Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Seismic Performance of Non-orthogonal RC Frame Buildings

Priyanka Limbu [a], Rabindra Adhikari [b], Piyush Pradhan [c]

[a, c] *Department of Civil Engineering, Thapathali Campus, IOE, Tribhuvan University, Nepal*
[b] *Department of Civil Engineering, Cosmos College of Management and Technology, Lalitpur 44600, Nepal*
[a] priyanka.782539@thc.tu.edu.np, [b] rabindraadhikari@cosmoscollege.edu.np, [c] ppradhan@tcioe.edu.np

Abstract

Among different building typology reinforced concrete buildings in current practice is more prevalent compared to other typology such as masonry and wooden buildings.Lately reinforced concrete buildings with different geometrical and architectural shapes are constructed for functional and aesthetic requirement.Among which non-orthogonal frame buildings construction are quite prevalent in Nepal due to the available limited irregular land geometry.Performance of these structures are different as the structure dynamic behavior is dependent on structural geometrical configuration and shape.In that case designers should design such building to resist the lateral loads induced during the earthquake for safe occupancy.This paper aims to evaluate the performance of non-orthogonal frame buildings.For this study, G+6 story orthogonal and non-orthogonal frame buildings are taken.Modelling, design and analysis of orthogonal and non-orthogonal frame buildings are carried out using finite element based software(ETABS V 20)as per NBC 105:2020 code guidelines.The performance of the non-orthogonal RCC frame and the orthogonal frame building is assessed using both linear and non-linear static analysis.Seismic response such as story drift,displacement and fundamental time period are obtained based on response spectrum analysis.Further pushover analysis is performed to evaluate the non-linear behaviour of the buildings.Seismic performance assessment showed non-orthogonal frame building which are designed as per codal provisions can achieve life safety performance criteria as per the codal performance requirement.

Keywords

Orthogonal frame, Non-orthogonal frame, Response spectrum analysis, Pushover analysis, ETABS

1. Introduction

Nepal is located in a high seismic zone with a long history of earthquakes, resting in the boundary of two colliding plates i.e. the Indian and Urasian plates. So the structures are more prone to severe damage. Reinforced cement concrete (RCC) is one of the common typology of building constructed in Nepal in recent years. Although most buildings are rectangular or square, irregular land or design choices may cause structures to be irregular in shape [1].

Depending on the geometrical arrangements and shapes, structures respond differently. Structures do not always have uniform dimensions and forms.One of the common cause of failure of RCC structure during earthquake is the shape of the building configuration.Generally there are two building configuration systems which are orthogonal and non-orthogonal building system known as parallel and non-parallel system in Nepal building code NBC 105:2020 [2] where the orthogonal frame buildings have frames mutually perpendicular to each other whereas non-orthogonal frame building frames are not mutually perpendicular to each other.Orthogonal frame buildings tend to be more rigid and stable due to their regular geometry.Non-orthogonal frame buildings exhibit different seismic behavior due to the irregular layout or non-rectangular shape.These buildings unique geometry can amplify seismic response at certain locations.Analyzing these vulnerabilities is essential to ensure overall structural safety.Therefore it is very important to study how geometry influences dynamic response and performance of the buildings.

Construction of non-orthogonal frame buildings are quite prevalent in our country due to the irregular geometry of the land.Studies have shown that these type of structure leads to significant damage of the structural system as per the previous researchers.In context of Nepal,2015 Gorkha earthquake has showed failure of structure were due to different structural deficiencies among which irregular geometry is also one of them.Building asymmetry in terms of plan as well as elevation is more common Nepal[3].Figure 1 shows damaged non-orthogonal frame building during 2015 Gorkha earthquake.As the structures in this region are at high risk to collapse during ground shaking,there is need to study the performance of non-orthogonal frame structures more rigorously.

Figure 1: Non-orthogonal frame commercial building with severe damage in Kathmandu [3]

The objective of the study is to analyze and compare the seismic performance of the non-orthogonal frame buildings relative to orthogonal frame building.Performance based assessment is seen important for these type of structure as these structures behavior is different during seismic event compared to the orthogonal frame buildings and also to evaluate whether the performance criteria of these buildings are within acceptable limit or not as per NBC codal provisions.This study is very important to determine the relative performance of non-orthogonal building, compared to their orthogonal counter-part.This can be useful to quantify the non-linear behavior of these type of buildings to estimate potential damage and ensure occupant safety.

2. Literature review

Several studies have conducted on orthogonal frame buildings but there is limited study in case of non-orthogonal frame buildings.

Tezcan & Alhan (2001) conducted parametric analysis to evaluate the response of asymmetric building under seismic loading.Three building models with 1,5 and 10 storey with varying rigidity was considered.Equivalent static and dynamic analysis was performed to study the effect of non-orthogonal shear walls by changing the position of shear walls to create torsional irregularity.It was found that lower limit of the torsional irregularity coefficient specified in Turkish code i.e 1.2 was too low and based on the parametric analysis it was proposed to increase the limit to 1.4 whereas higher limit was proposed to decrease to 1.8[4].

