Probabilistic Assessment of Torsional Buildings

Philip Luke Karuthedath\textsuperscript{1*}, Robin Davis\textsuperscript{2} and Pradip Sarkar\textsuperscript{3}
\textsuperscript{1} PG Scholar, National Institute of Technology Rourkela, India
\textsuperscript{2} Assistant Professor, National Institute of Technology Calicut, India
\textsuperscript{3} Professor, National Institute of Technology Rourkela, India
\textsuperscript{*}k.philip.luke@gmail.com

Abstract. Asymmetry/irregularity is an undesired building characteristic that nevertheless exists commonly due to modern-day structural definitions. Asymmetry in plan, due to the uneven distribution of mass or stiffness can cause torsional coupling under seismic loads. A well-defined parameter that can sufficiently represent the damage of torsional buildings is non-existent, which may be why probabilistic seismic assessment methods such as fragility analyses have not been done for such buildings. The present study proposes ‘Resultant Drift’ as a parameter that can define the failure behaviour of asymmetric buildings and utilises the 2000 SAC FEMA method to analyse the seismic risk and develop fragility curves. The study observes the dependency of the extent of asymmetry and storey height on the failure probability. Investigations on the maximum storey rotation for the selected parameters show the necessity of international standard definitions in the performance levels of rotation behaviour.

1. Introduction
Plan asymmetry in building structures is said to exist when the Centre of Mass (CM) and Centre of Stiffness (CS) are not co-incident. When hazardous loading such as earthquakes occur, such buildings possess rotational motion in addition to lateral movement. This torsional-translational coupling poses a serious threat to the buildings regarding their stability. The vulnerability of such plan asymmetric structures has been of interest to many researchers. Tso and Dempsey [1] studied the effect of the ratio of torsional frequency on lateral frequency and observed the variation of ductility demand. A study on the time-history response of asymmetric buildings [2] showed the inadequacy of building codes. Tso and Ying [3] divided the structural elements into flexible and rigid elements based upon their distance from asymmetry and observed their varying ductility demands. Samali et al. [4] investigated the effectiveness of base isolators on asymmetric buildings, while Vial et al. [5] observed the decreasing seismic demands when a frictional damper is incorporated. Numerous other studies [6–11] investigate the behaviour of torsional buildings and their seismic demands and attempts to understand or to provide a solution to this statement.

However, a proper index that can adequately represent the damage and quantify the vulnerability in an asymmetric building has not been accounted for and is virtually non-existent. Probabilistic methods such as fragility curves [12] provide an excellent base for risk as well as uncertainty quantification and have been generally used for various structural systems [13–19] but not for complex torsional buildings. Fragility curves represent the cumulative probability distributions that indicate whether a component/system will be damaged to a given damage state or a more severe one, as a function of a particular demand, such as the intensity of ground motion. The present study thus attempts to develop fragility curves for torsional buildings. Firstly, the study attempts to propose an engineering damage
parameter that can adequately represent the damage of an asymmetric building. Using this parameter, the seismic vulnerability of the torsional buildings is quantified using fragility curves.

2. Modelling of the structure
Since the investigation is on torsional buildings, the study considers 3 dimensional RC frames having 5 bays in both the plan directions. The number of storeys for the frames vary evenly from 4 to 10. They are designed according to relevant Indian standard IS 456: 2000 with the grades of concrete and steel as 25 MPa and 415 MPa, respectively. A storey height of 3.2 m and a bay width of 5 m is given for each of the frames considered. The base of the frames is assumed to be fixed. Elevation, plan, and section details of all the frames are given in figures 1-3. Rigid diaphragms are provided at each floor level to model the slab stiffness.

To account for the asymmetry in the models, mass eccentricity is induced by lumping heavy masses along the selected axis for each of the floors such that eccentricity to breadth ratio ($e/b$) of the models are varied, thereby obtaining various asymmetric levels for each of the building models. A symmetric counterpart is also considered as a reference. The study limits itself to uniaxial mass eccentricity that remains equal for every floor level. The terms eccentricity and asymmetry will be used interchangeably from now on to denote the level of difference between CS and CM.

