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Comparative Analysis of Vertical Geometric Irregular Buildings by Fragility Curve Using Pushover Analysis

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Abstract

The present work deals with the analysis of vertical geometric irregular structures, such as step buildings and setback buildings, which exhibit stiffness irregularity at different locations. These structures are analyzed using pushover analysis, a nonlinear static analysis method that provides insight into the performance of buildings under seismic loading by incrementally applying lateral forces until a target displacement is reached or the structure collapses. Stiffness irregularities in buildings can significantly affect their seismic response, making it crucial to understand how different configurations influence the overall performance. In this study, buildings with stiffness irregularity located at various points along their height—specifically at the bottom, middle, and top—are evaluated. The stiffness irregularity can result from various factors such as variations in column or beam dimensions, changes in material properties, or abrupt changes in the structural system. From the data obtained using pushover analysis, fragility curves are plotted for different damage states of the structures. Fragility curves represent the probability of reaching or exceeding a certain damage state as a function of seismic intensity measures, providing a probabilistic assessment of the seismic vulnerability of the structures. A comparative analysis is carried out to assess the relative performance of the step and setback buildings with different stiffness irregularities. It is found that step buildings with stiffness irregularity located at the middle can transfer loads more effectively compared to those with irregularity at the bottom. This is because the concentration of stiffness in the middle portion helps in distributing the loads more uniformly, thereby enhancing the overall stability and reducing localized damage. On the other hand, setback and step buildings with stiffness irregularity at the top may experience less damage in the initial stages due to their ability to dissipate energy through higher flexibility at the top. However, as the seismic intensity increases, these buildings become more vulnerable to extensive or complete damage due to the larger displacements and increased demands on the structural elements.

Keywords: Vertical irregularity, pushover analysis, fragility curves, irregular buildings, setback buildings

INTRODUCTION

India recently became the most populated country in the world, and as the population is increasing day by day there is a huge demand for accommodation. Use of irregularities such as planar irregularity and vertical irregularities are key factors practices for recent projects. The effect of seismic ground motion on these structures needs to be inspected. Thus, there is need of understanding the behavior of the structure fragility curves parameter can be a game changing. Many previous researchers had worked on vertical geometric irregularities but without introducing any type of irregularity hence need to inspect the behavior of damage states of those

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structures is done in this present work. Alex Barbat had worked on damage scenarios of urban areas of Barcelona and Spain with capacity spectrum. He formed an equation to plot probability of damage states at different levels. Anil Chopra worked on six different height frames with nonlinearity methods like pushover analysis and nonlinear time history analysis. His research estimates that pushover analysis helps to investigate soft or weak story in the structure. Halder and Paul researched about vulnerability of low rise structures with the help of design basic earthquake (DBE) and maximum credible earthquake (MCE) levels. Patel and Vasanwala studied analytical method from HAZUS and pushover analysis concluding low-storied building are more susceptible to damages. Pijush Shil et al. investigated damage states with and without precast shear wall subjected to nonlinear pushover analysis and incremental dynamic analysis. They found that slight and moderate state had damage provability up to 90% of the structure but for extensive damage it is more than 80% for structure without precast shear wall. Paul along with Debnath further continued their research with DBE and MCE levels by consideration of low- and mid-rise structures. Ravikumar et al. investigated sloping ground buildings with pushover analysis method. They concluded that sloping ground is the most vulnerable type of building.

AIM AND OBJECTIVES

The objectives of this work are:

1. Study of seismic fragility curve by using pushover analysis for regular and vertically geometric irregular building having stiffness irregularity at bottom, middle, and top.
2. To study pushover curves, time period, and DBE and MCE levels of the structure.

LITERATURE REVIEW

Barbat et al. [1] worked on a seismic evaluation of structures with conceptual aspects of vulnerability, damage and risk evaluation. They studied the capacity spectrum method and obtained damage scenarios from urban areas of Barcelona and Spain with the help of capacity and fragility curves. Barcelona had nearly 97% of reinforced and unreinforced buildings with waffled slab flooring. To analyze these structures with seismic damage, they considered five different damage states of structures. Through these results they figured out that mid-rise and high-rise masonry buildings were significantly damaged due to slenderness and weakness in strengths. Waffle slabs which were observed in entire Barcelona for reinforced buildings were found to be damaged when prone to low seismic capacity.

Chopra and Chintanapakdee [2] compared seismic demands of vertically irregular and regular frames with the help of nonlinear response history analysis. They also determined median and dispersion value ratio of story drift demand by modal pushover analysis and nonlinear response history analysis. They concluded that modal pushover analysis gives stories analysis with large drift demands and estimates them to sufficient accuracy by detecting critical stories of the frame. They used six different heights of frames of 3, 6, 9, 12, and 18, each designed for 5 different strength levels. This paper concludes that using modeled pushover analysis accuracy of results like stiffness and strength does not deteriorate even after irregularity is introduced in the structure. It also gives more precise results when estimating seismic demands of frames with soft, weak, or soft and weak story at certain location.

Halder Paul [3] evaluated the seismic vulnerability of low rise reinforced concrete (RC) frame structure which were designed for gravity loads as per Indian IS code. There special attention was for one to three stories, that is, low-rise buildings because many parts of India are filled with this category. They considered infill walls of 250 mm thickness and of partition wall of 125 mm at different stories of the structure. Slab of 125 mm was considered by them during evaluation. They found the structure at DBE level expects to be of probability 86% of slight damage, 70% of moderate damage, 39% of severe damage, and 11% of complete damage. Similarly, in MCE level probability of damage state found were of 98% of slight damage, 94% of moderate damage, 74% of severe damage, and complete collapse of 39%.

Patel and Vasanwala [4] informed about analytical method given by the HAZUS manual. They carried out study on three-story building resembling for short period of time, six-storied building with medium time period, and 12-storied structure for longer period. They analyzed these structure with the help of finite element method (FEM)-based software SAP2000. They used 6 bays of 4 m each for structure in both directions and floor to floor height of 3 m each. Grade considered for concrete by them was of M25 and Fe415 for steel. Slab considered was of thickness 150 mm and 2 kN/m^2 imposed load was applied. Column size reduction after certain floors, that is curtailment of column, was provided in their models. After analyzing the model by nonlinear pushover analysis, they evaluated performance of buildings, and found that less storied buildings are more susceptible to damage. The also observed that as story increases all four states of damage's probability of occurrence also increases. It is observed that 12-storied buildings have slight and moderate damage and are nearly equal as compared to three- and six-storied buildings.

