Design and analysis of hybrid composite-aluminum rocket motor case

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Abstract. Hybrid structures which combined of composite and metals materials are now widely used for design and construction of aircraft structures and rocket components due to the structure type provide lighter weight compared to a structure made entirely of metal. These two materials have different properties such as mechanical and thermal properties. Based on these differences, designing a structure with the optimal weight and assembly position of two different materials is a challenge. The objective of this work is to design a hybrid composite-aluminum rocket motor case that reduces weight to replace the traditional one, which is made entirely from aluminum. Carbon fiber reinforced polymer (CFRP) is used to increase the target range of the rocket and respond more effectively to its mission. The tube produced by a filament winding process and assembled with a threaded plug made of aluminum material, which is the same as the original part. This will result that the tube is strong enough and lighter than the original model. In addition, the connection to the existing parts can be done without the needed to modify the design. The motor case of weather modification rocket (WMR) has been selected for this work. The original design is made from AL6061 T6 with the maximum design pressure 10.4 MPa. This part was then replaced with hybrid composite-aluminum structure. The filament winding angles was designed for composite tube jointed with aluminum structure and analysis by using a commercial finite element software ANSYS. Then the results was consideration according to the failure criteria by using Inverse Reserve Factor (IRF) failure criteria for CFRP and Safety factor (S.F.) for aluminum parts. The results shown that the ply sequence for circumferential filament winding angle $\geqslant 60^\circ$ (± 60, ± 75, ± 85) provide analysis results that the tube can tolerate pressure with safety for all parts. A prototype was then built for mechanical properties and hydro-static pressure test. The study involved examining the adhesion between the matrix and fibers, as well as analyzing the fracture surface characteristics. This was accomplished using a combination of Scanning Electron Microscope (SEM) technique and Energy Dispersive X-Ray Spectroscopy (EDS) for elemental and compositional analysis. As expected the weight of the hybrid composite-aluminum motor case is less than aluminum tube about 38.9%.

Keywords: Composite motor case, Hybrid structural, Filament-wound composite tube, FE analysis

1. Introduction
A hybrid composite-metals structure is a type of structure that combines elements of both composite materials and metals. In such a structure, composite materials, which are typically made of fibers embedded in a polymer matrix, are integrated with metallic components. This integration can take various forms, such as layering composite materials onto metal surfaces, embedding metal components within composite structures, or bonding composite and metal parts together. The goal of using a hybrid composite-metal structure is often to leverage the

unique properties of both materials, such as the high strength-to-weight ratio of composites and the ductility and toughness of metals, to create a structure that exhibits enhanced performance and functionality for specific applications. These structures are commonly used in aerospace, automotive, marine, and construction industries where there is a demand for lightweight, durable, and high-performance materials.

Numerous studies have underscored the superior mechanical properties of hybrid structures over conventional materials. In a comprehensive review conducted by I. Hossam and Sh. Saleh [1], the challenges in designing rocket motor case structures were discussed. They emphasized the prevalence of composite materials in new rocket motor cases, owing to their exceptional strength-to-weight ratio, impact resistance, and design adaptability. Filament winding emerged as the preferred technique for rapid production of rocket motor cases, boasting excellent mechanical properties. Finite element tools like ANSYS and ABAQUE have proven instrumental in analyzing pressure vessels, significantly streamlining the design process. Among several failure criteria for composite materials, including maximum stress and strain, the Tsai-Wu criterion was identified as the most accurate. Echoing findings from Singuru Rajesh and Stein Tenden [2] with Kai Fossumstuen [3], carbon-fiber-reinforced polymers (CFRP) emerged as the optimal choice for constructing rocket motor cases, owing to their exceptional specific strength and the efficacy of filament winding in manufacturing. Utilizing Finite Element Analysis (FEA), S. Sulaiman and S. Borazjani [4] determined the ideal winding angle for CFRP pressure vessels, leveraging multiple failure criteria. Additionally, research by Yu-shan Meng and Li Yan [5] and Mohammad Irshad Ali and J. Anjaneyulu [6] introduced the Inverse Reserve Factor (IRF) parameter for evaluating composite failure, with an IRF greater than 1 signifying potential failure. Ivana Vasović [7] compiled methods for analyzing the strength of composite pipes, emphasizing Epoxy E-Glass fibers manufactured via filament winding. Further, Cevdet Kaynak [8] investigated the impact of resin types on hoop stress in composite pipes, concluding that fiber strength should be the primary consideration regardless of resin type. Collectively, these studies offer valuable insights into selecting appropriate failure criteria for designing rocket motor case made from composite materials. From the research studies conducted, it can be summarized that the design process for hybrid composite-metal structures, such as rocket motor cases, encompasses requirements analysis, material selection, conceptual and detailed design phases, finite element analysis, consideration of manufacturing constraints, prototyping and testing, as well as iterative optimization to achieve optimal performance, weight reduction, functionality, and reliability.

In this work, a hybrid composite-aluminum rocket motor case was design and analysis for replaced a metallic one. The selected materials are CFRP produced by filament winding process and assembled with a threaded plug made of aluminum. Finite element method (FEM) was utilized to investigate the effects of winding angle on filament-wound layers and safety factor of structure were used for structural analysis. IRF and S.F. criterion were selected as failure mode. Then a prototype was built for mechanical properties and hydro-static test.

