PERFORMANCE OF L-SHAPED TOWERS UNDER DYNAMIC LATERAL LOADINGS

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Abstract: Tall buildings are exposed to both static and dynamic loads. Depending on the method used and how the structure is modelled in finite element software the results vary. Some of the issues and modelling techniques introduced below are investigated. The variation in static results from reaction forces, overturning moments, deflections, critical buckling loads, and force distributions between concrete cores are investigated with different models. The models are evaluated by different elements and methods, to study the impact these have on the results. The 3D finite element software used for the analyses is ETABS v18. In the present study, plan and vertical irregularities will be addressed and effective methods to overcome these irregularities will be discussed. The behavior of structure in its natural mode of vibration will be studied for response of structure subjected to dynamic lateral loads. The effect of along and across wind forces in terms of inter storey drift ratio, comfort requirements and torsional behavior will be studied. From the results it can be observed, when modelling a high-rise building in a finite element software, that one model is often not sufficient to cover all different aspects. To see the global behavior, one model can be used, and when studying the detailed results another model with a fine mesh, that has converged, is often needed. The same principle applies when evaluating horizontal and vertical loads, different models or methods are usually needed.

Introduction: Wind and earthquakes exert dynamic effects on buildings, but their design considerations differ significantly. Wind design, characterized by force-type loading, involves pressure on a building's exposed surface area. In contrast, earthquake design, involving displacement loading, responds to the ground's random movement, subjecting the structure to inertia forces and stress. While wind forces induce gradual stress field fluctuations, earthquake forces, acting during the brief quake duration, cause rapid stress reversals due to cyclic ground movement. Wind, a force determined by speed, direction, and building attributes, generates lateral forces affecting structural integrity. Adequate design involves calculating wind loads based on local codes and standards, implementing measures like aerodynamic shapes and bracing systems. Earthquake forces include inertial, shear, and vertical forces, influenced by factors like magnitude and structural characteristics. Seismic design adheres to codes, considering flexibility, damping, and seismic-resistant materials. Balancing economic viability, earthquake-resistant design accepts controlled damage, categorizing shaking into minor, moderate, and severe with corresponding structural and non-structural implications. Ultimately, understanding wind and earthquake effects is pivotal for designing resilient structures, safeguarding lives, and property. Studies show that.

Studies show that there are impact of geometrical parameters on across-wind loads, specifically focusing on plan aspect ratios. By varying the building depth and width while keeping the height constant revealed that increasing depth decreased across-wind loads, while increasing width had a similar effect. Buildings with plan aspect ratios above one experienced higher across-wind static

wind loads. Hence, recommended avoiding square plans and keeping height aspect ratios below eight for stronger and safer buildings against wind loads, Singh *et al* [8].
The seismic response of asymmetrical buildings, studying T and L shapes shows Re-entrant corners were identified as stress concentration points during earthquakes. Pushover analysis revealed the significance of irregularities, with curved beams and shear walls mitigating torsional effects. Irregular structures exhibited increased storey drift and displacement, which emphasizes the importance of seismic design principles, Dixit *et al* [1].
Further, Naveen *et al* [5] had analyzed various structural configurations under seismic loads, revealing that not all irregularities amplify responses. Some combinations reduced structural responses, emphasizing the need to consider irregularities during design. The study highlighted the importance of type, location, and degree of irregularity in seismic design.
Gordan *et al* [2] studied the interaction of along-wind and across-wind forces on tall buildings, finding that across-wind dynamic responses were greater due to vortex shedding. Aerodynamic modifications were suggested to minimize lateral displacements caused by wind excitations.
The seismic performance of L-shaped irregular multistory buildings emphasizes the significant impact of plan irregularities on seismic response. Studies by Momen et al [3] underscored the importance of considering floor shape in seismic design to ensure structural safety.
The seismic behavior of H-shaped RC buildings with re-entrant corners with shear walls significantly reduced dynamic response parameters, emphasizing their effectiveness in seismic design, Sanketh *et al* [6]
Shreyasvi *et al* [7] compared buildings with and without re-entrant corners, revealing that the former undergo larger displacements and are more vulnerable to seismic damage. The study highlighted the need for special attention to columns and joints in re-entrant corners during design.
Murthy *et al* [4] outlined seismic design principles, emphasizing structural configuration, stiffness, strength, and ductility. The importance of damping in dissipating excess energy and considerations for gross and effective sectional properties during analysis were discussed.
Plumier *et al* [9] performed elastic analysis on an S-shaped reinforced concrete building, considering reconnection options between blocks to prevent support loss during earthquakes. The study emphasized the importance of relative rotational and translational moves between blocks to avoid high internal forces.

