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Design and Analysis of Architectural Systems for Earthquake Resilience



Abstract: - This research investigates the impact of wind and gravity loads on the seismic performance of a G+20 reinforced concrete building in Jordan. The study highlights the importance of non-linearities in earthquake-resistant design, with non-linear models showing a 39.66% increase in displacement compared to linear-elastic models. The analysis was conducted using the OpenSees platform. Using a fiber model to account for reinforcement plasticity and inelastic behavior, such as concrete cracking, a single element was used to represent an entire beam or column in the force-based finite element modeling technique. Geometric non-linearities, including large rotations, were addressed through the corotational formulation, and the P-Delta approach was used for result validation. Significant variations in load distribution across floors further highlight the importance of non-linearity in seismic analysis. The results of this study demonstrate how important it is to improve high-rise structures' earthquake resistance through the use of non-linear modeling and real-time electronic monitoring systems. Architects and engineers may greatly decrease structural damage during seismic events by incorporating these cutting-edge solutions into future building designs. This will improve building performance and safety in earthquake-prone areas.

Keywords: Non-linear seismic analysis, earthquake resilience, high-rise building design, OpenSees platform, reinforced concrete structures, electronic monitoring systems, structural load redistribution

1. INTRODUCTION:

It is still very difficult to understand how reinforced concrete structures behave under seismic loading, especially in urban settings like Jordan, where high-rise buildings must contend with intricate seismic requirements [1, 2]. In order to accurately predict seismic responses, traditional linear models are unable to capture important non-linear behaviors like large deformations and material inelasticity [3, 4].

Modern computational tools, such as OpenSees, offer detailed simulations of non-linear seismic behaviors, providing an affordable substitute for physical experiments in light of the logistical difficulties associated with large-scale testing [5, 6]. Few studies have combined real-time monitoring systems with non-linear models, despite their potential to improve seismic safety [7, 8].

Through the use of electronic monitoring systems and non-linear modeling, this project seeks to close these gaps and increase earthquake resilience. This study provides new insights into the behavior of high-rise buildings under real-world conditions by simulating the response of a 20-story reinforced concrete skyscraper in Jordan to seismic, wind, and gravity loads.

2. STRUCTURAL DESIGN AND MATERIAL SELECTION FOR SEISMIC RESILIENCE:

In order to ensure seismic safety, the 20-story reinforced concrete building was designed in agreement with the International Association for Earthquake Engineering (IAEE) guidelines while also taking Jordan's seismic demands into account [7]. In mandate to balance material efficacy and lateral force resistance, concrete with compressive strengths varying from 280 kg/cm² on the lower floors to 490 kg/cm² on the upper floors was chosen. Because of its ductility, which enables the structure to safely deform under seismic stress, reinforcing steel was selected, boasting a tensile robustness of 4200 kg/cm² [6].

The structure has rectangular beams positioned in two orthogonal guidelines for improved lateral and vertical resistance, as well as a stiff diaphragm for effective load transmission. The 20-cm-thick slabs satisfy service constraints for both seismic and vertical loads and permit deformation [6]. The building maintains cost-effectiveness and complies with well-being regulations while attaining high seismic resilience thanks to careful material choice and structural design [7].

When trying to couple structural walls that support emergency staircases and elevators, architects frequently limit beam heights to minimal values. In these types of structures, this design works very well. In these situations,

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beams are essential for connecting structural walls and enhancing the structural system's overall performance. These factors are taken into account while designing the layout of the structure, guaranteeing that the architecture preserves architectural coherence while improving system performance [7].

Through meticulous manipulation of the concrete strengths and the integration of an extremely flexible structural system, the building attains a high degree of seismic resistance while maintaining an economical construction process and material utilization. In addition to adhering to the IAEE's safety requirements, the choice of materials and structural layouts guarantees that the structure will be able to endure the seismic and wind-induced displacements typical of Jordan's urban setting [7].

