ABSTRACT

The failure process of a motor case in aramid/epoxy is analyzed. The residual stresses created in the cure process of the matrix epoxy are introduced in the model. This process is modelled numerically and compared with the measurements taken after the fabrication of the envelope. The non linear behavior is considered in the model. The damage of the matrix demonstrated to be a very important factor in the failure mechanism.

NOMENCLATURE

\[ E_l = \text{Elasticity modulus in longitudinal direction} \]
\[ E_t = \text{Elasticity modulus in transverse direction} \]
\[ F_{12} = \text{Coupling coefficient between the longitudinal and transverse directions} \]
\[ G_h = \text{Shear modulus} \]
\[ \alpha = \text{Polar winding angle} \]
\[ \alpha_l = \text{Longitudinal thermal dilatation coefficient} \]
\[ \alpha_t = \text{Transverse thermal dilatation coefficient} \]
\[ \nu_h = \text{Poisson coefficient} \]
\[ \sigma_l = \text{Lamina strength in traction in long. direction} \]
\[ \sigma_k = \text{Lamina strength in compressure in long. direction} \]
\[ \sigma_{tl} = \text{Lamina strength in traction in transv. direction} \]
\[ \sigma_{tc} = \text{Lamina strength in compressure in transv. direction} \]
\[ \tau_{ht} = \text{Lamina strength in shear} \]

1 - INTRODUCTION

The damage mechanism and the fibre/matrix degradation concepts are recently introduced in multilayers structures failure analysis. Prosser (1995), with acoustics emission results tried to determine the type and severity of the damage mechanism in structures under load. Doh (1995), developed a degradation model to predict the burst pressure of the filament-wound pressure vessel as a function of applied load. The work herein presented deals with predicting the burst pressure of a internal pressurized filament-wound pressure vessel (4th stage motor of the Brazilian Satellite Launcher). The motor’s envelope is a multilayer shell structure wound in aramid/epoxy. The envelope is composed by two domes, front and aft, and a cylindrical region, FIGURE 1. The envelope’s model combine the SHELL91, the SOLID95 and COMBIN14 elements. The model takes into account the residual stresses due to the cure process and the non linear behavior by introducing the SSTIF effect. The acoustic emission results taken during the pressurization of the envelope were used to interpret the degradation of the epoxy matrix. The progressive failure method is used to simulate the envelope failure process.

2 - DESCRIPTION OF THE MOTOR

The motor is composed by the following componds: one motor case in aramid fibre and epoxy matrix divided in aft dome, front dome and cylindrical region, two skirts in carbon fibre and epoxy matrix and two skirts in aluminium, FIGURE 1.

2.1 - Fabrication

In the fabrication of the motor case, two types of windings are used: the polar winding and the circumferencial winding. In the polar winding, the fibre is wound on the mandrel in order to touch the two openings of the domes, aft and front. The winding
angle varies from \( \alpha_0 \), constant at the cylindrical region, to 90° at the two openings of the domes. At the aft and front domes, the polar winding type is \([\pm \alpha_0/4]\).

In the circumferencial winding, the fibre is deposed on the rotate mandril with an angle of deposition of 90° with respect the axe rotation. At the cylindrical region the circumferencial and polar winding alternate making \([90º/\pm \alpha_0/4]\) stack, with \( \alpha_0 \approx 17° \).

The main dimensions of the motor are: diameter = 1m and total lenght = 1.1m. The evolution of the thickness of the dome wall, the winding angle \( \alpha \) on the aft and front domes and the properties of the materials compunds motor are given in Braga de Mendonça (1994).

The motor was meshed with 970 SHELL91 elements, 320 SOLID95 elements and 170 COMBIN14 elements, FIGURE 2. The COMBIN14 elements are used to model the domes/flanges interfaces.

The boundary conditions applied in the model are those that define the axisymetry of the motor. As in the experiments, it was assumed the motor is fixed in at end of the aft skirt, FIGURE 1, where the motor was upside down.

3 - CURE PROCESS ANALYSIS

The motor case is wound at room temperature and after that, put into a drying stove to cure the epoxy matrix. The thermal strains created in this process don’t warp the structure. Nevertheless, at the cooling of the motor case the layers tend to contract or to expand in a different manner in the longitudinal and transverse directions of the fibres causing the thermal stresses, (Berthelot, 1992). The stress distribution was adjusted to include the same displacements found in the real motor case. This stresses are later introduced in the model for the motor case failure analysis.

