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Performance Based Seismic Assessment of Asymmetric RC Structure by Pushover Analysis

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Abstract: Civil engineering constructions of many types of structures is becoming more distinctive in today's world, much like other engineering products. However, in recent decades, it has prompted concerns about the structural performance under intense seismic activity. In such cases, a nonlinear static pushover analysis can be used to avoid various sorts of structure and life hazard. Pushover study utilizes base shear, roof displacement, and hinge mechanism to examine the building's performance at multiple points. The focus of this research was on the seismic performance of buildings with various symmetric and asymmetric frame structures. Pushover analysis is used in SAP 2000 to identify the nonlinear behaviour of frame elements in the framework. In terms of roof displacement, hinge behaviour, and base shear, the data indicate how different structures behaved. For the same rise construction, asymmetrical structures have higher base shear and roof displacement than symmetrical structures. For seismic analysis of structure is carried out by the Capacity Spectrum Method (CSM) and Displacement Coefficient Method (DCM) according to ATC-40 and FEMA-356, FEMA-440 guidelines respectively. Four different plan asymmetrical models are assumed to understand unique behavioural performances and its seismic assessment.

Keywords: Pushover analysis, Plan irregularity, Demand spectrum, Capacity Spectrum Method, Roof displacement, Hinge behaviour, Base shear, Pushover curve.

I. INTRODUCTION

It is important to understand the behaviour and responses of such irregular structures to lateral loads and seismic performance of the building and are studied in depth to employ an alternative strengthening techniques, in order to limit the possibility for failure. The desired goal of seismic design is to give buildings enough strength and deformation capacity to withstand seismic demands imposed by ground motion with a considerable margin of safety. Nonlinear static analysis, also known as pushover analysis, has been developed over the past few decades and has become the most preferred analysis approach for style and instability performance analysis. The Non-linear Static Analysis or Pushover Analysis was developed and suggested by the Applied Technical Council (ATC) and the Federal Emergency Management Agency (FEMA) as part of earthquake rehabilitation programmes and standards. For the further approach of pushover analysis and the method taken for justification of it i.e. Capacity Spectrum Method (CSM), we must first understand the following procedures: Performance Based Seismic Design (PBSD), general pushover technique, pushover curve, capacity curve, demand curve and structural performance point.

Performance Based Seismic Design (PBSD):

The design goal of performance-based seismic design (PBSD) is to provide a structure capable of satisfying certain predictable performance criteria under various levels of earthquake motions. The structural parameters of strength, stiffness, and ductility or deformability should be balanced appropriately to provide the desired performance of buildings or structures. The goals of traditional seismic design are to offer life safety (strength and ductility) and damage control (serviceability drift limits). Estimations of seismic demands at varying levels of building performance necessitates explicit consideration of the structure's stiffness degradation, which necessitates high-level analytical methodologies.

II. METHODOLOGY

Pushover Analysis:

It is a nonlinear static procedure in which the magnitude of the lateral force is increased, sustaining the predefined load distribution pattern along the height of structure or building. It is made up of a sequence of consecutive elastic assessments that are stacked to approximate the overall structure's force-displacement curve. Gravity loads are applied first to a two- or three-dimensional model that comprises bilinear or trilinear load-deformation diagrams of all lateral force resisting parts. Predetermined lateral loads are spread along the building height. Loads are increased until some members begin to

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yield. The structural model is changed to account for the reduced stiffness of yielding members, and the lateral stresses are raised again until more members yield. The process continues until the structure becomes unstable or a control displacement at the top of the building reaches a predetermined deformation threshold. The global capacity curve is calculated by plotting roof displacement vs. base shear. The following is an example of a pushover analysis:

(i) Force Controlled:

In this approach, the force is given an approximate limit to execute the programme of pushover analysis in this type, and it is kept constant or the load is increased up to that limit. This method is only utilized when the load is known, such as when the load is gravity. Because of the growth of the load mechanism and the p-delta effect, some of the quantitative problems affect the result, as the desired displacement may be linked with very minimal positive or even negative lateral stiffness

(ii) Displacement Control:

When the magnitude of the applied load is unknown in advance, a displacement-controlled approach is used to find specified drifts (as in seismic loading). The load combination's magnitude is increased or lowered as needed until the control displacement reaches a predetermined value. The control displacement is selected to be the roof displacement at the structure's centre of mass. Internal forces and deformations calculated at the desired displacement are utilized as estimations of inelastic strength and deformation demands, which must be compared to available capacities in order to execute a performance check.

An elastic analysis of the structure can determine its elastic capacity and anticipate where the first yielding will occur, but it cannot predict failure mechanisms or account for force redistribution during progressive yielding (ATC-40, 1996). Pushover analysis can be used in these situations to anticipate the structure's strength beyond the yield capacity. It can also be used to estimate the structure's ultimate capacity. With the incremental increase in the magnitude of loads, certain failure modes of structure are obtained. The local nonlinear effects are modelled and the structure is pushed until a collapse mechanism gets developed. At each step, the base shear vs roof displacement graph is plotted and pushover curve is generated. The most important part to calculate performance level is to construct capacity curve transformed from base shear Vs roof displacement coordinates into spectral acceleration (Sa) Vs spectral displacements (Sd) coordinates and intersected with response curve and thus the intersection point will give the performance level of that building.

The Different Types of Pushover Analysis Methods are the Capacity Spectrum Method (CSM) defined in ATC-40 and the Displacement Coefficient Method (DCM) documented in FEMA-356 are the two forms of non-linear static analysis methodologies currently accessible. Both methods are based on non-linear static analysis of lateral load-deformation variation under gravity loading and idealized lateral loading due to seismic activities. This type of study is known as Pushover Analysis.

a) Method of Displacement Coefficient:

The Displacement Coefficient Method is based on a non-linear static analysis approach that uses a bilinear representation of capacity curves and a sequence of modification factors to calculate target displacements. The performance point in the capacity spectrum approach is the point on the capacity curves at the target displacement.

b) Method of Capacity Spectrum: The Capacity Spectrum Method is based on a non-linear static analytical process that intersects the structure's capacity spectrum with the earthquake's response spectrum (demand spectrum) to produce a graphical depiction of the projected seismic performance for the structure. The performance point is the intersection point, and the anticipated displacement demand on the structure for the specified level of seismic hazard is the displacement coordinate of the performance point.

