Seismic Response Analysis of a 14-Storey RC Building Using ETABS: A Systematic Study of Shear Wall-to-Floor Area Ratios and Structural Positioning

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Abstract - *Nonlinear static (pushover) analysis serves as the foundation of this study to address the limited systematic optimization of shear wall density and spatial distribution in reinforced concrete (RC) structures. This research comprehensively evaluates the seismic performance of a 14-story RC framework by investigating the interaction between varying shear wall-to-floor area ratios (0.5%, 1.0%, and 1.5%) and strategic planar configurations (core, corners, periphery and outermost bays). Utilizing CSI ETABS v22, the numerical modeling strictly complies with the severe seismic provisions of IS 1893:2016 and ductile detailing protocols of IS 13920:2016. By extracting structural capacity curves under monotonic lateral loading, the study captures global stiffness and inelastic strength degradation. The lateral control efficacy of each configuration is assessed by quantifying critical engineering demand parameters: maximum inter-story drift and peak roof displacement. It is found that geometric configuration heavily dictates structural performance. Misaligned or sub-optimally positioned walls can lead to compounding losses in base shear, whereas optimized configurations can act as structural multipliers, yielding dramatic increases in lateral resistance without necessarily requiring proportional increases in material volume. An optimized, symmetrical shear wall configuration with a lower overall wall percentage can actually provide greater lateral stiffness and better drift control than a non-optimized arrangement that uses significantly more concrete and steel. As the shear wall-to-floor area percentage increases, the baseline lateral stiffness of the building increases. The findings establish that while total shear wall area is a factor, the strategic placement and geometric arrangement of these elements are far more critical for maximizing structural rigidity and ensuring superior seismic resilience.*

Key Words: Shear Walls, SW-FAR, ETABS, Maximum Storey Drift, Maximum Storey displacement, Capacity Curve

1. INTRODUCTION

The key issue in the design of these structures is to ensure sufficient lateral stiffness, strength and ductility to provide a safe dissipation of the energy that can be generated from the earthquake. Shear walls are well recognized to exhibit the best in-plane rigidity among lateral load resisting systems to limit inter-story drift and to avoid catastrophic P-Delta (Δ) effect[1, 2]. But the size, shape, location and overall volumetric share of the shear wall component of the structures are key to the efficiency of a shear wall system. One of the major challenges in the recent evolution of the seismic design approach of Performance Based Seismic Design (PBSD) is the spatial layout of shear walls, especially for dealing with torsional vulnerabilities. When eccentricity is present, between the center of mass (CM) and the center of rigidity (CR) of a building, the effect is very strong and causes significant twisting moments that cause early yielding of the peripheral columns [3]. It has been proved that, when pure translational forces are applied, shear walls inside the central core will provide increased stiffness and will reduce torsional eccentricity[4, 5]. However, in the advanced studies it has been found that complex geometries such as T-shaped boundary walls or dumbbell shaped elements strategically located at the perimeter of a lateral system have shown beneficial effects on shear lag and rotational ductility. Under these very non-standard circumstances, the ability to resist the brittle failure modes which are sudden and often found in a soft-storey is the most important structural resistance property[6]. Spatial positioning is not the only parameter discussed; the Shear Wall to Floor Area Ratio (SW-FAR) parameter is also being discussed. The codes set minimum stiffness requirements so that the structure will not be subjected to non-structural damages, but at the same time, if the stiffness of a structure is made too stiff, the weight of the structure will increase, and so will the inertial forces [7]. An optimum value for SW-FAR around 1.0% to 1.5% is suggested as beyond this the lateral displacement reduction is not worth the additional weight of the structure[8]. The specific ratio has been found to provide optimum control of inter-storey drift without making the structure change from a ductile flexure-dominant frame to a quasi-brittle shear-dominant frame[9, 10]. Further, fenestrations (openings) or using discontinuous “flag walls” leads to local loss of stiffness which, in turn, makes it increasingly important to carefully calibrate the overall SW-FAR to meet the required level of life safety (LS) and collapse prevention (CP) performance margins [11, 12]. Non-linear Static (Pushover) Analysis is increasingly being used by engineers to appropriately simulate these complex inelastic load-deformation relationships. The distributed-plasticity modeling of the fiber approach (usually specified through use of the ETABS software) can be employed to represent the progressive deterioration of the structure during time [13]. The RC system should follow the "strong column-weak beam" design principles, with the idea of providing a controlled yield mechanism to dissipate energy from the system, instead of a sudden shear failure [14]. Many isolated research projects exist on wall thickness, basic positioning and volumetric ratios but there is a high need for a detailed, multivariate measurement of the interaction of these parameters, which are high seismic and highly regularized. Therefore, in the present study a detailed, non-linear static analysis of a 14-storey RC building will be carried out and the results will be compared with other buildings to fill this gap. The research purpose is to clearly define the global stiffness, strength degradation and optimum yielding behavior that would enable high seismic efficiency in high risk areas by gradually changing the SW-FAR (0.5%, 1.0% and 1.5%) between various topological layouts (central core, asymmetric periphery and corner placements)[15].

