Effect of Vertical Irregularities in Stiffness Due to Seismic Activity with and Without Girder

Musaddique Q. Bandirkar[1], Prof. Abhijeet R. Undre[2]

[1]ME Student, KJ's Educational Institute, KJ College of Engineering and Management Research, Pune, Maharashtra (Affiliated to Savitribai Phule Pune University)

[2]Associate professor, KJ's Educational Institute, KJ College of Engineering and Management Research, Pune, Maharashtra (Affiliated to Savitribai Phule Pune University)

Abstract

This research investigates the effect of vertical irregularities in stiffness on the seismic and blast performance of reinforced concrete (RC) multi-storey buildings with and without girders. Using ETABS software, analytical models were developed for G+6, G+9, G+12, G+15, G+20, and G+25 structures to assess their response under seismic and 100 kg TNT blast loading conditions at varying distances (10 m, 15 m, and 20 m). The study evaluates parameters such as storey displacement, storey drift, base shear, and stiffness, following the provisions of IS 1893 (Part 1): 2016. Results revealed that buildings with vertical stiffness irregularities exhibited increased displacement and drift, particularly in upper storeys, indicating higher vulnerability under dynamic loads. Conversely, structures with girders showed improved stiffness, reduced drift, and better stability, demonstrating their role in enhancing overall seismic and blast resistance. Moreover, increasing the standoff distance significantly reduced base shear and displacement. The findings highlight the necessity of maintaining proper stiffness distribution and girder placement to ensure structural integrity and safety in earthquake- and blast-prone regions. This study provides practical insights for optimizing structural design to achieve performance-based, code-compliant, and resilient buildings.

Keywords: Seismic Analysis, Vertical Irregularity, ETABS, Storey Drift, Base Shear, Blast Load.

1. Introduction

Earthquakes are among the most destructive natural phenomena, capable of causing severe damage to infrastructure and human life. The behavior of structures during seismic events largely depends on their mass and stiffness distribution, which governs how lateral forces are transmitted throughout the building. In ideal conditions, a structure with uniform stiffness and strength responds predictably to seismic motion. However, modern architectural practices often introduce vertical irregularities variations in stiffness or mass along the building height due to functional and aesthetic requirements such as open ground floors, setbacks, or material changes. These discontinuities alter the uniform flow of seismic forces, leading to excessive inter-storey drift, concentration of stresses, and in severe cases, partial or total collapse. Among the key components influencing lateral stiffness are girders, the horizontal load-bearing members that link vertical columns and distribute loads evenly across floors. Properly designed girders enhance overall rigidity, minimize drift, and control soft-storey effects. Conversely, buildings lacking sufficient girder continuity exhibit greater flexibility, increased displacements, and higher vulnerability during earthquakes. Thus, understanding the interactive influence of vertical stiffness irregularities and girder configurations is vital to improve seismic performance.

This study aims to analyze the effect of vertical irregularities in stiffness on the seismic response of reinforced concrete (RC) multi-storey buildings with and without girders using ETABS software. The primary objectives of the research are:

- To analyze the seismic performance of vertically irregular RC structures with and without girders using ETABS software.
- To evaluate storey drift, displacement, stiffness, and base shear under dynamic loading conditions.
- To assess the influence of girders in enhancing lateral stiffness and minimizing seismic effects.
- To propose design recommendations for improving the seismic resilience of irregular buildings based on ETABS simulation results.

