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ANALYSIS OF SPHERICAL DOME WITH OPENINGS USING THE FINITE ELEMENT METHOD

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Abstract—This study is devoted to the finite element analysis of Spherical Dome with openings under static loading which result from the weight of dome and a concentrated load at the crown to obtain the most economical size of opening that can be provided at different locations and to obtain the optimum location (in terms of angle with horizontal) at which an opening of a particular size can be provided. Equations have been developed for most economical aspect ratio and optimum angle at which openings should be provided for various cases of Spherical Dome with 2 openings, 4 openings and 6 openings. Variations in maximum stress intensity produced in the dome due to increase in aspect ratio and increase in angle of opening have been shown. Change in maximum stress zone due to increase in aspect ratio have also been shown.

Keywords: Most economical aspect ratio, Optimum location of openings, Maximum stress intensity, Maximum stress zones.

INTRODUCTION

A **dome** may be defined as a thin – shell generated by the revolution of a regular curve about one of its axes. The shape of the dome depends upon the type of the curve and the direction of the axis of revolution. In case of Spherical Dome, this curve is circular in shape. There are two main mechanisms by which a shell can support loads. On one hand, the structure can react with only in-plane forces, in which case it is said to act as a membrane. In practice, however, real structures have local areas where equilibrium or compatibility of displacements and deformations is not possible without introducing bending. The efficient load-carrying capabilities of shell structures have rendered their use widespread in a variety of engineering applications. The superiority of shell structures over their conventional flat counterparts i.e. plates, slabs and other similar forms can be attributed to the very shape or form. *The ratio of the load to be carried to the quantity of the material consumed in the case of shell is very high.* This is a very significant factor so far as the structural efficiency of shell structures are concerned.

Although analytical techniques are very important, the use of numerical methods to solve shell mathematical models of complex structures has become an essential ingredient in the design process. The finite element method has been the fundamental numerical procedure for the analysis of shells. The finite element method is a numerical procedure for analyzing structures and continua. Usually the problem addressed is too complicated to be solved satisfactorily by classical analytical methods. The finite elements procedure produces many simultaneous algebraic equations, which are generated and solved on a digital computer. Results are rarely exact. However, errors are decreased by processing more elements and more equations, and results accurate enough for engineering purposes are obtainable at reasonable cost. The finite element method originated as a method of stress analysis. Today finite elements are also used to analyze problems of heat transfer, fluid flow, electric and magnetic fields, and many others. This method is preferred for analysis over other conventional methods because the boundary conditions can be applied with ease even for complex problems and it is possible to determine the internal forces at a number of points, so as to plot its variation along any given direction.

OBJECTIVE OF STUDY

The main objective of this thesis is to carry out static analysis of Spherical Dome with different sizes of circular openings at different locations to develop equations for the most economical aspect ratio and the optimum location (in terms of angle with horizontal) of openings for Spherical Domes with 2 openings, 4 openings and 6 openings. Software used for analysis is Finite Element Method based ANSYS 12.1. Element used for discretization is SHELL99.

$$Aspect\ Ratio = \frac{Diameter\ of\ opening}{Diameter\ of\ dome}$$

SHELL99 ELEMENT

SHELL99 is an 8-node Structural shell p-element that supports a polynomial with a maximum order of eight. This element is particularly well suited to model curved shells. It is also suitable for analyzing thin to moderately-thick shell structures. It has six degrees of freedom at each node: 3 translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. However, when using the membrane option, the element has translational degrees of freedom only.

