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Influence of Earthquake Direction on the Seismic Response of Non-parallel System Irregular RC Frame Buildings

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Abstract
In the seismic design of the structures, the ground motions are usually applied along the fixed orthogonal axes. However, the ground motion can act along any horizontal direction which may not coincide with the reference X- or Y- axes. Therefore, there may exist a possible orientation of the seismic incidence that would increase the structural dynamic response. In this paper, the behavior of the RC structure is studied by varying the excitation angle of seismic incidence. The seismic components are given in terms of two orthogonal horizontal response spectra. To find the critical angle, the excitation angle is changed from 0 to 90° in increments of 5°. The response is then compared with the percentage combination rule of Nepal National Building Code, NBC. The longitudinal reinforcement in the beams and columns of the ground floor is compared. The results show the decrease in reinforcement demand when the ground motion is applied along the principal axis of the structure. The reinforcement demand is found to be uneconomical and conservative while structure is designed considering the 30% combination rule as per the design code.

Keywords
Earthquake Incidence Angle, Non-parallel System, Principal Axis, Response Spectrum Analysis

1. Introduction

The behavior of the structure against the earthquake plays a vital role in collapse of the structure and it depends on many factors such as architectural design, geometric configuration of structural elements, earthquake zone, geographical location, soil type and so on. One geometric configuration that may result in the collapse of the building is irregular configuration of non-parallel system. Irregular buildings are frequently built in almost every country including Nepal. Irregular multi-storied building is becoming popular because of its both aesthetic architecture as well as its functional use. Nepal is a seismically active zone making it covered with major earthquakes in the past. Regarding this fact, an attempt is done to study the effect of earthquake incidence on the non-parallel system buildings.

According to NBC 105:2020 [1], nonparallel system irregularity is defined to exist when the vertical lateral force-resisting elements are not parallel to the major orthogonal axis of the seismic force-resisting system. The ground motion can act along any horizontal direction therefore, the maximum value of a design parameter may occur at any excitation angle. In case of non-orthogonal structures, the principal axis of the structure may not align with the reference X or Y axes thereby, the effect of the incidence angle on such structures should be considered more realistically. The seismic demand in case of multistory structures can vary considerably on the direction of seismic incidence [2]. The critical direction of the ground motion can be defined as that direction which yields the maximum structural response and depends only upon the horizontal spectra and not the vertical spectra [3].

For the analysis of non-parallel system irregularity, the existing design codes requires that members be designed for "100 percent of the prescribed seismic forces in one direction plus 30 percent of the prescribed forces in the perpendicular direction". while some other codes and organizations require the use of 40 percent rather than 30 percent. However, the above rule does not account for the direction of the incident seismic waves and gives no clue about the critical angle of incidence i.e., the angle of the incident seismic wave for which the demand of the structure is maximum. For the regular symmetric structures having clearly defined principal axes, these "percentage" rules give fair result but in case of irregular and complex structures, the response may be under or overestimated. In this study, a new combination rule is proposed that comprises the effect of the critical angle. The new combination rule is compared with the existing percentage combination and its impact is observed as the variation in the longitudinal reinforcement of beams and columns.

The effects of earthquake incidence angle have been examined by a number of researchers.

Aydemir et al. (2022) investigated the effect of earthquake incident angle in case of orthogonal and non-orthogonal buildings. The authors performed the nonlinear dynamic time history analysis by rotating the direction of both orthogonal components by θ =20° in intervals from 0° to 180°. The study found out that seismic incidence angle is a more effective parameter on column axial force and beam shear forces for non-orthogonal structure [4]

Magliulo et al. (2014) also studied the influence of earthquake direction on the seismic response of building structure, particularly in case of L-shaped plan irregular building. In this study, the non-linear dynamic analysis is carried out by considering twelve different earthquake directions and rotating the direction of both the orthogonal components by 30° for each analysis (from 0° to 330°). The result showed that the critical seismic angle increased the roof displacement and plastic hinge rotations by up to 37%. [5]

