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Seismic Analysis and Design of an RCC Twisted Building Using with ETAB

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Abstract

This paper investigates the structural behavior of reinforced concrete (RCC)-twisted buildings subjected to seismic loads using ETABS software. The study focuses on analyzing various degrees of twist in RCC-twisted buildings, specifically examining the angles of 1.5, 2, 2.5, 3, and 3.5 degrees per floor. The study looks at how these different twist rates affect important structural parameters like base shear, story displacement, and story drift through detailed modeling and analysis in ETABS. The objective of this project is to determine the optimal angle of twist for RCC twisted buildings to ensure structural integrity and performance under seismic conditions. By systematically analyzing twisted buildings with incremental twist angles of 1.5, 2, 2.5, 3, and 3.5 degrees per floor, the study aims to identify the relationship between the rate of twist and the resultant seismic behavior of the structures. The results obtained from the ETABS simulations will be presented in detailed graphs and tables, illustrating the variations in story displacement, story drift, and base shear for different twist angles across multiple storys. Ultimately, this research seeks to enhance the understanding of how twisting impacts the seismic resilience of tall buildings, providing valuable insights for the design and construction of safer, more efficient RCC-twisted structures. The findings of this study will contribute to the development of guidelines and best practices for engineers and architects involved in the design of twisted high-rise buildings in seismically active regions.

Keywords: Twisted building, swimming pool, ETAB, seismic analysis, structural behavior

INTRODUCTION

An earthquake is a natural disaster that has claimed millions of lives throughout both recorded and unrecorded history. It is a sudden and disruptive disturbance that causes surface shaking due to subsurface movements along fault lines or volcanic activity. The forces generated by an earthquake are uncontrollable and typically last for a brief period of time. The unpredictability regarding the time and nature of an earthquake's occurrence has always puzzled humans. However, with advancements in knowledge over the years, a certain degree of probabilistic predictability has been achieved [1–5].

While our ability to predict the recurrence and magnitude of earthquakes in specific regions has improved, this only addresses part of the problem of anticipating what's coming. The next crucial phase is structural seismic design—ensuring that buildings can withstand these forces. This aspect has significantly evolved over the past century, with continuous advancements in design philosophy and methodology being researched, proposed, and implemented. This chapter introduces the concept

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of foundation isolation for designing earthquake-resistant structures. The effectiveness of seismic isolation is demonstrated through the modeling and analysis of multi-story buildings, bridges, and pools.

In recent years, the trend of constructing RCC high-rise structures has increased in India. These buildings often include various amenities, such as swimming pools and gardens, which are visually appealing but pose structural challenges. The swimming pool, being a heavy structure with complex detailing, presents unique challenges. If a pool were to rupture and release all its water, it could cause significant interior damage and possibly break windows. However, in many cases, the additional water mass can act as a liquid mass dampener, helping the building to resist earthquake forces. Tall buildings inherently carry large gravity and lateral loads.

This study focuses on twisted-tall buildings of various heights, height-to-width aspect ratios, and rates of twist. The structural efficiency of these designs is investigated. Twisted buildings, with their unique geometric configurations, differ significantly from conventional tall buildings with rectangular box forms. These twisted forms introduce not only structural but also architectural and constructional challenges [6–11].

Specifically, this project investigates the optimal twist angle for RCC buildings and the ideal position for a swimming pool within these structures. The inclusion of amenities like swimming pools in high-rise buildings is aesthetically pleasing but involves certain risks. These amenities add value to buildings but must be carefully considered from a structural perspective. This project aims to represent the structural behavior of RCC-twisted buildings subjected to static loads, providing insights into their design and construction (Figure 1).

