Prediction of Seismic Collapse Capacity of Folded Plate Structures Using Nonlinear Static Analysis Method

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Abstract-**Collapse of structural systems is the primary source of casualties and loss of life during and after a ground motion. Furthermore, collapse is a major contributor to monetary losses and downtime. The importance of space structures to survive earthquake have been noticed from the experience of severe earthquakes. At present various measures against the earthquakes are applied to the space structure. Hence, this paper illustrates how to predict the collapse capacity for a Folded Plate Structures under seismic loads by using nonlinear static (pushover) analysis. In this paper, pushover analysis of V- type folded plate structure is introduced. The first mode lateral loading pattern for the folded plate structures with twelve other cases are adopted to perform the pushover analysis. The analysis is performed using SAP2000.**

***Keywords* - Collapse Capacity, Nonlinear Static Analysis, Dynamic Response, Multi-bay folded plate.**

I. INTRODUCTION

Collapse of a building during and shortly after an earthquake is the consequence of loss of the building's structural system integrity due to excessive deformation or force demand initiated in one, or several, component(s) of the building's structural system. Excessive seismic demand triggers strength and stiffness deterioration in structural components and can lead to a partial or complete collapse of the building. Observations of collapsed buildings in past earthquakes show that two modes of collapse are the most common for a building: sidesway collapse and vertical collapse. Side-sway collapse is the consequence of successive reduction of load-carrying capacity of structural components that are part of the building's lateral load-resisting system, to the extent that second-order (P-Δ) effects accelerated by component deterioration overcome gravity load resistance. In contrast, vertical collapse is the result of direct loss of gravity load-carrying capacity in one or several structural components[2].

In the present scenario, because of the wide range of geometry possible with folded plates, the accumulated understanding is still limited, thus there is a need of an attempt to be proposed to lay down certain recommendations which will be used as general guidelines for the performance study of folded plate structures subjected to seismic loading. Therefore, on the basis of certain objectives, some methodology needs to be proposed for learning the behavior of folded plate structures under seismic type of loads. As an initiation, nonlinear static pushover analysis is considered for seismic performance of folded plate structures. These suggestions can be considered with some modifications if required in the future.

Nonlinear Static Procedure has been widely accepted as a useful tool for performance-based seismic design and evaluation of structures. In the short time that has elapsed since its introduction to the engineering community, the method has been a subject of extensive research and several new analysis approaches have been proposed. It is now common to estimate seismic demands in a simplified manner by nonlinear static analysis or pushover analysis, which seems to be the preferred method in structural engineering practice [1].

Pushover analysis has been widely adopted in the seismic analysis of low- and medium-rise structures; however, few research references about pushover analysis of the long-span spatial structures have been reported till now [2]. Whether it is accurate for large-span spatial structure, it needs to be studied by practical engineering projects. This paper introduces the application of pushover analysis of large-span RC spatial structure.

A three-dimensional finite element model for seismic analysis is then developed. A complete pushover analysis is performed using SAP 2000 finite element package software.

II. DESCRIPTION OF THE STRUCTURES

1) Structural model

In folded plate structures, the reinforcement bars that resist the in-plane stress resultants should be placed in two or more directions and should ideally be oriented in the general directions of the principal tensile stresses especially in regions of high tension. Reinforcement to resist stress couples should be placed near both faces, since the bending moments may vary rapidly along the surface. Under seismic loading, the two layers also include the membrane reinforcement. The provision of adequate clearance and cover may necessitate increasing the folded plate thickness. Special attention is required for edge members that must be proportioned to resist the forces imparted by the folded plate. Fig.1 shows the multi-bay folded plate structure. Table I gives the details of parameters considered for multi-bay folded plate structures.

