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Design and Analysis of Composite Hydraulic Cylinders Developed for Aerospace Applications

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Abstract

Nowadays, aviation and space applications are technologies that are becoming increasingly important. It is essential that these technologies are highly energy efficient and can be applied effectively. The central systems of an aircraft can be listed as navigation and communication, power control systems, flight control systems, and collision avoidance systems. Hydraulic energy is required for the flight control systems, one of the central systems of the aircraft. In an aircraft, hydraulic systems can generally be used in flight control (such as ailerons, horizontal elevators, high-lift gear), landing gear (such as brakes, steering, and landing gear bending), door and stair systems (such as cabin and cargo doors, ramps), and main power (such as propeller brakes, reverse engine operation). Cylinders (actuators), the final element of power transmission in hydraulic systems, are among the most important movement elements. Hydraulic cylinders are elements that convert hydraulic energy into mechanical energy linearly. Hydraulic cylinders are usually made of steel, aluminum alloy, or titanium alloys in aviation. Hydraulic cylinders are heavy due to the high working pressure conditions they provide. This makes it challenging to use in aircraft. A heavy cylinder can also limit the desired mobility in the system to be limited, causing excessive fuel consumption, shortening the aircraft's mission time, and reducing the range. For these reasons, it has been observed that there is a tendency towards composite materials in aviation and space applications. This study evaluates that a hydraulic cylinder is optimized with appropriate calculations and design and made of composite material and titanium alloy. The strength values of the cylinder formed with carbon fiber wrapped on the titanium alloy cylinder tube at two different angles were compared with the finite element method. Two different windings were made with angles of 75/90/-75/90 and 45/90/-45/90 using the finite element method. As a result of the comparison, it was determined that the 75/90/-75/90 winding had approximately 25% higher strength value than the 45/90/-45/90 winding.

Keywords: Hydraulic cylinder; Composite cylinder; Hydraulic applications in aviation system.

1. INTRODUCTION

Aviation and spacecraft are expensive and energy-consuming systems. In this context, there are requirements such as relative simplicity of aircraft designs, short service life, high levels of readiness for first and subsequent take-

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offs, and reliability in operation [1]. All control systems and equipment of the aircraft must be selected correctly to ensure coordinated operation of the equipment and, as a result, fulfill the conditions as mentioned above [1]. The latest in aircraft systems architectures consists of the complex integration of various technologies that make up the equipment used to power and fly an aircraft in the open air [2]. Hydraulic energy is used to provide flight control of aircraft. A typical aerospace vehicle comprises a hydraulic actuation system, a thrust vector control system, and an aerodynamic control system [3]. Aircraft hydraulic systems have a complex structure that performs many different functions. Hydraulic systems perform various functions, such as moving the aircraft's control surfaces (wings, horizontal and vertical stabilizers, etc.), extending and retracting the landing gear, controlling the brakes, and moving the flaps and spoilers. Hydraulic cylinders, the last element of the hydraulic elements, are very significant in providing this mobility. In addition to regular maintenance and inspections, backup systems and safety measures are applied to hydraulic cylinders in aircraft. This is important to ensure the safe and smooth operation of aircraft. Hydraulic cylinders convert hydraulic energy into mechanical energy using the power of fluids. A typical hydraulic cylinder consists of a tube, shaft, and joint. The hydraulic oil in the chamber pushes the cylinder shaft to move, providing displacement and force output simultaneously [4]. The pressure of the working hydraulic fluid acts on the cylinder, creating a force that causes the piston assembly to move [5]. The cylinders have the advantages of large output force, simple structure, easy maintenance, and safe operation [6]. A standard-type industrial cylinder is designed to operate at 250 bar. This design can vary depending on the desired features. There are two types of pressure classes in aviation applications. For this reason, the components are designed for 3000 PSI (210 bar) and 4000 PSI (280 bar) in aviation.

