DEVELOPMENT OF CARBON COMPOSITE/ALUMINUM LINER HYBRID ROCKET MOTOR CASE

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ABSTRACT

In the scope of the lightweight motor case development study, design, analysis, prototype production and verification phases of a 1 mm aluminum-lined, carbon fiber overwrapped rocket motor case presented. The development phase is completed by performing hydrostatic burst tests for six hybrid motor cases. All prototypes were conditioned to three different temperatures such as -35 °C, 23 °C and 70 °C. At the end of the test series, it was shown that all the prototypes satisfy mechanical/structural performance requirements. Hence, the motor with composite case development and verification studies were proved to be successful and in good agreement with the analysis results. The overwrapped motor cases are as much as 30 % more weight efficient than bare aluminum motor case.

1. INTRODUCTION

Composite materials are highly preferred in pressure bearing structures due to their high strength to density ratio. Pressure-bearing metal pipes with composite winding are more efficient than metal pipes which carry the same pressure. In an isotropic cylindrical pressure vessel, the circumferential tension is twice the axial tension. In this study, the design of solid fuel hybrid rocket motor cases manufactured by carbon-epoxy composite winding over metal liner is discussed for the audience of rocket motor design engineers. The hybrid motor case consists of two main components which are metal part and composite overwrapped part. The metal part has a liner section which acts as a sealant and carries a part of the internal pressure load (Ref. 1). In addition to the liner section, there are two connection interfaces for the attachment of igniter and nozzle parts. The metal part material is selected as Al-7075 T6 and overwrapped composite material is a combination of carbon fiber-epoxy matrix.

1.1 Design Theory

In the literature pressure vessel approach is applied in hybrid motor case design (Ref. 2). In hybrid cases, the pressure loading in composite overwrapped cases is divided between metal and composite winding. The case is designed such that the circumferential strain is equal in both metal liner and composite winding. In order to use analytical solution methods, the following assumptions should be made and the problem should be simplified as listed below;

- Thin walled pressure vessel approach is taken as $t<R/10$ (Ref. 3),
- Von-Misses yield criteria is applied (Ref. 4),

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- Only the cylinder section is examined,
- Fibers carry loads only in the circumferential direction.

The applied analytical solution procedure is as follows;

On a typical pressure vessel the hoop and axial stresses are the principal stresses and formulated as (Figure 1),

Notation: f denotes failure situation.

$$\sigma_a = \frac{P_f\, R}{2t}, \sigma_h = \frac{P_f R}{t} \quad [1]$$

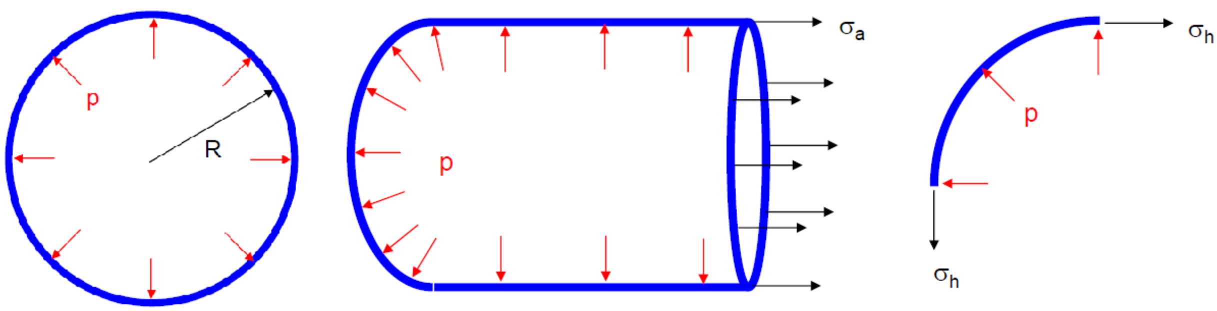

Figure 1. Equilibrium in Hoop and Axial Directions

And the Von-Mises yield criterion in two dimensions,

$$\sigma_y^2 = \sigma_h^2 - \sigma_h \sigma_a + \sigma_a^2 \quad [2]$$

Notation:

P, internal pressure
R, radius
t, wall thickness
σ, stress
h, hoop stress
a, axial stress

Failure occurs when load line reaches the Von Mises ellipse (Figure 2).

