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Seismic Performance of Steel Building with Vertical Irregularities

Ina Shrestha [a], Gokarna Bahadur Motra [b]

[a, b] *Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[a] 076MSSTe009.ina@pcampus.edu.np, [b] gmotra@ioe.edu.np

Abstract
The ground motion of an earthquake can cause damage to structures. Given the prevalence of steel construction in Nepal, it is important to investigate how these structures fare during earthquakes. This paper presents the results of analysis of five-story steel structures with vertical abnormalities, including mass, stiffness, and vertical geometric irregularities. It is necessary to research the seismic performance of those buildings if earthquake-resistant steel buildings with vertical irregularities are to be constructed. Here, a nonlinear static analysis study of five storey steel-frame buildings with vertical irregularities is taken into account. IS 1893(Part 1):2016 is used to analyze response characteristics including base shear, fundamental time period, storey stiffness, storey drifts ratio, and storey lateral displacement.Asymmetric buildings behave far more complexly and perform much poorer under seismic excitation than conventional buildings. The basic concept entails assessing the effects of asymmetric stiffness distribution, uneven mass distributions, and vertical setbacks and contrasting it with the seismic response of a conventional structure. It has been discovered that the seismic reaction is significantly impacted by irregularity. Out of all the vertical irregularities that were evaluated, vertical setbacks have been found to have the biggest effect on the reaction.

Keywords
Seismic Performance, Vertical Irregularities, Pushover Analysis, Steel-Framed Building

1. Introduction

1.1 Background

Earthquake is the most harmful and unpredictably occurring natural process. Stiffness, enough lateral strength and ductility, as well as a simple and regular configuration affect how buildings behave during seismic activity. It is critical to conduct study on how earthquakes effect buildings and how to develop structures with the least amount of damage. Traditional reinforced cement concrete structures are being replaced by new steel-frame buildings in the majority of emerging nations, including Nepal. Steel is the best material for earthquake-resistant structures because it is ductile and robust in both compression and tension. Due to establishment of various steel manufacturers growing around the nation, the cost of steel has decreased and demand for steel structures is rising right now. Steel structures are now more important and used more frequently as a result of the devastating earthquake in 2015. The building of these types of structures has increased during the past four to five years, along with the need for and consumption of steel, mostly for commercial purposes. [1, 2, 3]

The behavior of the structure is significantly influenced by its structural configuration and elemental arrangement. Experience from previous earthquakes has demonstrated that buildings with a straightforward and consistent design sustain less damage. The torsion that damages a building is greatly influenced by the position, size, and orientation of structural parts. Contradictory irregular structures with discontinuities are where pressures and deformities are concentrated. The position, type, and degree of irregularities present in that mostly determine the size of the building's response. Buildings' performance when subjected to seismic load can be ensured if all these factors are wisely taken into account during design.[4][5]
The structure's inertia generates seismic forces as it strives to offset ground motions. When two building components move apart, a force is produced equal to the ground acceleration times the mass of the structure. The building's center of mass (CM), which is located on each floor, is the site of this inertial force. A force must be opposed by an equal and opposite

reaction once it is there. As the structure resists the inertial force, the opposing force acts at the center of rigidity (CR) on each floor. Since absolute regularity is a very unusual idealization, real structures almost always have some degree of irregularity. The technique of analysis to be utilized for a structure is dependent on its irregularity, in addition to the structure's overall height and the seismic zone in which it is located, according to Clause 7.8.1 of IS:1893(Part 1):2016 [6].

Figure 1: Steel Building

1.2 Need of the research

Building facilities have objects that are economical, aesthetically pleasing, and practical. In addition to addressing the constraints imposed by the other parties involved in the process, such as the owner, architect, contractor, and so on, the role of the structural engineer is to provide a solution that meets the structural performance goals throughout the anticipated life of the structure. As a result, the structural engineer needs to be well-versed on the seismic response of various building structure types and configurations. Furthermore, there is a need for design procedure that accounts explicitly for the demands imposed by ground motions in which there has been a lot of research done for regular structure. However the seismic response of structures having vertical irregularities needs to be studied. Additionally, a method that enables the structural engineer to calculate the seismic requirements for irregular structures is needed. [7]

1.3 Objective

The main objective of this research is to evaluate the performance of steel structure having vertical irregularities and compare the response parameter with regular building. The specific objective of this work is:

- To assess the vulnerability of the selected steel buildings with and without vertical irregularities.