2. METHODOLOGY

2.1. Structural evaluation strategy

This study is carried out in the context of the Performance Based Seismic Design (PBSD) approach. The main aim is to study the seismic response of a 14-storey reinforced concrete (RC) building, under different SW-FAR (Shear Wall to Floor Area Ratio) ratios of 0.5%, 1.0% and 1.5%, as illustrated in Fig. **1**, Fig. **2** and Fig. **3** respectively. Detailed dimensions and reinforcement information for beams, columns, and shear walls are mentioned in Table **1**. Nonlinear Static Analysis (NSA) or Pushover Analysis is used to capture the inelastic behavior and structural capacity. This way, the strength and deformation limits of the building beyond elastic range can be determined. A 14-storey high rise residential structure. The building has a regular grid of 4.0 meters in both directions, and a symmetric plan. A fiber-based modeling approach is used for all beams, columns and shear walls to simulate realistic structural damage, Material characterization and nonlinearity. The Mender model is used to model stress-strain response of 25MPa concrete. The steel rebar is modeled using yield strength of 415 MPa and the kinematic hysteresis model is used for the strain hardening effect. Inelasticity is captured by using P-M2-M3 fiber hinges on the frame members and P-M3 fiber hinges. For shell-element shear walls. The three different ratios of shear wall to floor area (SW-FAR) are examined in conjunction with different layouts (central core, corners, and peripheral positioning) of the shear wall. The aim is to find the best lateral stability combination. The structural models are prepared for a dead load of 4kN/m^2 and live load of 1.5kN/m^2. Push over analysis is performed by constructing an additional horizontal load in the X-direction, including P-delta effects to assess the building's response to seismic loading.

2.2. Some important parameter

Performance Assessment Metrics: The seismic suitability of the 14-storey configurations is assessed by three main response parameters: Capacity Curves: Stiffness and strength assessment by plotting Base Shear with respect to Roof Displacement; Max. Storey Displacement: Maximum lateral displacement at different levels of the building.

2.3. Building Description

The model of the 14-storey Reinforced Concrete (RC) building is highly plan-symmetric and aims at highlighting the efficiency of the lateral load-resisting systems.

2.4. Geometric Configuration Plan

Regular square plan with an edge length of 24m (Total = 576 m^2). The Grid System is symmetry 6m×6m bay system with a uniform spacing of 4m in both directions. The structural member sectional properties are displayed. Structural member sectional properties are shown.

Table -1: Structural Member Sectional Properties[15]

Beams	All Floor levels (1 to 14)	30cm × 40cm
Columns	Stories (1 to 5)	50cm × 50cm
Columns	Stories (6 to 10)	45cm × 45cm
Columns	Stories (11 to 14)	40cm × 40cm
Shear Walls	All parametric models	25 cm (Thickness)

