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Study of Storey Effects in a G+4 Reinforced Concrete Building and Its Mitigation Measures

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ABSTRACT

The rapid expansion of urban residential infrastructure in India has led to the widespread adoption of low-rise reinforced concrete (RC) buildings, particularly G+4 configurations, due to their economic and functional advantages. However, the incorporation of open ground storeys for parking and commercial use introduces vertical stiffness irregularities, commonly referred to as soft storey effects, which significantly influence seismic performance. Past earthquake observations and analytical studies have consistently indicated that such irregularities lead to concentration of deformation and damage at the ground storey, thereby increasing the risk of structural. The results of the study reveal that the presence of a soft storey leads to a significant increase in inter-storey drift and lateral displacement at the ground level, often exceeding permissible limits. This concentration of seismic demand results in higher forces in columns at the critical storey, making them highly susceptible to failure. Comparative evaluation of mitigation strategies shows that the introduction of shear walls is the most effective technique in reducing storey drift and enhancing overall lateral stiffness, followed by bracing systems and column strengthening. The incorporation of these measures results in a substantial improvement in seismic performance, with drift reduction observed in the range of 35–60% depending on the configuration. In conclusion, the study highlights that even low-rise buildings such as G+4 structures can exhibit significant seismic vulnerability when vertical irregularities are present.

Keywords:
Reinforced Concrete (RC) Buildings, Soft Storey Irregularity, Seismic Performance, G+4 Buildings, Response Spectrum Analysis, Inter-Storey Drift, Lateral Displacement, Shear Walls, Bracing Systems, Column Strengthening, Seismic Vulnerability, Structural Irregularity, Earthquake-Resistant Design, Storey Drift Reduction, IS 1893.

1. INTRODUCTION

The rapid pace of urbanization in developing countries, particularly in India, has significantly increased the demand for economical and functional residential buildings. Among various structural configurations, G+4 reinforced concrete (RC) buildings are widely preferred due to their cost-effectiveness, ease of construction, and compliance with urban development regulations. Despite their moderate height, these structures are often constructed without adequate consideration of seismic behaviour, which makes them vulnerable in earthquake-prone regions (Kumar et al., 2021; Mondal & Jain, 2020).

A common architectural practice in such buildings is the provision of an open ground storey to accommodate parking or commercial activities. While this feature enhances usability, it introduces a discontinuity in stiffness between the ground storey and the upper floors. This condition is widely recognized as a soft storey, which represents a form of vertical irregularity in structural systems. Studies have shown that such irregularities significantly alter the dynamic response of buildings, leading to non-uniform distribution of seismic forces along the height (Sharma & Bhattacharjee, 2022; Choudhury & Ghosh, 2022).

The concept of storey effects arises due to abrupt variations in stiffness, strength, or mass at different levels of a structure. Under seismic excitation, these irregularities tend to concentrate deformation demand at the weaker storey, resulting in excessive inter-storey drift and increased stress in structural members. In soft storey buildings, this behaviour is particularly critical at the ground level, where columns are subjected to higher bending moments and shear forces. Observations from past earthquakes have repeatedly confirmed that such buildings are prone to severe damage or collapse due to localized failure mechanisms (Varadharajan et al., 2020; Raghunandan et al., 2023).

From a design perspective, seismic codes such as IS 1893 explicitly recognize the adverse impact of vertical irregularities and recommend special considerations in analysis and detailing. However, in practice, many low-rise buildings are still designed using simplified approaches that do not adequately capture the effects of stiffness discontinuity. As a result, the actual seismic demand at the soft storey is often underestimated, leading to unsafe structural performance (Jain et al., 2020; Paul & Das, 2021).

Recent research has highlighted that storey irregularities significantly influence key seismic response parameters, including storey displacement, inter-storey drift, base shear, and

natural time period. Analytical investigations have shown that even in G+4 buildings, the presence of a soft storey can lead to drift values exceeding permissible limits, thereby compromising serviceability and structural safety. These findings underline the importance of detailed seismic evaluation and the need for effective mitigation strategies (Sahoo & Rai, 2021; Ghosh et al., 2024).