2. Modeling and simulation

The motor case of weather modification rocket (WMR) was selected for this study. Figure 1 represents the main parts of this WMR are: nose cone, payload1, payload2, motor case and tail section. From the WMR static firing test, the maximum pressure was 10.4 MPa. This traditional rocket motor case weighs approximately 1,940 grams.

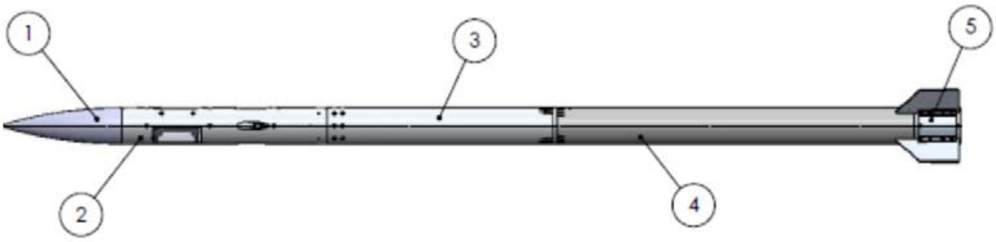


Figure 1 WMR rocket main parts
1. Nose cone, 2. Payload 2, 3. Payload 1, 4. Motor case, 5. Tail section

The aluminum WMR motor case was replaced with hybrid composite-aluminum. High strength moderate modulus carbon fiber and epoxy resin was used for design and analysis. Table 1 represents mechanical properties of the composite material (CFRP) which used for the simulation.
The design of the WMR motor case modified in order to hold the gases pressure especially in the connecting parts with the tube. The new motor case divided to three parts, the CFRP tube, front and rear Screw Adapter Plugs (SAP) (Figure 2). The maximum design thickness of the motor case become 3 mm according to the design drawing. The target of design is to maximize the safety factor for aluminum SAP and minimize the IRF by using Tsai Wu failure criteria. Modeling of composite filaments winding made by Ansys ACP pre-processing. The SAP solid parts modeled by mechanical modeler. The combination of the whole system done in static structural, then the internal pressures was added to the model and solved (Figure 3). The results was then analyzed in Ansys ACP post-processing to get the calculation results for each layers including IRF. From Ansys pre-process the examples ply design angles was show in Figure 6. Minimum of IRF for composite and maximum S.F for aluminum parts is main purpose of this ply design which the angle set to be from ±35° to ±85° (Figure 4).

Figure 2 the modified motor case with Hybrid composite-aluminum

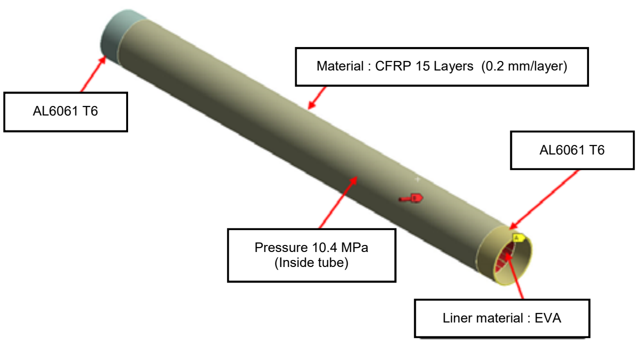
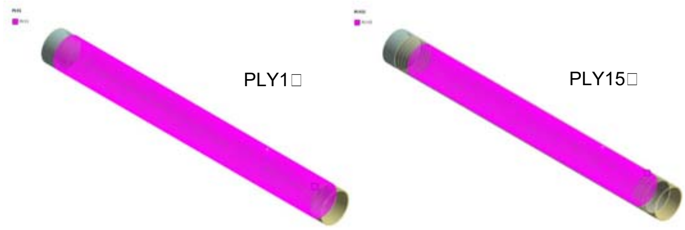


Figure 3 Modeled modified motor case with Hybrid composite-aluminum in Ansys



PLY No.	±35°	±45°	±55°	±60°	±75°	±85°	Mix. Angle1	Mix. Angle2
1	-35	-45	-55	-60	-75	-85	85	85
2	35	45	55	60	75	85	45	60
3	-35	-45	-55	-60	-75	-85	-45	45
4	35	45	55	60	75	85	85	-85
5	-35	-45	-55	-60	-75	-85	45	-45
6	35	45	55	60	75	85	-45	-60
7	-35	-45	-55	-60	-75	-85	85	85
8	35	45	55	60	75	85	45	60
9	-35	-45	-55	-60	-75	-85	-45	45
10	35	45	55	60	75	85	85	-85
11	-35	-45	-55	-60	-75	-85	45	-45
12	35	45	55	60	75	85	-45	-60
13	-35	-45	-55	-60	-75	-85	85	85
14	35	45	55	60	75	85	45	60
15	-35	-45	-55	-60	-75	-85	-45	45

Figure 4 Ply design angles modeling in Ansys

Table 1. Mechanical properties of composite tube.

