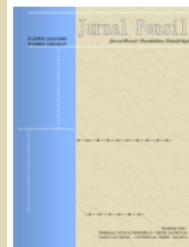


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STUDY OF STRUCTURAL IRREGULARITIES ON BUILDING PERFORMANCE IN HIGH SEISMIC RISK AREAS

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Abstract

Structural irregularities significantly affect the seismic performance of buildings, especially in high-risk earthquake zones. This study aims to analyse the influence of plan and vertical irregularities on structural response parameters, including lateral forces, shear forces, overturning moments, inter-story drifts, and fundamental periods. The object of study is a ten-story U-shaped reinforced concrete office building, modelled using ETABS software. Two structural systems are compared: the Special Moment Resisting Frame (SMRF) and the Dual System (a combination of SMRF and shear walls). The analysis follows the linear response spectrum method based on the Indonesian seismic code SNI 1726:2019. The results indicate that structural irregularities increase the concentration of internal forces and displacements in critical structural components, raising the potential for localized failure. The Dual System demonstrates better performance in controlling deformation and distributing seismic loads more evenly compared to the SMRF system is 20 percent. These findings highlight the importance of selecting an appropriate structural system and accounting for irregularities early in the design process to enhance seismic resilience.

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Keywords: Structural Irregularity, Seismic Performance, Dual System, SMRF, Response Spectrum

Introduction

Indonesia is one of the most seismically active countries in the world due to its location along the Pacific Ring of Fire. Buildings in this region must be specifically designed to withstand high earthquake risks (Chopra, 2016). One of the critical aspects in seismic-resistant structural design is geometrical irregularity, both in plan and elevation (Prayuda & Salsabila, 2023). These irregularities often lead to uneven lateral force distribution, stress concentration, increased torsional effects, and soft-story mechanisms that can increase the risk of local or global structural failure during seismic event (Mariam et al., 2019).

Irregular building configurations such as U, L, or T shapes have been shown to exhibit less favourable seismic behaviour compared to regular layouts (Priestley et al., 2017). Previous studies by Dražić & Vatin (2016) highlighted that irregular structures require special structural strategies to maintain their stability. Research by Mohod (2015) and Abdel Raheem et al. (2018) found that geometrical irregularities increase drift and internal forces, especially in re-entrant corners where damage tends to concentrate. Furthermore, vertical irregularities such as abrupt changes in mass or stiffness between floors have been associated with amplified inter-story drift and resonance effects (Deshmukh & Hamane, 2022). Therefore, evaluating appropriate design strategies to mitigate the impact of structural irregularities on seismic response is critical (Karunia & Fathonah, 2020).

This study aims to analyse the effect of structural irregularities on the seismic performance of multistorey buildings through numerical simulations using ETABS software. The focus is on parameters such as lateral force, overturning moment, inter-story drift, and fundamental period. Two structural systems are examined and compared: the Special Moment Resisting Frame (SMRF) and the Dual System (a combination of SMRF and shear walls), using a linear response spectrum method based on the Indonesian seismic code SNI 1726:2019.

The main contribution of this research is to provide practical and theoretical insights into the selection of suitable structural systems for irregular buildings in earthquake-prone regions. This study also strengthens design considerations for seismic-resistant structures with complex geometries. The limitation of this research lies in its linear approach; therefore, future studies are encouraged to incorporate nonlinear and performance-based modelling for more comprehensive evaluation.

Research Methods

This study is a quantitative exploratory research conducted through numerical simulation in Jakarta in 2024. The research subject is a ten-story U-shaped reinforced concrete office building modeled using two structural systems: SMRF and the Dual System. The analysis was carried out using ETABS software and the linear response spectrum method based on SNI 1726:2019 to obtain seismic parameters such as lateral force, overturning moment, inter-story drift, and fundamental period. Data were generated through simulation and analyzed by comparing the performance of both structural systems in addressing irregularities in buildings located in high seismic risk zones.

Research Results and Discussion

Irregularity refers to geometric conditions, mass distribution, stiffness distribution, or structural configuration that can affect a building's response to seismic loads. These irregularities may occur either in the horizontal direction (horizontal irregularity) or vertical direction (vertical irregularity). In Figure 1 shows the plan of the building.