Richard et al.(2015) conducted series of shaking table test on a three story reinforced concrete asymmetric model.13 distinct bi-directional input ground motions of varying intensities were applied to the model. The experimental test revealed that the RC specimen only sustained mild damage,whereas the primary damage was concentrated around the openings and the connection between the shear wall and the slab.Another finding was that the stiffness of the RC specimen decreased as seismic amplitude increased, and the model mostly responded in torsional mode[5].

Lim et al. (2018) examined asymmetric three-story RCC building taking torsional effect and material non-linearity into account. Non-linear analysis was performed using ANSYS to evaluate the behavior of asymmetric structure to high intensity ground motions. The result from finite element modal analysis was validated with the shake table test. Seismic response of asymmetric structure showed larger value compared to the symmetric structure. It concluded that the larger seismic response should be taken into account in the design of asymmetric structure with similar design conditions[6].

Teddy et al. (2018) investigated the seismic behavior of the buildings with non-parallel irregular configuration.Pushover analysis was performed using SAP2000 to assess the performance level of the building. The result showed that the more irregular the configuration of the building the larger the target displacement.It was also found that the columns which are not oriented in one axis had weaker rigidity than the beams due to the irregular arrangement of beams and columns.It was concluded that the triangle module beam can be connected to the column to have more rigidity which results in minimum formation of eccentricity[7].

(Eser Aydemir, Evliyaoglu, and Malkoc 2022)studied the effects of ground motion incident angle in four storied building with orthogonal and non-orthogonal frame.Non-linear dynamic time history analysis of four-storied RCC frame was performed using ZEUS-NL structural analysis program. The structure was analyzed by changing the incidence angle of ground motion from 0 degree to 180 degree.Axial force, shear force of column, shear force of beam and inter-story drift ratio was examined.It concluded that the variation in earthquake incidence angle resulted greater variation in axial force and shear force for non-orthogonal frame whereas inter story drift was found to be less sensitive to the earthquake incidence angle for both orthogonal and non-orthogonal structure[8].

Tehrani & Eini (2022) evaluated the non-linear response of multistoried steel moment resisting frame with non-parallel system irregularity. Pushover and non-linear time history analysis was performed using ETABS16 software.By adjusting the angle of one side of the frame, various levels of irregularity were investigated. It was found that the story drift increased with increased angle of rotation. The results of pushover analysis showed decrease in ductility capacity and response reduction factor with increased irregularity effect. Furthermore, non –linear time history resulted that the buildings are more vulnerable as the displacement was increased with increased degree of irregularity[9].

3. Methodology

This study consist of building sample selection followed with preparation of orthogonal and non-orthogonal frame buildings plan which represent the typical building built in urban and semi-urban areas.Modelling,design and analysis of selected building models in finite element based software ETABS were conducted.Response spectrum analysis was performed for the design and analysis as per NBC 105:2020. Further pushover analysis was performed resulting in development of capacity curve and the performance evaluation was done.

3.1 Building Configuration Description, Modelling, Analysis

In this study, G+6 story commercial buildings with orthogonal and non-orthogonal frame which represent the typical RCC MRF commercial building built in Nepal are taken.They are represented as M1, M2, M3 and M4.M1 model which has all of its frame orthogonal with each other,M2 model which has one of the non-orthogonal frame, M3 which has two of the frames non-orthogonal and M4 model in which all of the frames are non-orthogonal.Non-orthogonal frames are in x-direction and has an inclination of 25°.Figure 2 shows the architectural plan of the building models considered.Detailed information about the material and structural properties of the buildings models considered in this study which are mentioned below are given in Table 1.

This study is carried out in which all the building models with

Table 1: Material and structural properties

Building model	M1	M2	M3	M4	unit
Concrete	M25	M25	M25	M25	
Rebar	Fe500	Fe500	Fe500	Fe500	
Frame type	Moment resisting frame	Moment resisting frame	Moment resisting frame	Moment resisting frame	
Soil type	D	D	D	D	
Seismic Zone factor	0.35	0.35	0.35	0.35	
Importance factor	1.25	1.25	1.25	1.25	
No of bays in X-direction	3	3	3	3	
No of bays in Y-direction	5	5	5	5	
Story height	3.05	3.05	3.05	3.05	m
Total length along X-axis	16.005	16.005	17.595	17.595	m
Total length along Y-axis	24.575	26.15	24.575	24.575	m
Plinth area	422.22	390.08	427.33	427.33	m2
Column density	3%	3%	3%	3%	
Live load	0.75,1.5,3,4	0.75,1.5,3,4	0.75,1.5,3,4	0.75,1.5,3,4	KN/m2
Floor finish	1.25	1.25	1.25	1.25	KN/m2
Brick Wall load	8.4-10.5	8.4-10.5	8.4-10.5	8.4-10.5	KN/m
Brick wall Parapet load	2.42	2.42	2.42	2.42	KN/m
Open well Staircase load	15.9-21.63	15.9-21.63	15.9-21.63	15.9-21.63	KN/m

same column density of 3% are designed following the codal provisions i.e orthogonal frame building is designed with 100 percent earthquake load along the axis of the frame and non-orthogonal frame buildings are designed with 100 percent earthquake load in one direction plus 30 percent of earthquake load along the other direction for non-orthogonal frame buildings.