Properties		Carbon fiber/Epoxy Composite[1]
Yong's Modulus (GPa)	Ex	123.34
	Ey = Ez	7.78
Poission's Ratio	Vxy = Vxz	0.27
	Vyz	0.42
Shear Modulus (GPa)	Gxy = Gxz	5.0
	Gyz	3.08
Tensile Strength (MPa)	Xt	1632
	Yt = Zt	34
Compression Strength (MPa)	Xc	-704
	Yc = Zc	-68
Shear Strength (MPa)	Sxy = Sxz	80
	Syz	55

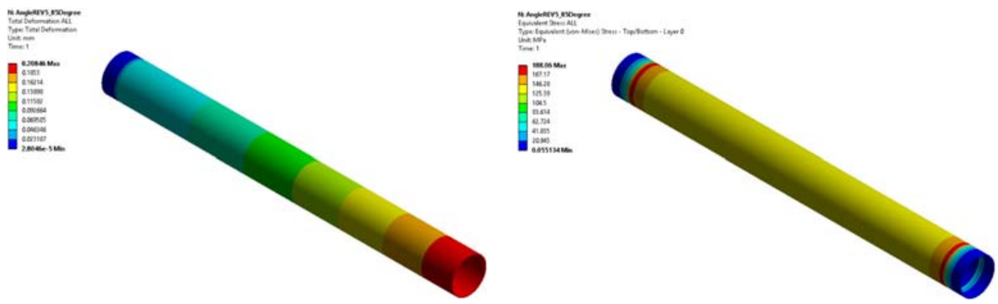
Remark: [1]ANSYS Materials data base

Table 2. Materials and mechanical properties of AL 6061T6.

Properties	AL 6061 T6[1]
Tensile Ultimate strength	310 MPa
Tensile Yield Strength	276 MPa
Poison's ratio	0.33
Modulus of elasticity	68.9 GPa

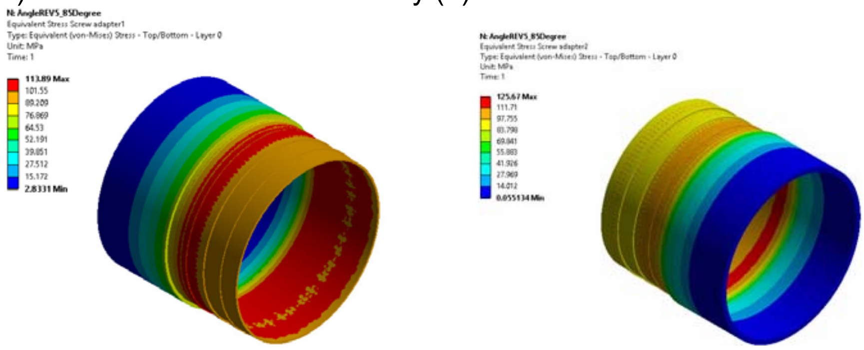
Remark : [1]www.matweb.com

The simulation results of the hybrid composite-aluminum motor case showed in Figure 5-7 and Table 3-4. From the analysis results, it was found that on different components for the winding angles the deformation and von-mises stress exhibited similar behaviors. Therefore, the analysts present the results specifically from using a winding angle of ±85° as an example for the behavior of the components and the Table 4-5 were summarized the analysis results for all winding angle cases.



(a) (b)

Figure 5 (a) Total deformation of assembly (b) Maximum von-Mises stress of assembly



(a) (b)

Figure 6 Maximum von-Mises stress (a) screw adapter plug 1 (b) screw adapter plug 2

