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ANALYSIS OF STRESSES AROUND ELLIPTICAL CUTOUTS AND INCLUSIONS IN LAMINATED COMPOSITE CYLINDRICAL SHELLS

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ABSTRACT

In thin shell structures, like pressure vessels, high pressure ducts and aircraft fuselages, openings are invariably necessary. Circular openings in structural members are generally preferred in practice due to its simple geometry; but, from a purely structural point of view, there are other configurations which offer certain specific advantage over the circular shape. The most important among these is the elliptical configuration. Elliptic configuration is used for window openings in aircraft fuselages and is recommended for manholes by the ASME Code for Unfired Pressure Vessels and the British Standard Specification (BS 1500) for Fusion Welded Pressure Vessels. Multilayered composite materials are being increasingly used in the construction of such structures. This has created the need of analysis of elliptical cutouts in composite laminated cylindrical shells. Also in certain cases the elliptical opening is closed by elastic inclusions as in case of transparent windows in pressurized cabins like aircraft fuselage and for radiation of heat in environmental chambers.
The present work deals with stress analysis of composite pressure vessel made of Boron/Epoxy, Glass/Epoxy and Graphite/Epoxy with cutouts/inclusions of elliptical shape. Commercially available software ANSYS is used to investigate the behavior of thin walled composite cylindrical shell. Validation is carried out for the cases available in literature. The validated finite element model is then applied to perform stress analysis of composite pressure vessels with elliptical cutouts/inclusion for stacking sequences such as $[0/90_2]_s$, $[0/45/0]_s$, $[0/45/90]_s$ and $[90/45/90]_s$. The numerical results of parametric studies are graphically presented and discussed.

KEYWORDS: Elliptical openings, Composites, Laminates, Pressure vessel, Shell, Stress concentration.

INTRODUCTION

Openings are invariably necessary in laminated composite shell structures, like pressure vessels, aircraft fuselages, high pressure ducts, missile casings, boilers, reactors and deep-diving vehicles. Multilayered composite materials are increasingly used in the construction of shell type structures for various industrial and aerospace applications, owing to its high strength, stiffness as well as tailoring capabilities. This has created the need for analysis of laminated composite cylindrical shells with elliptical cutouts. Also in certain cases the elliptical opening is closed by elastic inclusions as in case of transparent windows in pressurized cabins like aircraft fuselage and for radiation of heat in environmental chambers. Thus, there is a need to carry out analysis for predicting stress concentration due to various types of openings/inclusion in laminated composite shell and design suitable reinforcements that keeps the stresses in the desired levels.

LITERATURE REVIEW

Using Analytical method, several researchers have carried out, analysis of cylindrical shell with cutouts in isotropic domain [1-5] and in composite domain [6-8]. Finite Element method has emerged as a powerful tool owing to its inherit capabilities in solving such complex problems. Some of the important works are Srinath H.R et al. [9], Lakshminarayana H.V. et al. [10], and Vijay Kumar R. et al. [11, 12].

Lakshminarayana H.V. et al. [10], have formulated the stiffness matrix for a high precision triangular laminated anisotropic cylindrical shell finite element and coded into a composite structural analysis program. The versatility of the element's formulation enables its use in the analysis of multilayered composite plate and cylindrical shell type structures taking into account actual lamination parameters. Vijay Kumar R et al. [11, 12], have presented an improved finite element model for the analysis of composite shells having cylindrical shape with cutouts/ inclusions. Analysis is carried out for axial tension and internal pressure loading in composite pressure vessel with stacking sequence $[0/90_2]_s$ and with three different material system. The present work is an extension of this work using commercially available software ANSYS.

The Finite Element Method (FEM) is a technique that is currently used to solve engineering problems in a variety of fields such as solid mechanics, fluid mechanics and heat transfer. The acceptance and growth of FEM has occurred almost concurrently with advancements in computer technology and processing power in the recent decades, which has enabled the solutions to increasingly complex problems to be analyzed and solved within a reasonable timeframe. However, FEM was first developed as a tool for evaluating linear elastic solids, which is the type of the problem being discussed in this paper. Therefore, the following subsections will provide an explanation of FEM as it pertains to this fundamental application.