Torsional Irregularity (1a and 1b)

Torsional irregularity is defined to occur when the maximum story drift, calculated including accidental torsion with $\Delta x = 1.0$, at one end of the structure transverse to an axis, exceeds 1.2 times the average story drift at both ends. These requirements apply only to structures with rigid or semi-rigid diaphragms (SNI 1726:2019 Table 13).

Extreme torsional irregularity is defined when the maximum story drift, including accidental torsion with $\Delta x = 1.0$, exceeds 1.4 times the average story drift at both ends. These requirements also apply only to rigid or semi-rigid diaphragm structures.

Recapitulation of the ratios for each floor in the 10-story building is shown in Table 2.

Table 2. Torsional Irregularity Check

Floor	Dual System				Special Moment Frames			
	X Direction		Y Direction		X Direction		Y Direction	
	$\Delta_{max}/\Delta_{avg}$	Check	$\Delta_{max}/\Delta_{avg}$	Check	$\Delta_{max}/\Delta_{avg}$	Check	$\Delta_{max}/\Delta_{avg}$	Check
10	1.014	OK	1.005	OK	1.07	OK	1.079	OK
9	1.015	OK	1.001	OK	1.069	OK	1.08	OK
8	1.015	OK	1.001	OK	1.068	OK	1.081	OK
7	1.016	OK	1.003	OK	1.065	OK	1.081	OK
6	1.016	OK	1.008	OK	1.066	OK	1.084	OK
5	1.017	OK	1.003	OK	1.064	OK	1.086	OK
4	1.019	OK	1.003	OK	1.063	OK	1.086	OK
3	1.03	OK	1.003	OK	1.064	OK	1.083	OK
2	1.033	OK	1.015	OK	1.075	OK	1.08	OK
1	1.046	OK	1.024	OK	1.096	OK	1.077	OK

The $\Delta_{max}/\Delta_{avg}$ ratios in both structural systems are below the limit of 1.2 as specified in SNI 1726:2019, indicating that no torsional irregularity occurs at any floor level.

In the Dual System, $\Delta_{max}/\Delta_{avg}$ ratios range from 1.001 to 1.046 in the X direction and 1.001 to 1.024 in the Y direction. The highest values occur at floor 1, with ratios of 1.046 (X) and 1.024 (Y).

Meanwhile, in the SMRF system, the ratios are generally higher, ranging from 1.061 to 1.096 in the X direction and 1.065 to 1.107 in the Y direction, with the highest values also at floor 1: 1.096 (X) and 1.107 (Y). This comparison shows that the Dual System has a more uniform distribution of column displacements compared to SMRF, resulting in more stable torsional performance.

Re-entrant Corner Irregularity

This irregularity occurs when both projection dimensions of the structural plan from the re-entrant corner exceed 15% of the plan dimensions in the considered direction. In Figure 1 shows the re-entrant corner review.

$$P_x = 41.45 \text{ m}$$

$$P_y = 24 \text{ m}$$

$$L_x = 81 \text{ m}$$

$$L_y = 54 \text{ m}$$

The analysis is shown in Table 3.

Table 3. Torsional Irregularity Check

Px/Lx	Py/Ly	Check
0.5117	0.444	OK

Based on this analysis, it can be concluded that the office building structure exhibits re-entrant corner irregularity on each floor, considering all floor plans have a similar typical configuration.

Diaphragm Discontinuity Irregularity

This irregularity is defined to occur when a diaphragm experiences discontinuity or sudden stiffness changes, including cut-outs or openings exceeding 50% of the gross closed diaphragm area, or a stiffness change exceeding 50% between adjacent levels. This type of irregularity is not present in the structure under review.

Table 4. Diaphragm Discontinuity Check

	Dual System		Moment Frames	
A_{total}	2061	m ²	2061	m ²
$A_{opening}$	640.8	m ²	640.8	m ²
Check	OK		OK	

Based on Tables 4, the total slab area is 2061 m² and the opening area is 640.8 m². The resulting ratio (0.31) is less than the allowable limit of 0.50 per SNI 1726:2019. Therefore, the diaphragm discontinuity check is satisfied, and it can be concluded that there is no diaphragm discontinuity irregularity in the Moment Frame structural system.