Shil et al. [5] studied G+5 story RC frames with and without precast RC shear wall. These structures were subjected to nonlinear pushover analysis and incremental dynamic analysis. They compared their seismic performances and found that the building with precast shear wall has 20.7% more lateral resistance if joints are negligible than that of structure without a shear wall. Slight and moderate damage probabilities were found to be almost same but in the case of extensive and collapse state structure with no shear wall showed 16% less probability, which shows yield capacity of the structure with shear wall is more. Through fragility curves they reached to conclusion that probability of reaching slight and moderate damage is more than 90%, and the probability of extensive damage is more than 80%, but complete damage state is 50% less as compared to structure without shear wall.

Paul and Debnath [6] evaluated seismic damage in reinforced concrete structures mainly containing low- and mid-rise buildings. These low- and mid-rise buildings were designed by IS456 and IS1893 as a gravity-loaded and earthquake-resistant building. They used HAZUS methodology to analyses structures by static procedure of AC-40 and fragility analysis. Damage probability matrices were formed to evaluate maximum considered earthquake and design basis earthquake levels of damage state. Their study illustrates that earthquake-resistant building provides better performance as compared to gravity-loaded design building. Vertical distribution of force acting on building structure is given in FEMA-365. They had considered predetermined lognormal variability, that is, β values form HAZUS-MH MR5 as $\beta_c = 0.3$ for low-rise building and $\beta_{T,ds} = 0.4$ for mid-rise building. The displacement of low-rise structure used by these researchers is about 53 mm and for mid-rise structure and for MCE level spectral displacement is of 48 mm.

Ravikumar et al. [7] identified vulnerable buildings both by seismic demands in linear and nonlinear way. They also considered the effect of three different lateral load patterns on performance if various irregular buildings in pushover analysis. They analyzed their model with severe earthquake zone, that is, Zone V with soil type I. The behavior of structure was analyzed by time period, base shear, lateral displacement, and story drift in linear analysis and pushover analysis was conducted to receive performance point and hinge status. They concluded that equivalent static method does not consider the irregular effect of the structure in building because it depends on imperial formula. They found that center of mass eccentricity and center of rigidity varies even if shear wall is considered. They found that the performance of sloping ground and in between life safety and collapse prevention state thus making sloping ground category more vulnerable state of buildings.

SYSTEM DEVELOPMENT

In the present work, vertical geometric irregular buildings like open ground story buildings, setback buildings, and step buildings are considered. These buildings are assigned with stiffness irregularity at different portions such as at base, at middle, and at the top stories of the structure. After assigning these irregularities, pushover analysis is carried out. After performing the pushover analysis, fragility curves are plotted (Tables 1 and 2) [8, 9].

The parameters considered for the present work are presented in Table 1 and the different structural systems considered are presented in Table 2.

Table 1. Parameters considered during modeling.

Parameters	Data
Number of stories	G+12
Bays in x-direction	5
Bays in y-direction	5
Length of each bay in x-direction	3 m
Length of each bay in y-direction	3 m
Grade of steel	Fe500
Grade of concrete	M25
Column dimension	400 × 400
Beam dimension	300 × 400
Slab thickness	150 mm
External wall thickness	230 mm
Internal wall thickness	115 mm
Height form base to first story	1.5 m
Height of typical story	3 m

Table 2. Different structural systems considered for current work.

Types of Models
Setback building (SB)
Setback building with stiffness irregularity at bottom (SB-IR-B)
Setback building with stiffness irregularity at middle (SB-IR-M)
Setback building with stiffness irregularity at top (SB-IR-T)
Step building (ST)
Step building with stiffness irregularity at bottom (ST-IR-B)
Step building with stiffness irregularity at middle (ST-IR-M)
Step building with stiffness irregularity at top (ST-IR-T)

Following are G+12 setback building (SB) model along with setback building having stiffness irregularity at locations: bottom (SB-IR-B), middle (SB-IR-M), and top (SB-IR-T) of the building (Figures 1–4). Following are G+12 step building (ST) model along with step building having stiffness irregularity at locations: bottom (ST-IR-B), middle (ST-IR-M), and top (ST-IR-T) of the building (Figures 5–8).

Pushover Analysis

Pushover analysis is a nonlinear-static method for analysis of structure. It can be performed by two different parameters, namely force control and displacement control. For the present work, displacement control parameter is been taken into account as one can see the exact behavior of the structure through different damage states. The results of these two approaches are quite similar. Geometric nonlinearity has two methods for solving equations which are P-Δ effect and P-Δ + large displacement. P-Δ effect is considered in normal conditions for building analysis, whereas P-Δ + large displacement is used when structure is subjected to vertical acceleration or when subjected to oblique ground motion (Figures 1–8).

Fragility Curves.

The fragility curve is the function that describes the probability of structural damage state or performance levels of buildings at certain ground motion. Typically, fragility curves are plotted as probability of exceeding the damage threshold against intensity measures such as acceleration, displacement, or peak ground acceleration. These fragility curves are obtained for four different states of damage. Each damage state defines specific state of structure such as deformation, cracking or failure of elements. According to HAZUS, probability of damage state with respect to spectral displacement is found by

$$P[ds|Sd] = \emptyset[\frac{1}{\beta} In\left(\frac{Sd}{Sd,ds}\right)$$

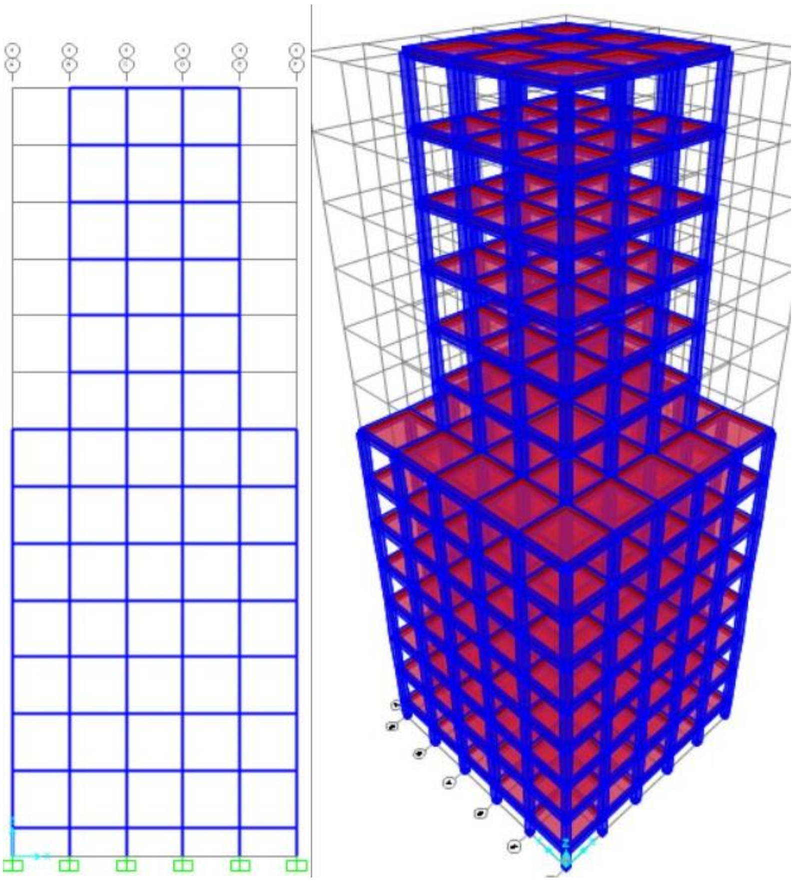

Figure 1. Setback building (SB).