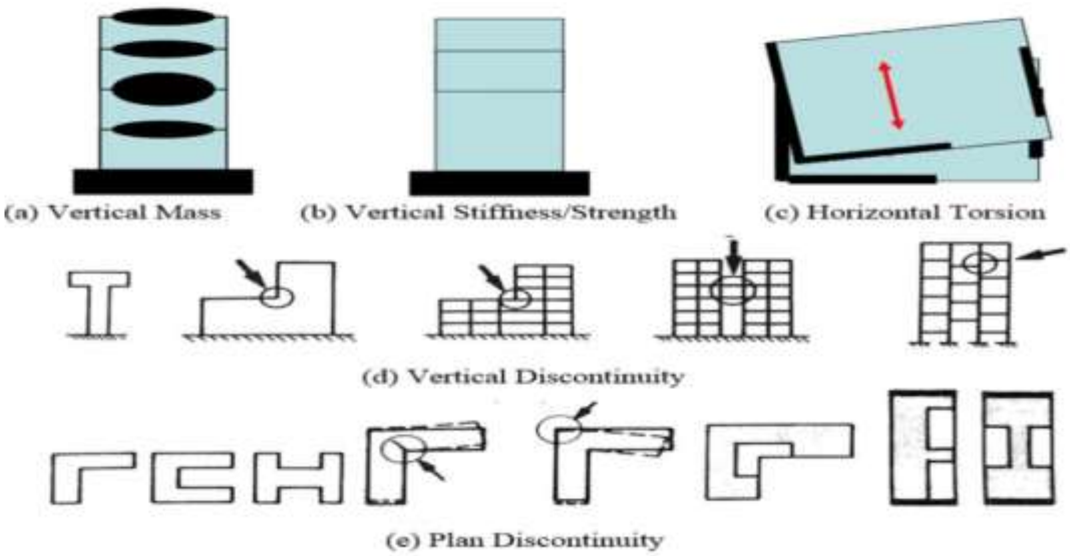

Fig 1. Types of Structural Irregularities in Buildings

2. Literature Review

Mahesh Raj Bhatt (2017) "Study on the Effect of Vertical Irregularities on Infilled RC Frames under Seismic Effect" This study investigates Special Moment Resisting RC frames with vertical mass and stiffness irregularities using ETABS 2000 and linear time history analysis, including Gorkha 2015 earthquake data. Mass irregularity was introduced by increasing live and dead loads, while stiffness irregularity was created by modifying infill masonry struts. Models with 6, 9, and 12 stories were analyzed, comparing bare frames, regular, and irregular infill buildings. Results showed that fundamental periods of irregular buildings were longer than regular but shorter than bare frames. Mass irregularity in top stories increased overturning moments, while stiffness irregularity in lower stories significantly affected inter-story drift. Masonry infill enhanced overall strength and stiffness. s**Kshithij G. Raj et.al (2025)** "Impact of irregularities on seismic fragility of reinforced concrete structures" This study evaluates the seismic performance of irregular reinforced concrete buildings using nonlinear static (pushover) analysis per ATC-40 and FEMA-356 guidelines. ETABS software was employed to model buildings with plan symmetry/asymmetry and vertical irregularities in stiffness, mass, or a combination of both. Key parameters, including base shear, lateral displacement, bending moments, and story shear, were analyzed to compare regular and irregular configurations. Results revealed that buildings with combined stiffness and mass irregularities exhibited the most critical seismic response, characterized by higher displacements and lower base shear capacity. Strategic placement of shear walls was proposed to mitigate these effects. **Davi Santos et.al (2024)** "Comparative Analysis of the Impact of Vertical Irregularities on Reinforced Concrete Moment-Resisting Frame Structures According to Eurocode 8" This study investigates the seismic response of irregular RC structures under Eurocode 8 provisions, focusing on vertical irregularities in elevation and column cross-sections. Thirteen five-storey moment-resisting frame buildings were designed using Robot Structural Analysis Professional according to Eurocodes 2 and 8, and analyzed with SeismoStruct v2024. The study evaluated the effects of height variations, column cross-section changes, and their influence on base shear and inter-storey drift. Results showed that increasing the height of lower or middle stories significantly worsens seismic performance, while column geometry variations strongly affect drift and base shear. Mass and resistance irregularities were not considered, suggesting the need for further research.

Mr. Gaurav Mungalkar et.al (2024) "Assessing Vertical Irregularity in Buildings across Seismic Zones: A Comparative Study" This study investigates the structural response of irregular buildings to seismic events of varying intensities. Fifteen models of irregular buildings are analyzed, categorized by height (21m, 30m, and 42m) and seismic loading conditions. The analysis reveals significant variations in period lengths across the different models, with shorter periods observed in shorter buildings with distributed mass, and longer periods in taller buildings with increased mass and stiffness. These findings underscore the impact of building height, mass distribution, and structural configuration on dynamic characteristics under seismic loading, providing valuable insights for the development of resilient structural designs in urban environments. **Akash Vijay Pandey et.al (2024)** "Comparative Study Of Seismic Analysis Of Vertically Irregular R.C. Frame Using Indian And Euro Code" The study compares Eurocode 8 and IS 1893:2016 to evaluate their effects on building durability, stability, and safety under seismic loads. It found that Eurocode 8 results in higher base shear and story drift, whereas the Indian Code provides better structural factor values and maintains performance within permissible limits, underscoring the importance of selecting suitable design codes for different regions. **Muzammil Ahmed et.al (2021)** "Seismic Analysis of Multi-Storey Building with Vertical Irregularities in Stiffness and Mass Under Various Soil Conditions" The study analyzes a G+6 storey residential building with stiffness and mass irregularities under seismic zone IV conditions as per IS 1893 (Part 1): 2002 using ETABS16 through response spectrum analysis. Parameters such as storey displacement, drift, stiffness, shear, and overturning moment were evaluated. Results revealed that Model H11 performed best, exhibiting the least displacement, drift, and shear, making it the most suitable configuration for earthquake-prone areas. **Amr Ghanem et.al (2023)** "Seismic Vulnerability of Reinforced Concrete Frame Structures: Obtaining Plan or Vertical Mass Irregularity from Structure Use Change" This study investigates the seismic fragility of reinforced concrete frames with mass irregularities in plan and elevation due to changes in structural usage. Unlike simplified 2D models, comprehensive 3D models were used to capture nonlinear interactions between torsional and lateral responses. Twenty-one frame models with varying vertical and plan irregularities were analyzed using nonlinear dynamic response history analysis with ten earthquake records. Seismic vulnerability was assessed through fragility surfaces derived from fragility curves across eight allowable drift ratios representing different damage states. Results showed that uneven live-load distribution significantly affects seismic performance, providing deeper insight into the behavior of irregular RC structures under earthquakes. **M. T. Raagavi et.al (2021)** "A Study on Seismic Performance of Various Irregular Structures" The study emphasizes that most modern buildings exhibit geometric and elevation irregularities due to aesthetic, economic, or site constraints, which make them more vulnerable during earthquakes. It examines various types of structural irregularities and their behavior under seismic loads by analyzing key parameters such as displacement, base shear, storey drift, stiffness, and strength using methods like Response Spectrum Analysis and Time History Analysis to evaluate overall seismic performance.