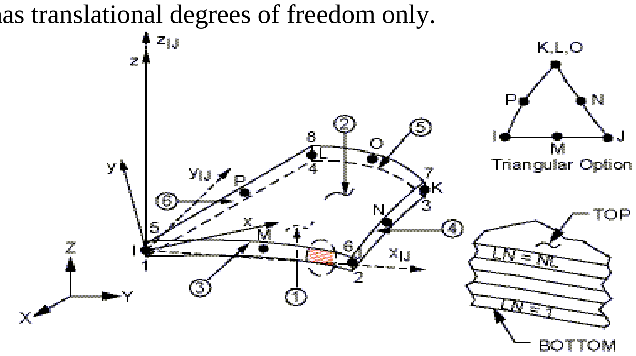

Fig.1 SHELL99 Element

The geometry, node locations, and the element coordinate system for this element are shown in Fig.1. The element is defined by eight nodes: I, J, K, L, M, N, O and P. Mid-side nodes may not be removed from this element. A triangular-shaped element may be formed by defining the same node number for nodes K, L and O. Zero-area elements are not allowed. Zero-area elements occur most often whenever the elements are numbered improperly. The element formulation is based on logarithmic strain and true stress measures. The element kinematics allow for finite membrane strains. However, the curvature changes within a time increment are assumed to be small. The element works best with full Newton-Raphson solution scheme.

For better accuracy, ANSYS recommends quadrilateral shaped elements. The use of elements in triangular form is not recommended, except as a filler element. Triangular shaped elements should be used sparingly and avoided especially in areas with high stress gradients. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. Thickness and other information can be defined through the use of either real constants or section definitions. The thickness of the shell may be defined at each of its nodes. The thickness is assumed to vary smoothly over the area of the element. If the element has a constant thickness, only TK(I) needs to be input. If the thickness is not constant, all four thicknesses must be input. Zero thickness elements or elements tapering down to a zero thickness at any corner are not allowed. However, zero thickness layers are allowed. A maximum of 250 layers is supported.

PROBLEM FORMULATION AND MODELING

In this study, Spherical Domes having span 10m and thickness 100mm have been taken. Variations in maximum stress intensity produced in the dome due to increase in aspect ratio and increase in angle of opening are compared for various angles of openings and aspect ratios respectively. The different cases for which the dome was modeled and analyzed are:

1) No. of openings

2openings / 4openings / 6openings

2) Aspect ratio of openings

Ranging from 0.02 ~ 0.28

3) Location of openings

30⁰ / 40⁰ / 45⁰ / 50⁰ / 60⁰ w.r.t. horizontal

Material Properties

1)	Grade of concrete	M30
2)	Density of concrete	25 KN/m3
3)	Young’s Modulus E	27386 N/mm2
4)	Poisson’s ratio ν	0.2

Analysis is carried out for Spherical Domes having span 10m and uniform thickness 100mm using Finite Element Method based software ANSYS 12.1 for above mentioned cases.

The steps required to follow to perform static analysis in ANSYS 12.1:

Preprocessor

- Prepare the Model in ANSYS 12.1
- Define Element type.
- Define Real Constants and Material Properties.
- Assign Element type, Real Constants and Material Properties through Mesh Attributes.
- Mesh the problem.

Solution Processor

- Define Analysis Type.
- Apply Loads.
- Specify boundary conditions.
- Run Analysis using *Solve*.

General Postprocessor

- List/Plot nodal displacements.
- Element forces and moments.
- Deflection plots.
- Stress contour diagrams.

The model created and analyzed in ANSYS 12.1 for one of the above cases is shown in Fig.2 below

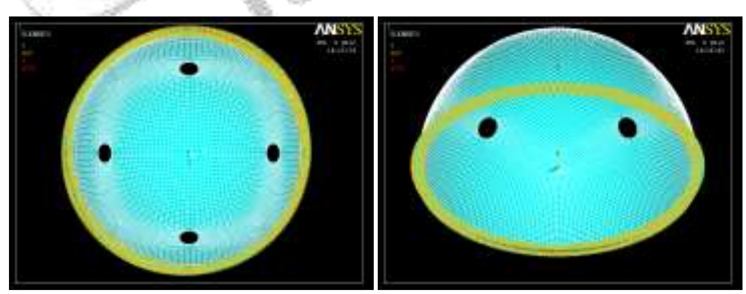

Fig.2 3-D Meshed Model of Spherical Dome with 4 openings@45⁰

ANALYSIS RESULTS

In this project, analysis results given by ANSYS 12.1 are represented in terms of maximum stress intensity produced in the Spherical Dome.

