https://doi.org/10.65091/icicset.v2i1.31

Effect of Plan Inclination on Seismic Response on Residential RC Buildings

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***Abstract*—In earthquake prone areas like Nepal, the plan irregularity significantly influences the seismic response of the buildings. This study analyses how progressive inclination of plan influences the seismic performance of the RC residential buildings. Seven analytical models were created: six irregular models with one wall inclined at 5°, 10°, 15°, 20°, 25°, and 30°, and one regular model with parallel lateral load resisting systems (0° inclination). ETABS 2022 was used to analyze all models in compliance with IS 875 for gravity loads and NBC 105:2020. Base shear, basic period, center of mass–center of rigidity eccentricities, story drift, displacement irregularity ratios, and internal forces (shear forces and bending moments) in beams are important response factors taken into account.**

The findings indicate that while all storey drift ratios remain well within the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) limits specified by NBC 105:2020, increasing inclination results in a slight increase in fundamental time period and base shear (less than 1% variation between 0° and 30°).The study comes to the conclusion that, when low-rise RC buildings are designed in accordance with NBC 105:2020, minor to moderate plan irregularity does not significantly affect global seismic stability; however, it does change local demand and detailing requirements close to irregular zones. Recommendations for mid- and high-rise buildings and other complex irregularities and nonlinear analysis are given.

Keywords— non-parallel structural system, base shear, story drifts, torsional irregularity, Centre of rigidity, eccentricities, NBC 105:2020

I. INTRODUCTION

Structural stability is a fundamental criterion in building design to ensure that structures securely withstand gravity and other environmental loads, such as seismic, wind, and soil-induced movements, without collapsing or withstanding unacceptable damage. Buildings having irregular forms in plan and elevation are often the result of modern architecture and site restrictions. These irregularities frequently result in uneven mass and stiffness distributions, which cause complex seismic reactions, including significant torsional effects.

Nepal's National Building Code NBC 105:2020 [1]makes a distinction between: Non-symmetry or discontinuity in horizontal mass or stiffness, such as re-entrant corners, diaphragm discontinuity, non-parallel systems, and torsional irregularity, are examples of plan irregularities. Abrupt changes in mass, strength, or stiffness along a height are known as vertical irregularities such as soft storey, weak storey, mass irregularity.

Despite the code's acknowledgement of plan irregularity, there is little specific research measuring the effect of geometrical non-parallelism on the seismic response of RC buildings designed in accordance with NBC 105:2020. A potential safety gap results from practicing engineers' frequent reliance on judgement or foreign codes.

This work fills and addresses the research gap by conducting comparison analysis of RC moment-resisting frame building with progressive plan inclination and area variation. The main focus is on the effects of non-parallel Lateral load resisting system (LLRS) on seismic response parameters under response spectrum method compatible to NBC 105:2020 method.

II. LITERATURE REVIEW

There are various studies regarding seismic behaviour of non-parallel structures and plan irregularity.

The parametric study of three-by-two bay five story steel moment resisting frames was conducted by Tehrani and Eini's.[2] A frame of a regular model was rotated about the central column to a different angle (15°,20°,25°,30°, and 35°), making six models at total for the study. To isolate the non-parallel irregularity the staircase was not considered in the plan and for the analysis and design the ETABS16 software was used. This study shows that the lateral force induced by the earthquake added to the axial force on the column, decreasing the capacity of perimeter columns significantly. Furthermore, the models with greater irregularities had a larger mean residual displacement of the

roof, suggesting the severe post-earthquake condition for irregular models.

Although Tehrani and Eini's research was in steel structures and conducted according to international standards such as American Society of Civil Engineers (ASCE), we have taken an additional step to apply the research to reinforced concrete (RC) structures according to a performance-based assessment according to Nepal's National Building Code (NBC). Not only has this localized the results to a more relevant Nepalese construction practice but it also allows for the assessment of the effect of progressive inclination on significant response parameters such as inter-story drift, base shear, and plastic hinge development in RC frames.

Madheshiya and Pandey[3] emphasised that non-parallel LLRS cause substantial torsional responses because of stiffness and mass asymmetry in their analysis of the seismic behaviour of RC buildings with horizontal irregularities. Their study illustrated that irregular buildings typically have higher levels of lateral displacement, storey drift, and base shear, and that these effects can be lessened by strategically placing shear walls.

One of the study [4]assessed the seismic behaviour of non-parallel irregular buildings, which frequently resulted from site-oriented architectural planning and often induced torsion and local stress concentrations because lateral force-resisting elements were not aligned with the major orthogonal axes. Performance was evaluated in terms of strength, stiffness, and ductility by comparing a number of models with same floor area with modified configurations that connected columns by triangular-module beams using SAP2000 pushover analysis.

