A REVIEW ON IMPACT OF P-DELTA EFFECTS ON THE SEISMIC PERFORMANCE OF HIGH-RISE RC BUILDINGS WITH VERTICAL GEOMETRIC IRREGULARITIES

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Abstract - *The seismic performance of high-rise reinforced concrete (RC) buildings with vertical geometric irregularities is a critical consideration for structural engineers, especially in regions prone to seismic activity. One of the primary concerns is the influence of P-Delta effects, which arise due to the interaction between lateral displacements and the axial loads on structural elements. This study investigates the impact of P-Delta effects on the seismic response of high-rise RC buildings with vertical geometric irregularities, including setbacks, changes in floor heights, and varying column sizes. A series of nonlinear dynamic analyses were conducted using various building configurations subjected to different seismic scenarios, considering both elastic and inelastic behavior. The results highlight the exacerbating influence of vertical irregularities on the seismic performance, with a significant increase in lateral displacements and internal forces due to the P-Delta effects. It was found that these effects can lead to increased inter-story drifts, potential non-uniform damage distribution, and overall system instability.*

Key Words: P-Delta, Time History Analysis, Shear Wall, Seismic Performance, Vertical Geometric Irregularities, high-rise RC Buildings.

1.INTRODUCTION

High-rise reinforced concrete (RC) buildings are particularly susceptible to seismic forces due to their height and mass, which lead to significant lateral displacements during an earthquake. While structural systems are typically designed to resist lateral forces through a combination of shear walls, bracing, and moment-resisting frames, high-rise buildings often face additional challenges due to their vertical geometric irregularities. These irregularities can take various forms, such as abrupt changes in floor height (step-backs), varying column spacing, or floor plans that reduce stiffness or mass distribution in certain sections of the building.

In seismic engineering, the P-Delta effect plays a crucial role in how buildings respond under lateral loading. This phenomenon refers to the secondary effects that arise when the building undergoes lateral displacement. The lateral drift causes vertical loads (axial forces) to create additional moments in structural elements like columns, leading to increased deformation and potentially significant damage. As the building's height increases, these P-Delta effects become more pronounced, particularly in buildings with vertical geometric irregularities. Such irregularities can lead to an uneven distribution of forces, exacerbating the impact of seismic events on the structure's overall performance.

1.1 The Role of P-Delta Effects in Seismic Performance

The P-Delta effect refers to the additional internal forces and moments that arise in a structure as it undergoes lateral displacement. These effects are most prominent in tall structures, as the lateral sway increases with height. As the building moves laterally under earthquake loading, the weight of the structure (P) acts on the displaced mass, creating additional forces that further amplify the lateral sway. This leads to increased axial forces in the columns and moment magnification at the joints and beams, which can significantly affect the building's stability.

Key aspects of the P-Delta effect include:

Increased Deformation: The displacement-induced moments in structural elements can increase overall drift and cause excessive deformations, potentially resulting in the failure of load-bearing components. For buildings with vertical irregularities, the P-Delta effect can exacerbate these deformations, especially in regions where the stiffness and strength may already be compromised.

Moment Magnification: The moment induced by the P-Delta effect can be especially severe in the upper floors of tall buildings. When combined with the vertical irregularities (e.g., reduced stiffness or mass at higher floors), the moment magnification becomes critical, potentially leading to the buckling of columns or failure of beams.

Instability Risk: In the most extreme cases, especially in tall buildings with significant vertical irregularities, the P-Delta effect can make the structure more prone to instability. Under large earthquake loads, even small lateral movements may induce large secondary moments that could lead to progressive collapse.

Amplification of Seismic Response: When vertical irregularities exist, the building's response to lateral forces becomes more complex. The P-Delta effect interacts with these irregularities, amplifying the response, particularly if the building's natural frequency aligns with the seismic frequency. This can result in higher story drifts, more significant torsional motion, and increased risk of structural damage.