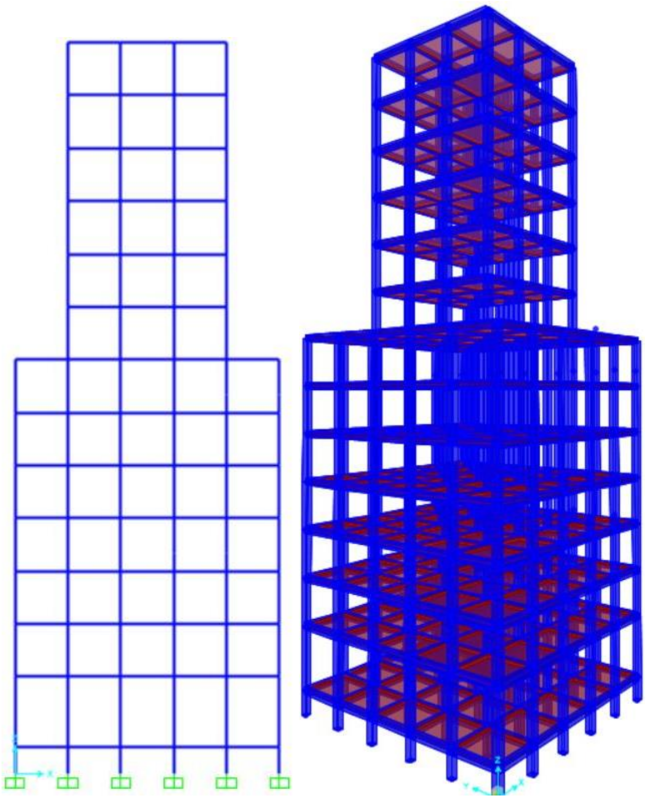

Figure 2. Setback building with stiffness irregularity at base (SB-I-B).

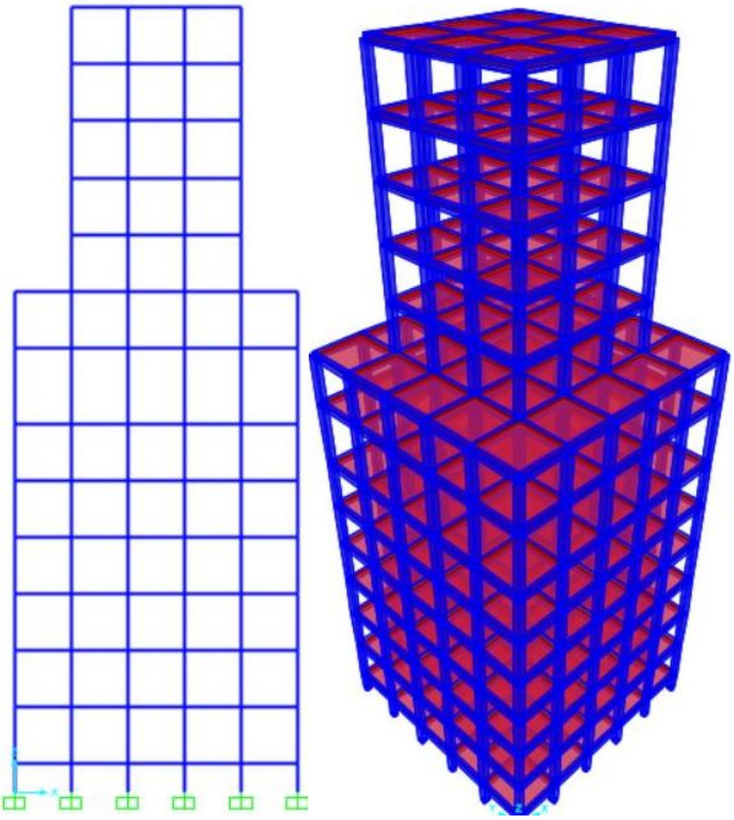

Figure 3. Setback building with stiffness irregularity

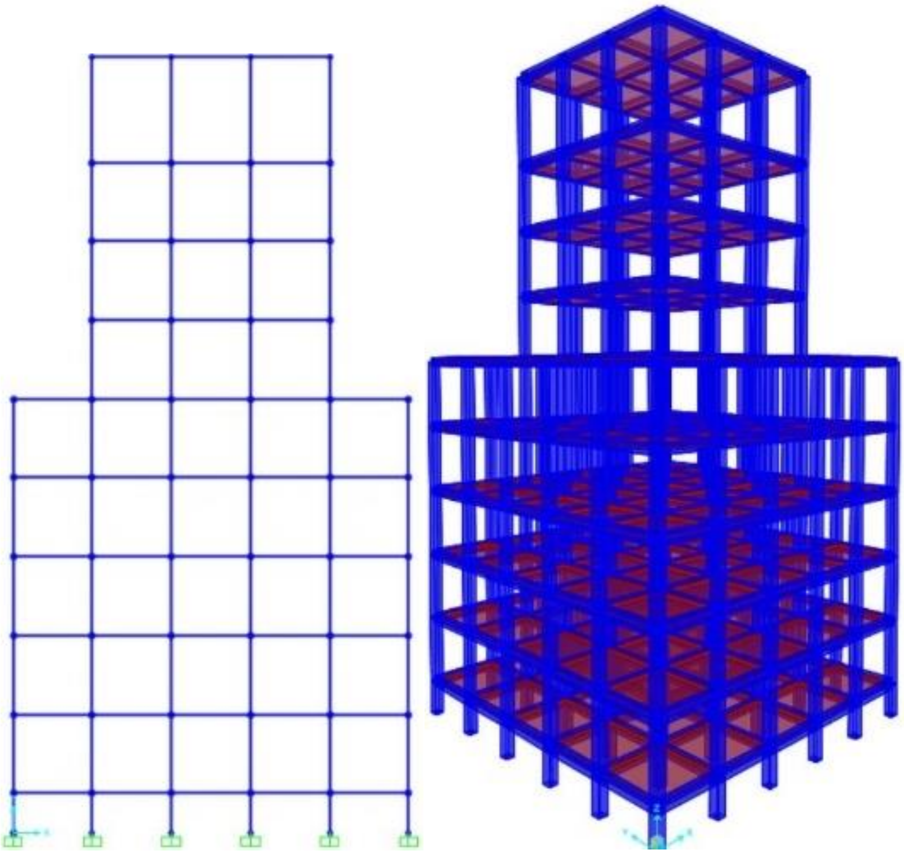

Figure 4. Setback building with stiffness irregularity at middle (SB-IR-M) and top (SB-IR-T).