2. Methodology

2.1 Section of Building

A G+4 storey regular steel-framed building model is considered. Then, it is altered by adding various vertical irregularities to create three asymmetrical forms. The goal is to evaluate each of these models and then contrast them using seismic response metrics including base shear, fundamental time period, storey lateral displacement, and storey drift, among others.

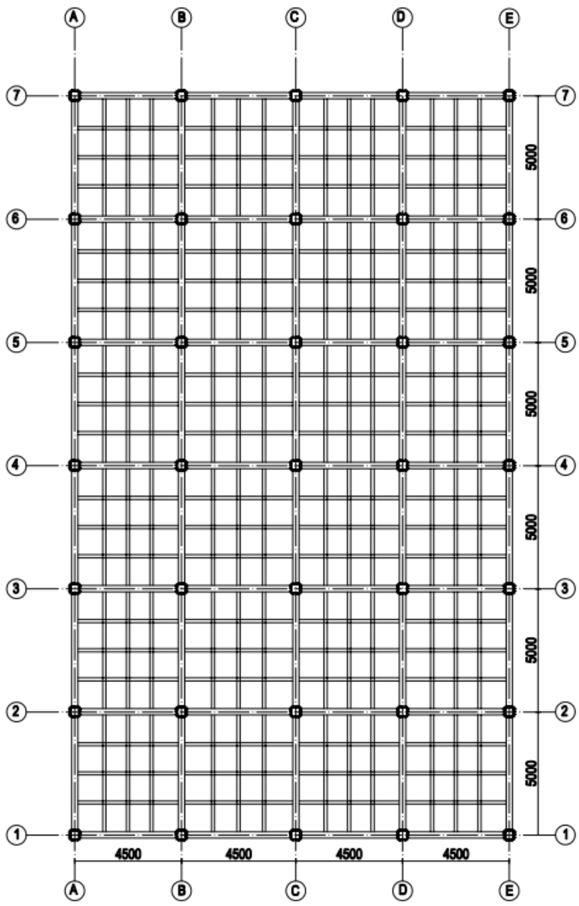

Figure 2: Ground Floor Plan

2.2 Material and Sectional Property

The building configuration and structural details are limited as stated.

Table 1: Structural Details and Input Parameter

Storey Height	3.048m
Total Height of the Building	15.24m
Dimension of plan in X-dir	18.0m
Dimension of plan in Y-dir	30.0m
Column used	2-ISMC400
Beam used	ISMB400
Secondary Beam used	ISB113.5*113.5*4.8
Bracing used	ISMC200
Grade of concrete	M20
Grade of steel	Fe250
Unit weight of brick masonry	20KN/m²
Live Load	2 KN/m²
Floor Finish Load	1.5 KN/m²
Seismic Zone	V
Seismic Zone Factor	0.36
Type of soil	Medium Soil
Response Reduction Factor	5
Importance Factor	1

2.3 Structural Modeling

2.3.1 Regular Building

Model I is the regular steel building which is symmetrical in elevation. It is a five storey building with brick masonry wall and steel frame. For this research purpose, the effect of staircase are considered negligible.