Methodology: In the present study, A building's behavior is determined by its structural elements' arrangement, with geometry, shape, and size being critical factors. Dynamic loads lead to inertia forces concentrated at the center of mass, resisted by vertical elements. The center of stiffness, when different from the center of mass, creates eccentricity, causing structural twisting. Torsional coupling, influenced by element location and size, can lead to structural damage. Regular structures lack noticeable discontinuities, while irregular ones, with plan or vertical variations, may perform differently under lateral loads. Vertical irregularities involve mass, stiffness, and geometry changes along the building's height, while horizontal irregularities are explained by plan discontinuities. Structural imperfections impact seismic response in diverse ways.

Problem Statement

Analysis of proposed Ground + 23 upper floors building with residential and commercial occupancy located at Virar, Mumbai is performed using commercially adopted non-linear analysis and design tool ETABS v18.0.0.

The building plan consists of two parts: one inclined and the other straight, connected by a common passage. According to Clause 6.3.2.2 IS 1893 Part (1): 2016, when lateral load resisting elements are not oriented orthogonally, the structure should be designed for the combined effects of the full earthquake load in one direction and 30 percent of the load in the other direction. This involves modifying load cases and combinations accordingly. Standard procedures in IS 875 Part (3): 2015 are insufficient for determining the structure's response to dynamic wind forces along and across; instead, Computational Fluid Dynamic analysis or Wind Tunnel studies are necessary for this architectural configuration. Additionally, the presence of re-entrant corners in the building plan may lead to stress concentration in the central region.

Table -1: Parameters used for structural modelling in ETABS v18.0.0

Description	Values
General Modeling parameters	
Plan Area (Two Buildings connected)	33×14.45 m (Bldg-I/Inclined Portion); 29.3×15.09 m (Bldg-II/Straight Portion)
Self-weight of structural members	25 kN/m^3 (program calculated)
Floor Finish	1.5 kN/m^2
Live Load	2 kN/m^2 and 3 kN/m^2
Partition wall density	10 kN/m^3
Grade of concrete	M30 (Slab and beams) and M40 (Shear-wall)
Grade of reinforcement	Fe500
Slabs Modeling Type	Membrane
Diaphragm Type	Rigid
Wind Loads as per IS 875 (Part 3):2015	
Location of Structure	Virar, Mumbai
Basic wind speed V_b	44m/s
Probability factor/Risk Coefficient (K_1)	1.0

Description	Values
Terrain Roughness and height factor (K_2), terrain category 2	Varies with height (program calculated)
Topography factor (K_3)	1.0
Importance factor for cyclonic region (K_4)	1.0
Direction of application	X and Y direction
Point of application	Diaphragm Center of Mass
Earthquake Load as per IS 1893 (Part1):2016	
Seismic zone	III
Seismic zone factor (Z)	0.16
Soil Type I	Pile Socketing in Hard Strata
Importance factor (I)	1.2
Lateral load resisting system	Buildings with ductile Reinforced Concrete structural walls
Response reduction factor	4
Damping	5%

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Property modifiers	As per IS 16700-2017
Design acceleration coefficient (S_a/g)	Program calculated as per; IS 1893(part1):2016, for corresponding type of soil and type of method used (Static or Response Spectrum)

Seismic weight	Program calculated with percentage of Imposed load to be 25%
Number of Modes	12
Method of Seismic Analysis	Equivalent static method and Response Spectrum Method
P-Delta	As per IS 16700:2017

Figure-1 below shows 3-D view of super structure with fixed base condition modelling in ETABS.

