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Finite element analysis of a helicopter pressurized composite reserve fuel tank

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Abstract - Helicopters are known to suffer fuel starvation during sharp maneuvers due to the centripetal forces that may pull fuel away from the fuel lines. To overcome this problem a composite reserve ferry fuel tank is proposed. The tank is pressurized to allow the fuel flow based on pressure difference, instead of gravity. Carbon fiber reinforced composite material is chosen because of its high strength to weight ratio compared to other metals such as aluminum. The design of this tank is optimized using a commercial program (PROMAL) in terms of strength and ply angle taking into account the Maximum Strain failure criterion and a crash resistance factor of safety. The design was also based on filament winding manufacturing technique. Abaqus® finite element analysis program was used to verify the design in terms of stresses and strains which showed that the chosen ply angle, number of plies and type of material was able to successfully withstand the ultimate design pressure and was in good agreement with PROMAL optimization program.

Keywords: Composite, Design, Failure Criteria, FEA, Fuel Tank

I. Introduction

The design of fuel systems on board modern helicopters must provide a proper and reliable management of fuel resources throughout all operation phases, notwithstanding changes in altitude or speed as required by governments regulations such as FAA Part 29 (Airworthiness standards: Transport category rotorcraft) [1]. As long as the helicopter is in coordinated flight, fuel will flow normally from the main tanks into the fuel delivery system. However, when the helicopter is not flying in straight-and-level attitudes such as during sharp maneuvers, centripetal forces may pull fuel away from the fuel lines leading to fuel starvation and engine stoppage. This requires having a fuel tank of sufficient volume to supply the flow needed while still maintaining adequate fuel system pressure. To overcome this issue, a pressurized fuel tank will assure the engine is always getting a stable fuel flow no matter what the fuel level is. This tank is to be carried onboard the helicopter as a ferry fuel tank giving it an extra flight time of around 30 minutes.

The tank includes an internal elastomeric bladder with nitrogen on one section and pressurized fuel on the other section. This fuel tank stores fuel when fuel system pressure is greater than fuel tank pressure and provides fuel when the fuel tank pressure is greater than fuel system pressure. These types of reserve fuel tanks were generally required to be designed using light metal alloy [2] but for better performance and weight savings, carbon fiber reinforced plastic (CFRP) composites are preferred for the construction of the fuel tank. The material selected for the construction of a particular fuel tank depends upon the type of aircraft and its mission. Fuel tanks and the fuel system in general are made of materials that will not react chemically with any fuels. Also, composite materials have superior mechanical properties like high specific stiffness, high specific strength and excellent fatigue characteristics. Unlike most metallic materials, composite materials offer high corrosion and chemical resistance. Besides, composite materials provide good dimensional stability and design flexibility, they are appropriate for near-net-shape processing, which eliminate

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several machining operations and thus reduces process cycle time and cost [3]. To manufacture this type of fuel tank, filament winding process is one of the most suitable methods to be used. In this process, fibers are wound from a spool onto a mandrel continuously and at a range of angles. Filament-wound products are produced by using one of the three basic types of winding patterns: polar, helical, and hoop. The choices made are based on the shape of the part and the reinforcement orientations required. Polar winding is used to lay down fiber close to 0^o to the longitudinal axis. Helical winding is used to lay fiber at angles from 5^o to 80^o to the longitudinal axis. These fibers are wound on the mandrel surface in alternating positive and negative orientations and result in a double layer of wound material. Hoop winding is a special form of helical winding and is used to deposit fiber close to 90^o to the longitudinal axis. Some researchers have reported that cylindrical laminated composites are best made with a fiber winding angle equal to 55^o [4]. Beakou and Mohamed [5] used reliability analysis of a $[\pm\theta]_n$ filament wound composite, that showed the optimum fiber winding angle can vary with the scattering of some design variables, such as strength, constituent elastic constants, load cases, etc.. The stresses are computed using the classical laminated membrane theory and the various composite failure criteria. Parnas and Katrc [6] investigated fiber reinforced pressure vessels under various loading conditions. Using classical laminated-plate theory, for a plane strain model of a thick-walled multi layered filament wound cylindrical shell, loading conditions such as internal pressure, axial force and body force due to rotation were considered. Environmental effects were also investigated. Optimization on winding angle for different axial forces, internal pressures, hygrothermal loading, and rotational speed loading were performed. The results of the analytical procedure, which was based on Lethnitskii's approach, were compared with experimental results. Thin wall and thick wall assumptions were compared. It was shown that, up to an outer to inner diameter ratio of 1.1, two assumptions gave similar result. Beyond this value, thick wall assumption is better to use. By the numerical solution performed, optimum winding angle for internal pressure is found to be ranging between 52.1º and 54.2º depending on the geometry of the tube and the type of failure criteria used for the analysis. In this work however, a commercial code (PROMAL) [7] is used to derive the optimum filament winding angle based on the maximum strain failure criterion. Then, the obtained results are to be further verified using abaqus finite element program.

