Effect of Setback Percentages in Vertically Irregular Concrete Buildings on Response to Earthquake

M. S. AZAD[1], M. M. SAZZAD[2], N. SAMADDER[3], M. F. RAHMAN[4]

[1]Department of Civil and Environmental Engineering, Mahidol University, Thailand (mdsamdani.aza@student.mahidol.edu)
[2]Department of Civil Engineering, Rajshahi University of Engineering & Technology, Bangladesh (mmsruet@gmail.com)
[3]Department of Hydrosciences, Technische Universität Dresden, Dresden, Germany (niloy.samadder@mailbox.tu-dresden.de)
[4]Department of Civil Engineering, Rajshahi University of Engineering & Technology, Bangladesh (farhad.civil.ruet@gmail.com)

Abstract

Setbacks in buildings are very common phenomena nowadays due to land requirements, architectural criteria and client requirements. The setback is a type of irregularity which can initiate different types of irregularities such as geometric, mass or stiffness irregularities and all of these along the vertical direction. Different seismic provisions provide guidelines for seismic assessments of buildings for both design purposes and assessment purposes. According to the seismic provisions in different countries, it is suggested that the irregular buildings having height more than 20 meters should be analyzed following the dynamic procedure. The dynamic procedures require higher computational times, efforts and costs. In this study, pushover analyses are carried out to find the capacity of building and to define the limit states of damages. Fragility curves are developed to see the differences due to the setbacks. The fragility curves are developed considering the dynamic properties of the buildings by using the concepts from previous studies. It should be noted that all buildings are with the same heights of 18 meters and same land areas of 400 square meters. The Pushover curves and fragility curves demonstrate that setbacks have considerable effects on the seismic capacity of structures.

Keywords: *Setback, irregularity, Fragility, Pushover*

1 Introduction

Seismic provisions for irregular building frames have some certain requirements as per different building codes (BNBC 2006, UBC 1997, IBC 2003). These provisions are required to be followed for the purpose of designing and assessing existing structures. Irregularity in building frames can be of two types, namely horizontal and vertical irregularities. Vertical irregularity includes the mass irregularity, geometric irregularity and stiffness irregularity. Geometric irregularities are often seen in building frames due to client requirements, the aesthetical point of view or other types of purposes. These other purposes include the construction of a water tank, constructing meeting rooms, seminar rooms etc. on the top floor. These other purposes might be the reasons for geometric irregularity. The setback is a type of vertical irregularity in which a certain part of the structure is missing after a certain height. The setback is commonly adopted in high-rise buildings. In case of low rise buildings, it may be occurred through adding additional construction in the roof level.

In recent years, the seismic responses of building frames have been comprehensively studied. Chintanapakdee and Chopra (2004) focused on the seismic responses of vertically irregular frames with three types of irregularities comprising of mass, stiffness and strength irregularities. Discontinuity in mass and overhanging masses were considered in the study. Effect of irregularity on story drift and floor displacements were presented vastly. Moreover, the accuracy of modal pushover analysis with respect to response history analysis was also delineated. Georgoussis et al. (2015) illustrated the seismic performances of multi-story building frames with the setback. The study was conducted performing the approximate seismic analysis. Aziminejad and Moghadam (2009) studied multistory shear buildings with asymmetry and different strength distributions. Seismic analyses of vertically irregular buildings were explored by Rahman and Salik (2016) and found that mass irregularity affects the floor displacements and stiffness irregularity affects the drift ratio as well. Montazeri et al. (2012) studied the dynamic properties of steel MRF (moment resisting frames) with setbacks along vertical directions. It was reported that the models with irregularity are more vulnerable to earthquakes. Kara and Celep (2012) inspected nonlinear responses of structural frames with irregularity in terms of column discontinuity. The outcome of this work delineated that column discontinuity changes the load path. Notable study of seismic response to vertically irregular frames was carried out by Valmundsson and Nau (1997). Two types of analysis method, namely the equivalent load method and time history method were incorporated. Relationships between ductility demand and mass ratio, stiffness ratio, and strength ratio were extensively studied. Poonam et al. (2012) demonstrated seismic responses of frames with response to seismic excitations. Mass and geometric irregularities along with weak story were reviewed in this study. Vulnerability due to irregularity was explained contemplating the lateral displacements and story drift ratios. A parametric study due to torsional irregularity as per new Turkish codes was studied by Tezcan and Alhan (2001). Seismic response of vertically irregular frames considering earthquake accelerograms represented some more criterions which prove that the Unified Building Code (UBC) provisions are not adequate (Magliulo et al., 2002). Relationships between probabilistic seismic demand analysis and incremental dynamic analysis were developed by Mackie and Stojadinovic (2002). Moheli and Alercon (1986) explained earthquake analysis methods for the study of irregular structures. Their study indicated that dynamic analyses method does not have clear advantages over static analyses rather inelastic analyses have advantages over elastic analysis. This study recommended further examination to clarify this issue more substantially. Michalis et al. (2006) assessed the effects of vertical irregularity on earthquake performance for nine-story steel frames. Kumar et al. (2014) described probabilistic assessments seismic vulnerability on concrete buildings. A method of probabilistic analysis was proposed and it was based on nonlinear static analysis. Das et al. (2003) presented seismic design aspects of concrete frames which delineated that equivalent load methods provide reasonable estimates of design forces. Athanassiadou (2008) studied seismic performances of concrete frames with irregularities along elevation. Pinho and Antoniou (2005) illustrated that displacement based adaptive pushover analysis can contribute more accurate results than that of force-based algorithms. Sazzad and Azad (2015) discussed different horizontal shapes of buildings and delineated applications of wind and earthquake forces.