Variations in this maximum stress intensity due to increase in aspect ratio of openings are compared for various angles of openings for Spherical Dome with 4 openings as shown below.

Table No.1 Maximum stress intensities - 4 openings.

	Maximum stress intensity (N/mm^2)				
Aspect Ratio	30°	40°	45°	50°	60°
0.02	3.4957	3.4874	3.4838	3.4804	3.4745
0.03	3.5012	3.4859	3.4801	3.4782	3.4712
0.04	3.5061	3.4868	3.4787	3.4719	3.4665
0.05	3.5182	3.4901	3.4796	3.4682	3.4605
0.06	3.535	3.4931	3.4782	3.4672	3.4531
0.065	3.6821	3.4935	3.4754	3.4618	3.4406
0.07	3.8744	3.4961	3.4751	3.4596	3.4363
0.075	4.0525	3.4994	3.4751	3.4574	3.4346
0.08	4.2369	3.5034	3.4754	3.4552	3.4293
0.09		3.5818	3.4773	3.4503	3.4186
0.1		3.8674	3.4811	3.4468	3.4014
0.11		4.1638	3.632	3.4435	3.3924
0.12			3.8843	3.4431	3.3792
0.125				3.4438	
0.1275				3.4512	
0.13			4.125	3.4928	3.3588
0.14				3.7392	3.3446
0.15				3.9658	3.3371
0.155				4.0808	
0.16					3.3232
0.17					3.3091
0.18					3.2952
0.19					3.2821
0.2					3.3419
0.21					3.4717
0.22					3.5107
0.23					3.5923
0.24					3.6534
0.25					3.7634
0.26					3.9171
0.27					4.046

A graphical representation of the above results is also shown below.

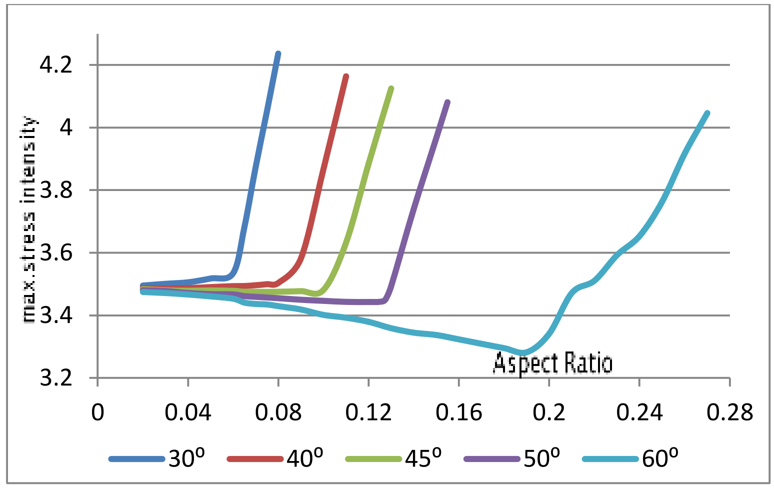

Fig.3 Variation of stress vs. Aspect Ratio for 4 openings provided at 30°, 40°, 45°, 50°, 60°

Variations in this maximum stress intensity due to increase in angle of openings are compared for various aspect ratios for Spherical Dome with 4 openings as shown below.