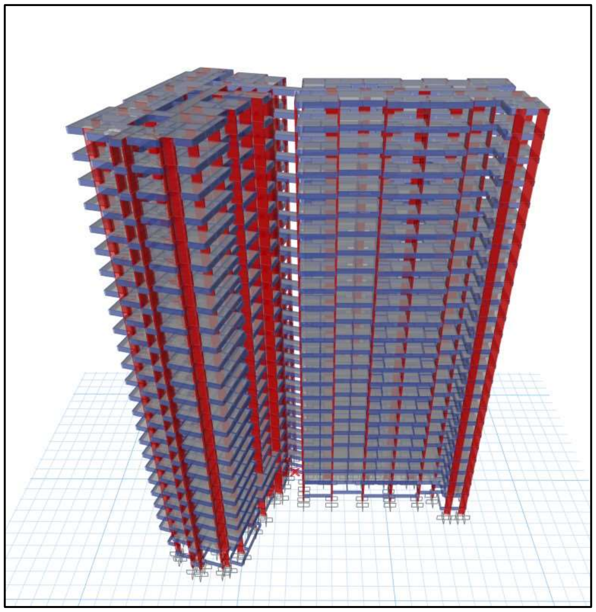

Figure 1: 3-D view structure with fixed base condition

Identification of Irregularities

Buildings with simple and regular geometry and uniformly distributed mass and stiffness in plan and in elevation, suffer much less damage than buildings with irregular configurations. All efforts shall be made to eliminate irregularities by modifying architectural planning and configuration. A building shall be considered to be irregular even if anyone condition is applicable. Summary of all irregularities observed in combined model are shown in table-2 below.

Table -2: Summary of plan and vertical irregularities

Type	**Condition**	**Identification**
Plan	Torsional Irregularity	*Present*
Plan	Re-Entrant Corners	*Present*

Plan	Floor Slab Having Excessive Cut-Outs or Openings	Not Present
Plan	Out of Plane Offsets in Vertical Elements	Not Present
Plan	Non-Parallel Lateral Force System	*Present*
Vertical	Stiffness Irregularity (Soft Storey)	Not Present
Vertical	Mass Irregularity	Not Present
Vertical	Vertical Geometric Irregularity	Not Present
Vertical	In-Plane Discontinuity in Vertical Elements Resisting Lateral Force	Not Present
Vertical	Strength Irregularity (Weak Storey)	Not Present
Vertical	Floating or Stub Columns	Not Present
Vertical	Irregular Modes of Oscillation in Two Principal Plan Directions	*Present*

Hence, both buildings in combined modelling are torsionally Irregular, have Re-Entrant Corner and also have Non-Parallel Lateral Force System. Higher time period may affect the performance of structure and comfort requirements. To overcome these irregularities, it is necessary to separate the two structures by providing seismic joint in between and separate analysis shall be performed.

Seismic joint as per IS 1893 (Part 1):2016
As per IS 1893 (Part 1):2016 Cl.7.11.3, two adjacent buildings or units must be separated by a distance of R times the sum of average storey displacements (Δ1 and Δ2) to prevent pounding during seismic events. When floor levels align, the separation distance or joint width is calculated as follows:

Width of joint = $\frac{R_1 \times \mathit{\Delta}_1 + \mathrm{R}_1 \times \mathit{\Delta}_1}{2}$;

Where,
R = Response Reduction Factor,
$\mathit{\Delta}$ = Displacement,
R_1 and Δ_1 corresponds to Building 1 and
R_2 and Δ_2 corresponds to Building 2.
Hence, in order to compute Δ1 and Δ2 separate analysis of each building 1 and building 2 shall be made and corresponding width of seismic joint shall be provided with respect to each floor level.

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Separate Structural Analysis

After introducing seismic joints between the two buildings, the separation joint width is calculated based on inter-storey drift and response reduction factors, ensuring compliance with IS 1893 Part (1):2016 limitations. Both structures must be regular to eliminate irregularities for controlled inter-storey drift under dynamic seismic and wind loads. Modal Mass Participation Factor is crucial for obtaining an appropriate structural response, indicating the effective percentage of mass moving in a specific direction for each mode. IS 1893 Part (1):2016 recommendations for Modal Mass Participation factors include:

1. The first two translational modes' natural periods along each principal plan direction should exceed the fundamental torsional mode's period.
2. The first three modes should contribute at least 65 percent mass participation in each principal plan direction.
3. The difference between fundamental lateral natural periods in the two plan directions should be at least 10% of the larger value.
4. The sum total of modal masses considered should be at least 90 percent of the total seismic mass.

Optimizing modal behavior is essential to reduce irregularities and enhance structural response to lateral forces.