Vertical Irregularities

The vertical irregularity requirements are presented in Table 5.

Table 5. Vertical Irregularities in Structure

Type and Description of Irregularity	Reference Clause	Application of Seismic Design Category
1a. Soft Story Stiffness Irregularity is defined as a story where the lateral stiffness is less than 70% of the stiffness of the story above or less than 80% of the average stiffness of the three stories above.	Table 16.0 SNI 1726:2019	D, E, and F
1b. Extreme Soft Story Stiffness Irregularity is defined as a story where the lateral stiffness is less than 60% of the stiffness of the story above or less than 70% of the average stiffness of the three stories above.	Table 16.0 SNI 1726:2019	E, and F D, E, and F
2. Mass (Weight) Irregularity is defined as a story where the effective mass exceeds 150% of the effective mass of the adjacent story	Table 16.0 SNI 1726:2019	D, E, and F
3. Vertical Geometric Irregularity is defined as a vertical geometric irregularity where the horizontal	Table 16.0 SNI 1726:2019	D, E, and F

Type and Description of Irregularity	Reference Clause	Application of Seismic Design Category
dimension of the seismic force-resisting system at one story is more than 130% of that in the story above.		
4a. Irregularity Due to Discontinuity of Vertical Elements of Lateral Force-Resisting System is defined as the condition where there is a vertical discontinuity in the lateral force-resisting element.	Table 16.0 SNI 1726:2019	B, C, D, E, and F D, E, and F
5a. Weak Story Irregularity Due to Discontinuity in Lateral Strength is defined as a story where the lateral strength is less than 80% of the strength of the story above.	Table 16.0 SNI 1726:2019	E, and F
5b. Extreme Weak Story Irregularity Due to Discontinuity in Lateral Strength is defined as a story where the lateral strength is less than 65% of the strength of the story above.	Table 16.0 SNI 1726:2019	D, E, and F B and C

Source: SNI 1726:2019

Soft Story Irregularity (1a and 1b)

The building structure under review satisfies the requirements for soft story irregularity 1a and 1b. Recapitulation of the stiffness checks for each floor is shown in Tables 6.

Table 6. Soft Story Check

Floor r	Dual System				Moment Frames			
	X Direction		Y Direction		X Direction		Y Direction	
	Stiffness kN/m	Cek	Stiffness kN/m	Cek	Stiffness kN/m	Check	Stiffness kN/m	Check
10	822508		1128744.02		830987		879890.108	
9	1693873	OK	2338639.06	OK	1350048	OK	1449753.62	OK
8	2496178	OK	3454174.02	OK	1560638	OK	1694439.72	OK
7	3246313	OK	4508248.99	OK	1638474	OK	1809460.94	OK
6	4096644	OK	5747986.9	OK	1843753	OK	2056449.94	OK
5	5022451	OK	7010571.49	OK	2119487	OK	2360624.52	OK
4	6184781	OK	8626903.15	OK	2449190	OK	2719260.6	OK
3	7785500	OK	10889861.7	OK	2987103	OK	3298039.68	OK
2	1.1E+07	OK	14565205.4	OK	4282518	OK	4648326.08	OK
1	2.3E+07	OK	28683660.9	OK	1.1E+07	OK	11772964.6	OK

From Tables 4.7 and 4.8, it is concluded that there is no indication of soft story irregularity in the SMRF system. This is shown by the stiffness values between floors, which are not less than 70% of the stiffness of the floor above in both X and Y directions. The stiffness values increase proportionally as the floor level decreases, indicating a well-distributed structural stiffness. Therefore, the structure meets the stability criteria against potential soft stories as specified in SNI 1726:2019.

Mass Irregularity

Mass irregularity occurs when the vertical mass distribution of a building is uneven. A structure is classified as having mass irregularity if the effective mass of any story exceeds 150% of that of an adjacent story, which can amplify seismic inertia forces. Therefore, controlling story mass within this limit is important to ensure stable seismic performance.

