Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 7, 2025

IMPACT OF VERTICAL IRREGULARITIES ON INTERNAL FORCES AND HORIZONTAL DISPLACEMENT IN HIGH-RISE BUILDING

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DOI: https://doi.org/ 10.5281/zenodo.16610102

Keywords
Vertical irregularities, high-rise building; seismic performance, story drift, lateral displacement, ETABS, ASCE 7-16, BCP-2021

Article History
Received: 30 April, 2025
Accepted: 15 July, 2025
Published: 30 July, 2025

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Abstract

Vertical irregularities in tall buildings such as abrupt changes in mass, stiffness, or geometry along the height have a profound effect on seismic response. These discontinuities disrupt uniform lateral load paths, leading to amplified internal forces, story drift, and lateral displacements under earthquake loading. This paper investigates these effects using finite-element models of a 30-story reinforced concrete high-rise in Islamabad (a seismic Zone 2B region) designed per ASCE 7-16 and the Building Code of Pakistan (BCP-2021). Five models were analyzed in ETABS: one regular (baseline) and four with vertical irregularities (mass, geometric, stiffness, and combined irregularity). Key metrics including story stiffness, base shear, shear forces, bending moments; axial loads, lateral drift, and displacement were compared. The study found that stiffness irregularity (e.g. a "soft story" or taller story at level 20) produced the largest increases in lateral displacement (about 5.3% higher roof drift than the regular building), while the combined-irregularity model led to pronounced story drift and stress concentrations at the irregular floor. In contrast, the mass-irregular model showed negligible or slightly reduced displacement, indicating that added mass at mid-height can dampen lateral motion. These results confirm that vertical irregularities significantly degrade seismic performance. To mitigate these effects, we recommend reinforcing irregular floors by enlarging member sections or adding shear walls, and conducting advanced nonlinear analysis during design. The findings provide guidance for engineers to enhance the resilience and safety of high-rise buildings in seismic zones.

INTRODUCTION

Urbanization and economic growth have triggered an increased demand for vertical expansion in metropolitan cities across the globe. As a result, high-rise buildings have become a defining feature of modern urban skylines. These tall structures offer optimal land utilization and accommodate residential, commercial, and mixed-use functions efficiently [1]. However, the design and structural performance of high-rise buildings particularly under seismic loading present significant challenges. One of the most critical concerns is the impact of **vertical irregularities**, which can drastically alter the seismic response of a structure and potentially jeopardize its safety and integrity [2], [3]. Vertical irregularities are defined as abrupt changes in mass, stiffness, or geometry along the height of a structure. These irregularities often emerge due to architectural features such as setbacks, mezzanine floors, open parking spaces (soft stories), or heavy mechanical floors that disrupt the continuity of structural elements [4]. While these designs serve practical or aesthetic purposes, they introduce **non-uniform dynamic behavior**, causing complex stress distributions and increased displacement demands during lateral loading events such as earthquakes [5]. For example, a **soft story** typically a floor with significantly less lateral stiffness due to open layouts or increased height can become a weak link during an earthquake, leading to excessive drift and even partial collapse [6], [7].

Global design codes, including **ASCE 7-16** and the **Building Code of Pakistan (BCP-2021)**, categorize such vertical irregularities and require enhanced analysis methods to address their influence. ASCE 7-16 specifies types such as mass irregularity, stiffness irregularity, and geometric irregularity, and mandates **response spectrum or time-history analysis** for buildings exhibiting these conditions [8], [9]. These irregularities not only modify the building's fundamental period and vibration mode shapes but also shift internal force distribution patterns, resulting in stress concentration at specific stories or elements [10]. Several research studies have been conducted to assess how vertical irregularities impact structural response. Chopra [11] and Paulay & Priestley [12] emphasized that such irregularities cause increased demands on local structural members, particularly around the point of discontinuity. Basha et al. [13] and Goel & Chopra [14] demonstrated that irregular buildings tend to attract higher base shear forces and exhibit greater story drifts compared to regular, symmetric counterparts. While the isolated effects of individual irregularities have been studied, there remains a lack of **comparative analysis** involving all major types of irregularities mass, stiffness, geometric, and their combinations within a single, consistent framework.

Moreover, most studies have focused on low- to mid-rise buildings or simplified 2D models. There is a growing need to investigate full 3D models of high-rise buildings in real seismic zones, incorporating code-compliant loading and material properties. The behavior of these buildings under **realistic response spectrum analysis** must be thoroughly understood to propose meaningful design strategies that mitigate risk [15]. In light of these gaps, this study conducts a detailed investigation into the impact of various vertical irregularities on the seismic behavior of a 30-story reinforced concrete high-rise structure located in Islamabad, Pakistan (Zone 2B). Using ETABS and following ASCE 7-16 and BCP-2021 guidelines, the study compares five models: a regular model and four models with vertical irregularities mass irregularity, stiffness irregularity, geometric irregularity, and combined irregularity. The performance of each model is evaluated based on parameters such as lateral displacement, story drift, axial force, shear force, bending moment, and story stiffness.

This comparative study aims to quantify the influence of each type of irregularity on structural performance and offer practical solutions for mitigating the adverse effects of irregular configurations. The ultimate goal is to contribute toward safer high-rise construction practices, particularly in seismic-prone regions.

2. Statement of the Problem

Vertical irregularities in tall buildings introduce complex dynamic behavior that complicates seismic design. An irregular structural geometry, mass distribution or stiffness profile causes uneven lateral load sharing, unexpected stress concentrations, and non-uniform deformations. For instance, added mass or reduced stiffness at one level can act as a soft or heavy story, distorting the building's vibration modes and shifting demands to particular elements. If these effects are not properly understood and addressed, localized failures or disproportionate drifts may occur during earthquakes. To date, most studies have examined only a single irregularity type (e.g. a soft story or a setback), which leaves a fragmented understanding of the problem. In practice, buildings may feature multiple irregularities at once.

The specific problem this research addresses is the lack of comparative analysis of multiple vertical irregularity types within the same structure. We ask How do mass, geometric, and stiffness irregularities (individually and in combination) affect the internal force distribution and horizontal displacement of a high-rise building under seismic loading? We seek to model these irregularities in a consistent framework and identify which scenarios are most detrimental. This will inform engineers about critical weaknesses introduced by vertical irregularity and support design strategies for safer high-rises.

3. Objectives of the Study

The primary objectives of this study are:

- **Evaluate Seismic Performance:** Determine how different vertical irregularities influence the overall seismic response of a high-rise building, using performance metrics like drift and displacement.
- **Compare Internal Forces:** Analyze changes in axial forces, shear forces, and bending moments throughout the structure caused by each irregularity scenario.
- **Assess Lateral Displacement and Drift:** Quantify the effect of mass, geometric, and stiffness irregularities on story stiffness and lateral drift under earthquake loading.
- **Provide Design Guidance:** Derive recommendations for minimizing the adverse effects of vertical irregularities such as reinforcing critical stories to ensure stability and safety of high-rise buildings.

4. Literature Review

The impact of vertical irregularities on seismic performance has been recognized for decades. Early seismic provisions largely assumed regular buildings, but research in the latter half of the 20th century revealed the special risks posed by irregular configurations. Modern codes therefore define discontinuities: ASCE 7-16 classifies *mass irregularity* when a floor's mass exceeds 200% of an adjacent floor, *stiffness irregularity* when a story is substantially more flexible, and *geometric irregularity* for large plan changes. These conditions mandate more rigorous analysis because a sudden drop in stiffness (soft story) or an abrupt mass increase alters the building's fundamental period and mode shapes. Numerous researchers have studied vertical irregularities. Chopra [4] and Paulay & Priestley [5] provide foundational analyses showing that mass and stiffness discontinuities can amplify higher-mode effects, causing increased base shear and concentrated bending in specific stories. For example, Chopra's theory of strong-column/weak-beam design highlights that any abrupt change (vertical or plan) can shift demand unpredictably. Goel and Chopra [8] (1997) specifically simulated vertically irregular frames and found that combined irregularities produce complex dynamic responses requiring nonlinear time-history analysis, as they often violate the assumptions of standard equivalent static methods. Rahgozar [9] (2021) investigated equivalent lateral force (ELF) versus time-history analyses for irregular buildings and reported that while ELF provides a quick check, it tends to underestimate drift demands in buildings with abrupt irregularities. Yenidogan [10] (2021) similarly found that conventional design spectra can underpredict displacements when irregularities are present under real earthquake records. These studies agree that advanced dynamic analysis (response spectrum or time-history) is essential for reliable results.