Another study [5] examined the seismic response of torsional plan-irregular buildings, where eccentricity between the centre of mass and centre of stiffness resulted in substantial rotation about the vertical axis and increased earthquake damage potential. The best shear wall shape and location that reduced torsional displacement and changed the basic mode from torsional to translational was determined by comparing the findings.

A study[6] used nonlinear response spectrum analysis to evaluate how various structural irregularities influenced seismic response, with a particular focus on non-parallel system irregularity in RC buildings with non-parallel shear walls. Non-parallel components in the lateral force-resisting system were found to enhance torsional response and have a significant effect on earthquake resilience.

The implications of plan shape have also been extensively researched. Mohod [7] used IS 1893:2002 [8] to examine the seismic response of RC structures with different plan configurations (L, C, T, E, plus shapes). He found that irregular shapes have more lateral displacements and inter-story drifts than regular rectangular forms. According to Krishna and Arunakanthi's investigation [9] of various shear wall shapes and locations in asymmetric high-rise buildings, shear wall geometry and location have a significant impact on stiffness, torsion control, and base shear distribution.

Papageorgiou & Lin [10]conducted a detailed system identification study of three high-rise buildings that were subjected to the 1984 Morgan Hill earthquake, with special focus placed on the function of different lateral load resisting systems shear walls, moment-resisting frames, and mixed systems during their seismic response. The study illustrated how the spatial arrangement and organization of the lateral load resisting systems played a crucial role in the dynamic response of the structures, particularly the modal coupling and the torsional response. Closely spaced natural frequencies bred large torsional responses and a beating effect, emphasizing the overwhelmingly crucial function of system geometry and stiffness distribution. Where their study focused on full scale buildings and modal coupling through observational data, our study complements these results by analytically investigating how the progressive inclination of RC frames a plan geometric irregularity affects seismic response measures such as base shear, inter story drift, and plastic hinge formation.

Homaei and group [11] conducted an Incremental Dynamic Analysis (IDA) study on the seismic performance of vertically irregular steel moment-resisting frames, emphasizing the impact of soil structure interaction on the frame. Their study reviewed a handful of types of vertical irregularities, those having to do with mass, stiffness, strength, and a combination of stiffness versus strength at a range of locations of the frame. The focus was on quantifying how these lead to inter-story drift, ductility, and seismic capacity under nonlinear dynamic loading. The authors concluded that irregularities in stiffness and strength, especially for lower stories greatly increase seismic demand and reduce capacity, especially at higher performance levels like Collapse Prevention (CP) and Global Instability (GI).

López & Torres[12] provided an effective method for calculating the critical angle of seismic incidence anticipated to produce the maximum structural response to multi-component ground motion. They employed a modal response spectrum analysis framework and use standard load cases, and their method effectively quantifies directional factors without requiring the running of numerous time histories for each angle of incident seismic energy. To support the hypothesis of progressive inclination-related conditions affecting how a structure performs under seismic loading, one of the conclusions from Lopez and Torres' work is that the critical response angles are dependent on the characteristics of the horizontal ground motion and some structural characteristics, but not on the vertical excitation. Hence, the findings of Lopez and Torres provide an excellent theoretical basis to consider how directional sensitivity reacts to progressive inclination when considering the topic of RC buildings from a pragmatic performance-based viewpoint.

Building on previous investigations, the current study employs NBC 105:2020 to analyse RC moment-resisting frames with progressively inclined plans in order to give Nepal-specific insights into how non-parallel LLRS affects seismic response.

III. METHODOLGY

A. Research Approach and Framework

A quantitative, analytical, performance-based design (PBD) approach is used in the study. Seven idealised configurations based on plan inclinations of a three-story RC moment-resisting frame (MRF) residential building differ only in the plan's inclination of one wall. To isolate the impact of plan irregularity, all other parameters—storey height, material characteristics, member sizes, and gravity loads—are maintained constant.

The Modal Response Spectrum Method (MRSM) in ETABS 2022 is used for dynamic analysis, and seismic input

is defined in accordance with NBC 105:2020. Each model's response parameters are calculated and contrasted between configurations and code restrictions. The overall methodology is illustrated in Fig. *1*. Its main framework contains:

- Seven three-dimensional construction models were created (0 to 30 angular degrees of wall variation).
- The same material, geometric, and loading values were used to isolate the factor of torsional irregularity.
- The seismic loads are applied as a response method spectrum according to the NBC 105: 2020.
- Comparison of the response parameters like the story drift, base shear, and displacement, and sensitivity to torsional irregularity.
- Evaluation of the performance of RC structures based on the limits of the established drifts and response.

