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Pushover Analysis of Diagrid Structure

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***Abstract* – Diagrid is a particular form of space truss. It consists of perimeter grid made up of a series of triangulated truss system. Diagrid is formed by intersecting the diagonal and horizontal components.**

The diagonal members in diagrid structural systems can carry gravity loads as well as lateral forces due to their triangulated configuration. Diagrid structures are more effective in minimizing shear deformation because they carry lateral shear by axial action of diagonal members. Diagrid structures generally do not need high shear rigidity cores because lateral shear can be carried by the diagonal members located on periphery.

In this paper study of diagrid system which is modeled with 12 storey diagrid building is analyzed using SAP 2000 by considering Dead, Live and Seismic Loads (IS 1893-Part-1, 2002) and designed using IS-800. Afterwards the FEMA 356 hinges are assigned to the same building and conducted Nonlinear Static (Pushover) to find out the performance points that is Immediate Occupancy, Life Safety, and Collapse Prevention of diagrid elements. At the same time Base Shear and Displacements are studied and Spectral Displacement Demand & Spectral Displacement Capacity is compared to know the adequacy of design. And it is evident that the designed 12 storey diagrid building doesn't require redesign.

***Index terms* – Diagrid, Nonlinear Static Analysis, SAP 2000.**

I. INTRODUCTION

The rapid growths of urban population and consequent pressure on limited space have considerably influenced the residential development of city. The high cost of land, the desire to avoid a continuous urban sprawl, and the need to preserve important agricultural production have all contributed to drive residential buildings upward. As the height of building increase, the lateral load resisting system becomes more important than the structural system that resists the gravitational loads. The lateral load resisting systems that are widely used are: rigid frame, shear wall, wall-frame, braced tube system, outrigger system and tubular system. Recently, the Diagrid – Diagonal Grid – structural system is widely used for tall steel buildings due to its structural efficiency and aesthetic potential provided by the unique geometric configuration of the system.

Diagrid is a particular form of space truss. It consists of perimeter grid made up of a series of triangulated truss system. Diagrid is formed by intersecting the diagonal and horizontal components.

The diagonal members in Diagrid structural systems can carry gravity loads as well as lateral forces due to their triangulated configuration. Diagrid structures are more effective in minimizing shear deformation because they carry lateral shear by axial action of diagonal members.

Compared with conventional framed tubular structures without diagonals, Diagrid structures are more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional framed tubular structures carry shear by the bending of the vertical columns (Moon, 2007). Diagrid structures generally do not need high shear rigidity cores because shear can be carried by the Diagrid located on the perimeter. In this study the seismic performance of Diagrid structural system was investigated using nonlinear static analysis.

II. LOADS ON STRUCTURE

A. Dead Load

It is a gravity loading due to the structure simply calculated as the product of volume and material density of the structure.

B. Imposed Load [5]

The imposed loads to be assumed in the design of buildings shall be the greatest loads that probably will be produced by the intended use or occupancy, but shall not be less than the equivalent minimum loads specified in Table. In our analysis only Commercial building loads are considered.

C. Seismic Load [6]

If a structure is situated in an earthquake prone region, the earthquake or seismic forces are given due consideration in the analysis. An earthquake causes vertical and horizontal forces in the structure that will be proportional to the weight of the structure. IS: 1893 Part-1 is referred for the actual design loads.

III. NONLINEAR STATIC (PUSHOVER) ANALYSIS

The use of the nonlinear static analysis came in to practice in 1970's but the potential of the pushover analysis has been recognized for last 10-15 years. This procedure is mainly used to estimate the strength and drift capacity of existing structure and the seismic demand for this structure subjected to selected earthquake. This procedure can be used for checking the adequacy of new structural design as well.