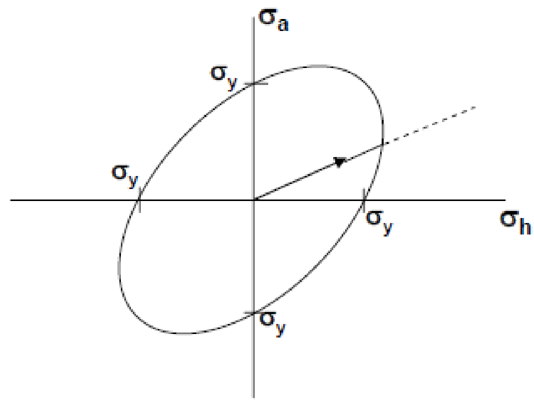

Figure 2. Von Mises Failure Criterion in Two Dimensions

Substitute for the hoop and axial stresses and simplify,

$$\sigma_y = \frac{\sqrt{3}}{2}\frac{P_f R}{t} \qquad [3]$$

The equilibrium in the axial direction is,

$$\sigma_a = \frac{P_f\, R}{2t} \qquad [4]$$

The equilibrium in the hoop direction is,

$$t\sigma_h + t_w\sigma_w = P_f R \qquad [5]$$

Since the problem is statically indeterminate additional equation is needed. The hoop strain in the metal liner and composite wrap must be equal and since the metal has not yielded Hooke's law applies,

$$\frac{1}{E}(\sigma_h - \upsilon\,\sigma_a) = \frac{1}{E_w}\sigma_w \qquad [6]$$

Notation: w denotes hoop-wrap reinforcement.

Once the metal liner has yielded equation [4] is still valid. And hoop stress in the liner obtained from the yield criterion. Solving equation [2] for the hoop stress,

$$\sigma_h = \frac{\left[\sigma_a + \sqrt{\sigma_a^2 - 4(\sigma_a^2 - \sigma_y^2)}\right]}{2} \qquad [7]$$

The final hoop stress in the metal liner becomes,

$$\sigma_h = \frac{\left[\frac{P_f R}{2t} + \sqrt{4\sigma_y^2 - 3\left(\frac{P_f R}{2t}\right)^2}\right]}{2} \qquad [8]$$

Note that the value inside the square root must be greater and equal to zero,

$$t \geq \frac{\sqrt{3}}{4}\left(\frac{P_f R}{\sigma_y}\right) \qquad [9]$$

The hoop stress in the wrap comes from the equilibrium in hoop direction, equation [5],

$$\sigma_w = \frac{P_f\, R - t\sigma_h}{t_w} \qquad [10]$$

2. EXPERIMENTATION

2.1 Design Requirements

Mechanical design studies were carried out according to the size and performance requirements. Metal liner material is selected as aluminum 7075-T6. The design requirements for this study are determined as follows:

- The minimum burst pressure requirement is: 28 MPa
- The outer diameter limit is: 82 mm
- The length of the case is: ~ 235 mm
- Metal liner tensile strength is: 550 MPa
- Metal liner yield strength is: 480 MPa
- Composite tensile strength is: 1300 MPa

2.2 Metal Liner and Composite Layer Thickness Calculation

Using the minimum wall thickness equation [9], metal liner thickness is calculated according to the yield strength and tensile strength of the metal.

Minimum wall thickness (tensile) [mm]	0.87
Minimum wall thickness (yield) [mm]	1.0
Selected wall thickness [mm]	1.0

According to the selected metal thickness of the metal liner, the axial stress is observed to begin to yield in the metal. And the stress values in the metal liner are calculated using the equations [4] and [8].

Axial stress in metal liner [MPa]	550
Hoop stress in metal liner [MPa]	290

In the composite winding design, the approach described in equation [10] is used. The solution tool is based on Netting Theory. In this theory, it is assumed that the strength of the composite material is provided only by the fiber and the resin does not contribute to the strength. According to the calculations the hybrid motor case is modeled (Figure 3).