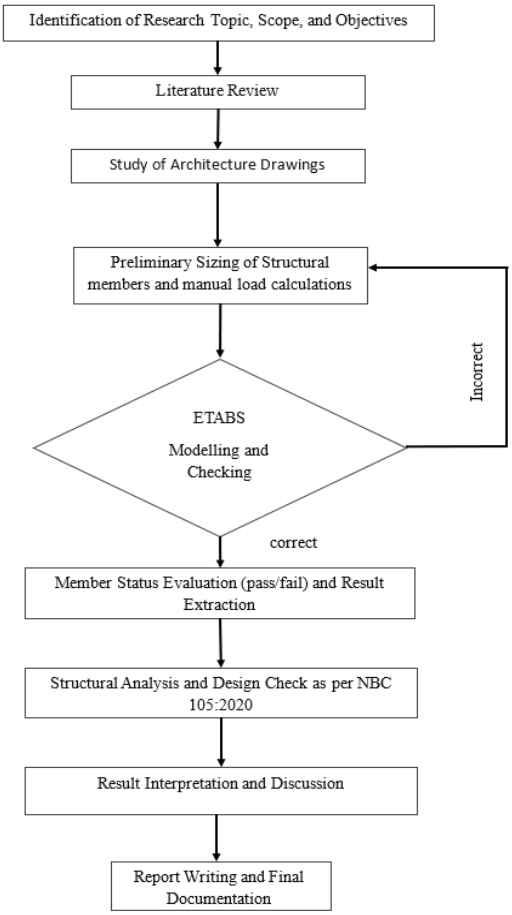

Fig. 1. Flowchart of Methodology

B. *Modeling Details and Building Configuration*

The building and model configurations used for research are summarized as follows: -

- Building type: Low-rise residential RC MRF
- Number of storeys: 3
- Storey height: 3.0 m (uniform)
- Plan area: constant for all models (site area ≈ 943.8 ft² ; ground coverage ≈ 728.8 ft²)
- Materials: - Concrete: M20
- Reinforcement: Fe500
- Members: - Slab thickness: 125 mm (150 mm for staircase slab)
- Beams: 230 mm (b) × 350 mm (D)
- Columns: 350 mm × 350 mm square

Seven models, M0: 0° is regular system and M5, M10, M15, M20, M25, M30 with inclination 5°, 10°, 15°, 20°, 25°, 30° respectively of one wall, are considered for the analysis. The inclination is obtained by rotating one vertical wall around the plan's centroidal axis and as a result torsional eccentricity is introduced while maintaining the constant plinth area and storey height. The base 0^0 and M30(30^0) are shown in Fig. 2. and Fig. 3.

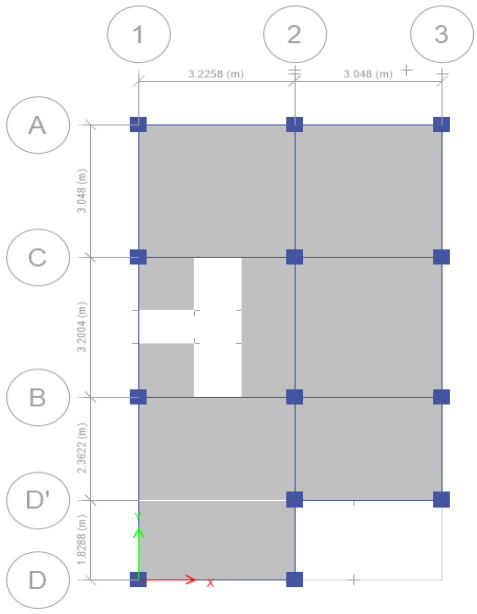

Fig. 2. 2-D base 0^0 inclination model

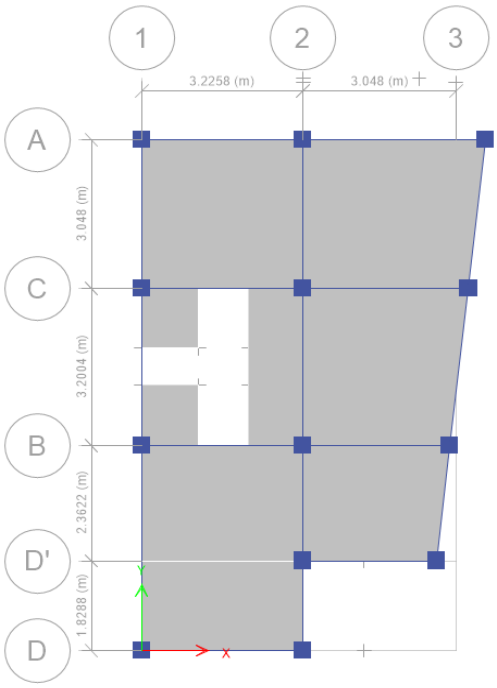

Fig. 3. 2-D 30⁰ inclination model

C. Loading and Design Codes

Gravity loads are assigned as per IS 875 (Parts 1 and 2)[13], [14] for dead loads and live loads respectively and RCC members are designed as per Is 456:2000 [15].

