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Finite element analysis of burst pressure of composite storage vessels

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ABSTRACT: *An Axis-symmetric finite element model of glass fiber reinforced polymer (GFRP) pressure vessel is established by ANSYS finite element software. A parametric finite element model of Glass fiber/epoxy composites is proposed to predict the damage evaluation and failure strength of composite hydrogen storage vessels. The maximum stress, Hoff-man, Tsai-Hill, Tsai-Wu failure criteria are used to determine the failure properties of composite vessels. A solution algorithm is proposed to investigate the progressive damage and failure properties of composite structures with increasing internal pressure.*

Keywords: *Finite Element; GFRP Pressure Vessel*

I. INTRODUCTION

Pressure vessels have been manufactured by filament winding for a long time. Although they appear to be simple structures, pressure vessels are among the most difficult to design. Filament-wound composite pressure vessels have found widespread use not only for military use but also for civilian application. The study was mainly focused for commercial application of pressure vessel that should be designed for minimum mass of the composite structures and the winding consist of unidirectional. The shape factor was used to optimize the structure with minimized mass [1].The degradation model used for analysis is sensitive to the mesh and the load step size. Computational efficiency (CPU time) of the finite-element model is very important in the degradation study, and accordingly, equilibrium is not re-established in the nonlinear solution procedure implemented in ANSYS (single-frame restart analysis). This is offset using a small load step size for the degradation studies of the pressure vessel [2]. "Unit load method" covers many of the weaknesses of traditional methods and carries out more detailed design using many factors that composite materials provide for designer. By increasing the vessel pressure acceptable and appropriate behavior is observed in strain-pressure curves [3]. A procedure combining particle swarm optimization (PSO) and finite element analysis (FEA) has been proposed. Numerical examples for the reliability design optimization (RDO) of a laminate and a composite cylindrical shell are worked out to demonstrate the effectiveness of the method. The advantages and necessity of RDO over the conventional equistrength design are addressed [4].These criteria can predict matrix and fiber failure accurately, without the curve-fitting parameters. For matrix failure under transverse compression, the angle of the fracture plane is solved by maximizing the Mohr-Coulomb effective stresses. A criterion for fiber kinking is obtained by calculating the fiber misalignment under load and applying the matrix failure criterion in the coordinate frame of the misalignment. Fracture mechanics models of matrix cracks are used to develop a criterion for matrix failure in tension and to calculate the associated in-situ strengths. [5].Possible winding patterns considering the windability and the slippage between fiber and mandrel surface were calculated using the semi-geodesic path algorithm. On the basis of the semi-geodesic path algorithm and the verified finite element analysis method, an optimal design algorithm for filament wound structures was suggested using the genetic algorithm [6].The relative dimensions of different sections of the vessel are designed according to the corresponding space and weight requirements and the pressure levels that the vessel is expected to withstand. Along with thickness and length dimensions, the shape of the end caps also plays a vital role in the design. This is due to the fact that the dome regions undergo the highest stress levels and are the most critical locations from the viewpoint of structure failure [7].Study deals with the influences of winding angle on filament-wound composite pressure vessel. An elastic solution procedure based on the Lekhnitskii's theory was developed in order to predict the first-ply failure of the pressure vessels [8].Optimize the design of the composite laminate vessel for minimizing the stress concentration. The optimum design of this study uses the finite element method combined with the simplified conjugated gradient method (SCGM) to find the minimization of Von Mises stress of the vessel. The winding angle and the thickness of composite layer are proposed as the optimal design variables. Through this optimization, the best combination of the thickness and the winding angle of composite layer can be obtained to reach the minimum stress concentration.[9].To analyze the stress and deformation of different angle ply pipes for the of multi layered filament wound composite pipes under internal pressure load are investigated [10].

II. FINITE ELEMENT MODEL OF THE VESSEL

1. The GFRP Pressure Vessel

The multilayered pressure vessel is orthotropic in nature and cylindrical in shape. It consists of glass fibers as the reinforcement material into a polymeric epoxy matrix. Because of the orthotropic nature of the composite materials, the finite element modeling of the pressure vessel requires the determination of nine different properties. The material properties of fiber reinforced composite depends upon the properties of both the matrix and the fibers. The angle of orientation of the fibers in the composite also plays a very important role determination of the properties and the behavior of the composite, since the fibers have superior mechanical properties along its length.

2. Element type

It is very necessary to select the appropriate element type for the accurate finite element analysis of the composite pressure vessel. The finite element software, ANSYS 15 provides the solid element types to model layered composite materials. A solid element 186 can be utilized to model layered composites layered structures and up to 84 uniform thickness layers can be modeled by this element. This model consists of 3342 nodes, 3323elements

3. Layered configuration

The composite layup is $[90_2/0_2/45/-45]_s$. Each layer is 0.1524 mm thick. The sub laminate has 12 layers and the sub-laminate is layered 7 times. The engine casing is 12.804 mm thick made up of a total of 84 layers. The 0 degree orientation is in-line with the casing axis but following the contour of the shell from top to bottom and the 90 degree orientation is in the hoop direction. This layup will give strength in the hoop direction for the pressure loading with the 90 degree fibers. The 0 and 45 degree fibers give the laminate strength for bending in the curved geometry at the top and bottom of the pressure vessels.