I.Fuel Tank Sizing

Fuel tank sizing is based on the gas charge. The change in gas volume and pressure determines the amount of fuel that can be added or withdrawn. To maintain minimum fuel system pressure, the tank must be able to supply sufficient flow over a determined period of time. The tank must provide fuel flow when the gas is between the nominal fuel system pressure and the minimum desired fuel system pressure. At initial conditions the gas section is to be pre-charged with nitrogen at some pressure. When the fuel pumped into the tank, the fuel pressure will press the gas section into certain volume and certain pressure. If there is a fuel demand, then the tank will release the fuel and makes the gas section expands as illustrated in figure 1. When carrying out the calculations for tank sizing, the following pressures are considered:

P_0 is gas pre-charge pressure at room temperature and with liquid chamber drained.

P_1 and P_2 are minimum and maximum operating pressures respectively.

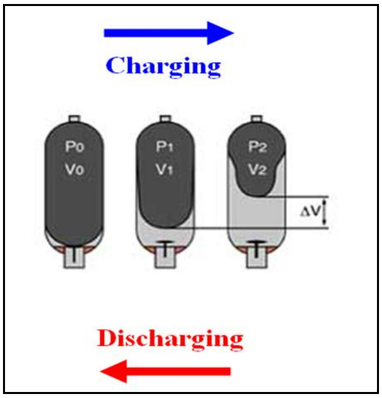

Fig.1. Basic principle of the pressurized fuel tank

The gas pre-charge pressure is to be slightly lower than the minimum fuel pressure

$$P_0 \approx 0.90\, P_1 \quad (1)$$

The compression ratio between P_1 and P_2 will adversely affect the elasticity of the bladder and reducing the pressure differential between P_1 and P_2 increases service life limit of the bladder. On the other hand, a lower pressure differential also reduces the utilization of available storage capacity. The maximum fuel pressure does not exceed more than 4 times of the pre-charge pressure

$$P_2 \leq 4 \cdot P_0 \quad (2)$$

The gas volumes V_0 and V_2 correspond to the pressures P_0 and P_2, respectively. V_0 is the rated volume of the tank. The available fuel volume ΔV corresponds to the difference between the fuel volume V_1 and V_2.

$$\Delta V = V_2 - V_1 \quad (3)$$

The variable gas volume for a given pressure difference is determined by the following equations:

a)For isothermal change of state of gases

During isothermal process the change in the gas volume takes place so slowly that there is sufficient time for the complete exchange of heat to take place between the nitrogen and its surroundings. The temperature change will be constant.

$$P_0\, V_0 = P_1\, V_1 = P_2\, V_2 \quad (4)$$

b)For adiabatic change of state of gases

During adiabatic process the change in the gas volume takes place so rapidly that the temperature of the nitrogen also changes. It is often the case that the charge takes place isothermally and the discharge adiabatically.

