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Seismic Performance of Offset Irregular Building

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Abstract: Here in this offset irregularity, the vertical members bearing horizontal force are located on other axes rather than its own axes. A 15-storey offset irregular building is modelled in SAP2000 software based on the codal provisions. Then pushover analysis is performed in which spectral displacements and base shears are examined in both X and Y directions. Fragility curves are developed to determine the failure probability of offset irregular building in slight, moderate, extensive and complete damage states. Using a thorough analysis using the pushover analysis approach, this study compares the seismic performance of a 15-storey offset irregular structure with a structurally regular building. For all building types, the study uses the SAP2000 software platform to assess spectral displacements and base shears in both the X and Y axis. The goal of this research is to measure and compare the complicated static response of the 15-storey building with that of a regular counterpart, given that the offset irregularity in the structure adds to its complexity. Accurate finite element models of both structures are developed, mode shapes and natural frequencies are extracted. After that, the pushover data is examined to determine the greatest displacements and base shear at crucial points in both the buildings. Understanding the impact of the offset irregularity on the static properties and seismic response of the 15-story building is given special attention. Moreover, the study goes so far as to use fragility curves to determine the likelihood of collapse for both buildings. Fragility curves provide a probabilistic evaluation of failure possibilities by offering important insights into a structure's susceptibility to seismic loads. The research looks at how the 15-story structure's abnormalities affect its fragility in comparison to the normal building, highlighting possible flaws and assisting in the improvement of seismic design. The results are intended to guide future design guidelines and construction rules, fostering increased safety and resilience in seismically vulnerable areas.
Keywords: Pushover analysis, Offset irregular building, SAP2000 software, Spectral displacement, Base shear, Fragility curves

I. INTRODUCTION

Irregular buildings, with their unconventional geometries, non-standard arrangements, and uneven mass distributions, pose a unique structural engineering problem. In contrast to its regular counterparts, which follow standard geometries and homogeneous layouts, irregular buildings contradict established structural design principles. These constructions may take on a wide range of forms, from asymmetrical floor plans and uneven facades to complicated geometries that defy traditional technical solutions. As a result, assessing and designing irregular structures need specialized knowledge, novel methodologies, and advanced computational tools to assure structural safety and performance, especially under seismic loading situations. An offset building is one having horizontally displaced floors or walls, resulting in a staggered or skewed look. It is used to improve aesthetics, break up homogeneous facades, and accommodate site restrictions. Offset structures can also give functional benefits such as more lighting, better vistas, and seclusion. However, they can cause structural engineering problems because to uneven load distributions and differential settling concerns.

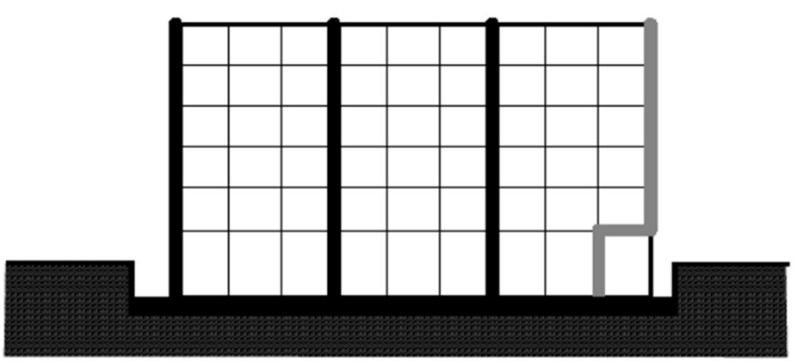

Fig.1: offset irregularity

Seismic analysis is an essential part of determining the earthquake resilience of buildings and other structures. It entails assessing how a structure responds to earthquake-induced ground motion in order to forecast future damage and ensure structural safety. Seismic analysis is very difficult in irregular buildings because to irregularities in geometry, mass distribution, and stiffness qualities. These variations can cause localized stresses, torsional effects, and uneven seismic force distribution, all of which might risk the building's structural integrity if not correctly accounted for throughout the study and design process.

II. METHODOLOGY

A. *Pushover Analysis*

Pushover analysis is an effective approach in structural engineering, notably for evaluating the seismic performance of buildings and other structures. It belongs to the domain of nonlinear static analysis methods and is commonly used in seismic design and retrofitting projects. The essential premise of pushover analysis is to mimic a structure's gradual collapse behavior under increasing lateral pressures, which are often seismic forces. To do a pushover analysis, engineers must first model the structure using finite element analysis or other numerical methods. This entails dividing the structure into smaller components, such as beams, columns, and braces, and describing their attributes and relationships. The structure is then exposed to lateral stresses in stages, beginning at a low level and gradually increasing to a predetermined maximum. During the study, the structure's reaction is tracked, including deformations, member forces, and displacements at crucial places. This data is used to create a force-displacement curve that depicts the connection between applied lateral forces and the resulting displacements. The force-displacement curve gives useful information on structural characteristics, such as strength, stiffness, and ductility.

B. *Fragility Curves*

Fragility curves are crucial for assessing structural seismic vulnerability, revealing the likelihood of different damage levels under different ground shaking levels. They depict the probability of exceeding certain damage states based on seismic intensity. The process involves defining damage states and analyzing structure’s response to seismic events using computational models and ground motion records. Damage states are estimated using simulated reactions at various degrees of ground shaking severity. Statistical approaches like as Bayes's inference and maximum likelihood estimation fit mathematical models, resulting in fragility functions. These probabilistic representations assist engineers in assessing seismic activity risk, making decisions about retrofitting structures, developing new buildings, and adopting mitigation measures to improve seismic resistance. Validating fragility curves against observed damage data from previous earthquakes is critical for ensuring their reliability and correctness. Engineers may also do sensitivity analysis to determine the influence of uncertainty in input parameters on fragility estimations.

C. *Building Description*

The buildings consist of 15 reinforced concrete floors, with each storey height of 3.0 m. The plan dimensions are 15.2 m x 12.0 m, with a 1.2m offset as shown in fig.3.1, fig.3.3 and fig.3.5. The plan dimension of regular building is 14 m x 12 m as shown in fig.3.2, fig.3.4 and fig.3.6. These buildings have four spans in each longitudinal and transverse orientations, with 3 m long spans in longitudinal and 3.5 m long spans in transverse. And offset building is having an extra span in longitudinal direction with 1.2 m span which is represented as offset. The lateral load resisting system consists of moment resistant frames in both directions.