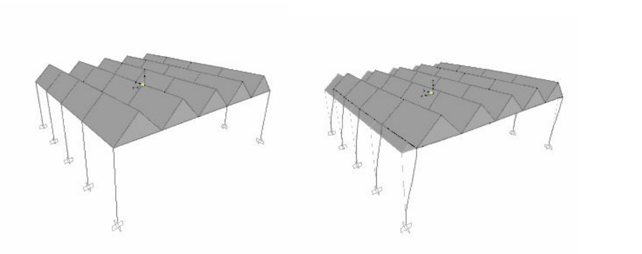


Fig.1 3D view and First Mode Shape of Multi Bay Folded Plate Structure

In practice, we can consider two regions in folded plate structures: (1) region where the stresses are primarily in-plane or membrane and, (2) regions with significant bending action. In the first case, direct tensile stresses should be resisted entirely by reinforcing steel in concrete folded plate. Regions with direct compressive stresses are generally controlled by stability requirements. In the second case, the moments or stress couples may be resisted by considering a concrete section with reinforcement near the surfaces to act as a wide flexural member. So, a suitable depth is required to facilitate the provision of ample reinforcing steel. The values of internal stress resultants and distribution are necessary to perform the design of reinforcement. Under lateral seismic loading with gravity loads, reinforcement design for RC folded plates is more complex than the case with only gravity loads.

2) Free vibration behavior

The first step in earthquake analysis must always be the solution of the free vibration problem. This is necessary to get a first important insight into structural dynamic properties. The modal characteristics of the multi bay folded plate structure are presented in the X, Y and Z directions in Table II.

III. FINITE ELEMENT MODEL

The structure is idealized as an assemblage of thin constant thickness shell element with each element subdivided into three numbers of layers as shown in Fig.2. The layered shell allows any number of layers to be defined in the thickness direction, each with an independent location, thickness, behavior, and material. Material behavior is considered to be non-linear. The layered shell usually represents full-shell behavior, although we can control this on a layer-by-layer basis unless the layering is fully symmetrical in the thickness direction. Three-dimensional modeling of the multi bay folded plate structure is performed using SAP2000 (Version 14) program. The finite element model is 3D shell element with non-linear layered shell capabilities. Both in-plane and normal loads are permitted.

IV. NON-LINEAR STATIC ANALYSIS

A pushover analysis is performed by subjecting a structure to a monotonically increasing pattern of lateral loads, representing the inertial forces, which would be experienced by the structure when subjected to ground shaking. Under incrementally increasing

TABLE I
SELECTED PARAMETERS FOR MULTI BAY FOLDED PLATE STRUCTURE

No.	Description	Parameter
1.	Span in X direction	20 m
2.	Span in Y direction	20 m
3.	Live load	0.5kN/m^2
4.	Grade of Concrete	M-25
5.	Type of Steel	HYSD bars
6.	Column Height	6.0 m
7.	Column Size	0.6 m x 0.6m
8.	Column Longitudinal reinforcement	2.5 % reinforcement
9.	Column transverse reinforcement	10d @ 150 centre to centre
10.	Column Support condition	Fixed
11.	Beam Size	0.50 m x 1.80 m
12.	Beam Reinforcement	0.0125 m^2 at top & bottom
13.	Folded Plate reinforcement	10d @ 200 centre to centre in single-face& in both-ways.
14.	Diaphragm thickness	0.50 m
15.	Thickness of Folded Plate	0.1 m
16.	Number of Folds	5 nos.
17.	Size of one fold	4 m
18.	Rise of Fold	2 m

TABLE II
MODAL CHARACTERISTICS OF MULTI BAY FOLDED PLATE STRUCTURE

Mode	Period (Sec)	Modal Participating Mass Ratios UX	UY	UZ
1	0.58416	0	0.989	8.1E-10
2	0.46521	0.98885	0	0
4	0.39807	0	4.6E-09	0.57004

loads various structural elements may yield sequentially. Consequently, at each event, the structure experiences a loss in stiffness. Using a pushover analysis, a characteristic non-linear force displacement relationship can be determined.

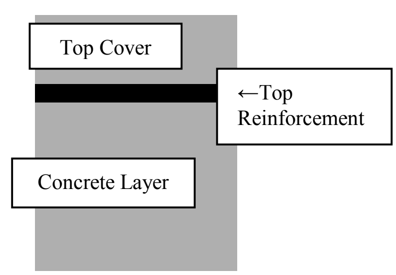


Fig.2 Layered Shell Model for single layer reinforcement

A well-designed structure should be capable of equally resisting earthquake motions from all possible directions [3]. Therefore, ten pushover analysis cases, as listed in Table III, are performed in three directions i.e. X, Y and Z directions.