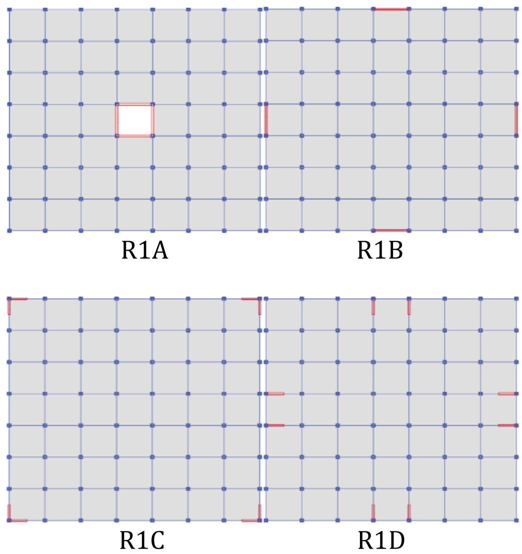

Fig.1 The analyzed models with 0.5% SW-FAR

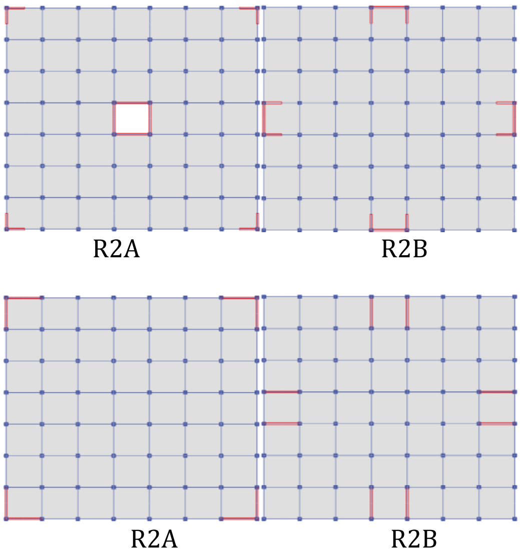

Fig.2 The analyzed models with 1.0% SW-FAR

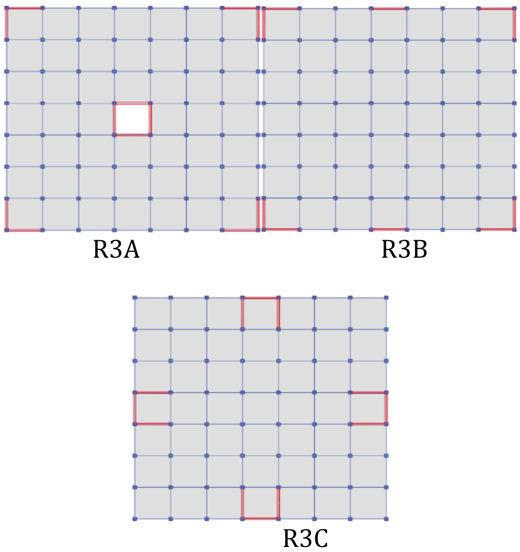

Fig.3 The analyzed models with 1.5% SW-FAR

3. RESULTS AND DISCUSSIONS

The capacity curve (Base Shear vs. Roof Displacement) serves as the primary tool for assessing structural strength. R1 (0.5%): Exhibits the lowest initial stiffness. The curve transitions to the plastic range at a lower base shear, indicating early yielding of structural components. R2 (1.0%): Shows a moderate increase in lateral strength. The elastic range is extended compared to R1, allowing the building to absorb higher seismic forces before significant damage occurs. R3 (1.5%): Demonstrates the most robust seismic capacity. The curve shows the highest peak base shear and the steepest initial slope, confirming that the 1.5% ratio provides the necessary rigidity for a 14-storey building to resist extreme lateral loads.14-story building to resist extreme lateral loads. The "location" of the shear wall significantly alters the building's center of stiffness. When the SW-FAR is kept constant at 0.5%, the variation in the capacity curve is a direct result of the structural symmetry and the efficiency of the lateral load path.

3.1. A shear wall-floor area ratio of 0.50% Capacity Curve

The capacity curve in the Fig. **4** for Non-linear Static Analysis (NSA) shows that the highest total lateral force at the base of the structure (base shear) is for model R1C. Roughly 14%, 21%, and 26% decreased, respectively, from model R1C, when the base shear strengths of the models are arranged in descending order. In addition, when referring to the largest displacement (the potential to move laterally and to be ductile during an earthquake), model R1A has the most of all the models. The models R1C, R1D and R1B have maximum resistances of approximately 18%, 30% and 46% less than model R1A respectively. Depicted in the Fig. **5**, the results demonstrate the differences in structural performances with peak ultimate base shear at (R1C).

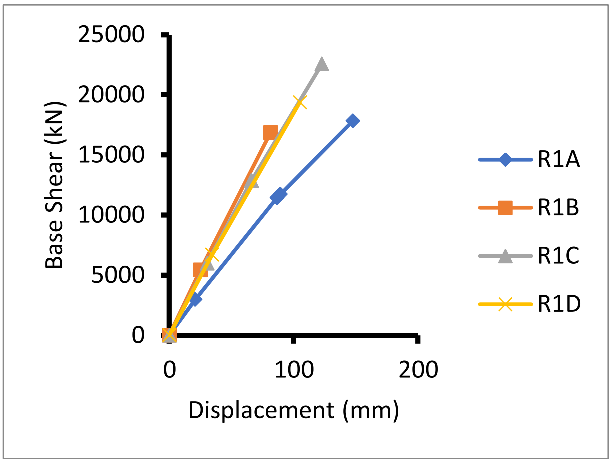

Fig.4 The curve of capacity

Maximum Storey Drift

Storey drift, the relative displacement between two successive floors divided by the story height (Δ/h), is an important design parameter in seismic design and it has a direct relationship with structural stability and damage to non-structural elements. The 14-story models are analyzed and compared, and the highly conservative design approach is confirmed. As per IS 1893: 2016 (Clause 7.11.1), the maximum permissible drift is limited to 0.004. The data presented here shows that all of the configurations evaluated in Fig. **6** (R1A, R1B, R1C and R1D) are still within these allowed safety limits. This is a performance test that must be taken into account when comparing the stiffness of different materials.

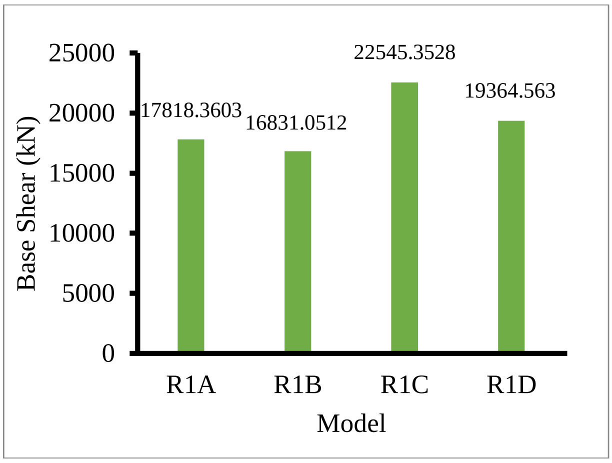

Fig.5 Maximum Base Shear

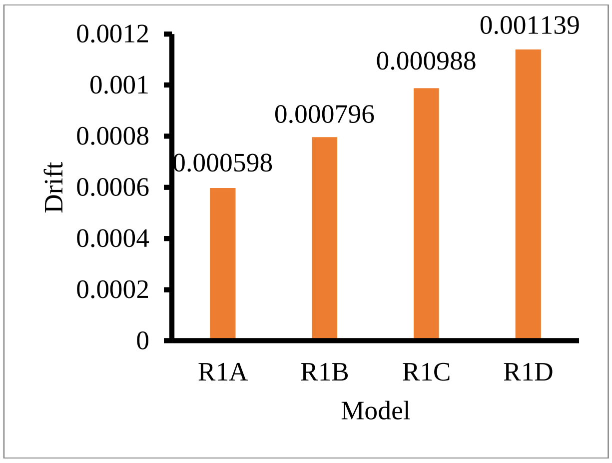

Fig.7 Maximum Story Drift

Configuration R1A is the most rigid configuration, Fig. **7** maximum drift of about 0.000598 at its greatest stiffness. The high stiffness gives maximum protection to non-structural parts. Both models R1B and R1C had moderate stiffness in the lateral direction with peak drifts equal to 0.000796 and 0.000988 respectively. The most flexible layout, on the other hand, was R1D, which was designed with a different philosophy from the rest, to achieve the highest peak drift of 0.001139. Model R1D always has the maximum values among the models. Models R1C, R1B and R1A show maximum drift of respectively about 13%, 30% and 47.5% less than R1D. Furthermore, in terms of structural stiffness and capacity to limit lateral drift during seismic events, model R1A is the lowest value for the maximum drift in all models. The maximum drift values for models R1B, R1C and R1D are respectively 33%, 65% and 90% greater than the value of model R1A. In particular, R1A exhibits an outstanding lateral stiffness, and thus the best lateral force ratio profile between the different storeys.