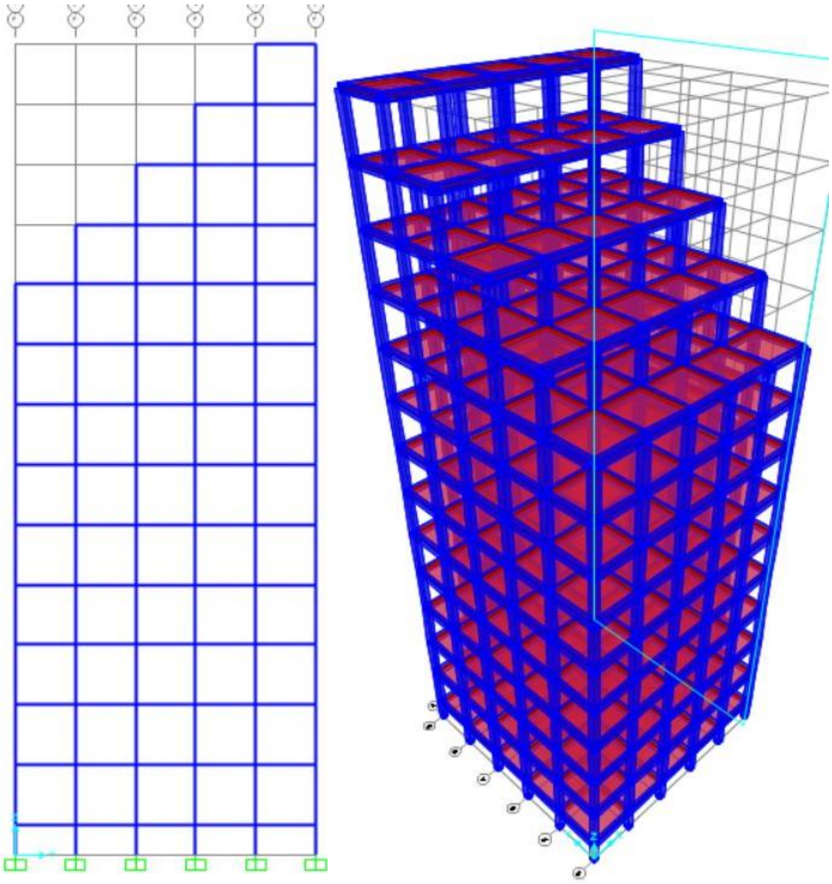

Figure 5. Step building (ST).

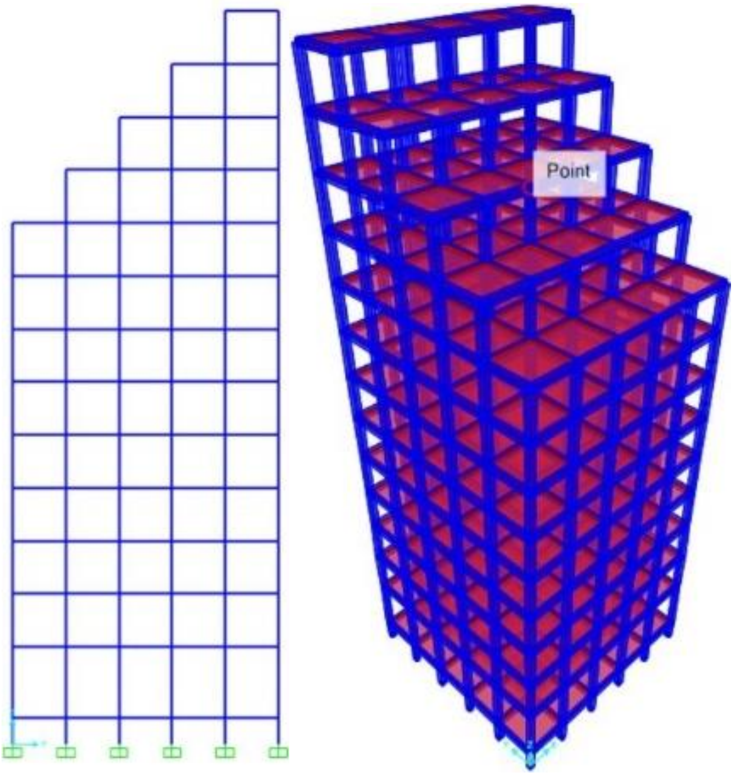

Figure 6. Step building with stiffness irregularity at bottom (ST-IR-B).

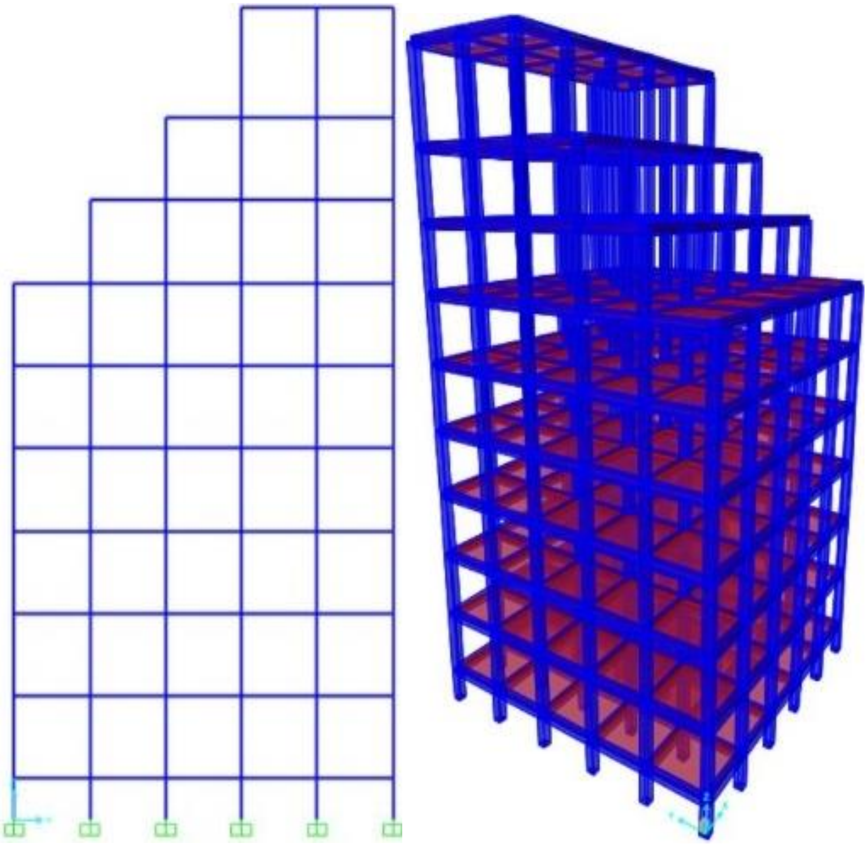

Figure 7. Step building with stiffness irregularity.