The general finite element package SAP 2000 (Linear and nonlinear static and dynamic analysis and design of three dimensional structures) is used as a tool for performing the pushover analysis. SAP 2000 (Version 14) static pushover analysis capabilities, which are fully integrated into the program, allow quick and easy implementation of the pushover procedures prescribed in ATC-40 [4] and FEMA-356 [5] for both two-dimensional and three-dimensional structures [6]. It also provides default-hinge properties and recommends PMM hinges for columns and M3 hinges for beams as described in FEMA-356.Multi bay folded plate are supported on edge beams and columns in X direction. M3 auto hinges are provided in edge beams and PMM auto hinges are provided in columns.

V. NON-LINEAR STATIC ANALYSIS RESULTS

The outcomes from pushover analysis are capacity curves, capacity-demand curves, performance points, drift ratios, base shear, stresses, deflection and plastic hinge mechanism in folded plates.

1) Capacity curve

The resulting capacity curves for the multi bay folded plate structure are shown in Fig.3. The curves are represented separately for different three directions. They are initially linear but start to deviate from linearity as the beams and the columns undergo inelastic actions. When the buildings are pushed well into the inelastic range, the curves become linear again but with a smaller slope.

2) Capacity Demand Curve

Capacity Demand (D) Curves are plotted between Spectral Displacement, S_d (m) and Spectral Acceleration S_a (g). The performance point for each analysis case is obtained from Fig.4.

3) Performance Point, Drift Ratio & Base Shear

Performance points are obtained by the intersection of capacity and demand curves. Drift ratio is the ratio of differential displacement Δ, between each end of the component over the effective height of the component (H). The base-reaction and displacement of control node at performance point and drift ratio for column node are listed in Table IV and Table V.

4) Stresses in Concrete and Steel Layers

Maximum principle stress and minimum principle stress for whole thickness and different layers are tabulated in Table VI and Table VII. SAP 2000 provides the facility to find stresses for defined layers separately. Maximum and minimum principle stresses for shell, concrete layer, and top reinforcement layer are then compared with permissible stresses.

Amongst all the 10 analysis cases the maximum stresses can be observed in the analysis case, first mode shape in the z direction (Case 6), for both concrete and steel as shown in Fig.5.

5) Deflection in Shell

The deflections in multi bay folded plate structure for 10 analysis cases in X, Y & Z directions are listed in Table VIII. The maximum deflection is 0.116 m in X direction, 0.097 m in Y direction and 0.116 m in Z direction.

TABLE III
LOADING DIRECTION AND PATTERN FOR EACH PUSHOVER ANALYSIS CASE

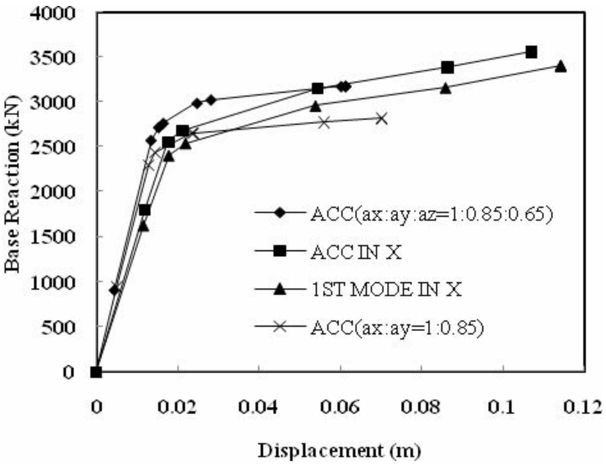
Analysis case	Loading direction	Loading pattern
1	X	Acceleration load
2	Y	Acceleration load
3	Z	Acceleration load
4	X	The first mode shape in the x direction
5	Y	The first mode shape in the y direction
6	Z	The first mode shape in the z direction
7	X and Y	Acceleration load (A_X:A_Y=1:0.85)
8	X and Y	Acceleration load (A_X:A_Y =0.85:1)
9	X, Y and Z	Acceleration load (A_X:A_Y:A_Z =1:0.85:0.65)
10	X, Y and Z	Acceleration load (A_X:A_Y:A_Z =0.85:1:0.65)