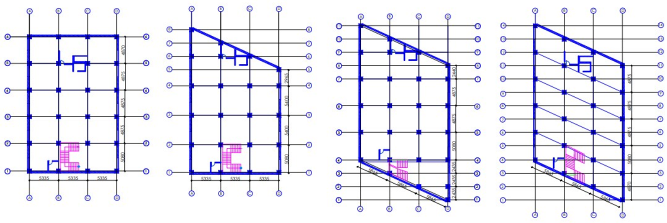

Figure 2: Typical floor plan of M1, M2, M3 and M4 models

3.2 Finite element Modeling and design

ETABS V.20 CSI finite element software has been used to model and analyze the chosen 3D reinforced concrete building frames.Response spectrum analysis is performed for the design and analysis of the buildings as per NBC 105:2020 provisions.The modeling of beam and columns are done considering the cracked section as given in NBC 105:2020.The

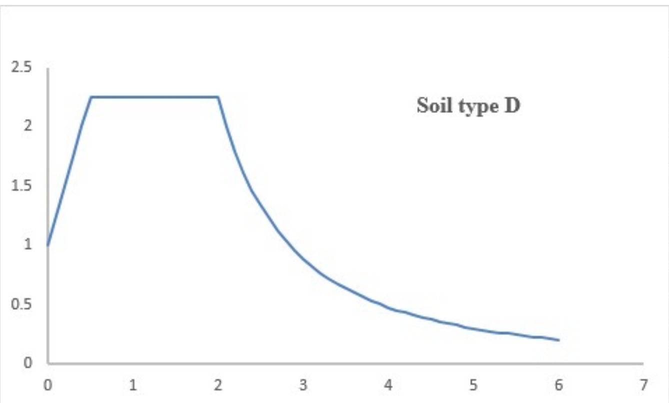

Figure 3: Spectral shape factor for model Response Spectrum method of Soil type D [2]

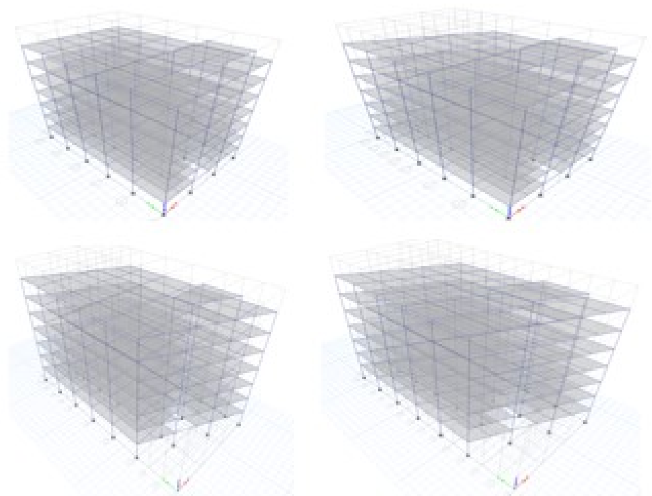

Figure 4: 3D finite element models of M1, M2, M3 and M4 building

beams and columns are modeled using frame element.Slab is modeled as thin shell element with rigid diaphragm effect.The open well staircase is not modeled, however,the load of the staircase is applied to the beams.The design response spectrum for soil type D is shown in the Figure 3.Table 1 provides the detailed information of the material and structural properties of the building models for both cases.The finite element model is shown in the Figure 4.Figure 5 shows the cross section of typical beam and column.Sectional properties of all the building models are shown in Table 2.

Table 2: Sectional properties of all building models

Building model	Column size	Beam size	Slab thickness	unit
M1 (All frames orthogonal)	700*700	700*400	125	mm
M2 (One frame non-orthogonal)	700*700	700*400	125	mm
M3 (Two frames non-orthogonal)	700*700	700*400, 600*400	125	mm
M4 (All frames non-orthogonal)	700*700, 800*800	700*550	125	mm

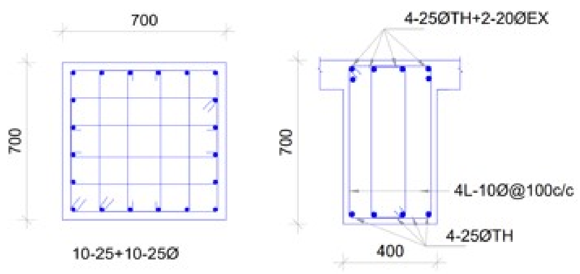

Figure 5: Typical column and beam section as per design

3.3 Nonlinear modeling

In this study,to account non-linearity concentrated plastic hinges and fiber hinges are assigned at a distance of 10% of member length in beams and column respectively.Similarly,geometric non-linearity has been accounted considering P-delta effect.Flexural M3 plastic hinge is assigned at each end of the beams from the auto hinge property as per ASCE 41-13 provisions of ETABS v20 and fiber P-M2-M3 is assigned in columns.Force-deformation relationship of typical plastic hinge is shown in Figure 6.Fiber P-M2-M3 hinge account non-linearity at material level and is used to stipulate the coupled axial and bi-axial bending behavior in column.Non-linear behavior of concrete and rebar is represented by Mander stress-strain curve and simple stress-strain curve respectively. Stress-strain curve for concrete and rebar is shown in the Figure 7.