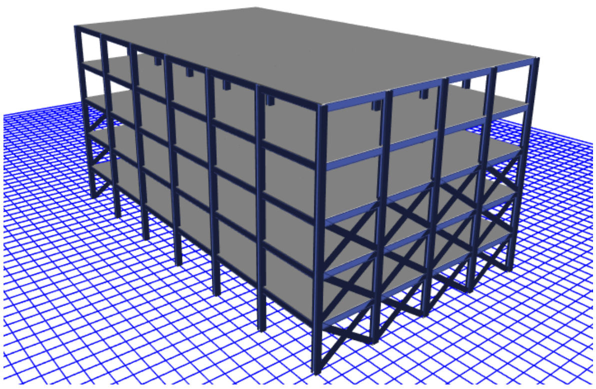

Figure 3: Model -I

2.3.2 Mass Irregular Building

This model's structural layout is identical to that of model -I. Heavy mass of 4 KN/m² is provided on third floor for mass irregularity. The remaining data are same as model-I. Hence, as per IS 1893 (Part 1): 2016, the structure shown in figure 4 is vertically irregular structure with mass irregularity.

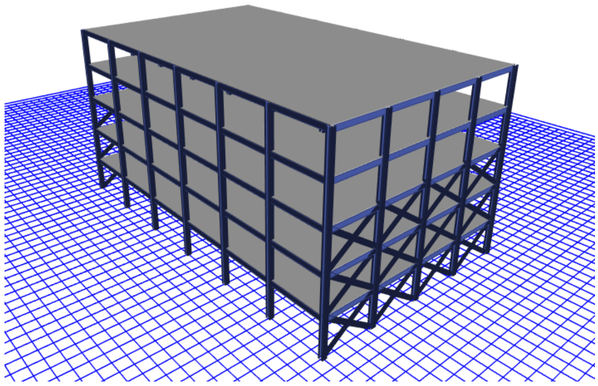

Figure 4: Model-II

2.3.3 Stiffness Irregular Building

This model's structural layout is identical to that of model -I. Stiffness irregularities introduced by increasing height of ground floor to 4.5m. All the remaining floor are of 3.048m height.
Stiffness of each column = $12EI/L^3$
Therefore, stiffness of ground storey/stiffness of other storey = $(3.048/4.5)^3 = 0.443 < 0.7$
Hence, as per IS 1893 (Part 1), the structure shown in figure 5 is vertically irregular structure with stiffness irregularity.

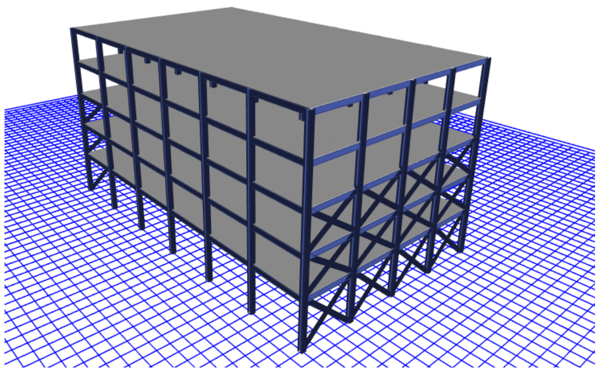

Figure 5: Model-III

2.3.4 Vertical (Geometric) Irregular Building

This is vertically irregular model having vertical irregularity with steps at each floor.
Width of top storey= 10m
Width of ground storey= 30
Width of top storey / Width of ground storey = 30/10= 3>1.5
Hence, as per IS 1893 (Part 1): 2016 the structure shown in figure 6 is vertically geometric irregular structure.The remaining data are same as model-I.

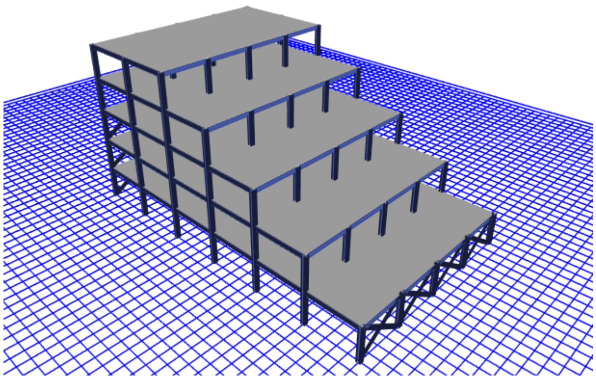

Figure 6: Model-IV

2.4 Non-Linear Static Analysis

Pushover analysis, also referred to as non-linear static analysis, is a technique for evaluating how well new or existing structures will withstand earthquakes. In this kind of study, the connection between applied forces and displacements is non-linear. Both material and geometrical non-linearity have the potential to cause these effects. An illustration of the results of this technique of analysis is a load verses displacement curve.

