SEISMIC BEHAVIOUR OF THE IRREGULAR RC STRUCTURE SUBJECTED TO SINGLE AND MULTIPLE EARTHQUAKE EXCITATIONS

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I, Gopal Patil, 2K21/STE/10, student of MTech Structural Engineering, hereby declare that the project Dissertation titled “SEISMIC BEHAVIOUR OF THE IRREGULAR RC STRUCTURE SUBJECTED TO SINGLE AND MULTIPLE EARTHQUAKE EXCITATIONS ” which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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I hereby certify that the Project Dissertation titled “SEISMIC BEHAVIOUR OF THE IRREGULAR RC STRUCTURE SUBJECTED TO SINGLE AND MULTIPLE EARTHQUAKE EXCITATIONS” which is submitted by Gopal Patil, 2K21/STE/10 Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Urban infrastructure often comprises buildings with irregular designs, influenced by occupational and architectural requirements. Irregularities can be observed in various aspects of a building, such as its floor plan, elevation, distribution of vertical elements, and allocation of mass across different levels. Finding perfectly regular buildings in reality is rare, making them more theoretical than practical. However, these irregularities can pose a significant risk during seismic activity, as they can amplify displacement and concentrate stresses within the structural components, potentially leading to severe damage and even collapse. One type of irregularity is vertical irregularity, which refers to variations in mass, stiffness, strength, or geometry along the height of a building. Another kind is rotational or in-plan irregularity, that develops whenever the centre of masses and rigidity are not aligned along a similar vertical direction at each floor level. When lateral forces or earthquakes occur, the resistive force operates along the centre of stiffness, whereas the force of inertia acts along the centre of mass. The operation of the structure is torsional if it possesses in-plan eccentricity.

This research aims to investigate the effects of repeated seismic waves on irregular RC buildings commonly found in urban infrastructure. Specifically, he main objective of the study is to assess the effects of mass and stiffness anomalies along the height of the building along with torsional irregularities in the structure's plans. To analyse these effects, nonlinear time history analysis is conducted using the software ETABS 20, comparing torsional responses under various scenarios. The analysis reveals that irregularities arising from differing shear wall positions exhibit more pronounced torsional irregularities compared to mass and stiffness irregularities, especially when subjected to single strong earthquakes or repeated earthquakes. The results demonstrate that double event earthquakes result in greater torsional irregularity compared to single events and triple events, while a triple event of moderate earthquakes yields similar results to a single event of a strong earthquake. This study provides valuable insights into the torsional behaviour of irregular reinforced concrete buildings when exposed to repeated earthquakes. Overall, the results highlight the critical importance of shear wall placements to assessing the torsional behaviour of such buildings, emphasising the need to take them into account when designing earthquake-resistant structures. The evaluation of different techniques involves comparing methods such as column resizing and reorientation, implementing Lead rubber base isolation systems to isolate a building's foundation from vibrations and seismic activity, and incorporating friction viscous dampers to minimize torsional impact during single and repeated earthquake excitations in the most vulnerable scenarios. The results clearly demonstrate the high effectiveness of these techniques in reducing torsional irregularity in structures. Notably, the incorporation of friction viscous dampers proves to be the most advantageous, resulting in the lowest displacement and minimal torsional irregularity compared to the other two techniques

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CHAPTER 1

INTRODUCTION

Real structures often display an extensive variety of differences with regard to their mass, stiffness, and strength across their height and layout, hence the idea of a totally regular building is frequently idealised. The advancement of modern construction techniques has allowed for the creation of multi-storey buildings with intricate designs and structural systems, which inherently introduce irregularities. Various factors, including architectural considerations, spatial limitations, and functional requirements, contribute to the irregular nature of buildings. Extensive research conducted following major earthquakes has shown that buildings with asymmetrical characteristics are particularly susceptible to seismic damage. These structures possess complex pathways for distributing lateral loads, and damage tends to originate at weak points resulting from irregularities in stiffness, strength, or mass distribution. Such flaws may cause the structure to gradually deteriorate and ultimately collapse. Practical applications rarely require buildings to achieve absolute symmetry, wherein the centre of mass and the centre of rigidity are aligned vertically at every floor level. Most buildings display varying degrees of asymmetry in their structural components, mass distribution, floor plans, elevations, or orientations. Although structures frequently display a combination of both categories, seismic standards categorise variations in plan irregularities and vertical irregularities. Plan irregularities are differences in the floor plan, whereas vertical irregularities are variations in mass, strength, rigidity, or design throughout the height of the building. This chapter provides an overview of the study's main focus, highlighting the classification of irregularities according to different codes. Additionally, the study offers a detailed description of the specific types of irregularities considered.

1.1 Vertical mass irregularity

Vertically irregular structures are characterised by significant variations in their vertically configuration or lateral force resisting systems. Vertical irregularity occurs when a building demonstrates inconsistencies in terms of stiffness, strength, or mass along its height or elevation. Mass and stiffness irregularities are particularly significant among the vertical irregularities extensively studied by researchers. Vertical discontinuity in the mass, strength, rigidity, or load routes within buildings have been studied for their effects. Recognized building codes establish specific subcategories for classifying vertically irregular structures. To assess the response and distribution of lateral forces, it is recommended to conduct time history analysis or response spectrum analysis. Setback structures and staggered structure frames, which introduce differences in mass and stiffness at every setback or step level, are another widely studied component of vertically irregular buildings. Mass irregularities manifest when there are variations in the distribution of mass across a building's plan or elevation. Such irregularities can arise when a specific floor carries a significant mass or when one floor substantially outweighs the others. Utility floor or machine floors in high-rise buildings are frequently built to support heavier loads than conventional levels. The inclusion of substantial water tanks or swimming pools on intermediate floors can also contribute to mass irregularities. As the mass increases in a particular story, so does the inertia force generate within that story. The impact of mass irregularity on the mode shape is low in regular buildings if the variation in mass or the change in mass compared to the total building mass is minor. However, when there is a significant variation in mass, the disparities in seismic response become evident during intense ground shaking. Mass irregularities impose increased demands for ductility at the irregular locations and can produce unforeseen effects on higher vibration modes.

Vertical mass irregularity is defined as being present when the mass of a given story exceed 1.5 times the mass of the story directly below it by standards such IS 1893:2016, FEMA 450 and ASCE 7-16.

1.2 Vertical stiffness irregularity

In reality, the concept of a perfectly regular building is mostly an idealized notion, as nearly all practical buildings exhibit some degree of irregularity. Architects and designers intentionally incorporate irregularities into building designs to serve various purposes. By removing the core columns and lowering the size of the beams and columns on the upper levels, for illustration, commercial basements can be built. Functional requirements, such as the need for housing heavy machinery or storing equipment, can also contribute to irregular designs. Along the height of the building, there are uneven distributions of mass, rigidity, and strength due to the distinct functions and planned uses of particular floors in comparison to nearby floors. Additionally, a lot of structures unintentionally have abnormalities because of things like differences in the materials, construction techniques, procedures, and strategies. Buildings with "soft storeys" exhibit stiffness irregularity. Shopping centres, hotels, and commercial structures frequently have soft floors, which are distinguished by a wide ground floor on the building's front side or tall ground levels. The building is more susceptible to seismic forces when a story has taller columns that are weaker and less rigid than necessary to sustain anticipated seismic forces.

Generally speaking, strength refers to the greatest force that a building can safely withstand, whereas stiffness refers to the force required to produce a unit displacement, which is represented by the gradient of the force-displacement curve. In a building, a weak storey denotes a segment with reduced strength, and a soft storey denotes an element with lower stiffness. A soft story is also referred to as a weak storey. Because of differences in stiffness between neighbouring floors, soft storey conditions develop. The IS 1893:2016 guidelines state that a structure has soft storey irregularity or stiffness irregularity when any storey's lateral stiffness is less than that of the story above it.

1.3 Torsional Irregularity

Seismic loads have a critical impact on the structural design of buildings. The behaviour of an irregular building during earthquakes is affected by various loads acting on both the horizontal and vertical planes of the structure. Irregularities within the building can alter the distribution of loads and lead to an increased demand for ductility.

Among the different types of horizontal irregularities, torsional irregularity stands out as the most crucial and noteworthy. Torsional responses occur in structures due to factors such as uneven distributions of mass and stiffness, resulting in a combination of torsional and translational responses. Torsional reactions may also result from changes in how the building's base is connected to the ground or from the impact of wave propagation. In an uneven or asymmetric construction, lateral-torsional coupling happens when there are differences or eccentricity among the centre of mass (CM) and the centre of rigidity (CS). Even though the ground motion is only translational, this interaction causes torsional vibrations. When a structure is subjected to earthquake load, the inertia force works via the mass centre and the resistance force acts via centre of stiffness. When these forces are out of balance, a rotating moment is created, which causes lateral vibration in addition to torsional vibration. This dynamic response reduces the system's ability for lateral ductility by combining rotation and translation in one or two perpendicular directions. Torsionally connected systems is the term used to describe such systems.

In accordance with IS 1893:2016, when the slabs of floor are rigid in-plane and the vertical parts that oppose lateral forces are proportional in line with their mass distribution, a building is considered to have an even rigidity distribution in its plan. Torsion is not anticipated to happen in such well-balanced structures. If the irregularity coefficient surpasses 1.5, torsional irregularity is recognised. This coefficient is calculated by comparing the highest horizontal displacement in the same direction at one side of the floor to the minimum horizontal displacement in the same direction at the opposite end of the same floor. Furthermore, in each primary plan direction, the torsional mode of oscillation of the building will have a longer natural period than the first two translational modes.

The difference between the locations of the centre of mass and the centre of stiffness at a particular floor level is used to compute the static eccentricity (es). In contrast to static load scenarios, the impact of eccentricity in uneven buildings is more obvious under dynamic stress conditions. Therefore, IS 1893:2016 recommends incorporating a dynamic amplification factor when determining the design or dynamic eccentricity (ed) at any given floor level 'i' using the floor plan dimensions 'b'.

$$e_{di} = \left[\begin{array}{r} 1.5\ e_{si} + 0.05\ b_i \\ e_{si} - 0.05\ b_i \end{array}\right]$$

Traditional seismic design practices commonly concentrate on analysing and modelling a structure for a single occurrence of an earthquake. However, in reality, earthquakes can happen repeatedly. The frequency of earthquakes can significantly affect a building the system's stiffness and strength, especially when it is subjected to numerous, strong ground vibrations. These repeated events can lead to escalated damage, leaving limited time for necessary rehabilitation actions.

Repeated earthquakes involve medium-strength ground motions that occur at regular intervals. These repetitive incidents can significantly influence the stiffness and strength of a structural system.Therefore, to ensure irregular buildings' safety during seismic events, it is essential to take into account the consequences of recurrent earthquakes. It is possible to reproduce the effects of multiple earthquakes on the structure by using nonlinear time history analysis. This analysis enables engineers to assess the performance of the system and implement necessary enhancements to improve its seismic resistance accordingly.

CHAPTER 2

LITERATURE REVIEW

2.1 Torsional irregularities in the structure due to single Earthquake ground excitations

A study conducted by **Rohan Bhasker and Arun Menon (2020) [1]** aimed to find a descriptor that showed a reasonably strong correlation with the behaviour of plan asymmetric structures during earthquakes. The descriptor was composed of the maximum to minimum (or average) elastic floor displacement ratio, the torsional radius to mass radius of gyration ratio, and the normalised static eccentricity ratio. But throughout all levels of shaking of the ground models, neither of the scalar indices looked at in their research demonstrated a strong association with the drift requirements.

F. Gulten Gülay and Gökhan Calim (2003) [2] observed that floors designed with irregularities resulted in a higher number of inelastic hinges compared to regular building Consequently, special attention and the enhancement of member sizes are necessary in regions with irregularities.

Francisco Crisafulli et al in (2004) [3] investigated modified design process that takes into account the structure's torsional strength and the elements' yield displacement to limit the system's ductility capacity was developed after research into the effects of rotational response in ductile structures.

Nina Zheng et al (2004) [4] examined the relationship between torsion effects and the criteria specified by different codes. They found no significant dependence between torsion effects and the criteria mentioned in the codes, and some regulations in the code were considered unreasonable.

R. Tabatabaei and H. Saffari (2011) [5] compared the eccentricities and ground excitations of three distinct structural systems. The findings showed that the suggested method, which combines updated static eccentricity with the adaptable modal combinations (AMC) method, produced torsional responses which were more reliable than those produced by the NL-SA method employing static eccentricity.

N. Özhendekci and Z. Polat (2008) [6] modified the ratio of effective modal masses and compared it with the ratio proposed by ASCE 7-05. The findings revealed that the use of the code parameter resulted in a maximum difference of 101% in the drifts of the corner columns, considering the ratio of eccentricity in the direction of excitation to the radius of gyration. In contrast, the modified Q ratio led to a maximum difference of 59%.

Rajalakshmi K R and Harinarayanan S (2015) [7] conducted a numerical analysis using SAP 2000 and determined that floors designed with irregularities resulted in a greater number of inelastic hinges compared to regular building models. Therefore, special attention and the enhancement of member sizes are necessary in regions with irregularities.

H. Gokdemir, H. Ozbasaran, M. Dogan, E. Unluoglu, and U. Albayrak (2017) [8] noted that L-shaped buildings experience increased torsion due to their geometry, even when they have the same mass and floor area as rectangular models. Under earthquake loads, torsion in the structure and shear forces on columns significantly increase with higher eccentricity. Calculations show that increasing adjacent rigidity in the weak direction and decreasing the strength of structural elements in the strong direction of the building, along with establishing adequate distances between building sections, can help reduce the impact of torsion on structures.

Mohamed Sherif Mehana et al (2019) [9] buildings were categorised according to eccentricity and frequency. According to ASCE 7-10, buildings classed as type 1b, exhibiting extreme torsional irregularity, have an eccentricity of 5% of the building size and a frequency ratio below 1.0. If the occurrence ratio is in excess of 1.0 and less than 2.0, Type 1a buildings display torsional irregularity. Structures having a frequency ratio higher than 2.0 have a predictable torsional response.

Pouria Bahman et al (2014) [10] shown that their suggested strategy is marginally cautious for nonlinear systems and extremely accurate for linear ones.

Chia-Hung Fang et al (2018) [11] examined six steel-braced, four-story buildings with various diaphragm in-plane stiffnesses and vertical force resistant system configurations. They discovered that stiff diaphragm constructions had higher ultimate strengths than semirigid diaphragm structures. The highest demands for ductility were demonstrated by asymmetric constructions with severe torsional irregularities and semirigid diaphragms.

2.2 Effect of Repeated Earthquakes on the structures

Ade Faisal et al (2012) [12] did a study to look into how the need for story ductility in inelastic concrete frames is affected by artificial recurrent earthquakes. They considered twenty ground motions consisting of single, double, and triple events, and their findings revealed a significant increase in ductility demand due to the repeated earthquakes.

D. Loulelis et al (2012) [13] exposed moment-resisting frames (MRF) to five genuine earthquake sequences that happened at the identical station, in the same direction, and over a brief period of up to three days. Additionally, they subjected the MRFs to 60 synthetic seismic sequences. They were able to precisely calculate the ductility demands, behavioural factor, and seismic damage brought on by the repetitive ground motions by properly integrating the associated demands of the single ground motions.

C. Amadio et al (2003) [14] compared the effects of a single seismic event with those of repeated earthquake ground motions on a non-damaged system using different hysteretic models. They concentrated on a moment-resisting steel frame and took into account variables including damage parameters, pseudo-acceleration response spectra, and behaviour factor (q). The investigation showed a q-factor reduction that was greater than that of a comparable single-degree-of-freedom (SDOF) system during repeated earthquake ground motions.

George D. Hatzigeorgiou (2009) [15] constructed an expressions for a particular ratio based on the vibration period, viscous damping ratio, strain-hardening ratio, force reduction factor, and soil class, thorough parametric experiments were done. The inelastic displacement ratio and, subsequently, the maximum inelastic displacement of SDOF systems were significantly impacted by the phenomenon of repeated earthquakes.

L. Di Sarno (2013) [16] used deteriorating and non-degrading hysteretic models to do thorough parametric response spectra evaluations, which allowed us to precisely predict how reinforced concrete (RC) constructions will react to numerous powerful earthquakes. According to the study, the strain on structures might be three times greater than it would be for a single event, suggesting that conventionally constructed structures may not be as safe as they should be when subjected to numerous earthquakes.