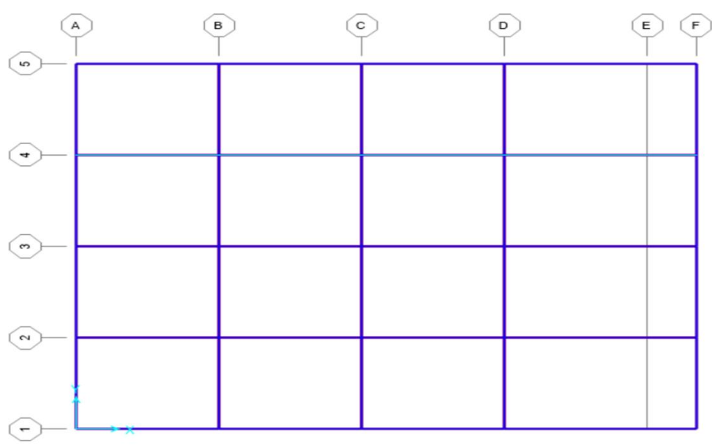

Fig.2: Floor plan of Offset Irregularity

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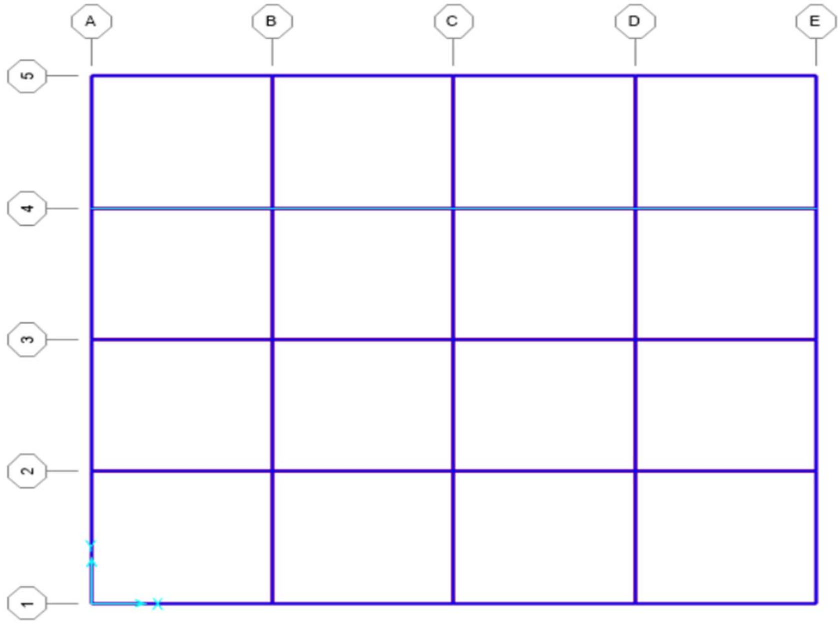
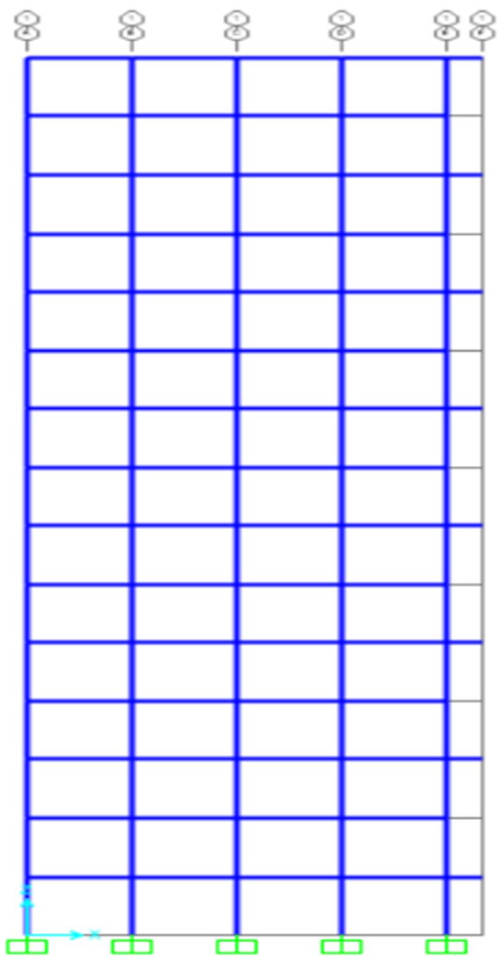


Fig.3: Floor plan of Regular building



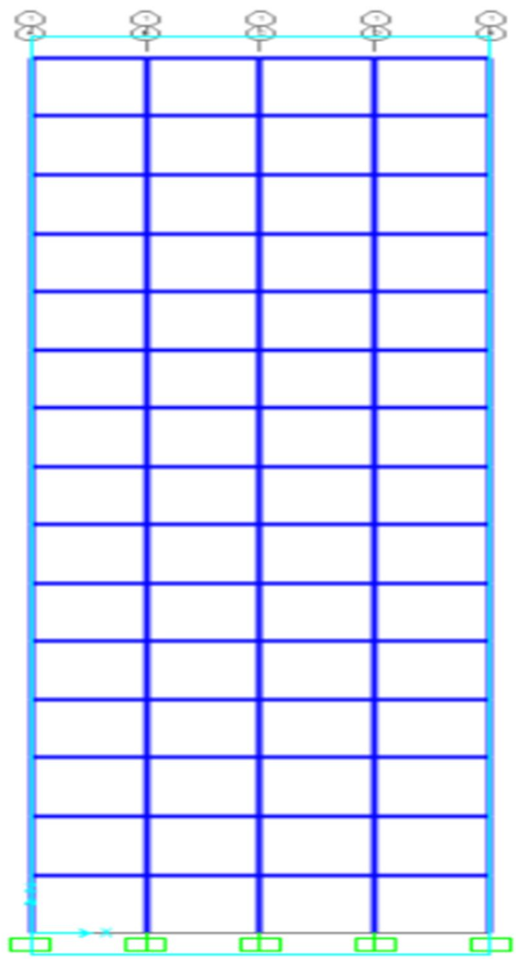


Fig.4: Elevation of Offset Irregularity Fig.5: Elevation of regular building

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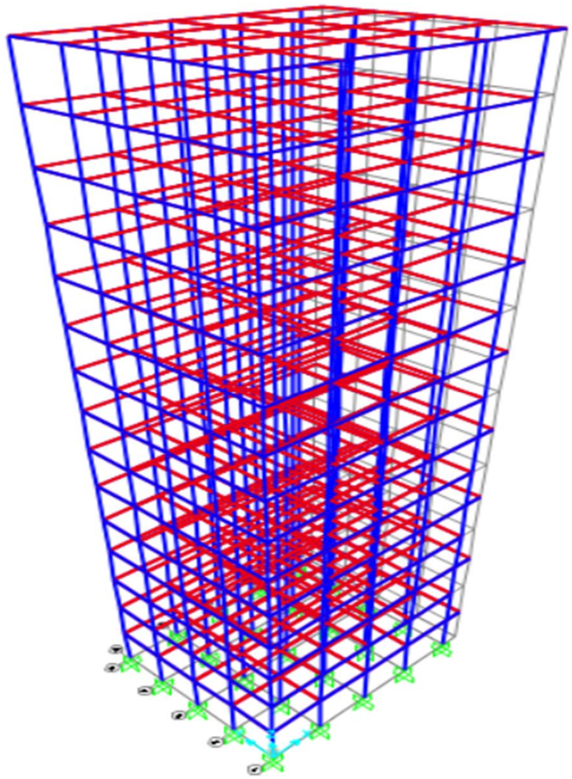