γ = ratio of the specific heats of the gas (adiabatic component); $\gamma = 1.4$ for nitrogen

$$P_0\, V^{\gamma}_0 = P_1\, V^{\gamma}_1 = P_2\, V^{\gamma}_2 \quad (5)$$

ΔV is about 50 to 70% of the rated tank volume. Consequently, the following table shows the general characteristics of the fuel tank. Figure 2 is a 2D computer aided design drawings of the proposed pressurized fuel tank and its components.

Table1. Fuel Tank Characteristics

Helicopter fuel consumption	**190 liter/hour**
Required time	0.50 hour
Maximum available pressure P_2	2 bar
Minimum working pressure P_1	0.556 bar
Nitrogen pre-charge P_0	0.50 bar
Compression pressure ratio P_2/P_0	4
Fluid volume to be stored ΔV	95 liters
Required tank size V_0	200 liters
Gas volume	105 liters
Diameter D	0.572 m
Total length from pole to pole	0.969 m

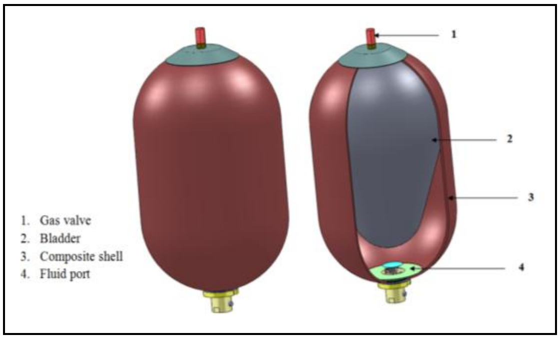

Fig.2. CAD drawing of the fuel tank and its components

II.Analytical strength analysis

A commercially available optimization program (PROMAL) [7] is initially used to determine the minimum number of plies and optimum winding angle for the composite tank to be able to withstand the ultimate design pressure. PROMAL calculates the total strains on a chosen winding angle and the number of plies then these strains are compared with the allowable strains to check if they satisfy the maximum strain criterion. Maximum strain criterion is a simple and direct way to predict failure of composites. It considers that the composite fails when the strain exceeds the respective allowable. It identifies composite material failure caused by three possible modes of loading: longitudinal failure, transverse failure, or shear failure (only tensile loading for our case).

$(\varepsilon_{11}^{T})_{ult} \equiv$ Ultimate longitudinal tensile strain in fiber direction (direction 1),

$$(\varepsilon_{11}^{T})_{ult} = \frac{(\sigma_{11}^{T})_{ult}}{E_{11}} \qquad (6)$$

$(\varepsilon_{22}^{T})_{ult} \equiv$Ultimate transverse tensile strain in fiber direction (direction 2),

$$(\varepsilon_{22}^{T})_{ult} = \frac{(\sigma_{22}^{T})_{ult}}{E_{22}} \qquad (7)$$

$(\varepsilon_{12})_{ult} \equiv$Ultimate in-plane shear strength (in plane 1-2),

$$(\varepsilon_{12})_{ult} = \frac{(\sigma_{12}^{T})_{ult}}{G_{12}} \qquad (8)$$

Fiber: $\varepsilon_{11} \geq (\varepsilon_{11}^{T})_{ult}$ or $|\varepsilon_{11}| \geq (\varepsilon_{11}^{C})_{ult}$ (9)

Matrix: $\varepsilon_{22} \geq (\varepsilon_{22}^{T})_{ult}$ or $|\varepsilon_{22}| \geq (\varepsilon_{22}^{C})_{ult}$ (10)

Shear: $|\varepsilon_{12}| \geq (\varepsilon_{12})_{ult}$ (11)

The form of the failure criterion is typically described as a mathematical function of the above variables which reaches the value of unity at failure as follows.