Minimum composite wrap thickness [mm]	0.63

On the other hand in the case of that the motor case is full metal the metal wall thickness calculated using basic pressure vessel approach is,

Full metal case wall thickness [mm]	2.08
Full metal case weight [g]	385

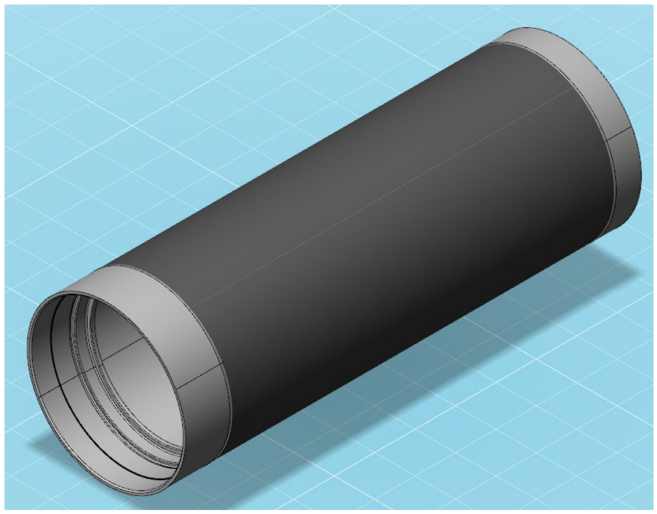

Figure 3. Model of Hybrid Motor Case

2.3 Manufacturing Method

Hybrid motor cases are planned to be manufactured by using filament winding machine and wet winding technique. Manufacturing operations are listed below:

- Before the winding process, alcoholic based solvent is used to remove the oil and dust.
- In order to improve the adhesion performance at the composite metal interface, the liner section of the aluminum part is sandblasted by using silica sand (Ref. 5). After sandblasting, sand and metal residues on the part are cleaned with alcoholic based solvent.
- The cleaned part is mounted to the filament winding machine using the winding connection apparatus.
- The resin system containing epoxy, accelerator and hardener components is mixed in a container for approximately 10 minutes and poured into the resin bath of the machine.
- Before starting the winding process, epoxy resin system is applied to aluminum liner by using brush.
- The winding process is carried out with 1 spool of carbon fiber material with approximately 2.5 mm bandwidth.
- After the 3 layers of circumferential winding is completed, shrink tape is applied on the part (Figure 4).

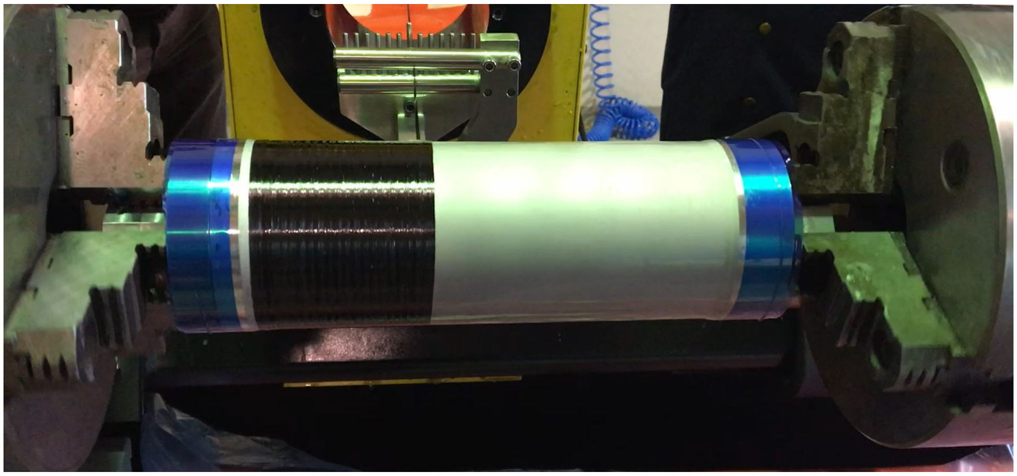

Figure 4. Wet Winding Process of Hybrid Motor Case Prototype

- The part is mounted to the rotation mechanism of the furnace for the curing process and the furnace is started.
- After the curing process is completed, the shrink tape on the part is removed and it is transferred to the burst testing area.

2.4 Hydrostatic Burst Testing

Burst tests were carried out in a closed cabinet for safety purposes (Figure 5). Two specially designed closure apparatus were connected to two ends of the cases with silicon based o-rings to prevent any leakage. There are two ports on the one of closure apparatus in order to circulate the water inside the case and achieve the required pressure level.

3 sets of the motor cases were subjected to the burst tests at different temperature conditions which are -35 $^{\circ}$C, 23 $^{\circ}$C and 70 $^{\circ}$C. Each set consist 2 motors for verification purposes. After the temperature conditioning burst tests are completed within 5 minutes.