Different codes of practices have provisions for irregular structures. As per Bangladesh National Building code and Uniform building code, it has been proposed that irregular structures more than 20 meters should be analyzed through dynamic analysis procedures. The aim of the present study includes the effect of setback percentages on the static and dynamic response. The considered building frames are at 18 meters. Setbacks of 33.33% and 66.66% have been taken into consideration to make the study more comprehensive. At first, the results from the nonlinear static analysis was observed. The results from lognormal distributions of the dynamic response are also plotted as fragility curves and probability density curves. The conclusion refers to the fact Percentages of setback governs the responses of structures significantly and the presence of inertia effect also influences remarkably.

2 Methodologies

2.1 Building Frames Considered in the Study

The study was conducted considering three different shapes of six-story building configurations. In this study, the concrete frame was considered having a story height of 3 meters and a total height of 18 meters. Four different shapes of building structures were adopted to determine the effect of vertical geometric irregularity. Pushover analysis method has been employed. According to BNBC2006, if the height of the irregularly shaped building structures exceeds 20 meters, the analysis of that structure should be carried out in the dynamic method. In this study, structures having height up to 18 meters and nonlinear static pushover analysis was performed. Fig-1 shows the elevation of different shapes of building structures containing setbacks at different positions at a different height. Considering this elevation, it is found that the first two models are asymmetric along the height while the other two models are symmetric to the vertical axis. The building frames are divided into two substructures, such as the base structure and the tower substructure. The base structure represents a uniform building system consist of floors, the dimension of 20 m × 20 m and the tower substructure which is composed of floors of reduced dimensions 10m × 20 m. In the first model as shown in Figure 1, the tower structure consists of two floors, in the second model, the tower structure consists of four floors and finally, the third model has a tower structure consisting of two floors and the last model consists of a tower structure of 4 stories. The cross-section of the lateral force resisting element of the column is considered as the dimension of 40x40cm and for the beam is 30x40 cm. The thickness of the slab is taken as 150 mm. The column to column distance is adopted as 5m.

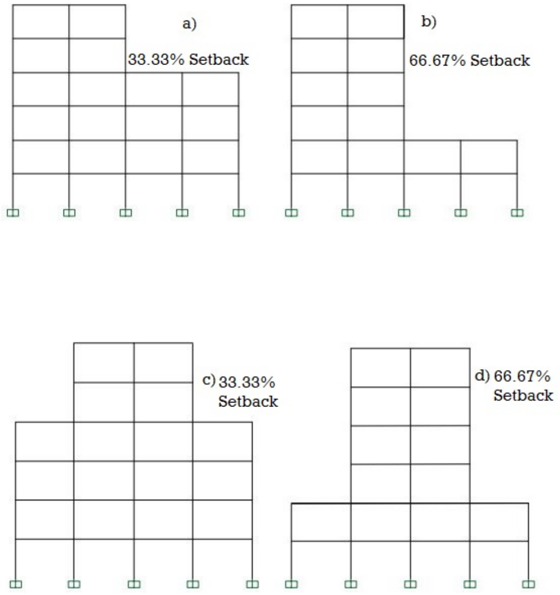

Figure 1: Selected Concrete Frames

2.2 Analysis Methods

For evaluating the nonlinear properties of different concrete structures in response to the seismic motion, pushover analysis has been performed in this study. This nonlinear static analysis involves applying lateral loads with an increment by following a prescribed loading pattern until the structure's target displacement. Pushover analysis is generally used for determining effective stiffness, secant stiffness, ductility, and target displacement along a certain direction. In this analysis, 4 different vertically irregular concrete frames have been considered and the pushover parameters have been taken from FEMA 356 prestandard.
The following equation implies the Base Shears which have applied for the pushover analysis.