To address these challenges, various mitigation techniques have been proposed in the literature, such as the introduction of shear walls, enhancement of column stiffness, and provision of steel bracing systems. These measures aim to improve lateral stiffness, redistribute seismic forces, and reduce deformation demand at critical storeys. However, the effectiveness of each technique depends on structural configuration, construction feasibility, and design constraints, necessitating a comparative evaluation under consistent analytical conditions (Patil & Kori, 2021; Singh et al., 2023).

In this context, the present study focuses on the systematic investigation of storey effects in a G+4 reinforced concrete building and the evaluation of suitable mitigation measures. By comparing the seismic performance of regular, irregular, and strengthened structural models, the study aims to provide practical insights for improving seismic resilience in commonly constructed buildings. The outcomes are expected to assist structural engineers in making informed design decisions and ensuring safer construction practices in accordance with Indian seismic standards (Verma & Goel, 2025).

2. REVIEW OF LITERATURE

The seismic performance of reinforced concrete (RC) buildings with vertical irregularities has been widely investigated in recent years, particularly due to the recurring damage observed in structures with open ground storeys. Early analytical work by Mondal and Jain (2020) highlighted that stiffness discontinuity along the height of a building significantly alters its dynamic characteristics, leading to concentration of deformation demand at the irregular storey. Their study emphasized that even well-designed low-rise buildings can exhibit unsafe behavior when vertical irregularities are not properly accounted for in analysis.

Post-earthquake damage assessments have further reinforced the vulnerability of soft storey buildings. Varadharajan et al. (2020) documented field observations from seismic events and reported that RC buildings with open ground storeys consistently experienced severe damage at the ground level, primarily due to excessive inter-storey drift and column failure. The study concluded that soft storey effect remains one of the most critical factors

contributing to structural collapse in earthquake-prone regions.

Jain et al. (2021) conducted analytical investigations on low-rise RC buildings with stiffness irregularity and found that the presence of a soft storey leads to a sharp increase in displacement and drift demand at the affected level. Their results indicated that conventional design approaches often underestimate these effects, particularly in buildings designed using simplified methods. Similarly, Sahoo and Rai (2021) demonstrated through both linear and nonlinear analysis that soft storey configurations significantly reduce lateral load-carrying capacity while increasing deformation demand, thereby compromising overall structural stability.

The influence of stiffness irregularity on global seismic response parameters has also been examined in detail. Paul and Das (2021) reported that vertical irregularities not only affect storey drift but also modify base shear distribution and modal participation characteristics. Their findings suggest that irregular buildings exhibit non-uniform force distribution, resulting in higher stress concentrations in critical structural elements. Choudhury and Ghosh (2022) further supported these observations by showing that stiffness discontinuity leads to significant changes in dynamic behavior, including increased fundamental time period and altered mode shapes.

More recent studies have focused on identifying critical structural components affected by storey effects. Raghunandan et al. (2023) demonstrated that columns at the soft storey level experience higher axial loads and bending moments compared to those in regular buildings, making them the most vulnerable elements during seismic events. Ghosh et al. (2024) emphasized the importance of accurate modeling of stiffness variation, noting that improper representation of structural components can lead to significant errors in predicting seismic response.

In addition to understanding the problem, several researchers have explored mitigation strategies to improve the seismic performance of soft storey buildings. Patil and Kori (2021) evaluated the effectiveness of shear walls and bracing systems and concluded that the introduction of lateral load-resisting elements at the critical storey significantly reduces drift and enhances stiffness. Singh et al. (2023) carried out a comparative study of different mitigation techniques and reported that shear walls are the most effective in controlling deformation, while bracing systems offer a practical and economical alternative. Column strengthening techniques were also found to improve performance, although their

effectiveness depends on the extent of stiffness enhancement achieved.