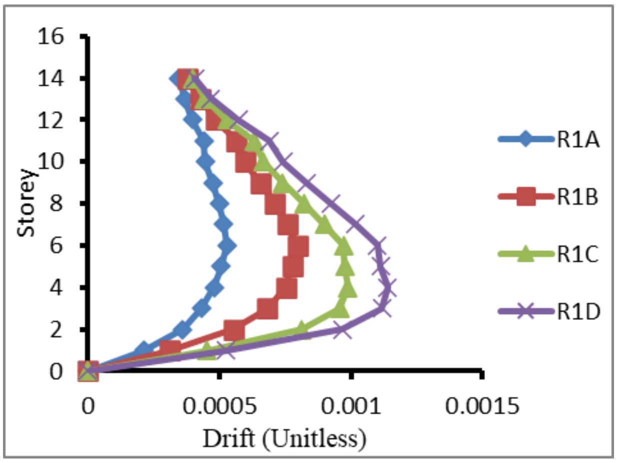

Fig.6 Story Drift

Maximum Storey Displacement

The lateral displacement profile as illustrated in Fig. **8**, the most flexible configuration is model R1D, with the absolute value of the top storey displacement being the highest one. On the other hand, model R1A demonstrates an increased structural rigidity and is able to effectively curtail lateral drift. The largest displacements of the models R1C, R1B and R1A are about 2%, 27% and 40% smaller than R1D, respectively, in a descending order. The displacements of R1B, R1C and R1D are 21.50%, 63%, and 67%, respectively; larger than the stiffest model, R1A. R1A minimal displacement is a result of its symmetric placement of shear walls that achieve an exact alignment of the Center of Mass and Stiffness. The displacement of R1D is higher as a result of eccentric wall positioning, creating torsional coupling. Although the R1D is almost twice as flexible as the R1A, its maximum displacement of 34.585 mm (see Fig. **9**) is still quite conservative.