Modal Mass Participating Ratio

Two separate analysis models are created for the two structures. Iterations are performed to improve their behavior by adjusting the lateral stiffness of structural elements for appropriate modal mass participation ratios. Building-I's (Inclined portion) irregularities are eliminated by modifying shear wall sizes to prevent torsion and reduce the fundamental time period. A total of nine iterations were meticulously conducted, with each iteration showcasing noteworthy improvements in modal mass participation, ultimately attaining the targeted behavior. The mass participation values for the ninth iteration are systematically tabulated in table 3 below. The Trial 'T9' for Building-I achieved satisfactory modal mass participation, with about 70% mass participating in the first three fundamental modes in each principal plan direction. A total of 92% of the total mass participated across all 12 modes. This indicates acceptable fundamental modes of oscillation, making Trial T9 suitable for lateral load application and related checks.

Table -3: Modal Mass participation for Building-I Trial T9

Mode	T	Modal Mass Participation Ratio						Diff. 'T'
	Sec	U_X	U_Y	$\sum U_X$	$\sum U_Y$	R_Z	$\sum R_Z$	
1	2.77	0.01	0.66	0.01	0.66	0.06	0.06	---
2	2.28	0.14	0.07	0.15	0.73	0.49	0.55	22%
3	2.03	0.55	0.00	0.70	0.73	0.15	0.71	11%
4	0.86	0.00	0.13	0.70	0.86	0.01	0.71	
5	0.66	0.04	0.01	0.74	0.87	0.11	0.82	
6	0.59	0.12	0.00	0.86	0.87	0.04	0.86	
7	0.44	0.00	0.04	0.86	0.91	0	0.86	
8	0.32	0.02	0.00	0.87	0.91	0.04	0.89	
9	0.29	0.04	0.00	0.91	0.91	0.01	0.91	
10	0.29	0.00	0.02	0.91	0.94	0	0.91	

11	0.20	0.01	0.00	0.92	0.94	0.02	0.93
12	0.20	0.00	0.01	0.92	0.95	0	0.93

Similarly, building-II underwent multiple iterations to achieve code compliance. After ensuring satisfactory service performance, lateral loads were applied. A total of five iterations were meticulously conducted, with each iteration showcasing noteworthy improvements in modal mass participation, ultimately attaining the targeted behavior. The mass participation values for the fifth iteration are systematically tabulated in table 4 below.

Table -4: Modal Mass participation for Building-II Trial T5

Mode	T	Modal Mass Participation Ratio						Diff.
	Sec	U_X	U_Y	$\sum U_X$	$\sum U_Y$	R_Z	$\sum R_Z$	'T'
1	2.49	0.01	0.66	0.01	0.66	0.00	0.00	---
2	2.25	0.70	0.01	0.70	0.67	0.04	0.04	10%
3	2.02	0.04	0.00	0.74	0.67	0.65	0.69	10%
4	0.72	0.12	0.00	0.86	0.67	0.00	0.70	
5	0.63	0.00	0.18	0.86	0.84	0.00	0.70	
6	0.59	0.00	0.00	0.86	0.85	0.15	0.85	
7	0.38	0.04	0.00	0.90	0.85	0.00	0.85	
8	0.29	0.00	0.05	0.90	0.90	0.01	0.86	
9	0.28	0.00	0.01	0.90	0.90	0.05	0.91	
10	0.24	0.03	0.00	0.93	0.90	0.00	0.91	
11	0.18	0.00	0.01	0.93	0.92	0.01	0.92	
12	0.17	0.00	0.02	0.93	0.93	0.02	0.94	

Modal mass participating ratio of Trial T5 for Building-II shows satisfactory performance with about 67% mass participating in each principal plan direction in first three fundamental modes and about 93% of total mass is captured in total 12 number of modes. Hence, fundamental modes of oscillation are acceptable, and Trial T5 for Building-II is appropriate for lateral load application and corresponding checks.

Results and Discussion: A residential G+23 building analyzed in ETABS v18.0.0 consists of two non-orthogonal parts, one inclined and the other straight, connected by a common passage. Various plan and vertical irregularities initially caused an unacceptable fundamental time period of vibration. To address this, a seismic joint was introduced at the common passage, creating two separate buildings, Building I (Inclined Portion) and Building II (Straight Portion). This separation facilitated the control of irregularities, and the regular shapes of both buildings aided in wind force calculations.

Effect of Irregularities

The combined building model exhibited plan irregularities (Torsional, Re-entrant corners, non-parallel lateral force system) and vertical irregularity. Separating it into Building I and Building II with a seismic joint and adjusting some lateral force-resisting elements resolved these issues. See chart-1 for natural mode time periods.