The building's structural layout is shown in Figure 1 and goes as follows:

The building consists of 20 floors plus a rooftop space designated for social events. Its dimensions are 43.75 meters by 26.25 meters to the axes, with a total area of 1,296.98 square meters.

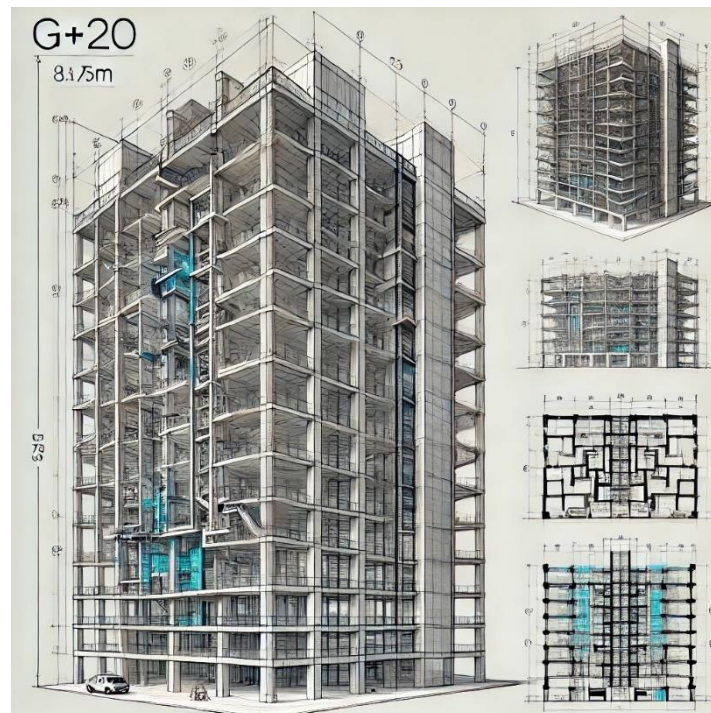


Figure 1: G+20 Reinforced Concrete Building Model

A G+20-story reinforced concrete skyscraper's structural elements and north and south elevations are depicted in this 3D schematic model. The main load-bearing components in the figure—columns, beams, and slabs—are highlighted. The lateral and vertical resistance systems are distinguished by color coding.

The OpenSees platform was chosen for this study because of its precision and adaptability while managing complex non-linear modeling assignments. Because of its great computing performance and utilization of C++, it is feasible to do in-depth simulations of concrete cracking and reinforcing plasticity. In particular, the force-based finite element modeling technique was used to account for inelastic behavior, which is a key parameter to take into consideration when investigating the seismic performance of high-rise structures. The corotational formulation and P-Delta approach accurately handled large rotational motions and geometric non-linearities, which is critical for simulating realistic earthquake reactions.

3. COMPUTATIONAL FRAMEWORK FOR SEISMIC ANALYSIS:

To test the 20-story reinforced concrete structure's seismic performance, two phases of PC modeling were created, simulating both non-linear and linear-elastic behaviors under seismic, gravity, and wind loads.

3.1. Preliminary Finite Element Model:

The first phase used SAP2000 software [8] to create a finite element mesh, representing the building's structural layout and analyzing the load distribution in slabs and beams under permanent and accidental loads.

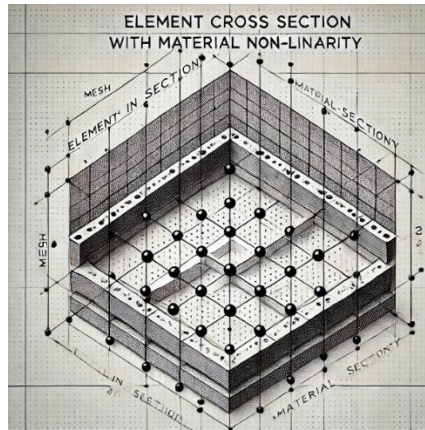


Figure 2: SAP2000-generated finite element mesh for the building's structural framework, showing shell elements for slabs and bar elements for beams

This early model provided a baseline knowledge of how the building would react to lateral and vertical pressures by assisting in the determination of the distribution of shear stresses in the columns and beams.

