor	15.2	Top	23.033	19.733	23.35	21.347	20.963	21.383
Second Floor	10.2	Top	13.975	10.636	14.31	12.296	11.917	12.681
First Floor	5.2	Top	4.451	2.46	4.742	3.445	3.23	4.207
Ground Floor	1.1	Top	0.077	0.105	0.178	0.135	0.144	0.176
Base	0	Top	0	0	0	0	0	0

Table 5 Max storey drift

Story	Elevation m	Location	RX Dir GF FULL	RX Dir HZ-GF+FF	RX Dir GF 8C	RX Dir SEL 8 80	RX Dir SEL 8 100	RX Dir VR-C16
Terrace	30.2	Top	0.000838	0.000887	0.0008	0.00087	0.00087	0.000879
Fifth Floor	25.2	Top	0.001219	0.001275	0.0012	0.00125	0.00125	0.001257
Fourth Floor	20.2	Top	0.001596	0.001652	0.0016	0.00162	0.00163	0.001634
Third Floor	15.2	Top	0.00189	0.00189	0.0019	0.00189	0.00189	0.001797
Second Floor	10.2	Top	0.001924	0.001649	0.0019	0.00179	0.00176	0.001709
First Floor	5.2	Top	0.001069	0.000575	0.0011	0.00081	0.00076	0.000986
Ground Floor	1.1	Top	0.00007	0.000096	0.0002	0.00012	0.00013	0.00016
Base	0	Top	0	0	0	0	0	0

Table 6 Base shear

Story	Elevation m	Location	X-Dir kN GF-FULL	X-Dir kN HZ-GF+FF	X-Dir kN GF-8C	X-Dir kN SEL-8-80	X-Dir kN SEL-8-100	X-Dir kN VR-C16
Terrace	30.2	Bottom	137.4043	147.5242	136.65	143.753	145.158	147.0566
Fifth Floor	25.2	Bottom	179.7574	189.6928	178.89	185.915	187.085	187.1567
Fourth Floor	20.2	Bottom	217.8012	231.0035	216.74	224.969	226.413	228.3852
Third Floor	15.2	Bottom	249.7666	263.3325	248.81	256.69	258.077	259.9916
Second Floor	10.2	Bottom	277.8525	301.1876	276.37	287.958	290.252	290.0089
First Floor	5.2	Bottom	320.8102	355.8489	319	335.134	338.742	337.1806
Ground Floor	1.1	Bottom	332.6634	362.0171	325.38	341.437	345.101	342.1276
Base	0	Bottom	0	0	0	0	0	0

Table 7 Storey stiffness

Story	Elevation m	Location	X Dir kN/m GF FULL	X Dir kN/m HZ-GF+FF	X Dir kN/m GF 8C	X Dir kN/m SEL 8 80	X Dir kN/m SEL 8 100	X Dir kN/m VR-C16
Terrace	30.2	Top	32777.08	33265.89	32705	33212.1	33309.5	33461.391
Fifth Floor	25.2	Top	29496.32	29765.67	29438	29810.2	29861.5	29767.263
Fourth Floor	20.2	Top	27299.78	27958.34	27239	27735.5	27824.5	27958.323
Third Floor	15.2	Top	26435.76	27873.03	26361	27202.5	27371	28943.156
Second Floor	10.2	Top	28880.65	36526.4	28576	32223.3	33084.4	33946.712
First Floor	5.2	Top	73273.34	151014.8	69127	100970	109136	83509.635
Ground Floor	1.1	Top	4555862	3480074	2536060.1	2676300	2708091	2007827.8
Base	0	Top	0	0	0	0	0	0

STATEMENTS AND DECLARATIONS

ConflictofinterestTheauthorsdeclarenocompetinginterests.

ConsenttoparticipateNotapplicable.

ConsenttopublishAllauthorshavereadandapprovedthismanu- script.

AuthorcontributionsAllauthorscontributedtothedevelopmentof manuscript.

FundingTheauthorsdeclarethatnofunds,grants,orothersupport werereceived duringthe preparationof thismanuscript.

DataavailabilityAlldatageneratedoranalyzedduringthisstudyare includedinthispublished article.