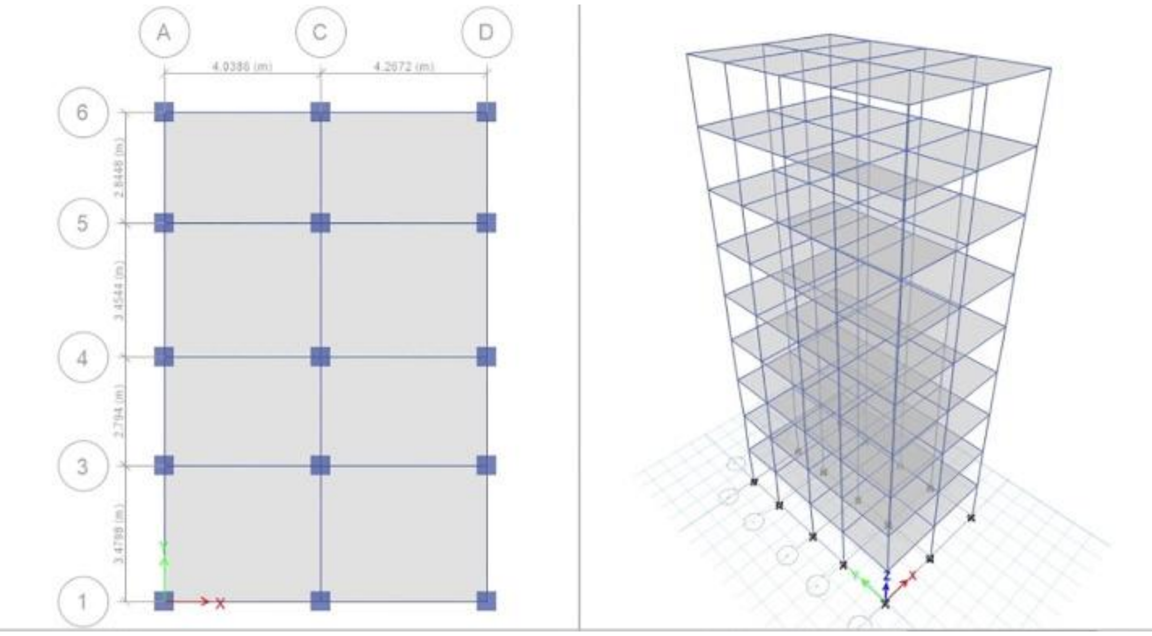

Figure 1. The optimal twist angle for RCC buildings.

PROBLEM STATEMENT

This study focuses on analyzing the structural behavior of a twisted RCC (reinforced concrete cement) building subjected to seismic loads using ETABS software. The research will examine the effect of various rates of twist on the building's performance. Each level of the building will have a unique rate of twist. The project aims to model the building using ETABS and evaluate key parameters such as base shear and story displacement. The ultimate goal of the project is to determine the optimal position and angle for incorporating a swimming pool within the twisted RCC structure under seismic conditions.

Aim

"To determine the optimum angle of twist and the best position for a swimming pool in RCC-twisted buildings subjected to seismic loads."

Objectives

- Conduct a comparative study on the design and analysis of RCC-twisted buildings with private swimming pools for a G+20 structure using ETABS.
- Analyze RCC-twisted buildings with twist angles of 1.5, 2, 2.5, 3, and 3.5 degrees per floor for a G+20 structure.
- Investigate the effects of placing swimming pools on alternate floors in RCC-twisted buildings.
- Examine structural parameters such as story displacement, story drift, and base shear.

Research Methodology

Methods of Earthquake Analysis

The analysis of multi-story structures under earthquake loads can be broadly categorized into two approaches:

1. *Static Analysis*
   - *Equivalent Static Method:* This linear static method uses formulas developed to approximate the behavior of regular structures. It involves calculating the base shear and distributing it across various floor levels. However, this method is not suitable for irregular structures.
2. *Dynamic Analysis*
   - *Response Spectrum Method:* A linear dynamic method that estimates the peak values of response quantities. It is applicable to any type of building and at all locations. This method provides a more accurate representation of the building's response to seismic activity.

Study Parameters

The study will focus on G+20 and G+40 buildings, each with specified angles of twist and varying swimming pool positions. For each angle of twist, there will be seven building configurations considering different swimming pool placements. ETABS will be used for modeling and analysis. Key structural parameters, such as story displacement, story drift, and base shear, will be evaluated and graphically represented.

Results and Conclusion

The study aims to provide conclusive data on the optimal angle of twist and swimming pool position to ensure structural integrity and safety under seismic loads.

Design Input Data

- *Material Grade:* M50 for concrete, FE500 for steel
- *Structural Elements:*
  - *Beam:* 0.815 m x 0.4 m
  - *Column:* 0.18 m x 0.8 m and 1.3 m x 1.3 m
  - *Wall:* 0.3 m and 0.4 m thickness
- *Load Patterns:*
  - Dead load
  - Live load
  - Superimposed load
  - Earthquake loads in X and Y directions
  - Wind loads in X and Y directions

The analysis will include a response spectrum analysis to evaluate the dynamic response of the building under seismic conditions. The findings will be documented in terms of story displacement, story drift, and base shear, providing a comprehensive understanding of the building's performance under different scenarios.

Design and Modeling

Response Spectrum Analysis

Response spectrum analysis is a critical technique in seismic design used to estimate the structural response of buildings to earthquake-induced ground motion. This method evaluates the peak response of a structure, such as displacement, velocity, or acceleration, based on the frequency content of the ground motion and the dynamic characteristics of the structure itself.

Theory of Response Spectrum Analysis

Concept

The response spectrum represents the maximum response of a series of single-degree-of-freedom (SDOF) systems subjected to a specific ground motion. These systems are characterized by different natural frequencies (or periods) and damping ratios. The response spectrum graph typically shows peak responses (such as displacement, velocity, or acceleration) plotted against the natural period of the SDOF systems.

Development

The development of a response spectrum involves the following steps:

- *Selection of Ground Motion:* Choose a representative earthquake ground motion record.
- *SDOF Systems Analysis:* Subject a range of SDOF systems, each with varying natural periods and damping ratios, to the selected ground motion.
- *Peak Response Calculation:* Record the maximum response of each SDOF system. This can be in terms of displacement, velocity, or acceleration.
- *Spectrum Plotting:* Plot the peak responses against the natural periods to form the response spectrum curve.