3.2. Advanced Non-linear Model in OpenSees:

In order to simulate intricate non-linear behaviors, such as material inelasticity, geometric non-linearities, and P-Delta effects, OpenSees [9, 10] was used in the second phase. In order to account for inelasticity along the bars that represent beams and columns, the force-based finite element method was utilized.

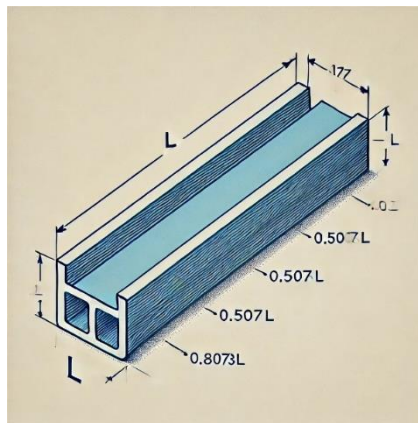


Figure 3: Cross-sectional fiber model of beams and columns in OpenSees

This figure illustrates the mesh used to depict the reinforcing steel and the concrete's behavior under stress.

3.3. Incorporation of Non-linearities:

Effects that are not linear, such as material inelasticity (e.g. g. concrete cracking and steel plasticity) as well as geometric non-linearities (e.g. g. large deformations and P-Delta effects) were simulated in order to replicate the structure's actual behavior during seismic activity.

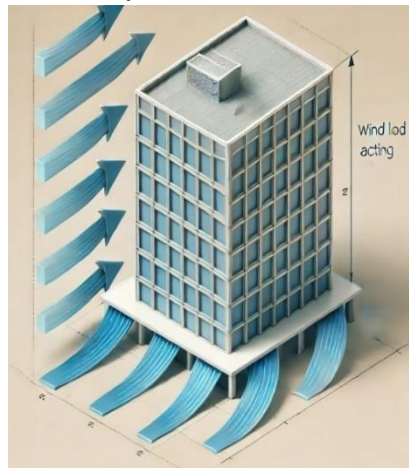


Figure 4: Example of beam-column interaction under non-linear conditions

The effects of significant deformations on structural stability are captured by the P-Delta method.

3.4. Simulation of Load Conditions:

In order to examine the behavior of the structure, two load situations were simulated:

- **Case 1:** The structure was subjected to both incidental and permanent loads, such as live loads and wind pressure, in order to evaluate how well it performed under normal operating circumstances.
- **Case 2:** In the direction of the building with the least stiffness, a mix of seismic, accidental, and permanent loads was simulated. This instance served as a worst-case study, illuminating how the building may respond in the event of a major earthquake.

Four models were developed to compare structural behavior:

1. Linear-elastic behavior.
2. Geometric non-linearity.
3. Material non-linearity.
4. Combined geometric and material non-linearity.

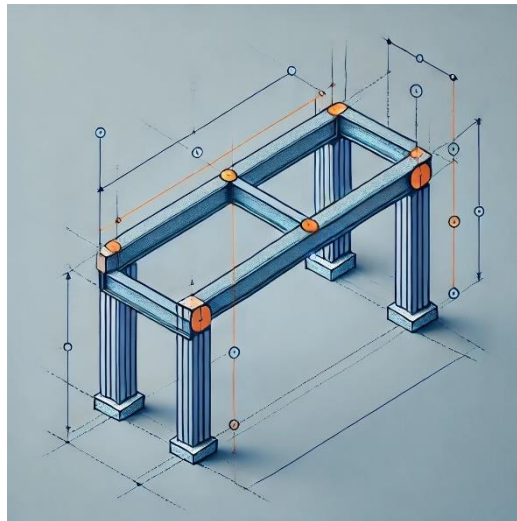


Figure 5: Comparison of load cases and structural response for linear-elastic vs. non-linear models

This figure illustrates how displacements increase in non-linear models compared to linear ones.