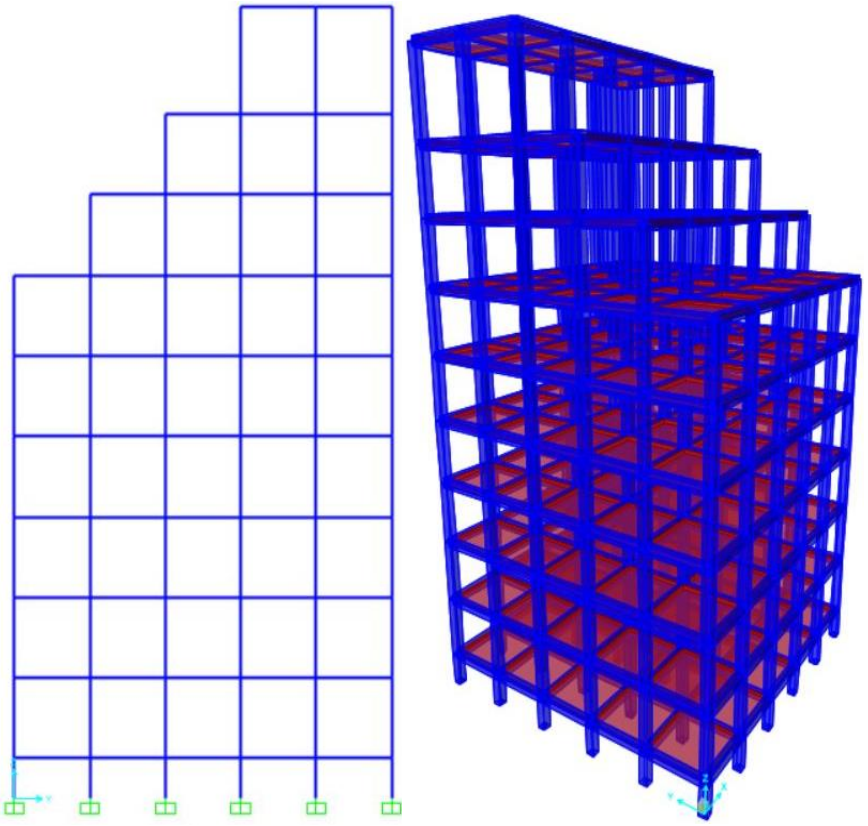

Figure 8. Step building with stiffness irregularity at middle (ST-IR-M) and top (ST-IR-T).

RESULTS AND DISCUSSION

Figures 9 and Figure 10 denote slight damage state of the SB building having stiffness irregularity at different locations. Probability of damage state at 2.5 cm, that is, 25 mm shows SB and SB-IR-T have close percentage of probability of damage state of about 50% of total slight damage state. Similarly, SB-IR-B and SB-IR-M shows percentage of probability of damage about 43.9% of total slight damage state.

Figure 11 represents moderate damage state of SB at different locations. It is observed that at displacement 3 cm, that is, 30 mm, SB with no irregularity has probability of damage state of about 46.23% which is observed large compared to other irregularities. SB-IR-B shows comparatively less damage state of about 42.64%. For SB-IR-M, percentage of damage is observed 44.46% which is second most damaged structure observed at moderate damage state. Compared to SB-IR-T, has least damage observed of only about 11.64%; thus, concluding that at moderate state it is the most stable structure.

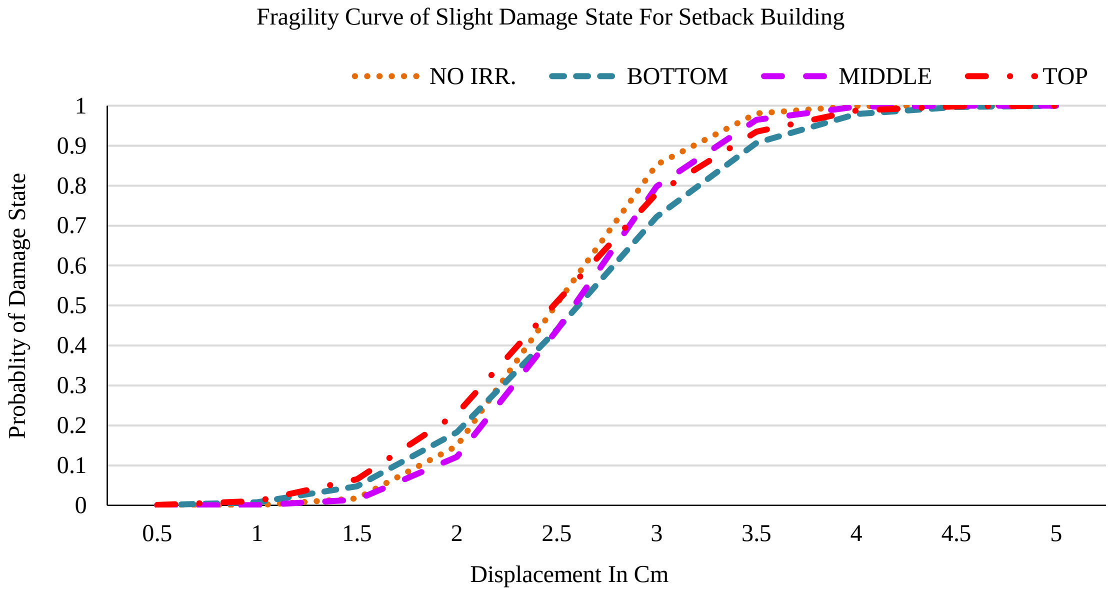

Figure 9. Fragility curve of slight damage state for setback building.