$$V = \frac{C_v}{RT} W \qquad (1)$$

$$\text{Where, } T = C_t (h_n)^{3/4} \qquad (2)$$

The calculated Base Shear (V) from Eq. (1) must be less than the calculated value from Eq. (3) and must be greater than the calculated value from Eq. (4).

$$V = \frac{2.5 C_a I}{R} W \qquad (3)$$

$$V = 0.11 C_a I W \qquad (4)$$

2.2 Fragility Curve Development

The adaptation of fragility function has been increased to a satisfactory level as an efficient method in the field of structural analysis. In this study, a statistical approach to evaluate the parameters of fragility function has been performed by using nonlinear dynamic structural analysis for estimating the fragility functions of the vertically irregular frames. Fragility function refers to the probability distribution of a system that is subjected to collapse or some other certain limit of damages as a function of a single predictive required parameter. Ground Motion Intensity Measure (IM) is such a function which is expressed as a measure of spectral acceleration at a certain period and damping. There are several ways to predict the response of structures to nonlinear dynamic motion. Incremental Dynamic Analysis (IDA) is one of the methods for determining the IM level at which each dynamic motion causes collapse by a repeated dataset of dynamic forces. Another commonly adapted approach is

Multiple Stripes Analysis which involves analyzing with a specified set of IM levels for a unique dynamic motion set. In this paper, the fragility function has been evaluated from the estimated data obtained from pushover analysis by using Incremental Dynamic Analysis (IDA). A variety of approaches such as static structural analyses, dynamic structural analyses, or field damage observations are used to derive fragility functions in general. This paper focuses on analytical fragility functions originated from the dynamic structural analysis for a specified IM level along with a defined number of analyses at each level. The fragility function is usually defined by a lognormal cumulative distribution function.

$$P(C \setminus IM = x) = \Phi(\frac{\ln(x/\theta)}{\beta}) \qquad (5)$$

Where P(C|IM=x) is the probability that a structure will collapse with IM=x due to seismic motion, Φ( ) is the standard normal cumulative function (CDF), θ is the median of the probability distribution (the IM level with 50% probability of collapse), β is the standard deviation of ln(IM). In this study, the fragility curve is developed following the procedure of Baltzopoulos et al. (2017). The spectral acceleration is considered as the intensity measure in this study. The structural damping ratio is 5%. While developing the fragility curves, the inertia of the frames are considered and then the frames are considered as equivalent SDOF systems.

3 Results & Discussion

Fig. 2 depicts the capacity curve of all models. The maximum value is for the Model-3 while the minimum stands for Model-2. Model-2 contains 67% setback and that is why the structure is least stiff. On the contrary, Model-3 illustrates maximum base shear capacity. It demonstrates this model as the strongest one. It can also be noted that the behavior of model-1 and model-3 are close and the percentages of setback are the same in these two models. The deviation of the pushover curve is due to the asymmetry along the vertical direction. The pushover curves of model-2 and model-4 are adjoining and the underlying reasons are same as for models (1&3).

Figure-3 Illustrates the lognormal fragility curves of the models. It can be noticed that the probability of failure for model-2 is highest in less intensity measure. But the Models (1&4) require more forces for the same probability of failure. Model-3 can be considered as the safest one as the probability of failure can be observed as lowest at higher values of intensity measure.