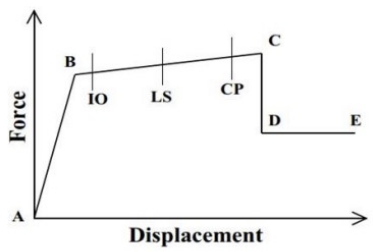

Figure 6: Force-deformation relationship of typical plastic hinge

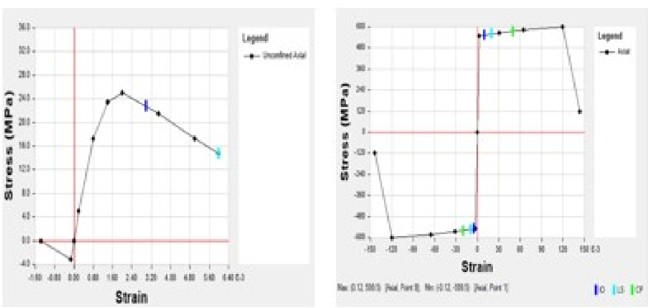

Figure 7: Stress-strain curve for concrete and rebar

3.4 Pushover analysis and performance point

Pushover analysis, a non-linear static analysis, identifies the structure's capacity and evaluates its performance beyond of the elastic state.Different codes and documents include provisions for pushover analysis procedure such as FEMA,ATC 40.The building was subjected to displacement controlled loading in order to observe the structure's behavior.The structure is initially subjected to gravity loading with DL+0.3LLother. After that, incremental lateral loads are applied to the structure, which progressively increase in magnitude until the structure reaches its maximum capacity.Eventually, pushover curve is obtained after the analysis which is known as capacity curve.

For the performance evaluation of the building, performance point is determined following the steps prescribed in ATC40,FEMA440.In this study capacity spectrum method is used to determine the performance point or the target displacement.The intersection point of capacity spectrum and demand spectrum gives the performance point i.e the expected displacement that the structure will undergo for the given seismic demand.Different code such as FEMA 356,ATC40 have prescribed the structural performance level as immediate occupancy(IO),life safety(LS),collapse prevention(CP) which determines the global performance level of the structure.Displacement values at different performance level is determined as given by Lagomarsino and Giovinazzi 2006[10] as shown in Table 3.

Table 3: Damage state based on yield displacement and ultimate displacement [10]

Damage state	Capacity function
Slight damage(IO)	0.7dy
Moderate damage(LS)	1.5dy
Extensive damage(CP)	0.5(dy1+du)
Complete damage	du

4. Results and Discussion

Altogether four building models assumed to be located at Kathmandu valley are studied.They are named as M1,M2,M3 and M4 which are described in section 3.Response spectrum analysis was performed to analyze and design the non-orthogonal frame buildings.Further pushover analysis was performed to quantify the capacity of these buildings and to evaluate the codal performance requirement.The results are presented and discussed below.

4.1 Fundamental time period

Figure 8 shows the fundamental time period variation of orthogonal and non-orthogonal frame buildings.The time period of the non-orthogonal frame buildings are slightly higher than that of orthogonal frame building.This implies that non-orthogonal frame building are more flexible having longer time period.The fundamental time period of M2 building model is greater by 2%, M3 building by 4% and M4 building by 7% than M1 model.

4.2 Inter-storey drift ratio

From the figure 9 and figure 10 ,it is observed that the difference in drift ratio for M1 and M2 building model has negligible variation in x direction whereas maximum drift

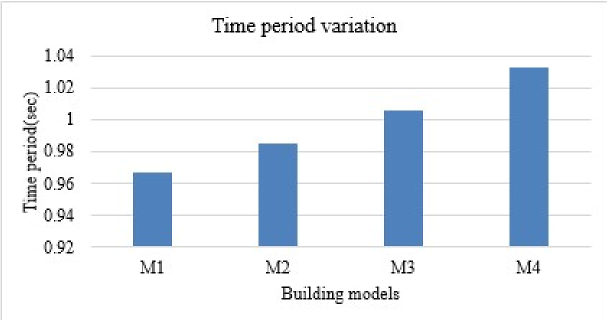

Figure 8: Fundamental time period variation of all the buildings

ratio has increased by 14% in y-direction relative to M1 building. In case of M3 and M4 buildings which has two frames non-orthogonal and all frames non- orthogonal respectively, the drift ratio has increased by 7% and 11% than M1 building in x direction. Likewise,the drift ratio has increased by 3% in M3 building model in y direction.However,18% in drift variation is observed in M4 building in y-direction which is less than M1 building model.The non-orthogonality of frames in x-direction has provided relatively higher rigidity in y-direction.Accordingly, the period of building for translation in y-direction is lowest for M4 building and hence the drift ratio is found to be lesser in y-direction.It showed that with frames non-orthogonal building having same column density designed as per codal provisions has increased drift ratio when compared with M1 building model.