1.2 Interaction Between P-Delta Effects and Vertical Irregularities

The interaction between P-Delta effects and vertical irregularities is critical in determining the seismic vulnerability of high-rise buildings. When a building has vertical irregularities, the way forces are distributed through the structure can become uneven, leading to more pronounced lateral displacements and torsional responses. The P-Delta effect further exacerbates these problems, as the induced secondary moments lead to increased lateral forces on the already vulnerable sections of the building.

For example:

Step-backs or tapered buildings: These buildings, which reduce in size at higher floors, may experience larger lateral displacements at the top, which are magnified by the P-Delta effect. The top floors may also be more prone to torsional effects, and the lack of stiffness at higher levels can further destabilize the structure.

Buildings with varying floor heights: If a building has floors with significantly different heights, the higher floors will tend to displace more during an earthquake. The P-Delta effect on these floors will amplify the forces acting on the building's structural elements, possibly leading to larger than expected deformations or structural failure in weaker sections.

2. LITERATURE REVIEW

Saheban Ali and Ajay Singh [2023] The thesis focuses on analyzing the effect of P-Delta on RCC moment resisting frames of buildings ranging from 10 to 30 storeys using SAP 2000. The study compares linear static and nonlinear static analysis to understand how P-Delta impacts structural response under vertical and lateral loads. For structures where displacement, axial forces, shear forces, moments, and stresses exceed code requirements, redesigning methods are considered. The research highlights the importance of considering P-Delta effects, especially in earthquake-prone areas. It is observed that the 20, 25, and 30 storey models do not meet the code specifications for storey drift limitations, indicating the need for redesign. The results suggest that P-Delta effects are critical for ensuring the safety and stability of high-rise RCC structures, particularly for buildings with more than 15 storeys.

Jane Alexander and Er. Lulu K Makkar [2023] The research focuses on the use of Steel Fiber Reinforced Concrete (SFRC) as a structural material and the importance of P Delta analysis in high-rise buildings. Previous studies on SFRC mechanical properties were referred to, and the material was simulated using software after experimental testing. The analysis was done on a G+9 RC frame structure using ETABS 18. 0. 0, comparing SFRC with conventional concrete. The SFRC structures were analyzed using ETABS 2018 software with steel fiber in the concrete. Linear analysis was done for seismic analysis, while non-linear P-Delta analysis studied SFRC structure performance.Values for maximum displacement and member force were computed for every vibration mode. SFRC showed better results compared to conventional concrete, with reduced storey displacement and drift. SFRC demonstrated improved flexural strength and toughness, making it a viable seismic resistant material for future research.

Yash Katare and Prof. Anubhav Rai [2023] The study compared four different structural models with 13-story heights using Staad Pro software, analyzing them with and without considering the P-Delta effect. The models had parameters like column and beam sizes, dead loads, live loads, seismic factors, and soil type. The analysis included considerations for seismic zones III and V, with and without P-Delta effects. The objective was to study the effects of P-Delta analysis on L-shaped RC buildings and compare different RC structures in different seismic zones. The research focused on earthquake behavior of G+13 multistory buildings, analyzing factors like bending moments, storey displacement, shear force, and axial forces. Results showed that storey displacement increased with the number of stories, with maximum displacement at the 14th storey in both seismic zones. The study concluded that storey displacement increased with storey height, and seismic zone V showed higher displacement compared to seismic zone III with the same P-Delta effect.

Shubam Kumar Balmiki and Himmi Gupta [2022] The study analyzed an overhead flat surfaced tank with and without p-delta analysis using Bentley's Staad. Pro software. Different parameters were determined before modeling the tank and different concrete properties were assigned to structural members. The tank was analyzed under working conditions and hydrotest conditions to determine water pressure. Support reactions from the models were imported to RCDC software to design the footing for the tank. For a tank with a 9m staggering height, it was observed that the maximum displacement and bending moment were slightly higher with P-Delta analysis compared to without. The same trend was seen for the shear force and total steel quantity, with small differences in values. For a tank with a 12m staggering height, similar results were found, with slightly higher values for displacement, bending moment, shear force, and total steel quantity with P-Delta analysis compared to without. The differences in forces and moments between the tanks with and without P-Delta analysis were very small.

