DESIGN OF COMPOSITE GAS BOTTLE WITH ELASTOMERIC LAYER

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ABSTRACT

Composites prove to be the best candidate in the fabrication of aerospace structural components, due to its high strength and specific stiffness. They are used to achieve higher payload capabilities in launch vehicle applications. Composite overwrapped gas bottles are commonly used in launch vehicles for storing high pressure gases. These gas bottles consist of a metallic liner overwrapped with a high strength fiber which offer weight savings when compared with a fully metallic option. But debond is a common problem occurring to composite overwrapped gas bottles, which often results in its failure. The current research focuses on understanding and minimising debonding in composites. Nonlinear static analysis of composite overwrapped gas bottle is carried out. The condition of partial debond is modelled and the stress and strain distribution in the component materials are studied. Also, a condition of full debond between liner and overwrap is analysed. The resultant stress and strain of each case are compared. As a solution to the debond occurring in composite overwrapped gas bottles, an elastomeric layer is proposed to be introduced between the metal liner and the fiber jacket. The analysis shows that the introduction of an additional hyperelastic layer between the liner and the composite overwrap results in a reduction of strain along the meridional direction in composite layer. The strain isolation effect imparted by the hyperelastic layer reduces the chances of debond occurring at the interface between liner and composite. By suitably designing the thickness and choosing a hyperelastic layer with optimal material properties, the strain in composite layer can be further reduced, thus achieving sufficient margin with respect to the bond strength at the interface.

Keywords: Debond, Hyperelastic Material, Nonlinearity, Strain Isolation Effect.
1. INTRODUCTION

Gas bottles are commonly used in launch vehicles, satellites and missiles for storing high-pressure gases (like gaseous helium) for propellant pressurisation and control system energisation. The structural integrity of these gas bottles is of prime importance as they play a critical role in the success of a mission. Therefore, the prevention of gas bottle failure to enhance safety and reliability has received considerable attention. Major characteristics for aerospace structural components include high strength and lightweight properties, coupled with their compatibility with fluid environment for structural stability in order to improve the performance of aerospace flight vehicles and maximize the on-flight carrying load. Apart from the usage of high specific strength materials like titanium alloys, further weight reduction is achieved by the use of composite materials. This leads to use of thin metallic liner thereby decreasing the weight of the gas bottle. Composites prove to be the best candidate in the fabrication of aerospace structural components, due to its high strength and specific stiffness. They are used to achieve higher payload capabilities and for storing high pressure gases in launch vehicle applications. But debond is a common problem occurring to composite overwrapped gas bottles, which often results in its failure. V. Ramachandra et al. 1 reported about the development of Ti-6Al-4V gas bottle for satellite applications. Titanium alloy gas bottles were imported since then in India. George Thomas et al. 2 reported about the development of titanium alloy high pressure gas bottles through plate forming route for PSLV second stage and its qualification. They suggested the plate forming route over the conventional closed-die forging. A finite element modelling of the filament winding process was developed by Liyang Zhao et al. 3 Abhay K. Jha et al. 4 conducted a failure analysis of a gas bottle with Ti–6Al–4V liner, fabricated by electron beam welding of two forged and machined hemispheres and wound with Kevlar fiber around it, which failed prematurely during the pressure testing. The primary goal of this project is to study the debond observed commonly in filament wound pressure vessels. To prevent the debonding it is proposed to provide an elastomeric layer between composite overwrap and the metal liner.