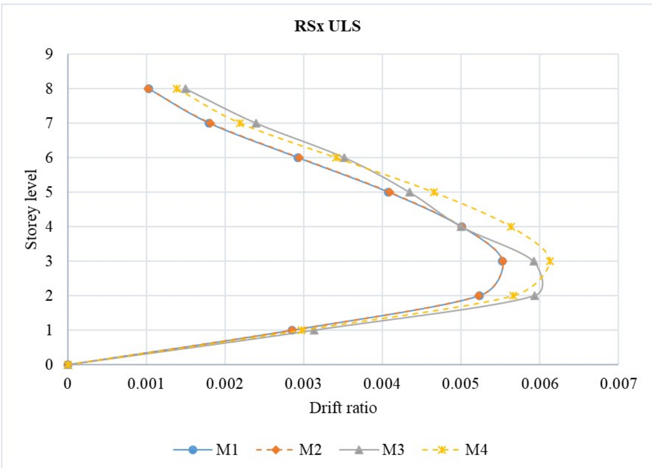

Figure 9: Drift ratio in X direction at ULS

4.3 Storey Displacement

From the figure 11 and figure 12,it is observed that the difference in storey displacement for M1 and M2 building model has negligible difference in x-direction whereas maximum displacement is higher by 15% in y-direction relative to M1 building.In case of M3 and M4 buildings,the displacement are higher by 7% and 8% in x-direction than M1 building.Likewise,the maximum displacement is greater by 4% in M3 building in y-direction compared to M1 building.However,18% variation in maximum displacement is observed in y-direction in M4 building model which is less