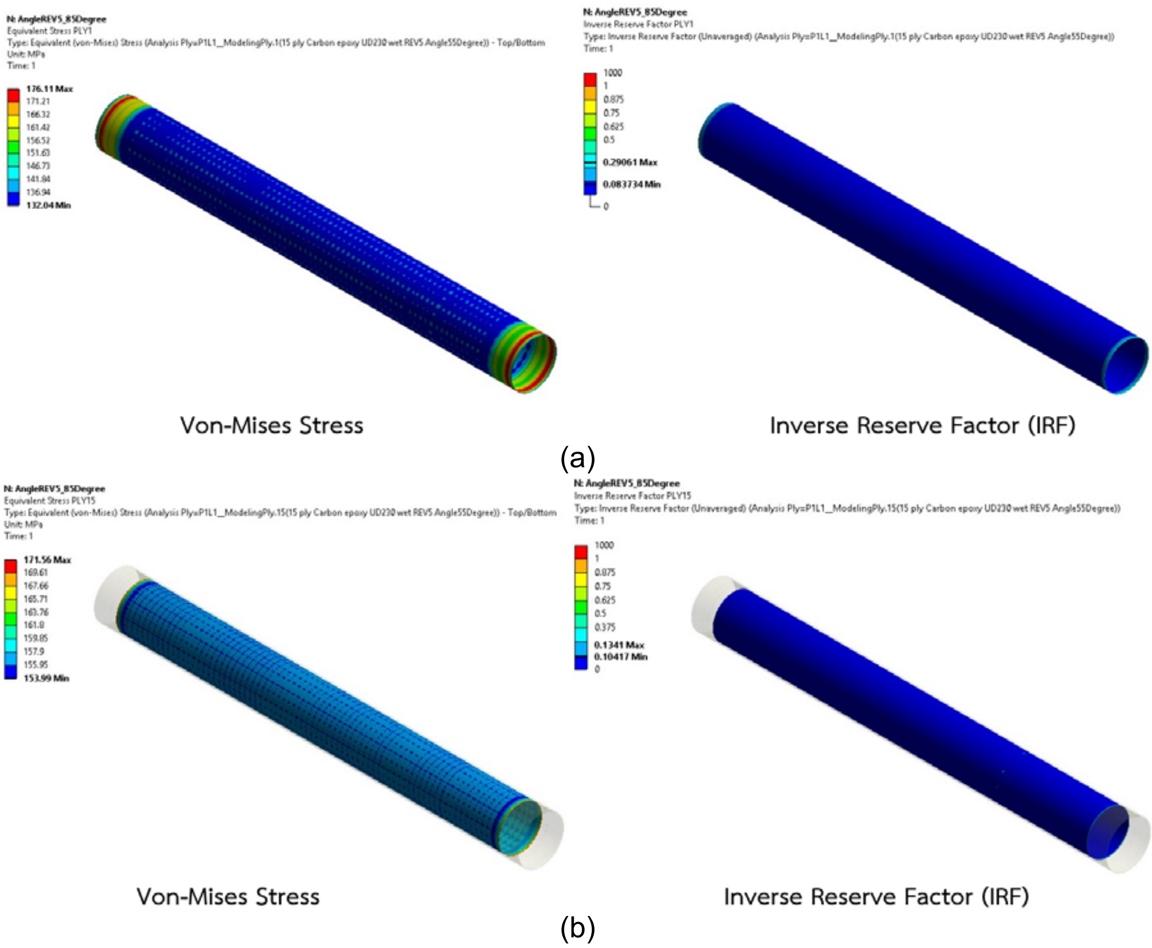


Figure 7 Maximum von-Mises stress and IRF (a) PLY No.1 (b) PLY No.15

Table 3. CFRP tube with 15 layers (±85).

PLY NO.	Thickness (mm)	Winding Angle ±35° Stress (MPa)	Winding Angle ±35° Inverse Reserve Factor (IRF)	Winding Angle ±45° Stress (MPa)	Winding Angle ±45° Inverse Reserve Factor (IRF)	Winding Angle ±55° Stress (MPa)	Winding Angle ±55° Inverse Reserve Factor (IRF)	Winding Angle ±60° Stress (MPa)	Winding Angle ±60° Inverse Reserve Factor (IRF)	Winding Angle ±75° Stress (MPa)	Winding Angle ±75° Inverse Reserve Factor (IRF)	Winding Angle±85° Stress (MPa)	Winding Angle±85° Inverse Reserve Factor (IRF)	Mix. Angle1 Stress (MPa)	Mix. Angle1 Inverse Reserve Factor (IRF)	Mix. Angle2 Stress (MPa)	Mix. Angle2 Inverse Reserve Factor (IRF)
PLY1	0.2	175.70	1.880	152.93	0.862	191.91	0.566	184.21	0.423	177.24	0.242	176.11	0.290	329.33	0.280	271.49	0.163
PLY2	0.2	181.08	1.860	191.44	0.815	204.62	0.561	198.28	0.429	182.25	0.200	178.11	0.250	97.84	0.308	151.34	0.229
PLY3	0.2	169.33	1.890	500.08	0.716	186.28	0.569	181.61	0.428	179.50	0.173	179.12	0.212	111.06	0.304	77.96	0.255
PLY4	0.2	175.07	1.870	185.88	0.813	200.43	0.564	195.34	0.435	184.50	0.172	181.24	0.174	336.72	0.290	282.73	0.169
PLY5	0.2	166.76	1.900	144.92	0.860	183.16	0.573	179.03	0.435	182.10	0.172	182.43	0.136	88.74	0.304	109.70	0.256
PLY6	0.2	172.84	1.880	182.59	0.820	198.10	0.569	194.02	0.444	186.99	0.180	184.64	0.124	101.40	0.303	181.65	0.214
PLY7	0.2	167.69	1.910	144.58	0.863	181.89	0.578	182.26	0.446	185.08	0.183	186.02	0.127	341.73	0.302	281.90	0.167
PLY8	0.2	174.54	1.890	182.89	0.829	198.36	0.575	194.21	0.457	190.92	0.192	188.72	0.138	85.41	0.341	169.79	0.236
PLY9	0.2	170.37	1.920	146.96	0.868	196.00	0.587	195.32	0.462	190.34	0.204	188.14	0.134	95.70	0.304	62.84	0.265
PLY10	0.2	178.03	1.900	186.64	0.840	201.17	0.587	194.74	0.484	192.28	0.221	188.48	0.140	350.67	0.322	294.57	0.211
PLY11	0.2	174.10	1.930	150.82	0.874	187.21	0.682	182.30	0.665	188.83	0.296	185.84	0.143	85.47	0.312	92.77	0.306
PLY12	0.2	182.61	1.920	191.46	0.852	204.74	0.600	199.28	0.539	188.81	0.244	179.82	0.136	84.97	0.309	185.14	0.243
PLY13	0.2	178.81	1.940	155.59	0.881	191.49	0.613	185.04	0.557	171.76	0.250	167.19	0.113	356.99	0.345	295.05	0.259
PLY14	0.2	187.85	1.930	196.91	0.866	209.50	0.616	202.72	0.552	179.60	0.254	170.20	0.119	73.92	0.316	158.20	0.268
PLY15	0.2	184.16	1.970	160.93	0.891	196.71	0.628	189.22	0.560	176.89	0.270	171.56	0.134	82.52	0.321	47.42	0.295

Table 4. Total deformation and maximum von-mises stress of assembly.