Pushover analysis is defined as an analysis wherein a mathematical model directly incorporating the nonlinear load-deformation characteristics of individual components and elements of the structure shall be subjected to monotonically increasing lateral loads representing inertia forces in an earthquake until a 'target displacement' is exceeded. Target displacement is the maximum displacement (elastic plus inelastic) of the structure at top expected under selected earthquake ground motion. Pushover analysis assesses the structural performance by estimating the force and deformation capacity and seismic demand using a nonlinear static analysis algorithm. The seismic demand parameters are global displacements (at roof or any other reference point), storey drifts, storey forces, and component deformation and component forces. The analysis accounts for geometrical nonlinearity, material inelasticity and the redistribution of internal forces. Response characteristics that can be obtained from the pushover analysis are summarised as follows:

a) Estimates force and displacement capacities of the structure. Sequence of the member yielding and the progress of the overall capacity curve.

b) Estimates force (axial, shear and moment) demands on potentially brittle elements and deformation demands on ductile elements.

c) Estimates global displacement demand, corresponding inter-storey drifts and damages on structural and non-structural elements expected under the earthquake ground motion considered.

d) Sequences of the failure of elements and the consequent effect on the overall structural stability.

e) Identification of the critical regions, where the inelastic deformations are expected to be high and identification of strength irregularities (in plan or in elevation) of the building.

IV. PUSHOVER ANALYSIS PROCEDURE

Pushover analysis is a static nonlinear procedure in which the magnitude of the lateral load is increased monotonically maintaining a predefined distribution pattern along the height of the Structure. Structure is displaced till the 'control node' reaches 'target displacement' or structure collapses. The sequence of cracking, plastic hinging and failure of the structural components throughout the procedure is observed. The relation between base shear and control node displacement is plotted for all the pushover analysis.

Generation of base shear – control node displacement curve is single most important part of pushover analysis. This curve is conventionally called as pushover curve or capacity curve. The capacity curve is the basis of 'target displacement' estimation. The seismic demands for the selected earthquake are calculated at the target displacement level. The seismic demand is then compared with the corresponding structural capacity or predefined performance limit state to know what performance the structure will exhibit.

V. NEED FOR NON-LINEAR STATIC (PUSHOVER) ANALYSIS

Conventionally, seismic assessment and design has relied on linear or equivalent linear (with reduced stiffness) analysis of structural systems. In this approach, simple models are used for various elements of the structure, which are subjected to seismic forces evaluated from elastic or design spectra, and reduced by force reduction (or behavior) factors. This ensures displacements are amplified to account for the reduction of applied forces.

The reduced force-amplified deformation linear elastic approach fails to fit within the principle of failure mode control, which is part of performance based assessment and design. This in turn has led to an increase in the use of inelastic analysis as a more realistic means of assessing deformational state in structures subjected to strong ground motions.

The pushover analysis is a significant step forward by giving consideration to those inelastic response characteristics that will distinguish between good and bad performance in severe earthquakes. The non linear static pushover analysis is a partial and relatively simple immediate solution to the complex problem for predicting forces and deformation demands imposed on the structure and its elements due to ground motions.

The pushover is part of an evaluation process and provides estimates of demands imposed on structures and elements. Hence, there is always a need of a method which is rational and accurate and at the same time able to identify seismic deficiencies correctly and that too in a correct order of vulnerability. Pushover analysis is able to satisfy these criteria satisfactorily and in a convenient way.

VI. CAPACITY SPECTRUM METHOD (ATC 40)

In this method the maximum inelastic deformation of a nonlinear SDOF system can be approximated from the maximum deformation of a linear elastic SDOF system with an equivalent period and damping. This procedure uses the estimates of ductility to calculate effective period and damping. This procedure uses the pushover curve in an acceleration-displacement response spectrum (ADRS) format. This can be obtained through simple conversion using the dynamic properties of the system. The pushover curve in an ADRS format is termed a 'capacity spectrum' for the structure. The seismic ground motion is represented by a response spectrum in the same ADRS format and it is termed as demand spectrum (Fig. 1). The equivalent period (Teq) is computed from the initial period of vibration (Ti) of the nonlinear system and displacement ductility ratio (μ). Similarly, the equivalent damping ratio (βeq) is computed from initial damping ratio and the displacement ductility ratio (μ). ATC 40 provides the following equations to

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calculate equivalent time period (Teq) and equivalent damping (βeq).