3. Research Methodology

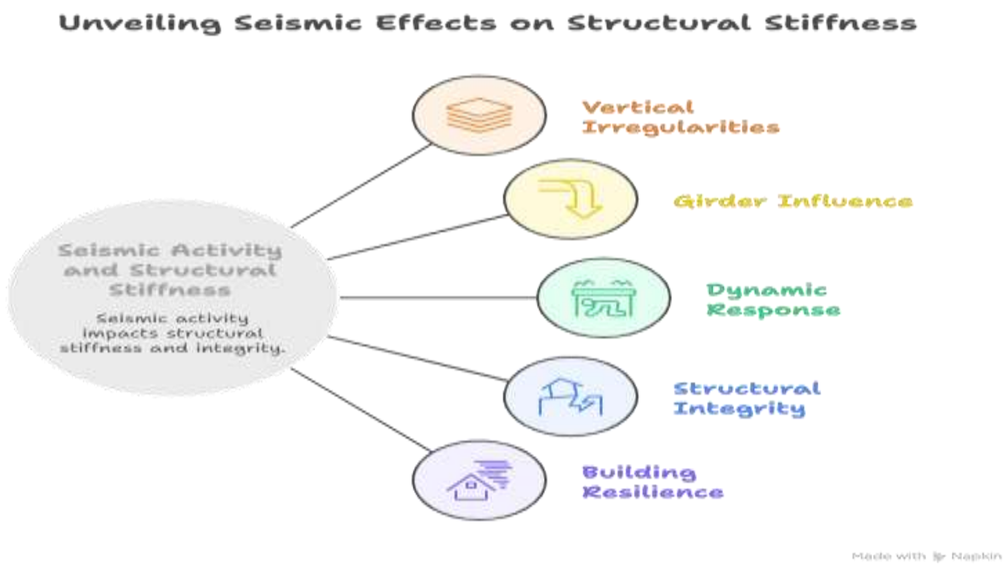

Fig 2. Methodology Flowchart

This study adopts an analytical and simulation-based approach to evaluate the effect of vertical irregularities in stiffness on the seismic performance of reinforced concrete (RC) buildings, with and without girders. The methodology integrates theoretical analysis, numerical modeling, and dynamic simulation using ETABS software in accordance with IS 1893 (Part 1): 2016 and IS 456:2000 standards. Initially, a comprehensive literature review was conducted to identify research gaps and establish the parameters influencing structural response under seismic loading. The study considers two structural configurations: (1) buildings with girders and (2) buildings without girders, both subjected to identical load and material conditions. Models of G+6, G+9, and G+12 storey RC frames were developed, incorporating vertical stiffness irregularities introduced through variations in column dimensions and floor heights. The analysis procedure includes the application of dead load, live load, and seismic load based on Indian Standard codes. Response Spectrum Analysis (RSA) and Nonlinear Time History Analysis (NLTHA) were performed to determine critical seismic response parameters such as storey drift, displacement, base shear, stiffness, and fundamental time period. The comparative evaluation between models identifies the role of girders in enhancing lateral stiffness and controlling inter-storey drift. Validation of results is achieved by comparing simulated outcomes with theoretical predictions and code-specified limits. The methodology ensures reliability, reproducibility, and adherence to ethical engineering practices. The findings are expected to guide structural engineers in designing safer, stiffness-balanced, and earthquake-resistant buildings in seismic-prone regions.