Yaghmaei-Sabegh et al. (2016) [17] studied earthquake ground motion records using wavelet transform analysis to look into the characteristics of the energy distribution and frequency content. Additionally, they looked at how single-degree-of-freedom (SDOF) systems responded nonlinearly to seismic sequences. The research compared these numbers to earlier hypothesised expressions that take seismic sequences into account. The results showed that the values obtained in this investigation, especially in the intermediate- and long-period spectral areas, were underestimated by the prediction expressions for factors that reduce strength (R) and inelastic displacement ratios (IDR).

George D. Hatzigeorgiou et al. (2010) [18] studied inelastic behaviour of eight reinforced concrete (RC) planar frames' in the presence of forty-five successive ground motions was tested. The study highlighted how ground motion sequences have a substantial influence on the design of reinforced concrete frames. By aggregating the associated demands of the separate ground motions, the ductility requirements of all of the subsequent ground motions were precisely determined.

A. Rashidi et al. (2019) [19] examined the torsional behaviour of a single-story, three-dimensional asymmetric building when it was subjected to both one-time and repeatedly strong ground motions. The centre of strength (CR) and the centre of stiffness (CS), two interrelated elements that have a substantial impact on a building's ability to withstand torsional forces, were the main focus of the study. The research showed the value of conducting elastic/inelastic analysis under repetitive ground vibrations, especially for lower CR ratio values, by looking at eighty positions of strength eccentricities (er) and stiffness eccentricities (es). This method challenges conventional wisdom by ensuring that the intended structure can endure elastic and inelastic forces.

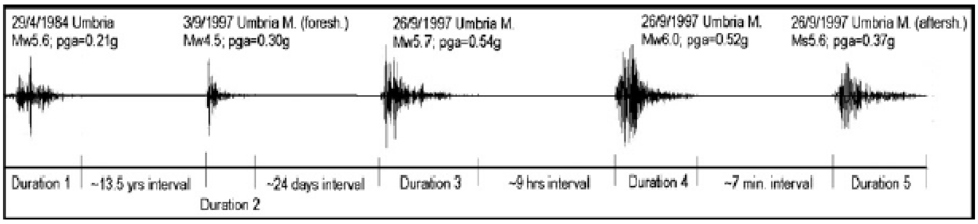


Fig. 1. Example of repeated earthquake ground motions recorded from Norcera Umbra Station, Italy.

Fig 2.1: Example of repeated earthquake ground motion (Norcera Umbra Station,Italy) **[12]**

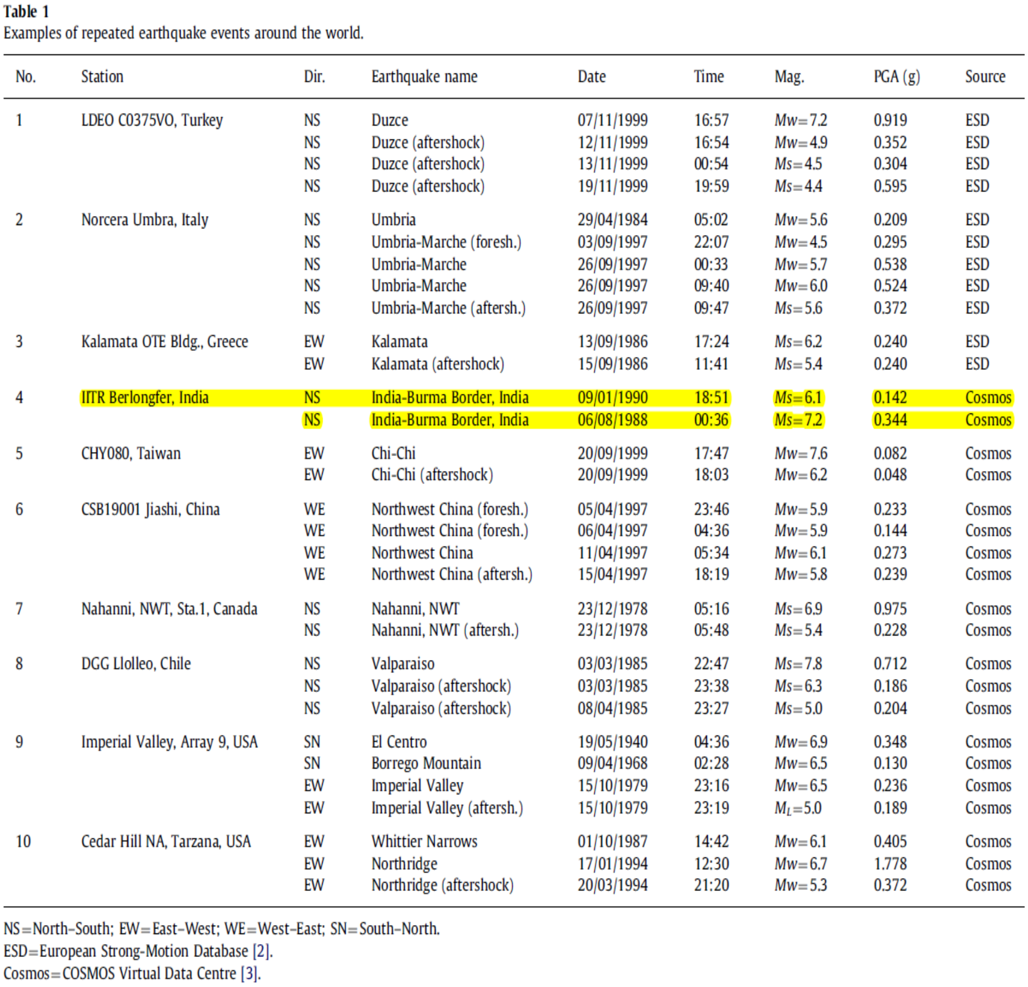


Table 1
Examples of repeated earthquake events around the world.

No.	Station	Dir.	Earthquake name	Date	Time	Mag.	PGA (g)	Source
1	LDEO C0375VO, Turkey	NS	Duzce	07/11/1999	16:57	$Mw=7.2$	0.919	ESD
		NS	Duzce (aftershock)	12/11/1999	16:54	$Mw=4.9$	0.352	ESD
		NS	Duzce (aftershock)	13/11/1999	00:54	$Ms=4.5$	0.304	ESD
		NS	Duzce (aftershock)	19/11/1999	19:59	$Ms=4.4$	0.595	ESD
2	Norcera Umbra, Italy	NS	Umbria	29/04/1984	05:02	$Mw=5.6$	0.209	ESD
		NS	Umbria-Marche (foresh.)	03/09/1997	22:07	$Mw=4.5$	0.295	ESD
		NS	Umbria-Marche	26/09/1997	00:33	$Mw=5.7$	0.538	ESD
		NS	Umbria-Marche	26/09/1997	09:40	$Mw=6.0$	0.524	ESD
		NS	Umbria-Marche (aftersh.)	26/09/1997	09:47	$Ms=5.6$	0.372	ESD
3	Kalamata OTE Bldg., Greece	EW	Kalamata	13/09/1986	17:24	$Ms=6.2$	0.240	ESD
		EW	Kalamata (aftershock)	15/09/1986	11:41	$Ms=5.4$	0.240	ESD
4	IITR Berlongfer, India	NS	India-Burma Border, India	09/01/1990	18:51	$Ms=6.1$	0.142	Cosmos
		NS	India-Burma Border, India	06/08/1988	00:36	$Ms=7.2$	0.344	Cosmos
5	CHY080, Taiwan	EW	Chi-Chi	20/09/1999	17:47	$Mw=7.6$	0.082	Cosmos
		EW	Chi-Chi (aftershock)	20/09/1999	18:03	$Mw=6.2$	0.048	Cosmos
6	CSB19001 Jiashi, China	WE	Northwest China (foresh.)	05/04/1997	23:46	$Mw=5.9$	0.233	Cosmos
		WE	Northwest China (foresh.)	06/04/1997	04:36	$Mw=5.9$	0.144	Cosmos
		WE	Northwest China	11/04/1997	05:34	$Mw=6.1$	0.273	Cosmos
		WE	Northwest China (aftersh.)	15/04/1997	18:19	$Mw=5.8$	0.239	Cosmos
7	Nahanni, NWT, Sta.1, Canada	NS	Nahanni, NWT	23/12/1978	05:16	$Ms=6.9$	0.975	Cosmos
		NS	Nahanni, NWT (aftersh.)	23/12/1978	05:48	$Ms=5.4$	0.228	Cosmos
8	DGG Llolleo, Chile	NS	Valparaiso	03/03/1985	22:47	$Ms=7.8$	0.712	Cosmos
		NS	Valparaiso (aftershock)	03/03/1985	23:38	$Ms=6.3$	0.186	Cosmos
		NS	Valparaiso (aftershock)	08/04/1985	23:27	$Ms=5.0$	0.204	Cosmos
9	Imperial Valley, Array 9, USA	SN	El Centro	19/05/1940	04:36	$Mw=6.9$	0.348	Cosmos
		SN	Borrego Mountain	09/04/1968	02:28	$Mw=6.5$	0.130	Cosmos
		EW	Imperial Valley	15/10/1979	23:16	$Mw=6.5$	0.236	Cosmos
		EW	Imperial Valley (aftersh.)	15/10/1979	23:19	$M_L=5.0$	0.189	Cosmos
10	Cedar Hill NA, Tarzana, USA	EW	Whittier Narrows	01/10/1987	14:42	$Mw=6.1$	0.405	Cosmos
		EW	Northridge	17/01/1994	12:30	$Mw=6.7$	1.778	Cosmos
		EW	Northridge (aftershock)	20/03/1994	21:20	$Mw=5.3$	0.372	Cosmos

NS=North–South; EW=East–West; WE=West–East; SN=South–North.
ESD=European Strong-Motion Database [2].
Cosmos=COSMOS Virtual Data Centre [3].

Fig 2.2: Example of repeated earthquake events around the world **[12]**

CHAPTER 3

SCOPE OF THE STUDY

1. Effect of torsional response on irregular RC structure is limited to single Earthquake ground motion but in reality, the earthquakes normally repeats after the first event.
2. Asymmetric structures with strong torsional responses can also be studied, however only three-dimensional symmetric frames can meet the story ductility requirements of inelastic concrete frames exposed to repeated earthquakes.

CHAPTER 4

OBJECTIVE OF THE STUDY

1. Comparison of torsional effect of irregular RC structure when subjected to single and multiple earthquakes for different cases
2. To reduce the torsional irregularity of the most vulnerable case when the structure is subjected to single and repeated Earthquake Excitations

CHAPTER 5

METHODOLOGY

This study delves into the anomalies observed in buildings, specifically focusing on the irregularities arising from variations in mass, stiffness, or a combination of both. To comprehensively investigate these irregularities, the researchers employ ETABS 20, utilizing single and repeated strong ground motions and conducting inelastic dynamic time history analyses under both elastic and inelastic conditions. The study explores three distinct scenarios of irregularities to analyse the torsional response of the structure:

1) Change in shear wall position resulting in stiffness and mass irregularities.

2) Vertical mass irregularity accompanied by eccentricity within the floor plan.

3) Vertical stiffness irregularity accompanied by eccentricity within the floor plan.

5.1 Nonlinear Time History Analysis

The research encompasses a nonlinear time history analysis to investigate the behaviour of structures under dynamic loading conditions, accounting for their inelastic characteristics. Unlike assuming linear behaviour, this analysis method considers the actual nonlinear response of the structure as it evolves over time. By adopting this approach, the study aims to accurately capture the intricate and realistic behaviour of the structure, which is crucial when assessing irregularities and their impact on the overall structural response.

In the field of structural engineering and dynamics, time history analysis is a numerical technique employed to study the behaviour of structures when subjected to dynamic loads that vary over time. It is commonly used to evaluate how structures respond to events such as earthquakes, wind, explosions, and other transient phenomena.

During time history analysis, the dynamic loads acting on a structure are represented as time-dependent functions, referred to as time histories. These loads can be obtained from recorded data, such as actual earthquake records, or they can be artificially generated based on design criteria or simulated scenarios.

The analysis involves solving the equations of motion for the structure while considering the mass, stiffness, and damping properties of the system. These equations describe the relationship between the forces acting on the structure, including the dynamic loads, and its response in terms of displacements, velocities, and accelerations.

By simulating the dynamic behaviour of the structure over time, time history analysis allows engineers to assess the structural response and evaluate various factors, including stresses, deformations, and dynamic amplification effects. It aids in determining the structural integrity, identifying potential areas of failure or excessive deformation, and designing appropriate measures to ensure the safety and performance of the structure under dynamic loads.

Computer software is commonly utilized to perform time history analysis as it efficiently solves the complex equations involved and provides detailed results for further analysis and design considerations. This technique serves as a valuable tool in the field of structural engineering to ensure the reliability and resilience of structures when subjected to dynamic loading conditions.

Time history analysis is a method employed to evaluate the dynamic behaviour of structures when exposed to time-varying loads. It involves simulating the behaviour of a structure over time by considering the forces acting on it at different points in time. This analysis is particularly significant in scenarios where the loads on a structure change rapidly or possess a complex time-dependent nature.

To perform a time history analysis, the following steps are typically undertaken:

1. <u>Defining Loads:</u> The dynamic loads acting on the structure are precisely defined. These loads can be acquired from recorded data, such as earthquake ground motion records, or they can be generated based on design criteria or simulated scenarios. The loads are typically specified as a function of time, describing how they change throughout the analysis duration.

2. <u>Structural Modelling:</u> The structure is represented using a mathematical model that encompasses its mass, stiffness, and damping characteristics. The complexity of the structure determines the inclusion of elements like beams, columns, slabs, and connections. The model incorporates properties of structural elements, such as material properties and cross-sectional dimensions.

3. <u>Equations of Motion:</u> The equations of motion for the structure are derived based on Newton's laws of motion. These equations establish the relationship between the applied

forces, structural properties, and resulting motion of the structure. Typically, they consist of second-order ordinary differential equations that relate the accelerations, velocities, and displacements of the structure.

4. Numerical Solution: The equations of motion are solved numerically using techniques like the Newmark integration method, the Wilson-θ method, or the direct time integration method. These methods divide time into small steps and iteratively solve the equations to compute the response of the structure at each time step.

5. Analysis and Results: The numerical solution provides information about the dynamic response of the structure, encompassing displacements, velocities, accelerations, and internal forces/stresses. These results are analysed to evaluate the structural integrity, assess potential failure modes, and identify critical locations within the structure. They are also instrumental in assessing the structure's performance against designated design criteria, such as allowable displacements, stresses, or accelerations.

Time history analysis empowers engineers to accurately capture the time-varying behaviour of structures subjected to dynamic loads. It facilitates the assessment of the structure's response under various loading scenarios and offers valuable insights for enhancing designs, formulating retrofitting strategies, or evaluating the effectiveness of structural control measures.

5.1.1 Validation of Time History Analysis using ETABS 20

Problem statement:

The study involved analysing a four-storey reinforced concrete (RC) building using two methods: the equivalent static method through manual calculations and the time-history method using ETABS 20 software. The analysis was conducted following the guidelines outlined in IS 1893 (Part 1): 2016. The purpose of this example was to showcase the step-by-step process of determining forces. To simplify the illustration, one of the plane frames in the transverse direction was selected, taking into account the building's symmetry in elevation and design.