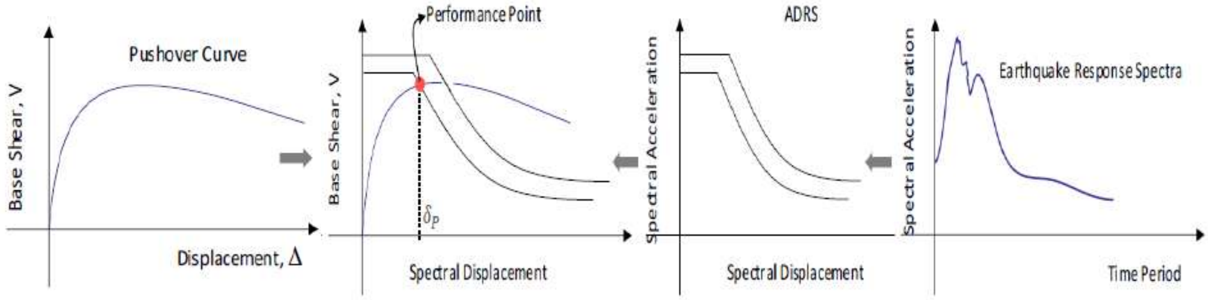

Figure 1 Capacity Spectrum Methodology

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The following is the further elaboration of this method needs the clarity terms:

Capacity Spectrum:
Individual structural component strength and deformation limits define the structure's overall capacity. To find capacity beyond elastic limits, non-linear pushover analysis is used. It employs a series of successive elastic studies to determine the RC frame model's force–displacement curve. To account for the reduced stiffness, the mathematical model is modified. Sequential lateral loads are applied until further components give. The above stages are repeated until the structure becomes unstable. When the elastic limit is surpassed, the capacity curve gives an estimate of the structural behaviour. The Capacity Curve, also known as the Pushover Curve, is a load-deformation curve that plots the base shear force against the horizontal roof displacement of the structure. This capacity curve is then converted into capacity spectrum by employing the Acceleration Displacement Response Spectrum (ADRS) format. The capacity spectrum procedure in its graphical implementation compares the lateral force and displacement capacity of structure with estimated demands from an earthquake ground motion.

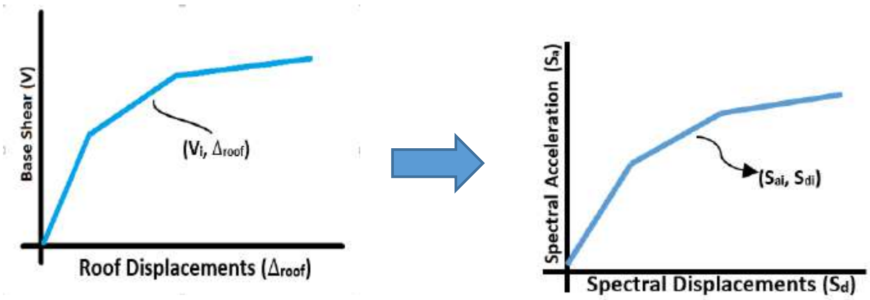

Figure 2 Capacity curve to Capacity spectrum

Capacity Spectrum conversion equations as described in ATC 40 are:

$$S_{ai} = \frac{V_i/W}{\alpha_1}, \quad S_{di} = \frac{\Delta_{roof}}{PF_1 * \emptyset_{1,roof}}$$

$$PF_1 = \frac{\sum_{i=1}^{n}(w_i \emptyset_{i1})/g}{\sum_{i=1}^{n}(w_i \emptyset^2{}_{i1})/g}, \quad \alpha_1 = \frac{[\sum_{i=1}^{n}(w_i \emptyset_{i1})/g]^2}{\left[\sum_{i=1}^{n}\frac{w_i \emptyset^2{}_{i1}}{g}\right] * [\sum_{i=1}^{n} w_i /g]}$$

Where α_1 and PF_1 are respectively the modal mass coefficient and participation factors for the first natural mode of the structure,
V = base shear,
W= building dead weight plus live loads
Δ_{roof} = roof displacement,
S_a = spectral acceleration, S_d = Spectral displacement.

Demand:
The maximum estimated reaction of the structure during ground shaking can be characterised as displacement demand of the Structural system during earthquake. The seismic ground motions during an earthquake is represented by response spectra in an Acceleration Displacement Response Spectrum format. This curve is called demand curve or demand spectrum. The relation to transform response spectra into demand spectra, is given as: $S_d = (\frac{1}{4\pi^2})S_a T^2$, where Sd is spectral displacement and Sa is the spectral acceleration.

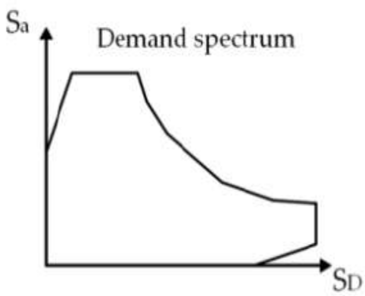

Figure 3 Demand Spectrum

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Evaluation of Performance Point:

The performance point is found in the next step of the capacity spectrum technique procedure. The 'performance point' is the intersection of the capacity and demand curves. The structure meets the target performance level if the performance point exists and the performance at that point is satisfactory. Be a result, such designs are referred to as performance-based designs. Under earthquake loading, hinges can express the force-deformation relationship. Flexural hinges, for example, illustrate the moment-rotation relationship. Hinges are introduced in the RC frame structure during Pushover analysis and Immediate Occupancy (IO), Life safety (LS), Collapse prevention (CP) represents the non-linear state of hinges throughout their ductile range.