Fig.6: 3D View of offset irregular building

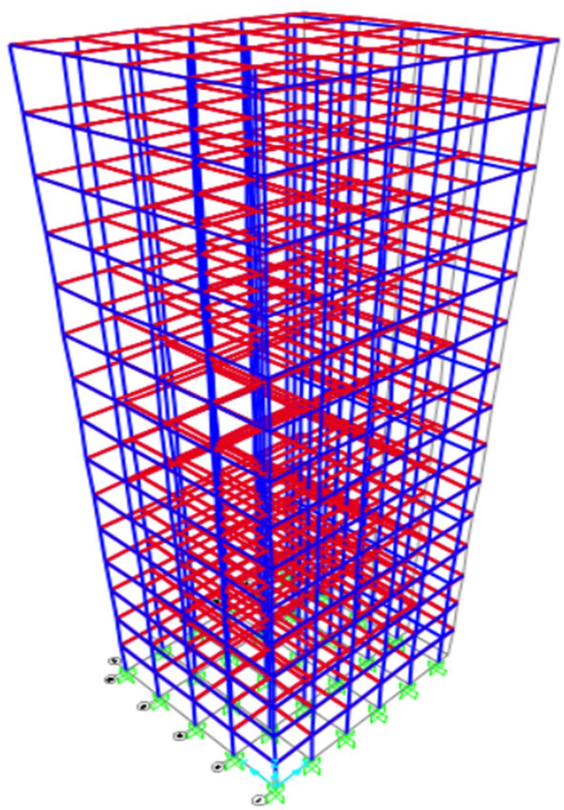

Fig.7: 3D View of regular building

M30 grade concrete slabs, columns, and beams as well as Fe 415 grade steel rebar were used in the creation of the model. The elastic properties of the materials were determined using IS 456-2000. The short-term modulus of elasticity (E) for concrete is $E_C = 5000\sqrt{fck}$. whereas the stress and modulus of elasticity for steel rebar are as per IS 800-2007. Here for these structures, loads applied on slab are floor finish (Dead)=1KN/m^2, live load is 3KN/m^2 and for parapet slab it is 1.5KN/m^2. The wall loads are applied on the frames of the beams based on the position of the beam weather it is external wall or internal wall. For external wall load applied is 13.8KN/m and for internal wall load applied is 6.9KN/m and for parapet external wall load applied is 2.85KN/m according to codal provisions, IS 875(part 1)1987 and IS 875(part 2)1987.

The limit state approach is utilized in seismic design of RC structures, considering four load combinations according to IS code provision, i.e., IS 1893:2016, clauses 6.3.2.1:

1. 1.5 (DL + LL),
2. 1.2 (DL + LL ± EL),
3. 1.5 (DL ± EL), and
4. 0.9 DL ± 1.5 EL

TABLE 1: Properties of concrete and reinforcing steel used in design

Description	Value
Geometry of building	Offset irregular RC building
Grade of concrete	M30
Grade of steel	Fe415
Number of storeys	15 storeys
Offset provided	1.2 m
Column dimensions	0.45 m x 0.45 m
Beam dimensions	0.45 m x 0.45 m
Floor height	3 m
Slab thickness	150 mm
Live load on floors up to 14floors	3 kN/m^2
Live load on top floor	1.5 kN/m^2
Floor finish	1 kN/m^2
External wall load	13.8 kN/m
Internal wall load	6.9 kN/m
Parapet wall load	2.8 kN/m

TABLE 2: Seismic provisions considered in design

Description	Magnitude
Earthquake zone	IV
Zone factor, Z	0.24
Importance factor	1
Response reduction factor	5
Eccentricity ratio	0.05
Soil type	Medium

D. Fragility Curve Calculations

1) For offset irregular building

Displacement (ultimate) = 0.269 m

K_i = 69309.23 kN/m

V_Y = 4922.3482 kN

K_i- stiffness at initial; V_Y-base shear

$K_i = V_Y/D_Y$
$D_Y = V_Y/K_i$
D_Y- Roof displacement at yield
$D_Y = 4922.3482 / 69309.23 = 0.071$ m
Roof displacement at yield = 0.071 m; Roof displacement at ultimate = 0.269 m
Spectral displacement= Roof displacement at 1st mode / (1st modal participation factor x 1st mode model displacement roof)
From push-X curve: $U_X = 69.63$ KN/m (1st modal participation factor)
$U_1 = 0.0043$ (1st mode modal displacement roof)
$D_y = 0.071 / (69.63 \times 0.0043) = 0.237$ m
$D_u = 0.269 / (69.63 \times 0.0043) = 0.898$ m
Spectral displacements:
$Sd_1 = 0.7 \times D_y = 0.7 \times 0.237 = 0.166$ m
$Sd_2 = D_y = 0.237$ m
$Sd_3 = D_y+0.25(D_u-D_y) = 0.237+0.25(0.898-0.237) = 0.402$ m
$Sd_4 = D_u = 0.898$ m

TABLE 3: Median and Standard Deviation of Offset Irregular building

State	Median (M) (m)	Standard deviation (β) (m)	Hazu's values (Inches)
Slight damage	0.45	0.016764	0.66
Moderate damage	0.643	0.016256	0.64
Extensive damage	0.836	0.017018	0.67
Complete damage	1.413	0.019812	0.78

$$P\left(\frac{Ds}{Sd}\right) = \emptyset\left[\frac{\ln(Sd) - \ln(M)}{\beta}\right]$$

Ø-Standard normal cumulative distribution factor

2) *For regular building*

Displacement (ultimate) = 0.296 m
$K_i = 33661.07$ kN/m
$V_Y = 1596.2621$ kN
K_i- stiffness at initial; V_Y-base shear
$K_i = V_Y/D_Y$
$D_Y = V_Y/K_i$
$D_Y = 1596.2621 / 33661.07 = 0.0474$ m
Roof displacement at yield = 0.0474 m; Roof displacement at ultimate = 0.296 m
Spectral displacement = Roof displacement at 1st mode / (1st modal participation factor x 1st mode model displacement roof)
From push-X curve: $U_X = 47.313$ KN/m (1st modal participation factor)
$U_1 = 0.0079$ (1st mode modal displacement roof)
$D_y = 0.0474 / (47.313 \times 0.0079) = 0.127$ m
$D_u = 0.296 / (47.313 \times 0.0079) = 0.792$ m
Spectral displacements:
$Sd_1 = 0.7 \times D_y = 0.7 \times 0.127 = 0.089$ m
$Sd_2 = D_y = 0.127$ m
$Sd_3 = D_y+0.25(D_u-D_y) = 0.127+0.25(0.792-0.127) = 0.293$ m
$Sd_4 = D_u = 0.792$ m

TABLE 4: Median and Standard Deviation of regular building

State	Median (M) (m)	Standard deviation ($\boldsymbol{\beta}$) (m)	Hazu's values (Inches)
Slight damage	0.089	0.016764	0.66
Moderate damage	0.127	0.016256	0.64
Extensive damage	0.293	0.017018	0.67
Complete damage	0.792	0.019812	0.78

III. RESULTS AND DISCUSSION

One technique for evaluating a structure's reaction to seismic forces is response spectrum analysis. Pushover analysis curves are created, important parameters are determined, peak displacements and base shears are assessed, interest periods are identified, results are compared to design criteria, mode shapes are analysed, irregularity effects are taken into account, seismic performance is interpreted, and vulnerabilities and mitigation strategies are discussed. To make that the building's performance satisfies predetermined performance targets, it aids in identifying key periods, 0.05 damping ratio, and possible structural adjustments.