Application in Multi-Degree-of-Freedom (MDOF) Systems

While the response spectrum is derived from SDOF systems, its application to MDOF systems, such as buildings, is accomplished through modal analysis. Each mode of vibration in an MDOF system can be treated as an equivalent SDOF system. The response of each mode is determined by using the response spectrum and then combined to estimate the total response of the structure.

Combination of Modal Responses

The total structural response is obtained by combining the responses of individual modes. Common methods for combining modal responses include:

- *Square Root of the Sum of the Squares (SRSS):* Suitable for structures with well-separated natural frequencies.
- *Complete Quadratic Combination (CQC):* More accurate for structures with closely spaced modes.

Advantages

- *Efficiency:* The method provides a computationally efficient way to estimate peak structural responses without performing detailed time-history analyses.
- *Simplified Design:* Engineers can use standard response spectrum curves provided in building codes to design structures for earthquake resistance.
- *Building Codes and Standards:* Various building codes, such as the International Building Code (IBC), Eurocode 8, and the Indian standards (IS 1893), provide guidelines for generating and using response spectra for seismic design. These codes typically specify design spectra based on seismic zoning, site conditions, and the desired level of damping.

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Response Spectrum Analysis in Practice

In the practical application of response spectrum analysis for the design of RCC-twisted buildings:

- *Modeling:* The building is modeled in software like ETABS, which allows for the input of the building's geometric, material, and loading details. The twisted configuration and the position of amenities like swimming pools are incorporated into the model.
- *Dynamic Properties:* The software calculates the natural frequencies and mode shapes of the building. Each mode is considered as an equivalent SDOF system.
- *Application of Response Spectrum:* The response spectrum is applied to each mode to determine the peak response for that mode.
- *Combining Modal Responses:* The peak responses of individual modes are combined using the SRSS or CQC method to estimate the overall response of the building.
- *Result Interpretation:* The results, including story displacements, story drifts, and base shear, are analyzed to assess the building's performance and ensure compliance with seismic design criteria.

By using response spectrum analysis, engineers can design twisted RCC buildings to withstand seismic loads, ensuring safety and structural integrity under earthquake conditions. This method provides a robust framework for understanding and mitigating the impact of seismic forces on complex building geometries (Figure 2).

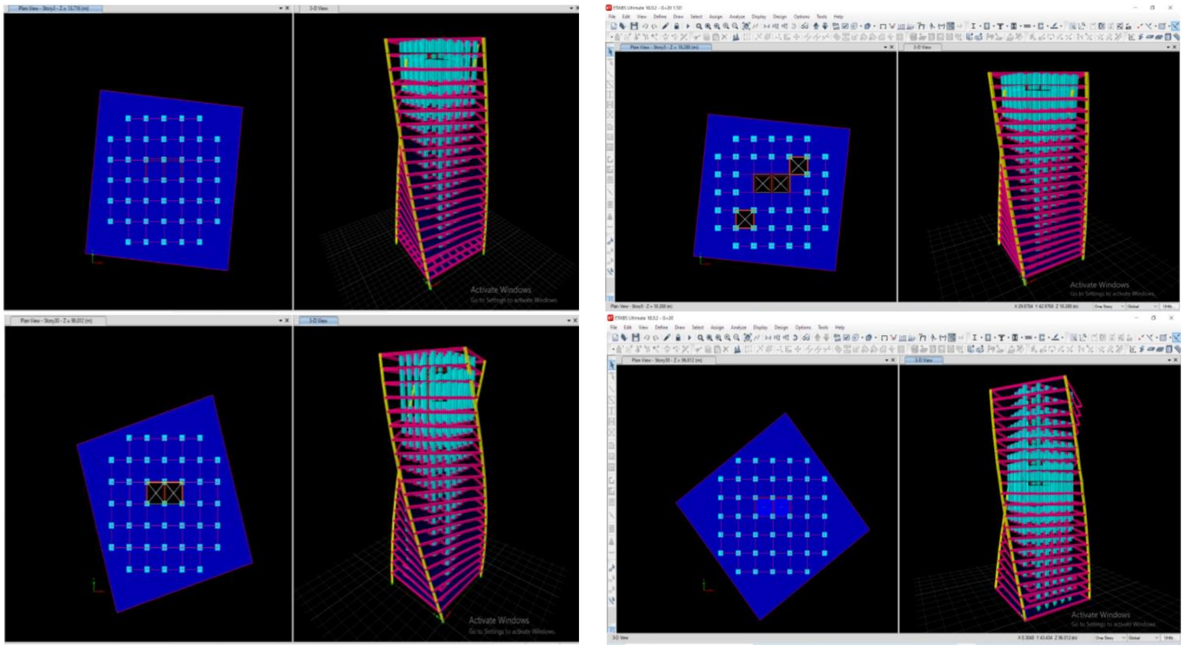

Figure 2. Degree model design.

RESULT AND DISCUSSION

Story Displacement

Story displacement refers to the lateral movement experienced by each floor level of a building during seismic events. It is a critical parameter in seismic design as it directly influences the structural performance and safety of buildings. Understanding and controlling story displacement are essential for ensuring the stability and integrity of the structure under earthquake loading.