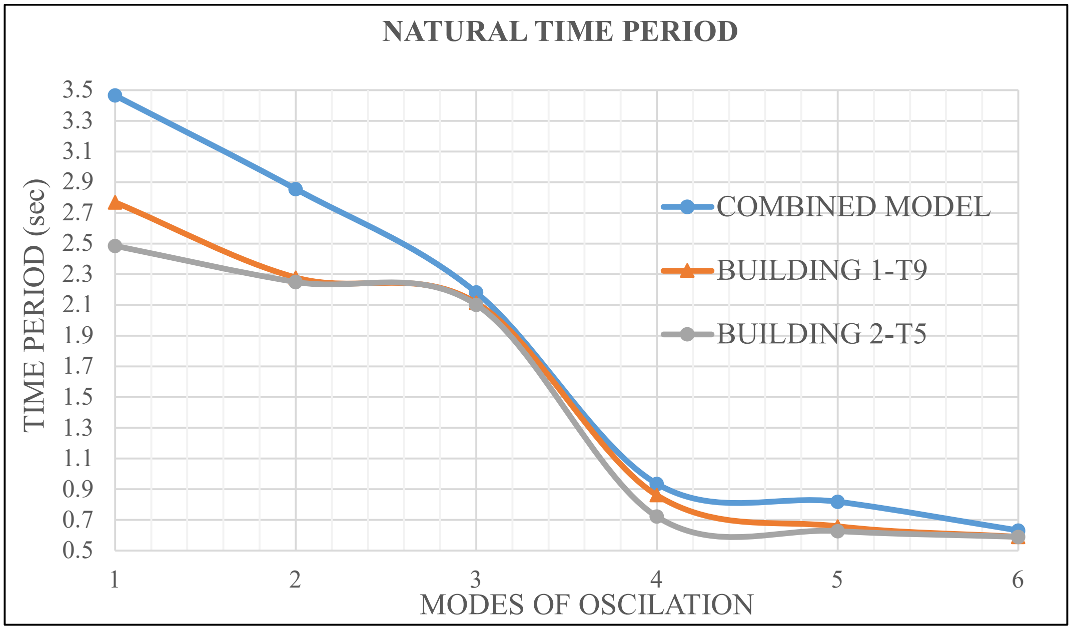

Chart 1: Comparison of Natural Time Period

Initially, the combined model had a fundamental time period of 3.5 sec for the 1st Mode of vibration. After separation and iterations, it reduced to 2.75 sec for Building I and 2.5 sec for Building II. The Torsional Irregularity ratio for the combined model was about 1.35 (X-direction) and 1.7 (Y-direction), exceeding the permissible limit of 1.5. However, after separate-structural analysis, it significantly decreased. See chart-2 for details.