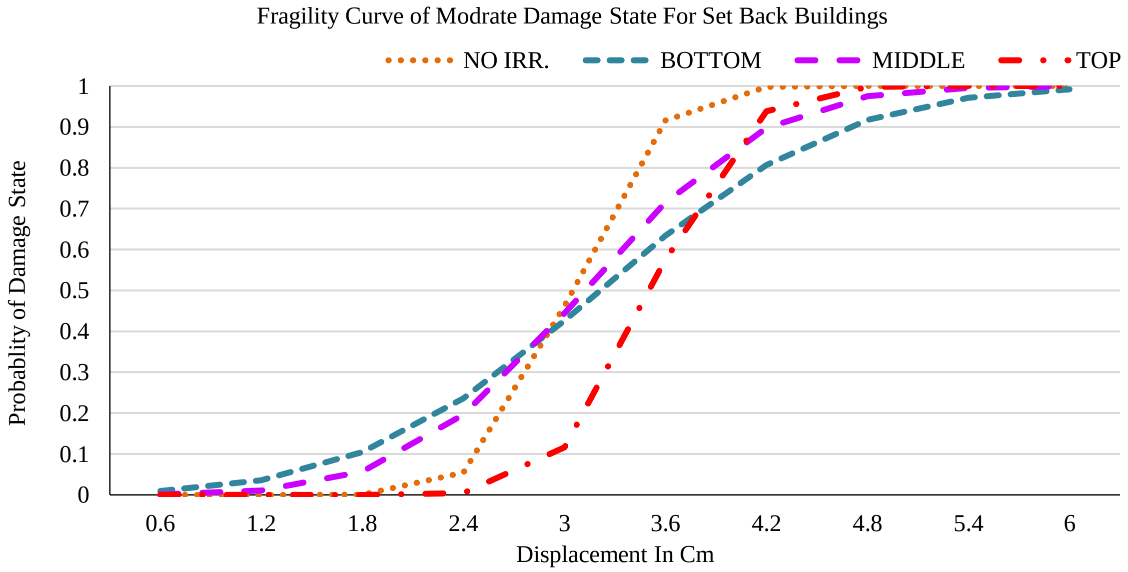

Figure 10. Fragility curve of moderate damage state for setback building.

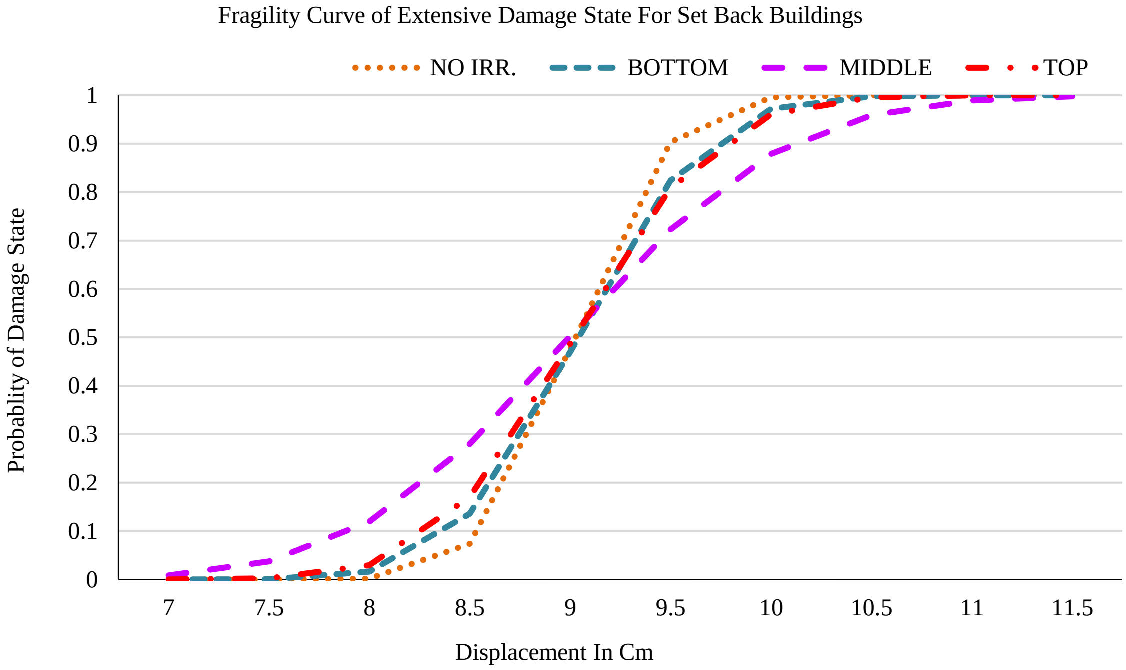

Figure 11. Fragility curve of extensive damage state for setback building.

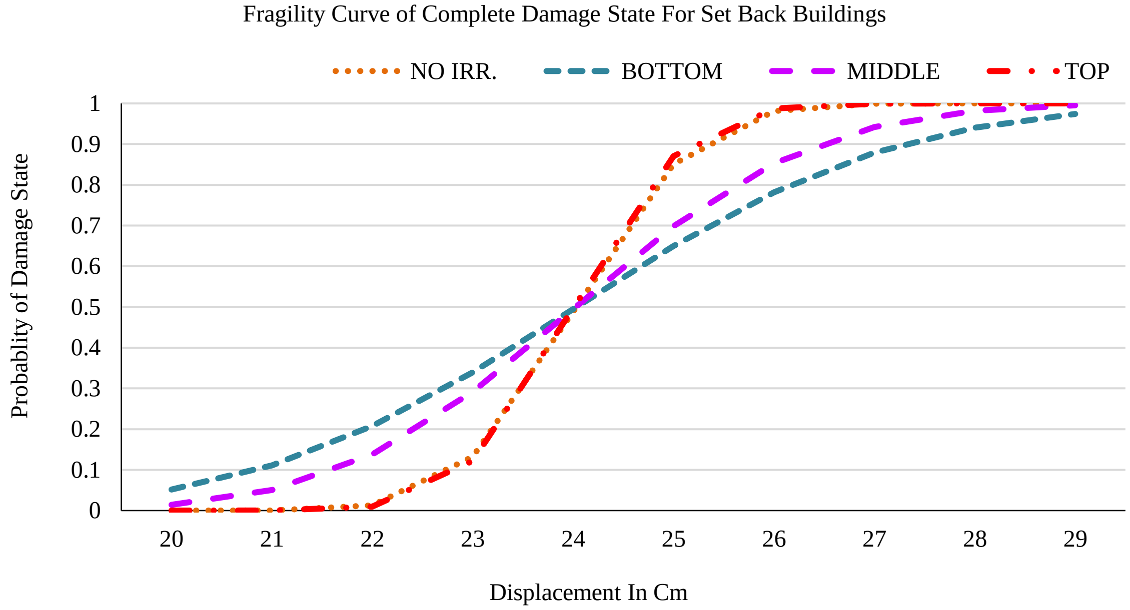

Figure 12. Fragility curve of complete damage state for setback building.

The denotes extensive damage state of SB, from this graph it is observed that at displacement of 9 cm, that is, 90 mm, percentage of damage observed for SB with no irregularity is about 47.67%, which is observed more than that of SB-IR-B of about 47.01%, for SB-IR-M and SB-IR-T probability of damage state is about 50.3% and 48.71%, respectively, of total extensive damage state.

Figure 12 presents the relationship between displacement and the probability of complete damage in setback buildings. At displacement of 25 cm, probability of damage to the structure with stiffness irregularity at top SB-IR-T shows huge percentage of damage state of 87.06%. Though SB-IR-B and SB-IR-M shows less probability of damage state is due to presence of fractures at the joints is about 64.94% and 69.88%, respectively.

