Seismic Fragility Analysis of Vertically Irregular Steel Framed Buildings

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Abstract: Disaster mitigation of the country requires the data of fragility curves for various typical buildings. As the number of steel buildings in the cities is increasing, development of seismic fragility curves of steel buildings are also the need of the hour. This study discusses the fragility curves and damage index functions of a 7-storey regular and irregular steel-framed buildings subjected to different earthquake ground motions. Each building was designed based on the codes, IS 800 (2007) and IS 1893 part 1 (2016). Time History Analysis of various vertically irregular framed buildings was performed and displacements of each floor were obtained. Inter-storey drift ratio and spectral acceleration at fundamental period are taken as damage parameter and intensity measure for deriving the fragility curves. The probabilistic seismic demand models for typical stiffness and mass vertical irregular buildings were developed. Steel framed buildings with ground storey open were found to be the vertically irregular building which is the most vulnerable out of all the selected vertical buildings.

1. Introduction

With the increase in demand for different types of usages of a building, it is no longer possible to design a regular building with equal distribution of strength, stiffness, and mass always. Changes in the parameters of different storeys can lead to the occurrence of irregularity in strength, stiffness or mass in a structure. The Indian standard earthquake code [1] defines two types of irregularities, vertical and plan irregularity. Many studies [2] & [3] have been done on the seismic performance of vertical irregular steel buildings. The seismic performance of various types of vertically irregular RC buildings was evaluated by [4]. Irregularity indicators were proposed [5] [6] [7] for the quantification of vertical irregularity in the buildings. [8] studied seismic performance of vertically irregular setback buildings and compared the fragility curves of irregular and regular steel frames by considering different limit states.

Although there are some studies on the seismic performance of vertical irregular buildings in general, the study on the seismic fragility of vertically irregular steel-framed buildings is very limited. Hence the present study is an evaluation of the various type of vertically irregular buildings for their seismic performance using fragility curves and damage index functions.

2. Details of the selected buildings

Regular steel-framed buildings (R) having 7 storeys with a storey height of 3.3 m is considered. The plan and elevation of the building considered are shown in figure 1a and 1b respectively. The building is assumed to be in seismic zone III (PGA=0.16g) and accordingly seismic design base shear is
calculated as per [1]. Members are designed according to [9]. Details of typical beams and columns are provided in table 1. The slab is considered as a reinforced concrete slab supported on steel beams. Slab thickness is taken as 120 mm [10]. Two types of mass irregular buildings are considered by assuming a swimming pool in the top storey and at the intermediate storey. Mass irregular building with a swimming pool at the top storey is assumed to have a mass of 500% compared to other typical storeys. This building is designated as MT-5. Other mass irregular buildings having a swimming pool at the intermediate storey are designated as MB-5. The performance of mass irregular buildings is evaluated regarding a regular building (MR) having uniform masses in all storeys.

To study the performance of various stiffness irregular buildings a reference regular building (SI-R) having cross bracings in all the storeys is considered. Various stiffness irregular (SI) buildings are considered by keeping a particular storey open (without bracings). The building having ground storey free of any infill walls is designated as (SI-G-O). Similarly, buildings having an intermediate open storey is designated as (SI-M-O). Details of all irregular buildings considered in the study are illustrated schematically in figure 2.

### Figure 1. (a) Plan of building considered (b) Elevation of building considered.

![Figure 1.](image1.png)

### Figure 2. Different cases of stiffness (SI) and mass irregular (M) structures.

![Figure 2.](image2.png)

### Table 1. Different type of sections.

| Type     | Column Section | Beam Section |
|----------|----------------|--------------|
| MR       | ISHB 350       | ISMB 350     |
| SI-R     | ISHB 350       | ISMB 350     |
| MT5      | ISHB 400       | ISMB 300     |
| MB5      | ISHB 400       | ISMB 300     |
| SI-M-O   | ISHB 250       | ISMB 300     |
| SI-G-O   | ISHB 300       | ISMB 300     |

3. **Methodology**

Seismic fragility curves of steel building frames in the present study are developed as per an accepted methodology proposed by [11]. It uses probabilistic seismic demand models (PSDM) which is the
relationship between $S_a$ and inter-storey drift (ISD) of the building for various ground motions. From the PSDM models, median Drift Demand $D$ is found which can be represented as:

$$D = a(S_a)^b$$

(1)

Where ‘$a$’ and ‘$b$’ are taken as constant coefficients. [12] defined $\beta_D|S_a$ as a measure of dispersion. Regression analysis of the inter-storey drifts from non-linear dynamic analysis gives the values of three constants $a$, $b$ and $\beta_D|S_a$ required for development of PSDM.

The probability of exceeding a certain limit state for a specific pseudo-spectral acceleration ($S_a$) is defined as seismic fragility. The fragility function is defined as a probability distribution function that demonstrates the probability of a structure being damaged at a given damage state for a particular ground motion intensity. Fragility curves can be developed for any particular limit state by using the expression:

$$P(C - D \leq 0|S_a) = \Phi\left(\frac{\ln (D/C)}{\sqrt{\beta_D^2 + \beta_C^2 + \beta_m^2}}\right)$$

(2)

Where $D$, $C$ is the median of demand and median of chosen performance level respectively. $\beta_C$ is defined as a dispersion in the capacity which is taken as 0.25.