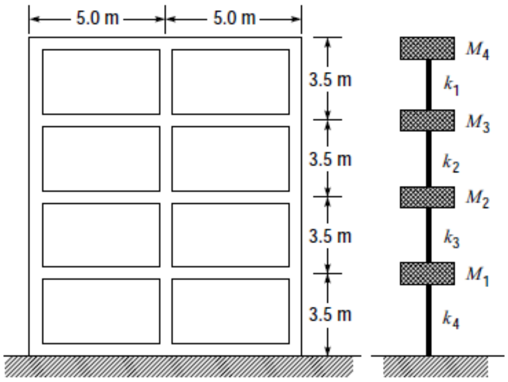


Fig 5.1: Plane frame structure and its lumped mass model

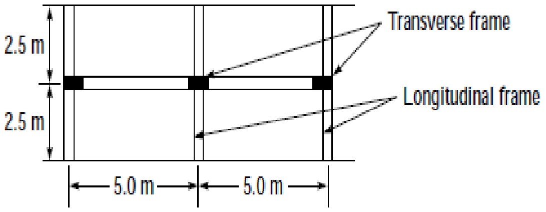


Fig 5.2: Plan showing the column and beams at floor levels of the plane frame

ETABS Modelling

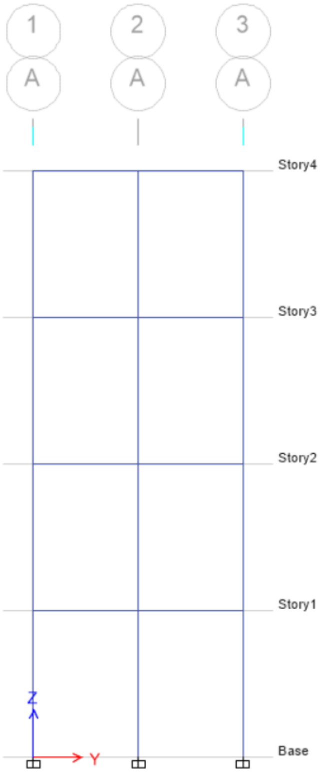


Fig 5.3: Elevated structure

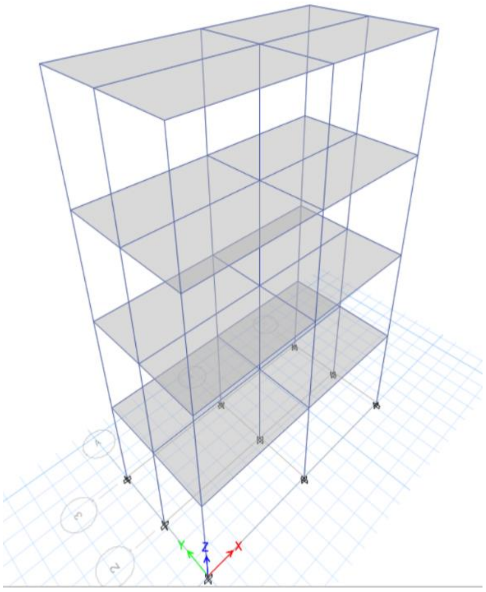


Fig 5.4: 3D structure

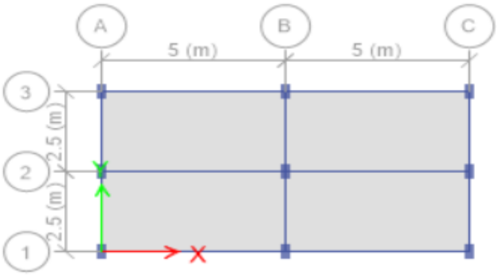
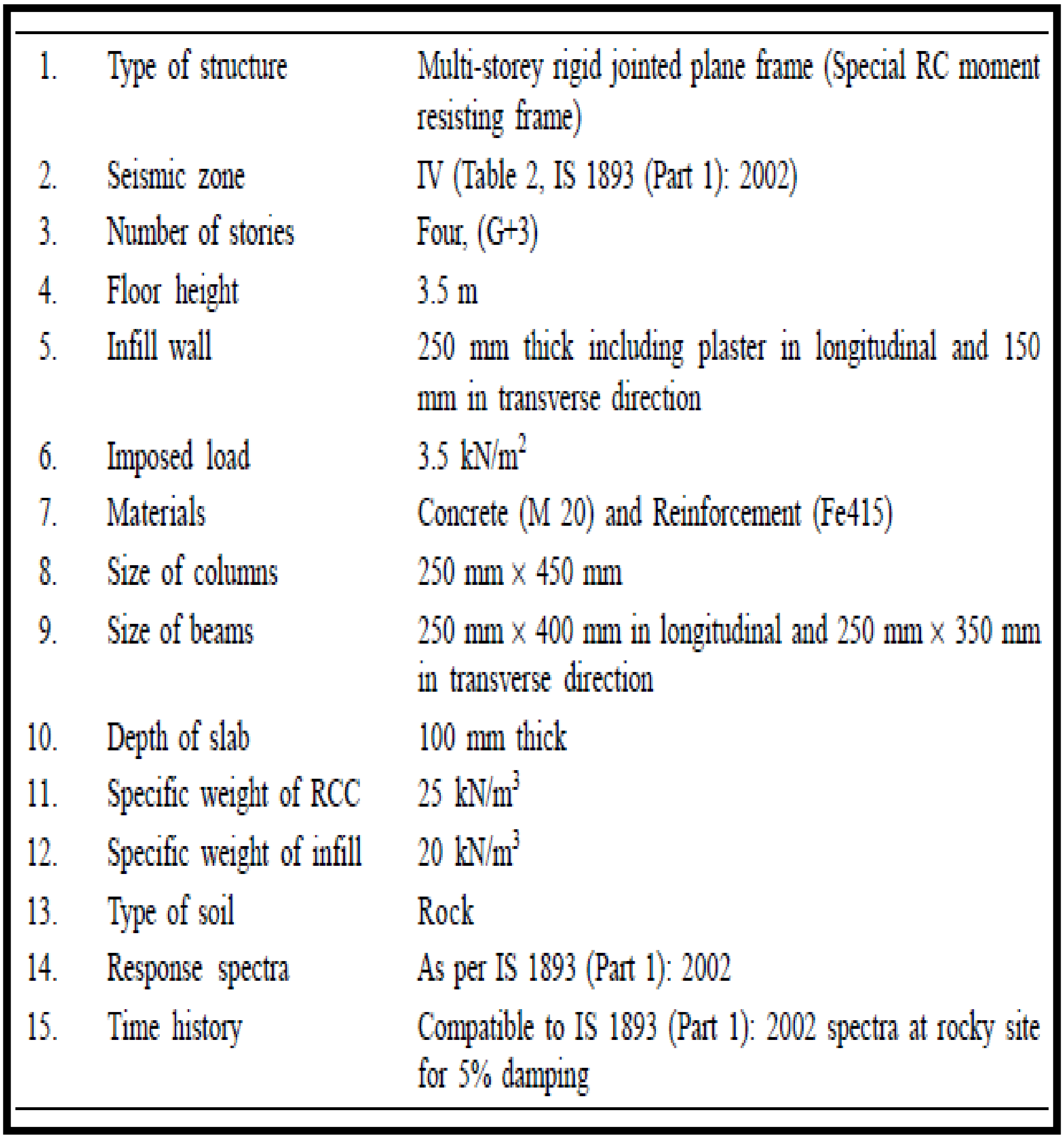


Fig 5.5: Structural plan



1.	Type of structure	Multi-storey rigid jointed plane frame (Special RC moment resisting frame)
2.	Seismic zone	IV (Table 2, IS 1893 (Part 1): 2002)
3.	Number of stories	Four, (G+3)
4.	Floor height	3.5 m
5.	Infill wall	250 mm thick including plaster in longitudinal and 150 mm in transverse direction
6.	Imposed load	3.5 kN/m^2
7.	Materials	Concrete (M 20) and Reinforcement (Fe415)
8.	Size of columns	250 mm × 450 mm
9.	Size of beams	250 mm × 400 mm in longitudinal and 250 mm × 350 mm in transverse direction
10.	Depth of slab	100 mm thick
11.	Specific weight of RCC	25 kN/m^3
12.	Specific weight of infill	20 kN/m^3
13.	Type of soil	Rock
14.	Response spectra	As per IS 1893 (Part 1): 2002
15.	Time history	Compatible to IS 1893 (Part 1): 2002 spectra at rocky site for 5% damping

Table 5.1: Preliminary data required for analysis of frame

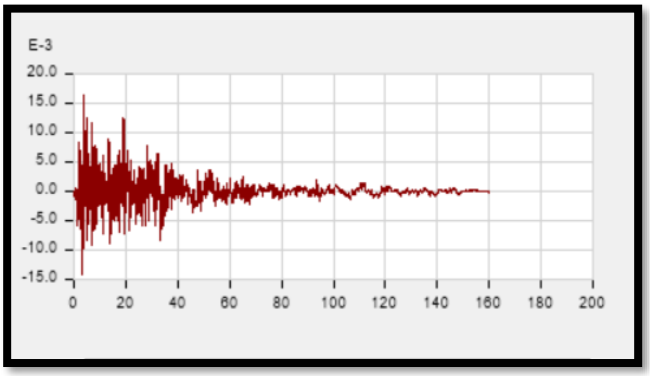
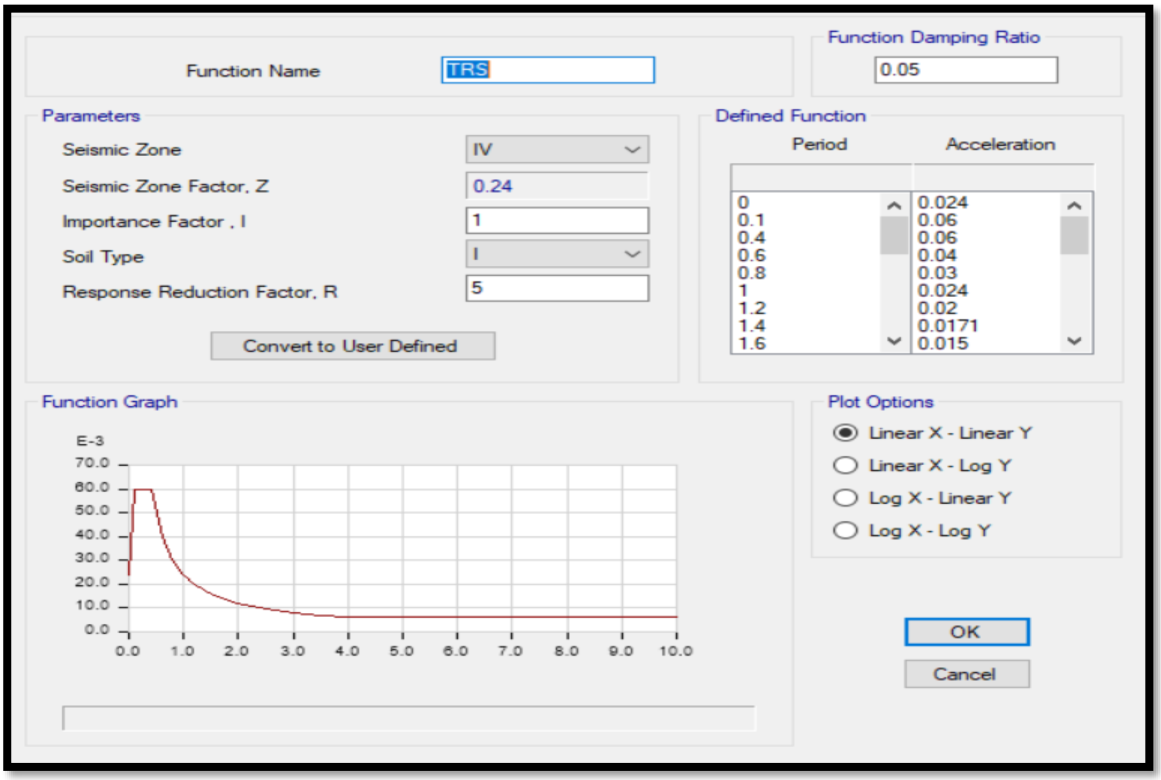


Fig 5.6: Earthquake record for the Analysis

Selection of Earthquake:
(Peer Ground Motion Database)

Station name: El Centro Array #9
Year: 1951
Earthquake name: Imperial Valley-03
Magnitude: 5.6
Damping ratio: 5%

Fig 5.7: Selection of Earthquake



Function Name: TRS

Function Damping Ratio: 0.05

Parameters

Seismic Zone: IV
Seismic Zone Factor, Z: 0.24
Importance Factor, I: 1
Soil Type: I
Response Reduction Factor, R: 5

Defined Function

Period	Acceleration
0	0.024
0.1	0.06
0.4	0.06
0.6	0.04
0.8	0.03
1	0.024
1.2	0.02
1.4	0.0171
1.6	0.015

Plot Options

● Linear X - Linear Y
○ Linear X - Log Y
○ Log X - Linear Y
○ Log X - Log Y

Fig 5.8: Target Response Spectrum

The concept of the target response spectrum (TRS) is utilized in structural engineering to define the desired or design-level response of a structure when subjected to ground motion during an earthquake. It presents a visual depiction of the highest anticipated response of a structure at different vibration periods or frequencies.

The development of the TRS typically involves conducting a seismic hazard analysis, which encompasses the examination of historical seismic data, geological information, and other relevant factors to determine the expected level of ground motion at a specific location. The TRS is established as a representation of the design criteria for the structure, considering factors like the desired safety level, structural significance, and intended purpose.

Typically, the TRS is represented by a graph that plots the spectral acceleration, denoting the maximum acceleration projected for a structure at various vibration periods. The horizontal axis of the graph corresponds to the periods or frequencies, while the vertical axis represents the spectral acceleration values. The TRS is commonly expressed as a percentage of the acceleration due to gravity (g), such as 5%, 10%, or 20% of g.

The shape of the TRS curve is derived from the characteristics of the expected ground motion at the specific site. It takes into account factors like the dominant frequencies of earthquake waves and site-specific amplification effects caused by local soil conditions. The TRS curve is formulated to ensure that the structure can adequately withstand the projected ground motion while maintaining satisfactory levels of performance and safety.

Engineers employ the TRS as a benchmark to design structures capable of withstanding the projected ground motion. They compare the response spectrum of the structure to the TRS to verify that the design aligns with the specified performance objectives. The structural design and detailing are adjusted as necessary to ensure that the structure's response remains within acceptable limits based on the provided TRS.

To summarize, the target response spectrum (TRS) is a visual representation of the highest projected response of a structure to ground motion during an earthquake. It is developed through a seismic hazard analysis and serves as the design criteria for the structure. Engineers utilize the TRS as a reference to design structures that can effectively withstand the projected ground motion while maintaining satisfactory levels of performance and safety.

MANUAL CALCULATION

Design seismic base shear, $V_B = A_h W$

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g} = \frac{0.24}{2}\frac{1}{5}1.842 = 0.0443$$

For $T_a = 0.5423 \Rightarrow \frac{S_a}{g} = \frac{1}{T_a} = 1.842$, *for rock site from* ***Figure 2 of IS 1893 (Part 1): 2002***

Design seismic base shear, $V_B = 0.0443 \times (230.43 \times 9.81) = 99.933$ kN

The design base shear (V_B) computed shall be distributed along the height of the building as per the expression,

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{i=1}^{n} W_i h_i^2}$$

where,

Q_i = Design lateral forces at floor i,
W_i = Seismic weights of the floor i,
h_i = Height of the floor i, measured from base, and
n = Number of stories

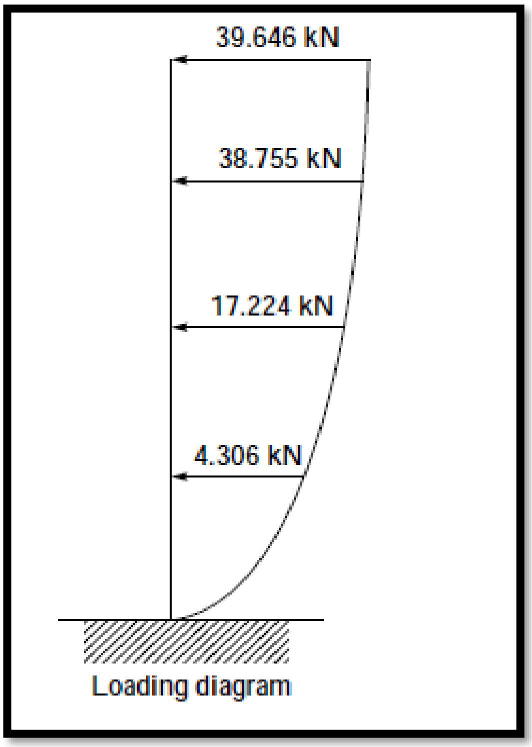
Using the Equation 18.1, base shear is distributed as follows:

$$Q_1 = V_B\left(\frac{W_1 h_1^2}{W_1 h_1^2 + W_2 h_2^2 + W_3 h_3^2 + W_4 h_4^2}\right)$$