D J Zavala et al. [2022] The study examines how reinforced concrete structures are affected by stiffness irregularity and the p-delta effect. Initially, structural responses such as drifts, shear force, and moments per floor are calculated using linear dynamic analysis. Nonlinear static analysis is then used to create a capacity curve for the structure, which helps determine post-elastic stiffness and overall ductility. Results show variations of up to 16. 50% in drifts, 11. 00% in shear force, and 14. 00% in moments per floor when stiffness irregularity and the p-delta effect are considered. Overall stiffness can be reduced by up to 59.85% when the p-delta effect is present. Nine models of a 20-story structure are created to estimate how stiffness irregularity and the p-delta effect impact structural behavior. Three groups of models are made: regular structures, those with stiffness irregularity, and structures with both stiffness irregularity and geometric non-linearity. The study concludes that tall buildings should consider the p-delta effect, especially when there is stiffness irregularity, as it can lead to significant variations in structural response and overall stiffness. Stiffness irregularity directly affects the degradation of stiffness and strength in a structure, leading to a decrease in rigidity and the formation of more plastic hinges in structural elements. Incorporating both stiffness irregularity and the p-delta effect can result in even greater degradation in overall stiffness.

Thokala Brahmendra Rao et al. [2022] ETABS2016 software was used in this study to analyze the P-delta influence on a G+29 RCC framed building. Wind and seismic loads were applied in accordance with IS-875 (PART-III) and IS-1893 (2002). The analysis included comparing displacements, storey drifts, Bending Moments, and Shear Forces with and without P-delta effect, as well as with shear walls at different locations. The study found that buildings with P-delta had increased displacements and storey drifts compared to those without P-delta. Shearwalls placed at the center of the frame were more effective than those at the corner. Bending moments in columns and shearwalls also increased after P-delta analysis. The results were consistent in both elastic and inelastic dynamic analyses.

S Bhavanishankar and Patil Rita [2021] The study focuses on the P-delta effect in structural software ETABS, which is the geometric nonlinearity effect that becomes more important as the number of stories in a building increases. To investigate a multi-story building with and without the P-delta effect, the study employs linear static analysis and second-order analysis. The study includes a G+24 storey building with constant height and considers models with and without shear walls. The analysis includes gravity and earthquake loads to determine maximum responses in terms of displacement, drift ratio, moment, and shear forces. The results show that P-delta analysis is essential for tall, slender structures as it considers both first and second-order loading effects. The study also highlights the importance of shear walls in reducing displacement and drift, with P-delta effects showing a significant reduction. It is recommended to always consider the P-delta effect in the analysis of high-rise buildings.

Aditya Bhandare and N.G Gore [2021] The study modeled G+60, G+70, and G+80 buildings in a C-shaped structure with a constant 3-meter storey height and a 40m x 40m plan in Mumbai. It was analyzed for three wind speeds of 44m/s with Type-II soil. The C-shaped model was chosen for its extended layout with core walls and shearwall. The study found that outrigger systems increase stiffness and efficiency in tall structures under seismic and wind loads. Top storey displacement was reduced in outrigger structures compared to conventional ones. Storey drift was also less in outrigger structures. Additionally, there were not significant changes in base shear and moment readings between the two structures, and modal time period decreased as the number of storeys increased.

Anup Subhash Kotekar et al. [2021] This paper discusses parameters not accurately estimated in traditional analysis, such as creep losses, column shrinkage, axial shortening, lateral sway due to P-Delta Effect, and varying longitudinal rebar percentages. ETABS v. 18. 1 was used to analyze structures with sequential and conventional methods following IS 1893 for Seismic Loads and IS 875 Part 3 for Wind Loads. Conclusions include heavier sections to counter P-Delta effects increase costs; as structure height increases, support shortening cannot be ignored, with bending moments and shear force decreasing and sway displacement increasing; lower construction rates result in less shortening and deflection on lower floors; grade of concrete and cross-sectional area changes do not significantly impact column shortening; as structure height increases, shortening differences between members also increase, especially near the top and mid-levels.