The literature has indicated a growing interest in the field of stress concentration analysis in the pressure vessels. Pressure vessels find wide applications in thermal and nuclear power plants, process and chemical industries, in space, ocean depths and fluid supply systems in industries. The main objective of this study is to design and analyze the features of pressure vessels. Various parameters of Solid Pressure Vessel are designed and checked according to the principles specified in American Society of Mechanical Engineers (A.S.M.E) Sec VIII Division 1. The stresses developed in Solid wall pressure vessel and Head of pressure vessel is analyzed by using ANSYS, a versatile Finite Element Package. The theoretical values and ANSYS values are compared for both solid wall and Head of pressure vessels.

In general, pressure vessels designed in accordance with the ASME Code, Section VIII, Division 1, are designed by rules and do not require a detailed evaluation of all stresses. It is recognized that high localized and secondary bending stresses may exist but are allowed for by use of a higher safety factor and design rules for details. It is required, however, that all loadings (the forces applied to a vessel or its structural attachments) must be considered.

METHODOLOGY

The basic dimensions used to predict the behavior of cylindrical pressure vessel is given in Table 1.

Table 1. Input data to predict the response of the cylindrical shell with cutout/Inclusion under internal pressure

Geometric Parameters		Loading
R (Radius of the shell)	= 100mm	p = 1Mpa
t (Thickness of the shell)	= 1mm	
L (Half length of the shell)	= 100mm	
β (curvature parameter)	= 2.0	
k (axis ratio)	= 0.5	

$$\beta^2 = a^2/8Rt[12(1-\nu^2)]^{1/2} \quad (1)$$

$$k = b/a \quad (2)$$

b (minor axis of the elliptical cutout) = 15.57mm

a (major axis of the elliptical cutout) = 31.14mm

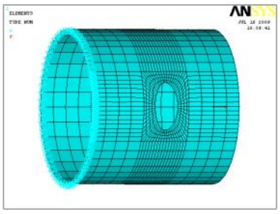
Table 2. gives the material properties of composites used and for inclusion part;

E_c = 28670 MPa and ν_c = 0.36.

Table 2. The material properties of Composite cylindrical shell [11,12]

Property	Units	Material Properties		
		Boron/Epoxy	Glass/Epoxy	Graphite/Epoxy
E_1	GPa	204	38.6	181
E_2	GPa	18.5	8.27	10.3
G_{12}	GPa	5.59	4.14	7.17
ν_{12}	-	0.23	0.26	0.28
X_t	MPa	1260	1062	1500
X_c	MPa	2500	610	1500
Y_t	MPa	610	31	40
Y_c	MPa	202	118	246
S	MPa	67	72	68

FE Model under specified boundary conditions for the analysis of composite pressure vessel is presented to predict the stress distribution around an elliptical cutout.
During the analysis, an axial force is applied to simulate the closed-end effect at one end and degree of freedom at space is constrained at other end. The hole has been considered to have a suitable closure to transmit the pressure at the cutout.



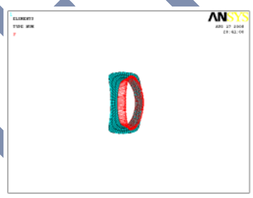


Fig. 1 Typical Finite Element Model with Transverse Elliptical cutout

RESULTS AND DISCUSSIONS

4.1 Target Solution

Previous attempt on the elliptical hole problem in the pressurized cylindrical pressure vessel was made by Ref. [4,11], with an assumption that the shear force is uniform along the hole boundary. An attempt on the elliptical hole with Low Modulus Inclusion problem in the pressurized cylindrical pressure vessel was made by Ref.[11,12]. Fig. 2 is the plot of normalized tangential stress along the hole boundary at top and bottom surface as obtained and compared with available literature [4,11]. The problem of cylindrical shell with elastic Inclusion for pressure loading case, the cutout has considered to have a suitable closure to transmit the pressure load over the area of the cutout to the edge of the opening in the shell. Fig. 3.The results compare well with available solution and thus the meshed Finite Element model is found to be satisfactory for further analysis.