Figure 13 shows the fragility curve of step building. The damage probability of step building ST at 2.5 cm is about 45.66% of entire damage state. Compared to bottom stiffness irregularity (ST-IR-B) structure damage probability is of 43.85% which shows building significantly distributes loads at this stage. More affected structure in slight damage state is of ST-IR-T, which shows nearly 50% of entire slight damage probability.

At displacement 3 cm percentage of moderate damage state for ST-I-B has high damage percentage of about 49.52% and lowest is for ST-IR-M, which is about 46.73% (Figure 14). Compared to SB-IR-T, it has less percentage of damage state of 47.81% than that of SB with 48.06%.

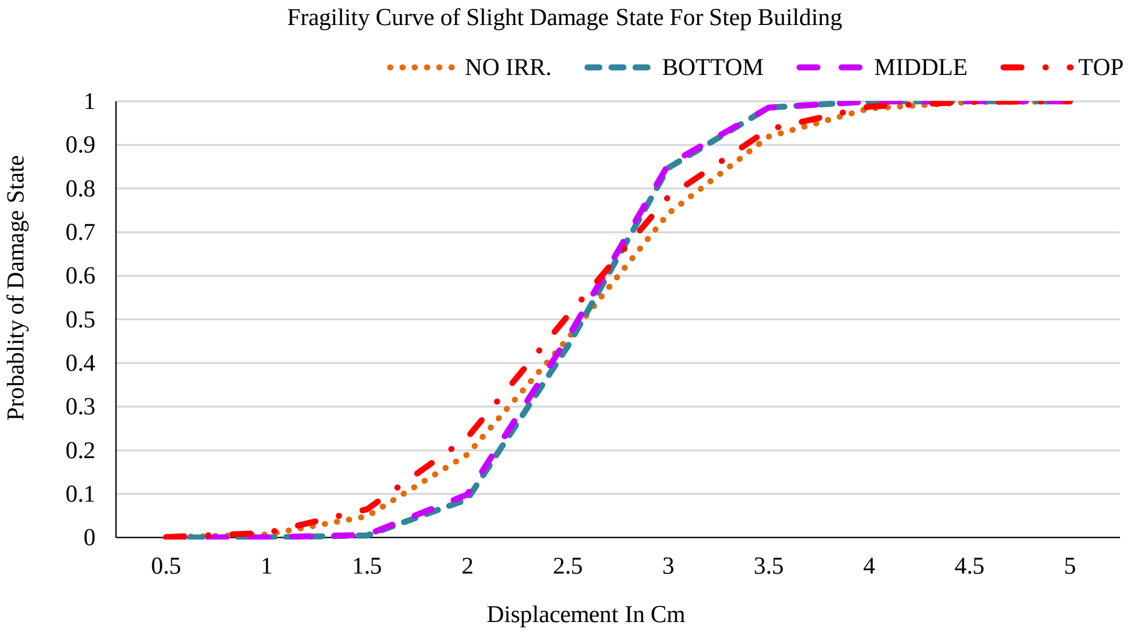

Figure 13. Fragility curve of slight damage state for step building.

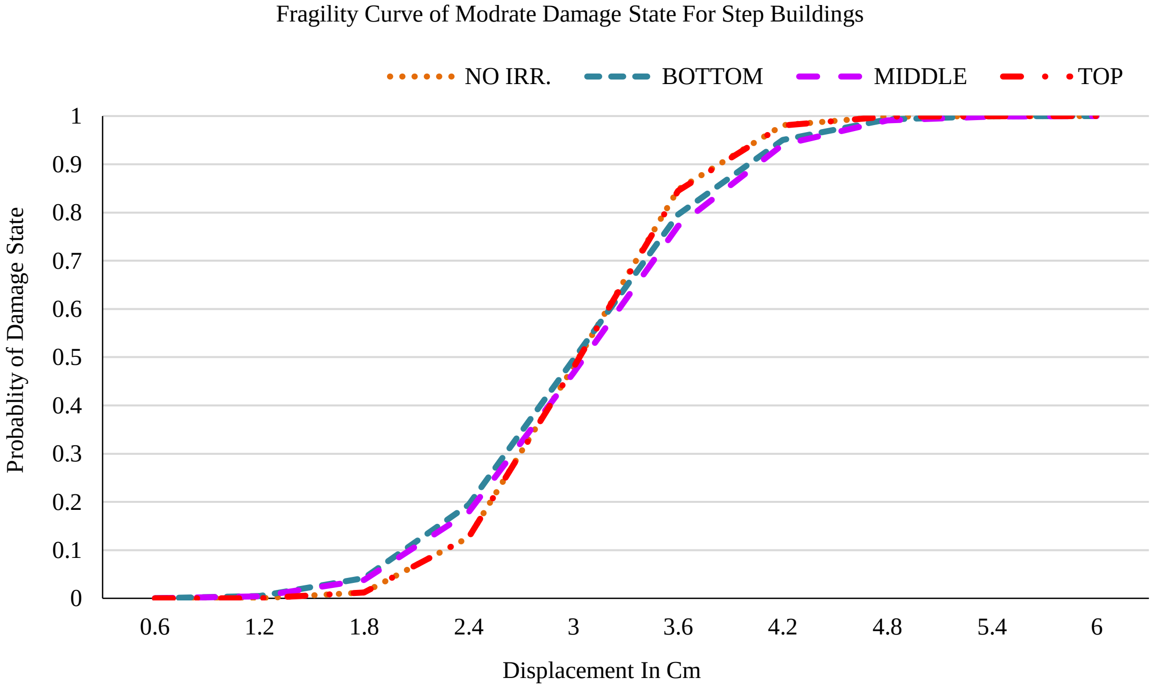

Figure 14. Fragility curve of moderate damage state for step building.

At displacement of 9 cm setback building having no stiffness irregularity has probability of extensive damage state of about 47.62%, which is less compared to other damage state thus less affected in this state. A total of 49.94% of damage state is obtained for ST-IR-M whereas ST-IR-B and ST-IR-T shows close that is 48.34% and 48.08% of damage for extensive damage state (Figure 15).

At the complete damage state for step building probability of exceedance at a displacement of 25 cm for SB is 73.67%, which is the second-highest damage (Figure 16). The ST-IR-M has 74.025% of damage. ST-IR-B and ST-IR-T show 72.7% and 70.7% of complete damage state, respectively (Table 3).