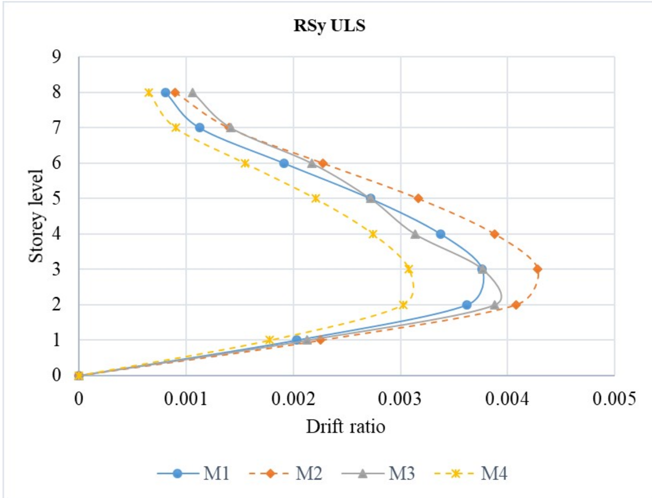

Figure 10: Drift ratio in Y direction at ULS

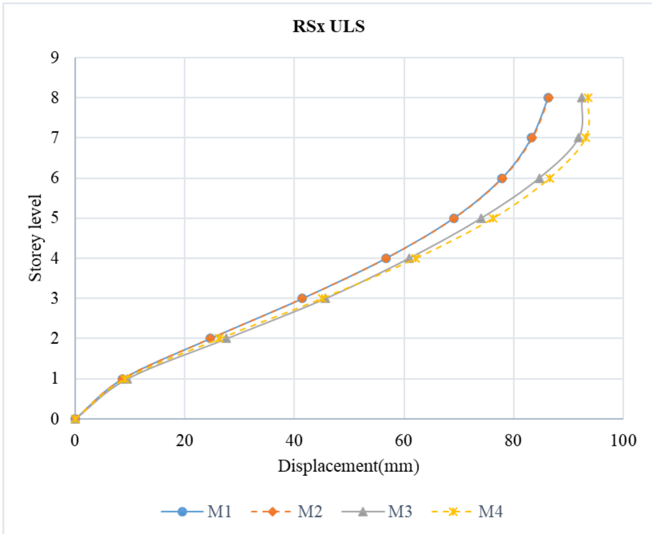

Figure 11: Displacement in X direction at ULS

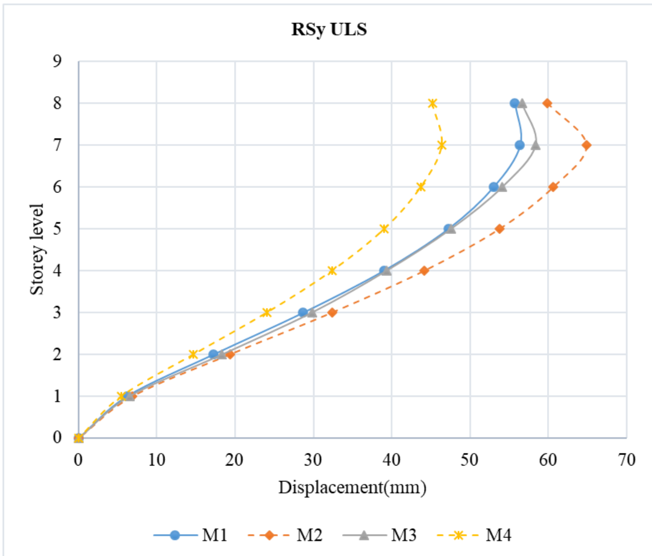

Figure 12: Displacement in Y direction at ULS

than M1 building.It showed that with frames non-orthogonal building having same column density designed as per codal provisions has increased displacement when compared with M1 building.

4.4 Pushover Analysis

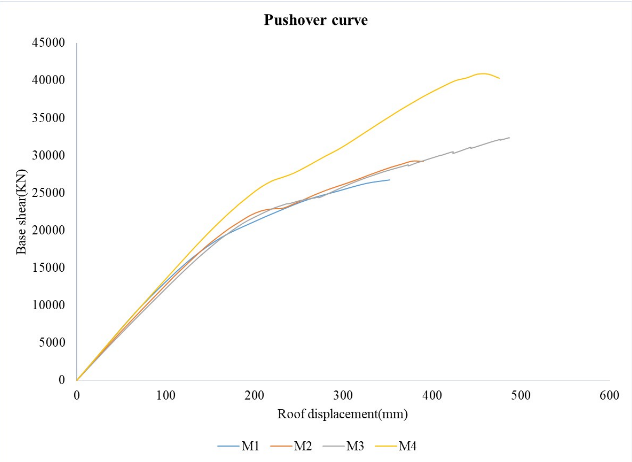

Figure 13: Pushover curve of M1, M2, M3 and M4 building in x-direction

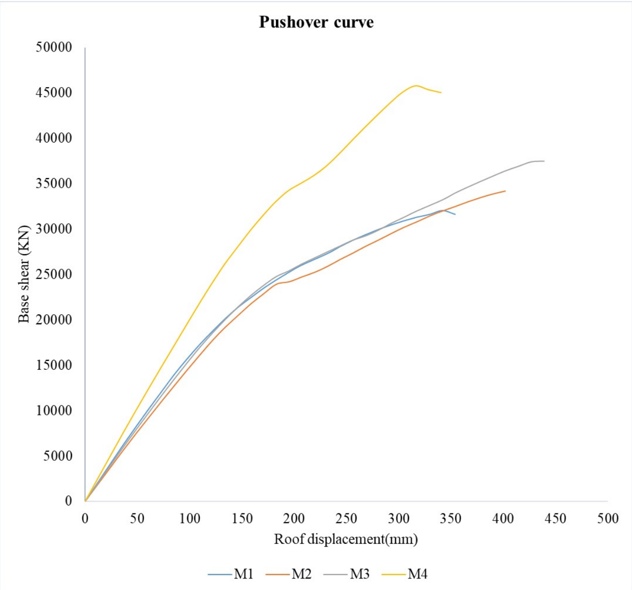

Figure 14: Pushover curve of M1, M2, M3 and M4 building in y-direction

From Figures 13 and figure 14, it can be seen that the base shear has increased with increased roof displacement. Considering the curves for M1, M2 and M3 building it can be seen there is marginal difference in base shear capacity. However, for M4 model with all frames non-orthogonal has significant increase in base shear capacity is observed compared to M1 model for same column density. Similarly, initial stiffness of M4 model is higher than the other models which can be seen from the pushover curve which suggests that the building is stiffer and can resist lateral deformation more effectively. It is also observed that the ultimate displacement of M2,M3 and M4 building is higher compared to M1 building model which shows these buildings have greater deformation capacity.

4.5 Performance level

Bilinearization of pushover curve is done as per FEMA 356.Then the yield displacement,ultimate displacement and their corresponding base shear is obtained from the bilinearized curve.For each building model,the yield and the ultimate displacement are obtained then the associated displacement at different performance levels is calculated.Deformation limits based on yield and ultimate displacement at different performance level is determined as given by [10] which is shown in Table 4 and Table 5.

Table 4: Displacement values corresponding to different performance level in x-direction

Building model	Yield displacement (mm)	Ultimate displacement (mm)	Damage State Displacement (mm)			
			IO	LS	CP	>CP
M1	144.77	352.28	101.34	217.15	248.52	352.28
M2	164.44	378.20	115.11	246.66	271.32	378.20
M3	174.56	486.20	122.19	261.84	330.38	486.20
M4	205.34	451.39	143.74	308.01	328.36	451.39

Table 5: Displacement values corresponding to different performance level in y-direction

Building model	Yield displacement (mm)	Ultimate displacement (mm)	Damage State Displacement (mm)			
			IO	LS	CP	>CP
M1	145.16	341.60	101.62	217.75	243.38	341.60
M2	150.29	401.46	105.20	225.43	275.87	401.46
M3	150.64	450.45	105.45	225.97	300.55	450.45
M4	167.82	315.89	117.47	241..86	251.73	315.89