Table 7. Mass Irregularity Check – Dual System

Floor	Dual System		Moment Frames	
	Mass kg	Check	Mass kg	Check
10	2637951	OK	2661063	OK
9	3182619	OK	3240481	OK
8	3163233	OK	3219796	OK
7	3201573	OK	3260189	OK
6	3253506	OK	3435016	OK
5	3372162	OK	3694501	OK
4	3389546	OK	3708189	OK
3	3371323	OK	3691852	OK
2	3319041	OK	3639436	OK
1	3390706	OK	3709232	OK

Vertical Geometric Irregularity

Vertical geometric irregularity is not found in the analysed structure, since the horizontal dimensions of the seismic force-resisting system at each level are similar and do not exceed 130% of the dimensions at the floor above or below. According to Table 16 in SNI 1726:2019, vertical geometric irregularity occurs if the horizontal dimension of the seismic force-resisting system at one level exceeds 130% of the dimension at the adjacent level. Based on the check, dimensions (L) from floor 10 to 6 are 850 mm, while floors 5 to 1 are 1000 mm. The comparison between floors 6 and 5 gives a ratio of $1000 / 850 \approx 1.176$ or 117.6%, which is below the 130% limit. Hence, all floors satisfy the requirement, and no vertical geometric irregularity is present.

Weak Story Irregularity (5a and 5b)

This irregularity occurs when a story’s lateral strength is less than 80% (5A) or 65% (5B) of the story above. For this building, such irregularities do not occur. Verification data are shown in Table 8.

Table 8. Weak Story Check

Floor	Dual System				Moment Frames			
	X Direction		Y Direction		X Direction		Y Direction	
	Shear kN	Check	Shear kN	Check	Shear kN	Check	Shear kN	Check
10	3652.22		4332.59		2862.72		3143.75	
9	7178.61	OK	8649.78	OK	5331.62	OK	5855.6	OK
8	9946.44	OK	12132.7	OK	7154.64	OK	7918.21	OK

7	12203.1	OK	15002.4	OK	8663.3	OK	9613.82	OK
6	14094.4	OK	17394.5	OK	10001.5	OK	11141.3	OK
5	15747.7	OK	19443.9	OK	11284.2	OK	12576.2	OK
4	17129.5	OK	21112.1	OK	12410	OK	13831.6	OK
3	18206.6	OK	22372.2	OK	13359.8	OK	14866.3	OK
2	18913.9	OK	23178.3	OK	14022.9	OK	15584.5	OK
1	19219.2	OK	23521	OK	14312.3	OK	15885.1	OK

Dual System Verification

Referring to SNI 1726:2019 Article 7.2.5.1, it is stated that the moment-resisting frame system (SRPM) must be able to resist more than 25% of the total design seismic force. Therefore, an analysis of the base shear received by the SRPM and shear wall is carried out to determine their respective contributions. The analysis results based on ETABS modelling are presented in Table 9.

Table 9. Dual System Verification

Direction	Location	Load Carried (kN)	Frame Percentage (%)
X	<i>Shear Wall</i>	9532.1312	34.18
	Entire Structure	14482.6434	
Y	<i>Shear Wall</i>	12334.6523	29.15
	Entire Structure	17409.6764	

Based on the above results, the moment-resisting frame contributes more than 25% of the total seismic design force, namely 34.18% in the X direction and 29.15% in the Y direction. Thus, the structural configuration in the office building under review meets the dual system requirements according to SNI 1726:2019.

Comparative Analysis Between Special Moment Resisting Frame (SMRF) and Dual System

This section compares the seismic performance of the Dual System and SMRF in terms of lateral forces, story drift, and overturning moments using finite element analysis in ETABS, with the aim of identifying the most effective system for multi-story buildings in high seismic zones.

Comparison of Lateral Forces (F_x, F_y)

A Moment Frame system is designed to resist the entire seismic lateral load through frame action with rigid beam–column connections; therefore, all shear forces are carried by the frame, requiring beams and columns to have high shear strength and ductility. In contrast, the Dual System combines moment frames with structural walls such as shear walls, allowing lateral forces to be shared, with shear walls resisting most of the load while moment frames are still required to carry at least 25% of the seismic load in accordance with SNI 1726:2019. Consequently, the Moment Frame system relies on stronger frame elements, whereas the Dual System improves structural efficiency and deformation control by distributing lateral loads between different resisting elements.