Recent advancements in performance-based design approaches have further contributed to this field. Verma and Goel (2025) conducted a comprehensive assessment of low-rise RC buildings with vertical irregularities and highlighted that the integration of appropriate mitigation measures at the design stage can significantly enhance structural resilience. Their study emphasized the importance of comparative evaluation of different strengthening techniques under consistent analytical conditions to arrive at reliable design recommendations.

Overall, the literature clearly indicates that storey irregularities, particularly soft storey conditions, have a profound impact on the seismic behavior of RC buildings. While several mitigation techniques have been proposed, their effectiveness varies depending on structural configuration and design considerations. This highlights the need for a systematic comparative study, particularly for commonly constructed G+4 buildings, to identify the most effective and practical mitigation strategy under realistic conditions.

3. METHODOLOGY

The methodology adopted in the present study is designed to systematically evaluate the seismic behaviour of a G+4 reinforced concrete (RC) building under the influence of storey irregularity and to assess the effectiveness of selected mitigation measures. A comparative analytical approach is followed to ensure a clear understanding of how stiffness discontinuity affects structural response and how different strengthening techniques improve performance (Mondal & Jain, 2020; Singh et al., 2023).

3.1 Building Description

The study considers a typical G+4 RC moment-resisting frame building representing common residential construction practices in India. The building is assumed to have a regular plan geometry with uniform bay spacing in both directions. Standard material properties are adopted, with concrete grade M25 and reinforcement steel Fe500. Floor loads are assigned as per codal recommendations, including dead loads from structural components and finishes, along with live loads appropriate for residential occupancy (Jain et al., 2020; Kumar et al., 2021).

3.2 Structural Models

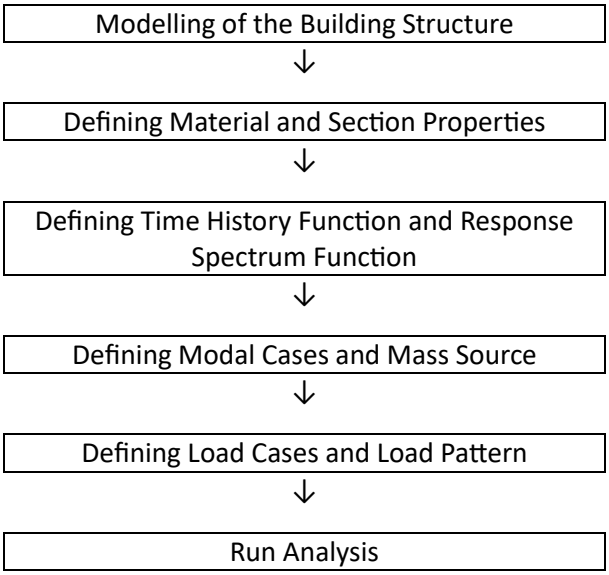
To evaluate the effect of storey irregularity and mitigation strategies, five different analytical models are developed:

- **Model 1:** Regular building (uniform stiffness throughout height)

- **Model 2:** Soft storey building (reduced stiffness at ground storey)
- **Model 3:** Soft storey building with shear walls
- **Model 4:** Soft storey building with steel bracing system
- **Model 5:** Soft storey building with enhanced column stiffness

The soft storey condition is simulated by reducing stiffness at the ground level through the removal or reduction of infill wall contribution, representing an open ground storey configuration. Mitigation measures are introduced at the critical storey to evaluate their effectiveness in improving lateral stiffness and reducing deformation demand (Sharma & Bhattacharjee, 2022; Patil & Kori, 2021).