4. Modelling for non-linear dynamic analysis

OpenSees laboratory tool [13] was used for non-linear time history analysis of the models of selected buildings. Beams and columns were modelled using non-linear beam-column fiber section elements for non-linear time history analysis. Seismic masses were assigned as lumped masses in each floor.

The uncertainty in the earthquake was modelled by a set of 44 ground motions with PGA increasing gradually from 0.1g to 1.0g. Global damping ratio and yield strength of steel are taken as random variables for considering uncertainty. 44 sets of random variables are generated using Latin hypercube sampling (LHS) method. The mean and coefficient of variation for the random variables considered are given in table 2.

Table 2. Random variables considered.

| Material                  | Mean  | COV (%) | Source                  |
|---------------------------|-------|---------|-------------------------|
| Yield Strength of Steel   | 250 MPa | 10      | Ranganathan (1999)     |
| Global Damping Ratio      | 5%    | 40      | Davenport and Carroll (1986) |

5. Probabilistic Seismic Demand Models

A total of 44 computational models were subjected to 44 ground motions with a particular PGA [14]. The range of each PGA is taken from 0.1g to 1.0g. Maximum ISD values obtained in each of the building model from non-linear time history analysis were recorded. The maximum inter-storey drift values and corresponding $S_a$ values were plotted to obtain the PSDMs of each frames as shown in figure 3. A power-law relationship was fitted using regression analysis to obtain the constant ‘$a$’, ‘$b$’ and $\beta_D|S_a$. The PSDM obtained from all the frames are shown in figure 3. Table 3 shows the equations of the PSDMs for the different models considered. Figure 3a depicts that inter-storey drift is highest for SI-G-O frame and lowest for SI-R. Figure 3b portrays that MB5 frame is having the highest inter-storey drift whereas it is lowest for MR frame.

Table 3. PSDM model and measure of dispersion.

| Frame | PSDM            | $R^2$ | $\beta_{D|S_a}$ |
|-------|-----------------|-------|-----------------|
| SI-R  | $0.9161(S_a)^{0.8929}$ | 0.8630 | 0.1752          |
| SI-M-O| $2.1976(S_a)^{1.0817}$ | 0.8351 | 0.2369          |
| SI-G-O| $2.5431(S_a)^{1.2995}$ | 0.8153 | 0.2891          |
| MR    | $3.8993(S_a)^{1.3736}$ | 0.7101 | 0.4003          |
| MB5   | $5.3982(S_a)^{1.3962}$ | 0.6314 | 0.4213          |
| MT5   | $4.7215(S_a)^{1.4294}$ | 0.5501 | 0.4831          |
6. Comparison of fragility curves

The fragility curves for the stiffness and mass irregular building frames in comparison with a regular building are shown in figure 4a and 4b respectively. The figure depicts the fragility curve at the IO limit state level. The vulnerability of SI-M-O frame is more than that of SI-R frame. The frame, SI-G-O is more vulnerable than the frame SI-M-O. In the case of mass irregular buildings, the vulnerability of MB5 frame is more than that of MR frame. MB5 frame is more vulnerable than MT5 frame. This is due to the fact that when heavier mass is introduced at the intermediate storey, it is more vulnerable than the building having heavier mass at the top storey.

7. Damage Index Function

A damage index function is used to determine the damage/loss of the structure at different damage states. In this paper, a standard probability of exceedance of 50% is used to convert a fragility function to a damage index format. Equation 3 is considered to determine the damage index where:

\[ s \text{ represents } S_a, \alpha, \beta \text{ represents the Weibull distribution factors and } F(S_a) \text{ represents damage index function.} \]

\[ F(S_a) = 1 - e^{-\left(\frac{S_a}{S_a^\alpha}\right)^\beta} \quad (3) \]

Figure 5 represents the graph between damage index and \( S_a \). It can be seen that the stiffness irregular building with an open ground storey (SI-G-O) is having the highest damage index as compared to SI-R.
and SI-M-O. It is also justified from the fragility curve that SI-G-O is the most vulnerable among all other buildings.

![Figure 5. Damage Index vs S_a (probability of exceedance = 50%)](image)

### 8. Conclusions
This paper focuses on vulnerability of various vertical irregular steel framed buildings. An accepted seismic risk assessment was used to evaluate the performance. The following conclusions can be made from this study.

- The effect of stiffness irregularity along the height of the structure influences the seismic response of the structure. When an irregularity is introduced at the open ground storey, the inter-storey drift and probability of exceedance were highest compared to a regular structure.
- The location of heavier mass has a significant effect on the seismic response of the building. When a heavier mass is positioned at the intermediate floor, the probability of exceedance is increased compared to a regular structure.

### 9. References

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