Theory of Story Displacement

- *Definition:* Story displacement is the relative horizontal movement of one floor level with respect to the ground or to the adjacent lower floor level. It measures how much each floor shifts horizontally during seismic activity.

Causes of Story Displacement

- *Seismic Forces:* Earthquake-induced ground motions generate lateral forces that cause the building to sway, leading to story displacement.
- *Building Flexibility:* More flexible buildings will exhibit greater displacements compared to stiffer buildings.
- *Structural Irregularities:* Irregularities in mass, stiffness, and geometry can lead to uneven displacement across different stories.

Importance in Seismic Design

- *Structural Integrity:* Excessive story displacement can lead to structural damage or even collapse. It is vital to design structures to limit such displacements.
- *Non-Structural Damage:* Displacements can also cause significant damage to non-structural elements like partitions, facades, and mechanical systems.
- *Occupant Safety:* Ensuring limited displacement is crucial for the safety and comfort of the building occupants during an earthquake.

Measurement and Analysis

- *Static Analysis:* In static seismic analysis methods, story displacement is calculated by applying equivalent static forces and solving for displacements.
- *Dynamic Analysis:* In dynamic methods like response spectrum analysis, displacements are obtained by combining modal responses to seismic excitations. Each mode's maximum displacement is determined and combined to estimate the total displacement.
- *Regulatory Guidelines:* Building codes and standards specify limits on permissible story displacements to ensure safety. For example, the International Building Code (IBC) and Indian Standards (IS 1893) provide criteria for acceptable displacement limits. Drift limits, which are the relative displacements between adjacent storys, are also regulated to prevent damage to both structural and non-structural components.

Factors Influencing Story Displacement

- *Building Height:* Taller buildings typically experience higher displacements due to their increased flexibility.
- *Structural System:* The type of structural system (e.g., moment-resisting frames, shear walls, or braced frames) significantly affects displacement behavior.
- *Material Properties:* The stiffness and damping characteristics of the materials used in construction influence how the building responds to seismic forces.

Mitigation Strategies

- *Base Isolation:* Incorporating base isolators can significantly reduce story displacements by allowing the building to move independently of ground motion.
- *Damping Devices:* Installing damping devices like tuned mass dampers or viscous dampers can help control excessive displacements.
- *Enhanced Stiffness:* Increasing the stiffness of the building by using shear walls or bracing can reduce displacements.

Story Displacement in RCC Twisted Buildings

In the context of RCC-twisted buildings, story displacement analysis becomes even more critical due to the unique geometric configurations. Twisted buildings tend to have more complex displacement patterns because of their non-uniform distribution of mass and stiffness. The study and control of story displacement in such buildings are essential for the following reasons:

- *Geometric Complexity:* Twisted forms create varying displacement demands across different parts of the building.

- *Seismic Performance:* Ensuring that the building can withstand seismic forces without excessive displacement is crucial for maintaining structural integrity.
- *Safety and Functionality:* Limiting displacement helps protect both structural and non-structural elements, ensuring the building remains safe and functional during and after an earthquake.

By analyzing story displacements in RCC-twisted buildings using ETABS, engineers can assess the performance of different design configurations and identify the optimal solutions for minimizing seismic risks. This involves evaluating various twist angles and swimming pool positions to understand their impact on displacement patterns and overall building behavior (Figures 3–7 and Tables 1–5).

Table 1. Maximum story displacement.

Maximum Story Displacement					
STORY	**1.5D**	**2.0D**	**2.5D**	**3.0D**	**3.5D**
Base	*0*	*0*	*0*	*0*	*0*
STORY 1	0.007826	0.010871	0.010439	0.010373	0.010111
STORY 2	0.021913	0.029927	0.02895	0.028899	0.028305
STORY 3	0.038784	0.052384	0.050964	0.051082	0.050196
STORY 4	0.057276	0.076441	0.074616	0.075017	0.073881
STORY 5	0.077074	0.102076	0.09995	0.100644	0.099255
STORY 6	0.097442	0.12832	0.126012	0.126925	0.125194
STORY 7	0.118302	0.155319	0.152852	0.153915	0.151748
STORY 8	0.139103	0.182189	0.179501	0.180689	0.177994
STORY 9	0.159909	0.209147	0.206493	0.207321	0.203906
STORY 10	0.180328	0.23561	0.232928	0.233213	0.228803
STORY 11	0.200431	0.261755	0.260082	0.258464	0.252742
STORY 12	0.219785	0.287126	0.283779	0.282577	0.275253
STORY 13	0.23839	0.311937	0.309597	0.305578	0.296358
STORY 14	0.256441	0.335806	0.332839	0.327187	0.315739
STORY 15	0.273905	0.358799	0.353382	0.347439	0.333484
STORY 16	0.290434	0.380697	0.376096	0.36607	0.349361
STORY 17	0.306007	0.4015	0.393854	0.383069	0.363463
STORY 18	0.320482	0.420995	0.413982	0.398302	0.375634
STORY 19	0.333793	0.439096	0.428531	0.411737	0.385969
STORY 20	0.345764	0.455488	0.443305	0.423135	0.394155
STORY 21	0.356105	0.469355	0.455509	0.431967	0.400068

Table 2. Maximum story stiffness.