Selected buildings are modelled for nonlinear time history analysis using the Open System for Earthquake Engineering Simulation (OpenSees) framework [20]. Concrete modelling is done using the modified Mander’s model [21]. Reinforcement steel behaviour is accounted for using a Menegotto-Pinto model [22] and the elements are modelled as fiber section [23].

3. Modelling of uncertainties & ground motion
Because of the error and randomness that can occur in the design, construction, and functioning; uncertainties are unavoidable in a real time building structure. They can occur as material, geometric properties, and loading conditions of the building. Significant material properties that can affect the nonlinear response of buildings are obtained from previous studies and are taken as random variables for the study. Table 1 presents the details of the selected random variables used in the study. Randomness
in the seismic load is considered by using a suite of 22 pairs of far-field earthquake ground motions [24] and converting them according to Indian standards.

### Table 1. Statistical details of random variables used for fragility analysis.

| Material/Property | Variable | Mean  | COV (%) | Distribution | Remarks        |
|-------------------|----------|-------|---------|--------------|----------------|
| Concrete          | $f_{ck}$ | 30.28 MPa | 21      | Normal       | Uncorrelated   |
| Steel             | $f_y$    | 468.90 MPa | 10      | Normal       | Uncorrelated   |
| Global Damping ratio | $\xi$    | 5%     | 40      | Normal       | Uncorrelated   |

#### 4. Resultant drift

The failure of a structure can be quantitatively related to certain standard parameters such as deflection, inter-storey drift (ISD), base shear etc.; exceedance of which indicates failure. Such parameters are known as Engineering Damage Parameters (EDP). For a symmetric building, the unidirectional translation of a building can sufficiently represent its inter-storey drift and thus the failure. However, for an asymmetric building, bidirectional translational is expected due to rotation even under uniaxial loading, and some alternate criteria that can represent its failure are requisite. Investigations on the nonlinear response of asymmetric buildings have shown that the resultant of lateral displacement in both the plan directions may adequately characterise its torsional behaviour. The idea behind this methodology is illustrated in figure 4 and formulated in Equation (1) and Equation (2).

$$R = \sqrt{(\Delta x)^2 + (\Delta z)^2}$$

$$ISD = \frac{R}{h} \times 100$$

#### Figure 4. Deflection behaviour of asymmetric buildings.
is another parameter that can represent the torsional behaviour, still the lack of existing standards of performance levels make it an unworthy option to obtain the seismic fragility.

5. Performance level

Non-linear time history analysis done on selected buildings give data on the selected damage parameters, which are compared with limit states or performance levels. The performance level stands for the structural and non-structural damage that may be allowed during earthquakes. In the present study, for the selected damage parameters, namely resultant translation and element strain, performance levels are specified from existing standards.

As for the resultant translation, maximum ISD limit states are taken from ASCE standards [25], which gives the failure criterion/performance levels for RC buildings. Table 2 summarises these limit states.

| Performance Level          | Permissible ISD |
|----------------------------|-----------------|
| Immediate Occupancy (IO)   | 1%              |
| Life Safety (LS)           | 2%              |
| Collapse Prevention (CP)   | 4%              |

6. Results and discussion

Asymmetry divides the plan into flexible and rigid sides. For the uniaxial mass eccentric system considered, the edge closer to the CM will act as the flexible side while the edge closer to the CS will be the rigid side. A schematic diagram representing the deflection of the torsional building in the plan is shown in figure 5.

For the present study, the ground motion is applied in a direction perpendicular to the axis of asymmetry, and the deflection behaviour of the building will depend upon the intensity of eccentricity. Eccentricity is varied for each of the building models considered, and a comparative study is done on the building fragility using the resultant translation as the damage parameter.