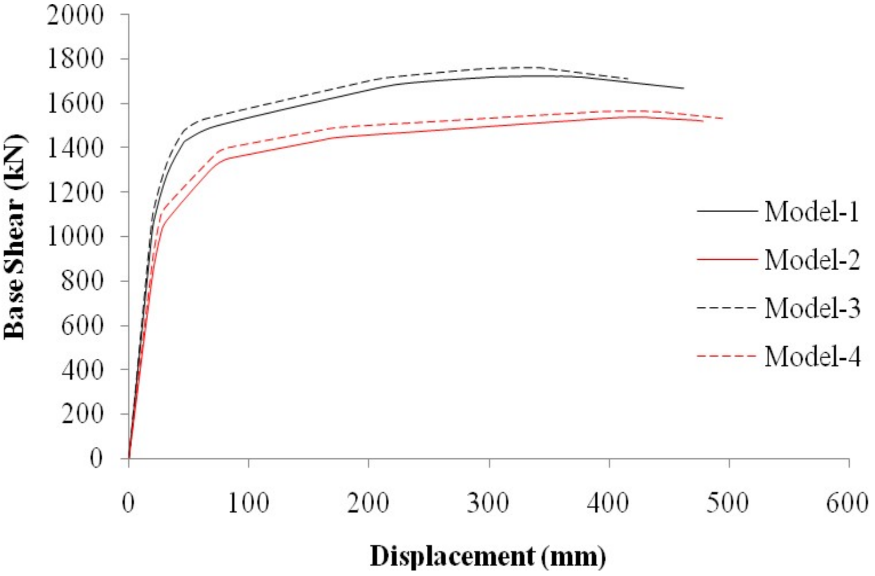

Figure 2: Pushover Analysis of selected models

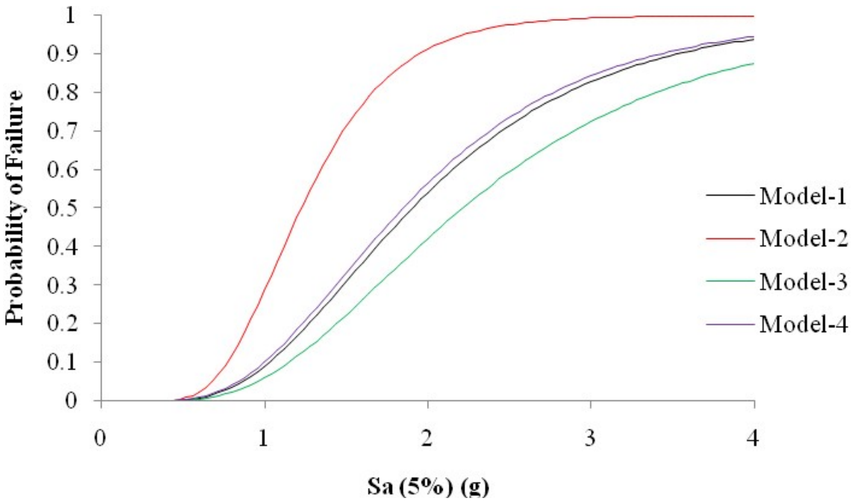

Figure 3: Fragility Curves of selected models

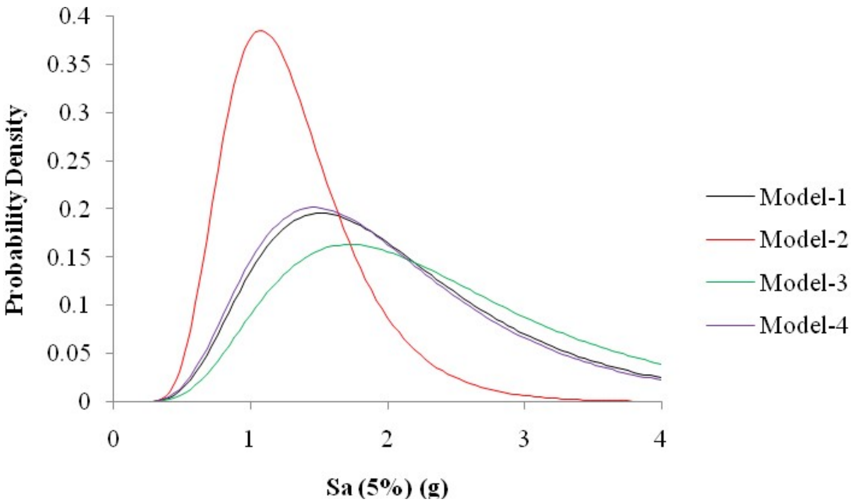

Figure 4: Probability density Curves of selected models

More clear observation can be noted in Figure 4. The probability density is plotted based on the intensity measurements. It can be noticed that peak probability stands for model-2 at lowest intensity measures. Fore models (1& 4), the peak probability is almost the same with same intensity measures. The peak probabilities of these two models are one-third considering the model-2. The peak probability of Model-3 is lowest and the corresponding intensity measure is highest. In both pushover analysis and fragility curve development, it can be noted that Model-2 is the least safe frame. The results of other models are different in fragility curve in comparison with the pushover curves. Fragility curves are included with the inertia of the frames but pushover curves are not included with the inertia.

4 Conclusions

Pushover analysis is an approximate approach of analysis to assess the structural capacity. It includes both the linear and nonlinear states of responses of the structures. It overlooks the inertia forces and damping forces and so fragility curves are developed to observe the inertia effects as well. From pushover analysis, the effects of location of setbacks are negligible. That's why the pushover curves with the same setback percentages are near. On the contrary, the fragility curves and probability curves are not closer because of the influences of inertia and induced torsion due to the irregularity. The results demonstrate that dynamic responses should be considered for vertically irregular structures even the height of the structure is less.

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