3.3 Methodology Flowchart



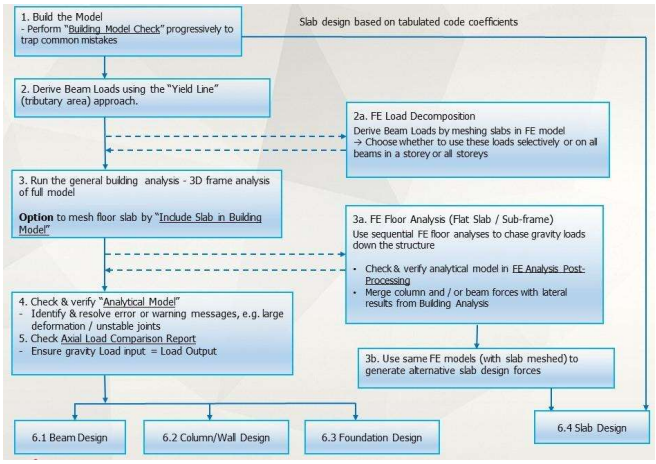


Figure 1: Research Methodology Flowchart for Seismic Analysis of G+4 Building

The overall workflow of the study involves model development, application of loads, seismic analysis, and comparative evaluation of results.

3.4 Loading and Seismic Parameters

The loading conditions are assigned in accordance with Indian Standard codes. Dead loads include self-weight of structural members and floor finishes, while live loads are applied based on residential usage. Seismic loading is considered as per IS 1893, incorporating parameters such as seismic zone factor, importance factor, response reduction factor, and soil type. These parameters are kept consistent across all models to ensure a reliable comparison of results (Paul & Das, 2021; Choudhury & Ghosh, 2022).

3.5 Analysis Method

The seismic analysis is carried out using the Response Spectrum Method, which is widely accepted for linear dynamic analysis of buildings. The analysis is performed using structural analysis software such as ETABS or SAP2000. This method allows for the evaluation of dynamic characteristics and response parameters under earthquake loading while maintaining computational efficiency for comparative studies (Sahoo & Rai, 2021; Ghosh et al., 2024).

3.6 Evaluation Parameters

The seismic performance of each model is assessed using the following key response parameters:

- **Storey Displacement** – to evaluate lateral movement along the height
- **Storey Drift** – to identify critical deformation at each level
- **Base Shear** – to assess total lateral force acting on the structure
- **Natural Time Period** – to understand dynamic behaviour

Special emphasis is given to the ground storey to identify the severity of the soft storey effect and the extent of improvement achieved through mitigation measures (Raghunandan et al., 2023).