Maximum Story Stiffness					
STORY	**1.5D**	**2.0D**	**2.5D**	**3.0D**	**3.5D**
Base	*0*	*0*	*0*	*0*	*0*
STORY 1	8983249	5834606	5951474	5624788	5411247
STORY 2	13677186	9192840	9268659	8421170	8062520
STORY 3	4200058	2738482	2771621	2612386	2489538
STORY 4	11272205	7523149	7558529	7025351	6682081
STORY 5	3720041	2395097	2418585	2304928	2190744
STORY 6	10557219	6752164	6791559	6412949	6098333
STORY 7	3529642	2188658	2218778	2133050	2030457
STORY 8	10139622	6340067	6349939	6020319	5688625
STORY 9	3408276	2072753	2066994	2026377	1930434

Maximum Story Stiffness					
STORY	**1.5D**	**2.0D**	**2.5D**	**3.0D**	**3.5D**
Base	*0*	*0*	*0*	*0*	*0*
STORY 10	9830047	6105459	6055533	5748765	5463091
STORY 11	3310616	1996202	2017826	1940511	1875497
STORY 12	9655483	5977616	5998779	5726804	5458274
STORY 13	3271079	1940678	1953992	1911379	1855916
STORY 14	9454883	5883059	5791902	5715927	5526493
STORY 15	3122760	1889671	1872090	1868699	1838983
STORY 16	9300014	5679889	5509233	5603154	5480627
STORY 17	2964887	1773377	1754852	1776520	1771011
STORY 18	8595911	5086785	4936588	5183900	5129346
STORY 19	2536232	1477177	1466834	1512942	1532359
STORY 20	6298010	3478627	3466862	3799235	3935475
STORY 21	1192626	672168.3	770685.7	793757.2	877197.4

Table 3. Maximum overturning moment.

Maximum Overturning Moment					
STORY	**1.5D**	**2.0D**	**2.5D**	**3.0D**	**3.5D**
Base	7992972	5039763	4843236	4767568	4664354
STORY 1	7435627	4687095	4505976	4435982	4341697
STORY 2	6895133	4350527	4183723	4119615	4034637
STORY 3	6374621	4032478	3878758	3820733	3745451
STORY 4	5875781	3733361	3591651	3539840	3474630
STORY 5	5398183	3451657	3321095	3275540	3220682
STORY 6	4940119	3184284	3064331	3024946	2980595
STORY 7	4498840	2927579	2817974	2784565	2750612
STORY 8	4071657	2677666	2578442	2550692	2526897
STORY 9	3655903	2431338	2362985	2320197	2305982
STORY 10	3249881	2186034	2108305	2090588	2085318
STORY 11	2851942	1940011	1873594	1860094	1862830
STORY 12	2462034	1692707	1637947	1628102	1637893
STORY 13	2079790	1444181	1401303	1394517	1410167
STORY 14	1707519	1196794	1165716	1161407	1181639
STORY 15	1348158	953289.2	933529	931151.5	954492.7
STORY 16	1009940	720176.1	710627.1	709652.1	734349.9
STORY 17	700400.9	503422.3	502382.4	502322.6	526574.4
STORY 18	432851.6	313656	318494.9	318922	340431.9
STORY 19	217695.6	159003.4	166592	167019.8	183761.7
STORY 20	70171.61	51918.8	62009.42	58253.51	67593.2
STORY 21	0	0	2.18E-05	1.04E-05	6.43E-06

Table 4. Maximum story acceleration (M/S2).

Maximum Story Acceleration (M/S2)					
STORY	**1.5D**	**2.0D**	**2.5D**	**3.0D**	**3.5D**
Base	0	0	0	0	0
STORY 1	0.878	0.966	0.954	0.954	0.944
STORY 2	2.282	2.431	2.41	2.425	2.411

Maximum Story Acceleration (M/S2)					
STORY	**1.5D**	**2.0D**	**2.5D**	**3.0D**	**3.5D**
Base	0	0	0	0	0
STORY 3	3.693	3.845	3.834	3.868	3.854
STORY 4	4.938	5.032	5.034	5.093	5.085
STORY 5	5.938	5.961	5.987	6.066	6.073
STORY 6	6.627	6.585	6.642	6.742	6.769
STORY 7	6.979	6.898	6.995	7.104	7.157
STORY 8	7.036	6.95	7.086	7.194	7.269
STORY 9	6.887	6.821	6.973	7.078	7.168
STORY 10	6.693	6.668	6.838	6.921	7.009
STORY 11	6.55	6.55	6.752	6.79	6.866
STORY 12	6.463	6.437	6.616	6.676	6.735
STORY 13	6.324	6.189	6.409	6.439	6.488
STORY 14	6.08	5.772	6.001	6.035	6.066
STORY 15	5.774	5.23	5.428	5.491	5.488
STORY 16	5.638	4.899	5.087	5.111	5.026
STORY 17	5.931	5.134	5.215	5.222	5.006
STORY 18	6.79	6.107	6.123	6.043	5.685
STORY 19	8.063	7.573	7.497	7.382	6.91
STORY 20	9.43	9.147	9.056	8.865	8.301
STORY 21	10.591	10.489	10.46	10.173	9.57

Table 5. Modal periods (SEC).