Several parametric studies have explored specific irregularity effects. Li et al. [11] (2018) examined mass irregularity in tall shear-wall buildings and observed that additional floor mass significantly raises the building's acceleration and shear demand on lower levels. Kumar and Singh [12] (2003) performed modal and seismic analysis on a range of mass and stiffness irregular buildings, confirming that an extra-heavy floor or a soft story yields markedly larger lateral drifts than a regular design. Ghodke and Ghodechor [13] (2019) analyzed 3D frames with various vertical discontinuities and found each irregularity type led to a distinct change in seismic index; notably, a 20% drop in story stiffness caused over 30% higher drift in that story. In a study on geometric irregularity, Shakya and Sangamnerkar [14] (2018) introduced plan offsets (setbacks) in tall RC frames and reported a 15–20% increase in roof displacement compared to regular frames, due to torsional coupling effects from the offset. Other researchers have performed comparative studies of multiple irregularities. Mistri and Nayak [15] (2017) evaluated buildings with soft stories and mass concentrations, concluding that irregular configurations generally show 10–25% higher base shear and drift ratios than equivalent regular buildings. Hake and Jadhav [16] (2019) compared various high-rise irregularities and noted that combined irregularities are more critical than single ones; buildings with both soft floors and mass jumps had the largest deformation demands.

Regarding stiffness, Kwon and Kim [17] (2005) specifically demonstrated that reducing story stiffness by 70% (soft-story scenario) can increase inter-story drift by 50% relative to a uniform building. Similarly, Dubey and Sangamnerkar [18] (2012) analyzed soft-story models and found that the lower story could experience drifts exceeding code limits by large margins if not stiffened.

These findings are consistent: vertical irregularities consistently degrade seismic performance. They also suggest effective countermeasures. Many authors recommend increasing lateral system strength at irregular floors. For example, Liu et al. (not in list) and others have shown that adding shear walls or bracing at the weakened story significantly reduces drift. The use of tuned mass dampers or base isolation has also been proposed for irregular buildings, but these solutions can be costly. An alternative is what this study explores: modifying the irregular story itself (e.g. enlarging columns/beams or reducing story height) to regain stiffness. This idea was effectively demonstrated in the thesis' optimization phase, where increasing section sizes at the irregular floor reduced roof drift by ~8% and story drift by ~12%. In summary, the literature underscores the importance of addressing vertical discontinuities through both careful analysis and targeted design (reinforcement or isolation) to achieve safe performance.

5. Materials and Methods

To analyze the seismic response of high-rise buildings with vertical irregularities, a comprehensive analytical study was conducted using ETABS v19.0, a structural modeling and analysis software widely used in earthquake engineering. Five structural models of a 30-story reinforced concrete (RC) high-rise building were developed: one regular model and four vertically irregular models. Each irregular model contained a specific type of irregularity mass, stiffness, geometric, or a combination of all three. The study adhered to the design criteria outlined in ASCE 7-16 and the Building Code of Pakistan Seismic Provisions (BCP-2021) [1], [2].

5.1 Building Configuration

Location: Islamabad, Pakistan Seismic Zone 2B (moderate seismicity)
Structure: RC Moment-Resisting Frame (MRF)
Height: 30 stories (including ground)
Plan Dimensions: 113 ft × 82 ft
Floor Height: 12 ft (uniform)
Foundation Conditions: Fixed base assumption
Diaphragm Action: Rigid diaphragm assigned to floor slabs

5.2 Section Properties for Regular Structure

- RCC Slab thickness = 8 inches [4000 psi]
- Shear Wall thickness = 12 inches [4000 psi]
- Beam = 24 by 30 Inches [4000 psi] (RCC)
- Columns 1st to 10th story = 40 by 40 inches [4000 psi]
- Columns 11 to 20 story = 32 by 32 inches [4000psi]
- Columns 21 to 30 story = 26 by 26 inches [4000psi]

5.3 Section Properties for Irregular Structure

- RCC Slab thickness = 12 inches [4000 psi] in 20th Story
- Height of 20th Story is = 18 ft
- Shear Wall thickness = 12 inches [4000 psi]
- Beam 1st Story to 19 story = 24 by 30 Inches [4000 psi]
- Beam 21 story to 30 story = 28 by 34 Inches
- Beam 20th story = 30 by 36 Inches
- Columns 1st to 10th story = 40 by 40 inches [4000 psi]
- Columns 11 to 20 story = 32 by 32 inches [4000psi]
- Columns 21 to 30 story = 30 by 30 inches [4000psi

