Design and Burst Pressures Analysis of CFRP Composite Pressure Vessel for Various Fiber Orientations Angles

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Abstract - The composite pressure vessels are used in various applications such as automobile, aeronautics and chemical engineering. Besides these, they have become very popular in oil and gas transport industries. These pressure vessels are experience very high internal pressures during their operation. The present paper demonstrates a study on cylindrical section of carbon fiber reinforced polymer (CFRP) composite pressure vessel having four layers. The pressure vessel is designed and modeled using the finite element software ANSYS 11. The step by step procedure for the finite element modeling of multilayered composite pressure vessels has been discussed in the paper. The modeling is performed for both hoop and helical windings of the fibers in pressure vessel. For helical windings the layers were oriented symmetrically for [+25°/-25°], [+35°/-35°], [+45°/-45°], [+55°/-55°], [+65°/-65°], and [+75°/-75°] orientations. The burst pressure for each of the fiber orientations is predicted based on the Tsai-Wu failure criteria.

Keywords – Burst Pressure, Composite Pressure Vessel, Tsai – Wu failure Criteria.

I. INTRODUCTION

The carbon fibers/epoxy pressure vessels are used in various applications these days such as, aerospace, automobiles, aeronautics, chemical engineering industries etc [1]. Besides these, the CFRP pressure vessels have suddenly become an attraction for the piping and sewage as well as oil and gas transport industries. These pressure vessels have a special characteristics of lightweight and high strength because of which the demands for these pressure vessels are increasing drastically in applications where, the weight is a very important concern. These pressure vessels provide an excellent compromise between high mechanical properties and low weight [2]. In most of the applications, these resin matrix composite pressure vessels are subjected to very high pressures during their service life. Therefore, the burst pressure analysis of these pressure vessels becomes vital for safety purposes. Few researchers have proposed some methods to study, design and analyze the resin matrix composite pressure vessels for stress and deformation under different conditions. For example, R.R. Chang studied the first ply failure strength of composite pressure vessels when the fibers were oriented symmetrically for different number of layers [3]. Levend Parnas et al. predicted the behavior of a rotating fiber reinforced composite vessel [4]. M.A. Wahab et al. analyzed composite pressure vessels of five different polygonal shapes [5]. While, R.M. Guedes evaluated the performance of a glass-fiber reinforced (GFRP) composite cylindrical pipe under transverse loading and large deflections [6]. Also, H. Bakaiyan et al. analyzed multilayered composite pressure vessels under thermo-mechanical loadings. The results were evaluated for various winding angles [7]. Besides these, Frank Ratter et al. performed finite element analysis for the prediction of lateral crushing behavior of segmented composite tubes [8].
The design and analysis of a composite pressure vessel is a very complex process. It requires the involvement of some critical decisive factors to be taken and for the design to be accurate. And the optimum choice of these decisive factors is necessary. This paper presents a study of the static burst pressure analysis of CFRP (carbon fiber reinforced polymer) cylindrical, pressure vessel under internal pressure. The study is performed with the utilization of the finite element software ANSYS 11. The pressure vessel is designed and modeled using this finite element software. This software features all the capabilities that are necessary for modeling a system with characteristics of the given problem.

II. FINITE ELEMENT METHOD

A. The CFRP Pressure Vessel –

This study deals with a resin matrix composite pressure vessel. The multilayered pressure vessel is orthotropic in nature and cylindrical in shape. It consists of carbon fibers as the reinforcement material into a polymeric epoxy matrix. The Figure 1 shows the CFRP cylindrical pressure vessel. 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.

B. Selection of Appropriate 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 11 provides the various shell and solid element types to model layered composite materials. A solid element can be utilized to model thick layered composites but it requires that the mesh divisions in thickness directions must be the same as the number of material layers. This increases the analysis and the calculation time for these elements. While, the shell elements does not require the mesh divisions in thickness direction and the calculation as well as the analysis time for these elements is much lesser than for the solid elements. Because of this property of the shell elements we have selected SHELL 99 as the appropriate element type for the purpose of our study. SHELL 99 is a linear layered structure shell element. Very thin to moderately thick layers can be modeled with this element. It may be used for the purpose of modeling layered structures and up to 250 uniform thickness layers can be modeled by this element. It is a 3D shell element and consists of 8 - nodes, with six degrees of freedom at each node. Among the 8 – nodes, four nodes are the corner nodes and the remaining four are the mid - side nodes. This element allows the user to define elastic properties, layer orientation and density for each layer.

The finite element model of the composite pressure vessel shown in Figure 1. The whole model is established through finite element software ANSYS 11.

Figure 1. Finite Element model of composite pressure vessel.
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C. Defining the Layered Configuration –

The layered configuration is the most important characteristic of a composite material. The layered configurations are determined by specifying individual layer properties and therefore the properties of the composite as a whole depends greatly on its layered configuration. The material properties, the fiber orientation angle, the layer thickness and the number of integration points per layer must be specified for individual the definition of the layered configuration to be complete.