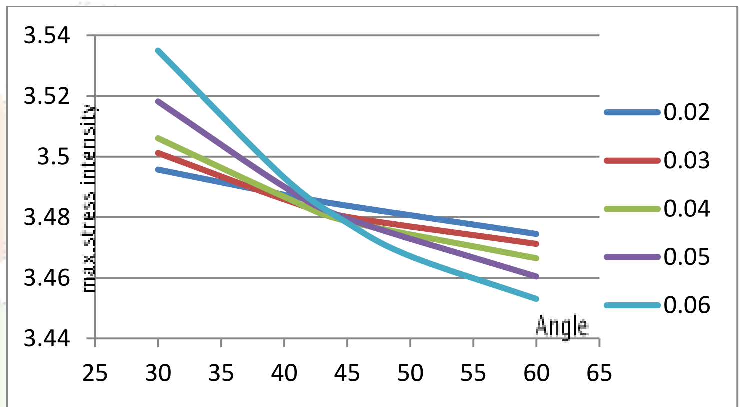

Fig.4 Variation of stress vs. angle w.r.t. horizontal for 4 openings with aspect ratios 0.02, 0.03, 0.04, 0.05, 0.06

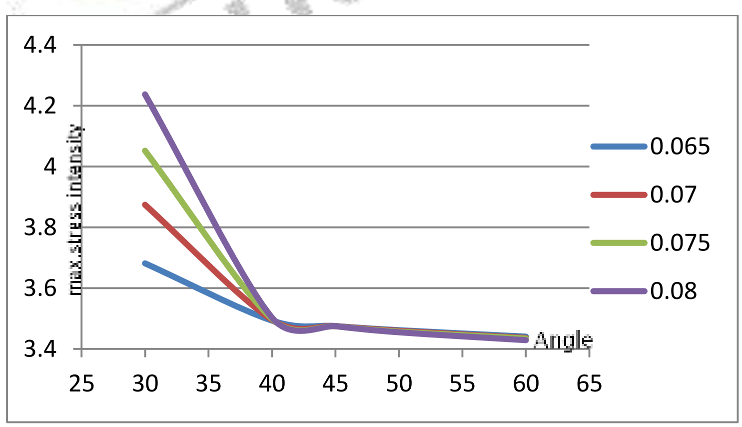

Fig.5 Variation of stress vs. angle w.r.t. horizontal for 4 openings with aspect ratios 0.065, 0.07, 0.075, 0.08

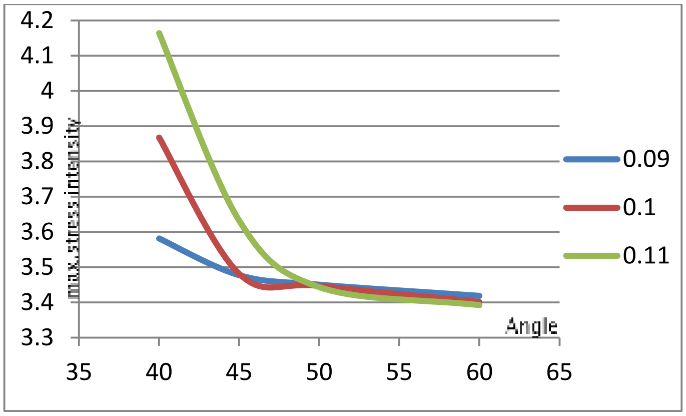

Fig.6 Variation of stress vs. angle w.r.t. horizontal for 4 openings with aspect ratios 0.09, 0.1, 0.11

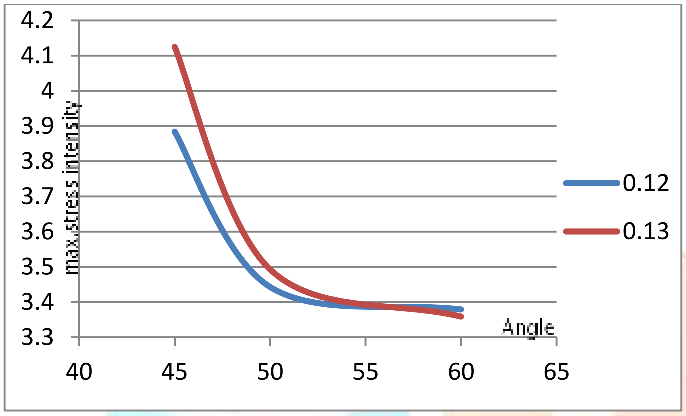

Fig.7 Variation of stress vs. angle w.r.t. horizontal for 4 openings with aspect ratios 0.12, 0.13

Observations are drawn from the above graphs and the following conclusions can be made:

Fig.3 shows that there is a sudden increase in maximum stress intensity beyond a certain aspect ratio which is different for different location of openings. Therefore, this aspect ratio can be considered as the most economical aspect ratio for that particular location of openings.