Environmental problems are becoming more and more important day by day. Therefore, it necessitates reducing or eliminating harmful substances, emissions, and the amount of waste produced. Efforts are also being made to design structures to consume as little energy as possible during operation. Reducing weight is a desirable step in this context because it is often associated with increased energy efficiency of the machine [7][8][9]. Most hydraulic cylinders are made of high-strength steel or titanium alloys to meet the durability requirements as they must carry alternating internal pressure [6]. When selecting materials, strength, durability, production technology, and cost issues should be considered [10][7]. Conventional hydraulic cylinders are mostly steel or aluminum alloys; the seals are plastic and bronze. As an example, for this kind of materials structural steel S355J2G3 [11], austenitic stainless steel AISI 304, and aluminum alloy Al7075 could be given [7]. Titanium alloy materials are generally used in cylinders used in the aviation field due to their high strength values. Standard hydraulic cylinders are heavy because they meet high working pressure conditions. This makes it challenging to use in aircraft. Heavy cylinders can also restrict the desired mobility in the system, cause excessive fuel consumption, shorten the aircraft's mission duration, and reduce the range. For these reasons, there seems to be a trend towards composite materials in the aviation industry. For example, the specific gravity of Ti Grade 5 (Ti-3Al-8V-6Cr-4Mo-4Zr) material is about 4.42 g/cm^3, and its tensile strength is about 1000 MPa. When the properties of carbon fiber material (CFRP) are examined, its specific gravity is about 1.8 g/cm^3, and its tensile strength is about 3800 MPa. As can be seen, if these two materials are used by optimizing each other with appropriate calculations and design, lighter components with much higher strength can be obtained. In particular, the need for lighter designs in aviation and space applications paves the way for the widespread use of composite hydraulic cylinders. Fiber-wound composites are preferred in many applications, such as solid rocket motor cases and pressure vessels, due to their high strength-to-weight ratio and stiffness properties [12].

Composite hydraulic cylinder designs are presented in two different types in the literature. One is composite winding on a thin-walled cylinder tube (liner), and the other is tubeless. In the design without using liner, composite winding is done by placing the rear and front covers [4] [6]. In addition, domed designs of the cylinder tube have also been studied in some applications [13]. However, the main problem encountered in designs where the cylinder tube is made entirely of composite is that the desired efficiency cannot be achieved due to the friction that may occur during the piston operation [14]. There is also the problem of insufficient material stiffness during fatigue internal pressure loading [14]. An alternative solution for designs without a liner is to apply a material coating with specially designed properties to the inner surface of the cylinder pipe. For example, coatings such as polymeric materials [15] or nanocomposites in the matrix of epoxy resins filled with Al2O3 and SiO2 nanoparticles can be used [14]. The joining of two materials with different hardness and thermal expansion coefficients can lead to stress concentration at the liner-reinforcement contact and reduce the fatigue strength of the member [14]. However, in this study, it is deemed appropriate to use liner on the inner surface to have the same wear resistance and surface roughness performance during piston movements as in traditional designs. Carbon fiber wrapping will be done on the outer surface of the liner to increase the pressure and force resistance. The method to be used in the design of the cylinder tube is filament winding. The filament winding technique is a known technique for producing composite structures. Continuous fibers are the cheapest and strongest form of fiber reinforcement [16]. These fibers can be oriented to adapt to the direction and magnitude of stresses in a structure [16].

The compatible working conditions of the thin-walled pipe and carbon fiber should be optimized by solving the finite elements with pressure, temperature, and force variables. The winding technique of the composite structure to be wound (winding angle, winding tension, number of fibers, winding speed, etc.) is important according to the strength values obtained from the analysis. Specifying a resin that can operate at high-temperature differences is especially important. These development activities will obtain a reliable composite hydraulic cylinder with high strength, lightweight, unaffected by temperature differences, and corrosion resistance verified by analysis.

2. MATERIALS AND METHODS

When designing a hydraulic cylinder, the cylinder tube must withstand the pressure applied from inside. In this context, Clavarino's equation [17] is used. Clavarino's equation, shown in Equation 1, describes stress distribution on a cylindrical shell. Stress is a function of the forces in the wall of the pipe. This equation expresses the relationship between the stresses on a cylindrical shell's inner and outer surfaces. This is crucial when engineers make design decisions such as material selection and pipe sizing.

$$t = \frac{\mathrm{di}}{2} * [\sqrt{\frac{\sigma ak + (1-2v)pi}{\sigma ak - (1+v)pi}} - 1] \quad (1)$$

In addition, composite mixture theory [18,19] is used in the design of composite materials for hydraulic cylinder design. Composite materials consist of fiber and matrix. The mechanical properties of the composite are calculated using composite mixture theory [18,19]. In Equation 2, the calculation of the young modulus of the composite structure with the ratios of the fiber and matrix and the final young modulus are given. Like the young modulus, other strength values are calculated according to fiber and matrix density.

$$E_c = E_f x V_f + E_m x V_m \quad (2)$$

In this article, winding will be done on a thin-walled titanium alloy pipe. Ti-3Al-8V-6Cr-4Mo-4Zr [20] was selected as the titanium alloy, and the wall thickness was 2 mm. Figure 1 shows a schematic diagram of the CFRP layer angle definition of the cylinder tube.