Failure Index = FI (load, strength) = 1 (12)

Consequently, the maximum strain criterion is calculated by comparing the allowable load with the actual strength for each component. Mathematically, it is defined by:

FI = Max. abs. value of

$$\left(\frac{\varepsilon_{11}}{(\varepsilon_{11}^{T})_{ult}}, \frac{\varepsilon_{22}}{(\varepsilon_{22}^{T})_{ult}}, \frac{\varepsilon_{12}}{(\varepsilon_{12})_{ult}}\right) \geq 1 \qquad (13)$$

The strength of a structure can then be given as a Strength Ratio (SR), which is the ratio by which the load must be factored to just fail. In this case

$$SR = 1/FI \qquad (14)$$

The laminate is optimized for getting the minimum thickness. PROMAL carries out the optimization by considering the number of plies to be a continuous variable. The initial assumption of stacking sequence considered is [±θ].

The design is considered of a symmetric and balance laminate with multiple angle-ply stacks ($[(\pm\theta_n)_{N_n}/(\pm\theta_n)_{N_{n-1}}/\dots/(\pm\theta_1)_{N_1}]_s$).

The orientation angles are fixed and the n unknowns are the numbers of layers of each specified orientation, N_i, where i = 1, …. , n, and n is the number of layers groups with distinct orientation angle. The stack-thickness design variable is defined to be the total thickness for each orientation; that is,

$$x_i = \begin{cases} 4tN_i, & if\ \theta_i \neq 0^o\ and\ \theta_i \neq 90^o \\ 2tN_i, & if\ \theta_i = 0^o\ and\ \theta_i = 90^o \end{cases} \qquad (15)$$

Where the factors of 2 and 4 are due to the symmetry and balance requirements [8].

The optimization problem is shown in following equation

$$min_{n,\theta} \sum_{i=1}^{n} 4tN_i \quad (16)$$

$$such\ that, [\varepsilon_{11}^{Total}] - \frac{(\sigma_{11}^{T})_{ult}}{E_{11}} \leq 0 \quad (17)$$

$$[\varepsilon_{22}^{Total}]_{\theta_n} - \frac{(\sigma_{22}^{T})_{ult}}{E_{22}} \leq 0 \qquad (18)$$

$$[\sigma_{12}^{Total}]_{\theta_n} - \frac{(\sigma_{12})_{ult}}{G_{12}} \leq 0 \quad (19)$$

$$-\frac{(\sigma_{12})_{ult}}{G_{12}} - [\varepsilon_{12}^{Total}]_{\theta_n} \leq 0 \quad (20)$$

$$0^o \leq \theta_n \leq 90^o \quad (21)$$

Script files are then generated in PROMAL optimization program to obtain the optimum winding angle for the pressurized composite fuel tank. The inputs of the program are the material properties shown in table 2 as well as the design limits and loading conditions. The ultimate design pressure is calculated with a factor of safety mainly driven by the crash resistance of the tank which is recommended to be 35 [9]. Therefore, the ultimate design pressure would be:

$$P_d = 35 * P_2 = 7 \text{ MPa} \quad (22)$$

Table 2. Properties of Laminas Used in Design (Graphite/Epoxy (T300/5208))

Property	**Symbol**	**Value**
Fiber Volume Fraction	V_f	0.70
Longitudinal Elastic Modulus	E_{11}	181 GPa
Transverse Elastic Modulus	E_{22}	10.30 GPa
Major Poisson's Ratio	ν_{12}	0.28
Shear Modulus	G_{12}	7.17 GPa
Ultimate Longitudinal Tensile Strength	$(\sigma_{11}^T)_{ult}$	1500 MPa
Ultimate Longitudinal Compressive Strength	$(\sigma_{11}^C)_{ult}$	1500 MPa
Ultimate Transverse Tensile Strength	$(\sigma_{22}^T)_{ult}$	40 MPa
Ultimate Transverse Compressive Strength	$(\sigma_{22}^C)_{ult}$	246 MPa
Ultimate In-Plane Shear Strength	$(\sigma_{12})_{ult}$	68 MPa
Density	ρ	1620 Kg/m^3
Ply thickness	t	0.125 mm

As shown in figure 3, the optimum angle is 52^o. Strength ratio is the ratio between the failure load and the applied load. The summary of PROMAL program optimization results are shown in table 3. The optimum laminate is given by $[\pm 52^o]_{20S}$. The value of N is rounded off to the next highest integer value of 20 with the total thickness being equal to 10 mm.