Kanchan Gupta and Md. Tasleem [2020] The study conducted seismic analysis of a multi storey flat slab building using ETAB software, considering zone V and soft soil. The analysis checked displacement and drift of the building at different storeys (G+9, G+19, and G+29) with and without P-delta effects. Flat slab buildings have simple formwork and reinforcement layout compared to normal slab buildings. P-delta analysis involves laterally displacing structures under gravity loads, causing deflection. P-delta effect on R. C. framed and flat slab buildings of varying storey heights was studied for stability design. The study concluded that flat slab buildings had higher displacement and drift compared to normal slab buildings, with an increase of over 10% when applying P-delta effects. Base shear also increased with the number of storeys.

M.U. Bhati and N.L. Shelke [2020] In this study, two cases were analyzed using response spectrum method and considering P-delta effect for a G+21 storied building with floating columns and transfer girders. The building model was created using Etabs 2018 software and analyzed under zone III conditions. The objectives of the study were to reduce structural failure risk during construction, understand high-rise structure behavior, and compare construction sequence analysis with conventional methods. The outcomes showed that construction sequence analysis resulted in higher moments, shear forces, deflections, and torsion moments in transfer girders compared to conventional lumped analysisIt has been established The impacts of the construction sequence must be taken into account when designing multistory buildings that have floating columns and transfer girders. Sequential load cases in RCC structures provide more realistic designs and improve analysis accuracy. The results also showed that values for maximum positive moment, negative moment, shear force, deflection, and torsion moment in transfer girders were significantly higher in construction sequence analysis compared to conventional lumped analysis. Overall, including sequential load cases in multistory RCC structure analysis leads to a more realistic design and better understanding of structural behavior.

Mahan S. Jadav et al. [2020] The study focuses on analyzing the P-Delta effects on tall structures using three different structural systems: moment frame, moment frame with structural wall, and composite columns. Earthquake loads are applied and P-Delta analysis is conducted with ETABS 2016 software. The analysis compares base shear, storey drift, and storey displacement to demonstrate the effectiveness of different methods based on storey height variation. The study aims to evaluate seismic parameters, such as storey stiffness, displacement, and drift, and calculate the Demand Capacity Ratio for earthquake design. Results show that for buildings up to 60m, Special Moment Resisting Frame structures are recommended, while for heights up to 160m, Structural Wall Moment Resisting Frame structures are suggested. Increasing beam size is more effective than increasing column size in preventing or delaying collapse in tall structures.

Henna Salam and Lekshmi Priya R. [2018] This paper discusses the P-Delta analysis of rectangular and circular hollow core wall panels. P-Delta analysis involves considering deflection-induced secondary moments in critically loaded members. The study used the LECwall software for modeling and analysis. The results showed that circular hollow core panels had higher shear force and cracking moments compared to rectangular ones, due to factors like self-weight, axial load, and pre-stress force. Adding mild steel to pre-stressed members can help meet cracking moment requirements. Opening in the panels reduced shear force and cracking moments due to a decrease in the axial strength ratio. The secondary moments in load-bearing panels were greater than in cladding panels, with tension stresses higher than PCI recommendations for serviceability. The midpoint bow was unaffected by the presence of openings or load-bearing nature, but rectangular panels experienced more bow due to suction, while circular panels bowed more due to pressure.