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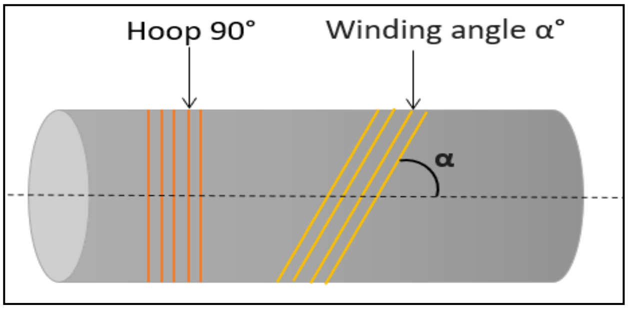

Figure 1. Schematic diagram of CFRP layer angle definition of cylinder tube.

Table 1 lists the cylinder's parameters. Table 2 shows the strength values of titanium material, and Table 3 shows the strength values of carbon fiber and epoxy.

Table 1. Parameters of hydraulic cylinder.

Parameter	Value
Max. Pressure (MPa)	38
Cylinder Tube Inner Diameter (mm)	63
Rod Diameter(mm)	36
Cylinder tube length (mm)	400

Table 2. Properties of titanium material [20].

Material	Density (kg/m^3)	Young Modulus (MPa)	Poisson Ratio (ν)	σ_y (MPa)	σ_r (MPa)
Ti-3Al-8V-6Cr-4Mo-4Zr	4820	104000	0,33	1034,21	1220

Table 3. Properties of composite materials [21].

Material	Density (kg/m^3)	Young Modulus (MPa)	Poisson Ratio (ν)	Shear Modulus (MPa)	Fiber Volume (%)
Carbon Fiber	1750	230000	0,3	50000	60
Epoxy Resin	1200	2800	0,4	50	40

Four layers of 2 mm thickness were wrapped on a 2 mm titanium alloy pipe using 60% carbon fiber and 40% epoxy resin. In the first design, composite winding was done with +45°, 90°, -45°, and 90° angles, and in the second design, composite winding was done with 75°, 90°, -75°, and 90° angles. Analyses were conducted for both designs under 38 MPa internal pressure using the finite element method in the SolidWorks environment. In the analysis, 172252 nodes and a total number of elements of 85984 were determined.

3. RESULTS AND DISCUSSION

Material values and winding conditions are integrated into SolidWorks software. The analysis results were examined according to the Von Mises damage theory criterion. For all analyses, as the precision of the beam elements increases, more precise values can be obtained. The maximum Equivalent stress of +45°, 90°, -45°, and 90° CFRP wound cylinder is shown in Figure 2. The maximum measured equivalent stress is 159.5 MPa. Yield strength was calculated using the offset technique [22,23]. The yield strength of the carbon fiber and epoxy mixture is 1100 MPa [22,23]. When these values were compared, it was determined that the design was 4 times stronger. The F.O.S was measured as 4. F.O.S. calculation is specified in equation 3. When designing a part, care is taken to ensure that the stresses in working conditions are lower than the stress value the material can carry. According to the maximum equivalent stress (von Mises) failure criteria [24], the system is safe if σ_{allow} is greater than or equal to von Mises stress.