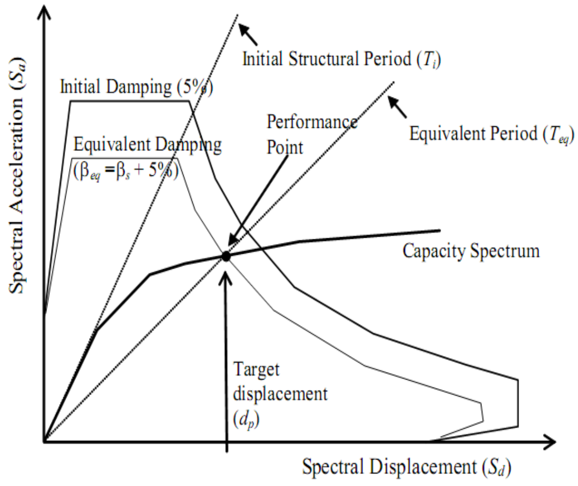

Fig 1. Schematic representation of Capacity Spectrum Method (ATC 40)

VII. PROBLEM DEFINITION

This paper presents about details of the building (Table 1) used for analysis such as dimensions of building, type of analysis and material used.

A 12 Storey Steel Diagrid Structure having height of 48 m and lateral dimensions of 27m X 27m. The loads and load combinations on the structure are studied and the same building is modeled in SAP 2000 and conducted Linear Analysis to get the maximum bending moments and the structure is designed as per IS 800. Afterwards the FEMA 356 Hinges are defined in the model and conducted Nonlinear Static (Pushover) Analysis using ATC-40 to calculate Base Shear vs. Displacements, Effective time, Spectral Displacement Capacity & Spectral Displacement Demand and to find out Performance points of Diagrid Structure.

Building Details		
Sl. No	Description	
1	Dimensions of Building	27m X 27m
2	Height of Building	48 m
3	No. of Stories	12 No's
4	Storey Height	4 m
5	Type of Structure	Diagrid Steel Structure
6	Degree of Diagrid Element	53°8´
7	Type of Analysis	Nonlinear Analysis