- The most economical aspect ratio for **4 openings** in a Spherical Dome are:

Table No.2 Most economical Aspect ratio - 4 openings

Angle of opening	Most economical Aspect Ratio
30°	**0.06**
40°	**0.085**
45°	**0.1**
50°	**0.1275**
60°	**0.19**

- A sudden increase in the maximum stress intensity is observed beyond the above mentioned aspect ratios.
- With increase in angle of opening with horizontal, a decrease in the maximum stress intensity was observed for any particular aspect ratio.

Similar results were obtained for Spherical dome with 2 openings and 6 openings which are listed below.

- The most economical aspect ratio for **2 openings** in a Spherical Dome are:

Table No.3 Most economical Aspect ratio - 2 openings

Angle of opening	Most economical Aspect Ratio
30°	**0.06**
40°	**0.09**
45°	**0.105**
50°	**0.13**

- The most economical aspect ratio for **6 openings** in a Spherical Dome are:

Table No.4 Most economical Aspect ratio - 6 openings

Angle of opening	Most economical Aspect Ratio
30°	**0.055**
40°	**0.08**
45°	**0.095**
50°	**0.11**

Based on the above results the following equations have been developed:

For 2openings,

$$\boldsymbol{y = 0.00001x^3 - 0.00115x^2 + 0.0465x - 0.57}$$

For 4 openings,

$$\boldsymbol{y = 4 * 10^{-7}x^3 + 0.00004x^2 - 0.002x + 0.078}$$

For 6 openings,

$$\boldsymbol{y = -1.667 * 10^{-6}x^3 + 2.25 * 10^{-4}x^2 - 0.007083x + 0.11}$$

where, $\boldsymbol{y}$ indicates the most economical aspect ratio for the particular location, and
$\boldsymbol{x}$ indicates the angle at which openings are provided.

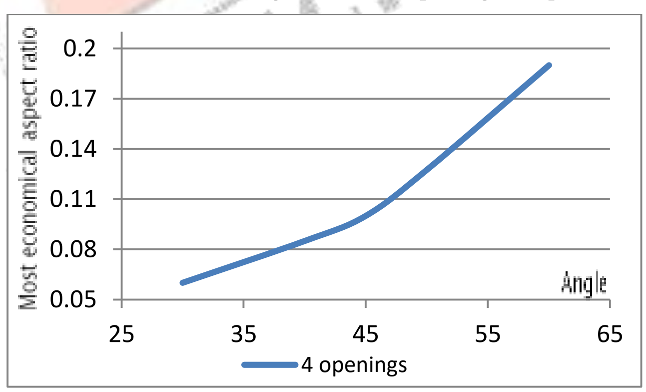

Fig.8 Variation of most economical aspect ratio vs. angle of openings for 4opening

Using the above equations, the most economical aspect ratio can be determined for any location (or angle with horizontal) of openings.

Similarly, equations for optimum location (or angle) of openings have also been developed:

For 2openings,

$$\boldsymbol{x = -47619.05y^3 + 12142.86y^2 - 673.81y + 37}$$

For 4 openings,

$$\boldsymbol{x = 15768y^3 - 7034y^2 + 1184y - 19.18}$$

For 6 openings,

$$x = 30303.03y^3 - 8636.36y^2 + 1146.97y - 12$$

where, x indicates the optimum location (or angle) at which the openings should be provided.
y indicates the aspect ratio of the openings.

Using these equations, the optimum location(or angle) of the openings can be determined for any particular aspect ratio.

STRESS ZONES AND CONTOURS

The maximum stress zones and stress contours for Spherical Dome analyzed in ANSYS are shown in Fig.9 below.