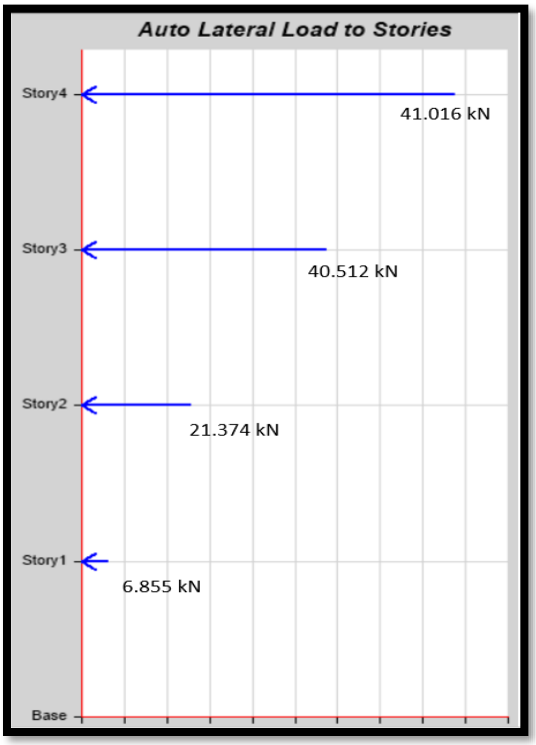
$$= 99.933\left[\frac{632.25 \times 3.5^2}{632.25 \times 3.5^2 + 632.25 \times 7^2 + 632.25 \times 10.5^2 + 363.82 \times 14^2}\right] = 4.306 \text{ kN}$$

Similarly,

$$Q_2 = 0.1724 \times 99.933 = 17.224 \text{ kN}$$
$$Q_3 = 0.3872 \times 99.933 = 38.733 \text{ kN}$$
$$Q_4 = 0.3967 \times 99.933 = 39.646 \text{ kN}$$



(Manually)



(Software)

Table 5.2: Equivalent static lateral load method

Story	**Elevation (m)**	**Location**	**X-Dir**
Story4	14	Top	39.646
Story3	10.5	Top	38.755
Story2	7	Top	17.224
Story1	3.5	Top	4.306
Base	0	Top	0

Table 5.3: Non-Linear Time History Analysis

Story	**Elevation (m)**	**Location**	**X-Dir**
Story4	14	Top	41.016
Story3	10.5	Top	40.512
Story2	7	Top	21.374
Story1	3.5	Top	6.855
Base	0	Top	0

Manually calculated results and software results shows

95% similar results

5.1.2 Structural Idealisation

Table 5.4: Structural data

Storeys	G+10
Plan Dimension	28m × 23m
Slab Thickness	0.2m
Beam Dimension	0.3m × 0.4m
Column Dimension on regular structure	0.5m × 0.5m
Column Dimension of irregular structure	0.48m × 0.48m and 0.52m × 0.52m
Shear wall thickness	0.15m
Live load on floor	3 KN/m2
Live load on roof	1.5 KN/m2
Concrete grade	M25
Rebar Grade	Fe415

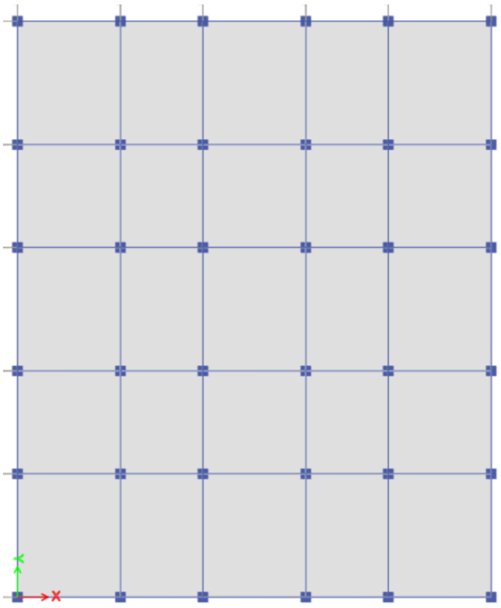


Fig 5.9: Structural plan

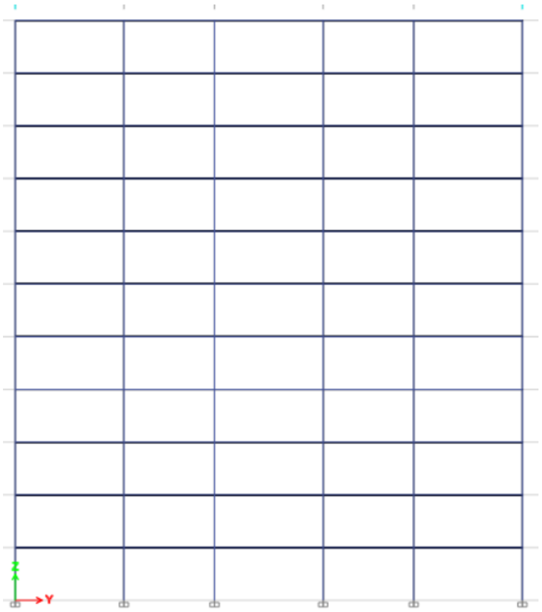


Fig 5.10: Elevated structure

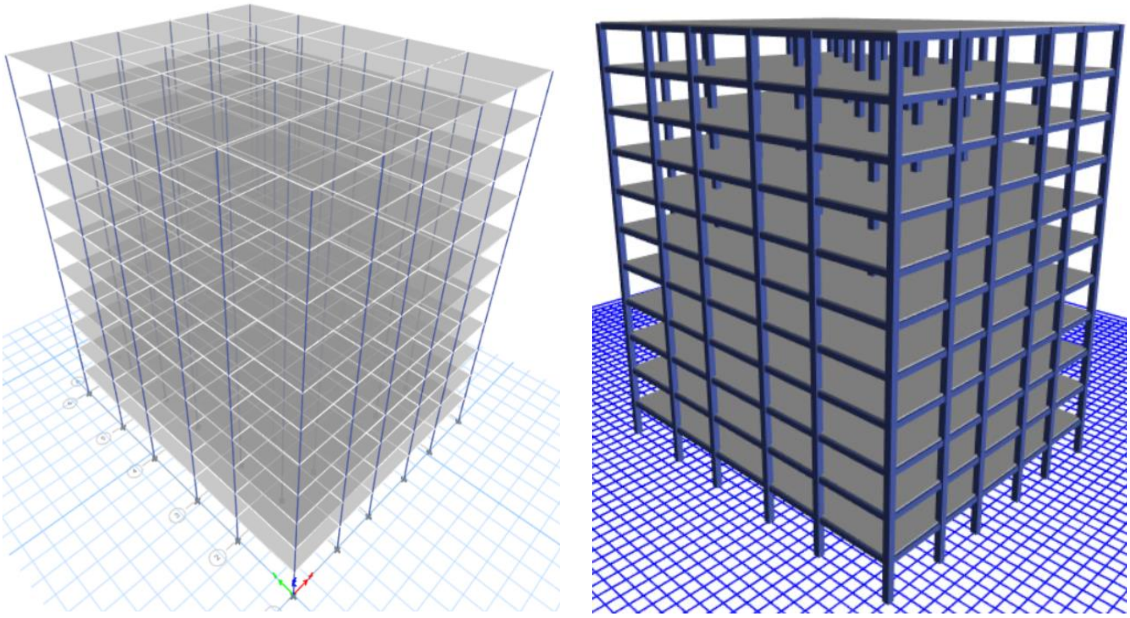
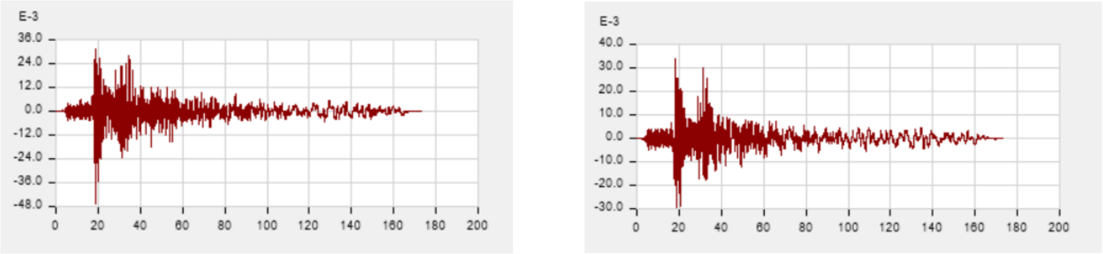


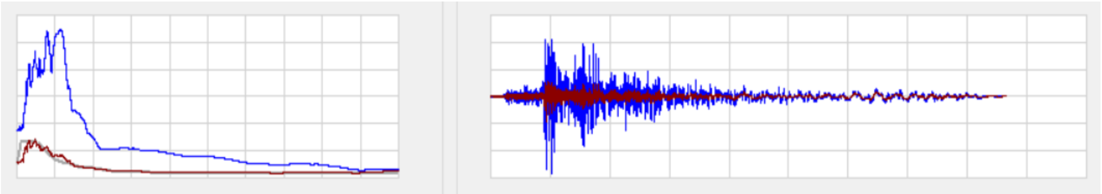
Fig 5.11: 3D view

5.1.3 Earthquake record

A. Single strong Earthquake – Single event



X Direction Y Direction



Spectral Matching

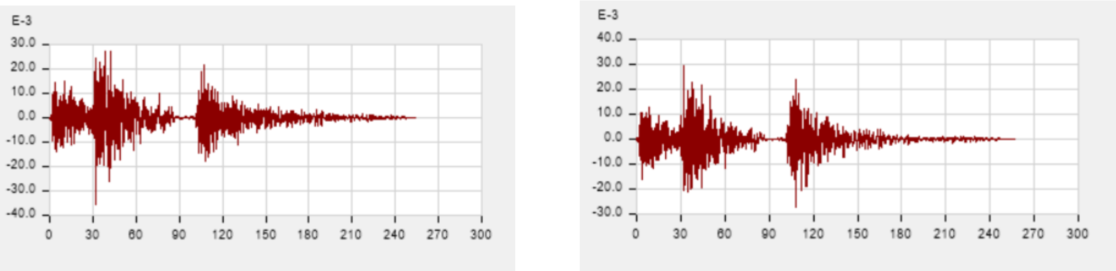
Fig 5.12**: Single Earthquake in X and Y direction**

Earthquake name	Magnitude	Year	Station name	Damping ratio
Denali, Alaska	7.9	2002	Anchorage - K2-05	5%

Table 5.5: Single Earthquake data

B. Repeated Earthquakes

Double event



X Direction

Y Direction

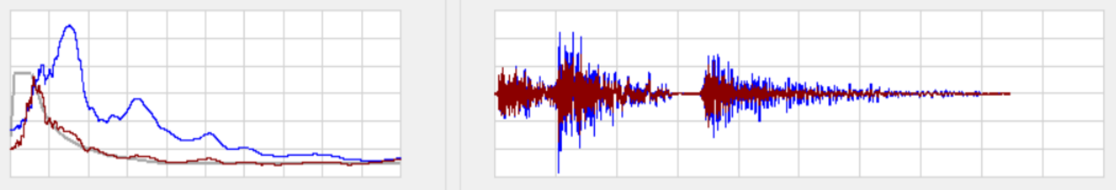
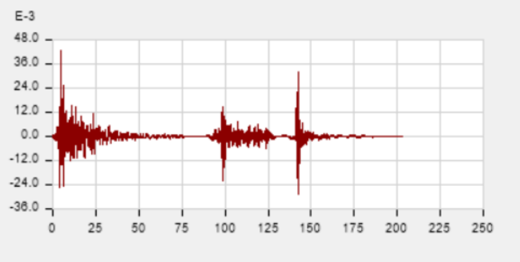


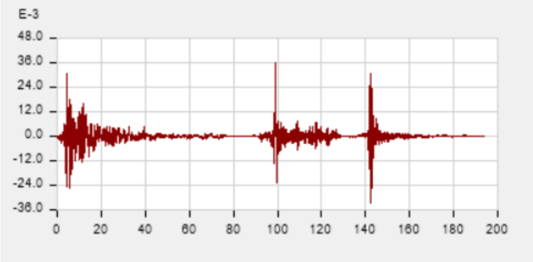
Fig 5.13: Double event earthquake in X and Y direction

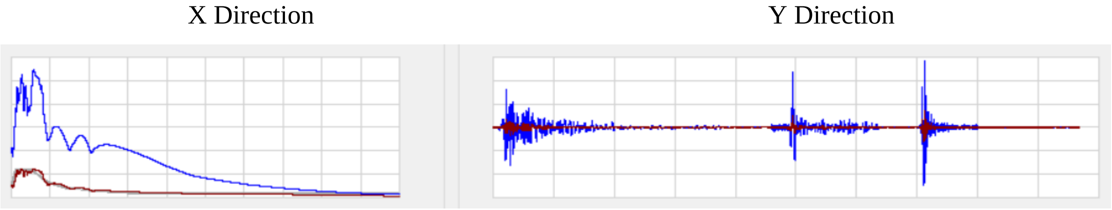
Table 5.6: Double event Earthquake data

Earthquake name	Magnitude	Year	Station name	Damping ratio
Managua_ Nicaragua-01	6.24	1972	Managua_ ESSO	5%
Imperial Valley-06	6.53	1979	Chihuahua	5%

Triple event







Spectral Matching

Fig 5.14: Double event earthquake in X and Y direction

Table 5.7: Triple event Earthquake data

Earthquake name	Magnitude	Year	Station name	Damping ratio
Northwest Calif-01	5.5	1938	Ferndale City Hal	5%
Imperial Valley-07	5.01	1979	Bonds Corner	5%
Helena_ Montana-01	6	1935	Carroll College	5%

The primary aim of this section is to comprehensively investigate the impact of repetitive earthquakes on structural response, with a specific focus on the accumulation of damage. Prior research in this field has been limited to analysing two-dimensional frames subjected to seismic excitation in a single horizontal direction. However, this study takes a distinct approach by simulating repeated earthquakes using a combination of ground motion in two directions, encompassing single, double, and triple events. Since actual seismic sequence records are not available, this paper solely concentrates on artificial sequences formed by logically combining real single events, maintaining a time interval of 100 seconds between double and triple events.

Repeated earthquakes, also referred to as earthquake sequences or aftershock sequences, occur when a mainshock (the initial large earthquake) is succeeded by a series of smaller earthquakes known as aftershocks. These aftershocks essentially represent the Earth's response to the redistribution of stress caused by the mainshock.

When an earthquake transpires, it releases accumulated strain energy that has built up along a fault line. However, the mainshock does not necessarily alleviate all of the accumulated stress in the surrounding rocks. Instead, it redistributes the stress along the fault and may trigger smaller movements or slip on adjacent or interconnected faults.

Here is a detailed explanation of the process:

1. Initial Mainshock: The earthquake sequence commences with a mainshock, typically the largest and most destructive earthquake in the sequence. The mainshock denotes the sudden release of accumulated stress along a fault line. It is commonly followed by a period of relative seismic quiescence.

2. Stress Redistribution: The mainshock alters the stress distribution in the rocks surrounding the fault. This redistribution of stress affects the neighbouring rocks and can reactivate or initiate slip along adjacent or interconnected faults.

3. Aftershocks: Aftershocks are smaller earthquakes that transpire in the vicinity of the mainshock. They result from the readjustment of stress caused by the mainshock. Aftershocks usually occur within hours, days, or weeks after the mainshock, although they can persist for months or even years, gradually decreasing in frequency and magnitude over time.

4. Omori's Law: Aftershocks generally adhere to a pattern known as Omori's Law. This empirical relationship, named after Fusakichi Omori, indicates that the rate of aftershocks diminishes with time. In general, the number of aftershocks decreases logarithmically as time progresses after the mainshock. However, the magnitude of aftershocks can vary, with larger aftershocks occurring less frequently.

5. Triggered Events: A mainshock can trigger earthquakes in regions far from the initial rupture zone. This triggering can transpire through stress transfer along fault systems or the propagation of seismic waves through the Earth's crust. These remotely triggered earthquakes are often termed secondary or triggered events.

6. Coulomb Stress Transfer: The mainshock has the ability to increase or decrease stress on neighbouring faults, depending on their orientation and proximity. If the stress is amplified, it can bring those faults closer to failure, augmenting the likelihood of additional earthquakes in the region.

7. Sequence Completion: As time elapses, the number and intensity of aftershocks decline. Eventually, the earthquake sequence reaches a point where the rate of seismic

activity returns to the background level, and aftershocks are no longer distinguishable from regular earthquakes.