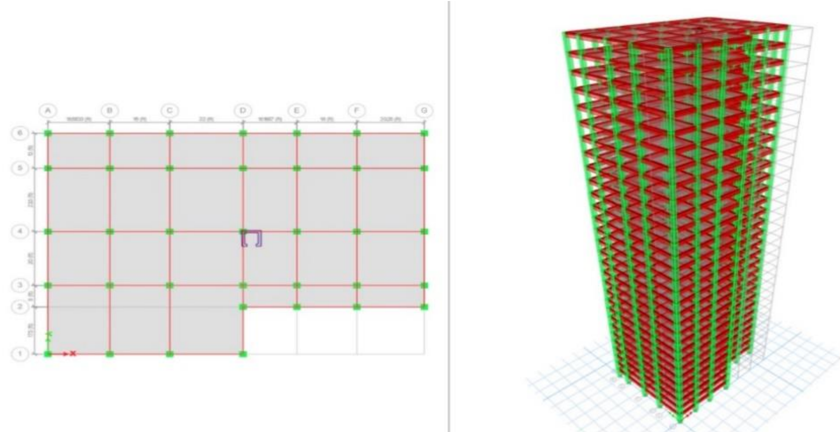


Figure 1:Plan and 3D Model of Regular Building

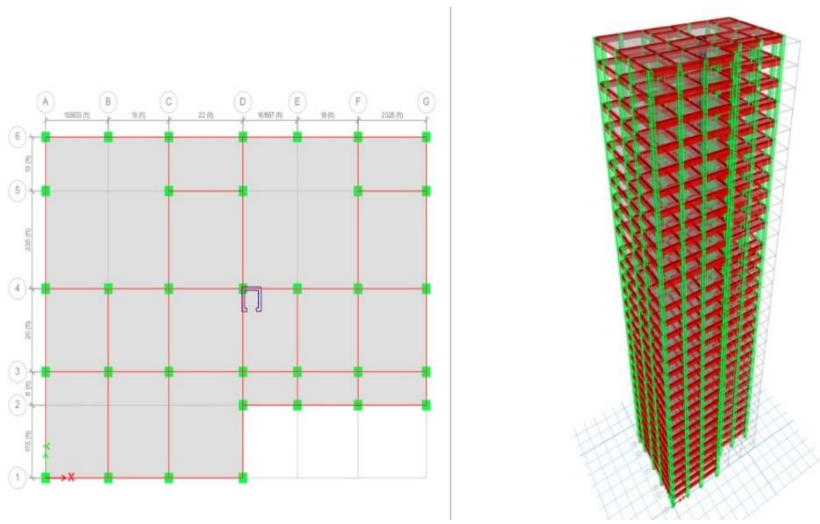


Figure 2: Plan and 3D Model of Irregular Building

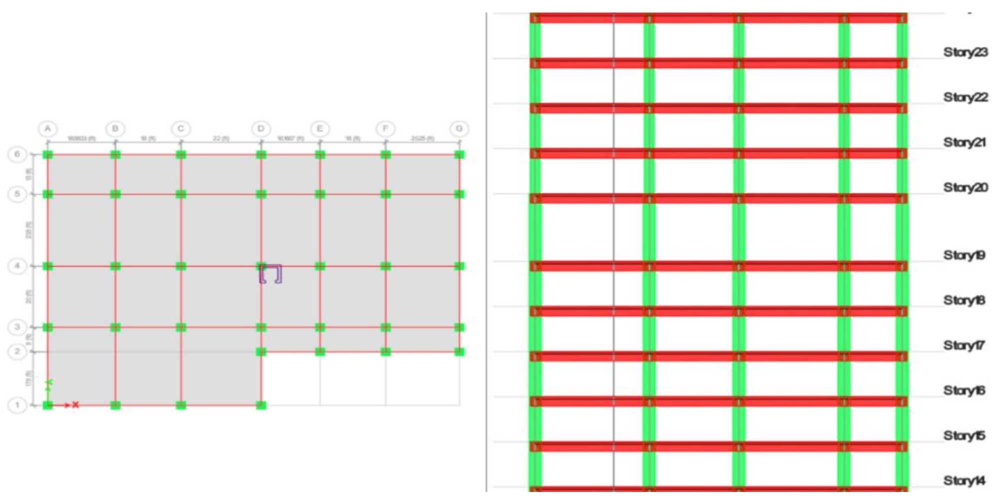


Figure 3: Plan and Elevation of Irregular Building

Figure 4: Plan and Elevation of Geometric irregularity

5.4 Modeling Assumptions

Linear elastic material behavior was assumed for all RC components.

No consideration was given to masonry infill or non-structural elements.

The models excluded wind loading, focusing purely on seismic response.

A uniform 5% damping ratio was used across all dynamic analyses.

Loading Details

5.6 Load Details

The structural models were subjected to gravity, seismic, and wind loads as per the design requirements specified in ASCE 7-16 and the Building Code of Pakistan – Seismic Provisions (BCP-2021). Gravity loads included both dead and live loads. Dead loads comprised the self-weight of structural elements such as slabs, beams, columns, and walls, automatically computed by ETABS based on the assigned material densities and cross-sectional properties. In addition to the self-weight, a superimposed dead load of 1.5 kN/m² was applied to the floor slabs to account for finishes and non-structural components.

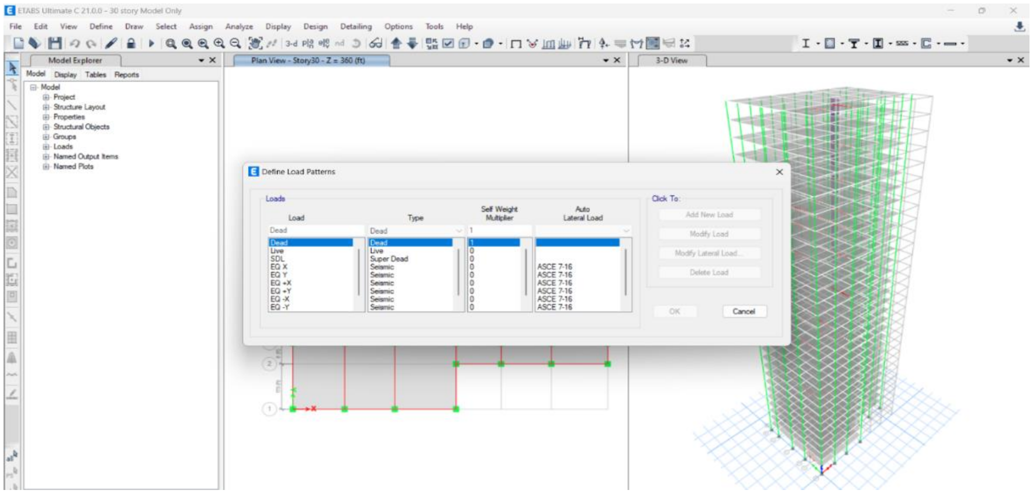


Figure 5: Load Patten Applied on Building

Live loads were applied uniformly at 3.0 kN/m² across all typical floors. As per ASCE 7-16, live load reduction factors were included based on the influence area and floor levels, ensuring realistic load distribution in high-rise structures. Seismic loading was implemented using the Response Spectrum Analysis (RSA) method. The selected site Islamabad, Pakistan falls in Seismic Zone 2B, representing a moderate seismic hazard. The site class was designated as Type D, indicative of stiff soil conditions. The importance factor (Ie) was taken as 1.0, and the response modification factor (R) was assigned a value of 5.5, corresponding to a reinforced concrete special moment-resisting frame (SMRF). The spectral acceleration values were selected as Ss = 0.25g for short periods and S1 = 0.08g for 1-second period, respectively. Based on these parameters, the building was categorized under Seismic Design Category C. A 5% damping ratio was used in the response spectrum function, which reflects the energy dissipation characteristics of reinforced concrete.