Modal Periods (SEC)					
Mode	**1.5D**	**2.0D**	**2.5D**	**3.0D**	**3.5D**
1	1.853	2.457	2.387	2.26	2.216
2	1.687	2.224	2.188	2.165	2.161
3	1.591	1.894	1.851	1.837	1.838

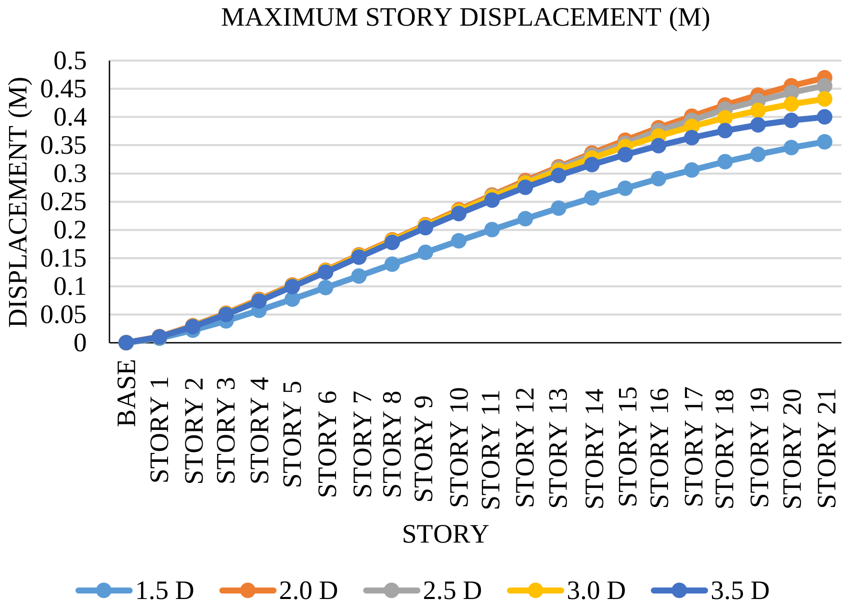

Figure 3. Maximum Story displacement (M).

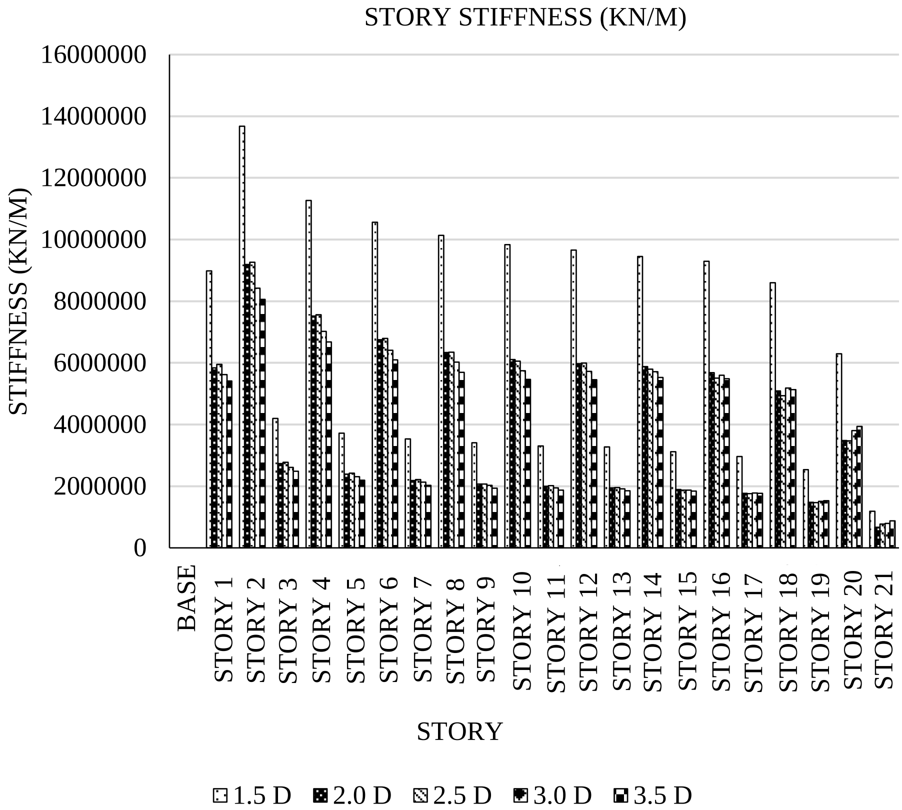

Figure 4. Story stiffness (KN/M).