Winding Angle	ASSEMBLY Deform. (mm)	ASSEMBLY Stress (MPa)	Motor tube CFRP Stress (MPa)	Screw Adapter 1 Stress (MPa)	Screw Adapter 1 Safety Factor	Screw Adapter 2 Stress (MPa)	Screw Adapter 2 Safety Factor
Mix. Angle 1	1.49	327.75	327.75	206.1	1.34	206.45	1.34
Mix. Angle 2	1.45	270.22	270.22	189.49	1.46	217.44	1.27
Winding Angle ±55 Degree	3.92	339.26	200.6	324.99	0.85	339.26	0.81
Winding Angle ±85 Degree	0.20	188.06	188.06	113.89	2.42	125.67	2.20
Winding Angle ±75 Degree	0.94	189.13	189.13	125.73	2.20	151.5	1.82
Winding Angle ±35 Degree	3.98	668.58	184.16	668.58	0.41	635.81	0.43
Winding Angle ±60 Degree	3.17	261.1	261.1	254.49	1.08	261.1	1.06
Winding Angle ±45 Degree	4.29	469.73	278.42	458.22	0.60	469.73	0.59

Note: A safety factor greater than 1.0 indicates that the component is safe for use. The yield strength of AL6061 T6 used in calculating the safety factor is 276 MPa.

From the analysis results of the designed motor case according to Table 3-4, it is possible to create a graph depicting the relationship for comparison as follows.