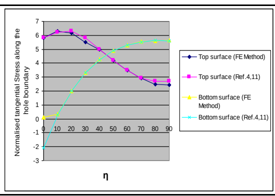


Fig. 2 with elliptical cutout

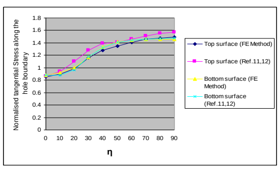


Fig. 3 with edge bonded elastic cover

Plot of normalized stress along hole boundary in isotropic pressure vessel, comparison with target solution

4.2 Composite (Boron epoxy) cylindrical shell with a transverse elliptical cutout under internal pressure

For a cross-ply laminated composite shell with elliptical cutout under internal pressure, the effect of material orthotropy was studied in the lamina coordinate system at top, middle and bottom of each lamina on the membrane and stresses at the critical location along the whole boundary.

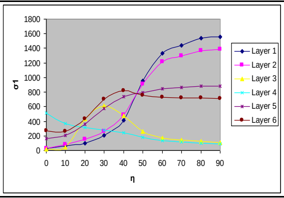


Fig.4 Variation of stress σ_1 (MPa)

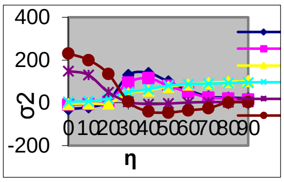


Fig.5 Variation of stress σ_2 (MPa)

Boron/Epoxy laminated composite shell $[90_2/0]_s$ with cutout along the bottom surface of each layer

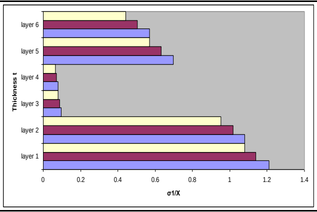


Fig.6 at $\eta = 90^o$

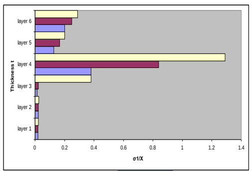


Fig.7 at $\eta = 0^o$

Stress distribution across the thickness of composite shell

Results from the finite elements analysis of composite Pressure Vessel with cutout are presented. Results show the influence of shear force for the stated loading condition on shell. The observed critical locations are at $\eta=0^0$ and 90^0 i.e. at the end of major axis and minor axis of the cutout respectively. The stress σ_1 occurs along the fiber direction of each individual layer in lamina coordinate system. Typical FEM results in Fig. 6 - 7 illustrate the effect of material orthotropy on distribution of stresses σ_1 across the thickness at the critical locations. The stresses σ_1 are normalized with respect to strength values. It was observed that the stress levels changes as the surfaces of the respective layer are approached. In general, it can be observed that gradual change in stresses occur within each layer across its surfaces. For a laminated shell with cutout the stress σ_1 decreases from top surface to bottom surface in each top and bottom layers (90^o fiber direction layers) at $\eta=90^0$ and, while it increases at the middle layers (0^0 fiber direction layers). The maximum value of σ_1 occurs on the bottom surface of layer 1. The stress σ_1 is almost negligible on top and bottom layers at $\eta=0^o$ and it decreases from top surface to the bottom surface in middle layers.