TABLE IV
YIELD POINT AND PERFORMANCE POINT BY PUSHOVER ANALYSIS

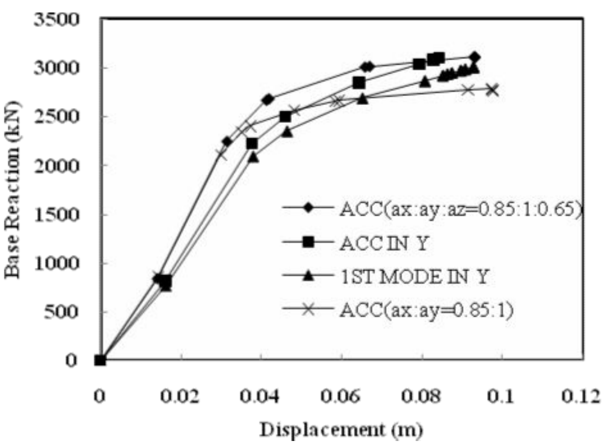
Analysis case	Yield point of control node		Performance point of control node	
	dy (m)	Fy (kN)	d (m)	F (kN)
1	0.018	2538.31	0.042	2959.77
2	8.7E-3	824.41	0.052	2799.77
3	0.029	6483.4	0.018	6880.67
4	0.0177	2432.2	0.043	2809.18
5	8.9E-3	793.22	0.054	2657.99
6	0.0332	4555.93	0.036	4626.52
7	0.0188	2123.4	0.065	2789.35
8	6.3E-3	882.72	0.076	2765.87
9	0.0116	2310.51	0.058	3137.71
10	6.4E-3	878.644	0.07	3094.75

TABLE V
DISPLACEMENT OF COLUMN NODE AND DRIFT RATIO BY PUSHOVER ANALYSIS

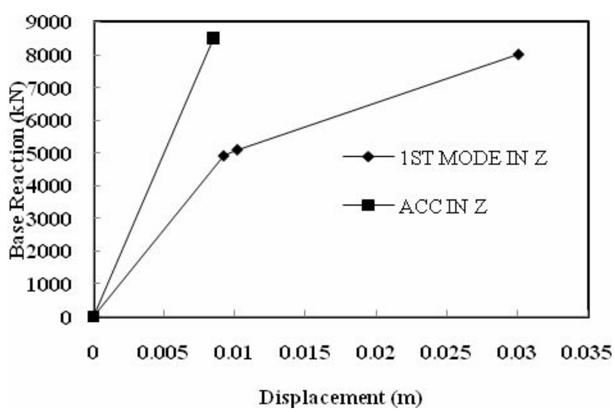
Analysis case	Displacement of column node	
	Δ (m)	Δ/H
1	0.114	0.0190
2	0.077	0.0128
3	0.000833	0.0001
4	0.115	0.0192
5	0.079	0.0132
6	0.00216	0.0004
7	0.087	0.0145
8	0.092	0.0153
9	0.083	0.0138
10	0.085	0.0142