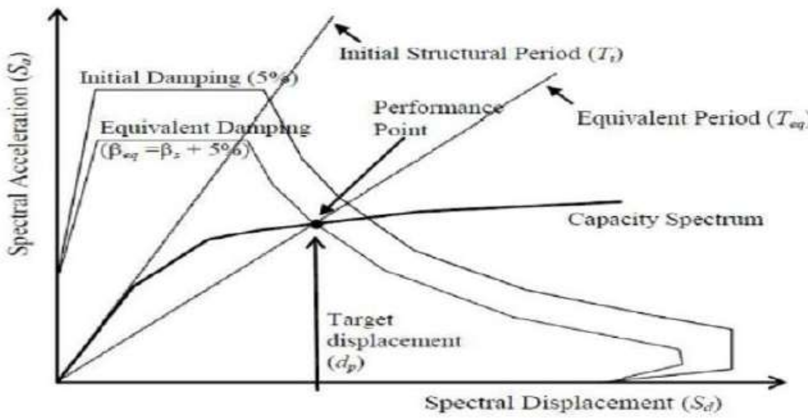

Figure 4 Schematic representation of performance point

The performance levels of a building are determined by combining the performance levels of both structural and non-structural components. The 'performance levels' refer to various structural deterioration conditions. The three performance levels, Immediate Occupancy, Life Safety, and Collapse Prevention, are observed and ordered in relation to the lateral and vertical load resisting systems' decreasing performance. Response values from pushover analysis should be evaluated for limitations of each performance level to determine if a building satisfies a particular performance objective. The following are the structural performance levels:

Immediate Occupancy (IO): Some damage is visible at this performance level, but it does not require repair for functional and safety reasons.

Life Safety (LS): At this level of performance, the structure has substantial structural and non-structural damage that is either irreversible or prohibitively expensive to fix, rendering repair impossible.

Collapse Prevention (CP): This is the stage of the performance when the structure is about to collapse.

III. SPECIFICATIONS OF MODEL

TABLE I SECTIONAL PROPERTIES OF MODEL

Floor to floor Height	3m
Size of Beam	350mm X 450mm,
Size of Column	600mm X 600mm,
Total Height of Building	24m
Slab thickness	125mm
Grade of concrete	M25
Grade of Steel	Fe500

TABLE II LOADS AND SEISMIC FACTORS OF MODELS

Dead Load	1 kN/m^2
Live Load	3 kN/m^2
Wall Load	11.5 kN/m

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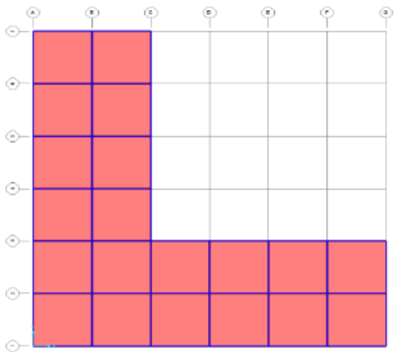
Parapet Wall Load	4.6 kN/m
Seismic Zone	V
Seismic Coefficient (zone factor)	0.36
Response Reduction factor	5
Importance Factor	1
Soil Conditions	Medium

The different plan shapes assumed for the analytical purpose are L, U, Z and T. These models were analysed in SAP2000 with considering the guidelines of Applied Technological Council, ATC-40 Capacity spectrum. The monitored displacement considered as four percent of the total height of structure under load control method as displacement-control method. The hinges were applied at ten percent relative distance from both the ends for each beams and columns except for the columns at the base, where the hinges are not applied at ten percent relative distance from fixed support. All the models considered for comparison have equal area with equal slabs, columns and beams. As per IS 875 Part-II, earthquake loading is combined with gravity loads, i.e. DL+ 0.25LL, where DL signifies dead loads, which comprise outside and interior walls, and LL denotes live loads. IS 1893:2016 is used to compute the overall seismic weight. The user coefficients used are C_a= 0.18 i.e. Z/2 and C_v= (1.36*Z)/2 i.e. for medium soil.

L-shape model specifications:



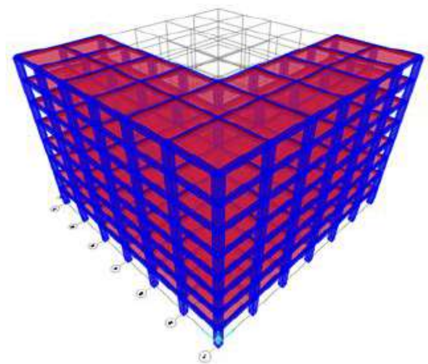
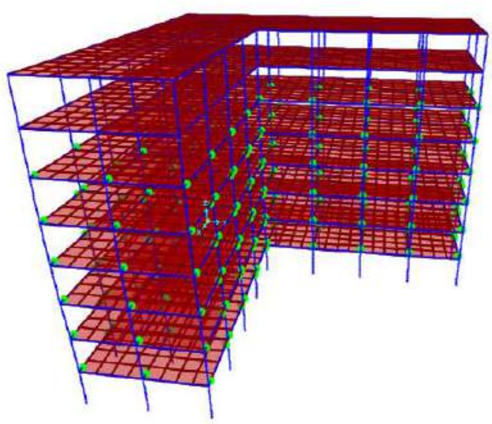


Figure 5 L-Shape model plan view (Left) and 3D view (Right)

Results of L-shape model:



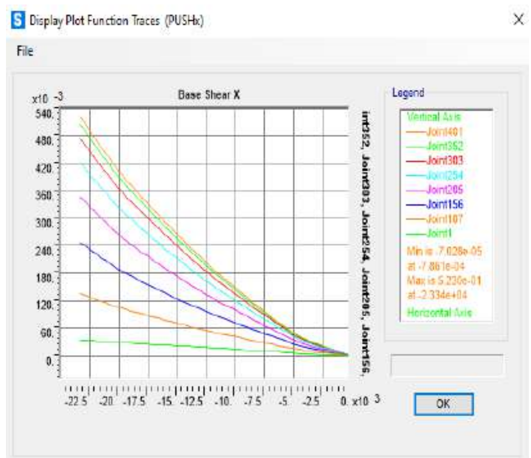


Figure 6 Hinges formed at Performance point (Left), Interstory displacements Vs Base shear (Right).