- Floor finish: 1.35 kN/m²
- Live load (typical floors): 2.0 kN/m²
- Staircase dead load: 1.875 kN/m²
- Staircase live load: 3.0 kN/m²
- Roof live load: 1.5 kN/m²

Seismic loading is calculated in accordance with NBC 105:2020 [1]:-

- Seismic zone factor: Z = 0.35 (e.g., Kathmandu region)
- Importance factor: I = 1.0 (ordinary residential)
- Ductility factor: Rμ = 4 (RC MRF)
- Overstrength factor: Ωu = 1.5
- Soil type: Type B (medium soil)
- Damping ratio: 5%

Live load participation factor for seismic mass is taken as λ = 0.3 for floors and 0.0 for the roof . Key load combinations at the Ultimate Limit State (ULS) include: -

- 1.2DL+1.5LL
- DL + λLL ± EQ for parallel system
- DL + λLL ± (EQx ± 0.3EQy) – for non-parallel systems
- DL + λLL ± (0.3EQx ± EQy) – for non- parallel system

D. Analysis Procedure

As required by NBC 105:2020 for plan-irregular mid-rise buildings, all models are examined in ETABS 2022 using linear dynamic Model response spectrum method(MRSM). The primary steps are illustrated in given points.

- Modal analysis to determine natural periods and mode shapes, making sure that at least 90% of the mass participates in both X and Y directions.
- Response spectrum analysis scaled by ductility and overstrength factors using NBC 105:2020 elastic spectra.
- Global response extraction: modal characteristics, fundamental periods, and basic reactions (FX, FY, MX, MY, and MZ).
- Extraction of storey-level responses: eccentricities, centre of mass (CM) and centre of rigidity (CR) coordinates, storey drift, and displacement.
- Shear forces and bending moments at critical grids and floors are extracted from internal forces in specific beams and columns.

E. Complaince with Performance Based Design Criteria

Aligned with Clause 2.1 of NBC 105:2020, this project considers two seismic performance targets:

1) Ultimate Limit State (ULS)

- Purpose: Prevent structural collapse under design-level earthquake (475-year return).
- Evaluation Method: Modal Response Spectrum Analysis
- Response Parameters Checked: Base Shear (V): To ensure overall lateral resistance
- Storey Drift Ratio (Δ /h): Limit: Δ /h ⩽ 0.025 (NBC 105:2020, Clause 5.6.3)
- Torsional Irregularity Index (TII): TII= δ max/ δ avg ⩽1.5(NBC Clause 5.5.2.1)

2) Serviceability Limit State (SLS)

- Purpose: Limit damage to structural and non-structural elements for frequent earthquakes.
- Evaluation Criteria: Inter-storey Drift Limit: Δ/*h* ⩽ 0.006 (NBC Clause 5.6.3)
- Post-earthquake usability: Small drifts ensure safe egress and reduced repair costs.

To aid interpretation, the performance of each building configuration is categorized using qualitative levels shown in Table I.

TABLE I. PERFORMANCE INTERPRETATION

Performance Level	*Criteria*	*Interpretation*	*Performance Level*
Operational	Drift ≤ 0.006	No significant damage; fully usable	**Operational**
Immediate Occupancy	Drift ≤ 0.01, no torsional irregularity	Minor damage, functional	**Immediate Occupancy**

Performance Level	*Criteria*	*Interpretation*	*Performance Level*
Life Safety	Drift ≤ 0.025, TII ≤ 1.5	Damage allowed, no collapse	**Life Safety**
Collapse Prevention	Drift > 0.025 or TII > 1.5	Unacceptable performance	**Collapse Prevention**

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IV. RESULTS

A. Mass and Rigidity

The centres of mass and stiffness at each floor were calculated for all models to determine eccentricities in the X and Y directions. Depending on the storey, the X-direction eccentricity for the base model (M0) ranges from approximately 2.1% to 2.9% of the plan dimension, whereas the Y-direction eccentricity ranges from approximately 0.2% to 3.9% as depicted in Fig. 4 and Fig. 5.