Rigato and Medina (2007) demonstrated that applying bi-directional ground motions only along the principal axes of an inelastic building underestimates the peak deformation demands when compared to those obtained at others angles of incidence. In this study, non-linear time histories with a set of 39 ground motion pairs were conducted in case of both symmetrical and asymmetrical structures. [6]

Lopez et al. (1996) studied the use of SRSS combination of two 100 percent spectra analysis over the 100/30 or 100/40 percent combination rules to account for the orthogonal effects of incident seismic waves. In this paper, the authors clarified that the use of percentage rules although, do not introduce any major errors; however, they have no theoretical justification so, needs to be immediately discontinued and the use of SRSS combination be followed for the design of building systems. [7]

2. Methodology

The non-orthogonal building layout is selected for the study. The modal response spectrum method is used for the analysis. The response spectrum analysis is a linear dynamic method which evaluates the likely maximum seismic response of an elastic structure by assessing the contribution from each natural mode of vibration. As per the NBC 105:2020 code, response spectrum can be used for structures where the equivalent static method is not applicable such as in case of irregular structures. The response spectrum method also allows for the application of earthquake loads at any desired angle, providing flexibility in determining the principal axes. Considering the aforementioned facts, the response spectrum method is chosen for the analysis. Given that this type of plan irregular buildings is predominantly observed in core urban areas like the Kathmandu Valley, which is characterized by the soft soil deposits. Therefore, the design response spectra curve is selected from the NBC 105:2020 code considering the soil type D as shown in the Figure 1.

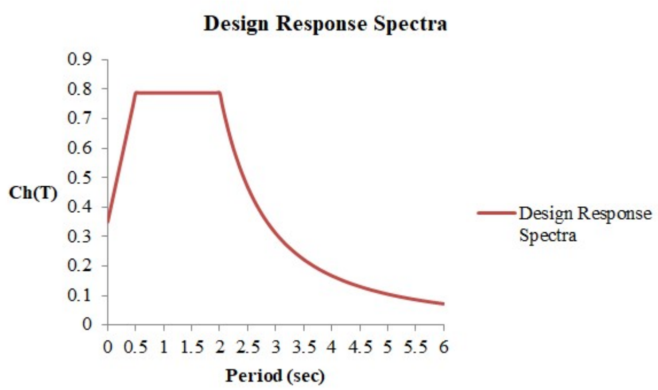

Figure 1: Design Response Spectra Curve for Soil Type 'D'

The principal axis of the structure is found out by changing the loading direction in ETABS. The direction that generates the largest base shear in the structure is the principal axis of the structure. For varying the excitation angle, horizontal orthogonal response spectrum components RSx and RSy are applied varying from 0 to 90° in increments of 5°along both the axes. After, the principal axis verification, the model is then analyzed for different load combinations. Two distinct load combination cases are compared to study the effect of incidence angle on the structure.

Case 1:

The load combination used for this case is as suggested by the NBC 105 code for the non-parallel system irregularity which mandates that the structures be designed for simultaneous effects due to full design earthquake load in one direction plus 30 percent of design earthquake load along the other horizontal direction i.e.,

1.2DL + 1.5LL

DL + λ LL + RSx + 0.3RSy

DL + λ LL + RSy + 0.3RSx

Case 2:

In this case the percentage combination rule is not used instead, the response spectra components acted along the principal axis of the structure are combined directly as follows:

1.2DL + 1.5LL

DL + λ LL + RSx(θ)

DL + λ LL + RSy(θ); θ is the critical excitation angle.

where, RSx(θ) and RSy(θ) represents the maximum absolute seismic load effect when the structure is excited by the critical response spectrum load.

Building features used for the study are listed in Table 1. To make the non-parallel orientation of structural members, the building is shaped like a trapezoidal with its one grid aligned with 30° to the y-axis as shown in figures 2 and 3.