2. NONLINEAR STATIC ANALYSIS OF COMPOSITE OVERWRAPPED GAS BOTTLE

The material properties used are shown in TABLE 1 and TABLE 2 respectively.

| Table 1: Mechanical properties of Ti-6Al-4V (metal liner) |
| E | 110107.907MPa |
| ν | 0.31 |
| σ | 740MPa |

| Table 2: Mechanical properties of Kevlar/epoxy (composite overwrap) |
| E₁ | 134780 MPa |
| E₂ | 9250 MPa |
| E₃ | 9250 MPa |
| G₁ | 4800 MPa |
| G₂ | 4800 MPa |
| G₃ | 4800 MPa |
| ν₁ | 0.286 |
| ν₂ | 0.286 |
| ν₃ | 0.286 |
ABAQUS 6.10 FEM packages are used to predict the mechanical behaviour of the gas bottle. The composite gas bottle is modelled as 3D deformable shell. It is fully modelled using the symmetry and to reduce the volume of computations, only 1/8th of the vessel is modelled. The structure is idealized using S4R and is shown in Fig. 1. Typical ply slack plot of composite layup is shown in Fig. 2.

![Figure 1: FE model of composite gas bottle in shell model](image1)

![Figure 2: A typical ply slack plot of composite gas bottle](image2)

2.1 Results for Analysis of Composite Overwrapped Gas Bottle in Shell Model

The results obtained from the analysis is shown in Fig. 3 to Fig. 6.

![Figure 3: Meridional stress in liner of composite gas bottle in shell model](image3)

![Figure 4: Meridional strain in liner of composite gas bottle in shell model](image4)

![Figure 5: Meridional stress in fiber jacket of composite gas bottle in shell model](image5)

![Figure 6: Meridional strain in fiber jacket of composite gas bottle in shell model](image6)

2.2 Observations and Inferences from Analysis of Composite Gas Bottle

Even though the liner contribute partially to the internal pressure capability, the main role of the liner is to provide a high level leak proof structure. The composite overwrap mainly meets the structural strength requirements. Here, the liner undergoes stresses beyond its yield point and thereafter operates in an off-set elastic strain range. There is strain incompatibility between metal liner and composite jacket. Thus there occurs a chance of debond. Hence the composite overwrapped gas bottle with partial debond is modelled and analysed.
3. NONLINEAR STATIC ANALYSIS OF COMPOSITE OVERWRAPPED GAS BOTTLE WITH PARTIAL DEBOND

The structure is modelled in such a way that partial debond occur at the location where there is a geometric discontinuity in the liner. Interactions applied in the composite overwrapped gas bottle with partial debond is shown in Fig. 7.

![Figure 7: Interactions applied in the composite overwrapped gas bottle with partial debond](image)

3.1 Results from Analysis with Partial Debond

The results obtained from the analysis are shown in Fig. 8 to Fig. 11.

![Figure 8: Meridional stress in liner of composite gas bottle with partial debond in shell model](image)

![Figure 9: Meridional strain in liner of composite gas bottle with partial debond in shell model](image)

![Figure 10: Meridional stress in shell model in fiber jacket of composite gas bottle with partial debond in shell model](image)

![Figure 11: Meridional strain in liner of composite gas bottle with partial debond in shell model](image)

3.2 Observations and Inferences from Analysis of Composite Gas Bottle with Partial Debond

The liner undergoes stresses beyond its yield point and thereafter operates in an off-set elastic strain range. The results obtained show a stress concentration at the location where the debond starts. Once debond occurs, there is no load transfer between titanium liner and the fiber jacket. The partial
debond condition is not favourable as the root of debond progresses along the meridional direction and gas bottle failure occurs. So composite gas bottle in a full debond condition is analysed.

4. NONLINEAR STATIC ANALYSIS OF COMPOSITE OVERWRAPPED GAS BOTTLE WITH FULL DEBOND

The structure is modelled in such a way that the vessel is having a full debond condition. Inner layer is assigned with the properties of liner and the outer one is given the properties of Kevlar/epoxy. Fig. 12 depicts the interactions applied in the composite overwrapped gas bottle with full debond.

![Figure 12: Interactions applied in the composite overwrapped gas bottle with full debond](image)

4.1 Results from Analysis with Full Debond

The results obtained from the analysis are shown in Fig. 13 to Fig. 16.