3.5. Analysis of Results:

The non-linear models displayed significant differences in load-bearing capacity, displacement, and stress redistribution in comparison to the linear-elastic model. Specifically, when both geometric and material non-linearities were considered, the displacement at the top of the building increased by 39.66 percent, highlighting the importance of accounting for non-linear effects when designing for seismic activity. The load redistribution among the columns also indicated notable variations, with stress levels in some columns increasing by as much as 24.5 percent.

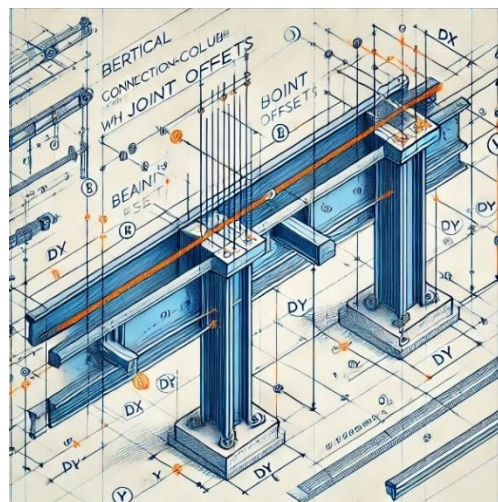


Figure 6: load redistribution in columns under non-linear circumstance

This bar graph shows how stress levels rose in some columns (P20, for example) by more than 20 percent.

3.6. Impact of Electronic Monitoring Systems:

In addition to modeling structural behavior, this study looked into the integration of electronic monitoring systems, such as seismic sensors and real-time monitoring devices. These systems provide essential data that allows dynamic adjustments to the building's load distribution and overall structural response during seismic events. When combined with non-linear modeling, these electronic devices offer increased safety by enabling the early identification of potential vulnerabilities.

4. RESULTS:

The seismic analysis's results indicate that linear-elastic and non-linear models differ significantly from one another in terminology of displacement, load redistribution, and stress differences in beams and columns.

4.1 Displacement at the Top of the Structure:

In comparison to the linear-elastic model, the non-linear models displayed a maximum displacement of 12.01 cm at the surpass of the structure, a 39.66 percent increase. This emphasizes how crucial it is to take non-linearities into account in order to prevent underestimating deformation during seismic events.

	Model-1	Model-2	Model-3	Model-4
Case -1	..	30.6	3.66184	3.315
Case -2	..	21.9301	2.8051	1.9992

Table 1: Collapse factors for different models under various load conditions.

Model-1: Linear-elastic behavior.

Model-2: Geometric non-linearity.

Model-3: Material non-linearity.

Model-4: Combined geometric and material non-linearity.

The collapse factors are displayed in this table; non-linear models have noticeably larger values, which suggest a higher probability of deformation.

4.2 Load Redistribution Across Columns:

There were notable differences in the redistribution of loads among columns between the non-linear and linear-elastic models. Stress increases over 10% were seen in many columns by the non-linear models, with Pillar 20 registering the largest stress increase of 24.5%. These findings highlight the need to take non-linear effects into account in order to minimize localized overstressing during seismic occurrences, especially for load-bearing materials.

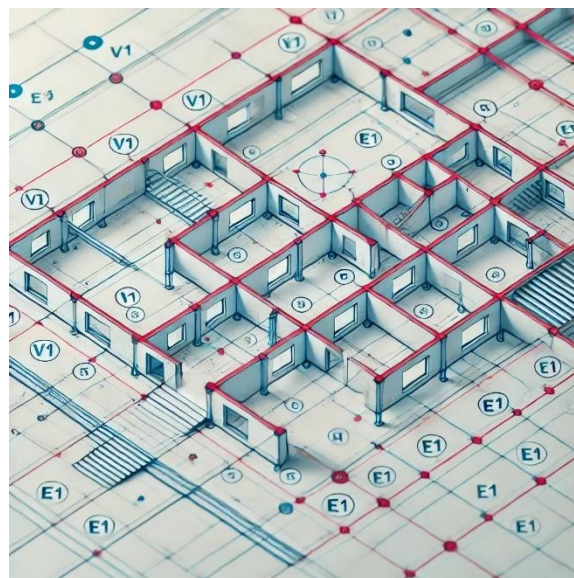


Figure 7: Redistribution of loads in columns under non-linear conditions

The highest rise in stress is seen in Pillar 20, which is shown by a bar chart that shows how the stress distribution varies across major columns (P2, P3, P6, P13, P14, P15, P18, P19, and P20) when non-linear effects are taken into consideration.