Table 1. Building Details

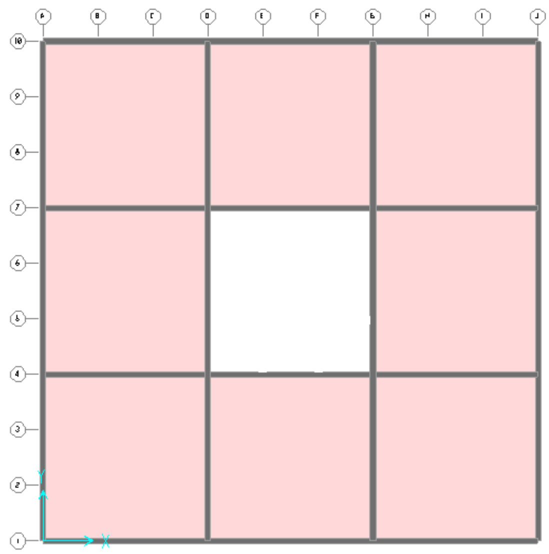

Fig 2. Plan of Diagrid Structure

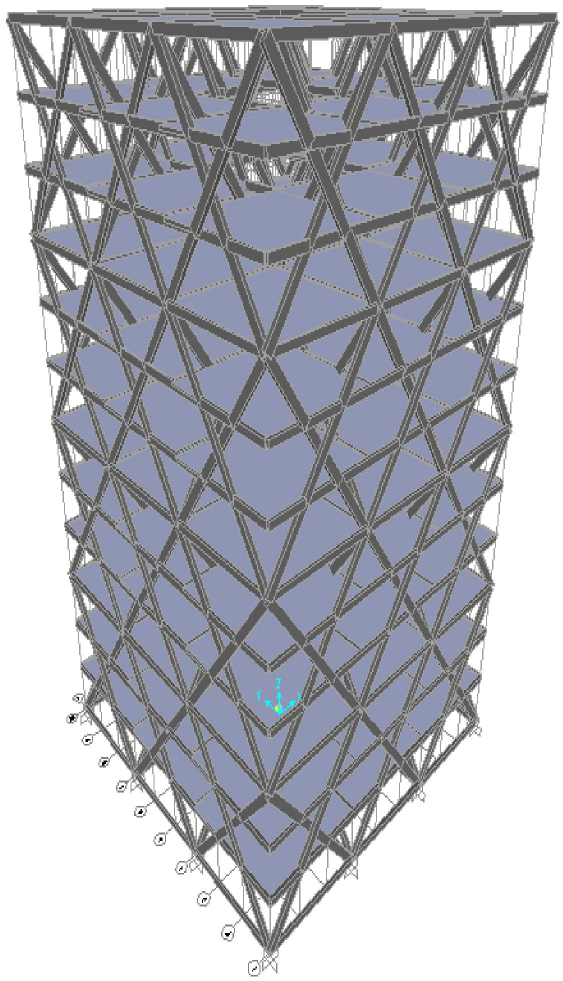

Fig 3. Diagrid Structure Model in SAP 2000

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A) Modeling of Flexural hinges

In the implementation of pushover analysis, the model must account for the nonlinear behavior of the structural elements. In the present study the plastic hinge is assumed to be concentrated at a specific point in the frame member under consideration. In this study flexure (M3) hinges (FEMA 356 - Auto hinges) modeled at possible plastic regions under lateral load. Properties of flexure hinges must simulate the actual response of structural steel components subjected to lateral load.

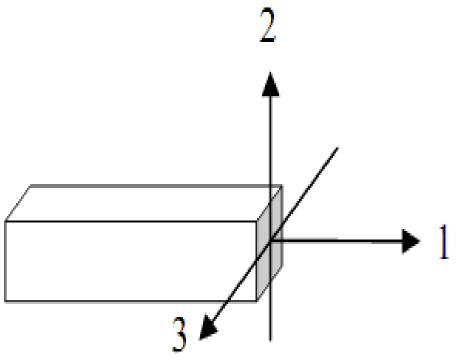


Fig 4. Coordinate system used to define the flexural hinges

Flexural hinges in this study are defined by moment-rotation curves calculated based on the cross-section and member details at the possible hinge locations. For calculating hinge properties it is required to carry out moment–curvature analysis of each element. Constitutive relations for structural steel, plastic hinge length in structural element are required for this purpose.

B) Moment-rotation parameters

Moment-rotation parameters are the actual input for modeling the hinge properties and this can be calculated from the moment-curvature relation. The moment-rotation curve can be idealized as shown in Fig. 5, and can be derived from the moment-curvature relation. The main points in the moment-rotation curve shown in the figure can be defined as follows:

1) The point ‘A’ corresponds to the unloaded condition.
2) The point ‘B’ corresponds to the nominal yield strength and yield rotation θ_y
3) The point ‘C’ corresponds to the ultimate strength and ultimate rotation θ_u, following which failure takes place.
4) The point ‘D’ corresponds to the residual strength, if any, in the member. It is usually limited to 20% of the yield strength, and ultimate rotation, θ_u can be taken with that.
5) The point ‘E’ defines the maximum deformation capacity and is taken as $15\theta_y$ or θ_u, whichever is greater.