5.1.4 Numerical analyses using ETABS 20

5.1.4.1 Comparison of torsional effect of irregular RC structure when subjected to single and multiple earthquakes for different cases

A. Mass irregularity within plan eccentricities

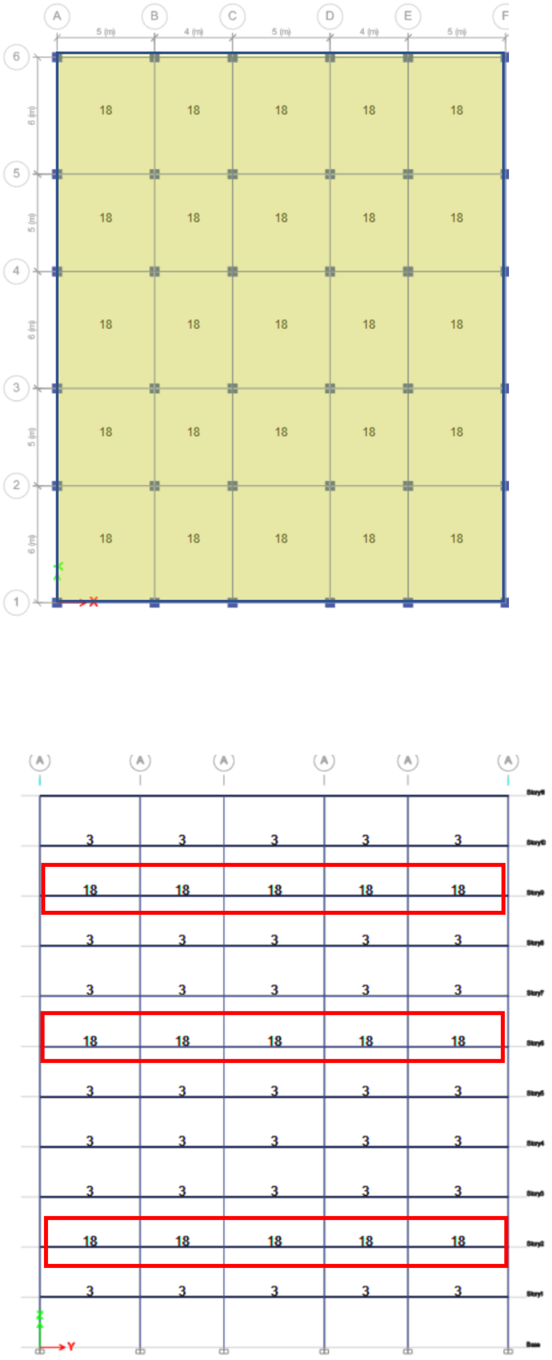


Fig 5.15: Type 1

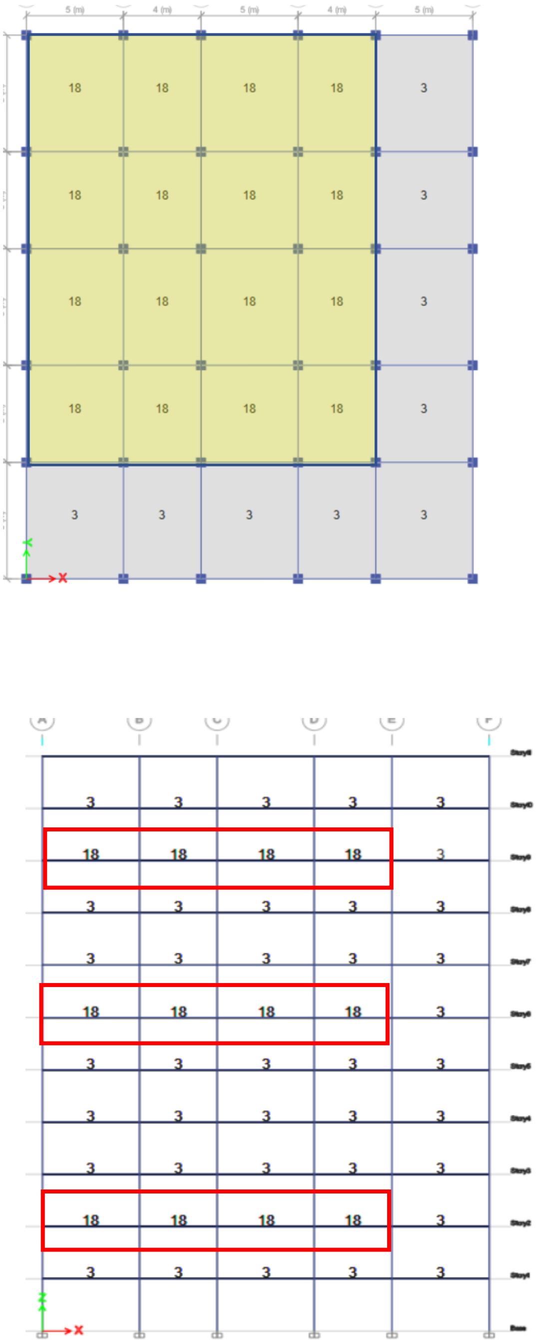


Fig 5.16: Type 2

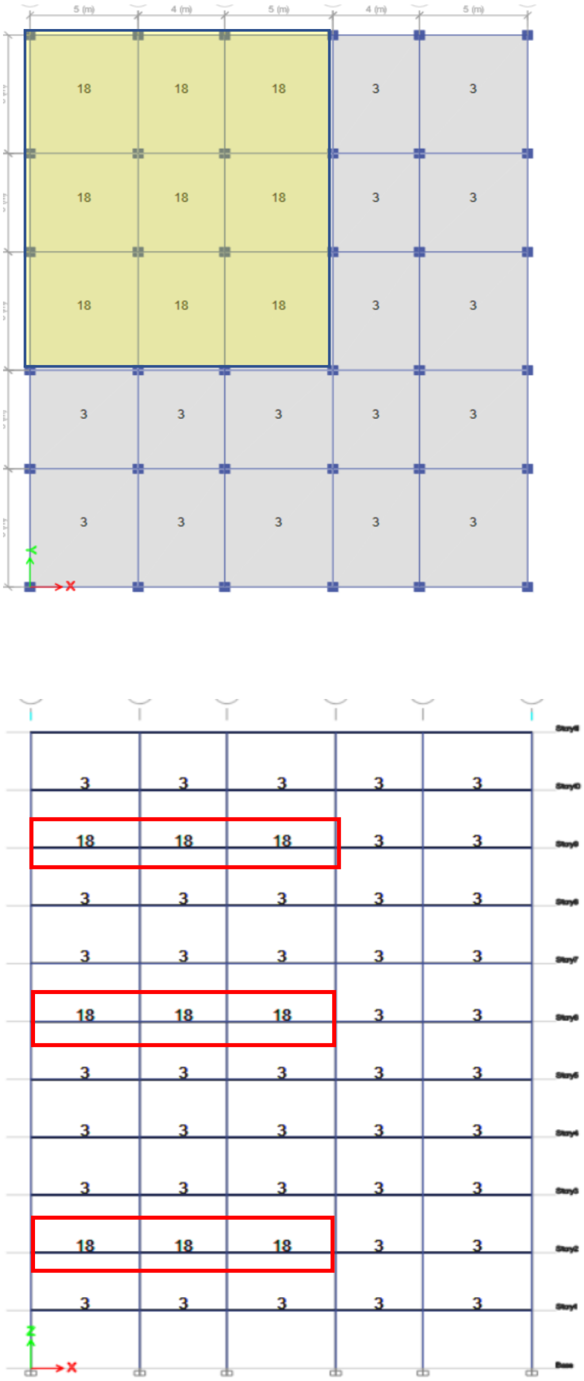


Fig 5.17: Type 3

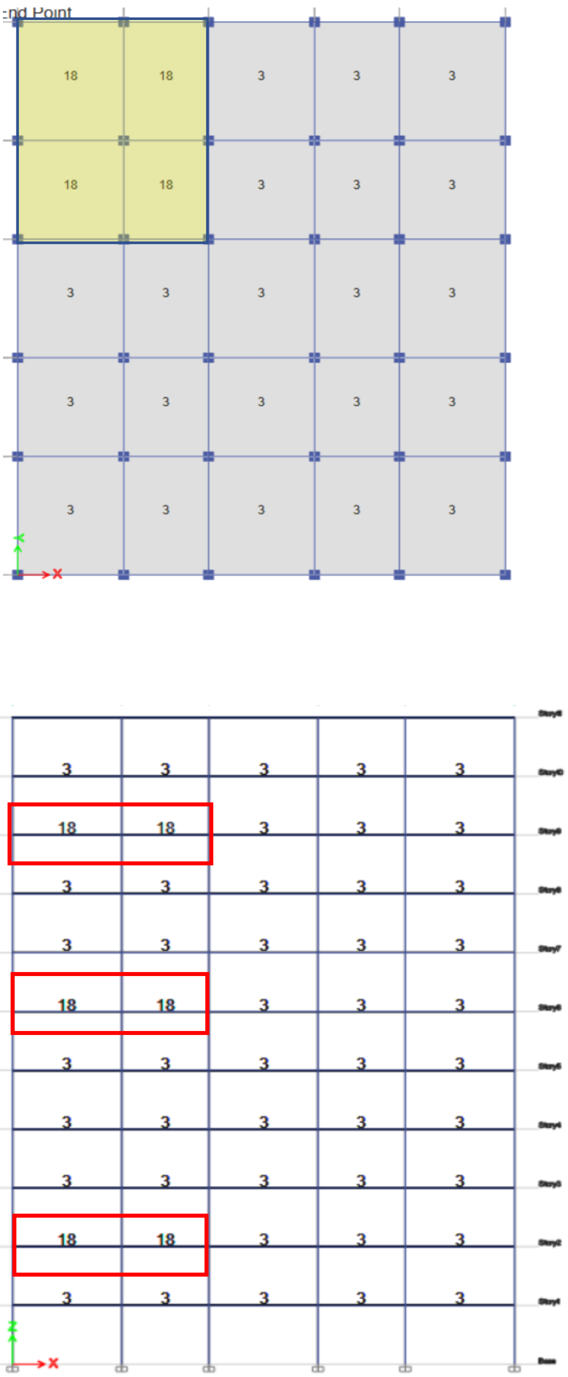


Fig 5.18: Type 4

As per the guidelines specified in IS 1893:2016, it is recommended that the mass of a specific storey should not exceed 1.5 times the mass of the storey immediately below it, resulting in a mass ratio of 1.5 between adjacent storeys. In order to introduce in-plan eccentricity, eccentricity, adjustments were made to the original mass density of the floor slab, which was initially set at 2500 kg/m³. These adjustments involved increasing the mass density in specific sections along the floor slabs, following three distinct patterns. This modification in the distribution of mass aided in achieving the desired in-plan eccentricity within the structure.

B. Stiffness irregularity within plan eccentricities

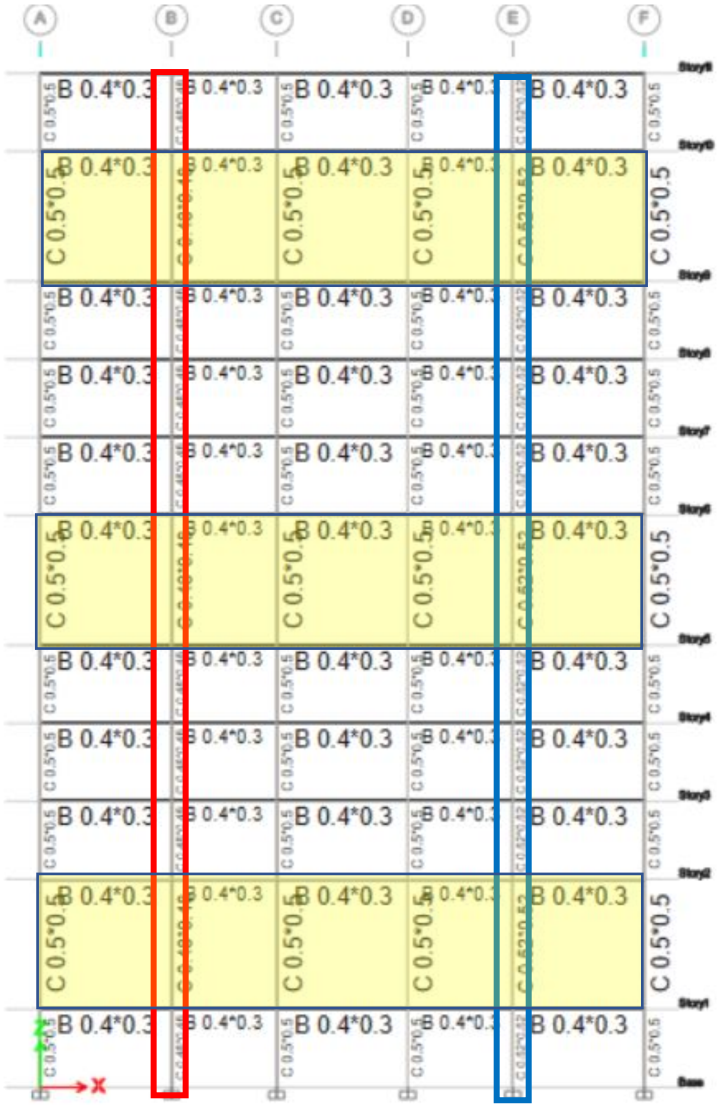


Fig 5.19: Type 1

🟥 Column 0.48m*0.48m

🟨 Soft storey of height 5m

🟦 Column 0.52m*0.52m

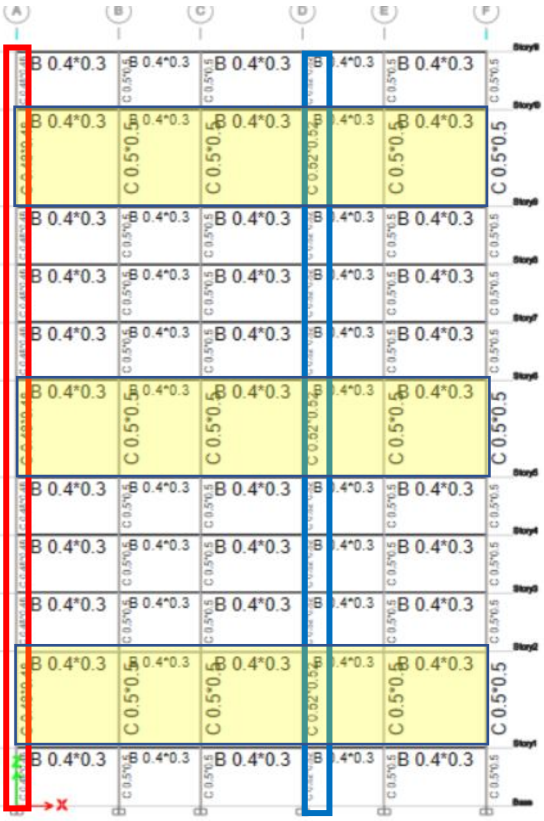


Fig 5.20: Type 2

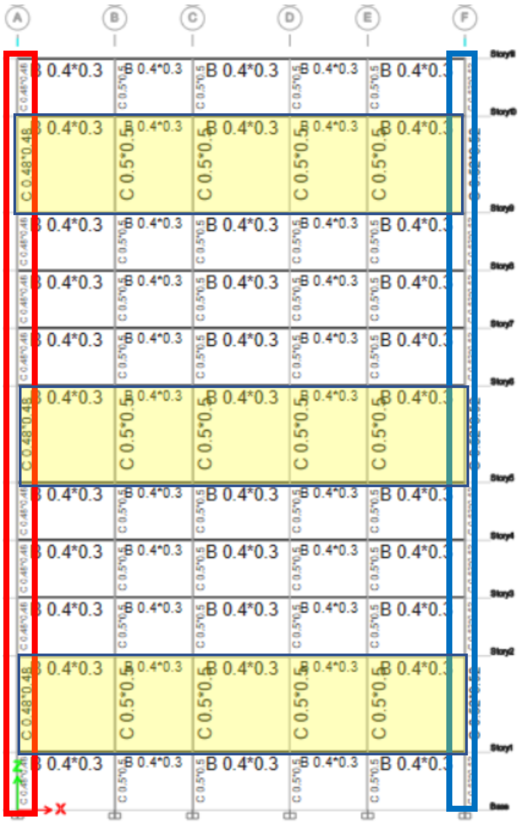


Fig 5.21: Type 3

In compliance with the specifications outlined in IS 1893:2016, the identification of a vertical stiffness irregularity, commonly referred to as a soft storey irregularity, occurs when the stiffness of a specific storey is less than that of the storey above it. To investigate the influence of in-plan stiffness eccentricity, a methodology was employed involving the systematic variation of column dimensions around a central Y axis while maintaining a constant centre of mass.