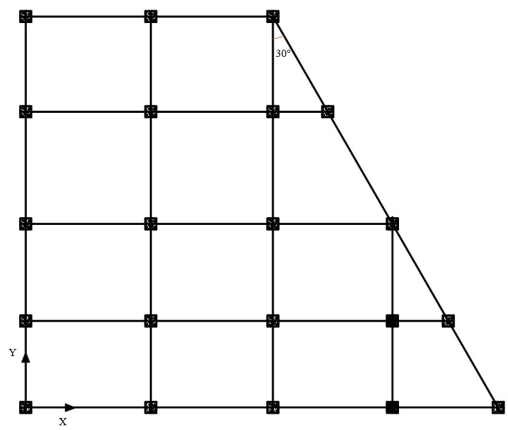

Figure 2: Building plan used for the analysis

Table 2: Performance Requirement as per NBC Code

Modal Properties:	
Fundamental time period	0.922 sec
Modal Mass participation:	
Ux, Uy, Uz	0.7047, 0.6655, 0.6359
Story Drifts:	
RSx	0.005203 <0.00625
RSy	0.004775 <0.006

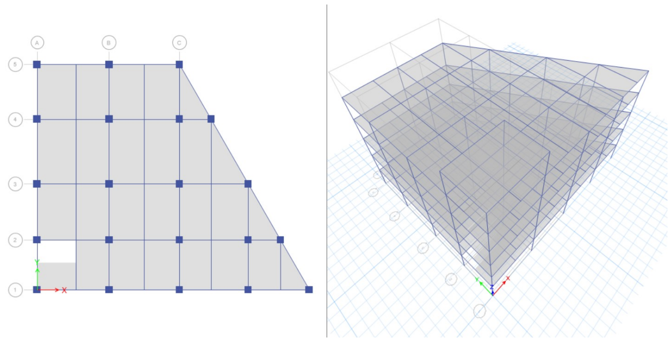

Figure 3: Three dimensional model of the building with ETABS

Table 1: General Features of the Building

Title	Specification
Type of building	Office building
Structure System	RC Moment Resisting Frame
Plinth Area	423.24 m2
No. of story	5 (five) story + stair cover
Floor to floor height	3.35m
Types of Slab	125mm thick; Two-way slab, 150mm thick staircase slab
Types of Beam	Rectangular main beam (400mm x 600mm)
Types of Column	Square Column (700mm x 700mm)
Unit weight of brick	19.2 KN/m3
Grade of Concrete	M25
Grade of Steel	Fe500
Method of Analysis	Response Spectrum Method

The ductility and the over-strength factor is coherent with the code provisions for reinforced concrete moment resisting frame. The dead loads used in the analysis is taken from the Indian Standard (IS 875 (part 1):1987) and the live load is considered from IS 875 (part 2):1987 [8]. The seismic load is calculated following the NBC code.

The building is checked for the inter-storey drift limitation and the modal mass participation factor. The drift value for the Ultimate Limit State (ULS) is obtained by multiplying the horizontal deflection obtained from the Response Spectrum Method by the ductility factor. And the drift value for the Serviceability Limit State (SLS) is obtained by taking equal to the horizontal deflection. The drift requirement and the modal mass participation is shown in Table 2.

3. Results and Discussion

Modal Response Spectrum analysis is conducted to study the effect of earthquake incidence angle on the structural response. To this purpose, longitudinal reinforcement variation along the columns and the beams are taken as the observed parameters.