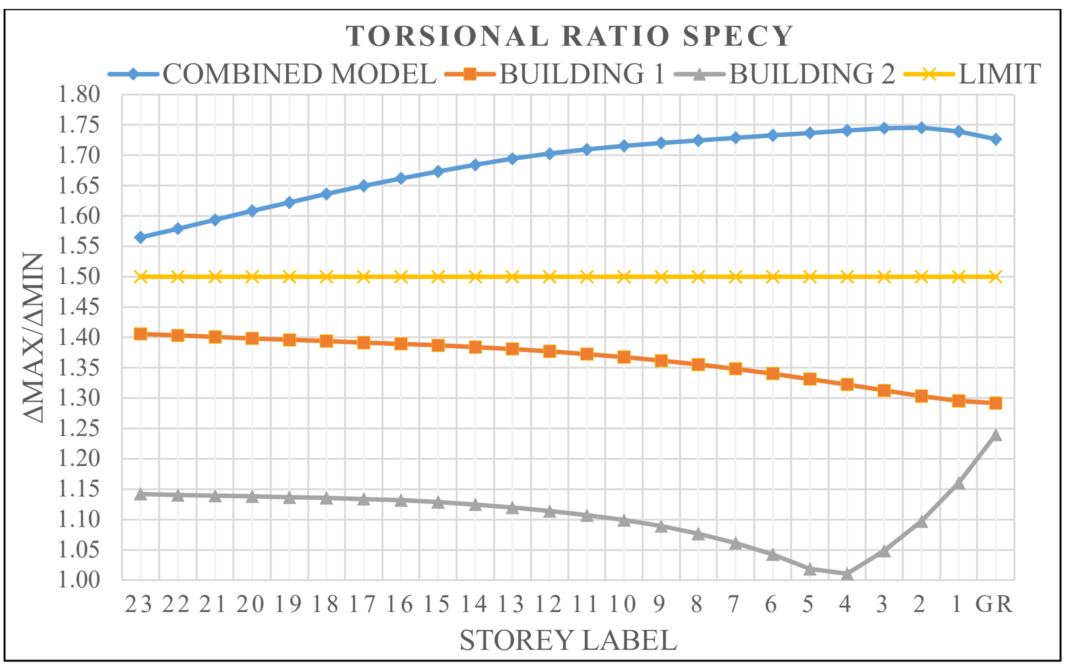

Chart 2: Comparison of Torsional Ratio

In the combined structure, re-entrant corners with eccentricity up to 2.5m existed, causing induced torsional moments. Separate analysis reduced this distance to 1.6m for Building I and 0.25m for Building II on upper floors. See chart-3 for a comparison of eccentricity.

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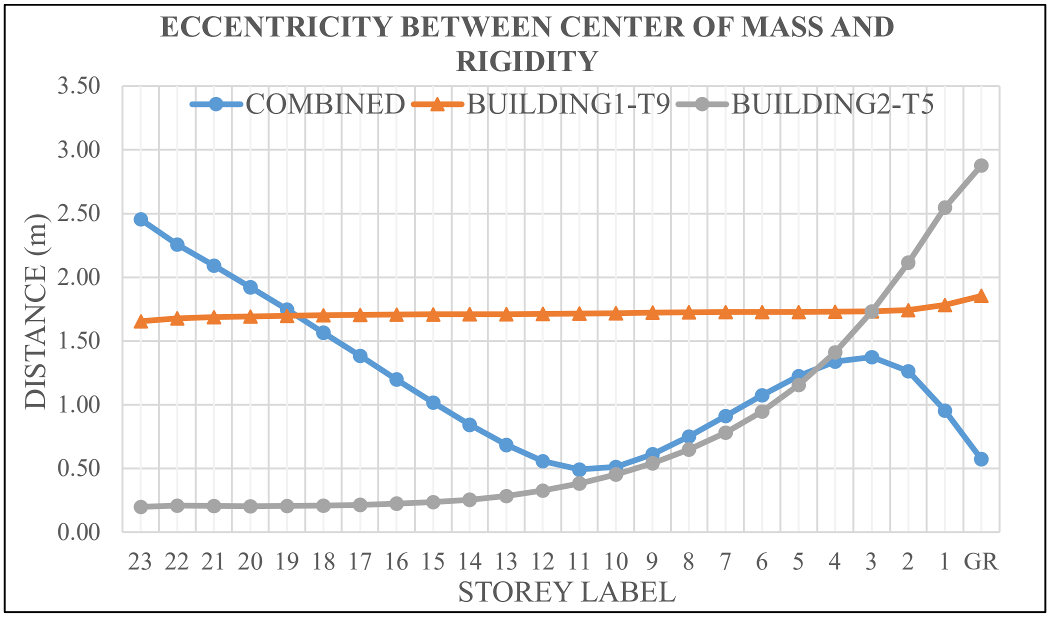

Chart 3: Eccentricity between Centre of Mass and Centre of Rigidity

Non-orthogonal orientation of lateral force resisting elements causes additional forces from the perpendicular direction. See chart-4 for a Seismic Base Shear comparison between Combined and Separate Structural Analysis.