Table 1
Material properties of E-glass/LY556

Properties of E-glass/LY556	Values
Volume fraction (V_f)	60%
E_1	53.3GPa
E_2	17.7GPa
υ_{12}	0.278
υ_{23}	0.4
G_{12}	5.83GPa
Tensile strength (X_t)	1140Mpa
Transverse Tensile strength (Y_t)	35MPa
Compressive strength (X_c)	570MPa
Transverse Compressive strength (Y_c)	113Mpa
Shear Strength (S)	72Mpa

III. FAILURE THEORES

Failure analysis is a tool for predicting the strength of a laminated composite. Failure criteria are categorized into two: independent and interactive criteria. Failure theories are based on stresses in a material axes or local axes because a lamina is orthotropic. Failure theories are not based on principal normal stresses and maximum shear stresses. Failure theories are based on first finding the stresses in the local axes and using five strength parameters of a unidirectional lamina to find whether a lamina has failed.

An independent criterion, such as maximum stress or maximum strain is simple to apply and more significantly but it neglects the effect of stress interactions.

An interactive criterion, such as Tsai-Wu, Tsai-Hill, and Hoffman includes stress interaction in the failure mechanism and predicts first ply but it requires some efforts to determine parameter.

1.Maximum stress criterion:

When yielding occurs in any material, the maximum shear stress at the point of failure equals or exceeds the maximum shear stress when yielding occurs in the tension test specimen. From analysis of plane stress situation the maximum shear stress in plane stress is also given in terms of plane stress elements. Failure types are dependent on loading stacking sequence and specimen geometry.

$$\tau_{\max} = \pm\sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}} \qquad (1)$$

Maximum stress criterion is no interaction between the modes of failure, i.e., the critical stress for one mode is unaffected by the stresses tending to cause the other modes. Failure then occurs when one of these critical values σ1u , σ2u and τ12u is reached. These values refer to the laminar principle axes and can be resolved from the applied stress system by using the equation.

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix} = [T]\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix}$$

where
$$[T] = \begin{bmatrix}\cos^2\theta & \sin^2\theta & 2\cos\theta\sin\theta\\ \sin^2\theta & \cos^2\theta & -2\cos\theta\sin\theta\\ -\cos\theta\sin\theta & \cos\theta\sin\theta & \cos^2\theta-\sin^2\theta\end{bmatrix} \qquad (2)$$

2. Hoffman failure criterion:

The Hoffman criterion is a modification of the criterion proposed by Hill through inclusion of terms that are linear in the stress. In this way the restriction of the Hill criterion, i.e.no difference between tensile and compressive yield strength can be described is avoided. Hoffman originally formulated his failure criterion by the quadratic function.

The expanded form is given by

F11σ12+F22σ22+F66σ62, +F1 σ1+F2 σ2+2F12 σ1σ2≥1 (3)

The strength parameter F11, F22, F66, F1, F2,and F12 are given by XtXc

F11=1/XtXc F22=1/YtYc F66=1/S2 F1=1/ Xt - 1/Xc F2=1/ Yt - 1/Yc F12= - (F11+F22)/2

3. Tsai-Hill failure theory:

Tsai-Hill failure theory is based on the distortion energy failure theory of von-Mises distortional energy yield criterion for isotropic materials as applied to anisotropic materials. Failure in a material takes places only when the distortion energy is greater than the failure distortion energy of the material. Compressive strength is not used in the Tsai-Hill failure theory.

The expanded form is given by

F11σ12+F22σ22+F66σ62+2F12 σ1σ2≥1 (4)

The strength parameter F11, F22, F66, andF12are given by

F11=1/X2 F22=1/Y2 F22=1/S2 F12= -1(F11+F22)/2

4. Tsai-Wu failure theory:

Tsai-Wu failure theory based on total strain energy failure theory. Tsai-Wu applied the failure theory to a lamina in a plane stress condition. It is more general than Tsai-Hill failure theory because it distinguishes between the compressive and tensile strengths of a lamina.

The expanded form is given by

F11σ12+F22σ22+F66σ62, +F1 σ1+F2 σ2+F12 σ1σ2≥1 (5)

The strength parameter F11, F22, F66, F1, F2, and F12 are given by

F11=1/XtXc F22=1/YtYc F66=1/S2 F1=1/ Xt - 1/Xc F2=1/ Yt - 1/Yc F12= -1√ (F11F22)/2

Where σ1 and σ2 are the on-axis stresses in the longitudinal and transverse directions and σ6 is the on-axis in-plane shear stress. Xt and Xc are the longitudinal tensile and compressive strengths respectively.Yt and Yc are those for the transverse direction. S is the in-plane shear stress.