4. Results and Discussion

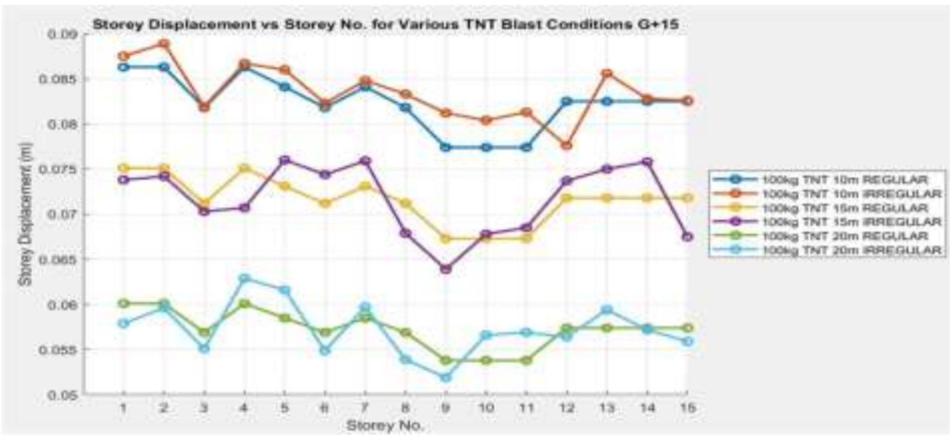

Fig 3. Storey Displacement vs Storey No. for Various TNT Blast Conditions G+15

The graph shows the displacement of different storey (1 to 15) under various TNT blast conditions (100kg TNT at different distances of 10m, 15m, and 20m for both regular and irregular conditions). The storey displacement is highest for the 100kg TNT at 10m in regular conditions, while the displacement decreases as the distance from the blast increases, with the lowest displacements observed at 20m under both regular and irregular blast conditions. The pattern of displacement fluctuations across the storey is consistent, with slight variations as the blast distance changes.

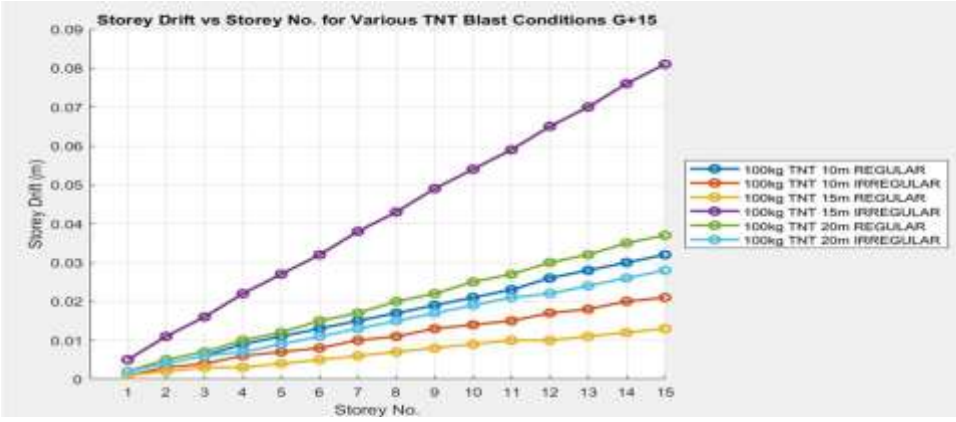

Fig 4. Storey Drift vs Storey No. for Various TNT Blast Conditions G+15

The graph illustrates the storey drift in response to varying TNT blast conditions at different distances (10m, 15m, and 20m) for a 100kg TNT explosion. It shows an increase in drift with the height of the building (storey number). For each distance, regular blast conditions exhibit higher storey drifts compared to irregular ones, with the drift magnitude rising with proximity to the explosion.