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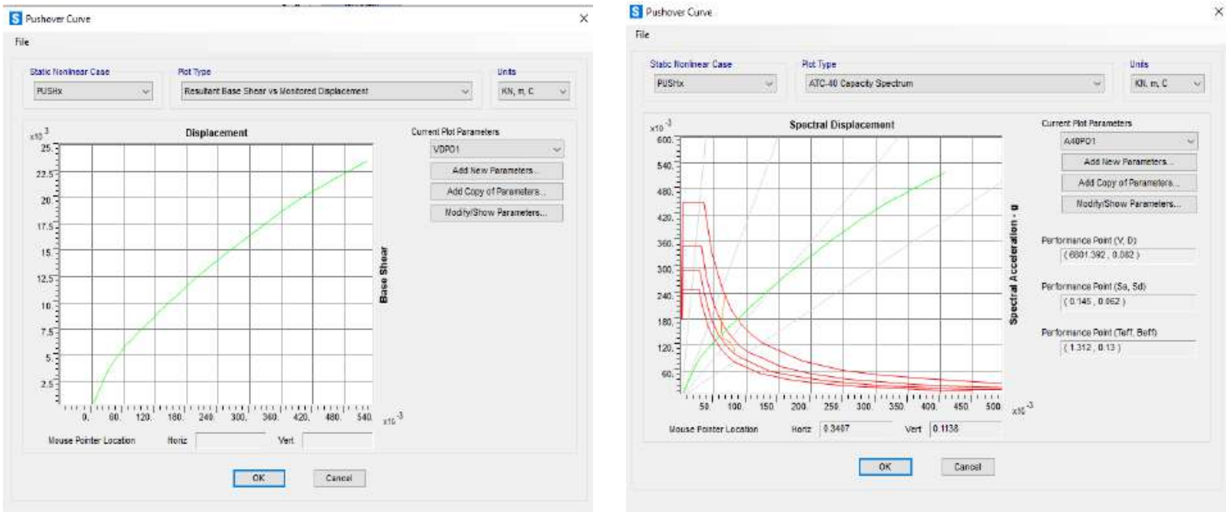

Figure 7 Pushover curve (left), Performance point obtained by ATC-40 CSM (right).

T-shape model specification:

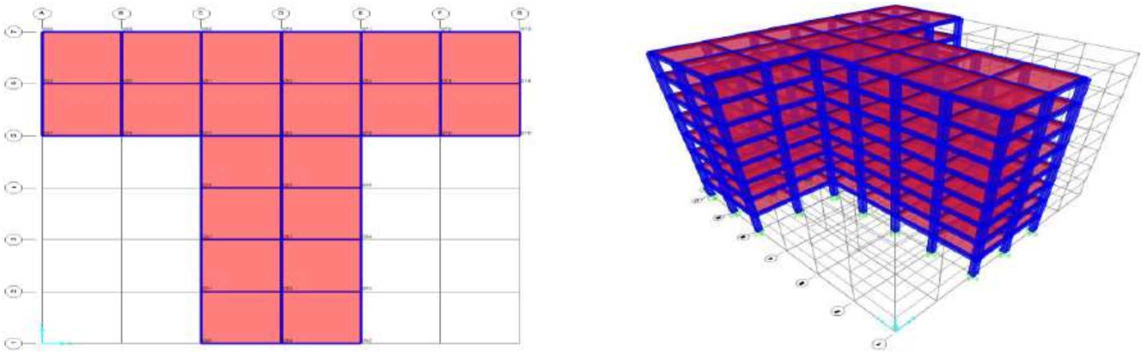

Figure 8: T-shape model plan view (left), T-shape model 3D view (right)

Results of T shape model:

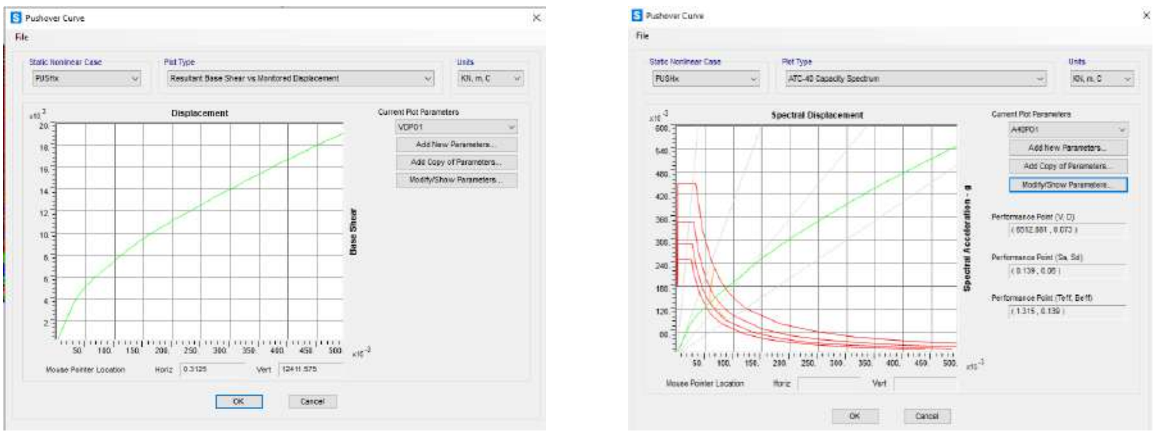

Figure 9: Pushover curve of T-shape model (Left) and Performance point by CSM (Right).

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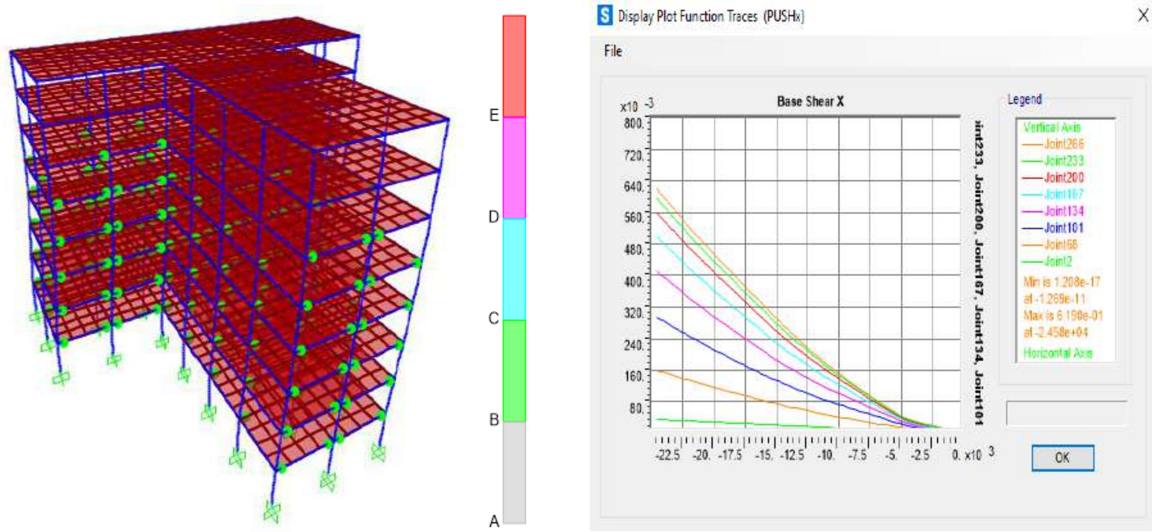

Figure 10 Hinges formed at Performance point (left), Inter-storey displacements Vs Base shear (right).