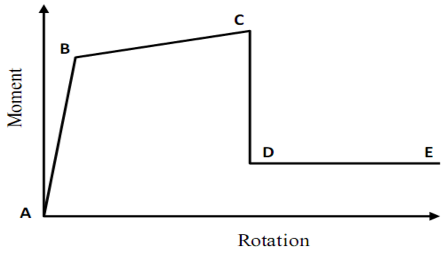


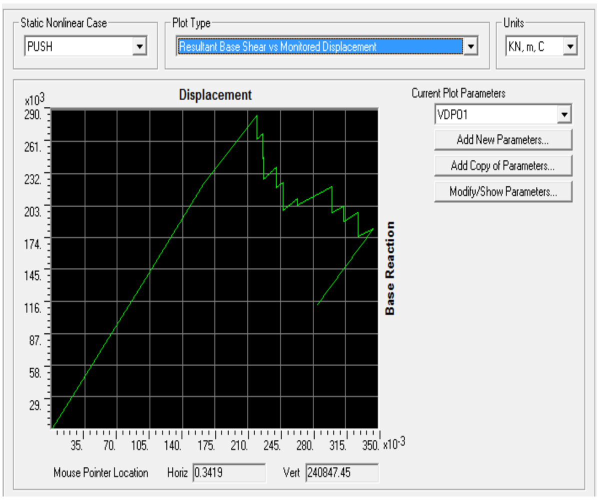
Fig 5. Idealized moment-rotation curve

VIII. RESULTS

The modeled building is analysed using Nonlinear Static (Pushover) analysis. This chapter presents Nonlinear Static (Pushover) analysis results and its discussions. Pushover analysis was performed first in a load control manner to apply all gravity loads on to the structure (gravity push). Then a lateral pushover analysis in transverse direction was performed in a displacement control manner starting at the end of gravity push. The results obtained from these analyses are checked by comparing spectral displacement demand and spectral displacement capacity from the pushover curve.

A) Nonlinear static (pushover) analysis

Nonlinear Static (Pushover) Analysis permits to identify critical members likely to reach limit states during the earthquake. Nonlinear Static Analysis is carried out after assigning flexural hinges (FEMA 356 Auto hinges) using ATC 40 Capacity Spectrum Method. As a result performance points & levels (IO, LS, and CP) are found in different pushover steps (Fig 6 to Fig 9) and Base shear vs. Displacement Graph (Table 2 & Graph 1) & Spectral Acceleration vs. Spectral Displacement Graph (Table 3 & Graph 2) is drawn and Spectral Displacement Demand & Spectral Displacement Capacity is calculated.



Graph 1. Base Shear vs. Displacement

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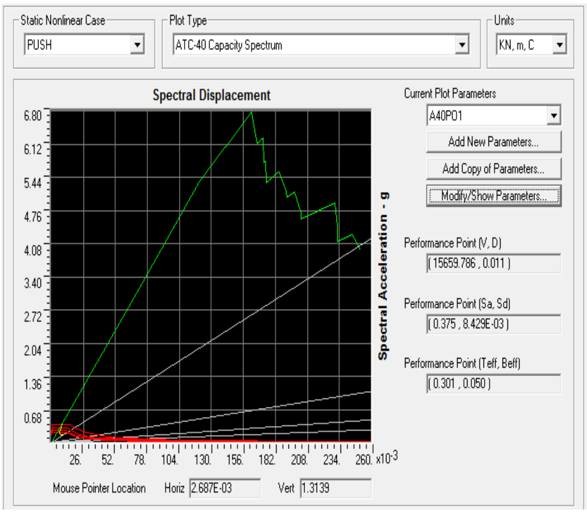
Table 2. Base Shear vs. Displacement

Step	Base Shear	Displacement
	KN	m
0	0	0.000039
1	136899.174	0.100039
2	222856.176	0.162827
3	284985.307	0.219658
4	263707.831	0.219668
5	268281.579	0.22565
6	245620.866	0.22566
7	246819.898	0.227053
8	227219.076	0.227063
9	237728.881	0.240471
10	225303.553	0.240481
11	219414.809	0.240491
12	224582.491	0.24803
13	198330.277	0.24804
14	209413.302	0.26341
15	203894.231	0.26342
16	219816.986	0.300175
17	196858.807	0.300185
18	202744.179	0.312539
19	189099.878	0.312549
20	196119.064	0.328297
21	174905.96	0.328307
22	181815.673	0.344237
23	112332.892	0.28418



Graph 2. Pushover Demand Capacity Curve (ATC 40)

Table 3. Pushover Demand Capacity Curve (ATC 40)

Pushover Curve Demand Capacity - ATC40 - PUSH				
Step	T eff	B eff	Sd Capacity (m)	Sd Demand (m)
0	0.30081	0.05	0	0.00843
1	0.30081	0.05	0.07369	0.00843
2	0.30081	0.05	0.11995	0.00843
3	0.31086	0.0714	0.16259	0.00795
4	0.33107	0.12874	0.16711	0.00709
5	0.33302	0.13027	0.17181	0.00714
6	0.34827	0.17648	0.17284	0.0067
7	0.34851	0.1757	0.17389	0.00673
8	0.36347	0.22164	0.17444	0.0064
9	0.36608	0.21231	0.18482	0.00667
10	0.38626	0.24949	0.19112	0.0067
11	0.39149	0.25895	0.19141	0.00672
12	0.39304	0.25412	0.19736	0.00686
13	0.41522	0.30097	0.20261	0.00713
14	0.41616	0.28299	0.20271	0.00729
15	0.42181	0.2911	0.23011	0.00786
16	0.43397	0.2778	0.23215	0.00863
17	0.45665	0.34035	0.23275	0.00931
18	0.45897	0.32496	0.24431	0.00944
19	0.47664	0.37142	0.25115	0.0105