3.1 Demonstration of Principal Axes

To find out the principal axis, the response spectrum load angle is changed from 0 to 90° and the result is shown in figure 4. The figure shows that the base shear along the x-direction is maximum when the excitation angle is 5° and the maximum base shear along the y-direction occurs at 0°. This shows that the principal axes of the model are oriented at 5° from the reference X-axis and coinciding with the reference Y-axis of the model. As shown in the figure 5, **X, Y** are the reference axes of the model or say the global axis of the structure. After the analysis, it is found that the critical angle of incidence (for x direction ground motion) is 5° acting in the anticlockwise sense from the X axis. However, the ground motion is coinciding with the global Y axis so, critical angle for y-direction motion is along the Y axis. The lines I and II shown in the figure 5 represents the principal axes of the model.

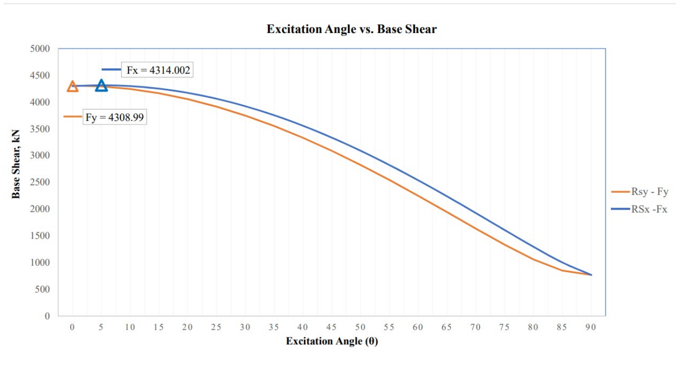

Figure 4: Plot of Excitation Angle and Base Shear

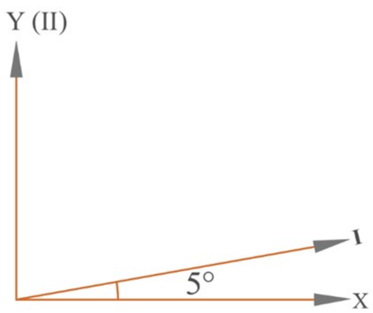

Figure 5: Demonstration of Principal Axes of the Model

Thus, it can be concluded that the principal axes in case of the above non-orthogonal type irregular model does not necessarily coincide with the reference orthogonal X-Y axes. This shift of the principal axis from the original reference axis in such structures can be due to their plan irregularity which in turn causes the uneven distribution of strength and stiffness across the plan.

The variation in the base shear with the excitation angle is also plotted for a regular symmetrical structure which yields the graph as shown in figure 6. It is evident that the maximum base shear along both the axes occur at 0° meaning that the principal axes in this case coincides with the reference X-Y axes. Therefore, it can be concluded that in regular symmetric structure, the excitation angle has no significant impact however, in case of non-orthogonal framed structure, the response is observed to vary with the excitation angle and the maximum response occurring at critical angle of incidence.

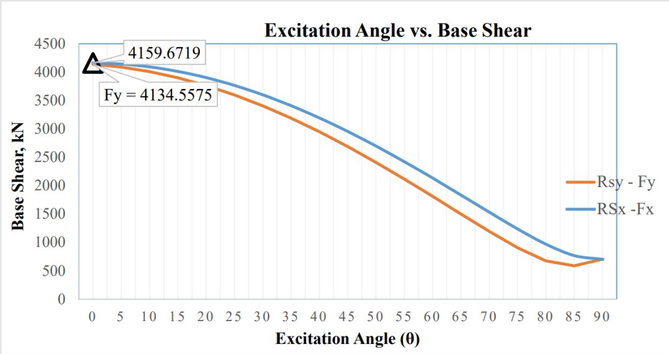

Figure 6: Plot of Excitation Angle and Base Shear For Regular Structure

3.2 Evaluation of Longitudinal Reinforcement in Columns

The reinforcement area for the ground floor columns is plotted for two different cases of load combination:

Case 1:

1.2DL + 1.5LL

DL + λ LL + RSx + 0.3RSy

DL + λ LL + RSy + 0.3RSx

Case 2:

1.2DL + 1.5LL

DL + λ LL + RSx(5)

DL + λ LL + RSy(0);

Here, the load combination shown in 'case 1' accounts for the 30% combination rule as per the NBC code as required in case of non-parallel system irregularity. While the 'case 2' combination takes into account the effects due to the full design earthquake load in the X and Y directions along the specified critical direction i.e., RSx(5) & RSy(0).