The nonlinear static analysis method known as ”Pushover Analysis” is a streamlined method that can be used to estimate structural deformations brought on by seismic forces. A load vs. displacement curve serves as the process’ output. The imposed lateral loads to the structure roughly correspond to the seismic forces. The seismic forces are roughly represented by the lateral loads placed on the structure. The analysis is carried out until the structure fails, which aids in identifying the ultimate load at which the collapse takes place as well as the ductility of the structure.

The pushover curve, which is depicted in Figure 7 and is also known as the curve between base shear and roof displacement, contains the crucial information for calculating the overstrength and ductility components. In order to use the nonlinear static approach to compute the seismic demand, the structure is subjected to a lateral force that increases monotonically. Up until the intended displacement value or the final limit state is reached, the lateral force is applied. [8, 9]

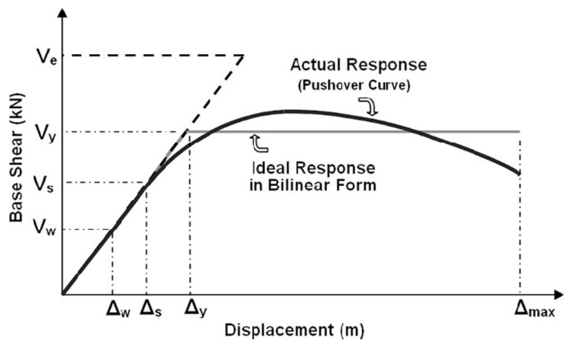

Figure 7: Capacity Curve([8]))

3. Result and Discussion

The comparison of all the models is carried out considering X-Direction and Y-Direction of the building. Model I is the regular structures without any vertical irregularity. Model-II is structure with mass irregularity. Model-III is structure with stiffness irregularity and Model-IV is structure with vertical setback. Model-II, III and IV are compared with respect to model-I.

3.1 Base Shear

Table 2 shows the base shear of four models considered for this research. In comparison to model-I, the base shear of model-II is more. This is due to heavy mass present at third storey of the building. As we know base shear is directly proportional to seismic weight, base shear of model-II is more in comparison to others. Model-III has slightly more base shear than model-I as the height of ground storey is slightly more. Model-IV has lower base shear in comparison to model-I because of vertical setbacks present at each floor.The vertical setbacks present in each floor decreases seismic weight of the building which in result decreases the base shear in significant amount.

Table 2: Base Shear in X and Y- Direction

Building Model	Base Shear	(KN)
	X-Dir	Y-Dir
M-I	2410.5416	1626.7943
M-II	2604.9416	1682.1119
M-III	2414.8903	1559.3884
M-IV	1708.1135	1404.1122

3.2 Fundamental Time Period

Since all models have the same dimensions, the fundamental time period defined by the empirical formula of code

$$T_a = \frac{0.09 * h}{\sqrt{d}} \quad (1)$$

is also same for all models.
Here,
Height of the building(h) = 15.24m
Width of the building (d_x) = 30.0m
Width of the building (d_y) = 18.0m
According to IS 1893 (Part-I): 2016,
Time period (T_x) = 0.25s
Time period (T_y) = 0.32s

Table 3: Time Period in X and Y- Direction calculated by FEM model

Building Model	Time Period	(Sec)
	X-Dir	Y-Dir
M-I	0.412	0.806
M-II	0.416	0.816
M-III	0.419	0.842
M-IV	0.467	0.662

Table 3 demonstrates how the time period of the building changes when various types of irregularities are present. The fact that the time period calculated by the software varies for each model suggests that, contrary to what IS 1893 (Part 1): 2016 recommends, the fundamental time period of an irregular building depends on the type of irregularity present as well as the building's height and base width. Vertical (geometric) irregular building is observed to have the shortest time period in the direction under consideration, while rigidity irregular building (M-III) has the longest (M-IV). In comparison to model I, model IV has a shorter time period. This is caused by the mass and stiffness being lower than those of the model-I.