Figure 5. Hydrostatic Burst Pressure Setup

3. RESULTS

The burst test results of the all 6 motors are given in Table 1. When weight of motor cases examined it is clearly seen that there is slight deviation between them. The reason for that could be explained as limitations at the stability of wet winding process. Due to change in the bandwidth of fiber bundle and tension, the fiber overlapping ratio in a single hoop layer is able to be kept constant at a certain level. The fiber/matrix weight ratio is determined according to the ASTM D 3171-99 standard (Ref. 6) test method by using nitric acid to digest the matrix content. The samples collected from each case after burst tests are examined and the average fiber/matrix weight fraction is occurred to be 0.74.

Burst pressure values for each case also deviate. Deviation in the burst pressure and weight values is coherent with each other as expected. In other words; when fiber overlapping ratio increases, the total amount of fibers in a single hoop layer increases and this causes improvement at the burst pressure values. On the other hand, it is observed that conditioning temperature has no significant effect on burst pressure values. Due to the fact that there is no significant contribution to the load carrying of matrix in axial direction, the expected strength reduction at 70 $^{\circ}$C is considered in the composite has no remarkable effect on the burst pressure.

Table 1. Hydrostatic Burst Pressures and Weights of the 6 Prototypes

Motor Cases	Conditioning temperature [$^{\circ}$C]	Weight of the cases [g]	Burst pressure [MPa]
MC 1	-35	272	29.0
MC 2	-35	282	30.6

MC 3	23	257	28.0
MC 4	23	275	30.2
MC 5	70	285	30.6
MC 6	70	290	31.3

After the hydrostatic burst tests, the failure modes of the motor cases were examined and the same failure mode was observed for all motor cases. With the further evaluation of the failed parts it was determined that the cases were separated in axial direction (Figure 6). The axial strength of the body is mainly provided by the metal liner with the negligible contribution of matrix material in the composite. Considering the axial and hoop stress calculations on the metal liner, it can be said that the axial stress is almost twice of hoop stress which supports the observed failure mode.

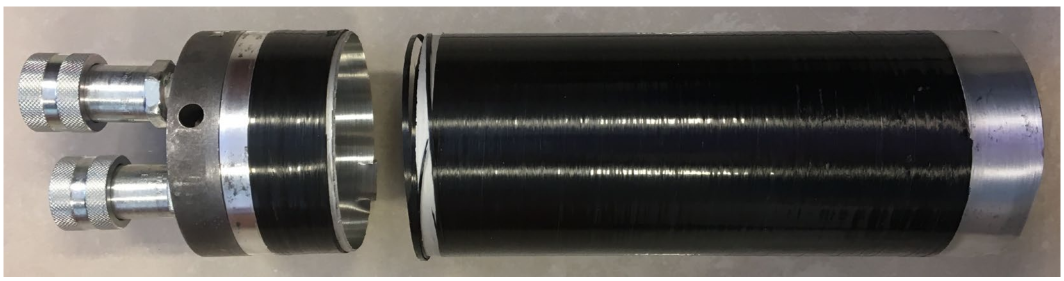

Figure 6. Failure of the Motor Case 3

The following Table 2 shows weight comparison between the metal case bearing the same pressure and 6 hybrid cases that were produced. It is clear that there is approximately 30% weight reduction in hybrid cases.

Table 2. Weight Reduction of 6 Prototypes Compared to Aluminum Motor Case Bearing the Same Pressure

Motor cases	**% weight reduction**
MC 1	29
MC 2	27
MC 3	33
MC 4	28
MC 5	26
MC 6	25

4. CONCLUSIONS

The carbon fiber overwrapped aluminum liner hybrid pressure vessels could be considered as an alternative rocket motor case compared to metal motor cases. In this study, the theory of design for the hybrid motor case has been studied and an aluminum lined carbon/epoxy composite hybrid motor case has been designed in a specific geometry. For the verification of the designed motor case, 6 prototypes were produced and these cases were subjected to burst test at temperatures of -35 ˚C, 23 ˚C and 70 ˚C. In the light of the results, it was observed that the burst pressures and failure modes of the hybrid cases were consistent with the calculations. To conclude, this study shows that the hybrid motor casings are lighter up to 30% hence more efficient compared to the motor case made of same aluminum material. As a future work, it is aimed to make static firing tests of hybrid motor cases in order to verify the motor case under working conditions.

5. REFERENCES

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