Figure 7 and 8 shows the longitudinal reinforcement area variation in ground floor columns and the percentage reduction in the reinforcement area. It is clear from figure 6 that the column reinforcement area is decreased when the case 2 load combination is used for the analysis. The trend shows that on an average 22% (figure 7) reduction in the reinforcement area has occurred which showed that the percent combination rule gave conservative and uneconomical result. Similar variation can also be seen in the upper floors of the model however, for the current study the results are limited to the ground floor only.

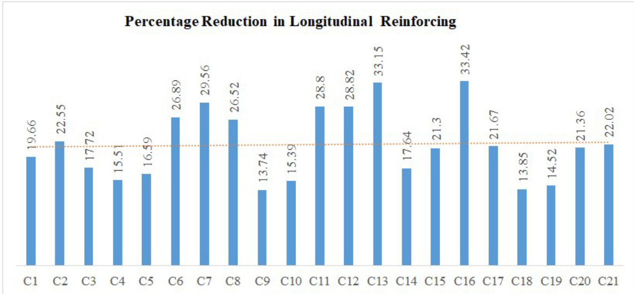

Figure 8: Percentage Reduction in Reinforcement Area

3.3 Evaluation of Longitudinal Reinforcement in Beams

The figures 9, 10 and 11 shows the variation in the longitudinal reinforcement areas in case of beams of the ground floor only. Here, the beams located at three different locations are analyzed. For example, figure 9 shows the variation in case of beams lying along the x-axis of the model. Similarly, figure 10 shows the variation in case of beams lying along the y-axis of the model and the figure 11 shows the variation in beams lying at inclination of 30° with vertical.

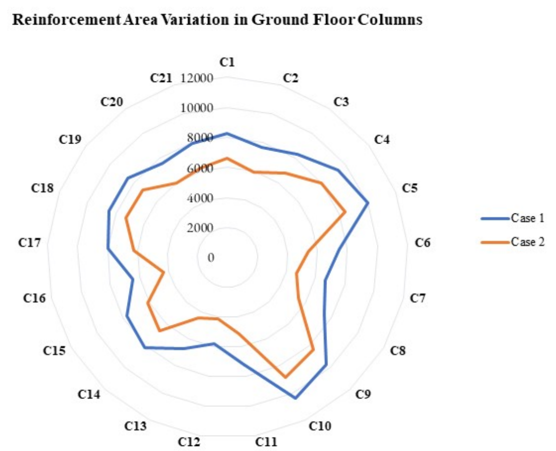

Figure 7: Plot of Reinforcement Area Variation in Ground Floor Columns

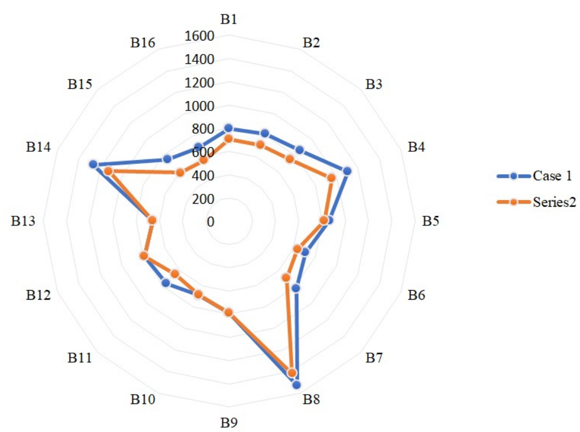

Figure 9: Reinforcement Area Variation in GF Beams along X-axis (Bottom Max reinforcement)