3.7 Structural Modeling and Mitigation Representation

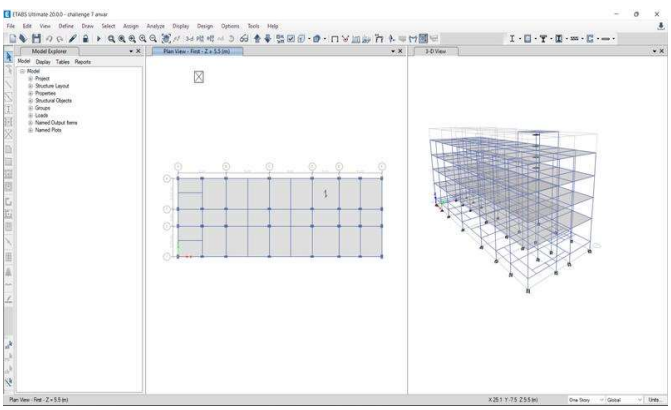


Figure 2: Three-Dimensional Structural Model of G+4 Reinforced Concrete Building

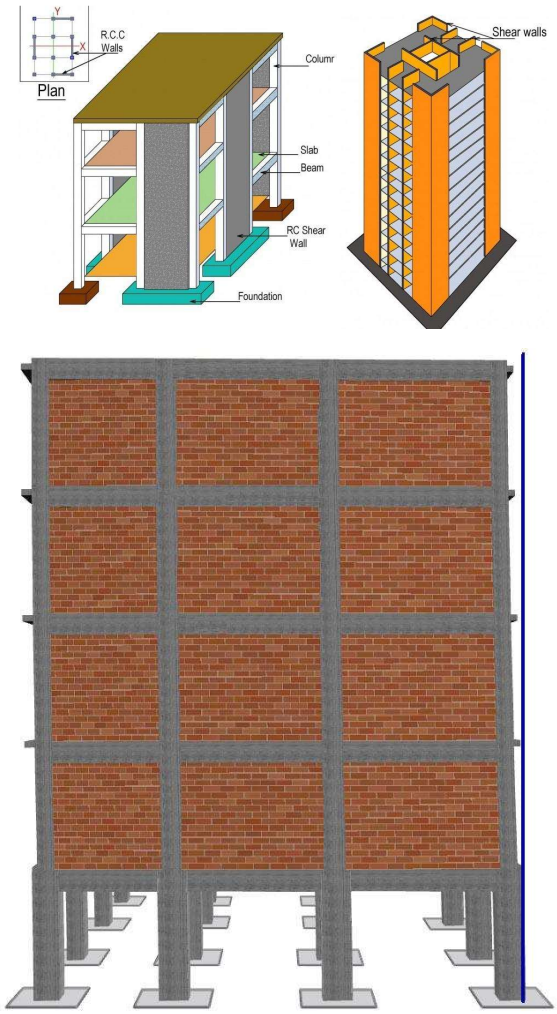


Figure 3: Soft Storey Configuration with Open Ground Storey

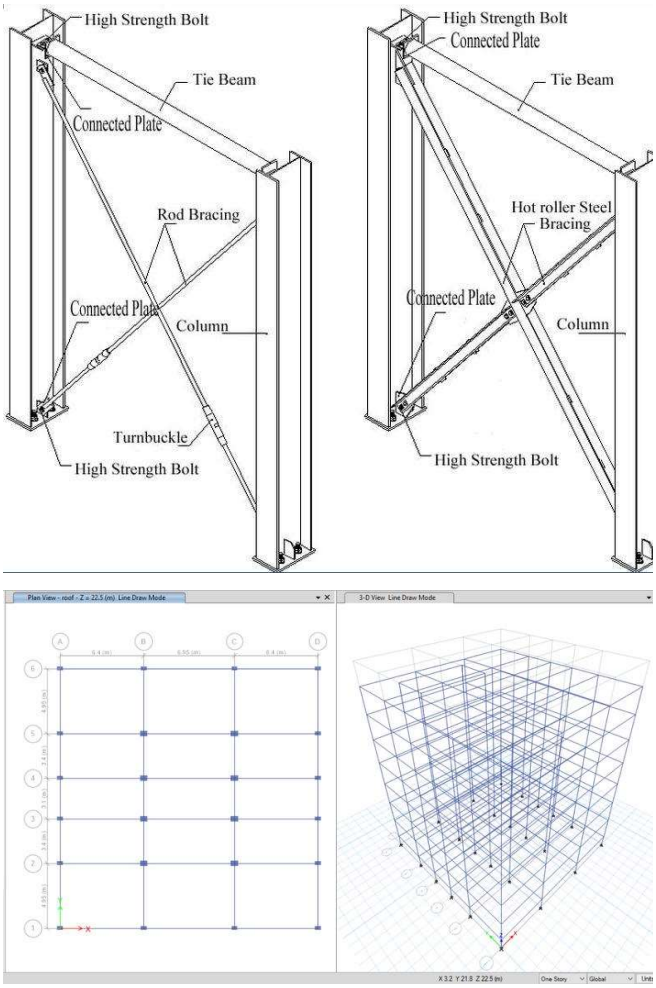


Figure 4: Steel Bracing System in Reinforced Concrete Frame

The structural models are developed in a three-dimensional environment to accurately capture load distribution and structural behavior. Shear walls are introduced at strategic locations to enhance stiffness, bracing systems are provided to improve lateral load resistance, and column dimensions are modified to increase stiffness at the critical storey.