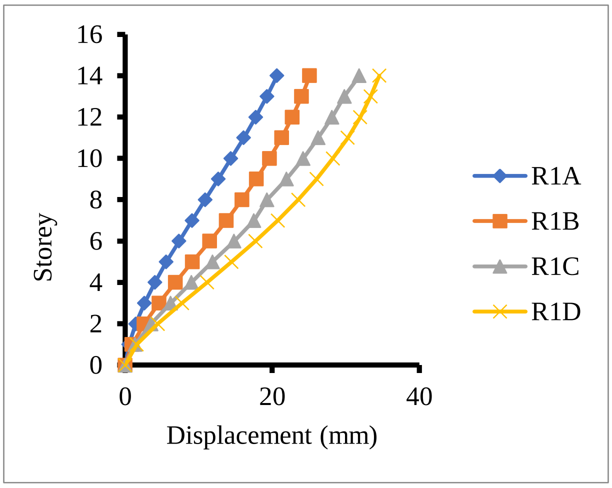

Fig.8 Storey Displacement

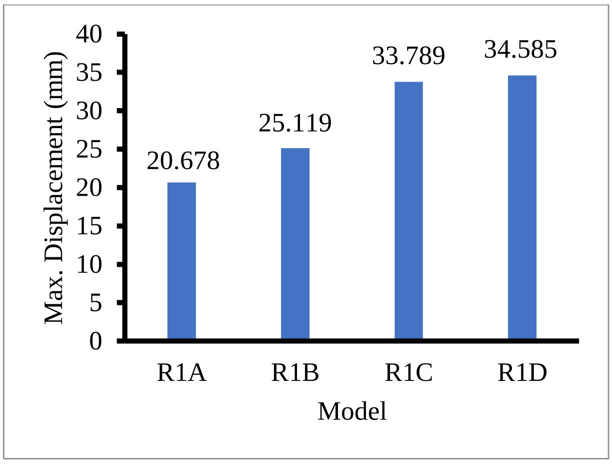

Fig.9 Maximum Storey Displacement

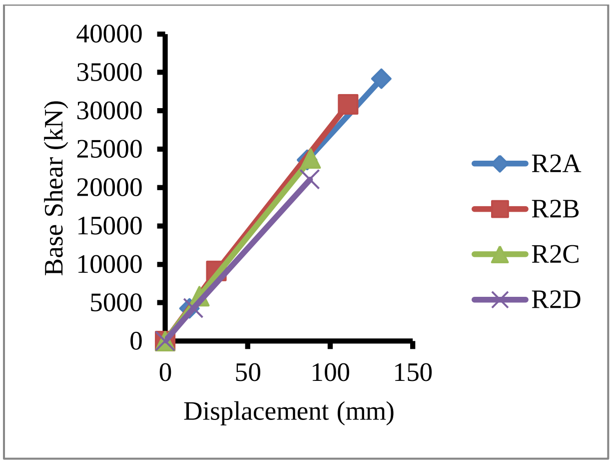

Fig.10 Capacity Curve

3.2. A shear wall-floor area ratio of 1.0%

Capacity curve

The following analysis of the NSA in Fig. **10** outcomes shows that models R2A and R2B have the best lateral load resistance. Base shear reductions of about 30% and 39% respectively. R2A resulted in a dramatic reduction in the structural capacities of models R2C and R2D. More important, the latter models have a much lower ultimate displacement capacity (34% less than R2A). This small amount of lateral yielding suggests some deficiencies in design to allow adequate structural ductility and energy dissipation prior to collapse. This observed increase in lateral displacement in model R2D is of concern as it may be an effect of design limitations in reducing displacements. All the models have the same initial elastic stiffness, thus the fundamental period is the same. The disparity of performance comes when the material is yielding in an inelastic manner base Shear (Ultimate Strength) R2A is the highest configuration as shown in Fig. **11**, with 34,171.8137 kN. Models R2C and R2D are much weaker, with a reduction of up to 39%, suggesting the weakness of the "weak storey" effects. Displacement & Ductility, R2A has an excellent "Strong Column-Weak Beam" (displacement) characteristic, displacing up to 132 mm and is very ductile. R2C and R2D, on the other hand, are too brittle and fail prematurely at 88 mm.

Maximum Storey Drift

The graph in the Fig. **12**, inter-storey drift profile for the R2 series always shows that model R2B has the maximum drift and is the largest relative lateral movement between floors. The maximum values of Model R2B are the highest ones of all the models throughout the building height. The descending order of maximum drift values are obtained for models R2C, R2D and R2A as around 35%, 43% and 52% lower, respectively, than model R2B.

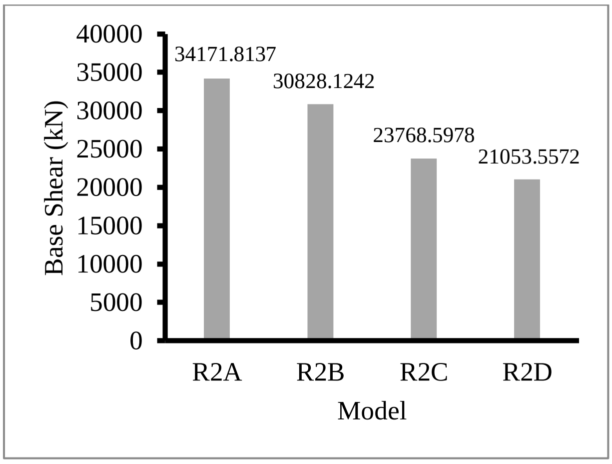

Fig.11 Maximum Base Shear

Furthermore, with respect to the maximum drift value, which is the most important factor for overall structural stiffness and restriction of lateral movement during earthquakes, model R2A has the smallest value of maximum drift as compared to other models. The peak drift of each of these three models as shown in Fig. **13** is approximately 18%, 36% and 109% greater than the peak drift of model R2A, respectively. These results add to the differences in structural performance between the models, particularly in terms of how inter-storey drift is controlled and structural rigidity is maintained in the models when subjected to lateral analysis. The drift profiles indicate that the structure has a non-linear evolution, parabolic in shape, typical of mid-to-high structures. All models have lateral drift starting at zero at the foundation level and peaking between Storey 5 and Storey 7. This suggests that at these levels this is a shear dominant response, as a result of the added base shear. The relative drift gradually reduces upward from Storey 7, as the seismic shear force reduces. Structural performance was analyzed based on the serviceability criteria provided in IS 1893: 2016. The inter-storey drift limit is specified as 0.004 in Clause

7.11.1. Peak recorded drift of 0.000921 in is even extremely conservative for the most flexible configuration (R2B) and is well within the limits Implications for engineering: All models are compliant, model R2A represents the most conservative approach and offers maximum protection against damage to non-structural elements that are susceptible (e.g., masonry infill, glass facades). On the other hand, the significant flexibility of R2B means that higher risk of non-structural damage is likely in severe seismic events and the need to consider secondary moments (P-Delta effects) is greater because of the higher lateral sway. The parabolic nature of the curves indicates that as the height of the building increases, the cumulative effect of story shear leads to an exponential increase in displacement, a phenomenon consistent with the behavior of high-rise cantilevered systems. Compliance with IS 1893 (Part 1): 2016: The seismic performance of the proposed 14-story building must be validated against the safety criteria stipulated by the Bureau of Indian Standards. According to Clause 7.11.1 of IS 1893: 2016, the story drift under design lateral force shall not exceed 0.004 times the story height. For a standard story height (hs) of 3.0 meters (3000 mm), the maximum permissible drift is calculated as Delta = 0.004 times 3000 = 12 mm per storey. Upon analyzing the slopes of the curves in Figure, the maximum inter-story drift (the difference in displacement between adjacent stories) for the most critical case (R2B) occurs between the upper levels but remains well below the 12 mm threshold.