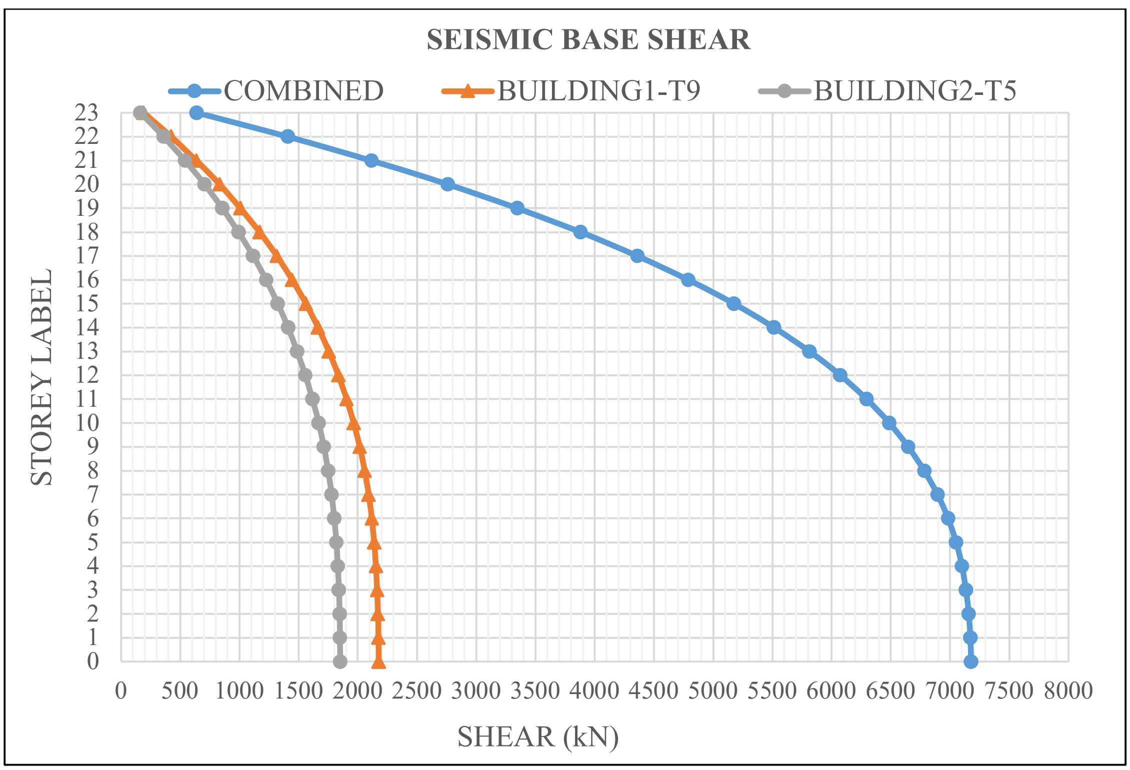

Chart 4: Comparison of Seismic Storey Shear

In the combined model, base shear is 7100 kN (X) and 5800 kN (Y). In the separate model, it significantly reduces to 2175 kN (X) and 2400 kN (Y) for Building I and 1850 kN (X) and 1650 kN (Y) for Building II.

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Conclusion: A G+23 residential building analyzed in ETABS v18.0.0 has a non-orthogonal configuration with an inclined and a straight section connected by a common passage. The combined model exhibited irregularities, non-orthogonal lateral force resistance, re-entrant corners, torsional irregularities, and irregular oscillation modes, leading to flexibility issues. Higher time periods made the structure more flexible, causing service and strength failures. Its irregular shape necessitated wind tunnel or CFD studies for wind force assessment, which is impractical. To mitigate these issues, a seismic joint was introduced at the common passage, separating the structure into Building I (Inclined Portion) and Building II (Straight Portion). This separation facilitates the control of existing irregularities, while the regular shapes help calculate wind forces per code-specified methods.

On the basis of results the following conclusion are made:

- The combined Model with a higher fundamental time period of 3.5 sec undergoes larger relative horizontal displacements and longer periods of oscillation which in-turn increases the flexibility of structure causing higher lateral loads and accelerations.
- The torsional irregularity of the combined model is 1.7 which is higher than code specified limit of 1.5, develops additional forces due to torsion on lateral force resisting elements.
- Combined Structure with Re-entrant corners having higher eccentricity between diaphragm center of mass and rigidity of 2.45m, develops additional twisting moment about vertical axis in addition to applied lateral loads.
- Non-orthogonal orientation of lateral force resisting elements increases the stresses in the member by additional force of other orthogonal direction.
- Fundamental modes of vibration are important to assess the response of the structure subjected to lateral forces.
- The first three modes of oscillation are more susceptible to getting excited during the event of seismic base excitation, hence shall be translational.
- Translational modes of oscillations for Building-I and Building-II are achieved by increase in mass participation of each principal plan direction UX, UY up to 50% and restricting rotational mass participation RZ up to 10% with lateral stiffness balancing of lateral force resisting elements.
- Improvement in modal mass participation requires several iterations, summary of iteration is helpful in assessment of the responses of structure with recent modification.
- Reduction in diaphragm center of mass displacement reduces the overall deflection of structure and lowers the eccentricity with center of rigidity.

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