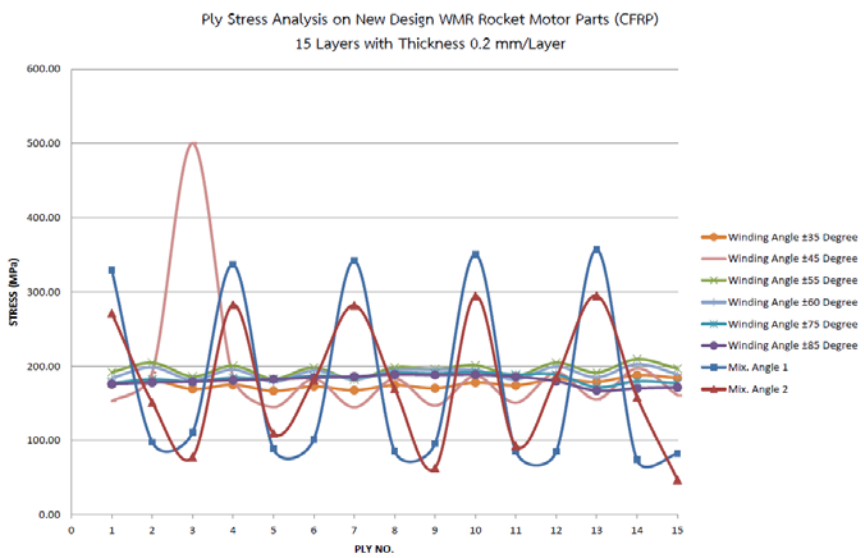


Figure 8 Ply stress analysis for different winding angle

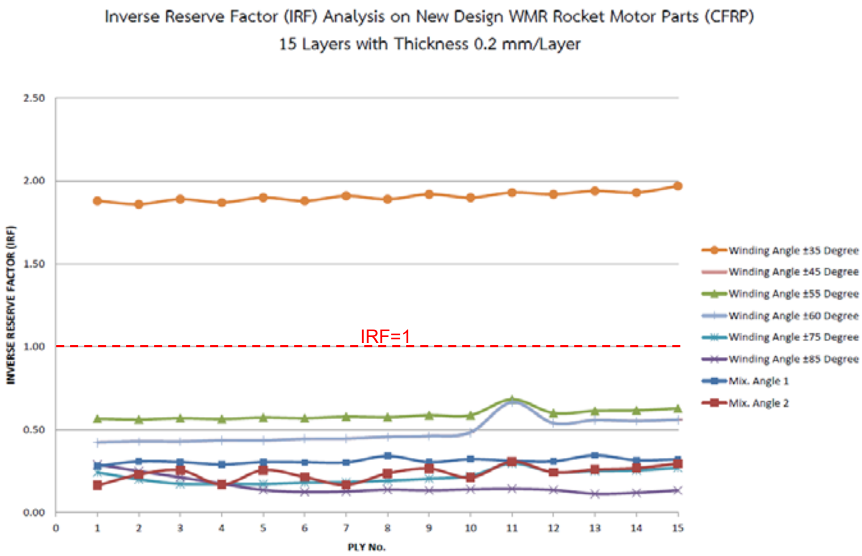


Figure 9 Ply IRF analysis for different winding angle

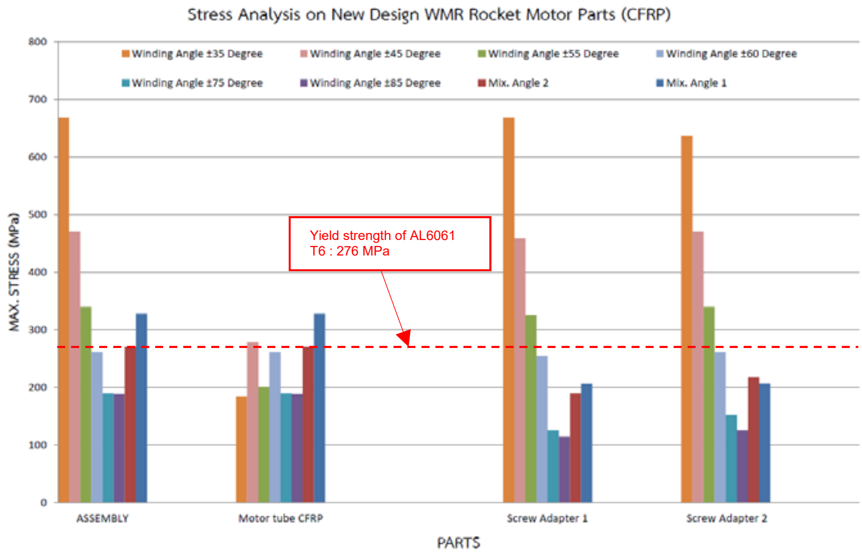


Figure 10 part stress analysis for different winding angle

From Figure 8, it can be observed that the stress values of the composite at winding angles ±55°, ±60°, ±75°, and ±85° are low and relatively consistent across each winding layer. There isn't much variation in stress values among these winding layers.
In Figure 9, considering the Inverse Reserve Factor (IRF) values from the analysis, it is found that winding with 15 layers of CFRP, interfacing with the SAP yields IRF values below 1 for every winding layer. This indicates that no damage occurs to the composite material layers, allowing them to be utilized for experimentation, except for at ±35° winding angles where the IRF value exceeds 1, rendering it unsuitable for use.
In Figure 10, analyzing the stress values separately reveals that the winding angles must exceed ±55° for both SAP1 and SAP2 to tolerate pressure.
In summary, for a safety usage, the winding angles for shaping should exceed ±55°, or as recommended in this report, angles of ±60°, ±75°, and ±85° are preferable. Winding angles below ±55° in the composite section made of CFRP can tolerate pressure but lead to stress values exceeding the capability of the SAP, making it unable to withstand the load.

3. Prototyping and testing results

To prototype a CFRP tube using filament winding, begin by defining specifications and creating a CAD model. Select appropriate carbon fiber material and resin system, and design and produce mandrels accordingly. Set up the filament winding machine, load carbon fiber rovings, and impregnate them with resin before programming the machine for desired fiber orientation. Begin winding process with consistent tension and alignment, following a helical or hoop pattern to achieve desired thickness. Cure the wound tube in an oven or autoclave as per resin system requirements. Post-processing involves removing the cured tube from the mandrel, trimming excess material, and coating for finish. Conduct mechanical testing to evaluate performance, comparing results to design requirements, and document the process for iterative improvements in future iterations.

3.1. Hybrid composite-aluminum motor case prototyping

In this project, carbon fibers with a diameter of 7 µm, YD-128 epoxy resin, and Lindride 46Q catalyst were selected for prototyping using the filament winding process. A filament winding machine operating at a speed of 5 rpm was utilized for this purpose. Following the winding process, the tube was cured in an oven at 160 °C for 2 hours and 40 minutes. Subsequently, excess materials were removed using a turning machine based on the provided drawing specifications, and the surface was refined with a resin coat. the summary of process is show in Figure 11 and finished part is show in Figure 12. The prototype rocket motor case using this hybrid composite-aluminum structure has a total weight of 1,185 g. Compared to the original model made of aluminum (1,940 g), it is found that the weight was decreased by 38.9%.

Figure 11 Hybrid composite-aluminum motor case prototyping processes

Figure 12 Hybrid composite-aluminum motor case prototype

3.2. Properties testing

The prototype was subjected to preliminary property testing as follows: General properties of CFRP including of density test according to ASTM D792 standard, hoop tensile strength test by split disk method according to ASTM D2290 standard. Following these tests, the adhesion between the matrix and fibers and the fracture surface characteristics was studied, utilizing Scanning Electron Microscope (SEM) technique combined with elemental and compositional analysis using Energy Dispersive X-Ray Spectroscopy (EDS). Apart from testing the properties of the CFRP material, the prototype was also tested for its ability to tolerate pressure according to the design. This was done to ensure that it could withstand pressure without damage and leakage, using a hydro-static pressure test of 10.4 MPa only in the radial direction (hoop pressure test). The detailed of jig fixture for hydro-static test and pressure profile is show in Figure 13.