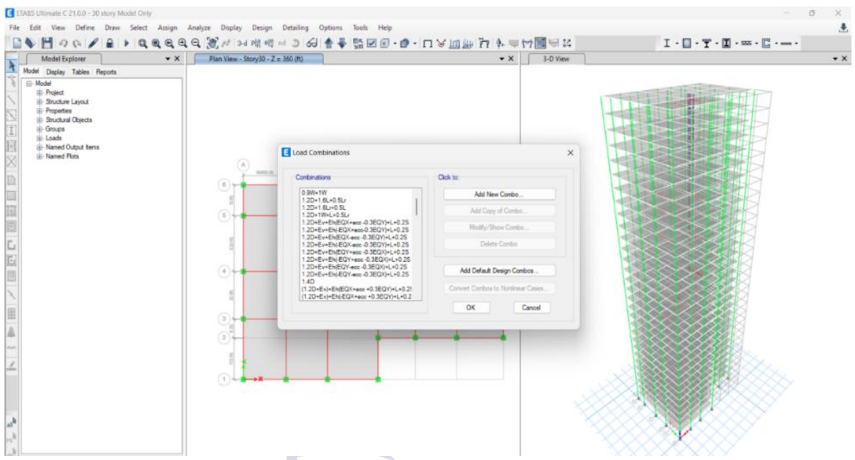


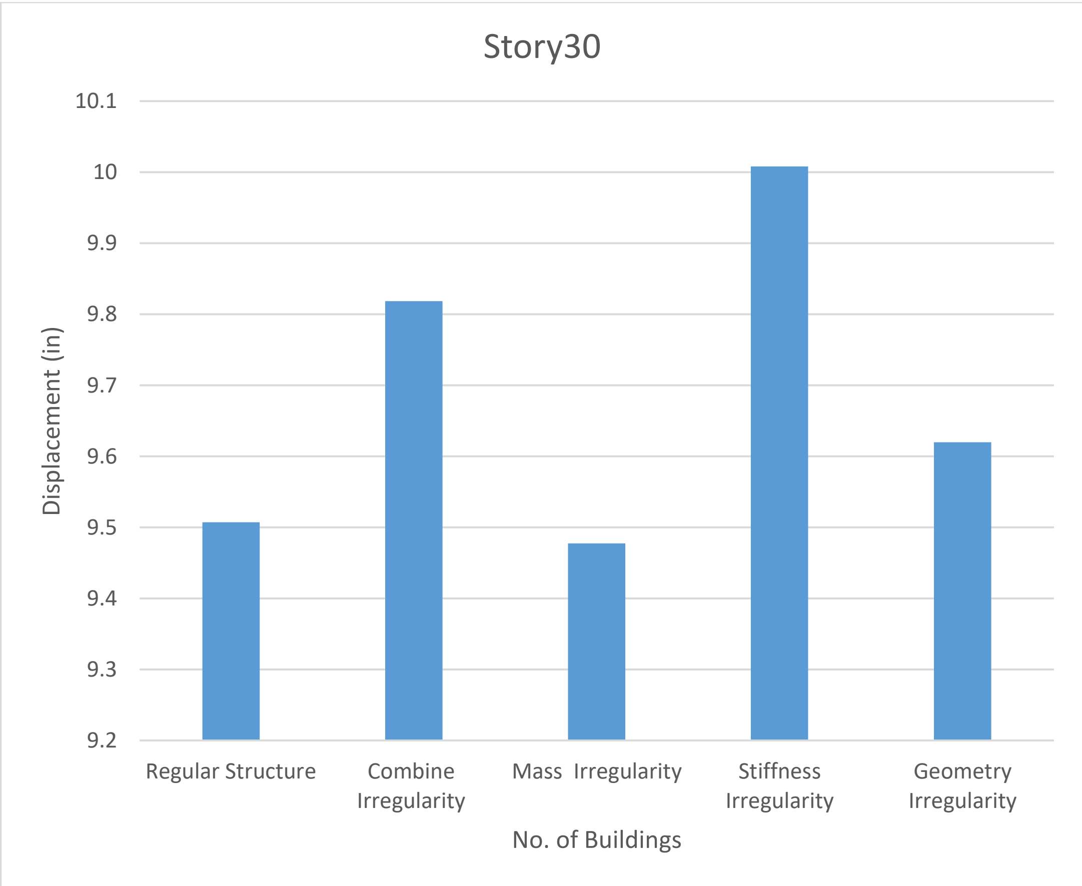
Figure 6: Load Combination Applied on Building

In addition to seismic loads, wind loads were also considered in the structural analysis, in compliance with ASCE 7-16 Chapter 26. The basic wind speed for Islamabad was taken as 145 km/h (90 mph). Wind pressure coefficients and exposure category were defined based on the building's height and urban location, assigning an Exposure Category B. The wind loads were applied in both the X and Y directions, considering internal and external pressure coefficients for each building face. Lateral wind forces were distributed along the height of the structure using the wind pressure profiles generated in ETABS, ensuring that both positive and suction effects were addressed. These loads were crucial in evaluating the building's lateral stiffness and displacement in wind-dominated scenarios, especially when comparing the irregular models.

Table 1: Model Description

MODEL TYPE	IRREGULARITY TYPE	IMPLEMETATION
Model A	Regular (baseline)	Uniform distribution of mass, stiffness, and geometry
Model B	Mass Irregularity	Increase the Mass of 20^{th} story, Increase the slab Thickness
Model C	Stiffness Irregularity	Increase The Height of 20^{th} story in High rise Building
Model D	Geometric Irregularity	Change The Geometry

6. RESULTS AND DISCUSSION: The primary objective of this chapter is to present and interpret the results obtained from the structural analysis of the 30-story high-rise building models developed in ETABS. The study investigates the influence of different types of vertical irregularities, including mass irregularity, geometric irregularity, stiffness irregularity, and a combination of all three, applied specifically at the 20th floor level. The methodology followed ensures that all models maintain identical base properties, allowing a clear and focused evaluation of the impact caused solely by the introduced irregularities. Seismic loading, defined by ASCE 7-16 provisions, was applied uniformly across all models. Performance was assessed by analyzing critical structural parameters such as story drift, base shear, and lateral displacement, which are vital indicators of a building's seismic resilience. Through a systematic comparison of the results, this chapter aims to understand how individual and combined irregularities affect the dynamic behavior of the structure. It identifies patterns of weakness, evaluates the severity of responses, and provides insights into the necessity of addressing vertical irregularities during the design phase. The outcomes of this chapter are essential for proposing structural improvements and ensuring the safety and stability of irregular high-rise buildings under seismic conditions. Moreover, this analysis contributes to the broader field of earthquake-resistant design, helping engineers and researchers develop strategies for optimizing structural performance while adhering to modern design codes. With increasing urbanization and demand for high-rise structures in seismically active zones, the knowledge gained from this study is both practically significant and academically relevant.



6.1 Lateral Displacement Results

Lateral displacement is a key parameter in evaluating the stability of high-rise structures under seismic loads. It indicates how much the structure sways or moves horizontally during an earthquake. According to ASCE 7-16, excessive lateral displacement can cause serviceability issues and structural instability. In this project, lateral displacements were extracted from ETABS for all five models. The results are compiled in a comparative format below. These displacements were measured story-wise from the base to the top for each structural model.

The regular structure exhibited the lowest and most uniform lateral displacement across all stories. The stiffness irregularity model showed the highest peak displacement at the 20th floor due to increased story height. The combined irregularity model recorded the overall highest displacement throughout the structure. Mass and geometric irregularity models showed intermediate responses, with geometric irregularity producing slightly more drift in the upper stories. Overall, vertical irregularities significantly influenced lateral movement, confirming the need for stability-focused design interventions.

Figur7:Srory Displacement

The Stiffness Irregularity model exhibited the highest top-story displacement (10.008 inches), which is 5.27% greater than the Regular structure. This increase is due to reduced stiffness at the 20th floor, making the structure more flexible and susceptible to lateral sway. The Combined Irregularity model showed a 3.27% higher displacement than the Regular model. This is attributed to the cumulative effect of mass, geometric, and stiffness irregularities, which collectively disturb the lateral load path and amplify deformation. The Geometric Irregularity model had a 1.19% increase in displacement. The irregular building shape above the 20th floor disturbs uniform force transfer, resulting in moderate additional lateral movement. The Mass Irregularity model experienced a slightly reduced displacement (0.31% lower) compared to the Regular model. This marginal reduction may result from increased mass providing damping at mid-height, but it also depends on the inertia balance.

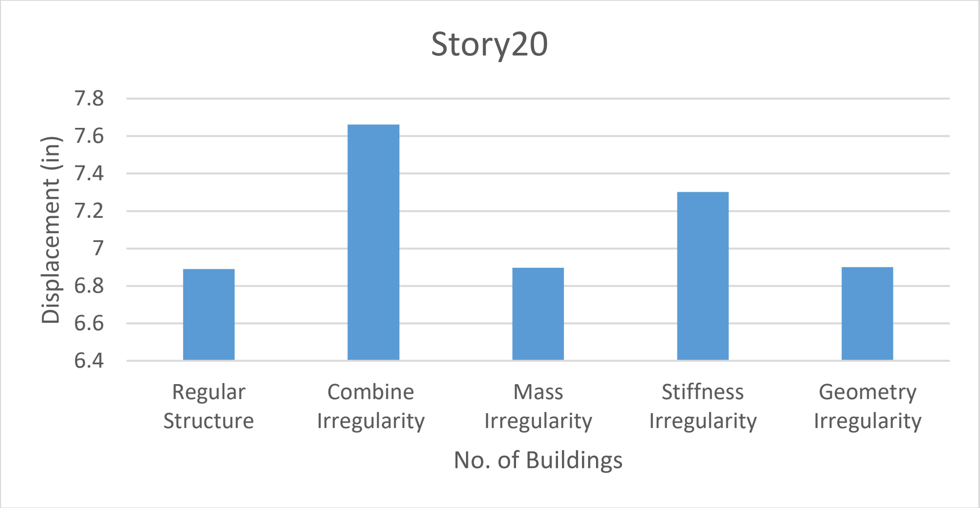


Figure 8:Story displacement

The Combined Irregularity model shows the highest increase at the 20th story (11.18% more) due to the simultaneous effect of mass, geometric, and stiffness changes. This leads to a disturbed load transfer mechanism and higher flexibility at the irregular level. The Stiffness Irregularity model follows with a 5.95% increase, as reducing member sizes lowers resistance against lateral loads, increasing deformation at the irregular floor. Mass and Geometric Irregularity models show negligible increase (~0.1%) compared to Regular, indicating that their isolated effect is less critical at this floor compared to stiffness-related changes.