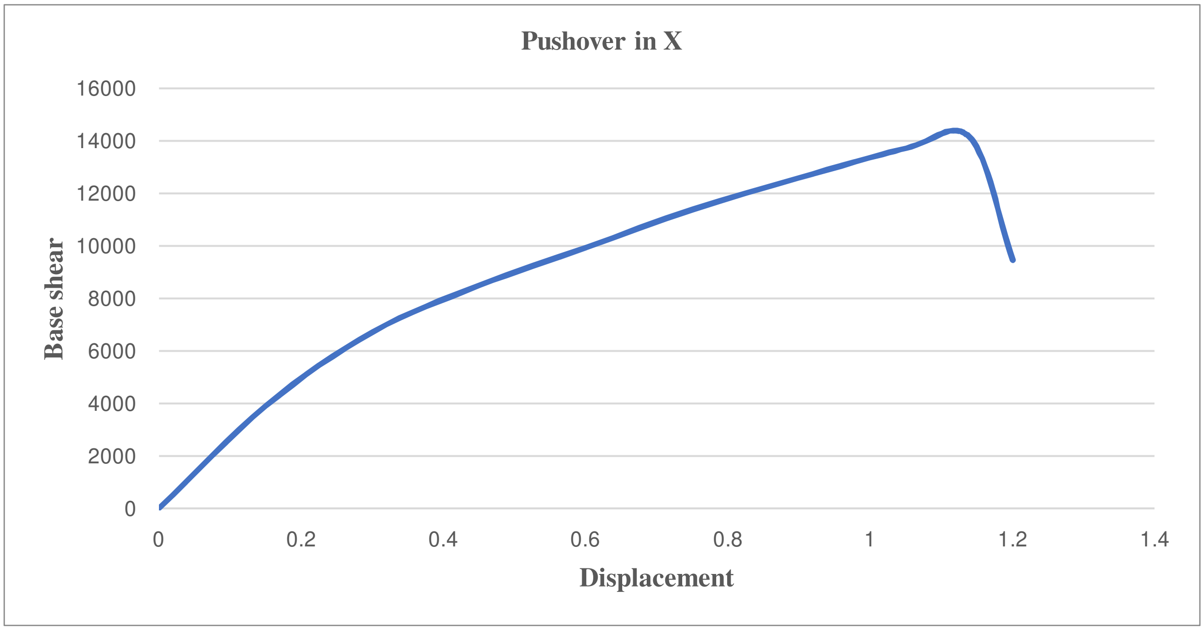

Fig.8: Base shear vs displacement curve of Offset Irregular RC building

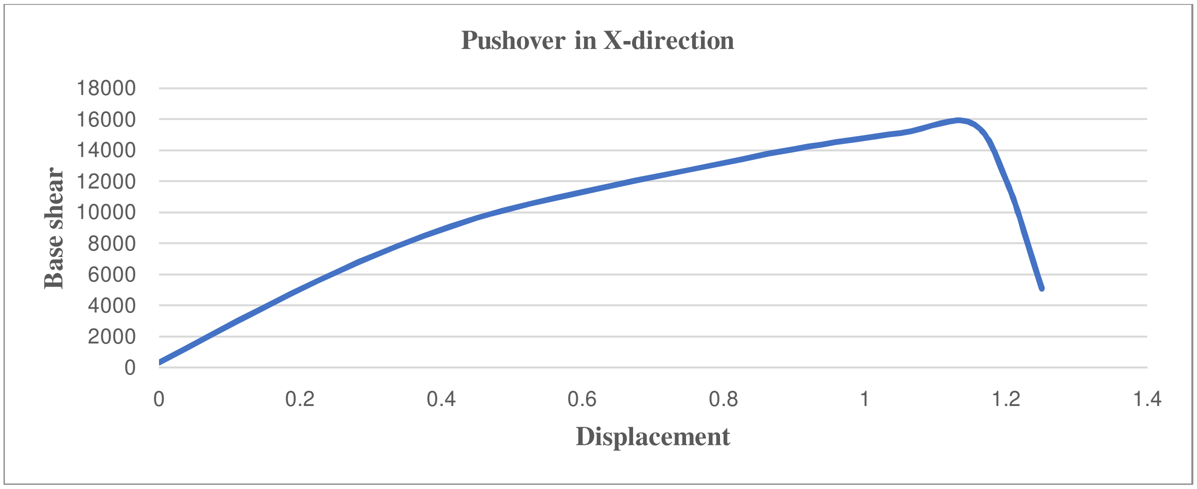

Fig.9: Base shear vs displacement curve of Regular RC building

Fig.8 & Fig.9, represents the base shear vs displacement of offset irregular building and regular building in X-direction. Here for offset building the maximum base shear is 14115.756 kN at the displacement of 1.14 meters whereas for regular building the maximum base shear is 15755.63 kN at the displacement of 1.15 meters. The offset irregular building and regular building exhibit immediate occupancy at a displacement of 0.3 meters, with base shears of 6720.257 kN and 7138.26 kN, respectively. Collapse prevention at a displacement of 1.05 meters with base shear values of 13713.826 kN and 15112.54 kN, respectively.

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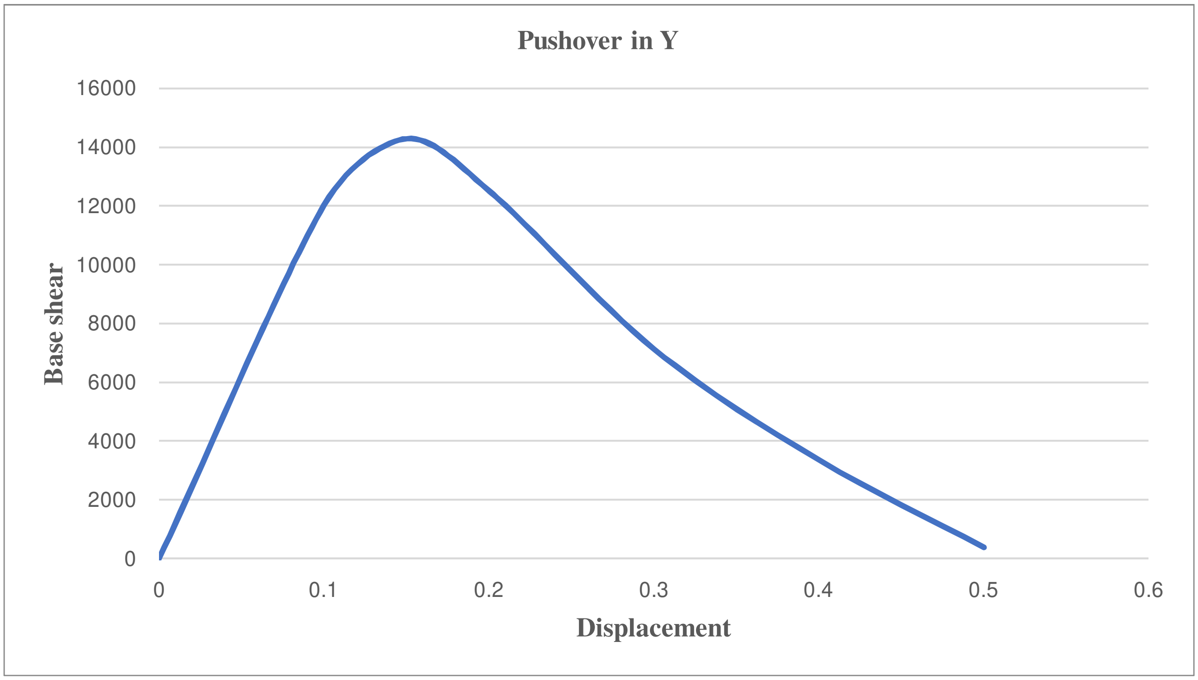