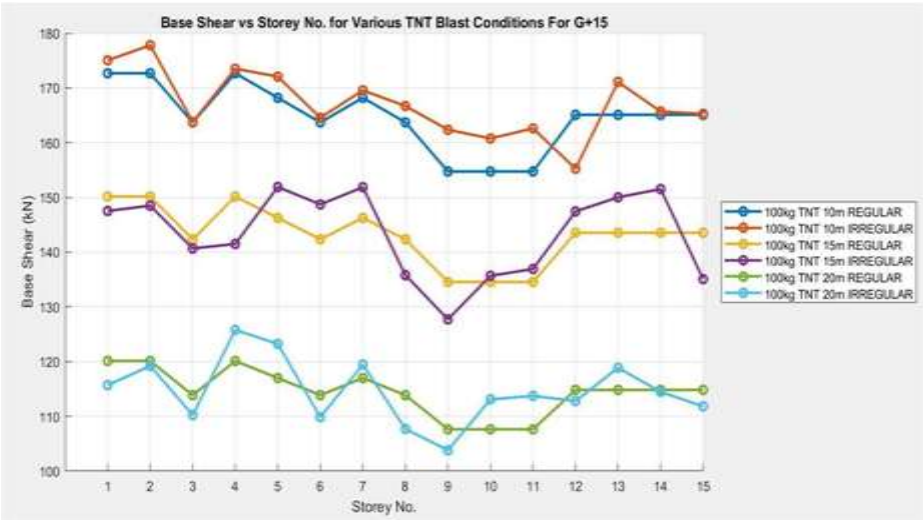

Fig 5. Base Shear vs Storey No. for Various TNT Blast Conditions for G+15

The figure shows that base shear decreases as the blast distance increases, indicating reduced impact with greater standoff. Regular buildings experience higher base shear compared to irregular ones, reflecting their greater stiffness and ability to resist lateral forces. Overall, the results suggest that blast intensity and structural configuration play a key role in determining building stability under explosive loads.

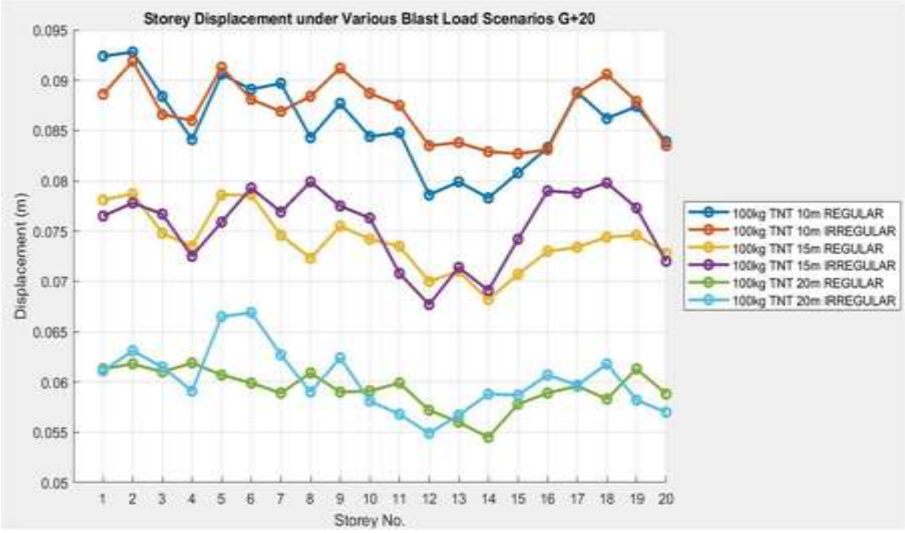

Fig 6. Storey Displacement under Various Blast Load Scenarios G+20

The graph shows the story displacement values for different blast load scenarios involving 100kg TNT at varying distances (10m, 15m, 20m) and under both regular and irregular conditions. The displacement increases with a decrease in the blast load distance, indicating a higher response under closer blast loads. Irregular scenarios generally cause greater displacement compared to regular scenarios, showing that structural stability is more affected by irregular loading patterns. The displacement values peak in certain storey, suggesting varying structural responses across different levels of the building.