Sardasht Sardar and Ako Hama [2017] Nonlinear static and dynamic analyses are used in this work to examine the impact of P-Delta on the seismic response of structures of varying heights. The results show that P-Delta significantly affects the peak amplitudes of buildings as height increases, with steel structures being more affected than concrete ones. The weight of the structure also plays a role, with heavier concrete models experiencing less influence from P-Delta. However, 25-story steel and concrete models failed due to structural collapse. Plastic hinge formation was used to measure structural performance, with higher levels of P-Delta affecting steel models more severely. The study concludes that the height of a building is a critical factor in P-Delta analysis, and that steel structures are more sensitive to height than concrete ones. The study recommends considering both building height and construction material when analyzing P-Delta effects, and emphasizes the importance of monitoring plastic hinge formation for structural performance evaluation.

Ajay Agnihotri and Raghvendra Singh [2017] A 20-story steel frame building that was 72 meters' high was the subject of the study, which employed ETABS software to simulate it while taking the P-delta effect into account. Different diagonal bracing patterns were investigated to determine their influence on lateral loading. The analysis was done for wind load based on IS 875 (part 3)-1987.According to the results, square buildings had the greatest column displacement and circular buildings the largest storey displacement. It was found that storey drift increased with the number of storeys in steel frame buildings, and cross bracing systems were effective in both linear and P-delta analysis. The main objective was to analyze different geometric steel frame buildings and compare their behavior under various loads and P-Delta effects. Conclusions included findings that P-delta effects increased storey displacement, circular buildings had the highest displacement, and cross bracings were effective in increasing stiffness. The study emphasized the importance of conducting P-Delta analysis for structures to consider second-order effects accurately.

3. SUMMARY OF LITERATURE REVIEW

The study's literature evaluation reveals that the P-Delta effect has been the subject of several investigations. According to a quick analysis of the various works that have been provided, the P-Delta effect is a significant problem for high-rise buildings. Furthermore, compared to regular structures, vertical irregular structures require more attention and are more susceptible to seismic loads. The following findings are derived from earlier research:

1. There is a significant increase in response quantities in irregular structures compared to regular ones
2. The drift demands in upper stories are more sensitive to irregularities in lower stories
3. The P-Delta effect is not very significant when only gravity loading is present, but becomes more important as the number of stories in a building increases
4. Generally, the P-Delta effect is minimal in buildings up to 7 stories tall
5. The effect of P-Delta is influenced by the characteristics of ground motion during an earthquake
6. Both linear static and P-Delta analysis are necessary for reinforced concrete structures
7. P-Delta analysis is required for structures taller than 7 stories due to wide displacement variation
8. The study compared structures with and without P-Delta effects, focusing on parameters such as time-history analysis and lateral displacement story drift
9. Software such as SAP2000, ETABS, and STAAD PRO were used to perform the analysis.

4. GAPS IN LITERATURE REVIEW

While significant progress has been made in understanding the seismic behavior of high-rise buildings, there are still several gaps:

1. Limited Studies on P-Delta Effects with Irregularities: There is a lack of comprehensive studies that specifically focus on the combined impact of P-Delta effects and vertical geometric irregularities on the seismic performance of high-rise buildings.
2. Interaction Between Vertical Irregularities and P-Delta Effects: More research is needed to understand how irregularities at specific heights (e.g., changes in stiffness or mass at certain levels) interact with the P-Delta effect, particularly in taller buildings where this interaction may lead to significant amplification of seismic response.
3. Realistic Modeling Approaches: Many existing studies use simplified models for irregular buildings, which may not capture the full complexity of P-Delta interactions. Further research is needed to develop more sophisticated modeling techniques that consider both P-Delta effects and vertical irregularities in more detail.
4. Impact of Nonlinear Behavior: Many studies assume linear behavior for simplicity, but the nonlinear response of materials under large deformations, especially in tall buildings with irregularities, needs more investigation.
5. Torsional Effects: The impact of torsional motion on buildings with vertical irregularities under seismic loads, in the context of P-Delta effects, remains underexplored.
6. Seismic Hazard Considerations: The influence of site conditions (soil-structure interaction) and regional seismicity on the severity of P-Delta effects in buildings with vertical irregularities requires more attention.

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