U-shape model specifications:

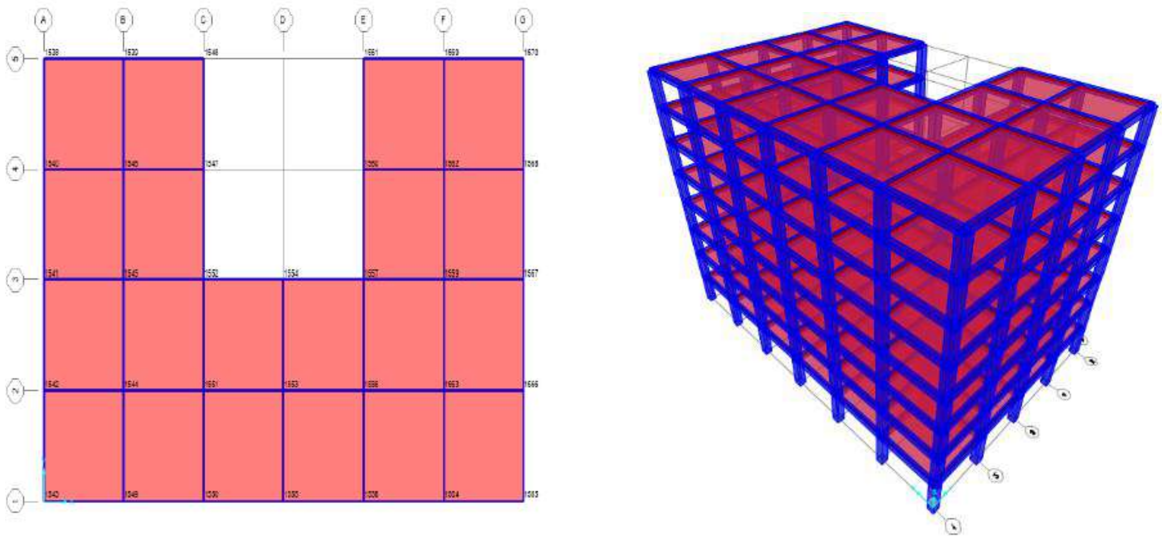

Figure 11: U-shape model plan view (left), U-shape model 3D view (right).

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Results of U-shape model:

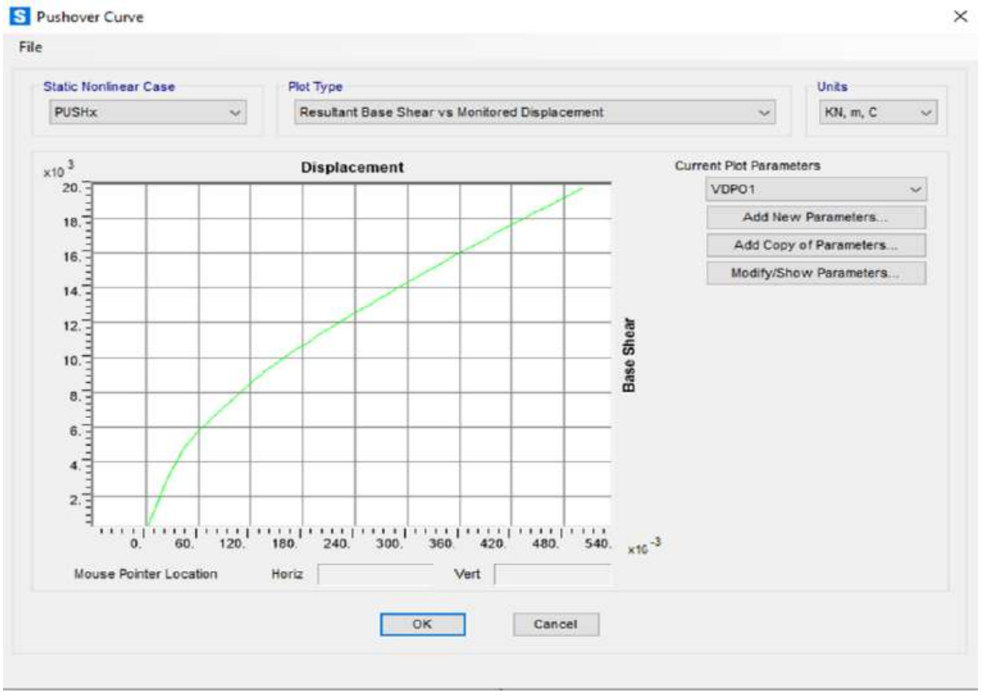

Figure 12: Pushover curve of U-shape model.