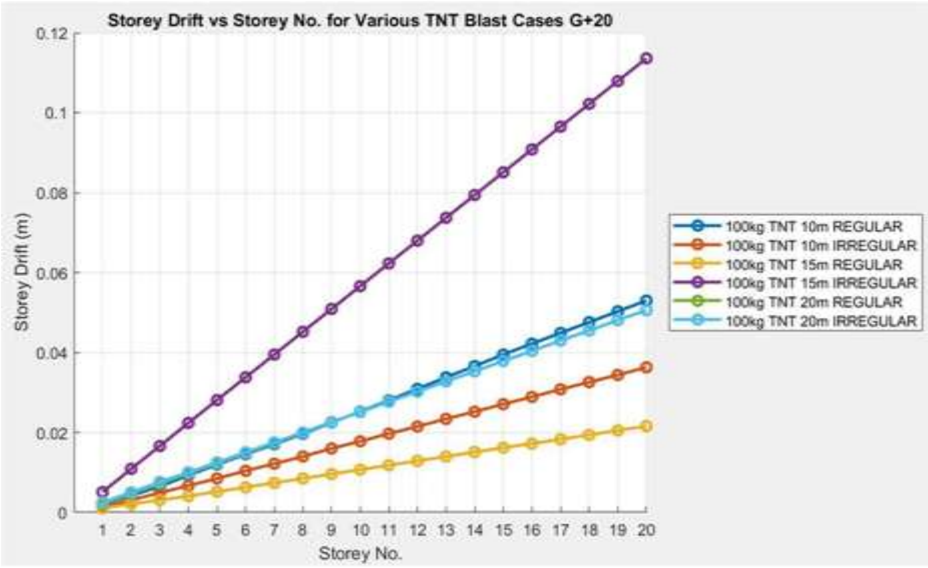

Fig 7. Storey Drift vs Storey No. for Various TNT Blast Cases G+20

This graph illustrates the storey drift of a building in response to TNT blast loads at different distances (10m, 15m, and 20m) and blast scenarios (regular and irregular). The storey drift increases with the number of storey, and the drift is more pronounced for TNT at closer distances (10m), especially under irregular blast conditions. Irregular blasts consistently result in higher drift compared to regular blasts across all distances.

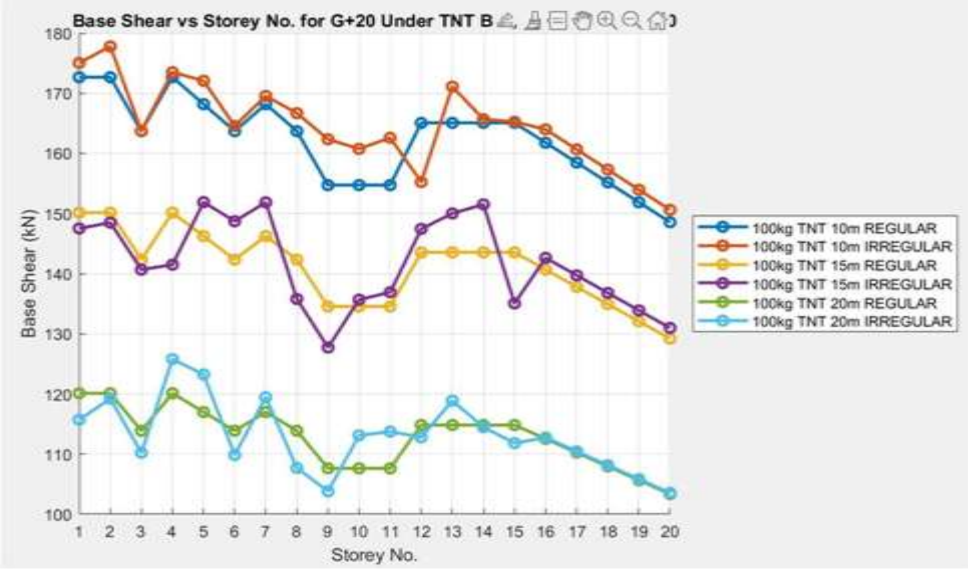

Fig 8. Base Shear vs Storey Number for G+20 Under TNT B.

The graph indicates that base shear is highest for 100 kg TNT at 10 m distance and gradually decreases as the blast distance increases to 20 m, showing reduced impact with distance. Regular G+20 structures exhibit higher base shear values than irregular ones, demonstrating greater stiffness and load resistance. Overall, the results confirm that blast intensity and structural configuration significantly affect the distribution of base shear along the building height.