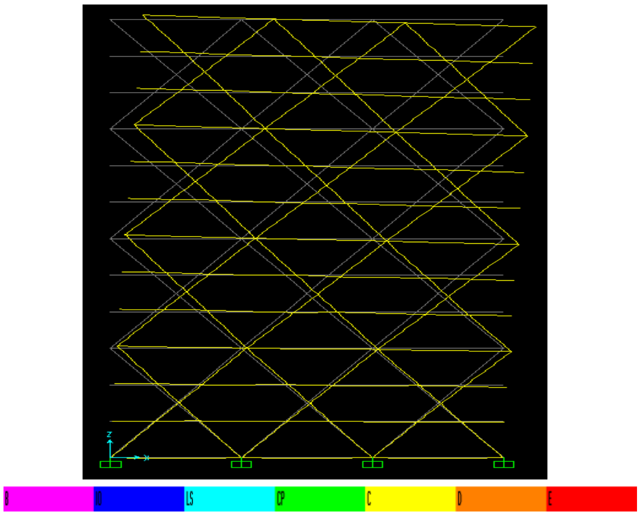


Fig 6. Pushover Step 1

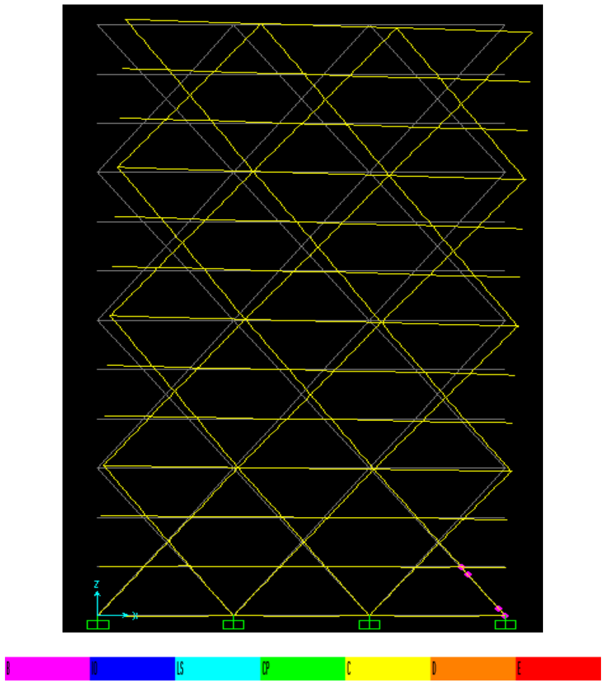


Fig 7. Pushover Step 2

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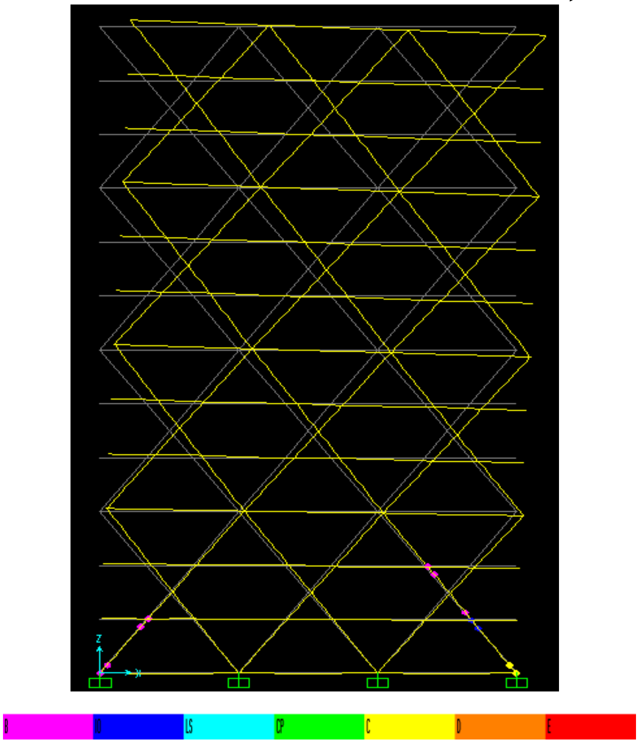