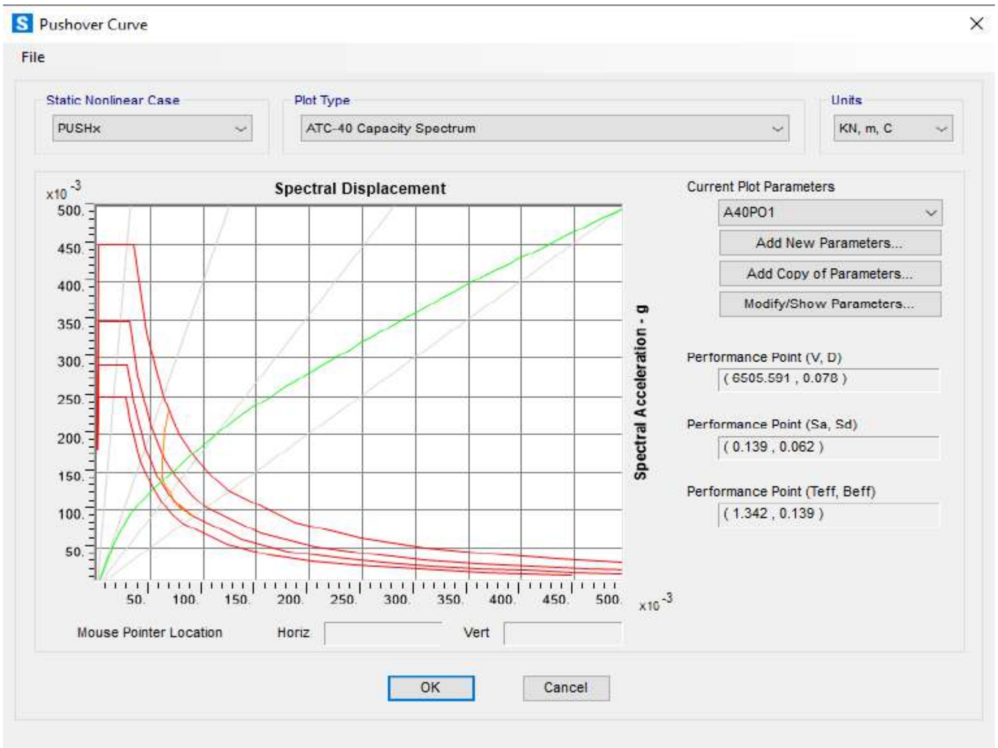

Figure 13 Performance point of U-shape model according to ATC-40.

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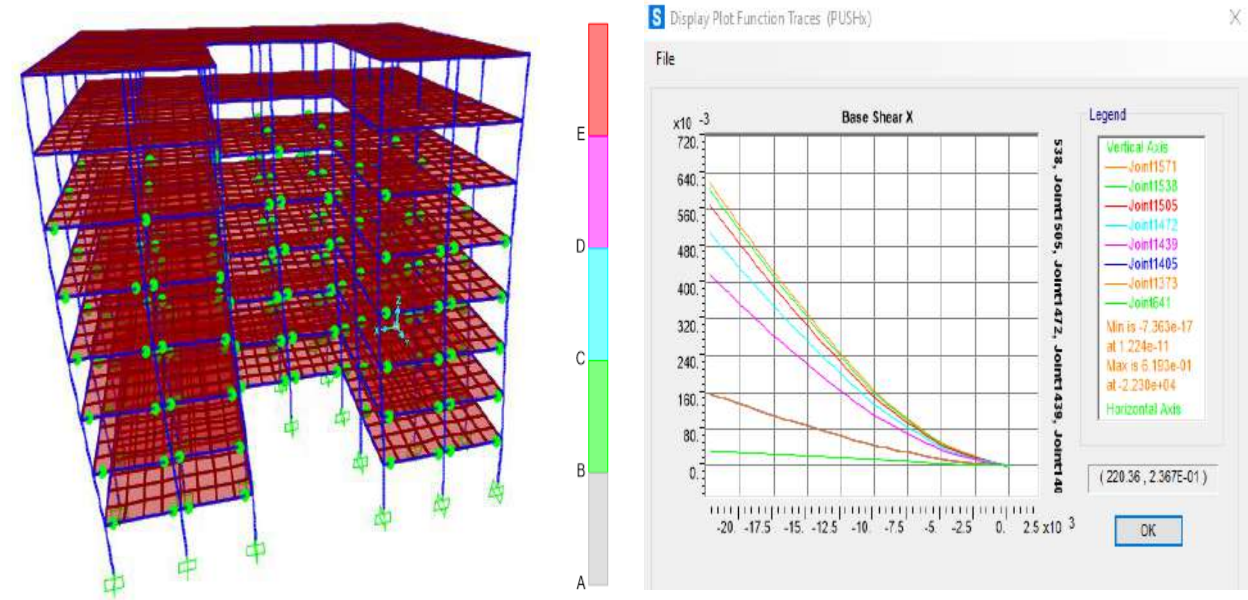

Figure 14: Hinges at performance point (Left) and Interstory displacements Vs Base shear (Right).

Z-shape model specifications:

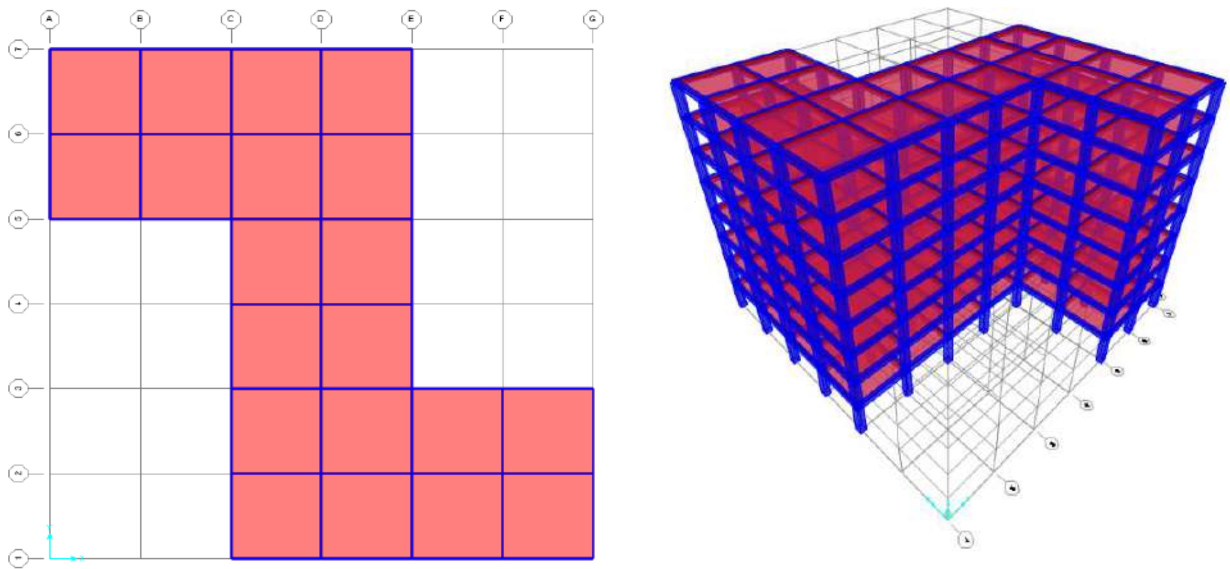

Figure 15: Z-shape model plan view (left), Z-shape model 3D view (right).