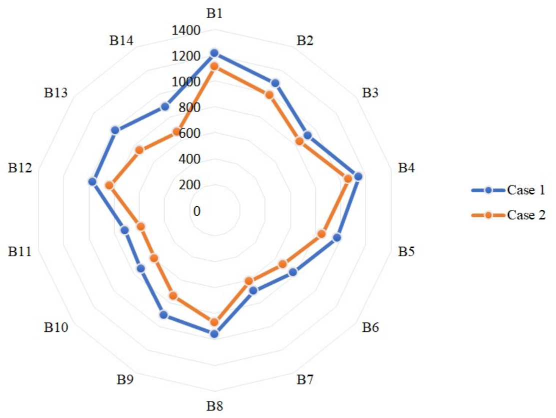

Figure 10: Reinforcement Area Variation in GF Beams along y-axis (Bottom Max reinforcement)

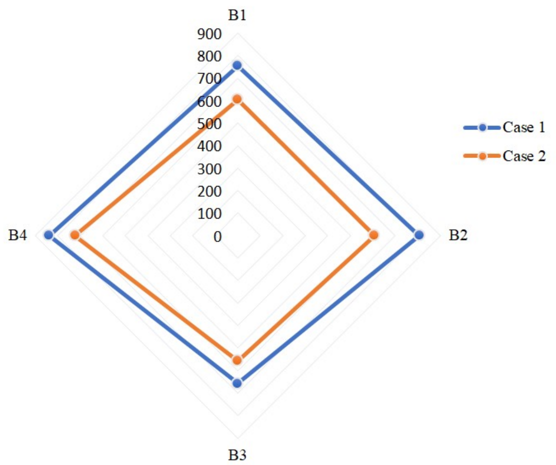

Figure 11: Reinforcement Area Variation in GF Beams Lying At-Angle (Bottom Max reinforcement)

The above figures shows that on an average 9.65% of the bottom reinforcement area has decreased using comb. 2 in case of beams lying along x-axis. Similarly, for the beams lying along y-axis, the reduction in the reinforcement is 14% and for the beams which are at angle, the reduction of 18% is obtained. This shows that the percentage combination rule overestimates the values of reinforcement area and is thus seen to be uneconomical for this case.

4. Conclusions

A study about the influence of earthquake direction is performed for a model having non-parallel system irregularity. To comprehend the effect of seismic incidence angle on the structure, a linear dynamic analysis i.e, response spectrum analysis is performed by rotating the direction of orthogonal components by 5° in the intervals from 0° to 90°. Reinforcement area of columns and beams is taken as the observed parameters which are compared for two different cases of load combinations. The following conclusions can be drawn from the results of the study.

- In case of non-parallel framed buildings, it is observed that the principal axes does not coincide with the reference X-, Y- axes while, in case of regular structure, the incidence angle seems to have no significant effect. Thus, the principal axes coincides with the reference structure axes in the case of symmetric buildings.
- The principal axes of the building is the one which are oriented along the direction of critical incidence. The critical incidence is the angle of excitation that creates the largest base shear along the component.
- For the buildings modelled as shown in this paper, the reinforcement area in the columns are reduced up to 22% when combination 2 is used for the analysis
- Similarly, for the beams, the bottom maximum reinforcement area is decreased by 9.65%, 14% and 18% for the beams lying along X, Y and inclined directions respectively.
- The above points highlights the fact that the code percentage combination rule overestimates the demand in case of non-parallel framed structure and is thus, uneconomical for the case studied here.
- Therefore, it should be noted that for the analysis of irregular structures, the effect of the seismic incidence direction be considered apart from the code provisions only.

5. Recommendations

- The above study has been revolved around the specific type of plan irregularity. The variation in plans and stories needs to be done to further validate the above conclusions.
- There are only two parameters dealt in this paper. Therefore, a more detailed parametric study should be conducted to fully comprehend the effect of excitation angle on various building components

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