![Figure 13: Meridional stress in liner of composite gas bottle with full debond in shell model](image)

![Figure 14: Meridional strain in liner of composite gas bottle with full debond in shell model](image)

![Figure 15: Meridional stress in fiber jacket of composite gas bottle with full debond in shell Model](image)

![Figure 16: Meridional strain in fiber jacket of composite gas bottle with full debond in shell model](image)
4.2 Observations and Inferences from Analysis of Composite Gas Bottle with Full Debond

The liner undergoes stresses beyond its yield point. However the stress is symmetric and uniform in the liner. But full debond condition is purely hypothetical. By taking the advantage of full debond condition, as an extension to it, the gap between the liner and the overwrap is filled by an elastomeric layer. So an analysis is carried out for a composite gas bottle with elastomeric layer.

5. NONLINEAR STATIC ANALYSIS OF COMPOSITE OVERWRAPPED GAS BOTTLE WITH ELASTOMERIC LAYER

In order to capture the through thickness variation of strain, an axisymmetric model of the composite overwrapped gas bottle is modelled and is shown in Fig. 17. Quasi isotropic property of Kevlar/epoxy composite is defined.

5.1 Results for Analysis of Composite Gas Bottle in Axisymmetric Model

The results obtained from the analysis are shown in Fig. 18 and Fig. 19.

5.2 Analysis of Composite Gas Bottle with Elastomeric Layer in Axisymmetric Model

An elastomeric layer is added between the metal liner and composite jacket. The thickness given to hyperelastic layer is 1.25mm. Finite strain element CAX8R, which can account for the geometric nonlinearity is used for meshing. Meshed axisymmetric model with hyperelastic layer is shown in Fig. 19. To correctly evaluate the behaviour of elastomeric layer, computational model, Mooney-Rivlin model is used.
5.3 Results of Analysis of Composite Overwrapped Gas Bottle with Elastomeric Layer

The results obtained from the analysis are shown in Fig. 20 and Fig. 21.

5.4 Observations and Inferences from Analysis of Composite Overwrapped Gas Bottle with Elastomeric Layer in Axisymmetric Model

Logarithmic strain of composite gas bottle with elastomeric layer along meridional direction is compared with that of composite overwrapped gas bottle and is shown in TABLE 3.

<table>
<thead>
<tr>
<th></th>
<th>Liner</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE22 Without elastomeric layer</td>
<td>4631</td>
<td>3829</td>
</tr>
<tr>
<td>LE22 With elastomeric layer</td>
<td>6232</td>
<td>3673</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

To study the failure scenario of composite overwrapped gas bottle due to debond, partial debond is modelled using shell model and a nonlinear static analysis is carried out. The results obtained show a stress concentration at the location where the debond starts. There is no load transfer from liner to fiber overwrap in the debonded region. Further, nonlinear static analysis is done with full debond introduced in the composite overwrapped gas bottle. A uniform stress distribution is obtained in the liner, though the strain rises beyond the yield point. To achieve a strain isolation between the liner and the composite, an elastomeric layer is introduced between the liner and the overwrap.
An axisymmetric model of composite overwrapped gas bottle with an elastomeric layer in between the liner and fiber overwrap is analysed. The nonlinear static analysis results show that the introduction of an additional hyperelastic layer between the liner and the composite overwrap results in a reduction of strain along the meridional direction in composite layer. The strain reduces by around 156µ. The hyperelastic layer, gets compressed between the liner and the composite layers thus allowing the liner to strain to slightly higher level. This in turn isolates the strain from getting transferred to the composite layer from the liner. This strain isolation effect imparted by the hyperelastic layer reduces the chances of debond occurring at the interface between liner and composite. By suitably designing the thickness and choosing a hyperelastic layer with optimal material properties, the strain in composite layer can be further reduced, thus achieving sufficient margin against the bond strength at the interface.

REFERENCES