(a) In X-direction



(b) In Y-direction

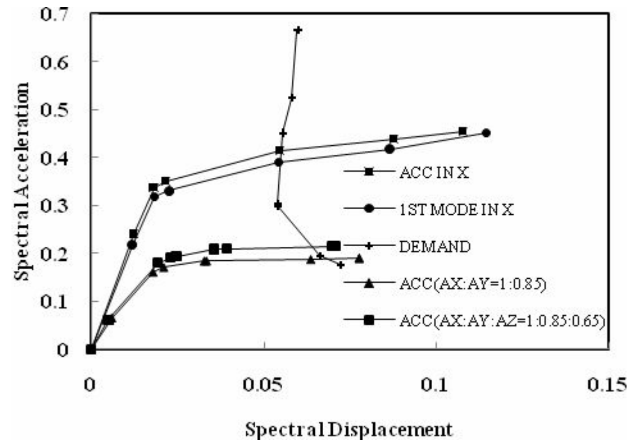


(c)In Z-direction

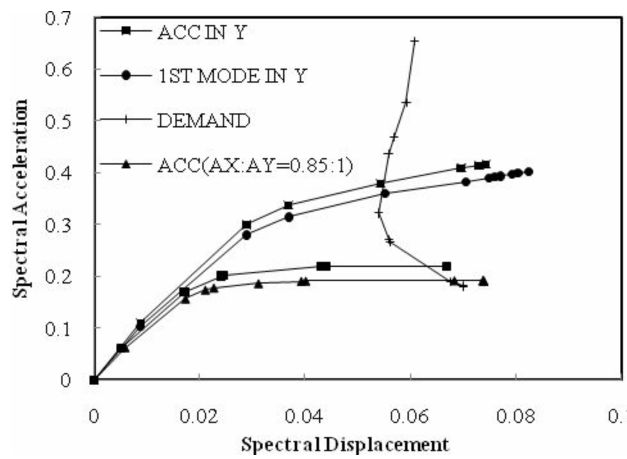
Fig.3 Capacity Curve for Multi Bay Folded Plate Structure

6) Plastic Hinge Mechanism

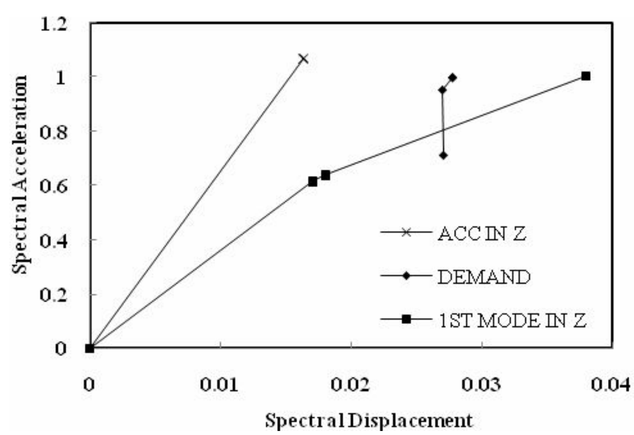
Table IX shows statistics of plastic hinges obtained by pushover analysis for multi bay folded plate structure from different pushover analysis cases. Step number in which hinges are formed is mentioned in bracket. Plastic hinges appear mainly in the columns and a few in the beams. In Z direction the plastic hinges are not formed as the entire load is taken by folded plate. Maximum hinges are in the phase of B-IO, means the member need not be repaired after earthquakes. The hinge formation represents the performance level of the structure. The maximum numbers of hinges are formed in the analysis case, the first mode shape in the X direction. Steps of plastic hinge mechanism are shown in Fig. 6 for the analysis case, first mode shape in the X direction (Case 4).



(a) In X-direction



(b) In Y-direction



(c) In Z-direction

Fig.4 Capacity-Demand Curves for Multi-Bay Folded Plate Structure

TABLE VI
MAXIMUM PRINCIPAL STRESSES BY PUSHOVER ANALYSIS

Analysis case	Overall Stresses	Concrete Layer Stresses	Steel Top Layer Stresses
1	5.12	3.07	25.18
2	4.72	4.7	34.4
3	3.35	3.2	23.92
4	5.33	3	24.82
5	4.67	4.6	37.58
6	5.82	4.7	129.9
7	5.135	3.3	26.2
8	5.2	5.24	26.5
9	5.35	5.3	46.7
10	5.5	5.14	33.3