The following patterns are seen as inclination increases (up to 30°):

- All floors show a minor increase in X-direction eccentricity (for example, first-floor eccentricity rises from approximately 3.79% at 0° to 4.13% at 30°).
- Y-direction eccentricity: minor increases at the top level but a little decrease at lower floors (ground-floor eccentricity, for example, drops from slightly 3.71% to 2.43%).

According to NBC 105:2020, all eccentricities stay below roughly 5%, indicating that although torsional demand is present, it is insufficient to cause significant torsional irregularity.

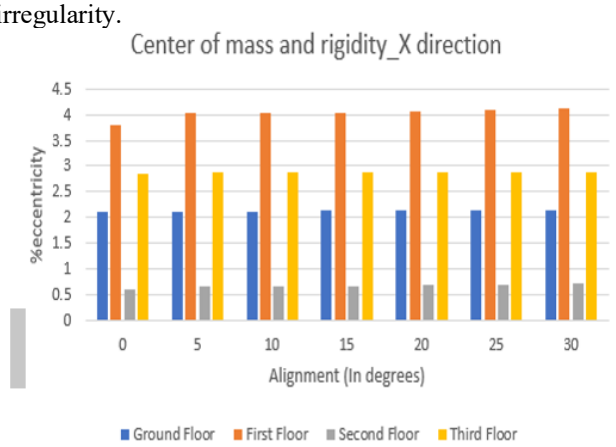

Fig. 4. Graph showing the eccentricity of different alignments along X-direction

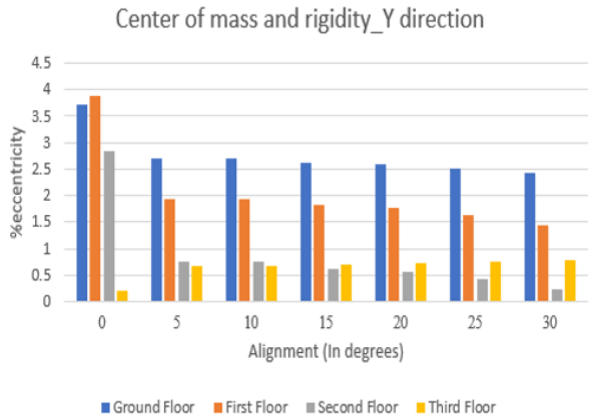

Fig. 5. Graph showing the eccentricity of different alignments along Y-direction

B. Base Reaction ans Shear

For both response spectrum situations (RSx and RSy) and static ULS cases, base shear and overturning moments were extracted from ETABS. Absolute maximum base shear F_X for EQ_{X_ULS} increases by roughly 0.73%, from 371.69 kN (0° inclination) to 374.42 kN (30° inclination) and for EQ_Y_ULS, it exhibits similar trends in F_Y. Response spectrum base shears (RSx, RSy) exhibit similar slight increases. The base reaction of different alignments along X-direction and Y-direction is shown in Fig. 6 and Fig. 7.

Torsional moment M_Z and overturning moments about X and Y (M_X, M_Y) both rise with inclination; M_Z shows the most noticeable relative increase, indicating increasing torsional demand.

Base shear generally stays about constant (<1% variation) across all inclination angles, suggesting that a low-rise building's plan irregularity of this size has little effect on the overall lateral force demand.

C. Story Drifts and Displacement Ratios

Horizontal storey displacements and inter-story drifts were used to assess story-level performance for all inclination models under both SLS and ULS load combinations. With the highest values concentrated around the middle storeys (≈6 – 9 m) and a slight amplification at the 6 m level indicating a mild soft-storey/stiffness discontinuity effect, ULS drifts (0.0015) are consistently greater than SLS drifts (0.0007) in the X-direction. The Y-direction, on the other hand, shows fairly regular drift profiles with little variation between models and lower total drift demands, indicating a more balanced lateral stiffness in that direction. Fig. 8 and Fig. 9 display the storey-drift envelopes in both directions.

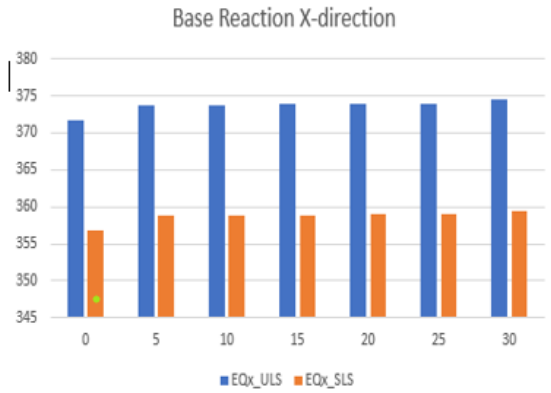

Fig. 6. Graph showing the Base reaction of different alignments along X-direction