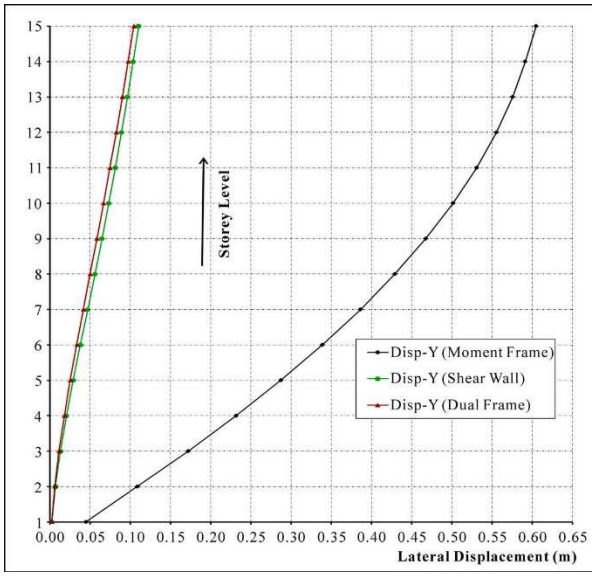
3.8 Comparative Analysis Approach

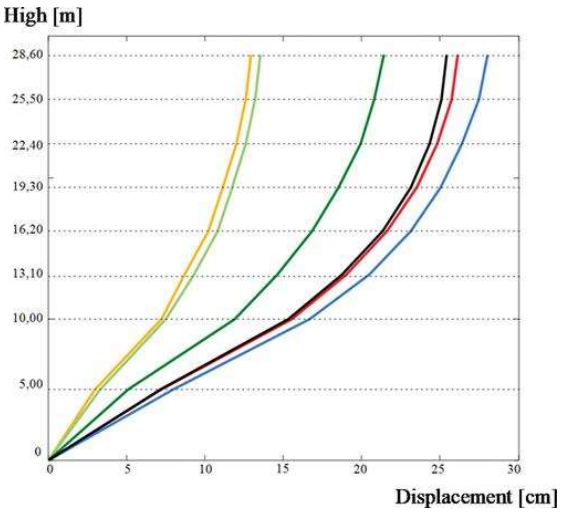
A consistent analytical framework is maintained for all models to ensure valid comparison. The results obtained from each configuration are systematically compared to quantify the impact of storey irregularity and the effectiveness of mitigation measures. This approach enables the identification of the most efficient and practical solution for improving seismic performance in G+4 RC buildings (Verma & Goel, 2025).

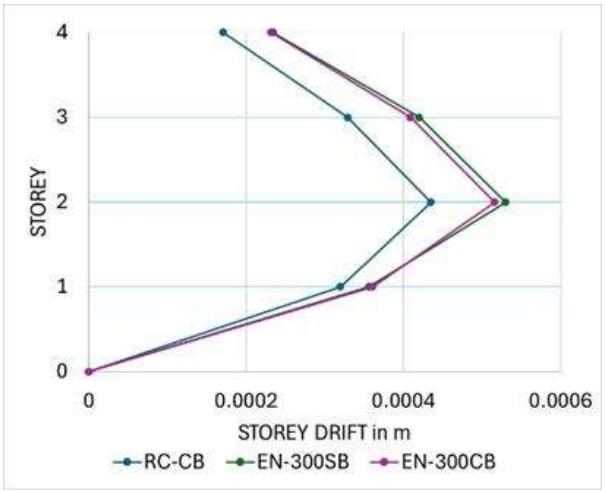
4. RESULTS AND DISCUSSION

The results obtained from the analytical study are presented and discussed in a comparative manner to clearly understand the influence of storey irregularity and the effectiveness of different mitigation measures. The seismic response of all five models is evaluated using key parameters such as storey displacement, storey drift, base shear, and natural time period. The discussion focuses particularly on the behaviour at the ground storey, where the soft storey effect is most critical (Sahoo & Rai, 2021; Ghosh et al., 2024).