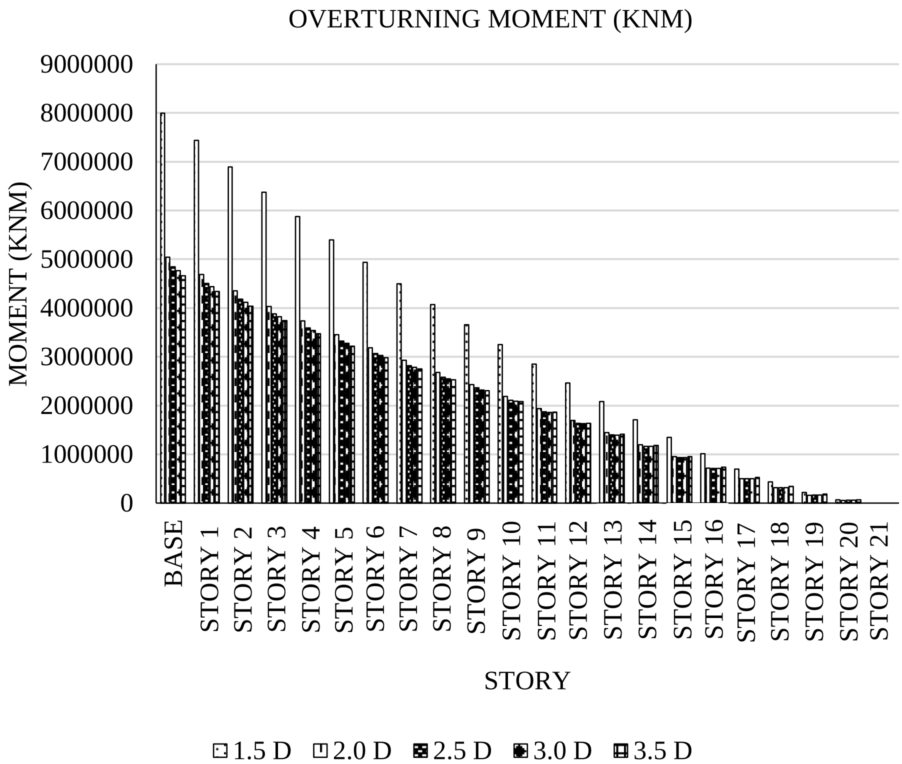

Figure 5. Overturning moment (KNM).

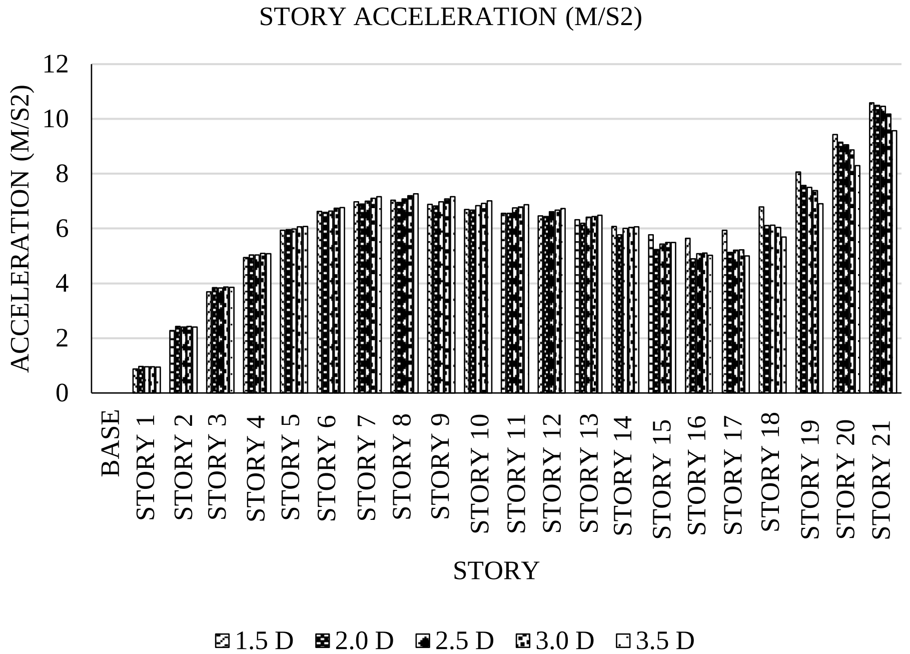

Figure 6. Story acceleration (M/S2).