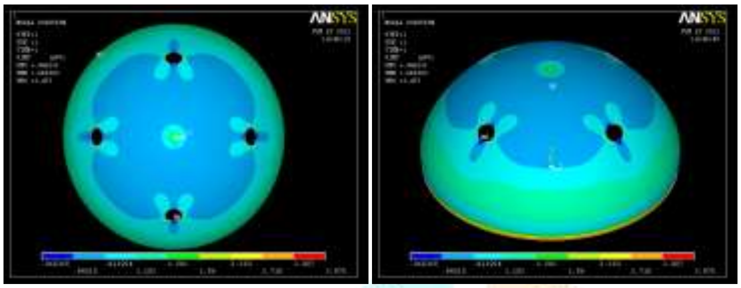

Fig.9 Stress Intensity contours of Spherical Dome with 4 openings@45^0

The increase in maximum stress produced near the openings and at the bottom of the dome due to increase in aspect ratio for Spherical Dome with 4 openings are shown below.
These graphs give a comparison between max. stress at opening and max. stress at bottom of dome.

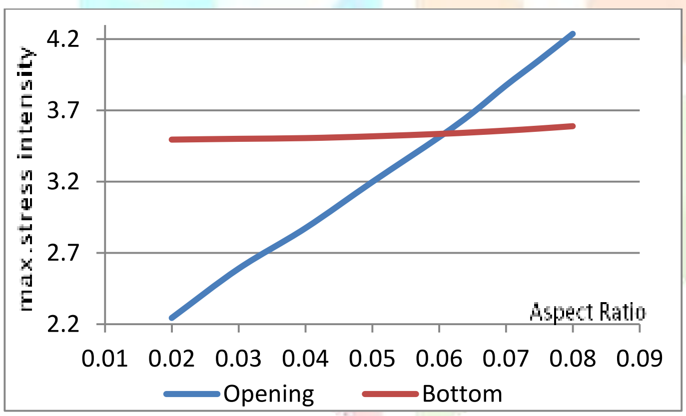

Fig.9 4 openings@30^o

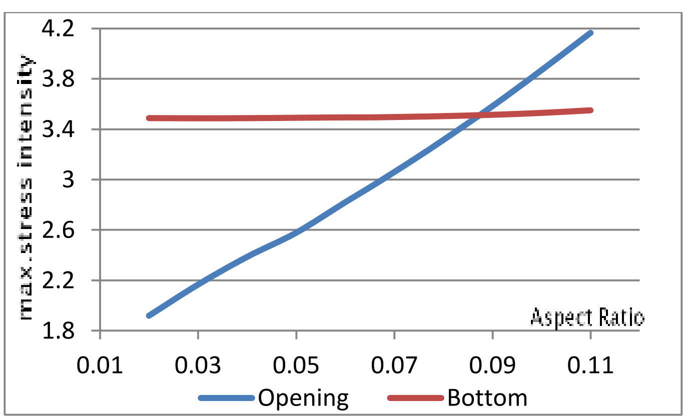

Fig.10 4 openings@40^o

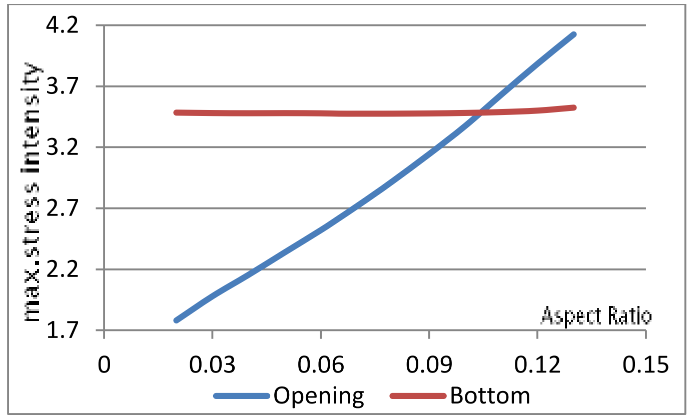

Fig.11 4 openings@45^o

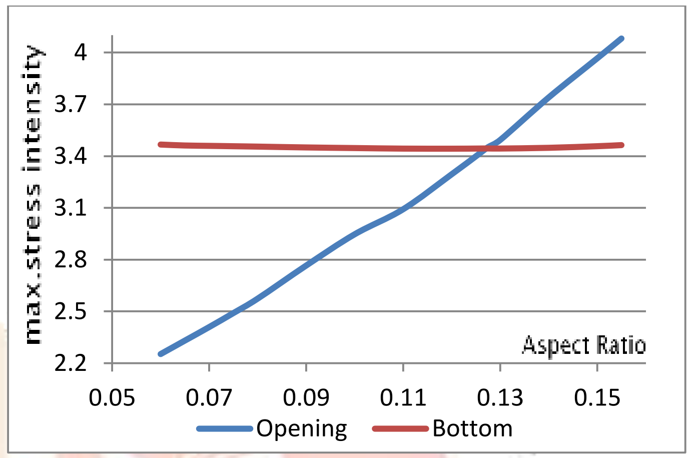

Fig.12 4 openings@50^o

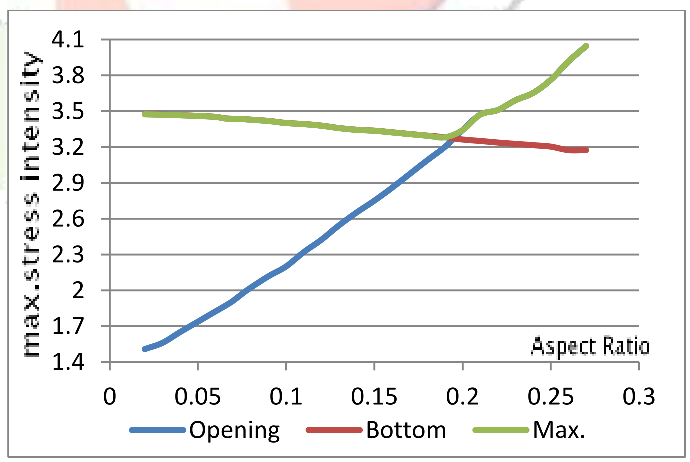

Fig.13 4 openings@60^o

Fig.13 shows that maximum stress produced in the dome coincides with that produced at the bottom of dome before point of intersection and with that produced at the periphery of the opening after point of intersection.

Based on the stress contours obtained in ANSYS 12.1, the following conclusions can be made:

- The maximum stress intensity in the zone around the opening increases linearly with the increase in aspect ratio.
- For aspect ratios less than the most economical aspect ratio, the maximum stress is produced at the bottom of the dome.
- For aspect ratios greater than or equal to the most economical aspect ratio, the maximum stress is produced at the periphery of the opening.

CONCLUSION

Main findings through this project are:

1) Most economical size of openings that can be provided at any particular location (or angle with horizontal) in a Spherical Dome for the different number of openings for which it is analyzed.
2) Optimum location at which the openings should be provided in a Spherical Dome for any particular aspect ratio for the different number of openings for which it is analyzed.
3) Increase in angle of opening w.r.t. horizontal has a significant contribution in reducing the maximum stress intensity produced in the dome.
4) Higher the angle of opening, lesser is the maximum stress intensity in the dome for any particular aspect ratio.
5) For aspect ratios less than the most economical aspect ratio, the stress produced at the bottom of the dome is the governing stress.
6) For aspect ratios greater than or equal to the most economical aspect ratio, the stress produced at the periphery of the opening is the governing stress.
7) Variation in maximum stress intensity due to increase in aspect ratio.
8) Variation in maximum stress intensity due to increase in angle of openings.
9) Percentage increase/decrease in maximum stress intensity of Spherical Dome due to the inclusion of openings as compared to Dome without opening.

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