4.3 Bending Moment Diagrams for Beams:

We examined the bending moments in beams on different levels, with particular attention to beam V4, which is situated in the core of the building. In comparison to the linear-elastic model, the non-linear models displayed much greater moments at the crucial junctions between beams and columns. These findings suggest that there is a greater chance of plastic hinge creation, especially in regions where the moments are greater than the concrete's and the reinforcing steel's material capacity.

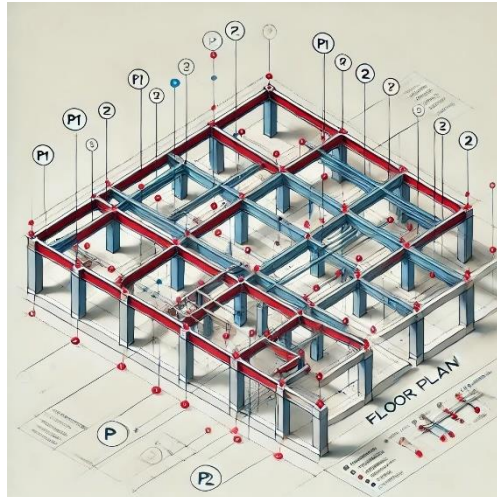


Figure 8: Bending moment diagram for beam V4 across different floors

The bending moments along beam V4 in the non-linear and linear-elastic models are contrasted in this diagram. Greater moments are seen in the non-linear models, particularly close to beam-column connections, which suggests the possibility of plastic hinge creation.

4.4 Comparison of Stress on Pillar Bases:

A comparison was made between linear-elastic and non-linear models for normal pressures and bending moments at the base of each column. Significant differences in stress were found in the investigation, and the non-linear models predicted substantially bigger forces at the bases of the pillars. The largest increase in stress was seen in Pillar 20, which rose by 24.5% in non-linear circumstances. These findings emphasize how crucial it is to take second-order effects into consideration when designing structures.