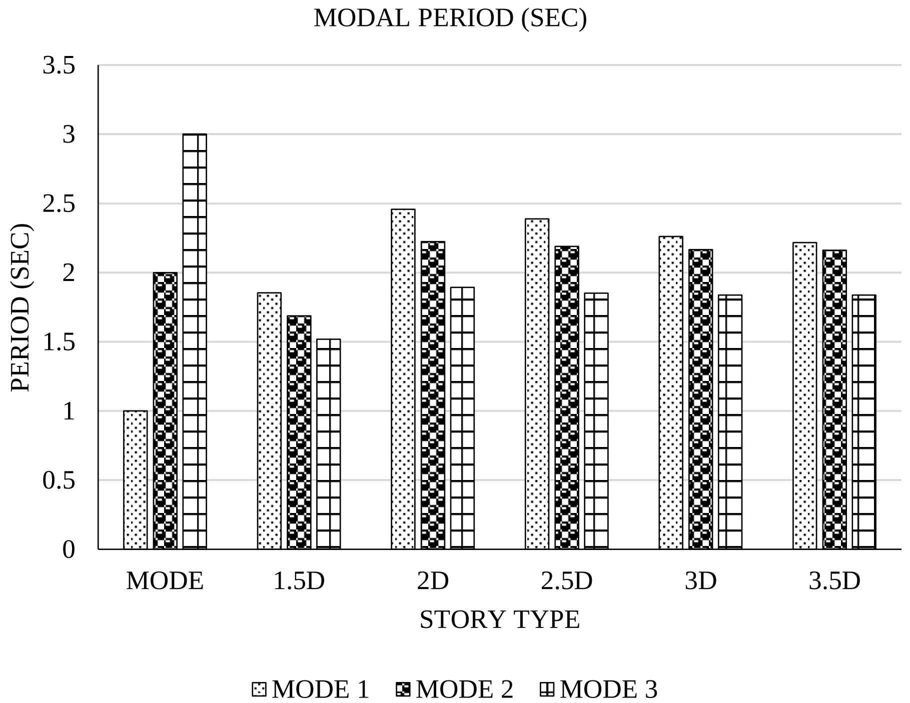

Figure 7. Story acceleration (M/S2).

CONCLUSION

The study on the seismic behavior of twisted RCC (reinforced concrete cement) buildings under varying angles of twist provides several key insights. The analysis, conducted using ETABS software, highlights the impact of different twist angles on critical structural parameters such as story acceleration, story stiffness, overturning moment, story displacement, base shear, and modal time period. The findings are summarized as follows:

1. **Maximum Story Acceleration**
   - The maximum story acceleration of the structure with a 1.5-degree twist angle (1.5D) increases by 2%, 1.5%, 3%, and 1.8% compared to structures with 2D, 2.5D, 3D, and 3.5D twist angles, respectively. This indicates that reducing the twist angle leads to an increase in acceleration, making the structure more responsive to seismic forces.
2. **Story Stiffness**
   - The story stiffness for the 1.5D model increases by 43%, 35%, 33.5%, and 26.4% compared to the 2D, 2.5D, 3D, and 3.5D models, respectively. Higher stiffness in the 1.5D model suggests that a lower twist angle enhances the rigidity of the structure, which can help in reducing lateral displacements during an earthquake.
3. **Overturning Moment**
   - The overturning moment for the 1.5D model is higher by 41%, 33.4%, 31.5%, and 24.4% compared to the 2D, 2.5D, 3D, and 3.5D models, respectively. This increase in overturning moments with lower twist angles underscores the need for careful consideration of structural stability and reinforcement in design.
4. **Maximum Story Displacement**
   - The maximum story displacement for the 2.0D model increases by 6% compared to other types of structures, but only by 10% compared to the 1.5D model. Displacement varies from floor to floor, indicating that higher twist angles can lead to more significant lateral movements across the building’s height.
5. **Base Shear**
   - As the rotation of the structure increases, the base shear also increases. The 3.5D structure experiences the highest base shear, which is 4% to 12% higher compared to other structures. This highlights the need for robust foundation design to handle increased seismic forces.
6. **Modal Time Period**
   - Increasing the twist angle results in a decrease in the modal time period. This suggests that higher twist angles lead to a stiffer and more dynamically responsive structure, reducing the duration of vibrations during an earthquake.

THEORY AND IMPLICATIONS

The study's findings illustrate the complex interplay between twist angle and seismic performance in RCC buildings. Lower twist angles generally increase stiffness, acceleration, and overturning moments, while higher twist angles tend to reduce these parameters but increase displacement and base shear. This implies a trade-off between rigidity and flexibility, where the optimal design must balance these factors to enhance overall seismic resilience.

1. **Seismic Design Considerations**
   - *Rigidity vs. Flexibility:* A balance must be struck between having a rigid structure that can withstand lateral forces and a flexible one that can dissipate energy without significant damage.
   - *Structural Reinforcement:* Structures with lower twist angles may require additional reinforcement to handle increased stiffness and overturning moments.
2. **Practical Applications**
   - *Building Codes:* The insights can inform updates to building codes and standards, ensuring that twisted RCC buildings are designed to optimize performance under seismic loads.
   - *Architectural Design:* The study aids architects and engineers in making informed decisions regarding the aesthetic and structural configuration of twisted buildings.
3. **Future Research**
   - Further studies could explore the impact of different materials, construction techniques, and damping systems on the seismic performance of twisted RCC buildings. Additionally, real-world case studies and experimental validations would provide deeper insights into the behavior of these structures under actual seismic conditions.

By thoroughly understanding and optimizing the twist angles and structural configurations, engineers can design RCC buildings that not only meet aesthetic and functional requirements but also exhibit superior performance and safety during seismic events.

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