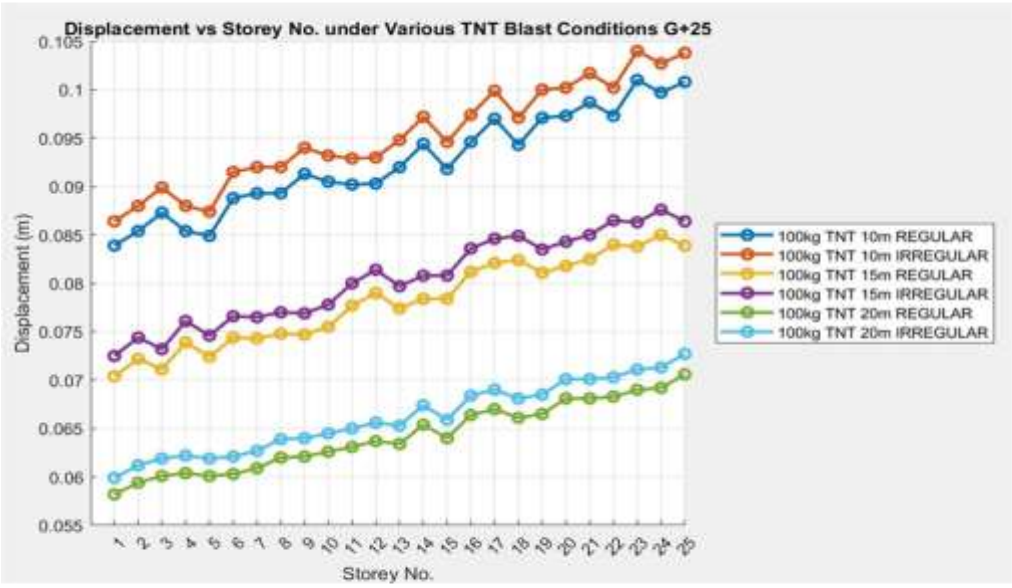

Fig 9. Displacement vs Storey No. under Various TNT Blast Conditions G+25

The graph shows that displacement increases progressively with storey height for the G+25 building under various TNT blast conditions. Maximum displacement occurs for 100 kg TNT at 10 m distance, while minimum displacement is observed at 20 m, indicating reduced blast impact with distance. Moreover, irregular structures experience higher displacements than regular ones, highlighting their reduced stiffness and greater vulnerability to blast-induced lateral forces.

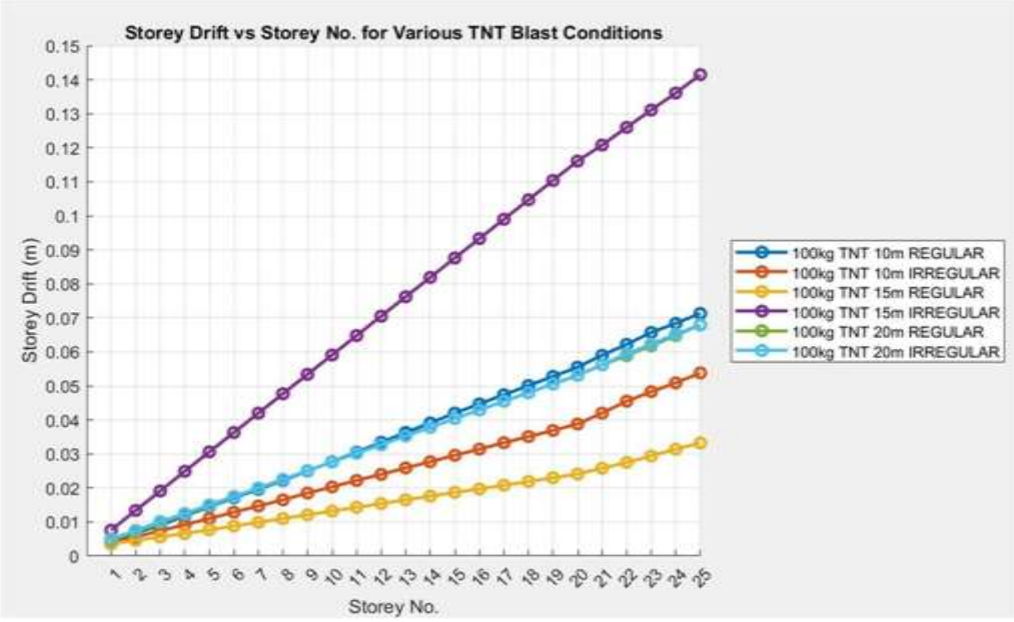

Fig 10. Storey Drifts vs Storey No. for Various TNT Blast Conditions

The figure shows that storey drift increases steadily with height for all TNT blast conditions, indicating greater lateral deformation in upper floors. Maximum drift occurs for 100 kg TNT at 20 m in irregular structures, while regular buildings show comparatively lower drift values, demonstrating better stiffness and load resistance. Overall, the results highlight that irregularity and blast proximity significantly influence drift behavior and structural stability.