Fragility curves for the four-storey frame having various levels of asymmetry for different performance levels are shown in figures 6 – 8. It is found that with each increase in eccentricity, the flexible side becomes more fragile while the rigid side becomes more strong while the fragility of the symmetric system remains the same irrespective of the side whose deflection is measured. This can be explained from the idea that, with each increment in eccentricity, the CM comes closer to the flexible side and farther to the rigid side. Thus when inertia force acts through CM, the nearness of the sides to the CM affects their damage behaviour. It can also be inferred that, the effective probability of exceedance of limit state in a building become higher with subsequent increase in eccentricity/asymmetry. Another observation that can be made is that, for a particular level of asymmetry, the flexible side is more vulnerable to earthquakes, which is illustrated in figure 9.
The 6, 8, and 10 storeyed frames were also observed to show similar behaviour with the variation of asymmetry. Because of space constraints, the results are not included in this paper. A storey-wise comparison of all the models considered for each level of eccentricity is as given in figure 10 and figure 11. The graphs show that no matter what the level of asymmetry is; with subsequent increase in the building height, the seismic fragility of buildings increases. Moreover, the stiffness of the sides doesn’t matter in this regard. However, the variation becomes negligible in higher storeyed buildings. The same trend is observed for all levels of asymmetry for all performance levels. The rest of the results are not included for the brevity of the manuscript.

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**Figure 6.** Fragility curves for 4 storied frame – IO performance level.

**Figure 7.** Fragility curves for 4 storied frame – LS performance level.

**Figure 8.** Fragility curves for 4 storied frame – CP performance level.
Asymmetry in the plan is defined by the presence of rotational movement in buildings in addition to translational movement. This causes a torsional-lateral coupling, thereby making the structure weak under ground motion. It is, therefore, necessary to investigate the effect of eccentricity and storey height on the rotational behaviour of buildings. It should be noted that the amount of rotation is independent of the relative edge stiffness and is equivalent to all the points of a particular floor. Figure 12 plots the magnitude of maximum rotation for the building frames concerning the intensity of the ground motion. Various levels of asymmetry are considered as before.

For the symmetric system, the rotation is in the order of zero as expected. Still, with each increase in the eccentricity between the CS and CM, the amount of rotation is observed to be increasing and reaches the peak when $e/b = 0.5$, the maximum possible eccentricity in a building. Figure 13 represents the storey wise variation in rotation. For a symmetric case, irrespective of the storey height, rotation value approximates to zero. In contrast, for an eccentric case, the rotation is observed to be a direct function of the building height.

Figures 12 and 13 show the presence and effect of rotation in buildings due to asymmetry as a result of the uneven distribution of mass/stiffness. Even though the present chapter deals with developing fragility curves of asymmetric building, the study deliberately avoids plotting fragility curves by considering the rotation as a damage parameter. This is because of the unavailability of international standards that define performance levels/limit states with which permissible rotation in buildings is quantified.

Figure 9. Four Storied building with eccentricity /breadth = 0.3, IO performance level.

Figure 10. Fragility curves for $e/b = 0.1$. 
The investigation thus proposes the necessity of developing adequate performance levels that can account for the rotational behaviour in buildings.

**Figure 11.** Fragility curves for $e/b = 0.3$.

**Figure 12.** Maximum rotation for the earthquakes considered.

**Figure 13.** Height wise distribution of maximum rotation.
7. Conclusions

The study investigates the seismic performance of asymmetric buildings by considering their seismic vulnerability as the performance index. Resultant drift is proposed as an alternate damage parameter that can define the damage of asymmetric buildings. Fragility curves using this parameter are developed. The study proves that the presence of asymmetry increases the probability of failure in a building and that this condition further increases with an increase in asymmetry. The fragility also depends directly on the building height. Further studies were carried out to evaluate the rotational behaviour as a function of eccentricity and building height and the increasing rate of rotation with an increase in eccentricity and storey height is observed. The study proposes the need for well-defined standards that can assess the performance level in terms of rotation in buildings.

8. References

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