C. Mass and stiffness irregularities due to varying position of shear wall

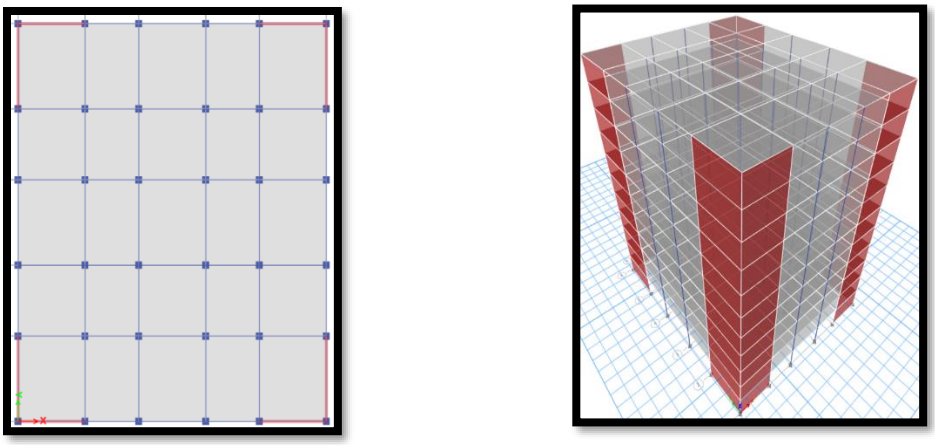


Fig 5.22: Type 1
(Symmetric Position)

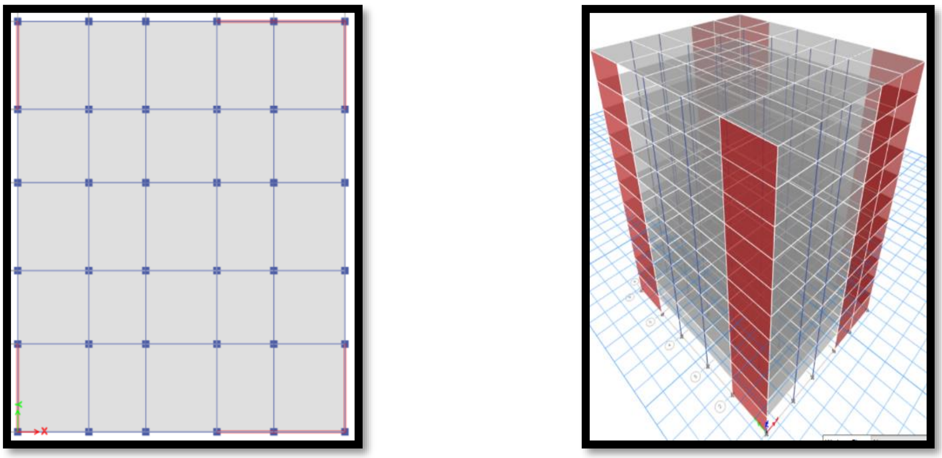


Fig 5.23: Type 2

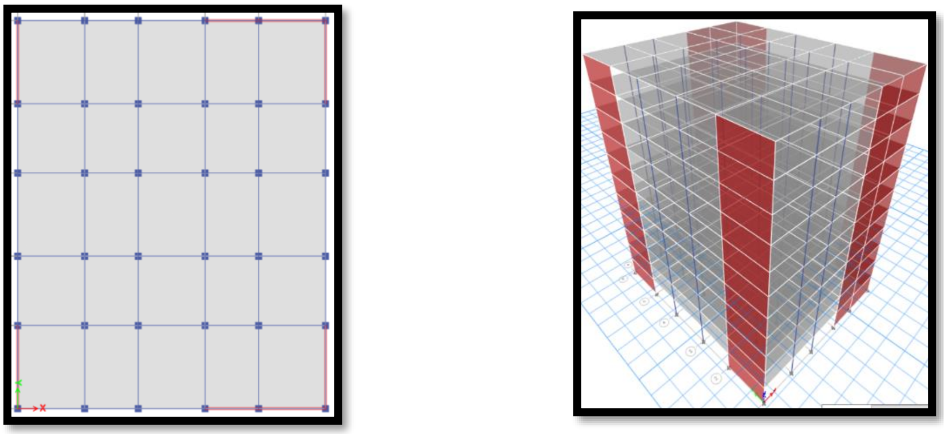


Fig 5.24: Type 3

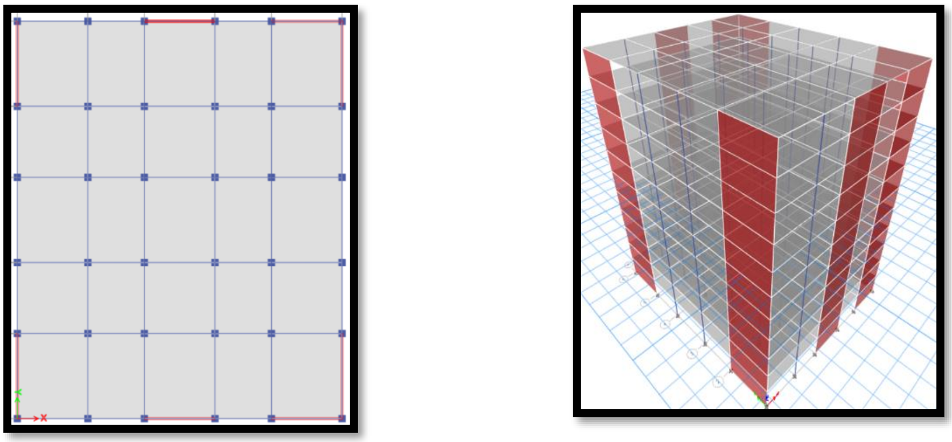


Fig 5.25: Type 4

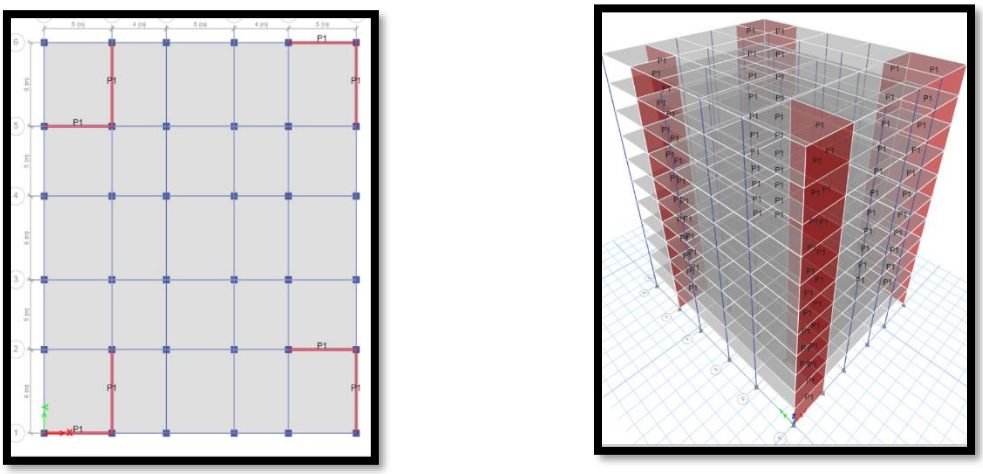


Fig 5.26: Type 5

To introduce eccentricity in the buildings, modifications were implemented to the positions and orientations of shear walls in the building layout. These adjustments resulted in changes to both the distribution of mass and stiffness, which were brought about by relocating the shear walls within specific areas. Shear walls with a thickness of 0.15 m were strategically placed at designated positions throughout the height of the building frames to incorporate the effect of in-plan eccentricity. It was assumed that the centres of gravity for each storey coincided with the geometric centres of the floor plans.

Shear walls were moved in a methodical manner, with the x- and y-directional shear walls being moved perpendicular to successive bays. These shear walls are referred to as "x walls" and "y walls," respectively. This method caused the building arrangement to be asymmetrical along one direction and eccentric in that same direction. These modifications were made in order to study the torsional behaviour of shear wall structures. The placement of one or two walls inside the building layout was changed in a single direction to produce a static eccentricity in the x-direction (es).

D. Results and Discussion

Torsional irregularity refers to the uneven distribution of a building's ability to resist torsional forces. It occurs when the centre of mass (CoM) and centre of rigidity (CoR) of the building are not aligned along the torsional axis.

Static eccentricity measures the difference between the CoM and CoR of a building when subjected to static loads. It quantifies the displacement or shift between these centres along the torsional axis. A building with a significant static eccentricity will exhibit a higher inclination to twist around its axis when subjected to external loads, making it more vulnerable to damage and failure.

In contrast, dynamic eccentricity gauges the difference between the CoM and CoR of a building under dynamic or seismic loads. It considers the displacement or shift between these centres along the torsional axis during seismic events. A building with substantial dynamic eccentricity will experience an uneven torsional response during earthquakes, potentially leading to increased torsional forces and a heightened risk of damage or collapse.

Both static and dynamic eccentricities play a crucial role in evaluating a building's torsional irregularity. Engineers and designers must ensure the proper alignment of the CoM and CoR along the torsional axis, while also ensuring that the static and dynamic eccentricities fall within acceptable limits. Various design techniques and analysis methods are employed to address torsional irregularities and minimize their impact on a building's structural integrity and safety.

In asymmetric building structures, torsional vibration develops as a result of the connection between the centre of mass (CM) and the centre of rigidity (CR). The eccentricity, which is the divergence between the lines through the centre of mass and the centre of rigidity or resistance, is used to express the degree of torsional irregularity in a structure. The positions of the centres of mass and stiffness at each floor level are compared to determine the static eccentricities (esi) for various layouts. Dynamic amplification must be taken into account because, when dynamic loading is used, the effect of eccentricity in irregular buildings is more pronounced than in the static load scenario. In accordance with IS 1893:2016, the design or dynamic eccentricity (e_{di}) at any given floor level i is calculated.

$$\boxed{\begin{aligned} e_{di} = 1.5\, e_{si} + 0.05b_i \\ e_{si} - 0.05b_i \end{aligned}}$$

Static and dynamic eccentricities are employed in the analysis and management of torsional irregularity in buildings. They aid in the detection of imbalances in the distribution of mass and stiffness, assess the response of the structure to static and dynamic loads, inform design decisions to mitigate irregularities, and ensure adherence to building codes and regulations. These measures are vital for comprehending structural behaviour, mitigating risks, and promoting the safety and integrity of buildings.

Table 5.8: Eccentricities for different cases

Sr no.	Cases	Static eccentricity	Dynamic eccentricity
1.	Combination of mass and stiffness Irr. Str		
	Type 1	0	1
	Type 2	0.0667	1.5
	Type 3	0.313	1.87
	Type 4	0.773	2.56
2.	Mass Irregular str		
	Type 1	0.02	1.05
	Type 2	0.066	1.5
	Type 3	0.2266	1.74
3.	Stiffness Irregular str		
	Type 1	0.71	1.87
	Type 2	0.24	1.16
	Type 3	0.48	1.52

As per IS 1893:2016, the Indian Standard Code for earthquake-resistant design of structures, torsional irregularity in buildings refers to an uneven distribution of resistance against torsional forces throughout the structure. This irregularity can be attributed to factors such as uneven mass or stiffness distribution, eccentricity of vertical elements, and non-uniform floor plans.

The torsion irregularity coefficient (N_t) is defined as the ratio between the maximum displacement (Dmax) at one end of a floor and the minimum displacement (Dmin) at the other end in the same direction. If the value of N_t surpasses a specified threshold, it indicates the presence of torsional irregularity in the building.

$$N_t = Dmax/Dmin$$

According to the code, torsional irregularity is classified into the following categories:

1. Regular buildings: Buildings with N_t values equal to or less than 1.5 are considered regular, indicating the absence of significant torsional irregularity.

2. Torsionally irregular buildings: Buildings with N_t values exceeding 1.5 are classified as torsionally irregular. These buildings exhibit an uneven distribution of torsional forces and require special attention during the design and analysis stages.

IS 1893:2016 provides additional guidance when N_t exceeds a higher threshold of 2. In such cases, it recommends a comprehensive revision of the entire building configuration, including the arrangement of vertical and horizontal elements, to ensure adequate resistance against torsional forces.

To efficiently handle torsional irregularity and improve the seismic performance of structures, the code incorporates design considerations, load combinations, and analysis procedures. It highlights the need for precise modelling and analytical methods to accurately capture torsional impacts and ensure the structural integrity of structures during seismic occurrences.

Table 5.9: Torsional irregularity for single event

Sr no.	Cases	Single Event		
		Max Disp. at one end (Dmax in mm)	Min Disp. At other end (Dmin in mm)	N= Dmax/Dmin
1	Regular str	0.154	0.153	1.006
2	Mass Irregular str			
	Type 1	8.056	6.15	1.31
	Type 2	10.32	7.121	1.45
	Type 3	8.897	6.012	1.48
	Type 4	9.19	6.089	1.51
3	Stiffness Irregular str			
	Type 1	10.446	6.941	1.505
	Type 2	9.498	6.596	1.44
	Type 3	10.134	6.894	1.47
4	Combination of mass and stiffness Irr. Str			
	Type 1 (Symmetric Position)	6.7	6.5	1.0307692
	Type 2	6.31	4.04	1.563
	Type 3	7.04	4.69	1.503
	Type 4	6.116	4.0	1.529
	Type 5	6.4	3.76	1.7

Table 5.10: Torsional irregularity for double event

Sr no.	Cases	Double Event		
		Max Disp. at one end (Dmax in mm)	Min Disp. At other end (Dmin in mm)	N= Dmax/Dmin
1	Regular str	0.895	0.895	1
2	Mass Irregular str			
	Type 1	8.91	6.6	1.35
	Type 2	11.657	7.93	1.47
	Type 3	10.213	6.791	1.504
	Type 4	10.396	6.831	1.522
3	Stiffness Irregular str			
	Type 1	11.355	7.52	1.51
	Type 2	10.47	7.174	1.46
	Type 3	11.09	7.447	1.49
4	Combination of mass and stiffness Irr. Str			
	Type 1 (Symmetric Position)	5.77	5.35	1.078505
	Type 2	7.1	4.152	1.71
	Type 3	7.34	4.4	1.67
	Type 4	7.3	4.2	1.738095
	Type 5	7.7	4.20	1.83

Table 5.11: Torsional irregularity for triple event

Sr no.	Cases	Triple Event		
		Max Disp. at one end (Dmax in mm)	Min Disp. At other end (Dmin in mm)	N= Dmax/Dmin
1	Regular str	2.6	2.6	1
2	Mass Irregular str			
	Type 1	10.986	8.789	1.25
	Type 2	14.019	10.086	1.39
	Type 3	12.29	8.418	1.46
	Type 4	12.71	8.535	1.49
3	Stiffness Irregular str			
	Type 1	15.784	10.622	1.486
	Type 2	14.173	10.271	1.38
	Type 3	15.248	10.516	1.45
4	Combination of mass and stiffness Irr. Str			
	Type 1 (Symmetric Position)	14.18	13.76	1.03052326
	Type 2	12.7	8.41	1.51
	Type 3	20.77	14.04	1.48
	Type 4	15.8	10.6	1.49
	Type 5	15.2	9.44	1.61

The type 6 model from case 4, which involves mass and stiffness irregularities due to the varying position of shear walls, represents the most susceptible scenario in terms of torsional irregularity.

5.1.4.2 Comparison between different techniques to reduce the Torsional Irregularity of the most vulnerable case

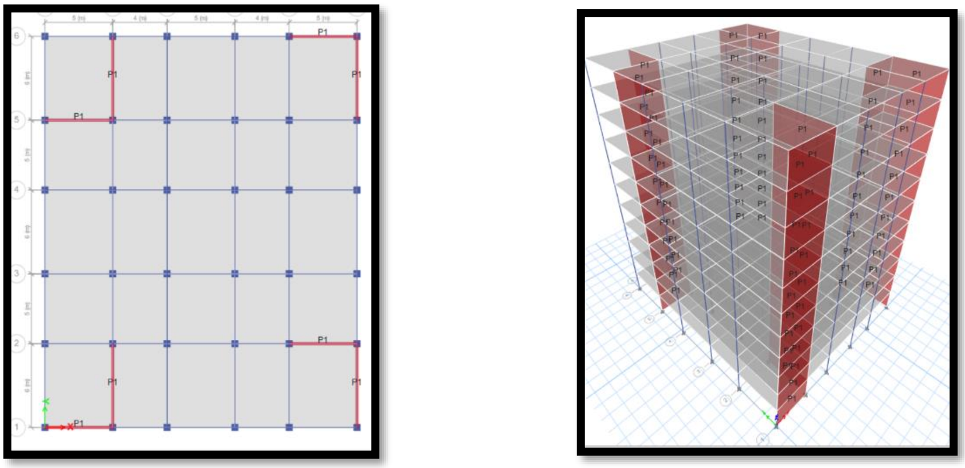
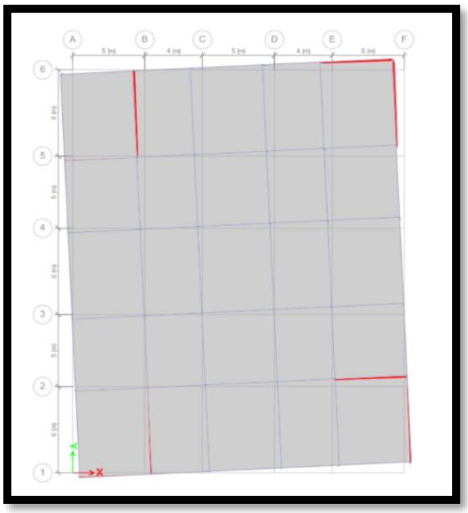


Fig 5.27: Case 4 – Type 5 (Most vulnerable case)

The most critical case of torsional irregularity occurs when the shear wall is positioned variably, leading to a combination of mass and stiffness irregularities and an eccentricity within the building's plan. This asymmetric placement of the shear wall amplifies the torsional response, making it the most vulnerable scenario in terms of torsional irregularity.