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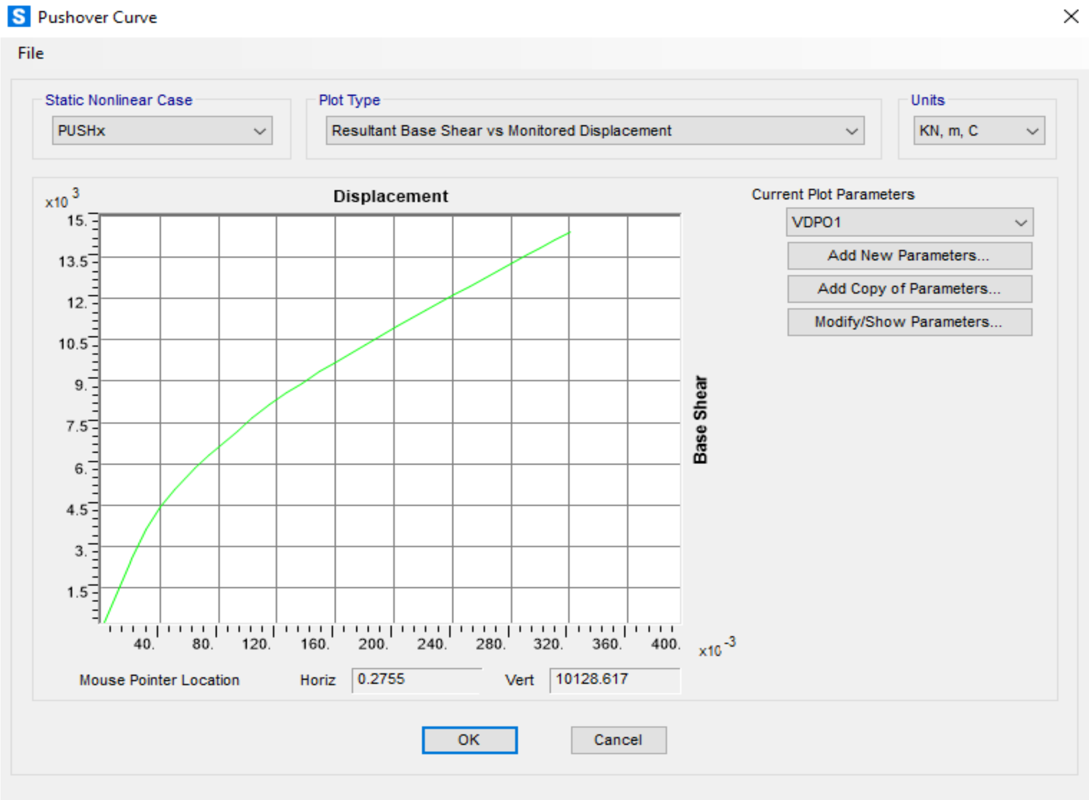

Figure 16: Pushover curve of Z-shape model

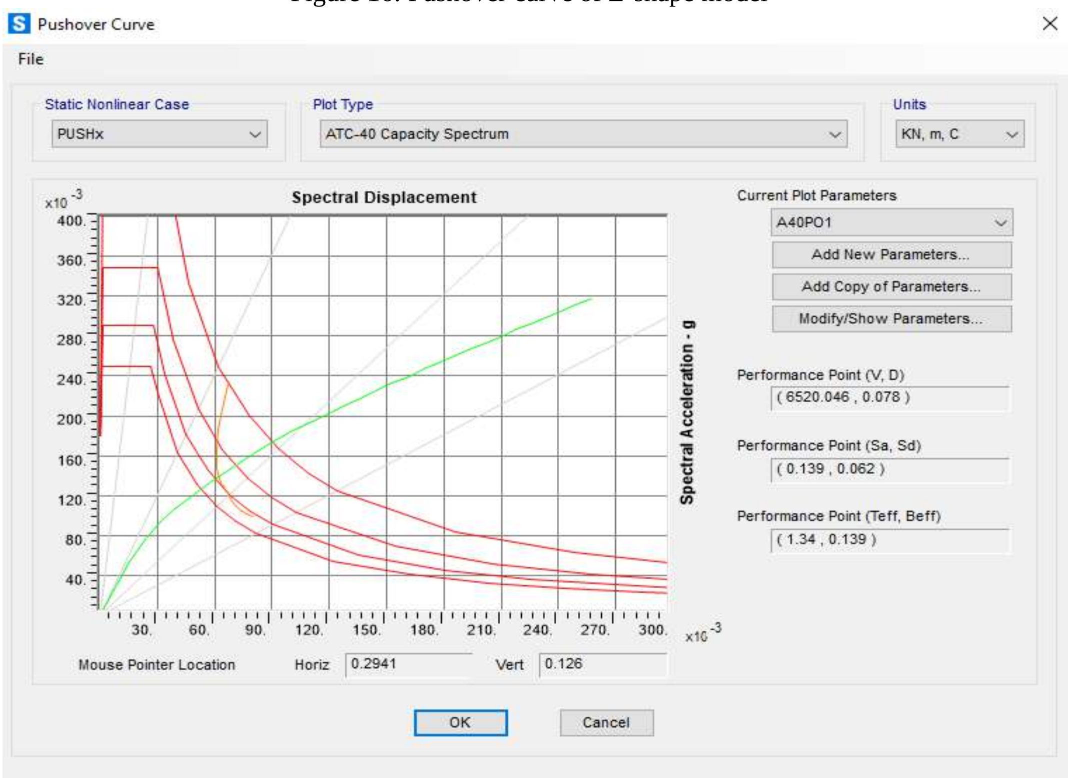

Figure 17: Performance point of Z-shape model according to ATC-40 Capacity spectrum.