The cure process effect is analysed numerically by assuming the temperature variation at the cooling of the envelope is \( \Delta t = -95 \) °C. The temperature of cure considered is 120 °C. The thermal dilatation coefficients used are: \( \alpha_l = -0.2e-5 \) °C\(^{-1}\), which correspond to aramid fibre and \( \alpha_t = 7e-5 \) °C\(^{-1}\), which correspond to epoxy matrix. The numerical/experimental comparison is given in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1 - NUMERICAL/EXPERIMENTAL DISPLACEMENTS COMPARISON</th>
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<tbody>
<tr>
<td>axial displacement ( u_z )</td>
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<tr>
<td>aft dome</td>
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<tr>
<td>front dome</td>
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</table>

It was observed the aft and front domes expand. This fact is due the negative aramid thermal dilatation coefficient.

4 - FAILURE ANALYSIS

The failure criteria of maxima stress and maxima strain don’t consider all mechanical properties (failure limite in traction and compressure in the longitudinal direction, failure limite in traction and compressure transverse direction, failure limite in shear, etc.). Moreover, these criteria exclude the existence of the interactions between the principal stresses and principal strains: the mechanisms of longitudinal failure, transverse failure or in shear failure are supposed to produce itself in a different way.

One of the criteria that allows linking the different
mechanisms of failure is the Tsai-Wu Criteria, applied to a plane stress state is defined in the following manner:

\[
\frac{1}{\sigma_{l_1}} - \frac{1}{\sigma_{c_1}} \sigma_{l_1} + \left( \frac{1}{\sigma_{l_1}} - \frac{1}{\sigma_{c_1}} \right) \sigma_{l_1} + \frac{\sigma_{l_1}^2}{\sigma_{l_1} \sigma_{c_1}} + \frac{\sigma_{c_1}^2}{\sigma_{l_1} \sigma_{c_1}} + \left( \frac{\tau_{l_l}}{\tau_{l_t}} \right)^2 + 2 \tau_{l_2}^2 + \frac{\sigma_{l_1} \sigma_{c_1}}{\sigma_{l_1} \sigma_{c_1}} = 1
\]

(1)

The aramid/epoxy lamina strenghts used in the numerical analysis are given in Tsai, (1980).

The coupling coefficient between the longitudinal and transverse directions \( F_{12} \), is frequently ajusted as a function of experimentals results, (Berthelot, 1992).

4.1 - Failure Process Experiments

The FIGURES 4.1, 4.2 and 4.3 show that the critical regions are the opening of the aft dome and the domes/cylindrical region interfaces. The motor case failure, characterized by the expelling of the aft flange, FIGURE 4.1, happens at 106 bar.

4.2 - Numerical Results

In the numerical analysis it is considered to have epoxy matrix degradation. The FIGURE 4.4 illustrates the acoustic emission results and show that from 15 s (\( \cong 10 \) bar) there is matrix cracking (low level of energy) and few fibre failure (high level of energy). The numerical simulation of the matrix degradation is expressed by a reduction of the transverse direction properties of the aramid/epoxy composite, i.e., \( E_t, G_{lt}, \nu_{lt}, e^{\alpha_t} \).

It is considered in the model to have a generalized degradation of the matrix. This supposition is independente of the failure analysis. For the ajustement of the model, it is supposed the degradation of the matrix is 30%.

In this analysis, the progressive failure methodology is used. One looks for the pressure \( p_1 \) where occurs the first failed ply. The stiffness of the fisrt ply is reduced and then one looks for the pressure \( p_2 > p_1 \) where the second ply failure occurs. This process is made until the burst pressure. The longitudinal properties of the failed ply is reduced in 50 %. The \( F_{12} \) coefficient is not the same for the failed ply and not failed ply.
The burst pressure obtained by the numerical model was 100 bar. The FIGURES 4.5 and 4.6 illustrate the critical regions of the envelope characterized by the values near 1.

5 - CONCLUSIONS

The SSTIF effect considered in this analysis allowed a good fit of the model.

The COMBIN14 elements provide a good representation of the expelling of the aft flange and reduces the numerical stiffness in the dome/flange interfaces.

The motor case modeled by shell elements is very dependent of the neutral superface position. In this case, this factor plus the coupling coefficient $F_{12}$ demonstrated to have a fundamental role in determining the critical regions.

The model adjusted satisfactorily of the critical regions of the motor case. The burst pressure, considered in the last failure ply, demonstrated be very depend of the degradation.

In future works, it is planed quantify the degradation of the matrix by looking at the acoustics emission results. It is also desired to identify the different modes of failure: fiber rupture, matrix cracking and fiber/matrix shearing failure and modify the mechanical properties in order to enhance the vessel properties.

6 - REFERENCES


7 - ACKNOWLEDGMENTS

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