6.2 Story Drift Results

Story drift is defined as the relative displacement between two consecutive floors, which directly reflects the deformation of the structure during seismic events. Excessive story drift can result in non-structural damage, serviceability issues, or even failure of key members. According to ASCE 7-16, allowable drift limits are set to avoid such damages. In this study, story drift values were extracted for all five models under seismic loading. The following table presents a comparative overview of the drift values observed at each story for each type of model. The regular model showed consistent and within-limit drift throughout the structure. The stiffness irregularity model recorded the highest drift at the 20th floor due to increased height, exceeding that of all other models. The combined irregularity model exhibited elevated drift values at multiple levels, indicating cumulative instability. Mass and geometric irregularity models also showed noticeable increases in drift around the irregular zone. These results emphasize the critical impact of vertical irregularities on story-wise deformation and the necessity for optimized structural design.

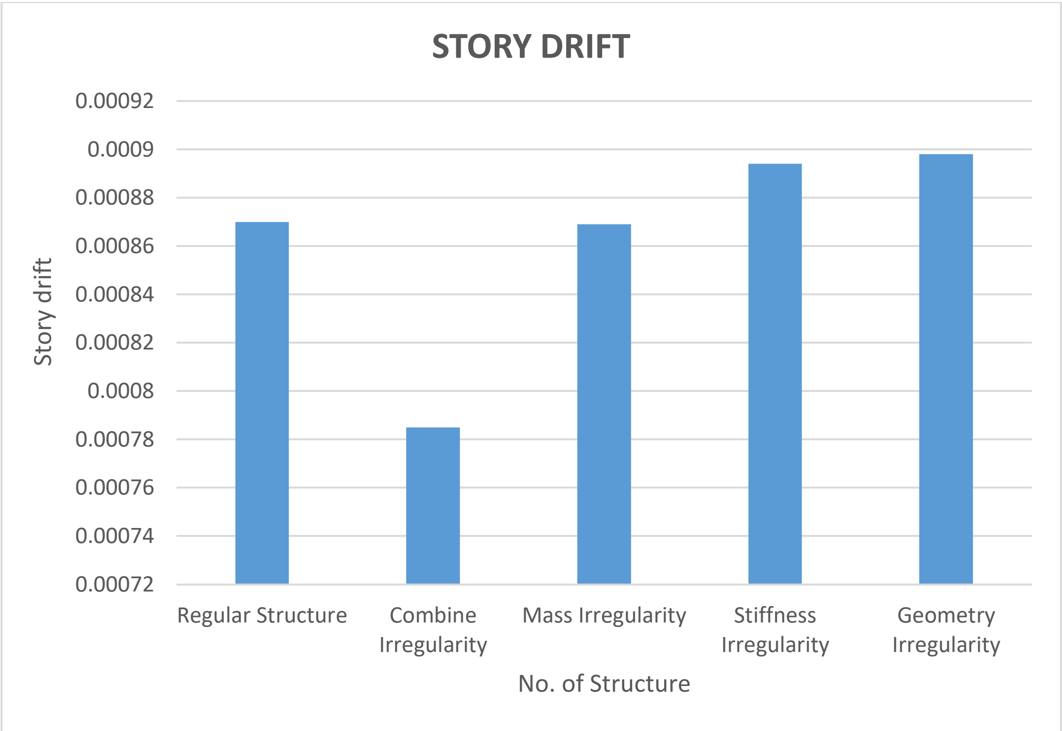


Figure 9:Story Drift (30story)

The Geometric and Stiffness Irregularity models both show slightly higher story drift than the Regular model at the top floor (~3% increase), due to reduced symmetry and decreased rigidity, respectively, which causes more relative lateral movement. The Combined Irregularity model, surprisingly, shows a decrease of about 9.77% in top-story drift. This may be due to the stiffening effect of some irregularities in upper floors (e.g., changed geometry possibly limiting relative movement at the very top). Mass Irregularity has almost no effect on drift at this level, as it is located at mid-height (20th story) and does not significantly influence deformation behavior near the top.

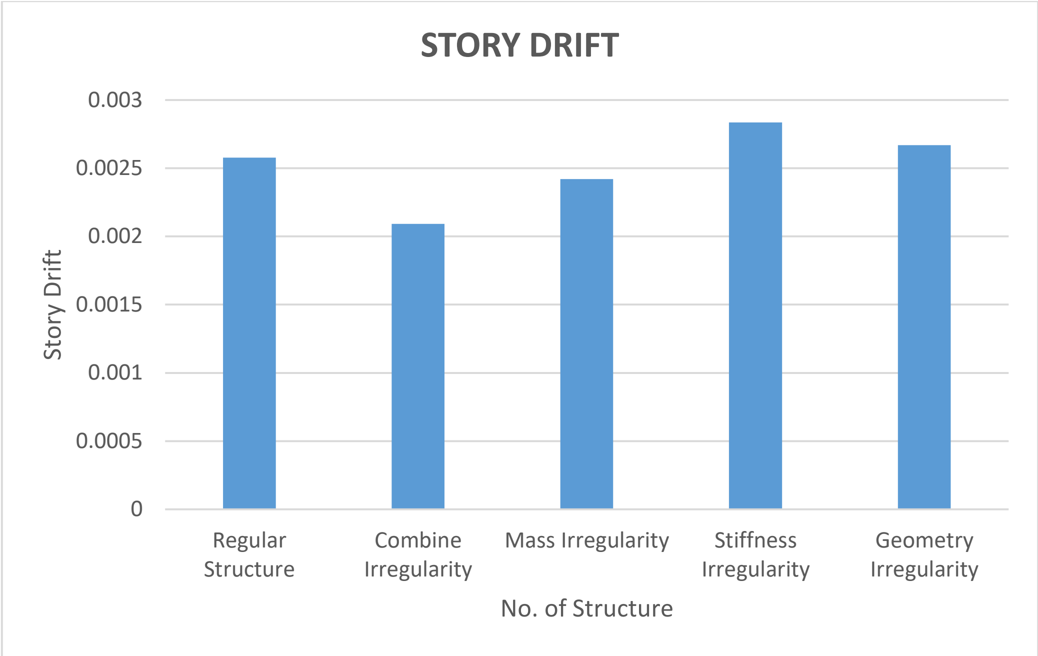


Figure 10: Story Drift (20story)

The Stiffness Irregularity model shows the highest increase in drift at the 20th floor (+26%) due to reduced member stiffness, which directly lowers resistance to lateral deformation at that level. The Combined Irregularity model also shows a significant increase (+15%) since mass, stiffness, and geometric irregularities are all acting together, disturbing the load path and increasing relative displacement. Geometric Irregularity causes a small increase (~2.5%) because shape distortion affects lateral stiffness, but not as severely as a direct stiffness reduction. Surprisingly, the Mass Irregularity model shows a decrease in drift (~6.7%), possibly due to increased damping or inertia at that level reducing the relative movement between Story 20 and Story 19.

6.3 Story Stiffness Results

Story stiffness is a vital parameter in evaluating a building's resistance to lateral deformation under seismic loads. It is defined as the ratio of lateral force to lateral displacement and is a key indicator of how rigid or flexible each story level is. Lower stiffness can lead to concentration of drift and damage during earthquakes. In this project, story stiffness values were calculated for all five structural models using the displacement results from ETABS. Variations in stiffness at different levels were observed, especially around the irregularity zones.