Maximum Storey Displacement

The results in Fig. **14** show a very clear difference in the lateral rigidity of the R2 series in the evaluation of the lateral displacement profiles. Model R2B has the highest maximum roof displacement (see Fig. **15**) of 31.4 mm, followed in descending order by models R2C (21.0 mm), R2D (17.6 mm) and R2A (15.2 mm), with the respective maximum roof displacement values being around 33%, 44% and 52% lower. However, in terms of the ability to restrict absolute lateral movement, model R2A (stiffest case) has better structural stiffness.

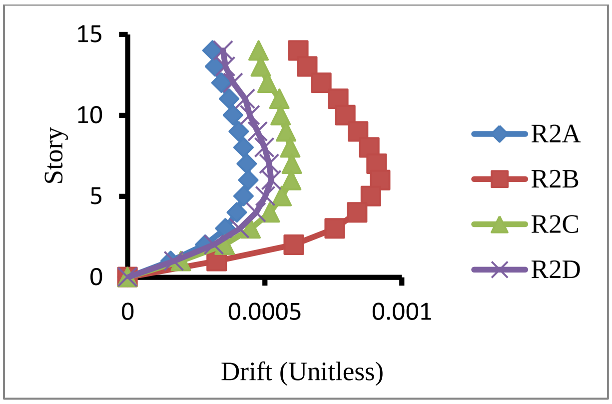

Fig.12 Story Drift

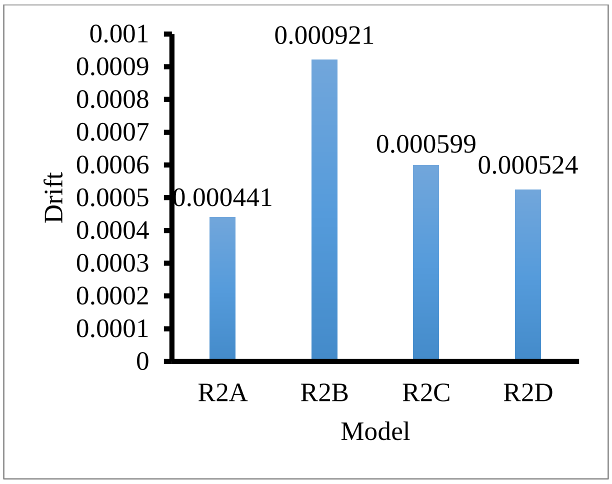

Fig.13 Maximum Story Drift

The roof displacement is calculated to be about 16%, 38% and 106% higher than the displacement of model R2A for models R2D, R2C and R2B respectively. Moreover, there are significant differences in behavior identified in the displacement curves. Model R2A has a near-linear response, suggesting flexure-dominant response with substantial shear wall reinforcement. The 106% displacement difference between models R2B suggests that there has been an increase in lateral bracing or a reduction in sidewall thickness, making the structure more ductile, but less rigid. The secondary P-Delta effects should be considered when the secondary moments are greater than 10% of the primary moments, as per the structural design standards. The overall drift ratio (Delta-H) of the 42-meter (14-storey) building for the most flexible model (R2B) is very small at about 0.00074 (31.4 mm / 42,000 mm). This is a very small value; therefore, geometric non-linearity (P-Delta effects) will not have a significant influence on the overall stability of these models. There is a fairly even distribution of lateral stiffness throughout the building's height.