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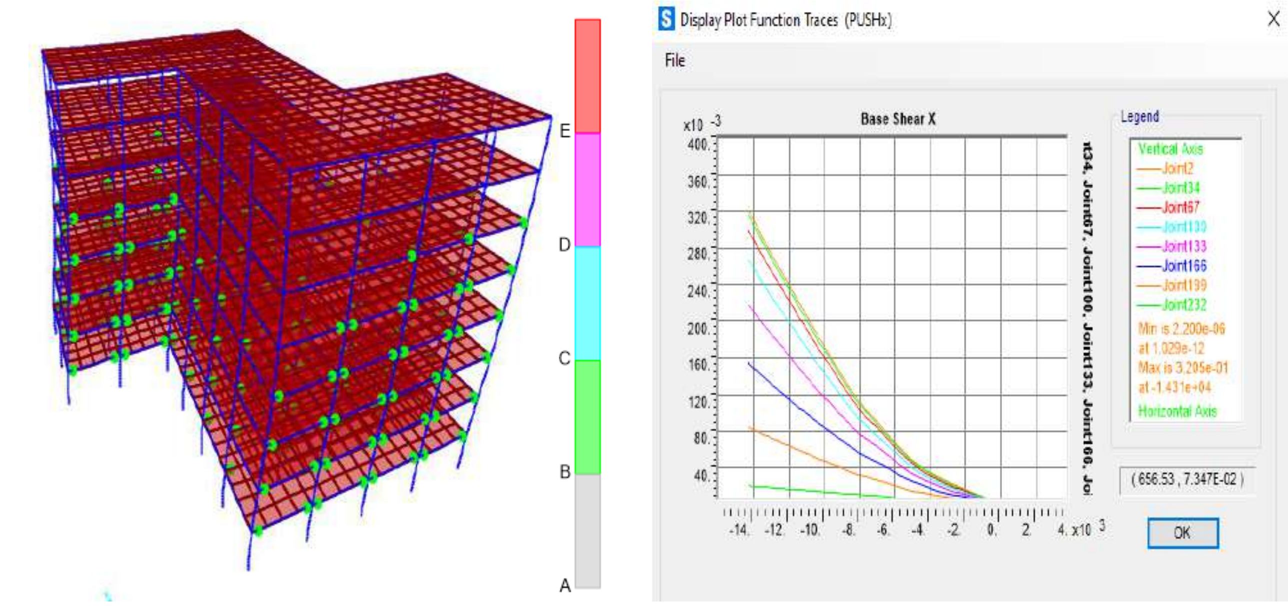


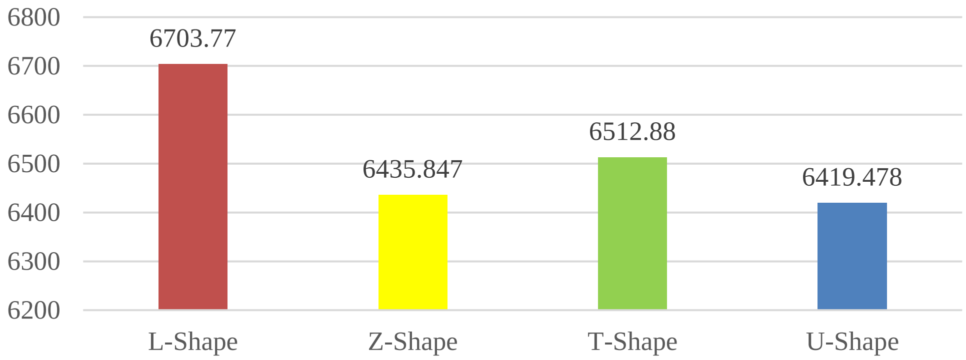
Figure 18 Hinges at performance point (Left) and Interstory displacements Vs Base shear (Right)

RESULTS AND DISCUSSION

Shapes	A-B	B-C	C-D	D-E	Beyond E	Total
Z-Shape	2089	532	0	0	0	2621
T- Shape	2086	568	0	0	0	2654
L-Shape	1043	284	0	0	0	1327
U-Shape	2142	512	0	0	0	2654

Figure 19: Hinges formed at performance point in different shapes.

Figure 20: Base Shear(kN) @Performance Point



International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified ⁂ Impact Factor 7.105 ⁂ Vol. 9, Issue 5, May 2022
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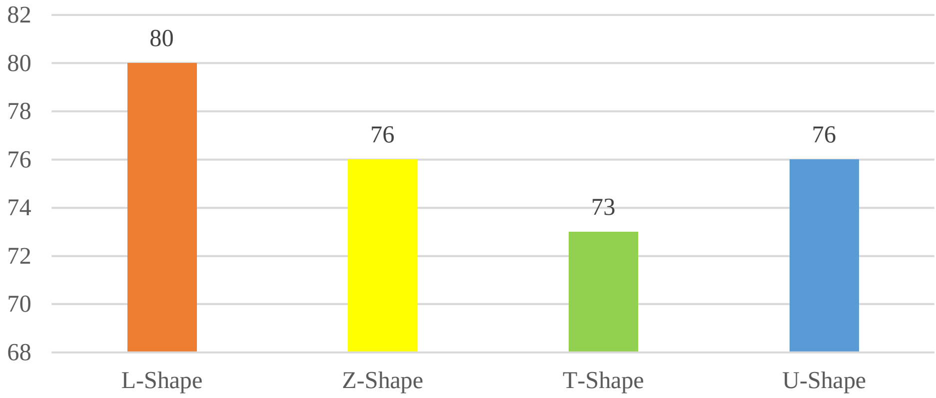
Figure 21: Roof Displacement (mm) @Performance Point



CONCLUSIONS:

- The base shear and roof displacement values for pushover analysis is more than linear static analysis.
- All assumed models are under without threaten stage as between immediate occupancy and life safety with pushover analysis.
- The roof displacement at performance point was found maximum in L-Shaped models compared to U, T and Z shaped frame structure.
- Based on Non-Linear Analysis, L shaped building had more base shear at performance point as compared to U, T and Z shapes.
- Hinges formed between immediate occupancy to life safety, reduces when bracings were applied to the frame structures.
- The performance points were achieved at lesser roof displacements in frame structures with bracing systems as compared to the frame structures without bracings.
- Nonlinear static analysis like pushover calculates seismic assessment to check the performance until a failure occurs in a structure and thus the base shear and storey displacements' values are higher compared to the linear static analysis.
- It is important to note that the pushover analysis is approximate and based on static loading. Because it is incapable of accurately representing dynamic processes. Some significant deformation modes that may occur in a structure subjected to large earthquakes may go undetected, while others may be exaggerated. Predictions based on invariant or adaptive static load patterns may differ dramatically from inelastic dynamic response.

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