TABLE VII
MINIMUM PRINCIPAL STRESSES BY PUSHOVER ANALYSIS

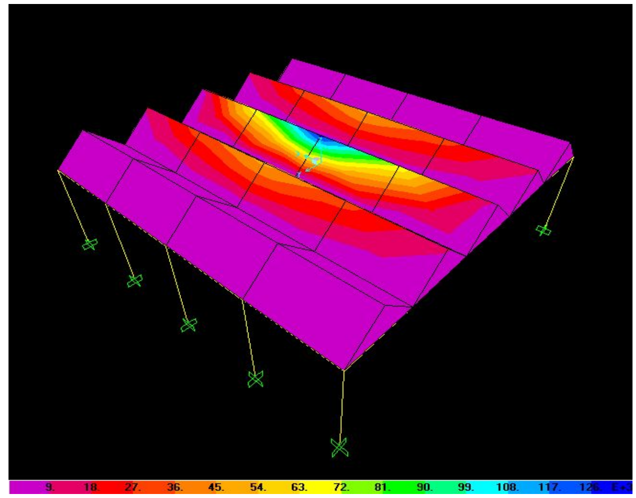
Analysis case	Overall Stresses	Concrete Layer Stresses	Steel Top Layer Stresses
1	5.05	3.919	29.3
2	8.25	7.6	61.5
3	3.2	3.29	19.6
4	5.34	4.03	29.32
5	8.17	8.1	64.84
6	7.04	8.28	52.5
7	6.136	6	46.71
8	6.6	6.6	51.5
9	7	6.2	33.17
10	6.9	6.84	52.89

TABLE VIII
DEFLECTION IN FOLDED PLATE BY PUSHOVER ANALYSIS

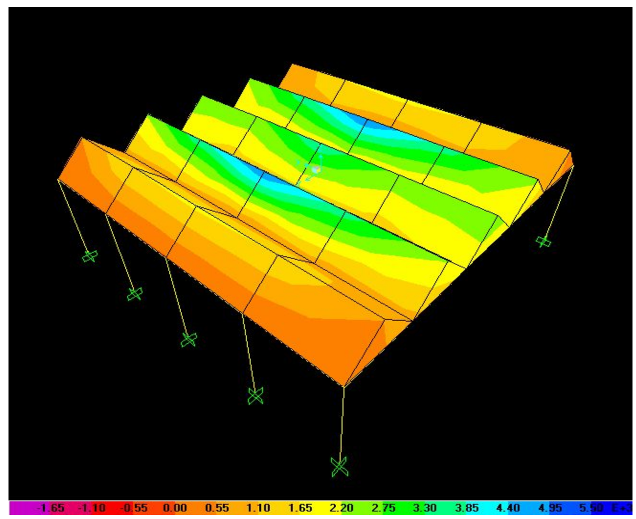
Analysis	Deflection (m)		
case	In X	In Y	In Z
1	0.1141	0.0166	0.0322
2	0.0023	0.0864	0.0322
3	0.0009	0.0078	0.0295
4	**0.1165**	0.0113	0.0337
5	0.0022	0.0887	0.0322
6	0.0138	0.0188	**0.1168**
7	0.0815	0.0974	0.0323
8	0.0665	0.1018	0.0335
9	0.0767	0.0956	0.0447
10	0.0603	**0.0978**	0.0436

TABLE IX
STATISTICS OF PLASTIC HINGES OBTAINED BY PUSHOVER ANALYSIS

Analysis case	Percentage (%) of Plastic Hinge Obtained (Step No.)			
	B	IO	LS	CP
1	19(3)	20(5)	5(8)	1(8)
2	10(4)	12(5)	-	-
3	4(1)	-	-	-
4	20(5)	20(7)	10(8)	1(8)
5	8(2)	12(6)	-	-
6	4(2)	4(3)	-	-
7	18(5)	20(6)	-	1(7)
8	14(5)	19(9)	-	1(9)
9	14(4)	19(7)	1(7)	1(8)
10	12(5)	15(7)	-	1(7)



(a) Maximum absolute principal stresses in steel layer–129.9N/mm^2



(b)Maximum absolute principal stresses in concrete layer–4.7 N/mm^2

Fig. 5 Maximum absolute principal stresses in steel and concrete layer in Z-direction for the analysis case, first mode shape in the Z direction (Case 6)

VI. DISCUSSION

The permissible storey drift as per IS 1893:2002[7] due to the lateral force, with partial load factor of 1.0, is H/250 where H is the storey height. The permissible storey drift is 0.024 m for 6 m storey height. The storey drifts are within limit for all cases. All of the hinges are developed in the columns and a few hinges are observed in the beams. Maximum hinges are obtained in columns in X-direction. In Y-direction and Z-direction, hinges are observed in columns only up to IO. The permissible vertical deflection in shell as per IS-456:2000[8] is 0.08 m (span/250). The vertical deflection i.e. deflection in Z-directions are within permissible limits except for analysis case 6.The permissible stresses in concrete and steel as per IS-456:2000 are 13.38 N/mm² ($0.446*f_{ck}$) and 361.05 N/mm² ($0.87*f_y$). The stresses in steel layer are within the permissible limit.