$U_{max} = 3.4$ mm

$U_{min} = 1.85$ mm

$N = 1.83$

A. Resizing and changing the orientation of column

To address torsional irregularity in a structure, effective strategies involve resizing and changing the orientation of columns. In this technique torsional effects are evaluated by conducting a comprehensive analysis of the structure to assess the extent of torsional irregularity and identify areas where it is most pronounced. This analysis provides valuable insights into the necessary changes for column resizing and reorientation.

The columns that significantly contribute to torsional irregularity are identified and by resizing these columns through dimension adjustments or additional reinforcement, the redistribution of torsional forces can be achieved, leading to a more even distribution across the structure. It is crucial to base these adjustments on accurate structural calculations and design requirements.

Altering the orientation of columns can effectively minimize torsional irregularity. Aligning columns with the building's principal axes or adopting symmetrical patterns enhances the distribution of torsional forces. This may involve repositioning columns or adjusting their angles to promote structural symmetry. Ensure that the column resizing and reorientation plans align with a comprehensive structural analysis. The analysis should consider the updated column sizes and orientations to evaluate the overall stability and integrity of the structure.

By implementing these measures, torsional irregularity in the structure can be reduced, leading to enhanced stability and seismic performance. It is essential to consider the specific project requirements and limitations while consulting with professionals to determine the most suitable approach for each situation.

If certain columns are experiencing excessive loads, one approach to address this issue is to redistribute the forces in order to achieve a more balanced system. This can be accomplished by modifying the path through which lateral loads are transmitted, which may involve implementing transfer beams, shear walls, or bracing systems. Additionally, when identifying columns that require resizing, it is essential to consider several factors. These include evaluating the material properties of the columns, such as their strength and stiffness. Furthermore, determining the expected design loads that the columns need to withstand, encompassing both gravity loads and lateral loads, is crucial. Lastly, it is important to analyse the column spacing and arrangement to ensure that the new sizes align with architectural requirements and do not negatively impact the functionality of the space.

<u>Resized Column size</u>:

- ⭕ - 750 mm × 750 mm
- 🟡 - 650 mm × 650 mm

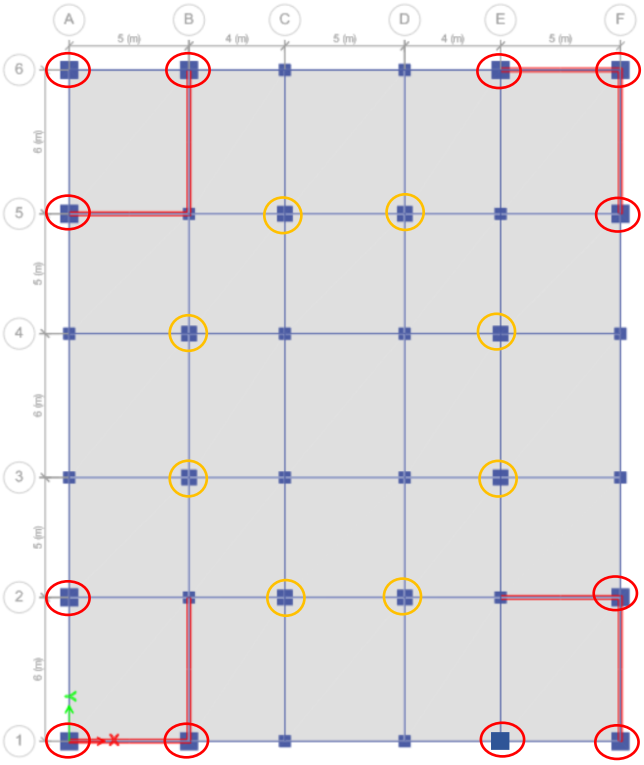


Fig 5.28: Plan layout with resizing and reorientation of columns

B. Lead Rubber base isolation system

Lead rubber bearings (LRBs) are a specific type of base isolation system utilized for safeguarding structures and buildings against the impact of seismic forces. The design of LRBs involves the arrangement of rubber layers positioned between steel plates, all enclosed within a steel housing. These bearings are distinguished by the insertion of lead plugs within the rubber layers, contributing to enhanced energy dissipation and damping properties, lending the system its name.

The primary function of LRBs is to undergo deformation and absorb energy during seismic events, thereby isolating the structure from the ground motion. When subjected to seismic forces, the rubber layers within LRBs undergo deformation, permitting the independent movement of the building relative to the ground. Consequently, the transmission of forces to the superstructure is reduced.

LRBs offer several notable advantages, including:

Energy Dissipation: LRBs exhibit the ability to absorb a significant amount of energy during seismic events owing to the hysteresis behaviour of the rubber material. This energy dissipation capability effectively mitigates the transmitted forces and safeguards the structural integrity.

Large Displacement Capacity: LRBs possess a substantial displacement capacity, enabling significant lateral movement of the superstructure when confronted with seismic activity. This capacity facilitates accommodating the building's response to seismic forces and minimizing potential damage.

Reliability: LRBs have a longstanding history of extensive utilization, proving their reliability and performance in mitigating the effects of seismic events.

Maintenance: LRBs typically necessitate minimal maintenance since the rubber layers are adequately protected within the enclosing steel housing. Nonetheless, periodic inspections are advisable to ensure their ongoing functionality.

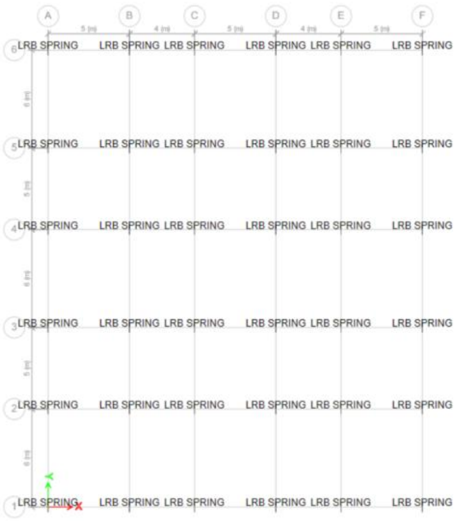


Fig 5.29: Structural Plan

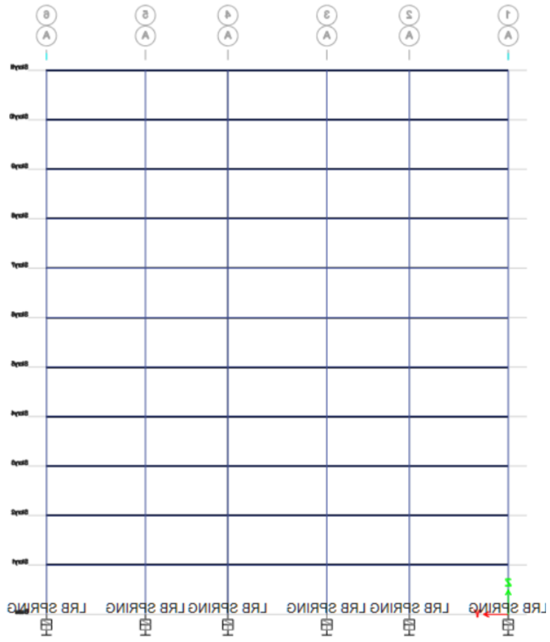


Fig 5.30: Elevated structure

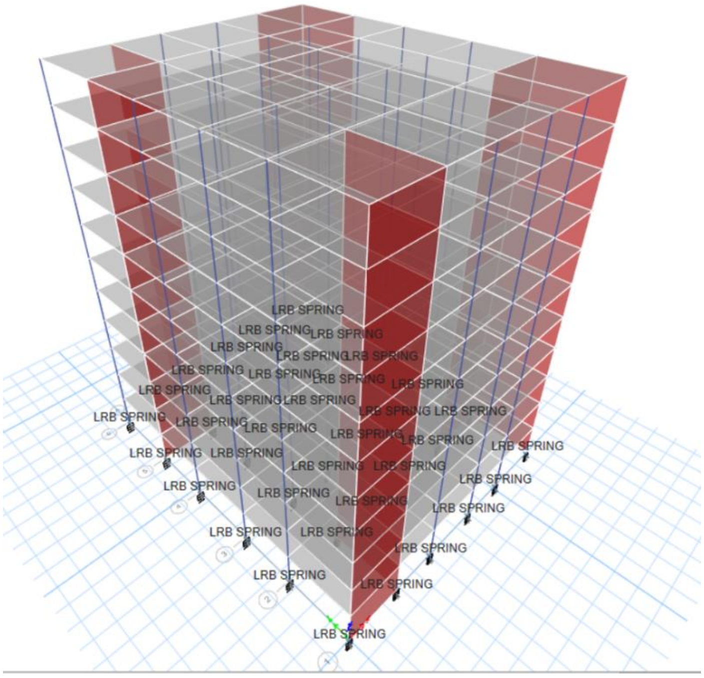


Fig 5.31: 3D Structure

The primary objective of base isolation systems is to mitigate the impact of seismic forces on structures by separating them from the ground. Although these systems are not explicitly designed to address torsional irregularity, they can indirectly assist in minimizing torsional effects within a structure by promoting a more uniform dispersion of lateral forces. Here's how base isolation systems can potentially aid in reducing torsional irregularity:

1. Enhanced Structural Stability: Base isolation systems enhance the overall stability of a structure during seismic events by diminishing the transmission of lateral forces to the superstructure. By reducing the differential forces acting on various sections of the building, the potential for torsional irregularity can be diminished.

2. Increased Global Structural Flexibility: Base isolation systems augment the flexibility and displacement capacity of the structure. This heightened flexibility enables the building to respond uniformly to lateral loads and diminishes the likelihood of localized stiffness variations that could result in torsional irregularity.

3. Improved Energy Dissipation: Base isolation systems incorporate mechanisms for energy dissipation, such as friction or rubber damping, which absorb and dissipate seismic energy. By efficiently dissipating energy, these systems help dampen vibrations and decrease the likelihood of torsional effects caused by imbalanced forces.

4. Balancing Mass and Stiffness: Base isolation systems involve a meticulous evaluation and redistribution of the structure's mass and stiffness. During the design process, emphasis is placed on achieving a more balanced distribution of mass and stiffness along different axes, thereby minimizing torsional irregularity.

While base isolation systems can indirectly contribute to reducing torsional irregularity, it is essential to consider specific measures that directly target torsional effects. These measures may include designing for symmetry in the floor plan and elevation, incorporating torsional bracing or moment frames, and employing appropriate structural analysis techniques to evaluate and address torsional irregularity.

Table 5.12: Input values in Etabs

Rotational inertia	0.016603 kN/m
For U1 Effective stiffness	1175418.57 kN/m
For U2 and U3 Effective stiffness	1175.42 kN-m
For U2 and U3 Effective Damping	0.05
For U2 and U3 Distance from End-J	0.00318 m
For U2 and U3 Stiffness	10831 kN/m
For U2 and U3 Yield Strength	34.70 kN

C. Friction viscous Damping system

Friction viscous dampers (FVDs) are utilized in structural engineering to counteract the impact of seismic forces on buildings and other structures, offering an effective means of energy dissipation. FVDs incorporate a combination of friction and viscous damping to absorb and dissipate energy.

An FVD consists of two key components: a sliding interface and a viscous fluid mechanism. The sliding interface typically comprises steel plates or a sliding mechanism featuring frictional elements. The viscous fluid mechanism involves a chamber filled with a viscous fluid, such as oil.

When subjected to lateral forces during a seismic event, the relative movement between the sliding interface components generates frictional forces. These frictional forces convert the kinetic energy of the structure into heat, resulting in energy dissipation and diminishing the overall response of the structure to the seismic forces.

In addition to the frictional element, FVDs also incorporate a viscous damping mechanism. The presence of viscous fluid in the damper chamber creates resistance to the movement of the sliding interface components, leading to further energy dissipation.

This viscous damping component contributes to reducing the structure's response to seismic forces.

FVDs prove effective in reducing the amplitude and duration of vibrations within structures, thereby enhancing their seismic performance. These dampers can be installed in various locations within a structure, such as between floors or strategically along lateral load-resisting elements.

The design of FVDs takes into account crucial factors such as the required damping coefficient, desired structural response, and anticipated seismic forces. Qualified engineers carefully design and install these devices in adherence to appropriate design guidelines and local building codes.

FVDs find widespread usage in both new construction and retrofitting projects, bolstering the seismic resilience of structures. By improving safety and safeguarding against potential damage during seismic events, FVDs contribute significantly to the overall structural integrity.

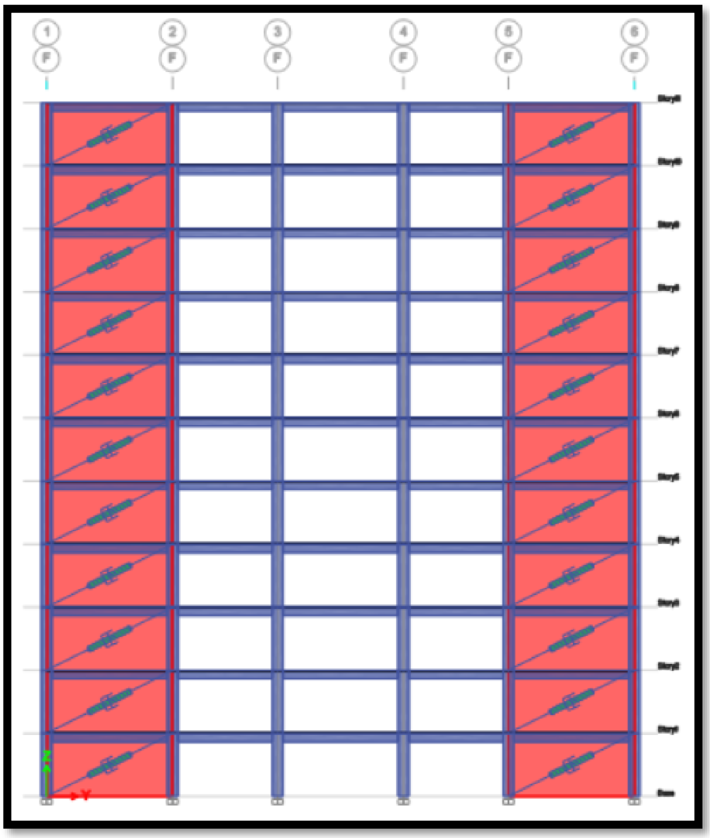


Fig 5.32: Elevated structure

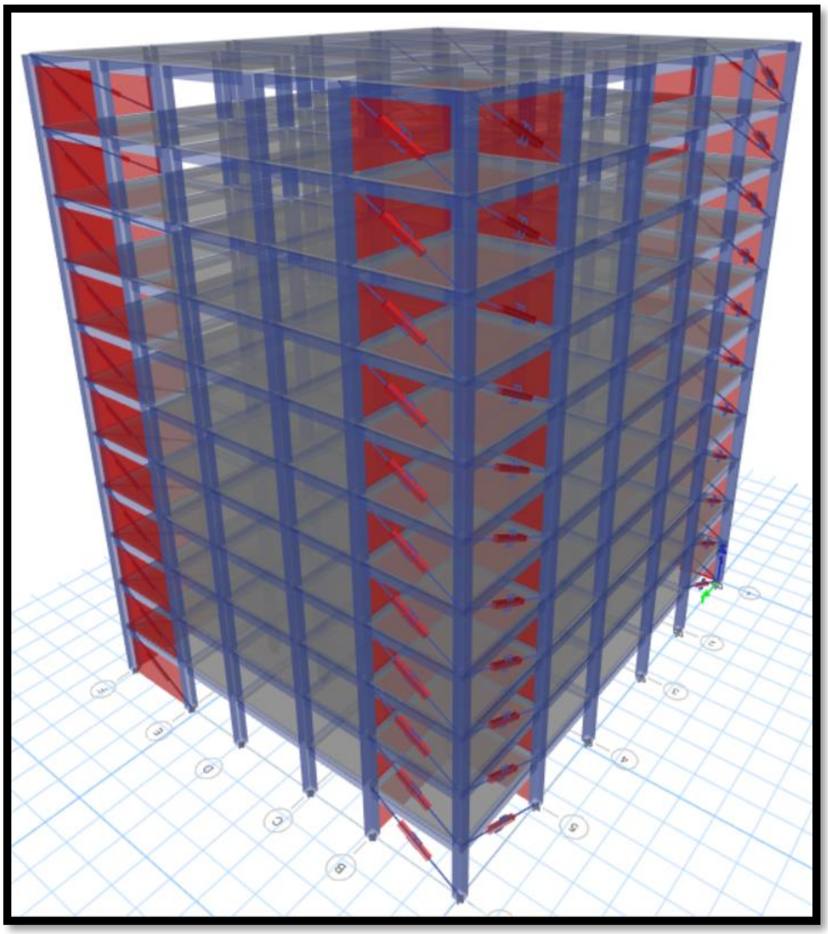


Fig 5.33: 3D structure

Table 5.13: Properties of friction viscous damper

Capacities force (kN)	500
Taylor device model number	17130
Spherical bearing bore diameter (mm)	50.80
Mid stroke length (mm)	997
Stroke (mm)	±100
Clevis thickness (mm)	55
Maximum clevis width (mm)	127
Clevis depth (mm)	102
Bearing thickness (mm)	44
Maximum cylinder diameter (mm)	150
Weight (kg)	98

To mitigate torsional irregularities in structures, dampers can be employed to dissipate energy and minimize vibrations. Torsional irregularities arise from imbalances or uneven forces that induce twisting or rotation around the vertical axis of a structure. These irregularities can lead to excessive torsional vibrations, compromising the structure's stability and performance.