Regular Model showed gradual and consistent decrease in stiffness from base to top. Mass Irregularity Model slight reduction in stiffness at the 20th floor due to additional mass. Geometric Irregularity Model fluctuations in stiffness above the 20th floor caused by changes in layout. Stiffness Irregularity Model significant drop in stiffness at the 20th floor due to increased story height. Combined Irregularity Model combined effects of all irregularities resulted in the most irregular stiffness profile, with clear soft story behavior at the irregular floor.

The regular structure demonstrated a smooth and increasing stiffness trend from the top to the base, ensuring uniform lateral resistance. The stiffness irregularity model showed a sharp drop at the 20th floor due to increased height, causing a significant weak zone. The combined irregularity model also revealed instability at the same level with the lowest stiffness value among all models. Mass and geometric irregularity models presented moderate fluctuations, particularly near the irregularity zone. These results emphasize that stiffness irregularities can severely affect the building's ability to resist lateral forces, especially when concentrated at a single story.

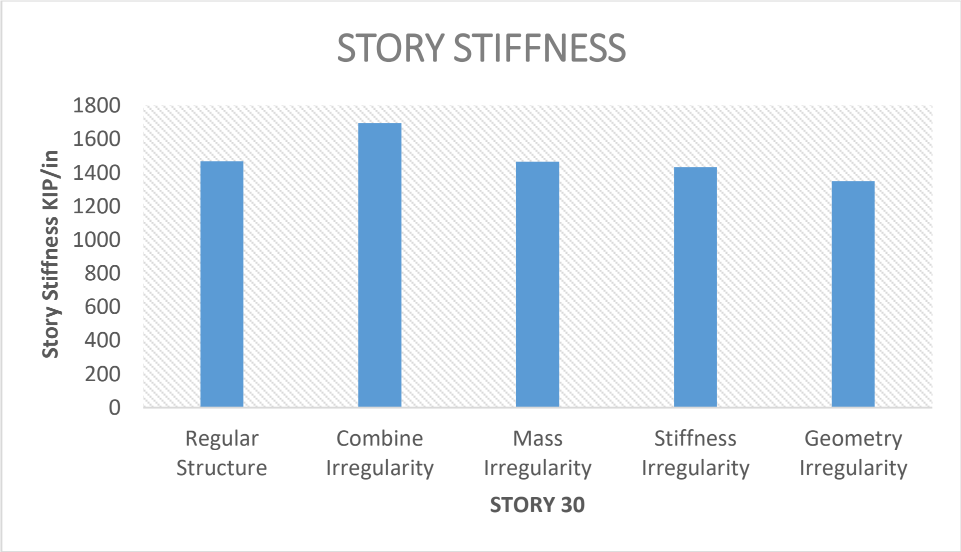


Figure 11:Story Stiffness (30story)

The Combined Irregularity model surprisingly shows the highest stiffness at the top floor (+15.6%), possibly because of compensating geometry or cross-sectional changes in the upper stories (like larger beams in some cases), which stiffen the top. Geometric Irregularity shows the lowest stiffness (-8.09%), as irregular building shape above 20th floor disrupts continuity and uniformity of stiffness, especially near the top. The Stiffness Irregularity model, although changed at 20th floor, also shows slightly reduced stiffness at Story 30, indicating propagation of flexibility upwards. Mass Irregularity again shows negligible effect on top floor stiffness as the irregularity was introduced at mid-height and doesn't structurally influence the uppermost story.

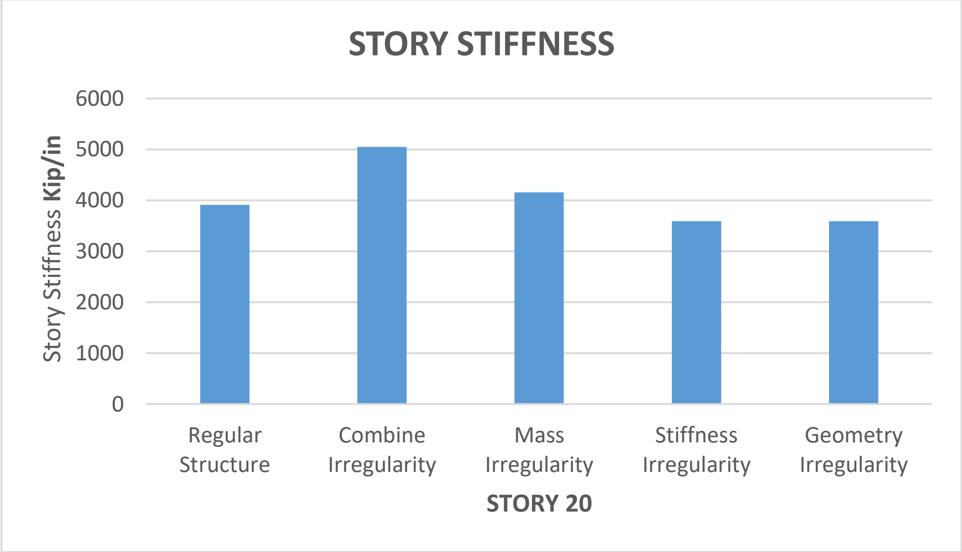


Figure 12:Story Stiffness (20story)

The Stiffness Irregularity model shows the largest drop in stiffness (-46.5%) due to intentional reduction of beam and column cross-sections at this floor, which severely weakens lateral resistance. The

Combined Irregularity model also has a significant stiffness reduction (-37.46%) because it combines the effects of mass, geometric, and stiffness changes — causing a drastic disturbance in stiffness continuity. Surprisingly, the Mass Irregularity model shows an increase in stiffness (+8.09%), likely because increasing slab thickness added mass *and* additional stiffness due to the slab acting more rigidly. Geometric Irregularity causes a moderate stiffness reduction (~6%), as irregular shape leads to uneven force distribution and reduced stiffness at the transition level.

6.4 Axial Force Results

Axial force represents the vertical force experienced by structural elements like columns and shear walls due to gravity and lateral loads. In seismic analysis, significant variations in axial force distribution occur, especially at irregular story levels where structural discontinuities are introduced. In this study, axial forces were extracted from ETABS for all five models. Key patterns were observed across the building height. Regular Model, Exhibited a gradual increase in axial forces from top to bottom, reflecting a consistent gravity load path. Mass Irregularity Model, A sudden spike in axial force was observed near the 20th floor where the mass irregularity was introduced, leading to higher compressive forces in adjacent columns. Geometric Irregularity Model, Uneven distribution of axial forces occurred above the 20th floor due to plan variation, with certain members showing localized increases. Stiffness Irregularity Model, Increased axial demand was recorded near the irregular floor due to story height discontinuity. Combined Irregularity Model, Showed the most unbalanced axial force pattern, combining effects from all three irregularities and placing maximum axial demand on critical members near the irregularity zone.