Table 6: Performance point and base shear at 0.35g seismic demand

Performance Point(mm)			Base shear(KN)	
Building model	PUSH X	PUSH Y	PUSHX	PUSHY
M1	207.37	169.94	21539.92	23421.75
M2	205.57	182.67	22487.76	23889.94
M3	234.03	190.97	23477.98	25204.50
M4	291.98	207.53	30617.61	35108.24

Table 7: Demand corresponding to LS level of all building models

Building model	Demand	Performance point(mm)	Base shear(KN)
M1	0.35g	207.37	21539.92
M2	0.41g	237.85	23222.67
M3	0.38g	254.51	24053.70
M4	0.35g	291.98	30617.61

From Tables 4, 5 and 6,it is observed that each code-compliant building has met the life safety performance requirements at 0.35g seismic demand.Therefore,code based designed building with non-orthogonal frame can also meet life safety performance requirement as mentioned in code.Further,capacity that the building can resist for life safety performance is obtained.M1,M2,M3 and M4 building have met life safety criteria at demand of 0.35g,0.41g,0.38g and 0.35g respectively which is shown in Table 7 and figures 15,16.From the table and figure,it can be observed that the non-orthogonal frame buildings M2 and M3 have higher capacity i.e it can achieve LS performance criteria even at higher seismic demand compared to orthogonal frame building.Hence,code based designed non-orthogonal frame buildings having same column density can achieve life safety performance criteria.