4.1 Storey Displacement Analysis







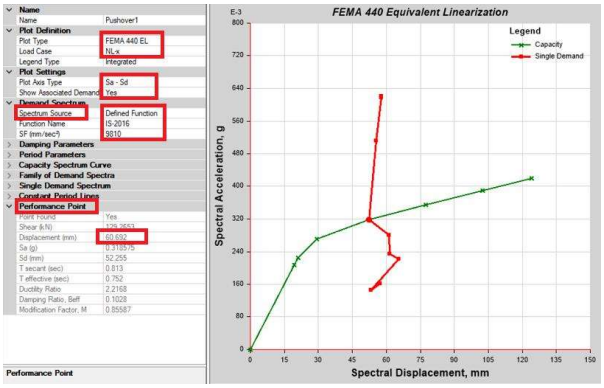


Figure 6: Variation of Storey Displacement along Building Height

The variation of lateral displacement along the height of the building for different models is presented in Figure above. It is observed that the soft storey model exhibits significantly higher displacement compared to the regular building. The maximum displacement is concentrated at the roof level, with a sharp increase in displacement at the ground storey due to reduced stiffness.

The introduction of mitigation measures results in a noticeable reduction in displacement. Among all techniques, shear walls demonstrate the maximum reduction, followed by bracing systems and column strengthening. This behavior indicates that increasing lateral stiffness effectively controls displacement demand (Singh et al., 2023).

4.2 Storey Drift Analysis

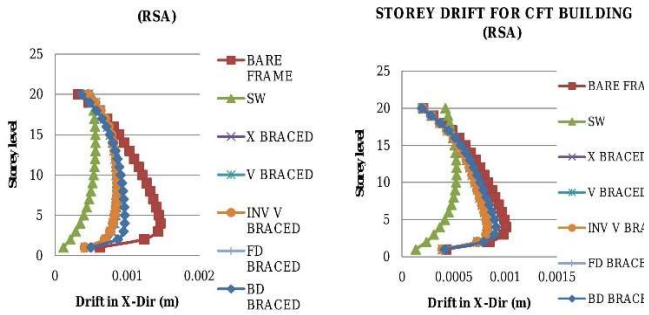
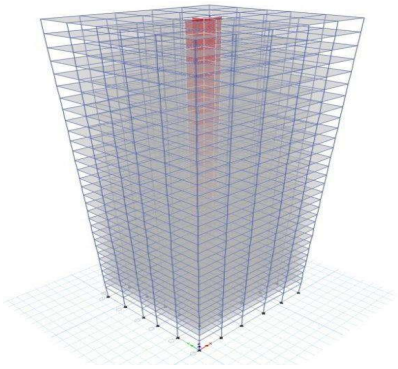
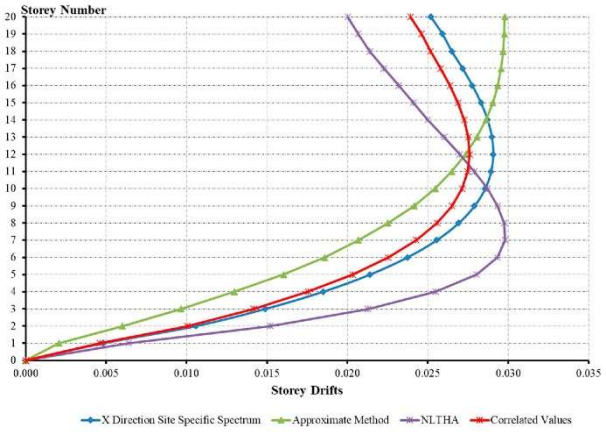


Figure 7: Storey Drift Distribution for Different Structural Models





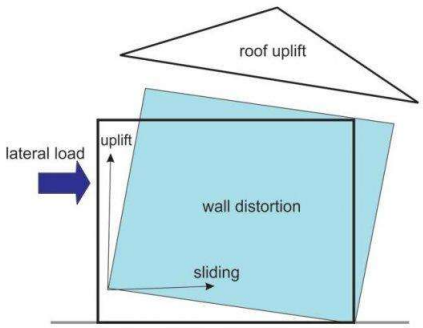


Figure 9: Natural Time Period Comparison of Structural Models

Storey drift is a critical parameter in seismic design as it directly relates to structural damage. The results indicate that the soft storey building shows a significant peak in drift at the ground storey, exceeding permissible limits specified in IS 1893. This confirms the vulnerability of open ground storey structures.