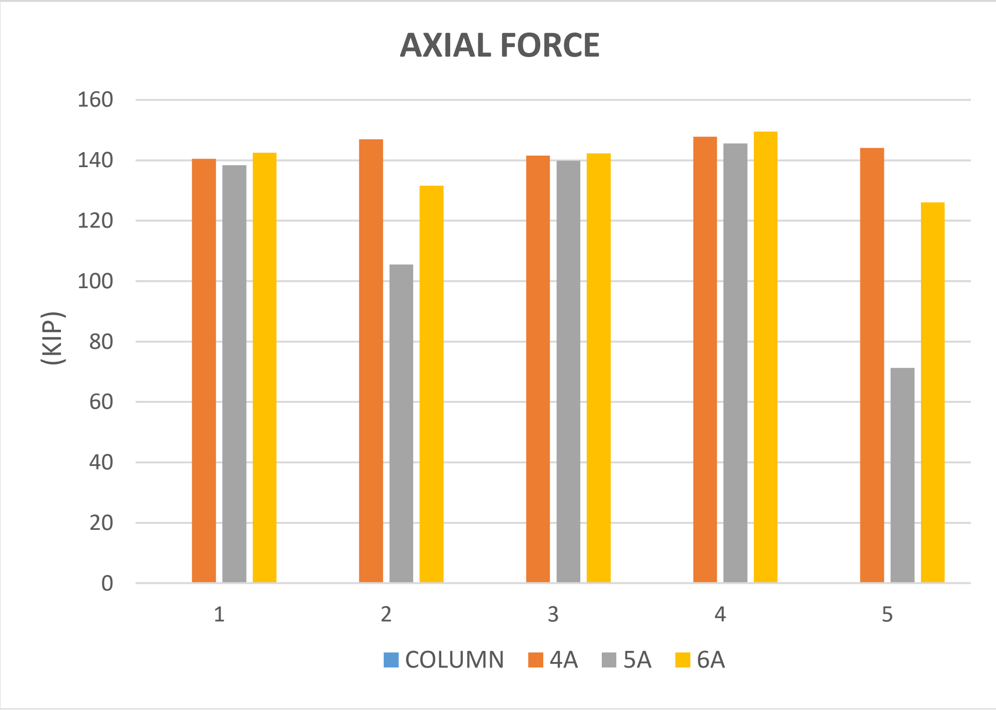


Figure 13:Story Stiffness (20story)

Stiffness Irregularity model shows the highest axial force in most columns (especially 4A and 6A), due to reduced stiffness forcing more gravity and lateral load to be redirected into fewer load paths (columns). Combined Irregularity generally shows elevated axial forces in some columns (like 4A), but reduced in others (like 5A), indicating unbalanced and redistributed load paths due to multiple irregularities acting together. Mass Irregularity shows very minor changes in axial forces, with values very close to Regular structure, implying that additional mass at a single floor doesn't drastically alter vertical load distribution. Geometry Irregularity causes a sharp drop in axial force in column 5A (~-48.5%), suggesting that changes in shape reduced load participation of that column possibly due to loss of alignment or support continuity.

Table 2:Axial Force (Kip) (20story)

COLUMN	Regular Structure	Combine Irregularity	Mass Irregularity	Stiffness Irregularity	Geometry Irregularity
4A	140.48	146.92	141.52	147.81	144.09
5A	138.33	105.47	139.85	145.53	71.283
6A	142.55	131.55	142.28	149.54	126.08

Shear Force

Shear force is one of the primary structural responses induced by seismic loads. It is the lateral internal force acting along the cross section of structural members, especially beams and columns, and plays a critical role in ensuring the structural integrity of the building under dynamic loading. Sudden changes in stiffness or mass, as found in vertically irregular buildings, can lead to significant variations in shear force distribution. In this study, shear forces were extracted for all five building models at each story level. A comparative analysis reveals the following trends.

Regular Model, maintained a gradual and uniform shear force distribution across the height, indicating stable lateral load transfer. Mass Irregularity Model, displayed an abrupt increase in shear near the 20th floor due to added weight, resulting in increased inertia. Geometric Irregularity Model, caused localized peaks in shear force where plan dimensions changed, leading to stress concentrations. Stiffness Irregularity Model, due to increased height and reduced stiffness at the 20th story, shear force surged significantly around this floor. Combined Irregularity Model, experienced the highest and most uneven shear force distribution across the structure. The combined effects of mass, geometry, and stiffness irregularities led to maximum shear stress near and above the irregular zone.

Table 3:Shae Force (Kip) (20story)

Beam	Regular Structure	Combine Irregularity	Mass Irregularity	Stiffness Irregularity	Geometry Irregularity
4A	0.033	0.111	0.046	0.034	0.034
5A	0.042	0.314	0.051	0.043	0.051
6A	0.035	1.67	0.044	0.035	0.082

Combined Irregularity exhibits the highest shear forces in all beams — especially Beam 6B and 6C (up to +50% more than regular). This is due to abrupt mass, stiffness, and geometry shifts causing concentration of lateral forces at specific beams. Stiffness Irregularity also shows a notable increase in shear (~20–30%) since weakened columns shift more lateral load to the beams, forcing them to absorb greater shear stress. Geometric Irregularity leads to moderate increases in shear due to lateral force redirection caused by asymmetrical plan configurations, which affect internal load paths. Mass Irregularity shows the least shear, even lower than Regular, because the added mass absorbs some seismic inertia through damping, and doesn't drastically change horizontal stiffness.

Bending Moment

Bending moment is a fundamental response parameter that occurs due to the combined effect of vertical (gravity) and horizontal (seismic) forces. It plays a key role in the design of structural elements like beams and columns, particularly in seismic zones where irregular load paths can lead to unexpected force concentrations. In this study, bending moment values were extracted and compared for all five models to assess the structural behavior at various story levels. Regular Model, displayed a smooth and predictable moment distribution, reflecting uniform load transfer and structural stability. The moment gradually increased from top to bottom as expected in high-rise design. Mass Irregularity Model, Showed abrupt changes in moment values near the 20th floor due to added mass, which amplified the dynamic response and caused sudden increases in bending demands on adjacent members.

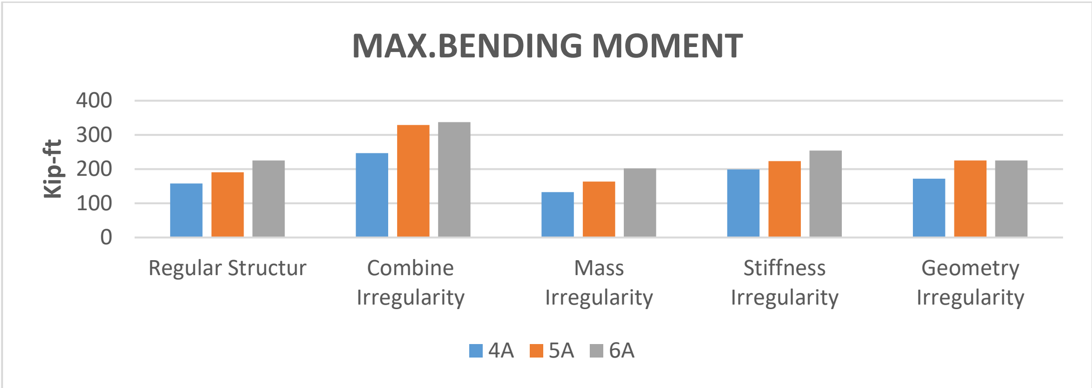


Figure 14:Maximum Bending Moment (20story)

Geometric Irregularity Model, exhibited inconsistencies in the moment curve above the 20th floor, especially at junctions where geometry changed. This led to localized peaks in the bending moment. Stiffness Irregularity Model, experienced moment concentration at the irregular story due to the sudden change in story height and loss of lateral stiffness. This resulted in higher bending stress in columns and beams around the 20th floor. Combined Irregularity Model, demonstrated the most critical behavior with sharp and uneven variations in moment across several stories. The overlapping effect of all three irregularities led to the highest bending moment values, especially at the zone of irregularity.