Fig.10: Base shear vs displacement curve of Offset irregular RC building

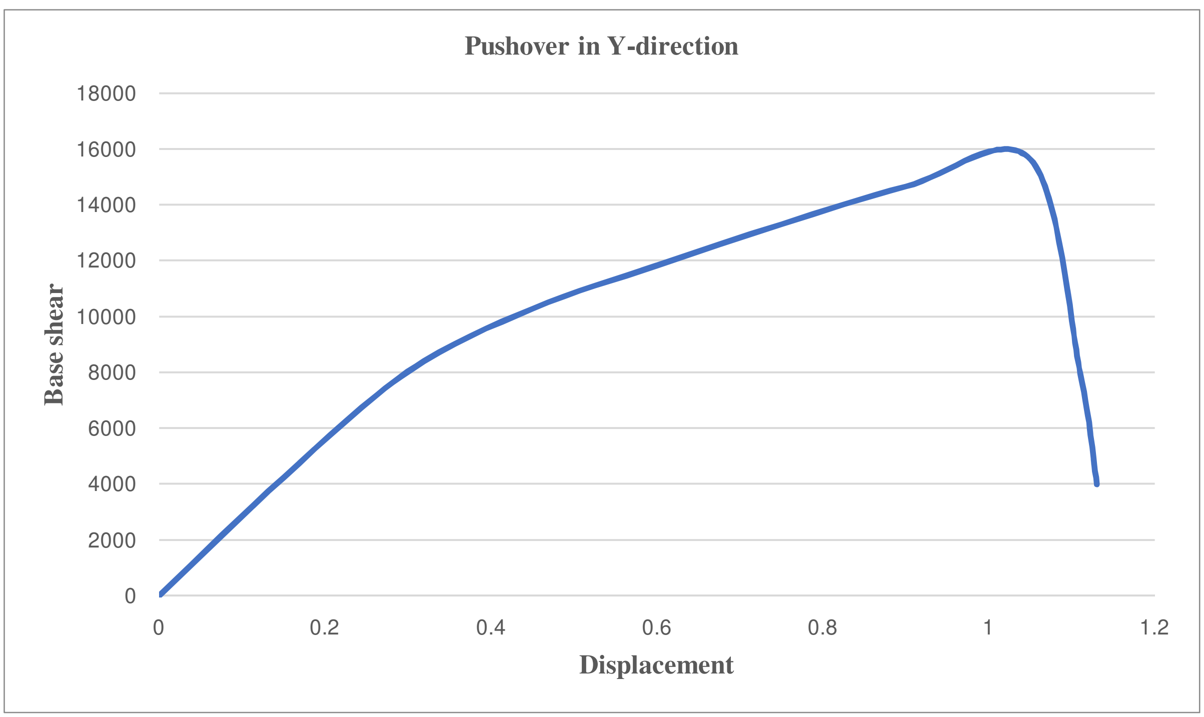

Fig.11: Base shear vs displacement curve of Regular RC building

Here in fig.10 & fig.11, represents the base shear vs displacement of offset irregular building and regular building in Y-direction. For offset irregular building the maximum base shear is observed as14284.565 kN at a displacement of 0.15 meters and for regular building the maximum base shear is 15620.579 kN at a displacement of 1.05 meters. In this case, an offset irregular building has immediate occupancy at a displacement of 0.1 meters with a base shear of 12033.762 kN and a collapse point at a displacement of 0.15 meters with a base shear of 14284.565 kN, whereas a regular building has immediate occupancy at a displacement of 0.3 meters and collapse prevention at 0.9 meters with base shears of 8032.154 kN and 14655.948 kN, respectively.