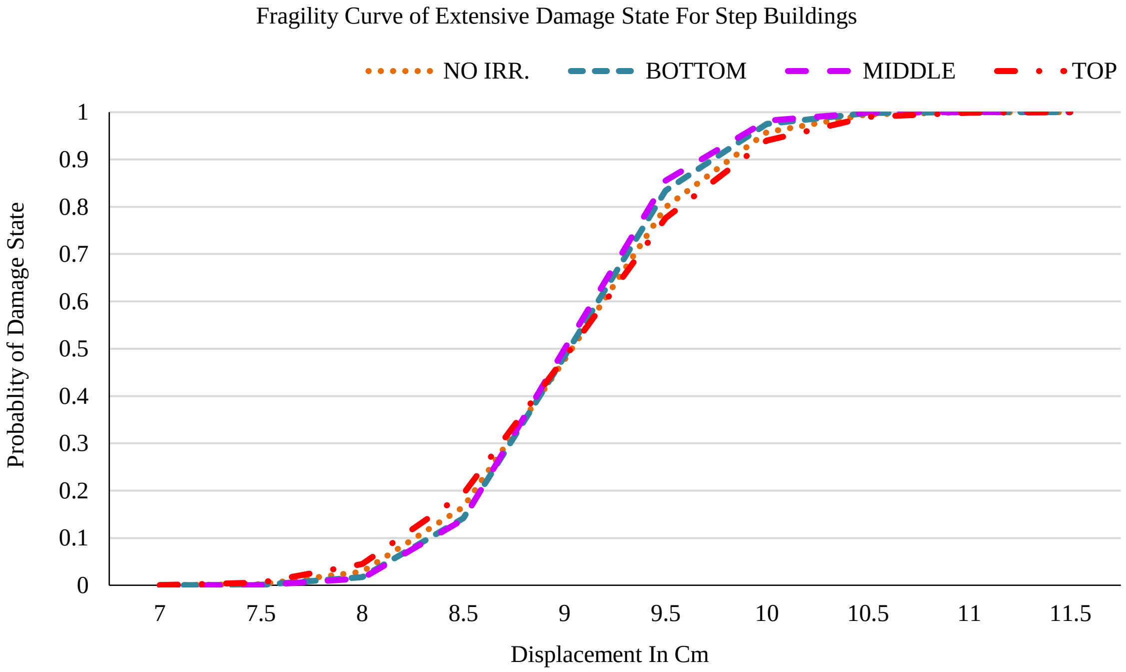

Figure 15. Fragility curve of extensive damage state for step building.

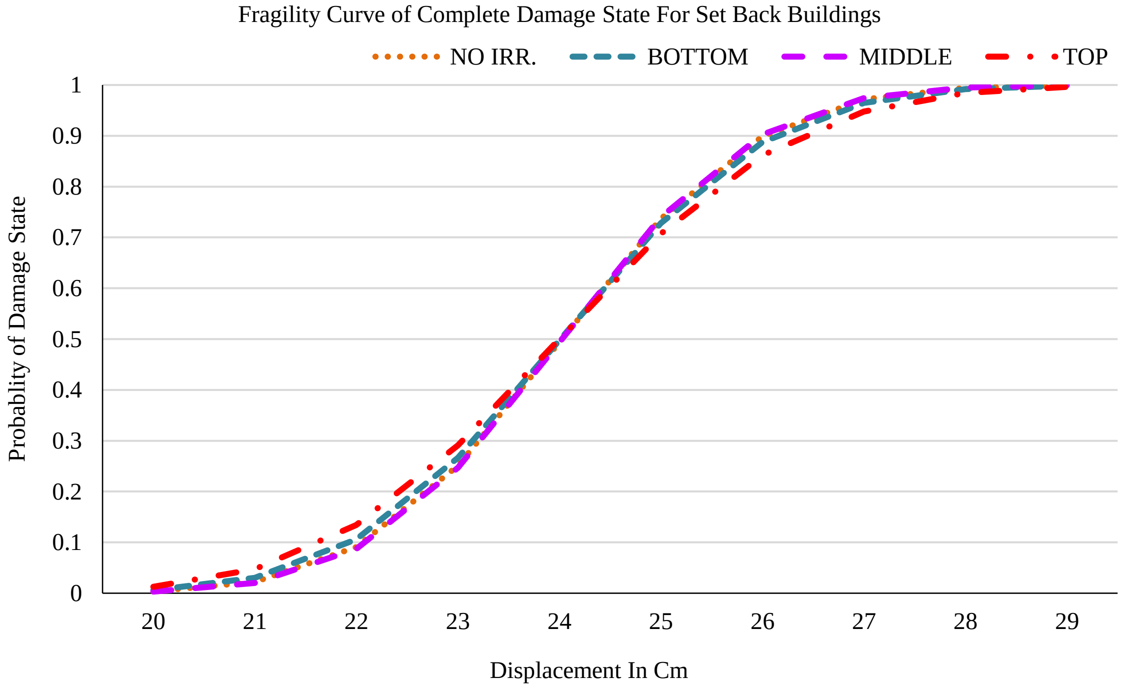

Figure 16. Fragility curve of complete damage state for step building.

Table 3. Percentage of probability of damage for particular damage state and type of structure.

Damage State	Setback Building				Step Building			
	SB	***SB-IR-B***	***SB-IR-M***	***SB-IR-T***	***ST***	***ST-IR-B***	***ST-IR-M***	***ST-IR-T***
Slight	50	43	43	50	45.66	43.85	45.85	50.87
Moderate	46.23	42.64	44.46	11.64	48.06	49.52	46.73	47.81
Extensive	47.67	47.01	50.3	48.71	47.61	48.34	49.91	48.08
Complete	85.1	64.94	69.88	87.1	73.67	72.77	74.03	70.73

CONCLUSIONS

The conclusions for each damage state based on the fragility curves are as follows:

1. Buildings with setback designs, characterized by stiffness irregularities at the base and lower levels, exhibit lower probabilities of damage at slight damage states that shows some hairline cracks at some beams and columns is observed at 20 mm displacement compared to other structures. This suggests that such buildings demonstrate better resilience during the initial stages of damage.
2. At moderate damage state, least damage is observed in setback building having stiffness irregularity at top and step building having stiffness irregularity at middle than any other types of structures. This denotes thjat few members of structure have reached their yield capacity.
3. At the state of extensive damage all the structures get affected by almost 50% of damage, but low damage is observed in the SB and ST having no stiffness irregularities. Large flexural cracks and buckled main reinforcement are observed in beams. Main reinforcement in column is slightly buckled which is partial collapse due to broken ties.
4. Setback buildings have the highest probability of damage at a complete collapse state, but is better than others because of stiffness irregularity.
5. Irregularities at the top level of structure represent high risk in completely damaged state because when structure is subjected to ground motion, large displacement may occur at top of the building.
6. At initial stage, structures having stiffness irregularity at bottom show large displacement, which is due to soft story effect hence it is needed to be strengthen when used.
7. When irregularity is added to middle of the structure, it can distribute load equivalently up to moderate damage state.

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