Several dampers are commonly utilized to address torsional irregularities:

Tuned Mass Dampers (TMD): TMDs consist of a mass connected to a structure via springs and dampers. By tuning the mass to match the structure's natural frequency, TMDs counteract torsional vibrations by oscillating out of phase with the structure's motion. This reduces torsional irregularities and suppresses vibrations.

Viscous Dampers: Viscous dampers comprise a piston and cylinder filled with a viscous fluid (e.g., oil). When torsional vibrations occur, the fluid within the damper generates resistance, dissipating energy and reducing vibration amplitude.

Hysteresis Dampers: Hysteresis dampers leverage materials exhibiting hysteresis for energy dissipation. Typically constructed from materials like steel or rubber, these dampers undergo energy loss during cyclic loading. As torsional vibrations arise, hysteresis dampers absorb energy, diminishing torsional irregularities.

Torsional Viscous Dampers: Tailored specifically for addressing torsional irregularities, these dampers resemble regular viscous dampers but are optimized for torsional motion. Torsional viscous dampers impede torsional vibrations by providing resistance, minimizing irregularities in the structure.

During seismic events, friction viscous dampers (FVDs) can be implemented as an effective approach to mitigate torsional irregularities in structures. FVDs are primarily utilized for energy dissipation and reducing the overall structural response to seismic forces, indirectly addressing torsional effects. Here's how FVDs can potentially contribute to diminishing torsional irregularity:

Vibration Damping: FVDs are engineered to dissipate energy by employing frictional and viscous damping mechanisms. When seismic forces induce torsional motion, FVDs absorb and dissipate energy, thereby reducing the amplitude and duration of torsional vibrations.

Enhanced Structural Stiffness: Strategically incorporating FVDs within a structure can modify its overall stiffness characteristics. FVDs offer additional lateral stiffness in specific directions, aiding in balancing the torsional response and minimizing irregularities.

Force Redistribution: FVDs assist in uniformly distributing lateral forces throughout the structure. By absorbing and dissipating energy, FVDs reduce force concentration that could lead to torsional irregularities, promoting a more equitable distribution of forces across different areas of the building.

Increased Damping Ratios: FVDs contribute to elevating the damping ratios of the structure. Higher damping ratios enhance the effectiveness of vibration damping, thereby reducing the potential for torsional effects arising from imbalanced forces.

To minimize the torsional response of a structure, a viable solution is the implementation of a friction viscous damper. This damper combines friction and viscous damping mechanisms to dissipate energy and alleviate torsional vibrations. Its construction typically involves stacked steel plates that are compressed together using a preloaded spring. When torsional vibrations occur, the movement between the plates generates frictional forces, which convert mechanical energy into heat, thereby dissipating energy. Furthermore, the interstitial spaces between the plates are filled with a viscous fluid, such as silicone oil. This fluid enhances damping by exerting resistance against the relative motion of the plates, thereby further reducing the torsional response.

The benefits of friction viscous dampers for reducing torsional response include:

Effective Energy Dissipation: The combination of frictional forces and viscous damping properties in this damper facilitates efficient energy dissipation, leading to a reduction in the amplitude of torsional vibrations.

Adjustable Performance: The damper's performance can be customized by modifying the preload of the spring or altering the properties of the viscous fluid. This adaptability allows for optimal tuning based on the specific requirements and characteristics of the structure.

Compact Design: Friction viscous dampers have a relatively compact design, enabling easy integration into existing structures or inclusion in the design of new structures without the need for significant modifications.

Long-Term Durability: The materials used in friction viscous dampers, such as steel plates and silicone oil, are highly durable and resistant to degradation over time. This ensures the long-term effectiveness and reliability of the damper.

D. Results and discussions

T1 - Case 4 Type 5 (Most vulnerable case)

T2- Resizing and changing the orientation of column

T3- Lead rubber Base Isolation system

T4- Friction viscous damping system

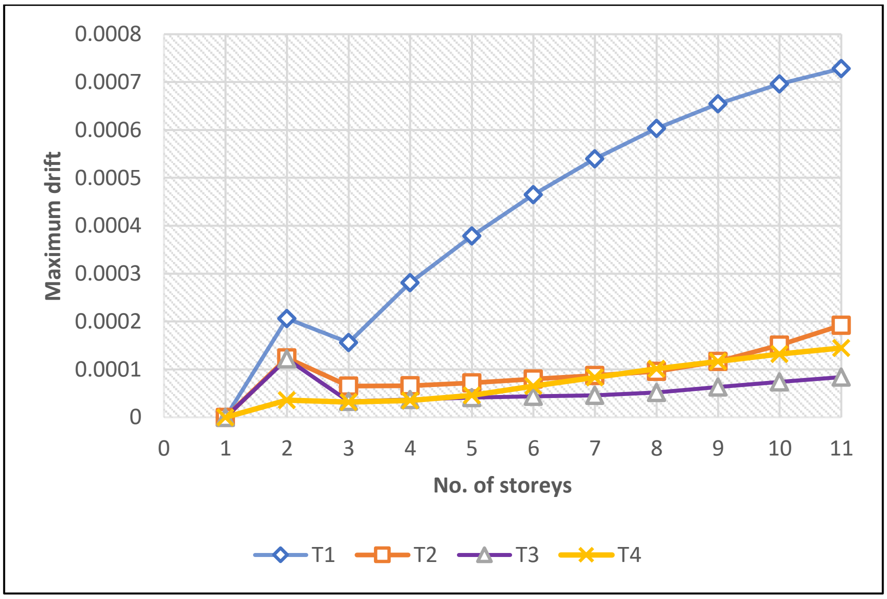


Fig 5.34: Maximum drift vs No. of storeys

Increasing the dimensions of columns can enhance their stiffness and strength, leading to improved resistance against lateral forces and a decrease in story drift. By carefully sizing the columns, the structure becomes more capable of withstanding lateral loads, resulting in reduced deformations. Altering the orientation of columns can also impact the overall stiffness and distribution of lateral forces within the structure. By strategically positioning columns in areas subjected to higher lateral load demands, such as corners or irregular geometries, the structure gains better resilience against lateral displacements, thus minimizing story drift. Precise column placement and alignment contribute to improved lateral load paths, enhancing the overall stability of the structure.

Another technique to reduce story drift is base isolation, which involves inserting a flexible layer or isolators between the building and its foundation. This method effectively isolates the structure from ground motion, thereby reducing the transmission of seismic forces to the building. By implementing base isolation, lateral displacements and subsequent story drift can be significantly decreased, promoting structural integrity.

Additionally, the utilization of damping devices, such as viscous dampers, within a building aids in absorbing and dissipating energy during seismic events. These devices mitigate vibrations and dampen the amplitude of motion, resulting in a reduction in story drift. It's important to note that these techniques are distinct and offer varying benefits in minimizing story drift, and their implementation depends on factors such as the specific structural requirements, site conditions, and adherence to applicable building codes.

By employing these three techniques, a noticeable decrease in story drift can be achieved compared to the drift observed in the most vulnerable scenario. Among the techniques, the installation of base isolation in the building yields the minimum observed drift, followed by the implementation of the friction viscous damping system. These techniques effectively mitigate the lateral displacements and minimize story drift, thereby enhancing the structural stability and performance of the building.

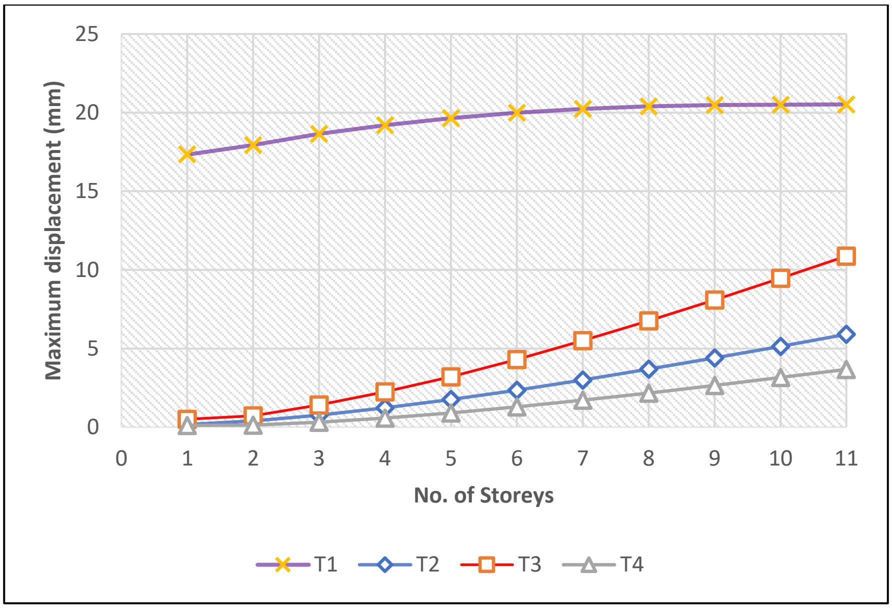


Fig 5.35: Maximum displacement vs No. of storeys

The installation of friction viscous dampers followed by the resizing and reorientation of columns results in the least amount of displacement observed in the structure. These techniques effectively minimize the overall movement and deformation, leading to improved structural stability and reduced displacement.

Torsional Irregularity coefficients after installation of different techniques for single, double and triple events are illustrated below in the table by comparing with the most vulnerable case.

Table 5.14: Torsional irregularity coefficient after applying different techniques for single event

Single event				
Sr no.	Cases	Maximum displacement at one end (mm)	Minimum displacement at other end (mm)	N= Dmax/Dmin
1	Most vulnerable case	6.4	3.76	1.7
2	Resizing and reorientation of column	5.7	4.04	1.41
3	Base isolation system	6.27	4.75	1.32
4	Friction viscous damping system	5.1	4.015	1.27

Table 5.15: Torsional irregularity coefficient after applying different techniques for double event

Double event				
Sr no.	Cases	Maximum displacement at one end (mm)	Minimum displacement at other end (mm)	N= Dmax/Dmin
1	Most vulnerable case	7.7	4.20	1.83
2	Resizing and reorientation of column	6.3	4.285	1.47
3	Base isolation system	6.91	5.195	1.33
4	Friction viscous damping system	5.6	4.341	1.29

Table 5.16: Torsional irregularity coefficient after applying different techniques for triple events

Triple event				
Sr no.	Cases	Maximum displacement at one end (mm)	Minimum displacement at other end (mm)	N= Dmax/Dmin
1	Most vulnerable case	15.2	9.44	1.61
2	Resizing and reorientation of column	12.12	8.358	1.45
3	Base isolation system	14.63	11.25	1.3
4	Friction viscous damping system	9.63	7.766	1.24

The above tables present the torsional irregularity coefficients for single, double, and triple events in various cases, including the most vulnerable case, resizing and reorientation of columns, introducing a base isolation system, and introducing a friction viscous damping system. The torsional irregularity coefficient is highest in all cases due to the asymmetric position of shear walls in the structure, with the highest coefficient observed in the double event.

Identifying the columns that significantly contribute to torsional irregularity is crucial. By resizing these columns through dimension adjustments or additional reinforcement, the redistribution of torsional forces can be achieved, resulting in a more balanced distribution throughout the structure. Altering the orientation of columns is also effective in minimizing torsional irregularity. Aligning the columns with the principal axes of the building or adopting symmetrical patterns enhances the distribution of torsional forces. This technique reduces the eccentricity between the centre of mass and the centre of stiffness, leading to a decrease in torsional response.

The introduction of a base isolation system reduces story drift. Base isolation systems aim to mitigate the impact of seismic forces by isolating the structure from the ground. While not explicitly designed to address torsional irregularity, they indirectly assist in minimizing torsional effects by promoting a more uniform dispersion of lateral forces.

The friction viscous damping system reduces both displacements and story drift. During seismic events, implementing friction viscous dampers (FVDs) effectively dissipates energy and reduces the overall structural response to seismic forces. This approach indirectly addresses torsional effects and proves beneficial in reducing torsional irregularity.

All three techniques—friction viscous damping system, base isolation system, and resizing and reorientation of columns—are effective in reducing torsional irregularity in both single and repeated earthquakes. The friction viscous damping system is observed to be the most effective technique, followed by the base isolation system and the resizing and reorientation of columns.

CHAPTER 6

CONCLUSION

The study shows the impact of recurrent seismic events on irregular reinforced concrete structures commonly encountered in urban areas. The research specifically concentrates on assessing the repercussions of irregularities in mass and stiffness distribution along the height of the building, as well as torsional irregularities in the building's floor plan. To investigate these effects, nonlinear time history analysis is performed utilizing ETABS 20 software. The analysis focuses on comparing the torsional responses across different scenarios to gain insights into the structural behaviour under repeated earthquakes.

<u>Analysis were carried out on these three cases:</u>

1) Change in shear wall position resulting in stiffness and mass irregularities.

2) Vertical mass irregularity accompanied by eccentricity within the floor plan.

3) Vertical stiffness irregularity accompanied by eccentricity within the floor plan.

The presence of irregularities in the structure, particularly due to varying positions of shear walls, leads to higher levels of torsional irregularity compared to mass and stiffness irregularities during single strong earthquakes and repeated seismic events. For double earthquakes of magnitudes 6.24 and 6.53, the torsional irregularity is 1.29 times higher than that observed in single events and 1.46 times higher than that in triple events of magnitudes 5.5, 5.01, and 6. The triple event of moderate earthquakes shows similar results to the single event of a strong earthquake. The most vulnerable case in terms of torsional irregularity is the type 5 model from case 5, which involves mass and stiffness irregularities due to varying positions of shear walls.

To address the torsional irregularity observed in the most vulnerable case, three different techniques have been introduced: resizing and reorientation of columns, the introduction of a base isolation system, and the introduction of a friction viscous damping system. Among these techniques, the friction viscous damping (FVD) system yields a lower torsional irregularity coefficient compared to the other two techniques across all events.

Furthermore, these techniques are effective in reducing both story drifts and displacements. They efficiently dissipate energy and help dampen vibrations, thereby decreasing the likelihood of torsional effects caused by imbalanced forces.

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