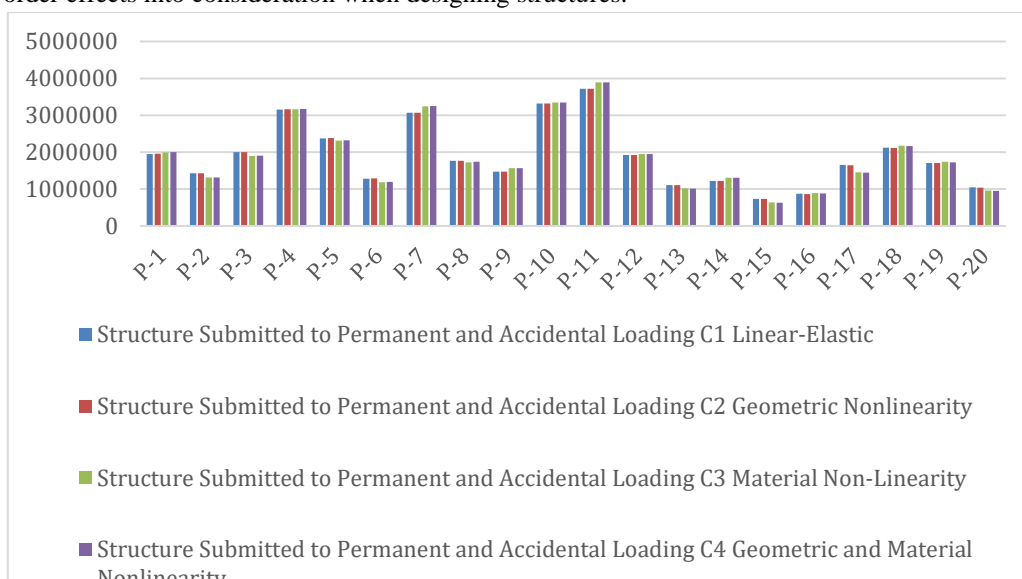


Figure 9: Numbering of pillars and stress variations at the pillar bases

The pillars of the structure are numbered in this Figure, which also illustrates the stress fluctuations at their bases under non-linear conditions. Pillar 20 displays the largest rise in stress.

4.5 Stress Distribution Across Models:

The non-linear models displayed up to 40% more displacements and stresses than the linear-elastic models, according to a study of the stress distributions across the various models. Under non-linear circumstances, pillars P15 and P17 showed notable increases in stress of 14.96% and 13.42%, respectively. According to these results, traditional linear-elastic models understate the real structural requirements, especially in important load-bearing components during seismic occurrences.

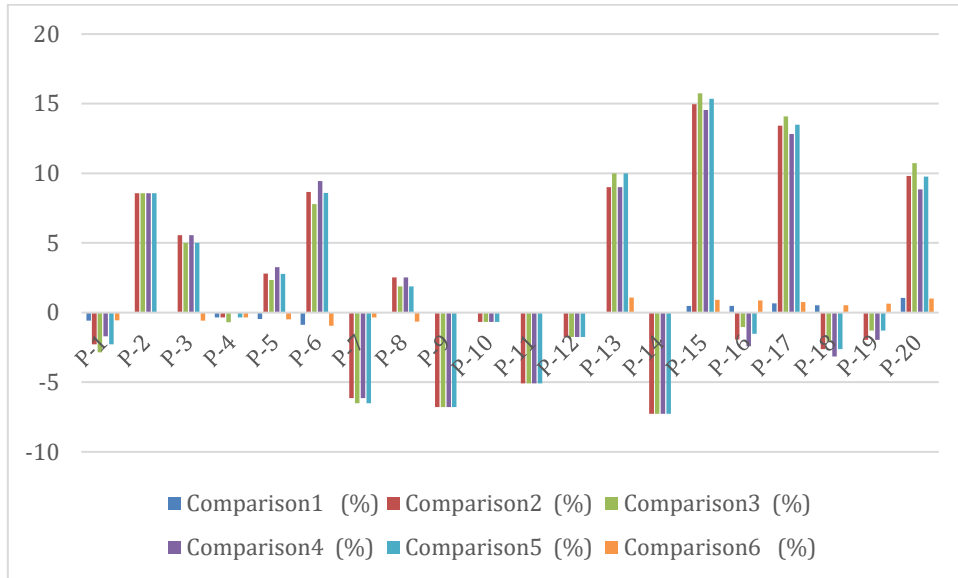


Figure 10: Stress increase percentages for Pillars 15 and 17 across different models

In four different models—linear-elastic, geometric non-linearity, material non-linearity, and combined geometric and material non-linearity—the % rise in stress for Pillars 15 and 17 is displayed in this Figure.

4.6 Comparison of Stress Distribution in Columns:

Lastly, an analysis of the total differences in column loads between models was conducted. The investigation revealed that in the non-linear models, columns such as Pillars P2, P3, P6, P13, P14, P18, and P20 had notable increases in stress. The fact that Pillar 20 showed the greatest stress spike highlights the crucial role that non-linear modeling plays in precisely forecasting stress concentrations during seismic occurrences [15]. [16]. [17]. [18]. [19]. [20].