3.3 Storey Stiffness

In ETABS after analysis the storey stiffness is dependent upon the storey lateral force and storey displacement. The storey stiffness of regular structure is considered 100 percentage for each storey. The storey stiffness of irregular structure has been reduced as compared to the regular one.

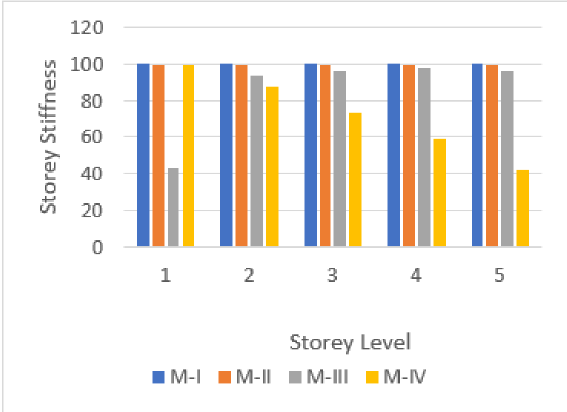

Figure 8: Storey Stiffness in X direction

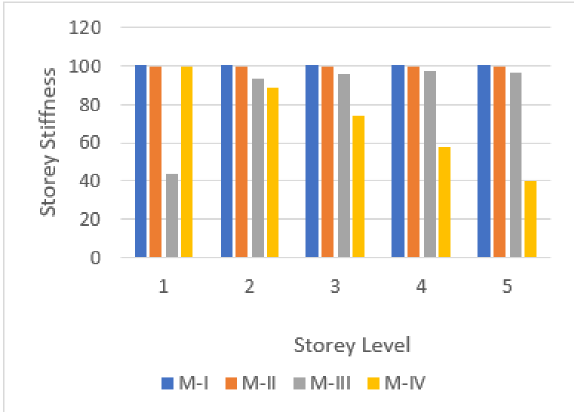

Figure 9: Storey Stiffness in Y direction

In figure 8 and 9, it is observed that the stiffness of irregular models is reduce as compared to the regular one. The stiffness of building with mass irregularity(M-II) is similar as compared to model-I. There is not much change in stiffness in this model because shape, size and number of columns are same. The stiffness of building with stiffness irregularity(M-III) is reduced as compared to model-I. As height of ground storey of model-III is more than that of model-I, the stiffness of ground storey is comparatively less than that of model-I. In building with vertical irregularities(M-IV), number of columns decreases with every storey. The stiffness also decreases with every storey in comparison to model-I.

3.4 Storey Lateral Displacement

The maximum displacement of a storey in a building in response of the excitation due to the earthquake in principal direction is called story displacement. The elastic force is the product of the spring stiffness and the displacement i.e. $F = K * y$. it is checked that the displacement does not exceed the IS codal provision of 0.4 percentage of H. The maximum lateral displacement of all models is within permissible limit prescribed by the code i.e. (0.004H= 60.96mm), where H is the overall height of the building

Table 4: Storey lateral displacement in X and Y-Dir

Building Model	Lateral Displacement	(mm)
	X-Dir	Y-Dir
M-I	16.346	17.206
M-II	15.741	16.828
M-III	15.549	16.948
M-IV	19.585	18.31