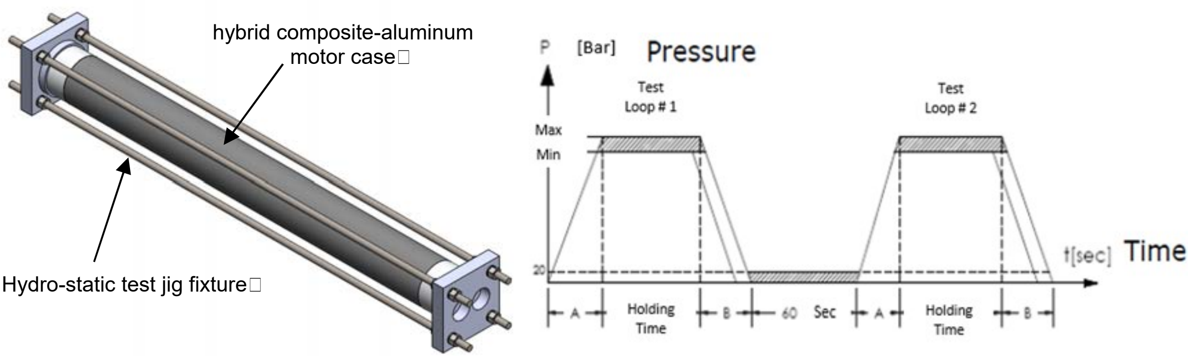
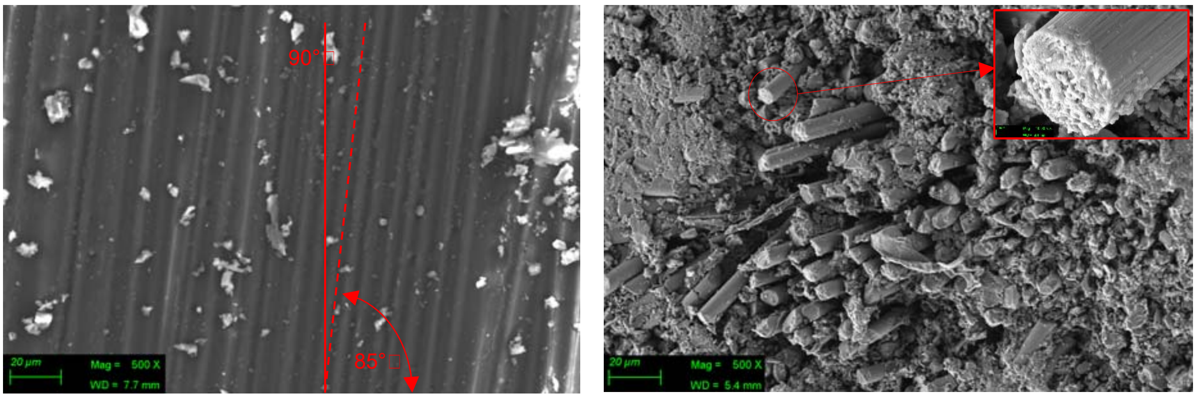


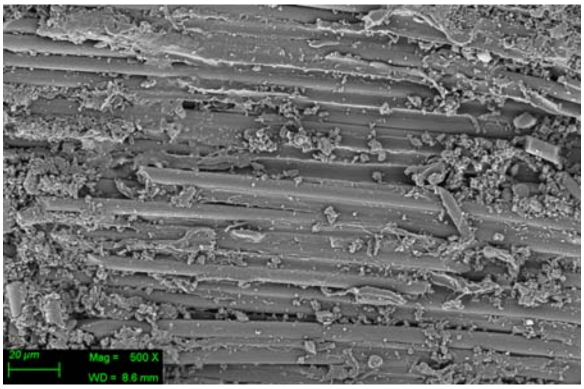
Figure 13 Jig fixture for hydro-static test and pressure profile

3.2.1. General properties

The area of the motor case made of CFRP material was cut into small pieces and subjected to density testing according to ASTM D792 standards. It was found that the average density was 1.4850 g/cm^3. Subsequently, examination using Scanning Electron Microscope (SEM) revealed good bonding between the carbon fibers and the resin, without any gaps between the fibers as shown in Figure 14.



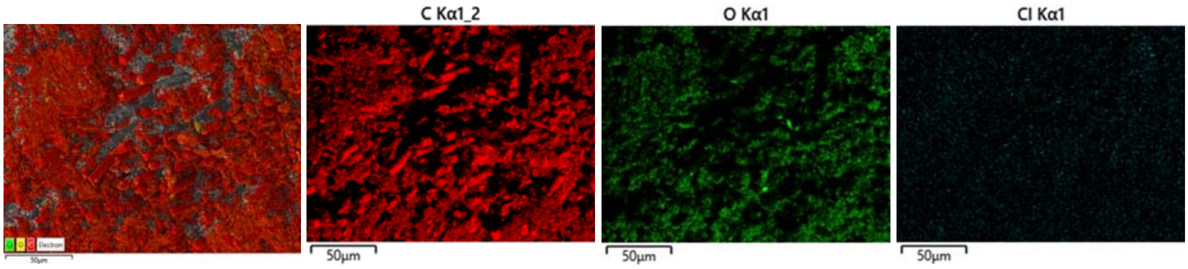
(a) (b)