$$\sigma_{\text{allow}} = \frac{\sigma y}{F.O.S} \tag{3}$$

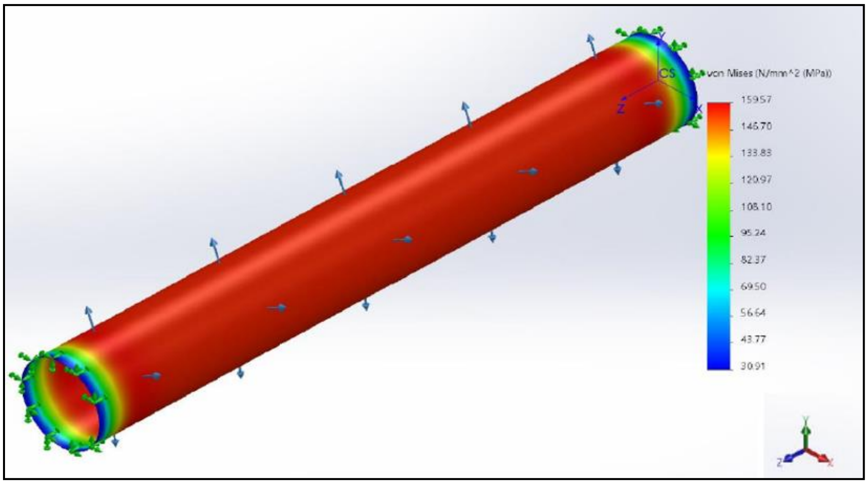

Figure 2. Strength value of +45°, 90°, -45°, 90° CFRP wound cylinder.

Figure 3 shows the maximum Equivalent stress value of the 75°, 90°, -75°, and 90° CFRP wound cylinders. The maximum equivalent stress measured is 120.2 MPa. When these values were compared, it was determined to be 4.4 times stronger. The F.O.S was measured as 4.4.

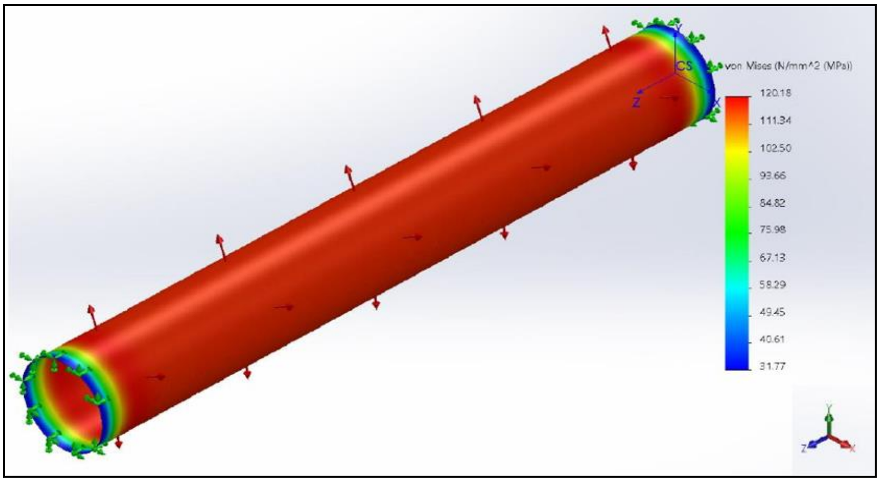

Figure 3. Strength value of +75°, 90°, -75°, 90° CFRP wound cylinder.

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2. CONCLUSION

This study presents the structural advantages of using carbon fiber-reinforced composite materials in hydraulic cylinder designs in aerospace applications. In particular, it has been shown that by selecting the appropriate winding angle and layer sequence, composite hydraulic cylinders can offer higher strength and lightness than cylinders produced from conventional materials. In this context, it was determined that the 75°, 90°, -75°, and 90° winding of the two windings examined had approximately 25% higher strength values than the +45°, 90°, -45°, and 90° winding. To meet the 3.5 F.O.S. required in hydraulic cylinder applications, when the necessary examinations were made according to the Tsai-Hill damage theory, it was found that the F.O.S was 4. Therefore, it was found that the designed hydraulic cylinder was approximately 14% safer. Finally, the results obtained from this study show that composite materials can expand their potential future applications in the aerospace industry.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

Authors' Contributions			
No	Full Name	ORCID ID	Author’s Contribution
1	Zeynep Guler	0000-0001-9673-4735	1, 2, 3, 4
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*In the contribution section, indicate the number(s) that correspond to the relevant contribution type.			
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

Nomenclature

E = Young Modulus
d = Diameter of the cylinder rod
t = Thickness of the cylinder tube wall
d_i = Inner diameter of the cylinder tube
σ_y = Yield stress of the cylinder tube
ν = Poisson ratio

F.O.S.= Factor of safety
σ_{allow} = Allowable stress

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