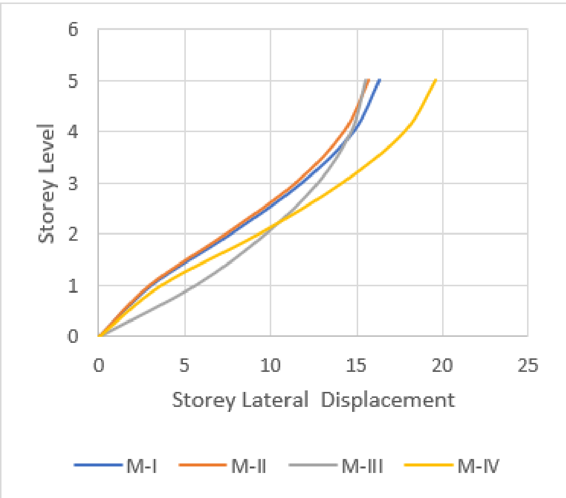

Figure 10: Storey Lateral Displacement in X direction

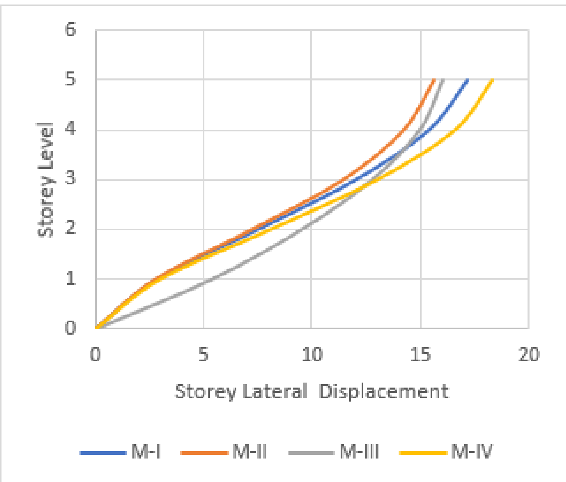

Figure 11: Storey Lateral Displacement in Y direction

It is observed that storey lateral displacement of model IV is higher in comparison to model-I in both X and Y direction. This is because there is reduction of lateral stiffness in model-IV which increases the storey lateral displacement. The path of storey lateral displacement of model-II and mode-III are similar to that of model-II. This is because stiffness of are three models are similar. However, for model-III stiffness of ground storey is more than compared to model-I, so we notice that lateral displacement of ground storey is more than that of model-I.

3.5 Storey Drift Ratio

Storey drift and storey drift ratio are distinct from one another. While storey drift ratio is the ratio of storey drift to the storey height, which is unit-less, storey drift is the lateral displacement of a story relative to another storey above or below that is actually measured in length. In actuality, they both explain how a building behaves. All of the models' storey drift ratios are within the code's permitted range. i.e.,($<$0.004).
According to the table, a vertical (geometric) irregular building has the largest drift ratio and a stiffness irregular building (Model-III) has the lowest. The same factor that caused storey lateral displacement also accounts for this. Storey drift ratio increases as the building's stiffness decreases, which increases lateral displacement..

Table 5: Storey Drift ratio in X and Y- Direction

Building Model	Storey Drift Ratio	
	X-Dir	Y-Dir
M-I	0.001523	0.001523
M-II	0.001467	0.001467
M-III	0.001348	0.001348
M-IV	0.001856	0.001856

4. Conclussion

The following findings have been obtained from this research after analyzing the tabular and graphical outcomes of all the models. To compare the seismic response of the regular and irregular buildings, linear and nonlinear static analyses have both been carried out.

The seismic weight of the building varies due to presence of irregularity. This affects the base shear of the building. Base shear for building with mass irregularity is found maximum and building with vertical (geometric) irregularities is found minimum.

The fundamental time period of an irregular building is not only dependent on the building's height and base width as prescribed in the code IS 1893 (Part 1); 2016. It also depends upon the type of irregularity present specially in buildings with setbacks. The time period of the vertically irregular building is lesser than that of the regular building.

Storey stiffness depends on the height and number of column present on any storey. Storey stiffness of building with vertical (geometric) irregularity decreases with increaing storey.

Storey lateral displacement and storey drift ratios increases with the presence of irregularity. A sudden increment was noticed in the storey drift ratio with vertical setbacks. This is because of the reduction of stiffness of the building. Hence at this point the building with vertical (geometric)irregularity should be strengthened.

Building having mass irregularity, stiffness irregularity and should be analyzed and designed properly. Special detailing and designing methodology should be utilized to keep the displacement and stress within permissible limit. The analysis shows that the vertical irregularities affect the performance of steel building under seismic loading.

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