4.3 Composite (Boron epoxy) cylindrical shell with edge bonded elastic cover under internal pressure

For a cross-ply laminated composite shell the effect of material orthotropy on σ_1 and σ_2 stress distribution in a laminated composite shell with edge-bonded cover at different layers is shown in Fig. 8-9. For a cross-ply laminated composite shell with $[90_2/0]_s$ lay-up the effect of material orthotropy was studied in the lamina coordinate system at top, middle and bottom of each lamina on the membrane and stresses at the critical locations along the hole boundary. Typical FEM results are shown in Fig. 10 – 11 for laminated shell with edge bonded cover, which gives the stress distribution across the thickness at critical locations. Predicted ply-by-ply stresses at these locations are at $\eta=0^0$ and 90^0 i.e. at the end of major axis of the cutout. From these results it was observed that the stress decreases from top surface to the bottom surface in layer 6 and layer 5 while it increases in layer 4 and 3. The stress decreases from top surface to the bottom surface in layer 2 and 1.

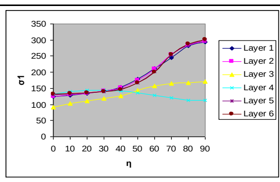


Fig. 8 Variation of σ_1 stress (MPa)

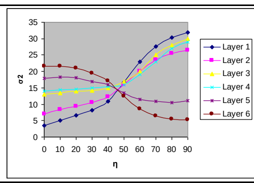


Fig. 9 Variation of σ_2 stress (MPa)

laminated Boron/Epoxy composite shell $[90_2/0]_s$ with inclusion along the bottom surface of each layer

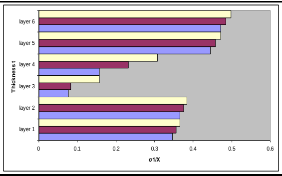


Fig.10 at η = 90°

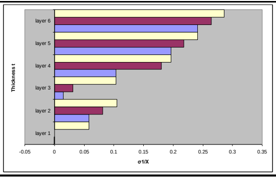


Fig.11 at η = 0°

Stress distribution across the thickness of composite shell

Table 4 Comparison of Max. Induced Stress in bottom surface of Boron epoxy composite laminate with elastic inclusion of various layers with different stacking sequence.

Layer No.	Maximum Induced Stress in MPa.							
	$[90_2/0]_s$		$[0/45/0]_s$		$[0/45/90]_s$		$[90/45/90]_s$	
	With Cutout	With Inclusion	With Cutout	With Inclusion	With Cutout	With Inclusion	With Cutout	With Inclusion
1	1559	293	1571	317	1567	303	1580	313
2	1388	295	1386	303	1391	299.5	1405	309
3	712	217	737	283	718	288	713	221
4	1778	143	1922	214	1799	271	1791	190
5	882	300	878	288	884	296	889	303
6	912	302	928	284	919	297	920	303

It is observed that the stress pattern is almost same for all the stacking sequence. The maximum stress is induced in the layer 1 for all the stacking sequence and minimum stress is seen in the stacking sequence $[90_2/0]_s$.
For Glass epoxy composite laminate with cutout/inclusion The maximum stress is induced in the layer 1 for all the stacking sequence and minimum stress is seen in the stacking sequence $[90_2/0]_s$.
For Graphite epoxy composite laminate The maximum stress is induced in the layer 1 for all the stacking sequence and minimum stress is seen in the stacking sequence $[90_2/0]_s$.

CONCLUSION

The discontinuities can cause abrupt change in cross sections of shells to lead large stress concentrations and analysis of these stress fields need complex design to reduce the stress concentrations. ANSYS commercial software is used to investigate the behavior of thin walled circular cylindrical shells made of laminated composite materials with an elliptical cutout and inclusion. The results show the influence of uniform shear stress along hole boundary is predominant and stress level vary as the fiber direction changes. The results show that in the case pressurized laminated composite shell, the influence of uniform shear stress along the hole boundary is very predominant. The stress level varies as the fiber direction changes in the respective layers which may cause failure of the fibers in the respective lamina as the stress exceeds the strength of the fiber. The results for different stacking sequences are observed and the stacking sequence $[90_2/0]_s$ is found to be optimum for cases of cutouts/inclusion. Pressurized shell with cutout and inclusion under pressure load mechanism predict significantly different stress fields.

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