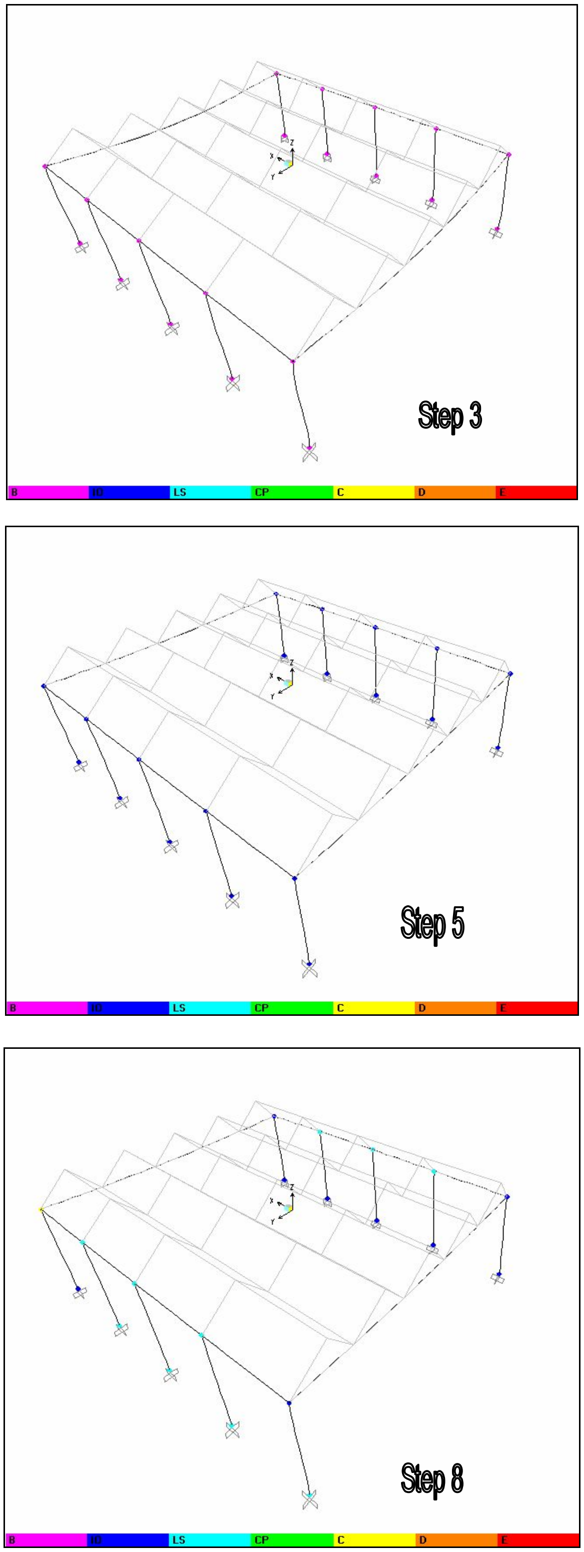


Fig. 6 Steps of plastic Hinge mechanism for the analysis case, first mode shape in the X direction (Case 4).

VII. CONCLUSIONS

By modeling the folded plate, as layered element it is possible to observe the behavior of each layer. The pushover analysis is relatively a simpler way to explore the nonlinear behavior of structures and same is here applied for multi bay folded plate structures. For large span structures, pushover analysis is accurate enough provided the modal participating mass ratio is larger than 0.50. From the capacity demand curves, it can be said that folded plate structures though have a very high capacity; still they will collapse at an earlier stage due to high demand. For multi-bay folded plate structures, pushover analysis has high efficiency to find out the weak part of the structure. The collapse capacity of the multi bay folded plate can be predicted on the basis of the base shear of the yield point and performance point of the control node.

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