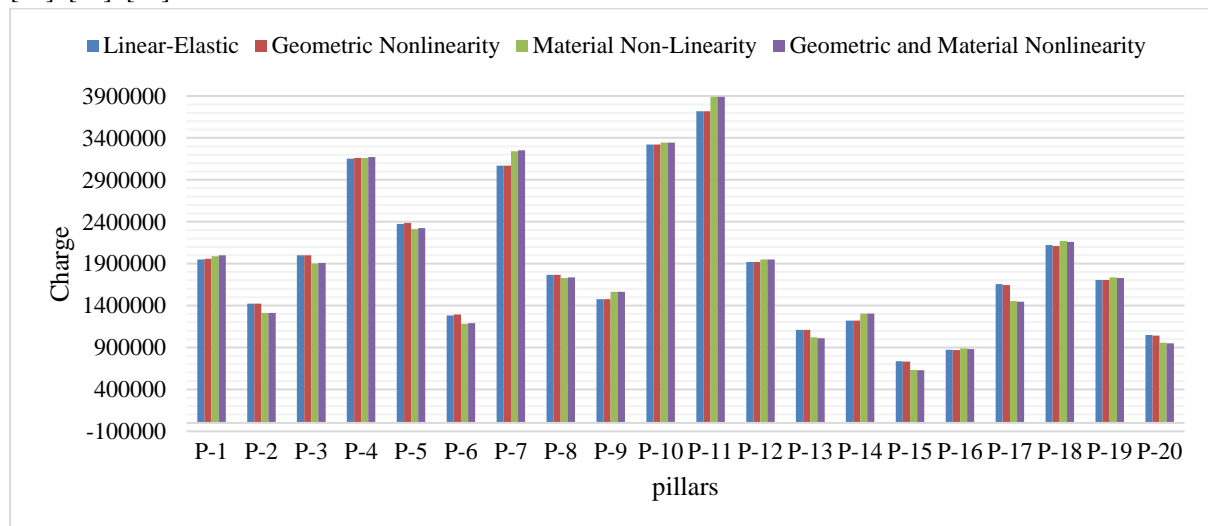


Figure 11: Variations in column loads for various analyses

This Figure, which takes into consideration non-linearities, compares the growth in stress in several columns. The largest spike is illustrated in Pillar 20, demonstrating the effects of non-linear impact on structural stability.

5. DISCUSSION:

The incorporation of non-linearities had a substantial effect on the seismic behavior of the building; in comparison to linear-elastic models, non-linear models displayed larger bending moments, higher displacements, and higher stress in the columns. These results highlight the necessity of non-linear models in order to precisely forecast how the building will behave when subjected to seismic loads, especially in terms of displacement and stress concentrations.

The danger of ignoring non-linearities are highlighted by the 39.66 percent increment in displacement seen in non-linear models, notoriously at higher levels where structural failure becomes more likely. In a comparable vein, Pillar 20's 24.5% stress increase highlights the significance of non-linear designs in anticipating load redistribution and averting stress concentrations that might cause localized failures.

The mixture of non-linear models and electronic monitoring systems enables for dynamic modifications and real-time data collection during seismic events, which enhances structural safety. These systems offer for the likelihood of quick interference in the event of an earthquake by allowing continuous monitoring of critical structural elements.

In conclusion, this study highlights the important role of non-linear models in accurately predicting seismic performance, particularly regarding displacement, load redistribution, and stress. Integrating electronic monitoring systems additionally enhances building resilience by permitting real-time adjustments. Additional research should study further inclusion of these technologies to boost earthquake resilience in high-rise buildings.

6. CONCLUSION:

Under geometric and physical non-linearity, the displacement at the top of the building was 12.01 cm, which represented an increase of 39.66% above the linear-elastic model. This demonstrates the importance of non-linearity, which has to be taken into account throughout the design stage. The investigation also demonstrated that there were notable fluctuations in beam effort between levels, highlighting the importance of taking floor-level variations into consideration. Second-order effects should be taken into account if they surpass 10% of primary effects, as was the case for many pillars with variances ranging from 10% to 24.5%, according to Eurocode 2. Significant changes were only observed between two pillars under accidental and permanent loads. To sum up, electronic monitoring systems that offer real-time input and adaptive reactions for better safety should be incorporated into designs to increase seismic resistance.

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