In the present study the GFRP composite pressure vessel is analyzed. The pressure vessel is analyzed for maximum stress for [902/02/45/-45]s stacking sequence. Fig 3, 4 and 5 give the stress distribution for GFRP pressure vessel. The pressure vessel is subjected to high internal pressure values and the burst pressure of the pressure vessel is predicted by incrementally increasing the values of internal pressure from working pressure of 30 MPa. At each increment in the value of internal pressure, the maximum stress is calculated and compared with the ultimate stress for the pressure vessel by the following relation.

$\sigma max \leq \sigma u$

Where σmax and σu are the maximum stress and ultimate stress for the pressure vessel.

Table 2

Failure criteria	Value (MPa)
Maximum Stress	35
Hoff man	36.99
Tsai Hill	35.71
Tsai Wu	38

IV. RESULT AND DISCUSSIONS

As shown in Figure 3 , the stress of the first GFRP ply is 647.24Mpa, which is less than 1140 MPa. The burst pressure is predicted further. As shown in Figure 4 and 5 , as the inner pressure increases up to 35MPa,the maximum tensile stress of the first GFRP ply reaches 1140 MPa. The results show that the vessel will be destroyed in this case, so the pressure 35MPa is regarded as the burst pressure.

V. CONCLUSION

In this study, the finite element model of a GFRP pressure vessel using axis symmetric finite element software ANSYSI5. All components of the GFRP layer are meshed using linear layered solid elements, respectively. The study presents a method to analyze such vessel subjected to internal pressure loading. Based on the maximum stress criteria, burst pressure of the vessel is predicted.

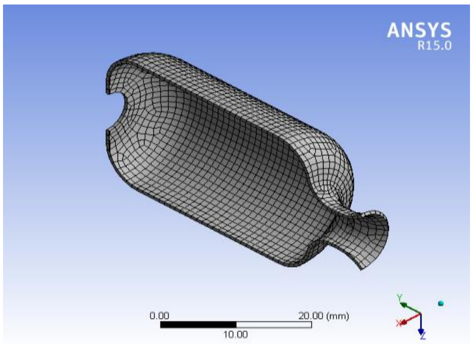

Fig 1: Finite element modeling of GFRP pressure vessel

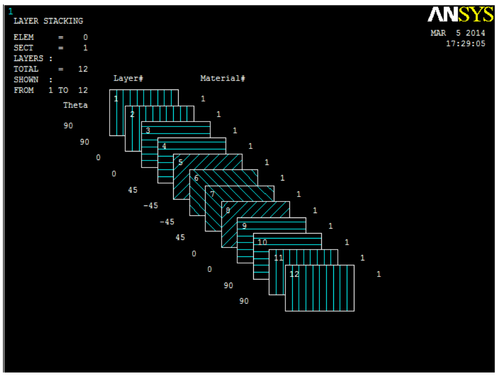

Fig 2: Symmetrical stacking sequence for $[90_2/0_2/45/-45]_s$.

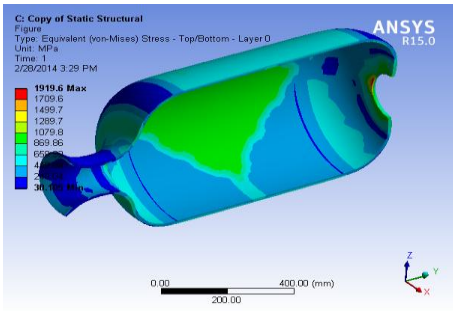

Fig 3: Equivalent Stress distribution for GFRP pressure vessel

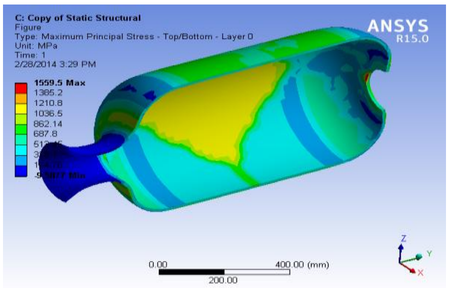

Fig 4: Maximum principal Stress distribution for GFRP pressure vessel

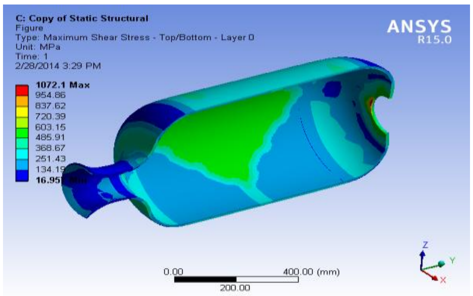

Fig5: Maximum shear Stress distribution for GFRP pressure vessel

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