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Modeling of Reinforced Concrete Folded Plate Structures for Seismic Evaluation

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Abstract— ***Folded Plates and spatial structures are adopted for construction of large span structures in which a large space is realized without columns as the structural components. In those cases, the structures are expected to resist against various design loads mainly through their extremely strong capability which can be acquired through in-plane or membrane stress resultants and this is just the reason by which they themselves stand for external loads without columns as their structural components in the large span structures. In civil engineering construction, folded plates are commonly used as roofing units. However, they are frequently subjected to dynamic loadings in their service life and hence, the knowledge of their dynamic behavior is important from the standpoint of analysis and design. To understand the performance and behavior of folded plate, the finite element modeling approach is a very important aspect. Finite Element Analysis is performed for both linear and non-linear problems to design and analysis evaluation situations. In this study the finite element modeling of multi bay cylindrical shell structures has been done to understand its performance during earthquake using SAP 2000 (version 14). The structure is idealized as an assemblage of thin constant thickness shell element with each element subdivided into 3 numbers of layers. The layered shell allows any number of layers to be defined in the thickness direction, each with an independent location, thickness, behavior, and material. This paper introduces the application of non-linear static and non-linear dynamic analysis of large-span RC spatial structure. In the present work an attempt has been made to convert the MDOF model of large span reinforced concrete shell structures into SDOF system using N2-method. With the help of this method, equivalent stiffness, mass and force can be obtained.***

Index Terms—**Multi Bay Cylindrical Shell, N-2 Method, Seismic Evaluation, Non-Linear Analysis.**

I. INTRODUCTION

Folded Plates belong to the class of stressed skin structures, which because of their geometry and small flexural rigidity of the skin; tend to carry loads primarily by membrane forces acting in their plane. On account of their multiplicity of types of reinforced concrete folded plate structures used in present day building practice their behavior under seismic conditions is not well known. 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. The estimation of nonlinear response of buildings subjected to a strong ground motion is a key issue for the rational seismic design of new structures and the seismic evaluation of existing structures[1]. For this purpose, the nonlinear time history analysis of Multi-Degree-Of-Freedom (MDOF) model might be one solution, but it is often too complicated whereas the results are not necessarily more reliable due to uncertainties involved in input data. To overcome such shortcomings, several researchers have developed simplified nonlinear analysis procedures [2]-[4]. This approach is often referred to as Nonlinear Static Procedure (NSP)[1]. It consists of a nonlinear static analysis of MDOF model and a nonlinear dynamic analysis of the equivalent Single-Degree-Of-Freedom (SDOF) model, and it would be promising as long as structures oscillate predominantly in the fundamental mode. Nonlinear Static Procedure has been widely accepted as a useful tool for performance-based seismic design and evaluation of structures. 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[5]. 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 of multi bay cylindrical shell structure is developed and complete pushover analysis is performed using SAP 2000 finite element package software. N-2 method has been widely used to convert the MDOF model in to SDOF model. An attempt has been made to convert the MDOF model of multi bay cylindrical shell structure in to SDOF model. Single degree of freedom (SDOF) models have been widely used for predicting dynamic response of concrete structures subjected to seismic loading. The popularity of the SDOF method in seismic resistant design lies in its simplicity and cost-effective approach that requires limited input data and less computational effort. SDOF model gives reasonable good results if the response mode shape is representative of the real behavior. Accuracy of the dynamic response calculations significantly depends on whether the adopted resistance function resembles the actual hysteretic behavior of the structure.

II. DESCRIPTION OF THE STRUCTURE

A. *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

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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.

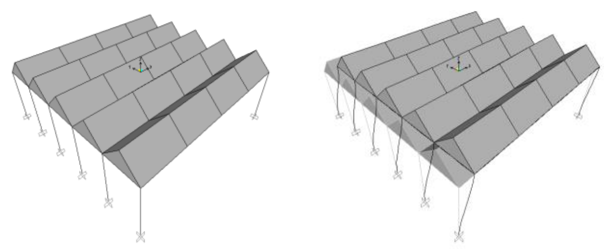

Fig. 1, 3D- view and First Mode Shape of Multi Bay Folded Plate Structure

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 for 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.

Table I Selected Parameters for Multi-bay Cylindrical Shell Structure

No.	Description	Parameter
1.	Span in X direction	20 m
2.	Span in Y direction	20 m
3.	Live load	0.5 kN/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	0.100 m

B. Free Vibration Behavior

The solution of the free vibration problem is considered to be the most prior step in any earthquake analysis. This is necessary to get the first important insight into structural dynamic properties. The modal characteristics of the multi bay folded plates are presented in the X, Y and Z directions in Table II. Since the mass participating factor in the first mode is more than 90% which means that the dynamic response will be dominated by the first mode and hence it is expected that the pushover analysis will yield realistic results.