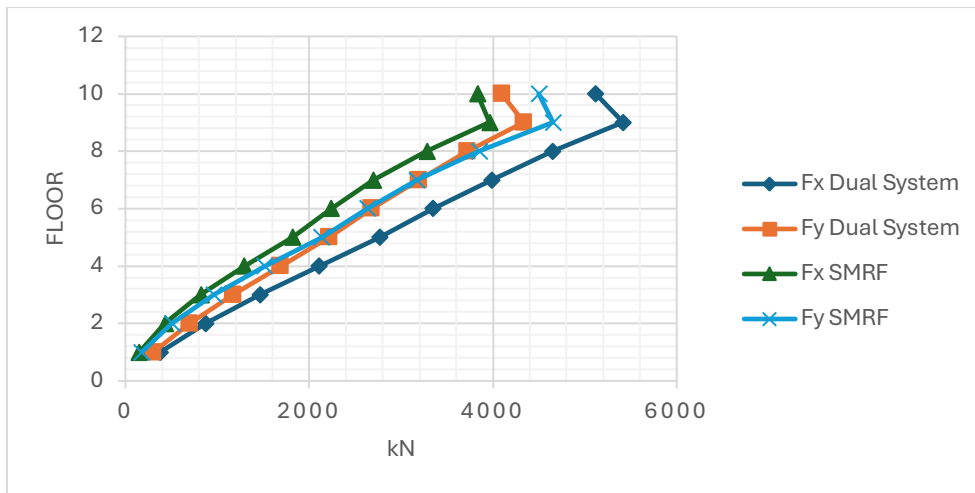


Figure 2. Lateral Force Comparison

In the Dual System, lateral force distribution (F_x and F_y) appears quite uniform at lower levels but diverges at the top levels. Lateral force in the Y direction (F_y) is greater at the top, indicating lower stiffness or geometric asymmetry in that direction. The increase in force is steady, showing effective distribution. In contrast, moment frames show dominant F_x across most floors, particularly at upper levels. F_y increases more gradually, indicating higher stiffness in X than Y. This imbalance can cause rotational effects and must be addressed in design.

Comparison of Shear Forces (V_x , V_y)

In a Moment Frame system, all seismic and wind-induced lateral forces are resisted solely by frame action, and the structure is intentionally designed to undergo significant inelastic deformation to dissipate energy through member yielding; therefore, high ductility and uniform load distribution are essential. In contrast, a Dual System combines moment frames with vertical lateral-force-resisting elements such as shear walls or braced frames, where lateral forces are shared and largely resisted by the stiffer elements, while moment frames are still required to carry at least 25% of the total seismic base shear in accordance with SNI 1726:2019. As a result, the Moment Frame system relies entirely on frame action, whereas the Dual System provides a stiffer response with more controlled structural deformations.