E. Fragility Curves

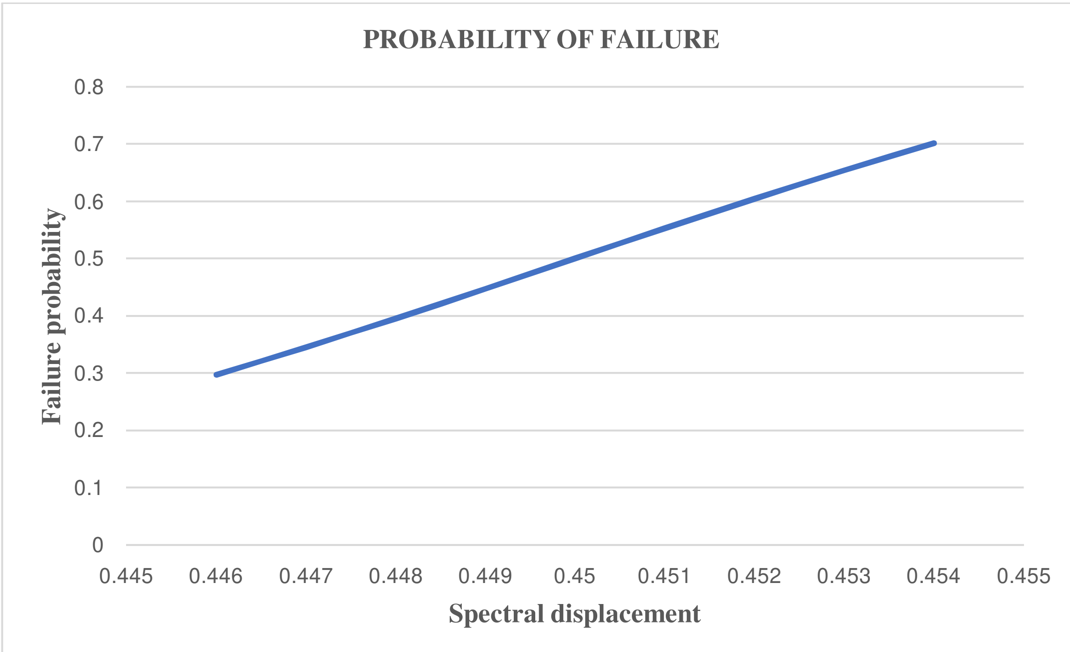

Fig.12: Failure probability of offset irregular at slight damage

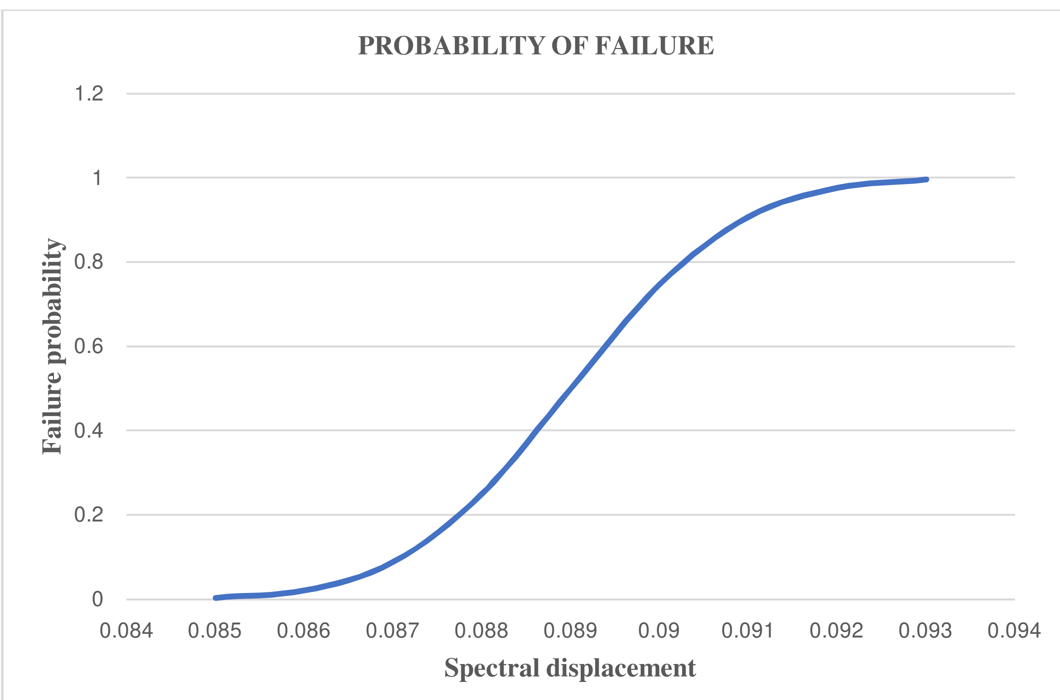

Fig.13: Failure probability of regular building at slight damage

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Fig.12 & fig.13 illustrate the probability of failure in relation to the spectral displacements. In slight damage state, the average spectral displacement for offset irregular building is 0.45m whereas for regular building it is 0.089m. It is observed that the failure probability at 0.446 meters is 30% and 70% at 0.454 meters of spectral displacement of an offset irregular building, whereas for regular structure the failure probability is 0% at 0.095 meters and 100% at 0.093 meters at slight damage condition

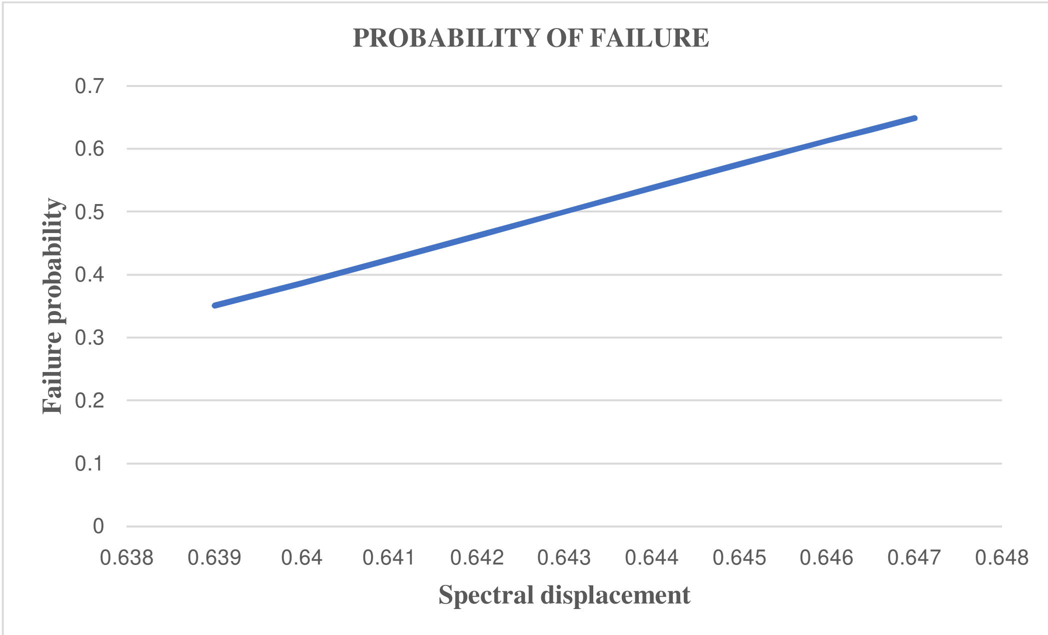

Fig.14: Failure probability of offset irregular at moderate damage

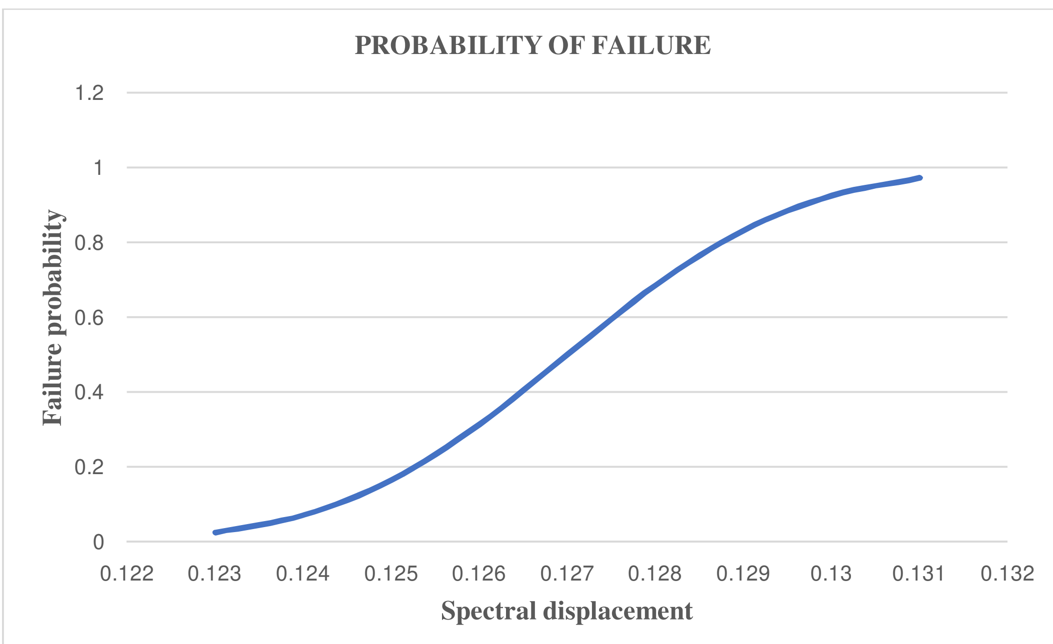

Fig.15: Failure probability of regular building at moderate damage

Fig.14 & fig.15 depicts the failure probability in terms of spectral displacements. In moderate damage, the average spectral displacement for offset irregular buildings is 0.643 meters, whereas regular buildings have an average displacement of 0.127 meters. It is discovered that the failure probability at 0.639 meters is 35% and 65% at 0.647 meters of spectral displacement of an offset irregular building, but for regular structures the failure probability is 5% at 0.123 meters and 95% at 0.131 meters at moderate damage condition.