Table II Modal characteristics of Multi-bay Folded Plate Structure

Mode	Period	Frequency	Modal Participating Mass Ratios		
			UX	UY	UZ
Unitless	Sec	Cyc/sec	Unitless	Unitless	Unitless
1	0.4659	2.1461	0.9926	0	2.2E-20
2	0.4281	2.3356	0	0.98955	2.9E-08
5	0.1823	5.4844	9E-19	2.3E-08	0.3496

III. FINTE ELEMENT MODEL

The structure is idealized as an assemblage of thin constant thickness folded plate element with each element subdivided into three numbers of layers as shown in Fig.2. The layered folded plate 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.

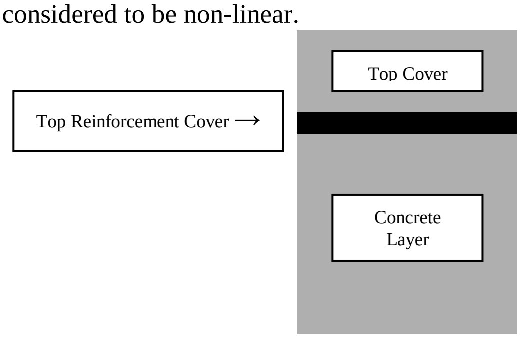

Fig.2, Layered Folded Plate Model

The layered folded plate usually represents full-folded plate behavior, although we can control this on a

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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. Both in-plane and normal loads are permitted.

IV. NON-LINEAR STATIC ANALYSIS

For performing pushover analysis, a structure is subjected to monolithically increasing lateral load patterns, which would be experienced by the structure when subjected to ground shaking. Under incrementally increasing 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.

Table III Loading Direction and Pattern for Each Pushover Analysis Case

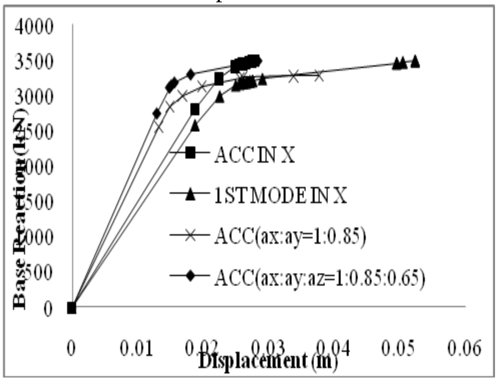
Analysis case	Loading direction	Loading pattern
1	X	Acceleration load
2	Y	Acceleration load
3	Z	Acceleration load
4	X	The first mode shape in the x direction
5	Y	The first mode shape in the y direction
6	Z	The first mode shape in the z direction
7	X and Y	Acceleration load (A_X:A_Y=1:0.85)
8	X and Y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

A well-designed structure should be capable of equally resisting earthquake motions from all possible directions. 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 [1] and FEMA-356 [6] for both 2 dimensional and 3 dimensional structures. 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.

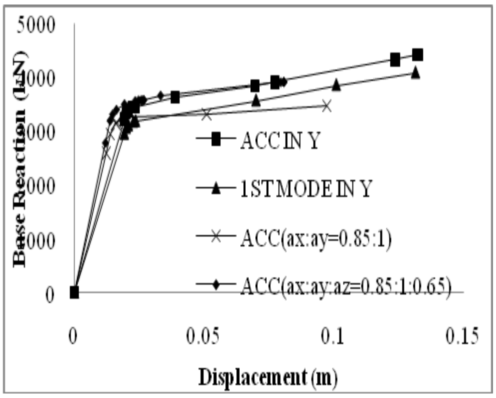
V. NON-LINEAR STATIC ANALYSIS RESULTS

A. *Capacity Curves*

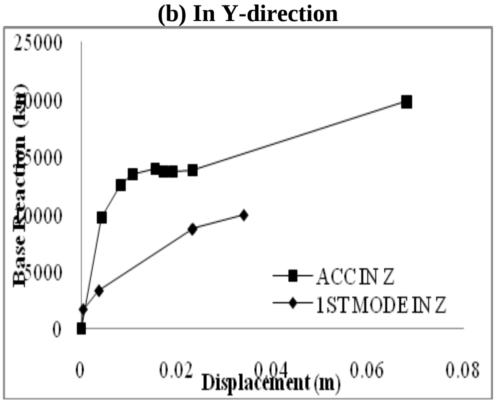
The resulting capacity curves for the multi bay folded plate structure are shown in Fig.3. The curves are represented separately for different three directions. They are initially linear but start to deviate from linearity as the beams and the columns undergo inelastic actions. When the buildings are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



(a) In X-direction



(b) In Y-direction



(c) In Z-direction

Fig. 3 Comparative Capacity Curves for 100 mm thickness and columns in Y-direction

B. *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. W is the seismic weight of the structure.

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Table IV Response of Multi-bay Folded Plate Structure by Pushover analysis