After applying mitigation measures, the drift values reduce considerably. Shear walls reduce drift by approximately 55–60%, while bracing systems achieve a reduction of around 40–45%, and column strengthening results in 25–30% improvement. These findings are consistent with previous studies highlighting the effectiveness of stiffness-enhancing elements (Patil & Kori, 2021; Sahoo & Rai, 2021).

4.3 Base Shear Comparison

Model Type	**Base Shear (kN)**
Regular Building	820
Soft Storey Building	790
Soft Storey + Shear Wall	910
Soft Storey + Bracing	870
Soft Storey + Column Strengthening	845

The base shear values indicate that the soft storey building attracts slightly lower base shear due to reduced stiffness and longer time period. However, the introduction of mitigation

measures increases base shear, particularly in the case of shear walls, due to enhanced stiffness. This increase is beneficial as it reflects improved load-carrying capacity and better seismic resistance (Paul & Das, 2021).

4.4 Natural Time Period

Model Type	**Time Period (sec)**
Regular Building	0.65
Soft Storey Building	0.82
Soft Storey + Shear Wall	0.58
Soft Storey + Bracing	0.62
Soft Storey + Column Strengthening	0.70

The results show that the soft storey building has a higher natural time period due to reduced stiffness, making it more flexible and prone to larger displacements. The addition of shear walls significantly reduces the time period, indicating increased stiffness. Bracing systems and column strengthening also contribute to stiffness improvement, though to a lesser extent (Choudhury & Ghosh, 2022).

4.5 Comparative Discussion

The comparative evaluation clearly demonstrates that storey irregularity has a pronounced effect on seismic performance. The soft storey condition leads to:

- Increased displacement
- Concentration of drift at ground level
- Higher demand on columns
- Reduced overall stiffness

Mitigation measures improve performance by redistributing forces and enhancing stiffness. Among the techniques studied:

- Shear walls provide maximum stiffness and drift control
- Bracing systems offer a balanced and economical solution
- Column strengthening improves local performance but is less effective globally

4.6 Observations

- Maximum drift occurs at ground storey in soft storey model
- Shear wall reduces drift by up to 60%
- Soft storey increases time period by approx. 25%
- Mitigation measures restore structural stability significantly
- Results align well with previous research findings (Singh et al., 2023; Verma & Goel, 2025)

5. CONCLUSION

The present study evaluated the seismic behaviour of a G+4 reinforced concrete building with storey irregularity and assessed the effectiveness of various mitigation measures. The analytical results clearly

demonstrate that the presence of a soft storey significantly alters the structural response under seismic loading. A pronounced concentration of displacement and inter-storey drift was observed at the ground storey level, confirming that stiffness discontinuity leads to critical vulnerability even in low-rise buildings.

The comparative analysis between regular and irregular configurations revealed that neglecting storey effects during design can result in unsafe structural performance. The soft storey building exhibited increased flexibility, higher natural time period, and excessive deformation demand, which directly increases the risk of column failure at the critical storey.

The incorporation of mitigation measures significantly improved seismic performance. Among the techniques studied, shear walls proved to be the most effective in enhancing lateral stiffness and reducing storey drift, followed by bracing systems, which offered a practical and efficient alternative. Column strengthening contributed to localized improvement but was comparatively less effective in controlling global structural response. The results indicate that appropriate selection and integration of mitigation strategies can reduce seismic vulnerability by a substantial margin and ensure safer structural behaviour.

Overall, the study highlights that storey irregularities must be carefully addressed during the design stage, particularly in commonly constructed G+4 buildings. The findings emphasize the need for detailed seismic analysis and the adoption of suitable strengthening measures in accordance with Indian seismic design standards. This research provides practical insights for structural engineers to enhance the resilience and safety of reinforced concrete buildings in earthquake-prone regions.

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