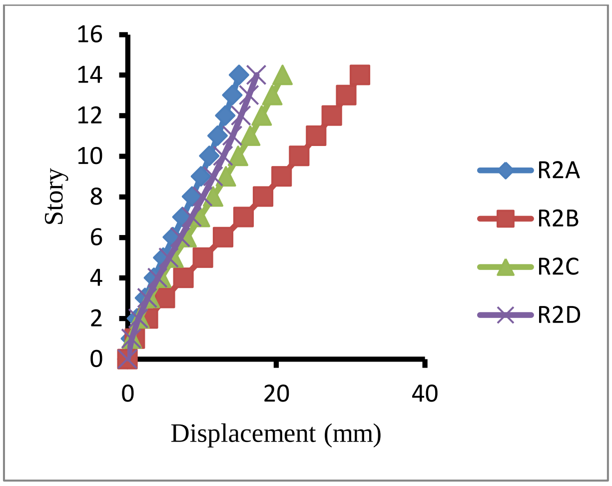

Fig.14 Storey Displacement

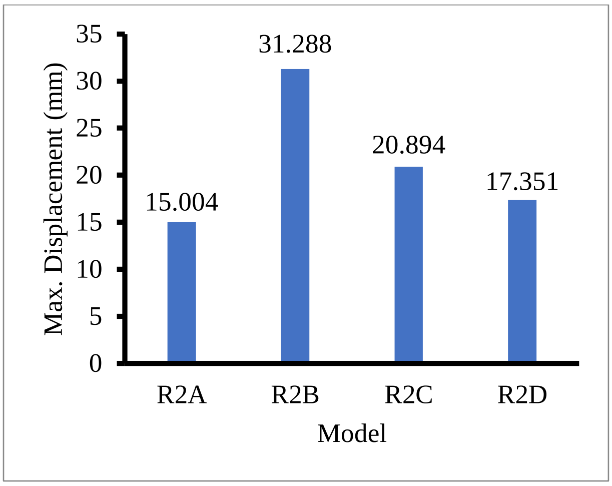

Fig.15 Maximum Storey Displacement

3.3. A shear wall-floor area ratio of 1.5%

Capacity Curve

The structural response to lateral forces for models R3A and R3B are found to be similar and their base shear capacities at maximum (see Fig. **17**) are comparable at approximately 20,000 kN, with maximum displacements in the order of 60 mm. In contrast, Model R3C had a significantly greater load bearing capacity with a maximum base shear that was nearly 75% greater than its counterparts (nearly 35,000 kN). In addition, model R3C showed an outstanding gain in overall deformation capacity, attaining an ultimate displacement of almost 50% more than the other models (up to 90 mm) in Fig. **16**, and significantly better structural resilience. The ultimate lateral load-carrying capacity (Vu) of the structures shows significant variation across the three models. R3C exhibited the highest lateral strength, reaching a peak base shear of 34,455 kN. In contrast, Model R3A and Model R3B showed substantially lower capacities, peaking at 19,600 kN and 18,800 kN, respectively. Model R3C demonstrated a maximum displacement of 91.1 mm, which is roughly 65% higher than R3A. This extended plastic range indicates that R3C can undergo significant inelastic deformation before global collapse, providing a higher safety margin for "Life Safety" and "Collapse Prevention" performance levels. All three models show a coincident linear elastic range up to a base shear of approximately 5,000 kN. However, as the displacement exceeds 15 mm, the curves diverge. The degradation of stiffness in R3A and R3B is more rapid, indicating earlier yielding of the structural components.

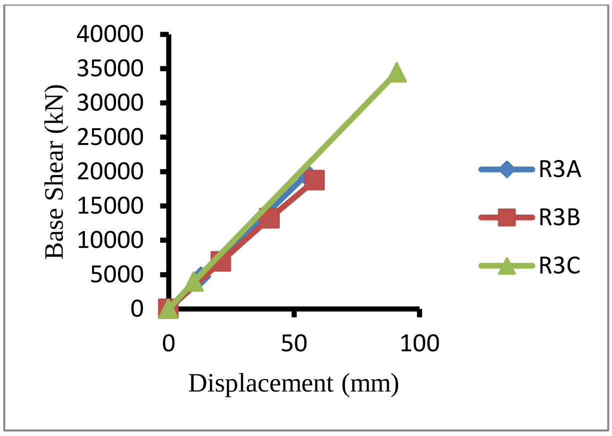

Fig.16 Capacity Curve

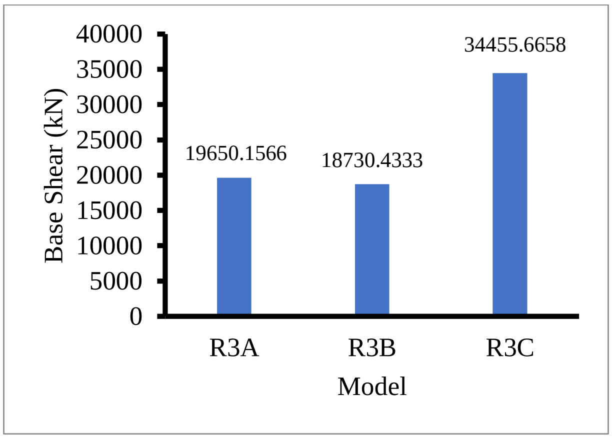

Fig.17 Maximum Base Shear

Maximum Storey Drift

Model R3B is the most susceptible to lateral deflection with a maximum absolute drift of about 0.06% in the mid-rise stories. On the other hand, model R3A achieves a drift of 0.04%, the most model R3C with a displacement that does not exceed 0.03%. If these structural deviations are expressed relative to others, they are striking. Model R3B has been tested to see a significant 100% deviation from the most rigid mode as shown in Fig. **l8**, R3C in lateral displacement. Besides, the drift of R3B is 50% higher than that of the intermediate model, R3A. While under baseline conditions an absolute drift of 0.06% is not necessarily a problem, the 100% relative drift increase in the lateral sway is definitely a sign of insufficient lateral stiffness in R3B. As such, when subjected to increase seismic loads R3B would be seen more much more vulnerable to structural degradation and critical P-Delta phenomena than the optimized R3C system. All three configurations exhibit a characteristic c-curve profile. The drift starts at zero at the base (fixed boundary condition), increases significantly in the lower-to-middle stories, and then stabilizes or slightly reduces toward the roof. For all models, the peak drift occurs between Storey 6 and Storey 8. This is typical for mid-rise frames where the cumulative effect of flexural and shear deformations peaks in the middle third of the height. R3B, Exhibits the highest drift, peaking at approximately 0.0006 in Fig. **19**. This suggests R3B is the most flexible configuration of the three. R3A, Shows intermediate stiffness with a peak drift around 0.00038. R3C, exhibits the lowest drift (approx. 0.00028), indicating it is the stiffest configuration. Discussion based on IS 1893 (Part 1): 2016.