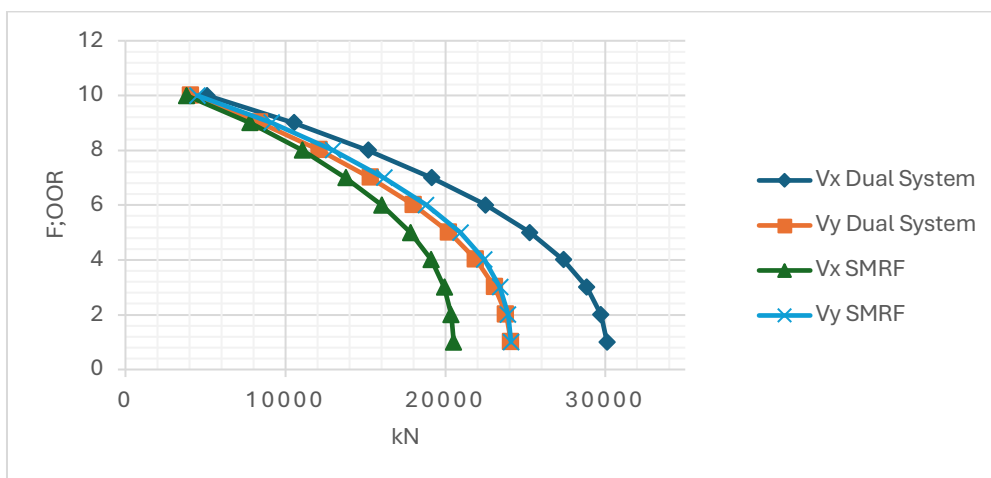


Figure 3. Shear Force Comparison

In the Dual System, shear forces decrease from base to top, with higher V_x than V_y , indicating greater lateral demand in the X direction and a stable structural response. In the Moment Frame system, shear forces also reduce with height, but V_y exceeds V_x , suggesting higher stiffness in X and load redistribution to Y, which should be carefully considered in design to avoid uneven structural behaviour.

Comparison of Overturning Moments

In a Moment Frame system, all lateral forces are resisted by relatively flexible frames, leading to larger lateral deformations and higher overturning moments. In contrast, the Dual System relies primarily on stiffer vertical elements such as shear walls to resist lateral loads, which reduces lateral displacement and overturning moments, thereby improving overall structural stability.

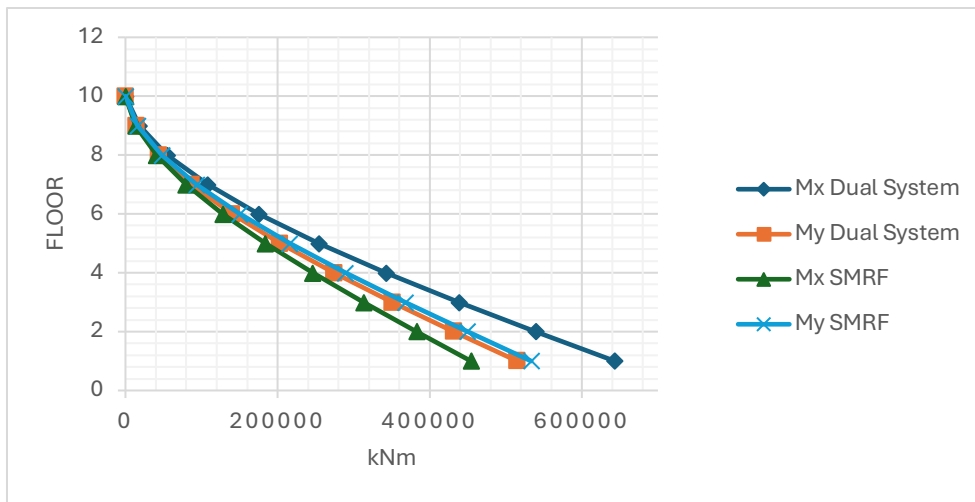


Figure 4. Overturning Moment Comparison

In the Dual System, overturning moments decrease steadily from the base to the top, with MY generally exceeding MX, indicating greater contribution from the Y direction due to higher flexibility and larger lateral displacements. In the Moment Frame system, overturning moments also reduce with height, but MX and MY are more balanced, with MX slightly dominant in some levels, suggesting a more symmetrical distribution of lateral loads.

Comparison of Modal Participating Mass Ratios (MPMR)

Modal analysis yields MPMR tables showing the mass contribution in each vibration mode. Total mass participation in X and Y directions exceeds 90%, fulfilling SNI 1726:2019 minimum requirements. This indicates that analysed modes sufficiently represent the structure's dynamic behaviour.

Table 10. Modal Participating Mass Ratios – Dual System

Mode	Period sec	UX	UY	SumUX	SumUY	RZ	SumRZ
1	0.949	0.695	2.976E-06	0.695	2.976E-06	0.0005	0.0005
2	0.808	2.285E-06	0.6985	0.695	0.6985	2.262E-05	0.0006
3	0.528	0.0005	1.144E-05	0.6955	0.6985	0.6998	0.7003
4	0.243	0.1858	6.866E-07	0.8813	0.6985	0.0001	0.7004
5	0.211	0	0.19	0.8813	0.8885	1.117E-06	0.7004
6	0.139	0.0001	3.535E-06	0.8815	0.8885	0.2016	0.902
7	0.116	0.0562	0	0.9377	0.8885	2.876E-05	0.902