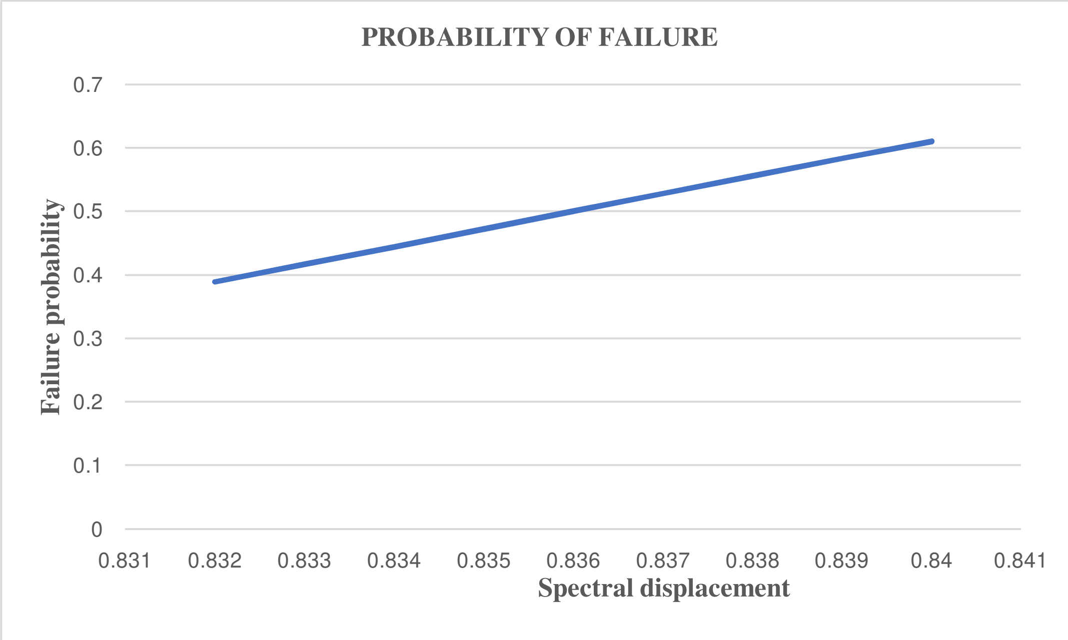

Fig.16: Failure probability of offset irregular at extensive damage

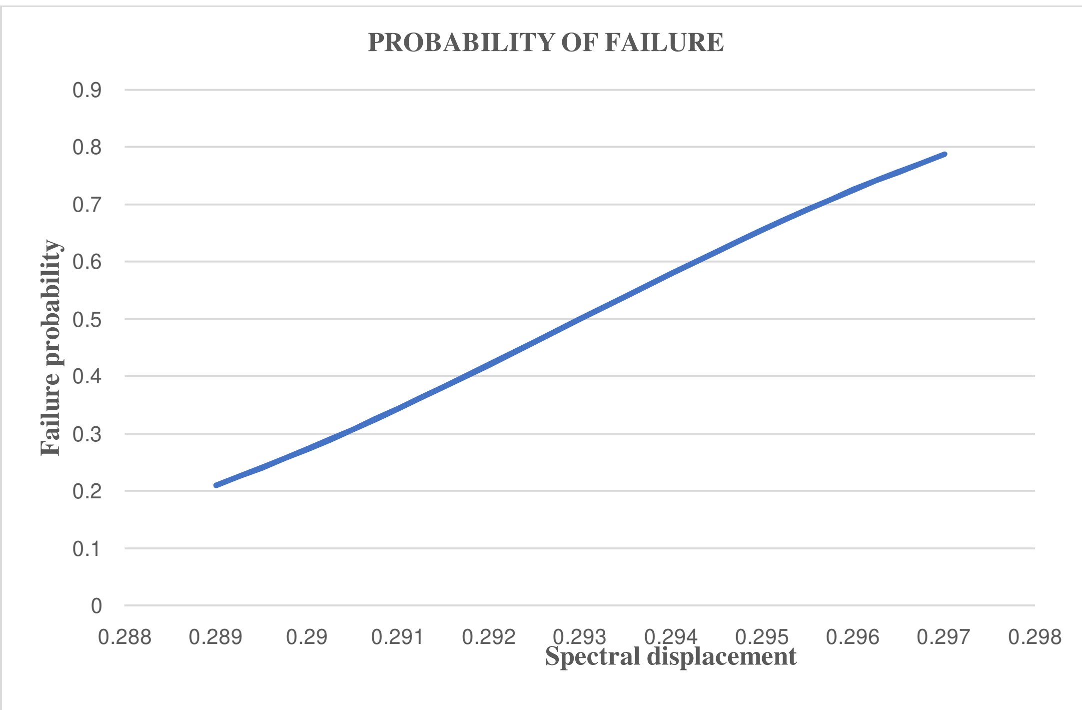

Fig.17: Failure probability of regular building at extensive damage

Fig.16 & fig.17 shows the failure probability in terms of spectral displacements. In extensive damage, the average spectral displacement for offset irregular structures is 0.836 meters, whereas regular buildings have an average displacement of 0.293m. It has been observed that the failure probability of an offset irregular building at 0.832 meters is 40% and 60% at 0.84 meters of spectrum displacement, respectively, whereas the failure probability for regular buildings is 20% at 0.289 meters and 80% at 0.297 meters of extensive damage.