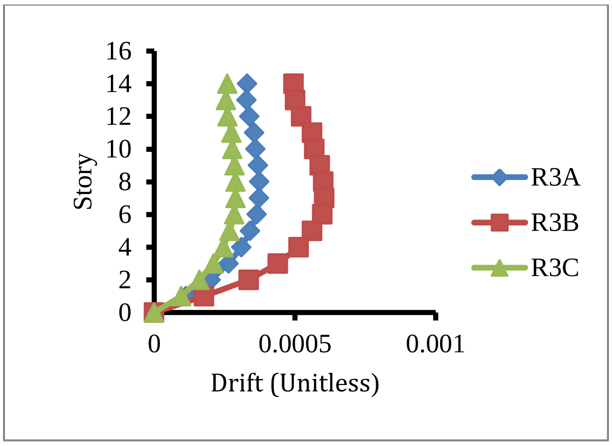

Fig.18 Storey Drift

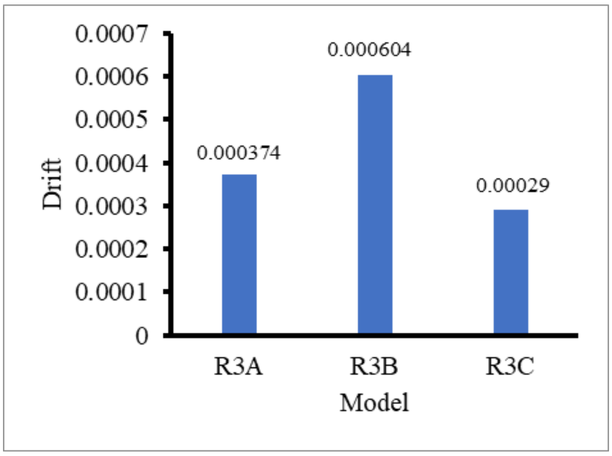

Fig.19 Maximum Storey Drift

Maximum Storey Displacement

R3C with the smallest top storey displacement about 10 mm. Model R3A deflects 25% more laterally, to 12.5 mm, than the R3C baseline. Model R3B has the lowest and most flexible structural performance of any model, with a peak displacement of 22 mm, or a dramatic 120% increase from Model R3C. However, looking at how much more it improves performance on the weakest configuration (R3B), the intermediate Model R3A can improve the top-storey drift by 43.1% and the superior lateral stiffness of Model R3C can reduce the overall maximum displacement by 54.5%. Model R3B is the most flexible model as it is based on the storey displacement profile shown in Fig. **20** and the maximum storey displacement shown in Fig. **21** for a structure with 14 stories under lateral load, with a maximum displacement of 21.017 mm at the top storey.

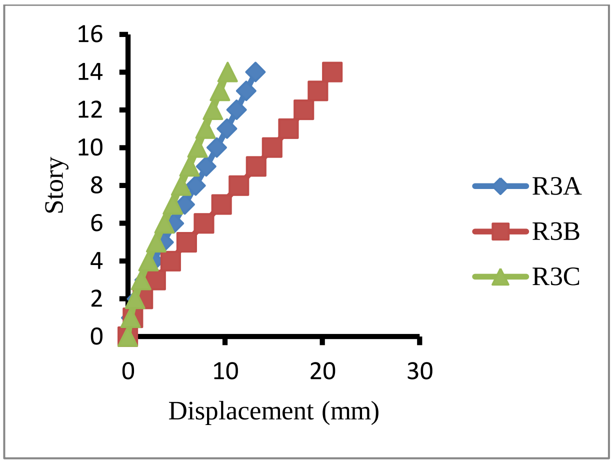

Fig.20 Storey Displacement

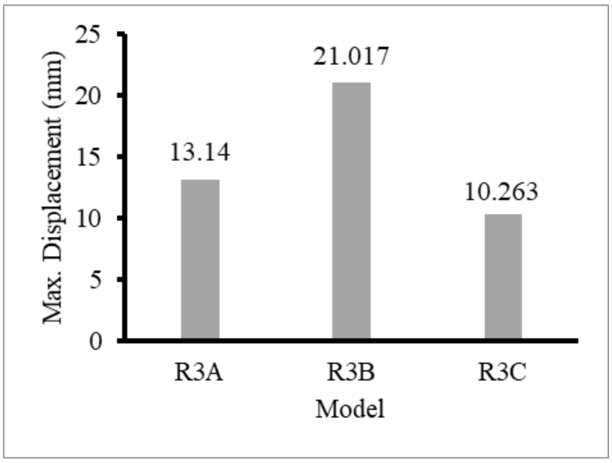

Fig.21 Maximum Storey Displacement

Overall, the most flexible configuration (R3B) shows a maximum lateral displacement offset of 13.14 mm, the most rigid (R3C) shows a maximum lateral displacement offset of 10.263 mm, which represents approximately a 51% reduction from the maximum lateral displacement offset of the most flexible configuration (R3B) when compared to the most rigid configuration (R3C).

4. CONCLUSIONS

- Positioning of walls is an important strength multiplier (Base Shear Capacity and Ductility). This model (R3C), with the optimized 1.5% SW-FAR, had the highest peak base shear (34,800 kN) which is 77% higher than the sub-optimal models.

Additionally, R3C applied plastic deformation to 91.1 mm, which was the most efficient to facilitate energy dissipation with respect to Life Safety.

- For the maximum lateral stiffness symmetrical models (R1A, R2A, and R3C) were maximized. In contrast, the eccentric models had extreme flexibilities, model R3B had a 100% relative increase in lateral sway at all levels (stories 5-7) compared with R3C.
- When walls are placed asymmetrically (e.g., R1D, R2B, R3B), there is a dangerous torsional coupling of the misalignment of the Center of Mass and Center of Rigidity. This twist was done away with by optimally aligned models.
- Structural performance due to spatial distribution is more important than total volume of material (Optimal Configuration). A highly symmetrical 0.5% SW-FAR layout (R1A) performed better than layouts with eccentricities and higher densities of walls (R1B, R2A). But an optimized layout can be scaled to 1.5% SW-FAR (R3C) to achieve maximum structural rigidity with no brittle failure.

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