Mode	Period sec	UX	UY	SumUX	SumUY	RZ	SumRZ
8	0.102	0	0.0532	0.9377	0.9417	0	0.902
9	0.074	0.0262	0	0.9639	0.9417	0	0.902
10	0.067	3.213E-06	0.0245	0.9639	0.9662	6.748E-06	0.902
11	0.053	0.0162	0.0006	0.9801	0.9668	0.0002	0.9022
12	0.049	0.0019	0.0138	0.982	0.9806	1.311E-05	0.9022
13	0.039	0.0045	0.0078	0.9865	0.9884	0.0003	0.9026
14	0.033	0.0117	0.0042	0.9982	0.9926	1.58E-05	0.9026
15	0.028	0.0015	0.0073	0.9997	0.9999	0.0002	0.9028

Table 11. Modal Participating Mass Ratios – Moment Frames

Mode	Period sec	UX	UY	SumU X	SumUY	RZ	SumR Z
1	1.418	0.7211	1.89E-06	0.7211	1.89E-06	0.0051	0.0051
2	1.35	5.75E-06	0.7239	0.7211	0.7239	0.0019	0.007
3	1.182	0.0053	0.0021	0.7264	0.726	0.7301	0.7371
4	0.421	0.1202	0	0.8467	0.726	0.001	0.7381
5	0.405	3.29E-06	0.1224	0.8467	0.8484	0.0001	0.7382
6	0.362	0.0009	0.0001	0.8475	0.8485	0.1179	0.8561
7	0.212	0.0585	1.48E-06	0.906	0.8485	0.0003	0.8565
8	0.202	2.93E-06	0.0585	0.906	0.907	0.0001	0.8566
9	0.174	0.0005	3.16E-05	0.9064	0.907	0.0521	0.9087
10	0.123	0.0311	2.48E-06	0.9375	0.907	0.0003	0.9091
11	0.118	2.10E-06	0.0305	0.9375	0.9375	1.77E-05	0.9091
12	0.078	0.0207	0.0058	0.9583	0.9432	0.0002	0.9093
13	0.076	0.0076	0.0199	0.9659	0.9632	0.0001	0.9095
14	0.044	0.0127	0.0198	0.9786	0.9829	3.13E-05	0.9095
15	0.04	0.0181	0.013	0.9967	0.996	0.0002	0.9097

In the Dual System, the first mode has a shorter period ($\approx 0.75\text{--}0.95$ s) with translational mass participation distributed across UX, UY, and minor UZ, requiring several modes to exceed 85–90% cumulative translational mass, while rotational mass participation remains low, indicating a well-balanced system. This reflects the influence of stiff vertical elements such as shear walls, which increase overall stiffness, shorten the fundamental period, and distribute seismic response over multiple modes. Higher-mode stiffness is significant, confirming that the Dual System behaves as a relatively stiff structure with controlled deformation.

In contrast, the Moment Frame system exhibits a longer fundamental period ($\approx 0.92\text{--}1.42$ s), indicating greater flexibility, with mass participation concentrated in the first one or two modes—particularly in the dominant horizontal direction—allowing the cumulative translational mass ratio to exceed 90% more rapidly. Rotational contributions are very small, and higher modes decay more quickly. Overall, the comparison shows that Moment Frames concentrate dynamic response in early modes due to their flexibility, whereas the Dual System distributes response across more modes because of higher stiffness, leading to different seismic response characteristics.

Comparison of Story Drift

Story drift is the relative lateral displacement between floors due to seismic or lateral loads. It reflects structural deformation and influences both structural and non-structural stability. Maximum allowable drift is defined in seismic codes.