Fig.3. Strength ratios as a function of winding angle

Table 3. PROMAL program optimization results

Case	Optimum Number of Plies	Optimum Angle	Optimum thickness (mm)
$[\pm\theta]_{NS}$	N = 19.4	52^{o}	9.65

IV.Numerical Analysis of the Pressurized Composite Fuel Tank

In order to verify the PROMAL results, the composite pressure fuel tank was modeled using Abaqus® software, which essentially defined the structure and properties of a 20-ply composite laminate material with various ply orientations such as [+52/-52]. Displacement was constrained in all direction and pressure applied as shown in figure 4. Once all boundary conditions, material properties, and internal pressure load were input into the model, abaqus quickly calculated the maximum strain values and their location on the composite tank.

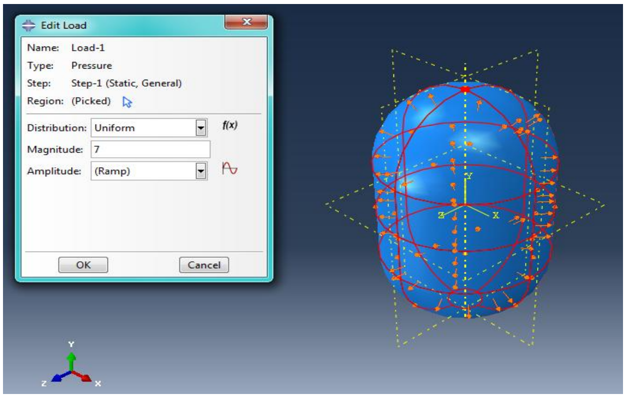

Fig.4. Finite element model setup in abaqus

FEA results for various angles were then carried out. The output maximum strain was transposed into strength ratio and compared to PROMAL optimization results. As shown in figure 5, the FEA results were in good agreement with PROMAL's and clearly show the 52 deg. angle to be optimum.

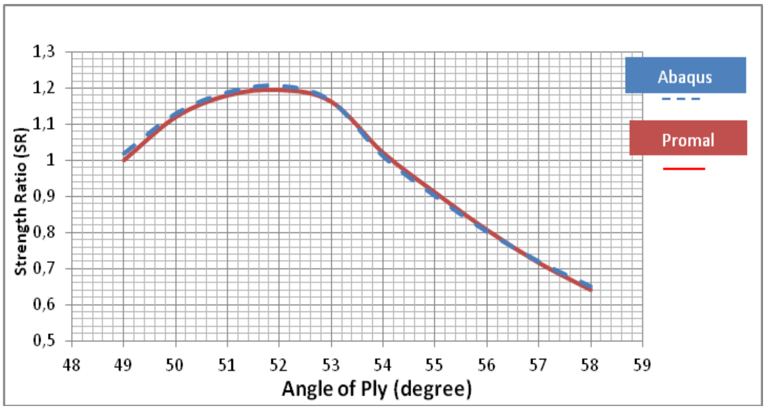

Fig.5. Strength ration versus ply angle agreement between abaqus and PROMAL

Figures 6 to 8 show maximum longitudinal, transverse and in-plane strains on the composite tank as obtained by abaqus for 51, 52 and 53 deg. ply angles. These finite element results clearly demonstrate that winding angles below and above 52 had either higher values of either longitudinal tensile strain or transverse tensile strain or in-plane shear strain leaving the 52 winding angle as the optimum choice. The quoted strains are worked out based on the active constraint in this case which is given as:

Longitudinal Tensile Strain:

$$[\varepsilon_{11}^{Total}] - \frac{(\sigma_{11}^{T})_{ult}}{E_{11}} \leq 0.008287$$

Transverse tensile strain: $[\varepsilon_{22}^{Total}]_{\theta_n} \leq 0.003883$

In-Plane Shear Strain: $[\sigma_{12}^{Total}]_{\theta_n} \leq 0.009483$

Thus, it can be concluded from the finite element study that the ±52 fiber orientation angle produces an optimum safe and conservative design.