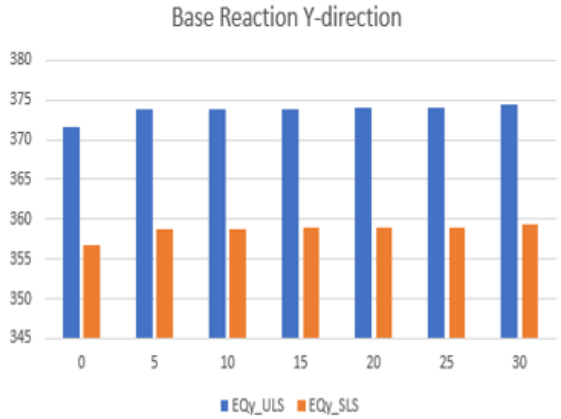

Fig. 7. Graph showing the Base reaction of different alignments along Y-direction

In accordance with NBC 105:2020, which classifies torsional irregularity when this ratio surpasses 1.5, the maximum-to-average storey drift ratio was analysed to evaluate torsional behaviour. While the Y-direction mostly maintains a consistent drift pattern, the X-direction exhibits a little increase in drift concentration at all inclination angles when compared to the base (0°) model. However, in all cases the maximum/average drift ratios remain below the NBC irregularity threshold. Fig.10 and Fig.11 shows these tendencies.

According to the comparison of storey maximum-to-average displacement ratios (Figs. 12),the base model (M0,0° inclination) showed ratios near 1.0 at all levels, indicating a largely uniform displacement profile and minimal torsional amplification. Displacement irregularity became increasingly noticeable when the inclination rose to 30°, particularly at the ground, first, and second stories, where the curves shifted to the right and the ratios increased, indicating higher mass eccentricity effects in the X-direction. The inclined configurations obviously deviated from the well-behaved symmetric response of Model 0, indicating a stronger inclination for torsional response and potential soft/weak storey behaviour at the lower levels, even though all models remained below the critical displacement-ratio threshold.