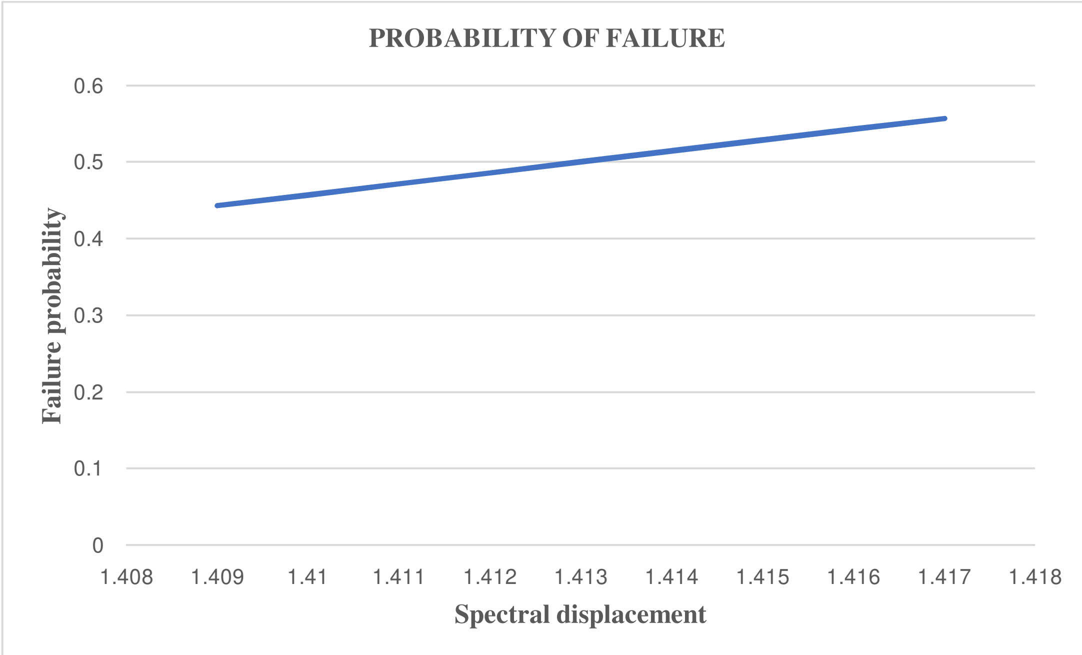

Fig.18: Failure probability of offset irregular at complete damage

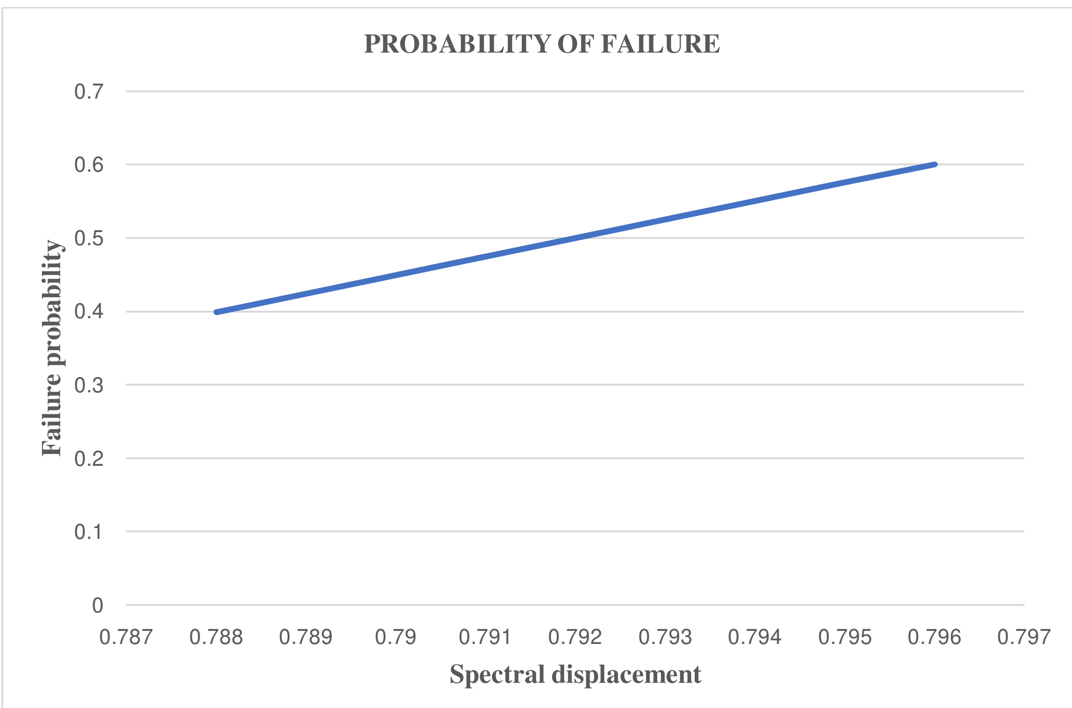

Fig.19: Failure probability of regular building at complete damage

Fig.18 & fig.19 shows the failure probability in terms of spectral displacements. In complete damage, the average spectral displacement for offset irregular structures is 1.413 meters, whereas regular buildings have an average displacement of 0.792m. It has been observed that the failure probability of an offset irregular building at 1.409 meters is 45% and 55% at 1.417 meters of spectrum displacement, respectively, whereas the failure probability for regular buildings is 40% at 0.788 meters and 60% at 0.796 meters of complete damage.

IV. CONCLUSIONS

The seismic performance and the failure probability of G+15 offset irregular RC building is compared with the G+15 regular building in which all the building parameters are considered to be same. The buildings were subjected to an elastic dynamic analysis using SAP2000 and applying loads according to codal provisions. Results from response spectrum analyses and fragility curves were used to estimate the seismic performance and failure probability of offset irregular building and comparison between offset irregular and regular is also done. The main conclusions from the findings are:

1) The maximum bending moment of offset irregular building is 45% greater than the regular building.
2) Pushover in the X direction, regular buildings have slightly higher base shears than offset irregular buildings for identical spectral displacements.
3) Pushover in the Y direction, offset irregular building exhibits high base shear at very less displacement. Regular buildings have higher base shears than offset buildings.
4) To improve the seismic performance of the offset irregular building dampers should be provided, it is seen that at 0.1% of damping ratios, the seismic performance of offset irregular building is similar to regular building.
5) The failure probability of offset irregular building is greater than the regular building in all damage states. It is concluded that for each damage condition, offset irregular building have larger spectral displacements, causes increasing in failure probability.

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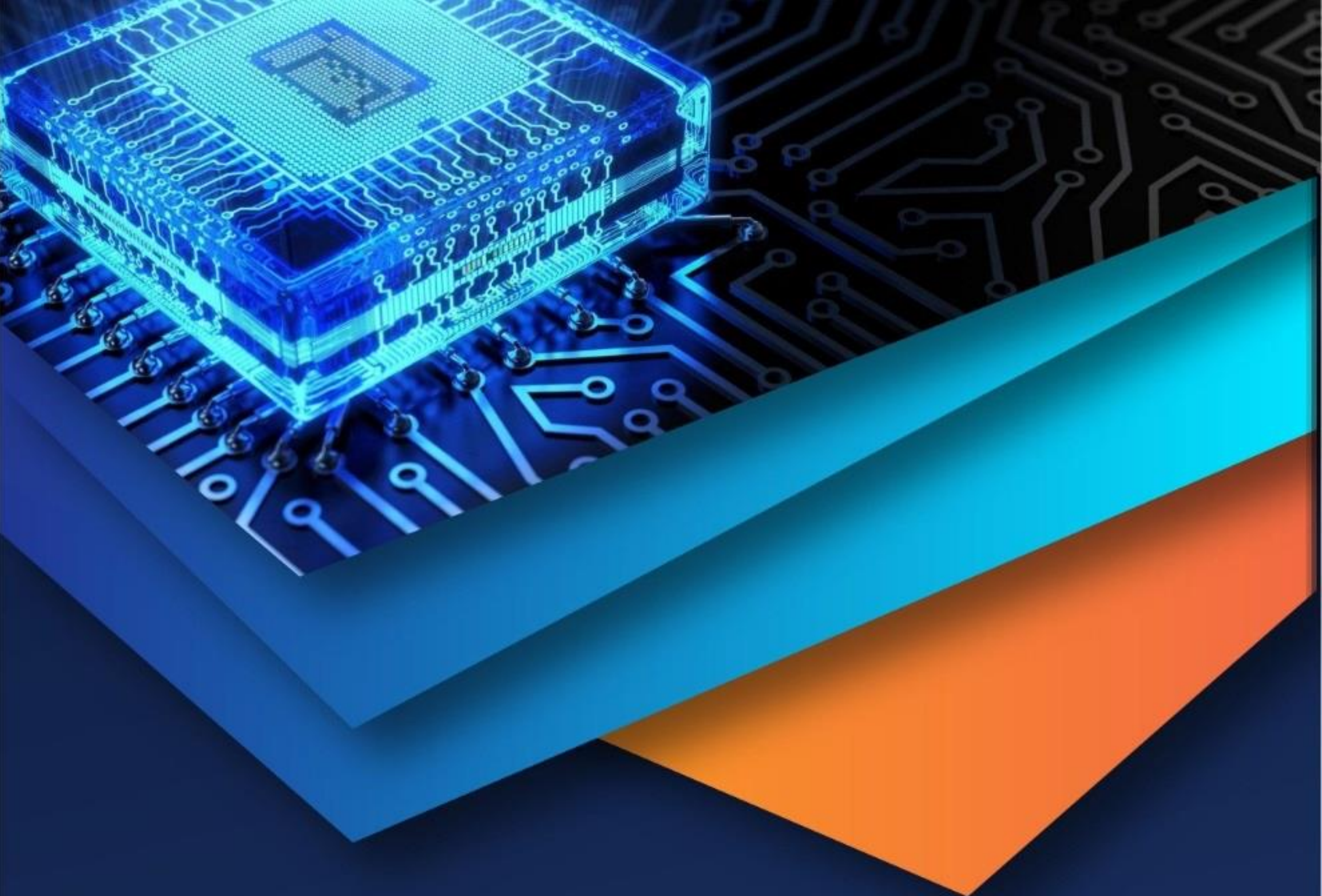

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