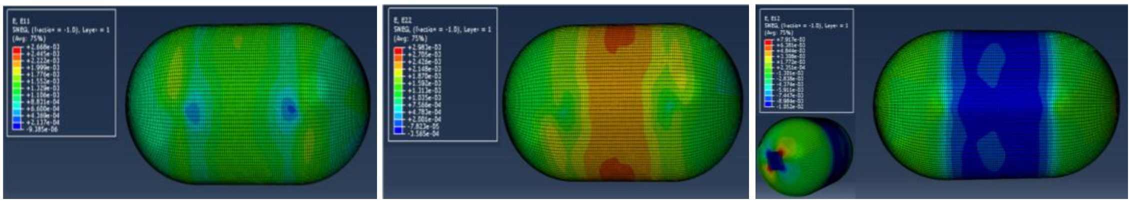

Fig.6. Longitudinal tensile strain (top), transverse tensile strain (center) and in-plane shear strain (bottom) for angle 51^{o}

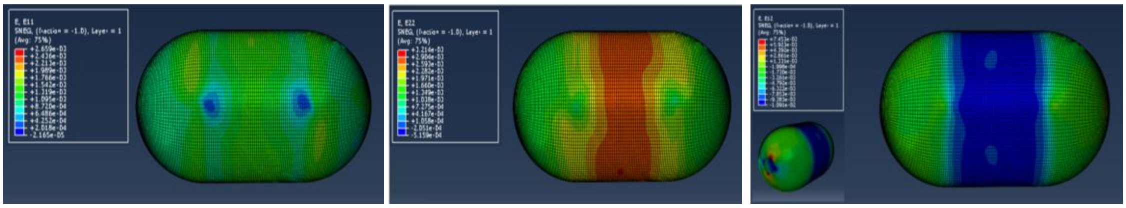

Fig.7. Longitudinal tensile strain (top), transverse tensile strain (center) and in-plane shear strain (bottom) for angle 52^{o}

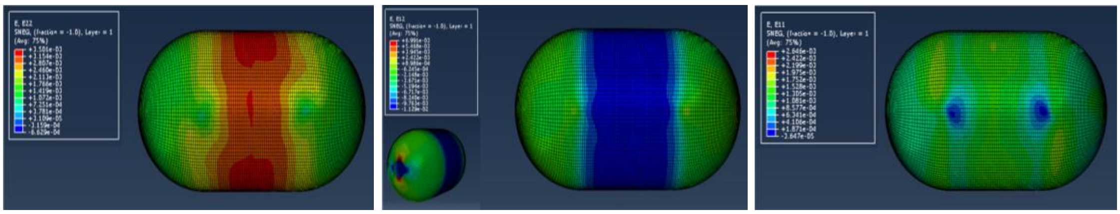

Fig. 8. Longitudinal tensile strain (top), transverse tensile strain (center) and in-plane shear strain (bottom) for angle 53^{o}

V. Conclusions

A pressurized helicopter reserved fuel tank is proposed for use in cases of fuel starvation. CFRP composite material with filment winding process as the manufacturing method is chosen for designing this fuel tank. For optimum performance and weight savings, an optimum winding angle and number of plies was achieved using commercial optimization software (PROMAL). This optimization was carried out considering the internal pressure, volume, vessel weight and the CFRP composite properties. The failure criteria used for designing the laminates is the maximum strain criteria. The load factor was chosen based on the tank ability to withstand a crash. The optimum angle for resisting maximum pressure for a filament-wound cylindrical pressure vessel was ± 52 which is slightly different from the widely reported ± 55 angle. FEA results showed that for the chosen ply angle and number of plies, the tank is able to withstand the ultimate design internal pressure without failure as indicated by the maximum strain criteria.

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