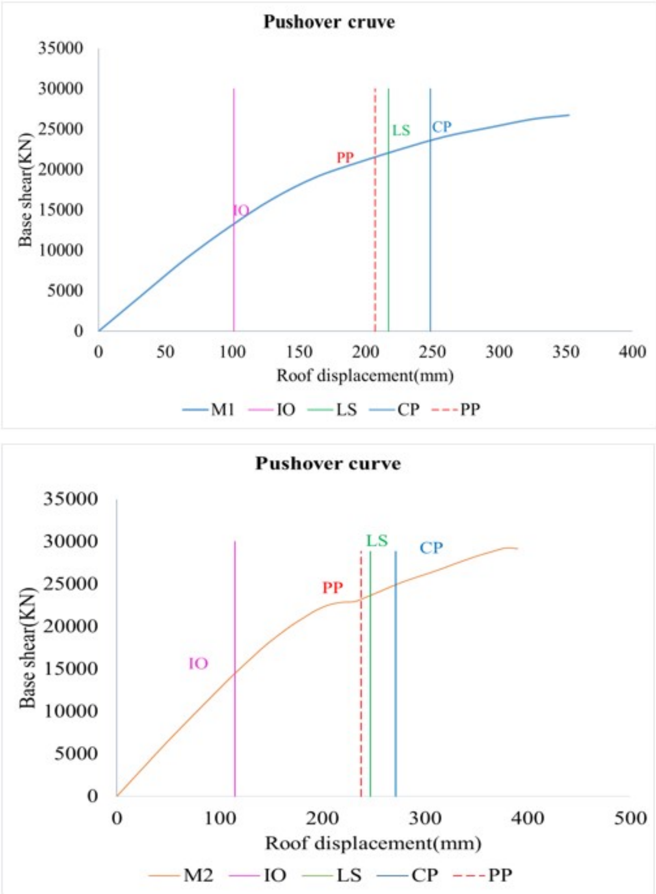

Figure 15: Pushover curve with performance point of M1 and M2 model

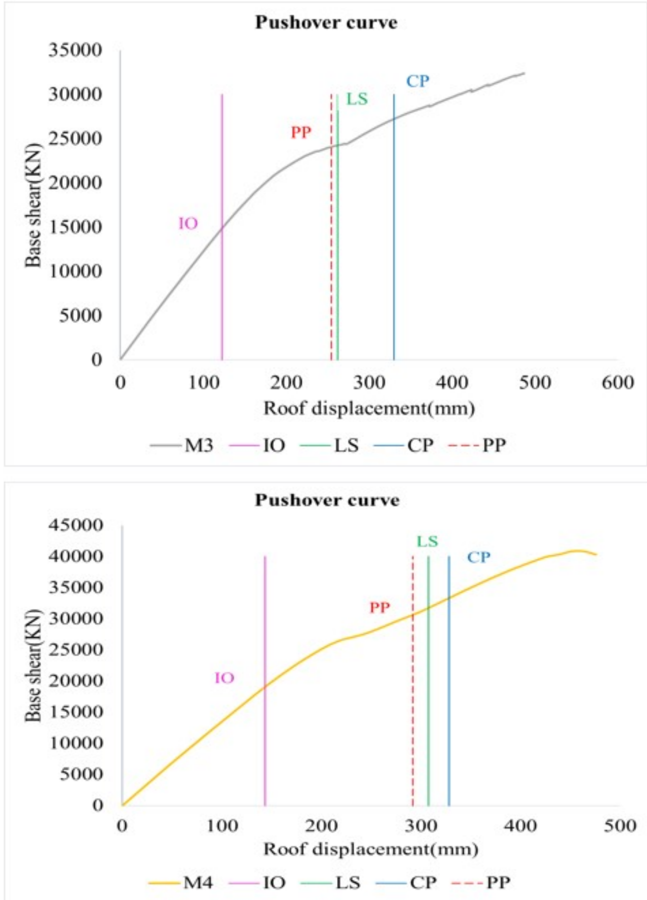

Figure 16: Pushover curve with performance point of M3 and M4 model

5. Conclusion and Recommendation

Four building models altogether,one with all frames orthogonal and the other three with non-orthogonal frames in increasing numbers with different configuration of non-orthogonality are studied.These structures have been analyzed,designed,and modelled.To assess the performance of the models and compare the outcomes,linear and nonlinear static analysis is carried out.The results obtained are presented and discussed in section 4.Following conclusion are drawn from the study.

1. Storey drift and storey displacement has increased with increase in number of non-orthogonal frames.These values are higher in non-orthogonal frame buildings relative to orthogonal frame building in x-direction whereas less value is observed in y-direction for M4 building.Natural period of vibration has increased in non-orthogonal frame building which shows the buildings are more flexible than orthogonal frame building. This is due the irregular geometry and mass distribution as the distribution of forces may vary according to the the building layout or configuration.
2. From capacity curve obtained from non-linear static analysis,the ultimate displacement is higher in non-orthogonal frame buildings than the orthogonal frame building as the reinforcement requirement are higher in non-orthogonal frame buildings.This shows that the buildings with non- orthogonal frame which are well–designed have higher deformation capacity.
3. All the designed buildings have met life safety requirement at 0.35g demand.Further capacity of building was determined for higher demand and it showed that the M2 and M3 model have achieved life safety criteria even at 0.41g and 0.38g respectively showing slightly higher capacity than M1 building. Hence, it is concluded that properly designed non-orthogonal frame buildings can have even more structural capacity than orthogonal frame building to resist the lateral forces. However,they require higher reinforcement requirement during the design process.
4. The results shows that NBC is more stringent for slightly non-orthogonal framed buildings (M2 and M3 cases),while the performance is similar for M1 and M4(higher non-orthogonality case),indicating that the performance of designed non-orthogonal building is not consistent, indicating that it may go below the desired performance level desired by the code for some cases of non-orthogonality. Hence, special attention is required in design of non-orthogonal buildings to verify if desired performance is met by the building.

References

[1] Theodore Cross, Flavia De Luca, Gregory ED Woods, Nicola Giordano, Rama Mohan Pokhrel, and Raffaele De Risi. Fast-nepal: Regionally calibrated spectral method for reinforced concrete with masonry infills. *Frontiers in Built Environment*, 7:689921, 2022.

[2] DUDBC. *Seismic design of buildings in nepal nbc 105:2020. 2020.* DUDBC, 2020.

[3] Dipendra Gautam, Hugo Rodrigues, Krishna Kumar Bhetwal, Pramod Neupane, and Yashusi Sanada. Common structural and construction deficiencies of nepalese buildings. *Innovative infrastructure solutions*, 1:1–18, 2016.

[4] Semih S Tezcan and Cenk Alhan. Parametric analysis of irregular structures under seismic loading according to the new turkish earthquake code. *Engineering structures*, 23(6):600–609, 2001.

[5] Benjamin Richard, Stefano Cherubini, François Voldoire, Pierre-Etienne Charbonnel, Thierry Chaudat, Salim Abouri, and Nicolas Bonfils. Smart 2013: Experimental and numerical assessment of the dynamic behavior by shaking table tests of an asymmetrical reinforced concrete structure subjected to high intensity ground motions. *Engineering Structures*, 109:99–116, 2016.

[6] Hyun-Kyu Lim, Jun Won Kang, Hongrak Pak, Ho-Seok Chi, Young-Geun Lee, and Janghwan Kim. Seismic response of a three-dimensional asymmetric multi-storey reinforced concrete structure. *Applied Sciences*, 8(4):479, 2018.

[7] Livian Teddy, Gagoek Hardiman, Sri Tudjono, et al. The effect of earthquake on architecture geometry with non-parallel system irregularity configuration. In *IOP Conference Series: Earth and Environmental Science*, volume 99, page 012004. IOP Publishing, 2017.

[8] Muberra Eser Aydemir, Umit Evliyaoglu, and Fatih Malkoc. The effects of ground motıon incıdent angle for orthogonal and non-orthogonal structures. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 46(6):4051–4065, 2022.

[9] Payam Tehrani and Ariya Eini. Seismic performance assessment of steel moment frames with non-parallel system irregularity. *Journal of Rehabilitation in Civil Engineering*, 10(4):109–128, 2022.

[10] Sergio Lagomarsino and Sonia Giovinazzi. Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. *Bulletin of Earthquake Engineering*, 4:415–443, 2006.