Cases	Yield point of control node		Performance point of control node		Displacement of column node	
	dy (m)	Fy (kN)	d (m)	F (kN)	Δ (m)	Δ/H
ACC IN X	0.022	3155.93	0.036	3613.9	0.05	0.00833
ACC IN Y	0.0189	3305.76	0.038	3617.9	0.12	0.02
ACC IN Z	3.9E-03	10447.46	2.53E-03	8195.8	0.08	0.01333
1ST MODE IN X	0.0188	2550.85	0.039	3419.7	0.04	0.00667
1ST MODE IN Y	0.0189	3090.2	0.04	3382.2	0.12	0.02
1ST MODE IN Z	4.0E-03	3984.06	0.011	5371.4	0.08	0.01333
ACC(ax:ay=1:0.85)	1.5E-02	2835.6	0.063	3323.0	0.1	0.01667
ACC(ax:ay=0.85:1)	1.4E-02	3001.7	0.06	3339.0	0.1	0.01667
ACC(ax:ay:az=1:0.85:0.65)	1.5E-02	3060.33	-	-	0.03	0.005
ACC(ax:ay:az=0.85:1:0.65)	0.013	3238.98	0.053	3763.8	0.1	0.01667

VI. CONVERSION OF MDOF MODEL TO EQUIVALENT SDOF MODEL

Peter Fajfar (2000)[3], has tried to emphasize on a technique based on the pushover analysis of a multi-degree-of-freedom model and the response spectrum analysis of an equivalent single- degree-of-freedom system, called the N2 method.

The following steps are included in the N-2 method -

a) Modeling of the folded plate and frame element is same as above procedure.

b) Apart from the gravity and Live load apply dynamic load on shell which is equal to the 1st mode shape of the structure by assuming linear mode shape displacement and normalized it the value at the top is equal to 1.

c) Run the Pushover analysis for the dynamic load case.

d) From the modal output choose 5 maximum modal participating factors. Apply cumulative addition and normalized it the value at the maximum is equal to 1. This will give the value of matrix **ϕ**.

e) From the output of Pushover analysis, base shear (V) and displacement (D) are obtained.

f) Equivalent mass for SDOF model is obtained by the given formul7a= **M* = ΣMϕ**.

g) The constant controls the transformation from the MDOF to the SDOF model is calculated as = **Γ =**

$$\frac{\sum m_i \times \emptyset_i}{\sum m_i \times \emptyset_i^2}$$

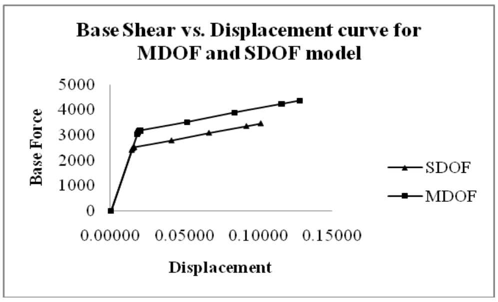

Fig. 4, Pushover Curve for MDOF and SDOF Model

h) Equivalent Base shear (F*) and displacement (D*) respectively can be calculated by the given formula:

$$F^* = V / \Gamma$$

$$D^* = D / \Gamma$$

i) Pushover Curve for SDOF model can be generated as shown in Fig. 4

VII. RESULTS OF N2 METHOD

The MDOF model of V-type 100 mm thickness with column under corrugations has been converted in SDOF model as per the steps mentioned in Slide 36.

Equivalent results for SDOF model are-

Equivalent force = F* = 2474.03 KN
Equivalent Displacement = D* = 15.15 mm
Equivalent mass = M* = 1826.77 KN
Equivalent Stiffness = K* = 205.76 KN/mm

VIII. CONCLUSION

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 drift is within limit for all 10 loading 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 i.e. Immediate Occupancy. The permissible vertical deflection in folded plate as per IS-456:2000 [8], is 0.08 m (span/250). The vertical deflection is within the permissible limit. The permissible stresses in concrete and steel as per IS-456:2000 are 13.38 N/mm^2 (0.446*f_{ck}) and 361.05 N/mm^2 (0.87*f_y). The stresses in steel layer are within the permissible limit. By modeling the folded palte, in layer 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 applied here. For large span structures, pushover analysis is accurate enough provided the modal participating mass ratio is larger than 0.90 and according to our study it can be said that pushover analysis gives us approximate behavior in x and y direction does not give true behavior in z direction as modal participating mass ratio is very less. 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 folded plate structures, pushover analysis has high efficiency to find out the weak part of the structure. In this paper, the equivalent SDOF model for reinforced concrete shell structures is formulated. N-2 method can be applied to the spatial structures with some modifications to convert the MDOF model to equivalent SDOF model. Using such an equivalent SDOF model, the engineer-user is able to generate accurate predictions of the seismic behavior of complex MDOF structures like shell structures and folded plate structures within a fraction of the time needed.

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