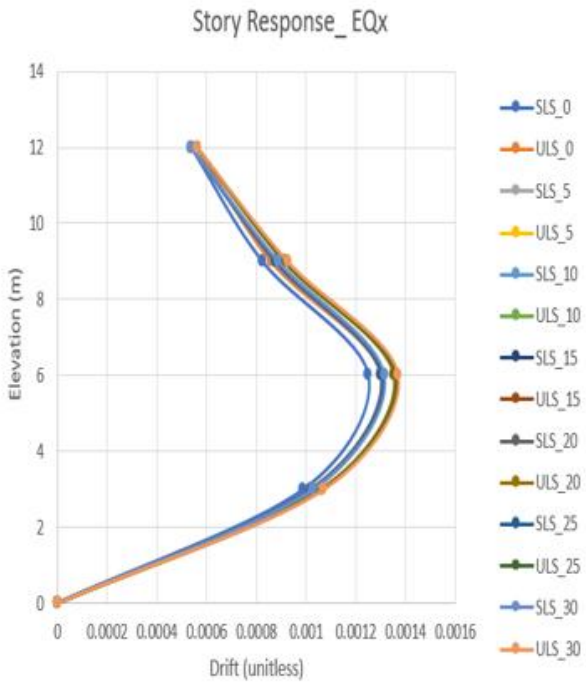

Fig. 8. Graph showing the Storey drift of different alignment along X-direction

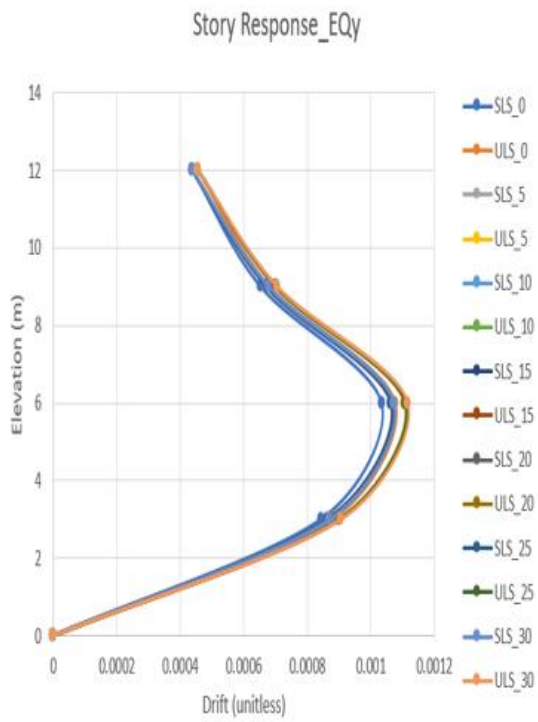

Fig. 9. Graph showing the Storey drift of different alignment along X-direction

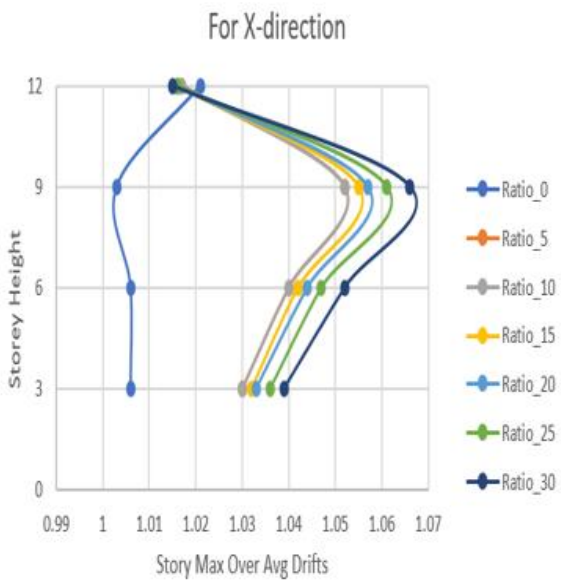

Fig. 10. Graph showing the Storey Max Over Avg Drift of different alignments along X-direction

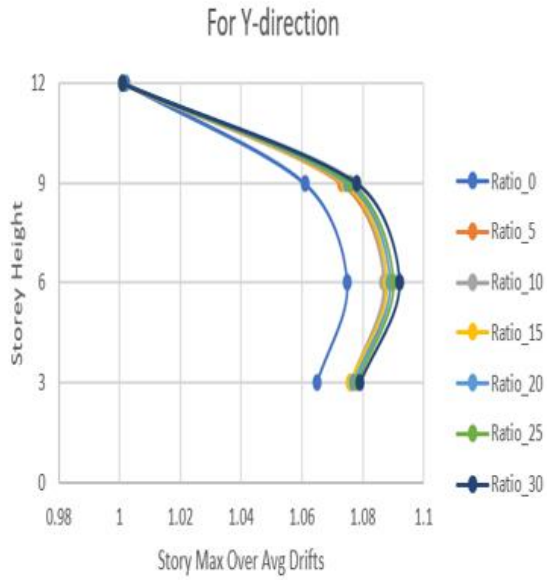

Fig. 11. Graph showing the Storey Max Over Avg Drift of different alignments along Y-direction

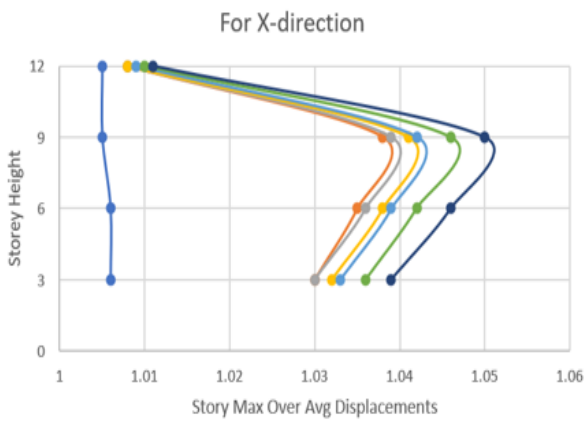

Fig.12. Storey Max over Avg Displacement Plot

D. Modal Characterstics

After observing the various layouts, Model 0(parallel walls) has the lowest modal period (T = 0.445 s) and, therefore, it is the stiffest one. By changing the position of the plane such that walls are no longer parallel (30 in this case), the modal period gradually increases (T = 0.451 s at 30), which means that the effective lateral stiffness of the system is slightly reduced.

E. Internal Forces in Beams and Columns

For different angles, internal shear forces (SF) and bending moments (BM) were studied between floors and grids.

- Beams: As inclination increases, ground-floor beams exhibit a little decrease in peak SF and BM (e.g., SF from about −50.72 kN at 0° to −50.21 kN at 30°; BM from approximately −41.18 kN·m to −40.66 kN·m). First-floor beams show slight decreases in SF and BM with inclination, ranging from 10° to 30°.There are just slight differences on the upper floors.
- Columns: At greater inclinations, some columns along grids near the inclined wall exhibit noticeable increases in SF and BM, indicating the redistribution of forces brought on by torsion. Only small changes are seen in columns that are farther away from the inclined wall

These results indicate that local internal force demands in members next to the inclined wall are greatly impacted and may control reinforcement details, even though global demand is almost unchanged.