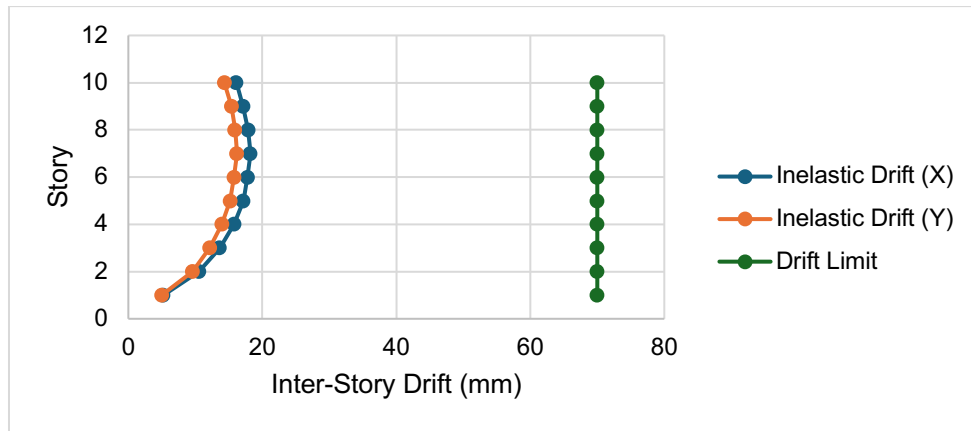


Figure 5. Story Drift Dual System

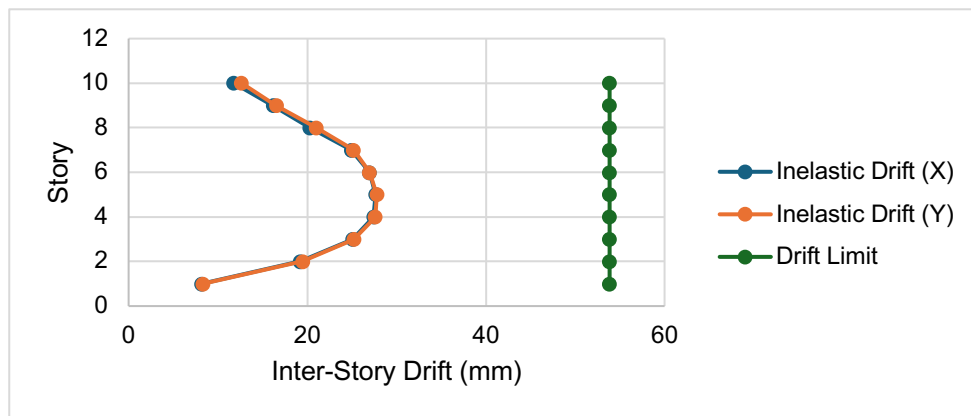


Figure 6. Story Drift moment frames

In the Dual System, the maximum inelastic drift occurs at the upper stories, while the minimum drift is observed at the base. All drift values remain below the allowable limit, indicating effective deformation control. The concentration of drift at higher levels suggests that lateral deformation is dominated by global structural behaviour, with the combined action of moment frames and shear walls effectively limiting deformation at lower stories.

In contrast, the Moment Frame system exhibits generally higher and more uniformly distributed drift along the building height. Although all drift values satisfy the prescribed limit, the higher deformation demand—particularly at lower stories—indicates a more flexible lateral force-resisting system compared to the Dual System. Overall, while both systems meet drift requirements, the Dual System demonstrates superior control of lateral deformation.

Conclusion

Based on the analysis and discussion, it can be concluded that irregularities in plan and elevation significantly influence the distribution of forces and the dynamic response of buildings during earthquakes. Horizontal irregularities, such as torsion and re-entrant corners, and vertical irregularities, such as differences in stiffness, mass, and geometry between floors, lead to uneven lateral force distribution and increased inter-story drift, reducing structural performance under

seismic loads. Structural irregularities also affect the natural period and global behaviour of the structure, where non-uniform configurations result in longer vibration periods and higher flexibility, increasing the risk of resonance and local failure, especially in soft-story conditions.

Furthermore, a comparison between Special Moment Resisting Frames (SMRF) and Dual Systems indicates that the Dual System performs more effectively in reducing lateral forces, shear forces, overturning moments, and inter-story drifts due to the contribution of shear walls that enhance lateral stiffness. This study confirms the critical importance of considering structural irregularities in seismic design and highlights the Dual System as a strategic solution for improving seismic performance in irregular structures, particularly in earthquake-prone areas.

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