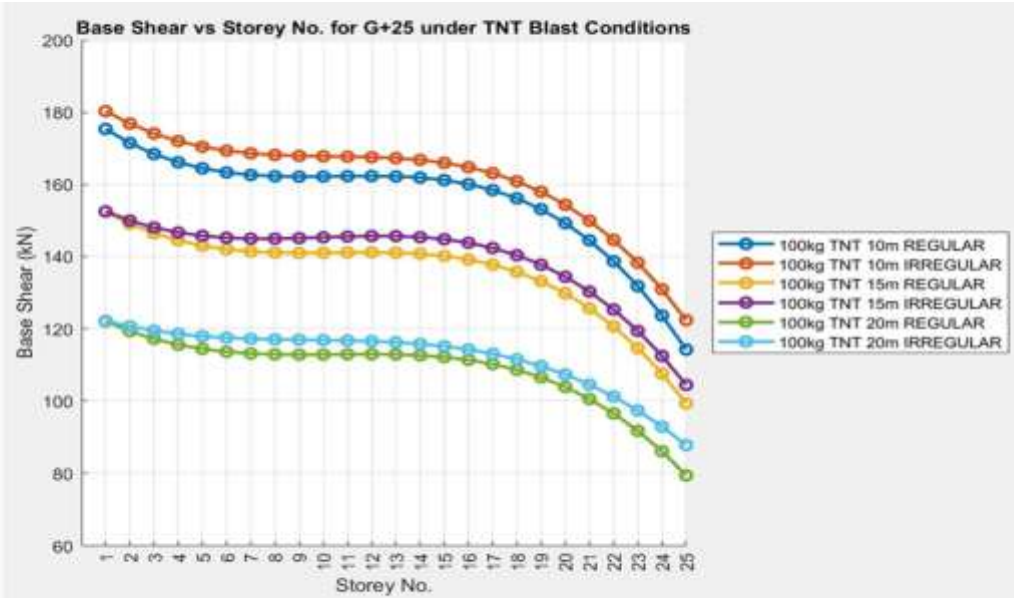

Fig 11. Base Shear vs Storey No. for G+25 under TNT Blast Conditions

The graph shows that base shear gradually decreases from the bottom to the top storeys for the G+25 building under various TNT blast conditions. Maximum base shear occurs for 100 kg TNT at 10 m, while minimum values are observed at 20 m, indicating reduced blast intensity with distance. Irregular structures exhibit slightly higher base shear compared to regular ones, emphasizing the influence of structural irregularities on lateral force distribution.

5. Conclusion

The present study investigates the effect of vertical irregularities in stiffness on the seismic and blast performance of multi-storey reinforced concrete (RC) buildings, with a particular focus on comparing structures with and without girders. Using advanced modeling and dynamic analysis in ETABS, parameters such as storey displacement, drift, base shear, and stiffness were evaluated under various loading conditions, including seismic and 100 kg TNT blast scenarios at different standoff distances. The analysis results indicate that vertical stiffness irregularities significantly influence structural response. Buildings with irregular configurations exhibited higher displacement and storey drift, especially at lower storeys, confirming their vulnerability to lateral and blast loads. Conversely, structures incorporating girders demonstrated enhanced lateral stiffness, reduced inter-storey drift, and better overall stability, highlighting the crucial role of horizontal load-distributing elements in improving seismic resilience. Furthermore, increasing the blast distance from 10 m to 20 m notably reduced base shear and displacement, emphasizing that standoff distance plays a key role in mitigating blast impact. Among all models, regular structures with girders performed most effectively, maintaining deformation and drift values within permissible limits as per IS 1893 (Part 1): 2016. These findings underscore the importance of proper stiffness distribution, adequate girder design, and adherence to code-based guidelines in ensuring safety and serviceability. In conclusion, the study provides valuable insights for the design and optimization of irregular high-rise buildings, recommending that vertical irregularities be carefully managed through appropriate girder integration and structural configuration to enhance earthquake and blast resistance.

Future scope

The present research provides a comprehensive understanding of how vertical stiffness irregularities and the presence or absence of girders influence the seismic and blast performance of reinforced concrete (RC) multi-storey buildings. However, there remains substantial scope for further investigation to enhance the accuracy, applicability, and practical relevance of the findings. Future studies can incorporate soil–structure interaction (SSI) effects to better capture the influence of foundation flexibility on overall structural response. Additionally, the impact of plan irregularities, mass irregularities, and combined stiffness–mass variations may be examined to provide a more holistic understanding of real-world building behavior under extreme loading conditions. The use of advanced damping devices, base isolation systems, and energy dissipation mechanisms can also be explored to improve structural resilience and reduce deformation under both seismic and blast excitations. Furthermore, the present study can be extended using nonlinear finite element analysis (FEA) with material nonlinearity and progressive collapse modeling to evaluate failure mechanisms more precisely. Incorporating different blast intensities, charge weights, and variable standoff distances would provide a broader spectrum of data for practical design scenarios. Finally, future research can emphasize experimental validation of the analytical models through scaled laboratory testing or full-scale structural monitoring under controlled blast and seismic simulations. Integrating artificial intelligence and machine learning for predictive damage assessment may also provide advanced design tools for engineers. These extensions will contribute significantly toward developing safer, more efficient, and performance-based design guidelines for irregular high-rise structures in seismic and blast-prone regions.

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