V. DISSCUSSIONS AND CONCLUSIONS

A. Discussions

The results show that, for the low-rise RC building under study, there is a considerable difference between the local and global effects of plan irregularity.

Globally, inclining one wall up to 30° has very little effect on base shear, fundamental period, and storey drift. The building can be classified between Immediate Occupancy and Life Safety levels under design-level earthquakes, and all models readily satisfy NBC 105:2020 performance criteria at ULS and SLS. According to NBC 105:2020, standard MRSM processes can be used to appropriately capture the overall seismic demand for identical low-rise buildings with minor plan irregularities.

Internal force distributions, however, are noticeably changed locally due to torsional effects and eccentric load paths brought on by plan inclination, particularly in columns and beams close to the inclined wall. Stronger sections or improved ductile detailing may be necessary for these members due to their increased shear and bending moment demands. Even when global performance indicators seem adequate, ignoring these localised amplifications could result in the under-design of critical components.

The slight increase in fundamental period and torsional moments with inclination is consistent with previous studies on non-parallel systems and theoretical predictions. The

building's low height and the relatively small degree of plan irregularity are the main reasons for the lack of torsional irregularity (Max/Avg drift < 1.5). Such torsional effects may be greatly increased in structures that are taller or have more severe plan irregularities. Overall, the results emphasize the necessity of thorough member-level checks and detailing in areas impacted by geometric irregularities and support NBC 105:2020 provisions that requires dynamic three-dimensional analysis for plan-irregular structures.

B. Conclusions

This research is able to achieve its intended goal which was to evaluate the effect of progressive plan irregularity on the seismic behaviour of low-rise RC frame. Making comparisons of models of progressive inclination of plan, the following conclusions could be made:

1) Seismic Demand:

- In both principal directions, base shears from response spectrum analysis show less than 1% difference between the most inclined (30°) and regular (0°) models.
- The dynamic behavior is stable and code-compliant, but fundamental periods slightly increase with inclination, suggesting a slight decrease in overall lateral stiffness.

2) Torsional Irregularities and Drift Performance:

- For both SLS and ULS, the maximum inter-storey drifts in the X and Y directions are much less than the NBC 105:2020 limits.
- For all storeys and models, the maximum to average drift and displacement ratios stay below 1.5; torsional irregularity according to NBC is not triggered.

3) Eccentricity and Torsional Effect:

- At lower floors, eccentricities between the center of mass and the center of rigidity generally decrease in the Y direction and increase somewhat with inclination in the X direction, but they still remain below roughly 5% of the plan dimension.
- Torsional moments at the base and displacement irregularities increase with inclination, confirming that plan irregularity introduces torsional effects, though these effects are relatively small for the case study.

4) Internal Forces:

- Internal shear forces and bending moments in beams typically exhibit minor increase as inclination increases.
- Shear forces and bending moments are noticeably higher in columns and beams next to the inclined wall, highlighting the necessity of careful element design and ductile detailing around irregular zones.

C. LIMITATIONS

1) Lack of Time-History Analysis:

The time-history analysis is not applied in the current study, and thus the actual seismic ground effect on the building by nonlinear dynamic analysis could not be simulated properly.

2) Idealized Modeling Assumptions:

The structural model does not account for the interaction with the soil, and the supports used are fixed, thus allowing the real-life structural performance to differ from that of the seismic event.

3) Single Building Structure:

Provided that the study is limited to one building structure and height (three-storey RC building), its results cannot be generalized easily to other structures, heights, and lateral load-resisting systems..

4) Code Dependency:

The only code on which the analysis is based is the Nepalese National Building Code (NBC 105:2020) and partly IS 1893. It has not been comparatively evaluated with the other international seismic design codes, e.g., Eurocode 8.

5) No Nonlinear Static Analysis:

Nonlinear performance comparison methods, such as the pushover analysis, were not used, and thus structural performance could not be evaluated beyond the elastic range.

D. Recommendations

Future research can be expanded the scope of this work by examining at mid and high-rise RC buildings, where higher mode and torsional amplification effects are more significant, and by conducting nonlinear dynamic analyses with recorded ground motions. The combined impact of plan and vertical irregularities, such as soft storeys, setbacks, and mass irregularity and as well as how they interact with non-parallel LLRS require more research. Finally, experimental studies, such as shake table tests, particularly for irregular buildings, can be used to validate analytical results.

ACKNOWLEDGMENT

The authors would like to thank Department of Civil Department, Nepal College of Information Technology(NCIT) for motivating and encouraging us to conduct research and NCIT for the platform for the research work.

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