The CFRP layers in the composite pressure vessels are assumed to be orthotropic. Therefore nine material properties are required for the purpose of the analysis. The material properties for CFRP are listed in Table 1.

Table - 1 Material Properties of CFRP [7]

<table>
<thead>
<tr>
<th>Properties of carbon/Epoxy (T300/LY5052)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$</td>
<td>135 GPa</td>
</tr>
<tr>
<td>$E_y = E_z$</td>
<td>8 GPa</td>
</tr>
<tr>
<td>$G_{xy} = G_{xz}$</td>
<td>3.8 GPa</td>
</tr>
<tr>
<td>$G_{yz}$</td>
<td>2.6845 GPa</td>
</tr>
<tr>
<td>$\nu_{xy} = \nu_{xz}$</td>
<td>0.27</td>
</tr>
<tr>
<td>$\nu_{yz}$</td>
<td>0.49</td>
</tr>
</tbody>
</table>

The cylindrical composite pressure vessel is designed for various fiber orientations. The modeling is performed for the CFRP cylindrical pressure vessel for both, the hoop and the helical windings of the carbon fiber. For the hoop windings of the carbon fibers, the fibers are oriented at an angle of 0° with the axis of the cylindrical pressure vessel. For helical windings the fibers are orientated for various fiber orientations such as ± 25°, ± 35°, ± 45°, ± 55°, ± 65° and ± 75°, in symmetrical stacking sequence. The Figure 2 shows the stacking sequence for ± 35° fiber orientation.

![Figure 2. The stacking sequence for ± 35° fiber orientation.](image)

The cylindrical composite pressure vessel is modeled for four uniform thickness layers and the number of integration points are taken as three to define the layered configuration completely.

III. ANALYSIS

The CFRP pressure vessel is analyzed by loading it by high internal pressures. The Tsai-Wu failure criterion is utilized for the purpose of analysis. The analysis is performed for the calculation of burst pressure for the pressure vessel. The burst pressure for the pressure vessel is predicted for various fiber orientation angles (0°, ± 25°, ± 35°, ± 45°, ± 55°, ± 65° and ± 75°). The calculation of the burst pressure for each fiber orientation requires separate model formation. The burst pressures are predicted by incrementally increasing the internal pressure from the working value of 35 MPa to the value of burst pressure step by step. For every increment in the internal pressure it is...
required to compare the value of maximum stress obtained with value of ultimate stress for the pressure vessel by the relation given by the Eq. 1

\[ \sigma_{\text{max}} \leq \sigma_u \]  \hspace{1cm} (1)

Here, \( \sigma_{\text{max}} \) , \( \sigma_u \) are the maximum stress and ultimate stress of the pressure vessel, respectively. The value of ultimate stress for the CFRP pressure vessel is 1210 MPa [9].

The Figure 3, Figure 4 and Figure 5 give the stress distribution for this pressure vessel for hoop, \( \pm 35^\circ \) and \( \pm 45^\circ \) fiber orientation at their burst pressure.

Figure 3. The stress distribution for hoop fiber orientation at its burst pressure.

Figure 4. The stress distribution for \( \pm 35^\circ \) fiber orientation at its burst pressure.
IV. RESULTS AND DISCUSSIONS

After the analysis for the burst pressure for various fiber orientation angles, the maximum burst pressure for the cylindrical composite pressure vessel is found to be maximum for ±45° fiber orientation angle. The Figure 6 shows the graph between the burst pressure and the different fiber orientations.

The graph gives an increasing slope from hoop to ±45° and the slope decreases from ±45° to ±75° fiber orientations. It can be further predicted that the pressure vessel can sustain the maximum internal pressure of 207 MPa when the fibers are orientated at ±45° in symmetrical stacking sequence, which is regarded as its burst pressure at ±45° fiber orientation. The Figure 4 shows the stress distribution in the composite pressure vessel at ±45° fiber orientation angle when the pressure vessel is subjected to its burst pressure of 207 MPa. It can be seen from the figure that, the maximum stress obtained is 1217 MPa which is more than 1210 MPa.

V. CONCLUSION

In this study, the finite element model of CFRP, cylindrical composite pressure vessel is established using finite element software ANSYS 11. The models obtained for various fiber orientations are meshed using a linear layered structure shell element, SHELL 99. The study discusses a step by step method for the analysis of cylindrical composite pressure vessel which is subjected to high internal pressure loading. The burst pressures for various fiber orientations are predicted using the Tsai-Wu failure criteria. The ±45° fiber orientation angle is obtained as the optimum fiber orientation angle for the composite pressure vessel subjected to high internal pressure loading. It can be concluded from the study that the capacity of the CFRP pressure vessel to bear high internal pressure is greatest among the various fiber orientations angles under study.
REFERENCES