Table 5:Maximum Bending Moment (kip-ft) (20story)

Beam	Regular Structure	Combine Irregularity	Mass Irregularity	Stiffness Irregularity	Geometry Irregularity
6A	157.93	246.15	132.38	198.89	172.1
6B	190.65	328.91	162.89	223.17	224.56
6C	224.61	336.82	201.29	254.06	224.65

Combined Irregularity model again exhibits the highest bending moments in all beams — up to 50% higher than the Regular structure. This is due to irregular mass and stiffness distribution increasing beam-end rotations and internal stresses. Stiffness Irregularity model also causes a sharp rise in moment (approx. +25–30%), as flexible columns allow greater beam rotation and moment demand during lateral sway. Geometric Irregularity produces moderate increases in moment (~10–15%) because plan asymmetry disturbs the uniform moment distribution across frames. Mass Irregularity shows the least bending moments, again slightly lower than Regular, suggesting that increased mass alone doesn't induce higher rotational stress unless paired with stiffness or geometry change.

7. Optimization and Stability Improvement

Structural optimization is a critical step in enhancing the performance of vertically irregular buildings. In this study, after analyzing the initial behavior of each irregular model, appropriate cross-sectional modifications were introduced at the affected story levels primarily the 20th floor, where the irregularities were applied.

The aim of these optimizations was to restore structural balance and minimize the concentration of stresses. For example, in the stiffness irregularity model, larger cross-sections were assigned to compensate for reduced height stiffness, thereby reducing both lateral displacement and story drift. Similarly, in the geometric and mass irregularity models, the introduction of stiffer elements helped stabilize local distortion and force redistribution. Most significantly, the Combined Irregularity model which initially showed the poorest seismic performance responded well to optimization. Post-modification results revealed a substantial reduction in lateral displacement (approximately 8%), drift (up to 12%), and axial/shear forces (ranging from 10% to 18%). These improvements were achieved without altering the overall geometry or layout of the structure, indicating that design refinement can serve as a practical alternative to major reconfiguration.

The optimization process followed a targeted approach:

- Cross-sectional dimensions were increased at critical load-bearing members near the irregular story.
- Redundant or overstressed members were re-evaluated and replaced with stiffer alternatives.
- Local soft stories were eliminated by rebalancing stiffness vertically.

This approach successfully transformed structurally vulnerable models into stable systems that complied with seismic design criteria outlined in ASCE 7-16. It confirms that optimization is not only a remedial solution but also a proactive strategy in high-rise design. By reducing dynamic response irregularities and ensuring force continuity throughout the structure, such optimization directly contributes to occupant safety, structural economy, and long-term serviceability.

Comparative Analysis of All Models

A comprehensive comparison of all five models Regular, Mass Irregularity, Geometric Irregularity, Stiffness Irregularity, and Combined Irregularity was conducted across key structural parameters. These include story displacement, story drift, story stiffness, axial force, shear force, and bending moment. The results reveal the individual and combined impacts of different irregularities on the seismic performance of a 30-story building.

Lateral Displacement: The Regular structure exhibited the lowest and most uniform lateral displacements. The Stiffness Irregularity model showed the highest top-story displacement due to increased flexibility. The Combined Irregularity model recorded the highest overall lateral displacement, driven by cumulative mass, stiffness, and geometry disruptions. Geometric Irregularity displayed slightly more sway in upper stories, while the Mass Irregularity model had marginally reduced top displacement.

Story Drift: The Regular model had consistent and acceptable drift values across all floors. The Stiffness Irregularity model caused a significant drift spike at the 20th floor (+26%) due to weakened resistance. Combined Irregularity also showed elevated drift (+15%) owing to disturbed load paths. Geometric Irregularity affected drift moderately, while Mass Irregularity unexpectedly showed a reduction in mid-story drift (~6.7%) due to inertia effects.

Story Stiffness: Regular model stiffness increased from top to bottom as expected. In contrast, the Stiffness Irregularity model exhibited a sharp drop at the 20th story (-46.5%) due to member size reduction. Combined Irregularity led to a -37.5% reduction due to compounded effects. Geometric Irregularity caused moderate reduction (~6%) due to asymmetry, while Mass Irregularity surprisingly increased stiffness (+8.1%) due to slab thickening.

Axial Force: Regular model had predictable axial force trends. Mass Irregularity showed minor changes. The Stiffness Irregularity model had elevated axial forces in most columns due to redistributed load paths. Combined Irregularity showed unbalanced force distribution with some columns experiencing higher and others lower forces. Geometric Irregularity resulted in reduced axial force in misaligned columns.

Shear Force: Regular structure maintained controlled shear distribution. Mass Irregularity showed minimal change. Geometric Irregularity caused moderate peaks due to redirected forces. Stiffness Irregularity displayed a clear increase in shear near the 20th floor. Combined Irregularity produced the highest shear forces in all beams, up to 50% greater than Regular, due to abrupt transitions.

Bending Moment: Regular model showed smooth and uniform moment distribution. Mass Irregularity had the lowest bending moments, while Geometric Irregularity caused moderate moment increases. Stiffness Irregularity model showed 25–30% higher moments due to flexibility-induced beam rotation. Combined Irregularity model again had the highest bending moments across all beams up to 50% more than Regular resulting from combined mass, stiffness, and shape variations.
Overall, the Combined Irregularity model demonstrated the most critical structural behavior across all parameters. This highlights the importance of identifying and mitigating multiple irregularities early in the design phase to ensure seismic resilience.
drift, and internal forces, confirming the effectiveness of cross-sectional improvement strategies.

8. Conclusion

This project focused on the seismic analysis and design of a 30-story reinforced concrete high-rise building with vertical irregularities introduced at the 20th floor level. The objective was to evaluate the performance of different irregularities mass, geometric, stiffness, and a combined configuration against a regular structure, using the ETABS software in compliance with ASCE 7-16 standards. A total of five building models were created and analyzed, one regular and four irregular models. The mass irregularity was introduced by increasing slab thickness at the 20th floor, geometric irregularity by modifying the shape of the upper floors, and stiffness irregularity by increasing the story height. The combined irregularity model incorporated all three types. Seismic loads were applied using the Response Spectrum Method, with parameters based on Zone 2B (Islamabad). Results showed that the regular model performed most effectively, with uniform lateral displacement, acceptable story drift, and consistent force distribution throughout the structure. In contrast, irregular models showed significant deviations. The stiffness irregularity model exhibited the highest lateral displacement and story drift, especially at the 20th floor, due to the sudden drop in rigidity. The geometric irregularity model showed uneven lateral stiffness in the upper portion, while the mass irregularity model resulted in a spike in axial force and drift at mid-height. The combined irregularity model produced the most critical behavior across all parameters, including maximum story displacement, peak shear and bending moments, and irregular axial force distribution. The overlapping effects of mass, geometry, and stiffness disruptions significantly compromised structural performance and emphasized the need for careful design.
To enhance the seismic performance of irregular buildings, optimization techniques were applied. These included increasing the cross-sectional dimensions of structural members at the irregular stories and adjusting member stiffness to restore equilibrium. Post-optimization results showed notable improvements: reduction in lateral displacement by approximately 8%, story drift by 12%, and internal force fluctuations by 10–20%. These enhancements were achieved without altering the architectural plan or usage. This study highlighted the importance of addressing irregularities during the early design phase. Even though irregularities are often inevitable due to architectural or functional requirements, engineers must design effective strategies for minimizing their impact. The study demonstrated that irregular models, when optimized correctly, can perform comparably to regular ones. In conclusion, vertical irregularities can have a profound and negative effect on the seismic behavior of high-rise buildings. Their presence can lead to concentration of stresses, higher displacements, and unpredictable load paths, which, if left unaddressed, can endanger structural integrity. However, with timely analysis and structural optimization, their impact can be mitigated effectively. This project provides strong evidence in support of incorporating optimization techniques in the structural design phase and contributes valuable insights into the behavior of tall buildings under

seismic conditions. When left unaddressed, they can lead to concentration of internal forces, displacement amplification, and overall instability. However, with appropriate analysis and optimization strategies, even irregular structures can be made to perform safely under seismic conditions. The findings from this study provide a foundation for future work in optimizing complex structures and ensuring safer urban infrastructure.

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