Fig 8. Pushover Step 3

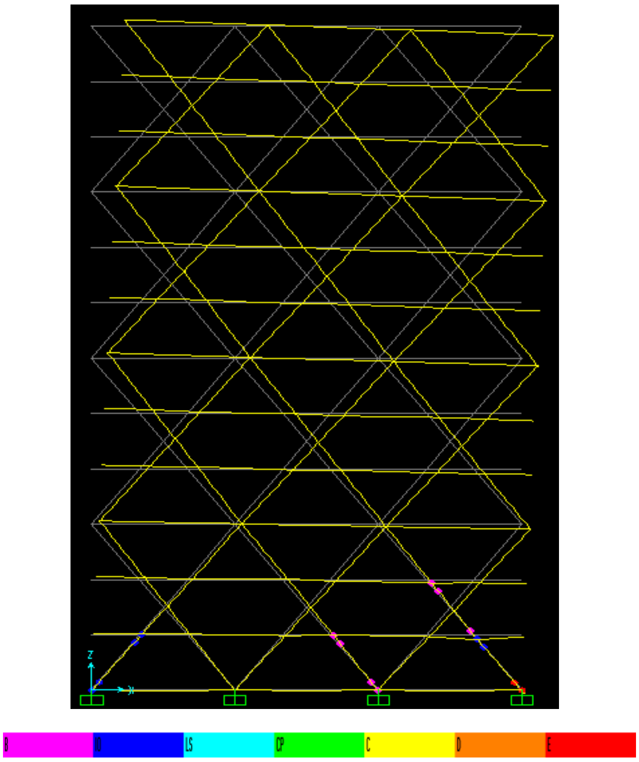
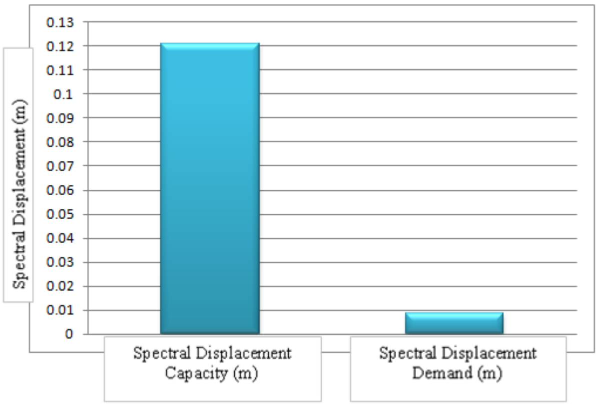


Fig 9. Pushover Step 4

The effective time is 0.301; it is in between pushover step 2 and step 3. At effective time the Spectral Displacement Capacity (m) and Spectral Displacement Demand (m) is calculated by interpolating values in the Table 3. The Table 4 shows the Spectral Displacement Capacity and Spectral Displacement Demand values according to Capacity Spectrum Method ATC 40 at effective time 0.301 secs.

Table 4. Comparison between Capacity & Demand (ATC 40)

Pushover Step	Effective Time, Teff (Sec)	Spectral Displacement Capacity (m)	Spectral Displacement Demand (m)
Between 2 & 3	0.301	0.120778	0.008420



Graph 3. Comparison between Sd Capacity & Sd Demand

IX. CONCLUSION

From non linear static analysis using FEMA 356 hinges we can identify the zones of, immediate occupancy, Life safety and Collapse prevention point are found out.

From the Analysis, Spectral Displacement Capacity is more than the Spectral Displacement Demand, so the analysed Diagrid Building doesn't require redesign.

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