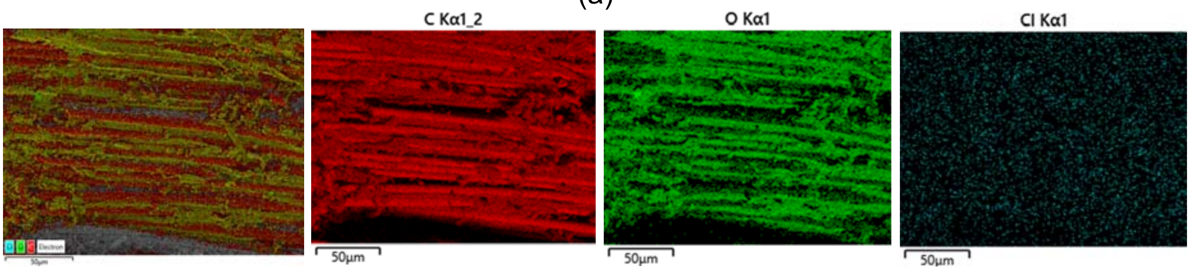
(c)

Figure 14 CFRP region observed by SEM
(a) radial direction (b) longitudinal cross-section (c) transverse cross-section

From Figure 14 (a), it is found that the adhesion between the matrix and fibers is good, with no gaps occurring at the winding angle of 85°. The cross-sectional image in longitudinal direction of the tube illustrates the fiber density per unit area and the adhesion of the matrix on the surface of the fibers, indicating that the selected matrix for production is appropriate as shown in Figure 14 (b). Figure 14 (c) shows the fiber arrangement in the layer of winding, revealing that the matrix can effectively penetrate between the gaps of each fiber.



(a)



(b)

Figure 15 Elemental and compositional analysis of CFRP region by using EDS
(a) longitudinal cross-section (b) transverse cross-section

The elemental and compositional analysis of the CFRP material using EDS, as shown in Figure 15, reveals approximate compositions of carbon (C) at about 83.33%, oxygen (O) at 15.86%, and chlorine (Cl) at 0.81%.

3.2.2. Hoop strength

The 10 tons universal tensile testing machine was used for hoop tensile strength testing by split disk method according to ASTM D2290 and tested specimen show in Figure 16. Subsequently, the fracture surface was analyzed using SEM technique, as depicted in Figure 17.

Figure 16 Hoop tensile strength testing for CFRP (±85)

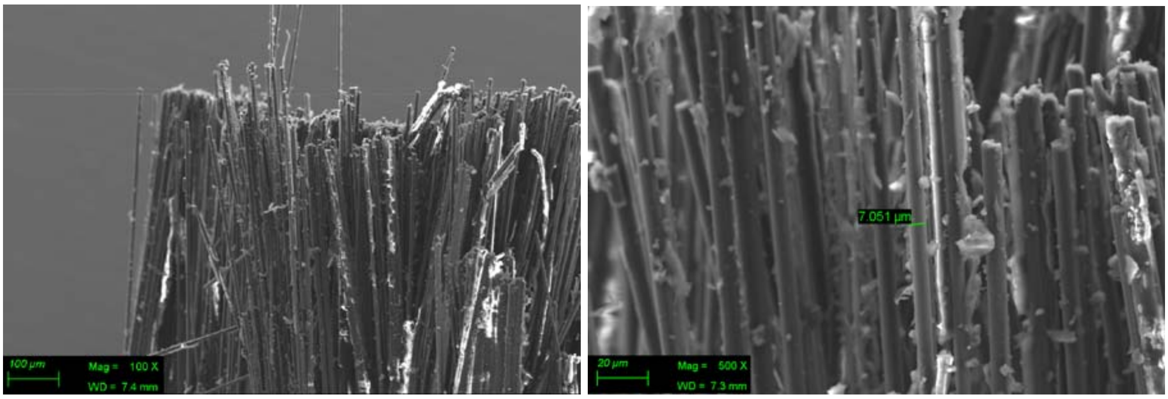


Figure 17 Fracture surface analyzed by using SEM

The hoop tensile strength test results, conducted according to ASTM D2290 standards, revealed that the CFRP has an average hoop tensile strength of 738.91 MPa. This value is derived from testing five samples, with a standard deviation of 64.04 MPa.

From Figure 17, it can be observed that the fracture of the CFRP material begins with damage to the matrix first (delamination), followed by the fibers being tensioned by the force until reaching the ultimate tensile strength, causing the fibers to break. This can be noticed from the area of fractured fiber surfaces, where each fiber tends to separate from one another. A brittle fracture characteristics was found by examining the fractured fiber surfaces.

3.3. Hydrostatic testing

The prototype has been tested for its ability to withstand pressure, using hydro-static test. It was installed with a jig fixture and subjected to water pressure testing following the setup depicted in Figure 13. From the testing results, it was found that the motor case can tolerate pressure according to the test specifications without experiencing damage or leakage, as shown in Figure 18.

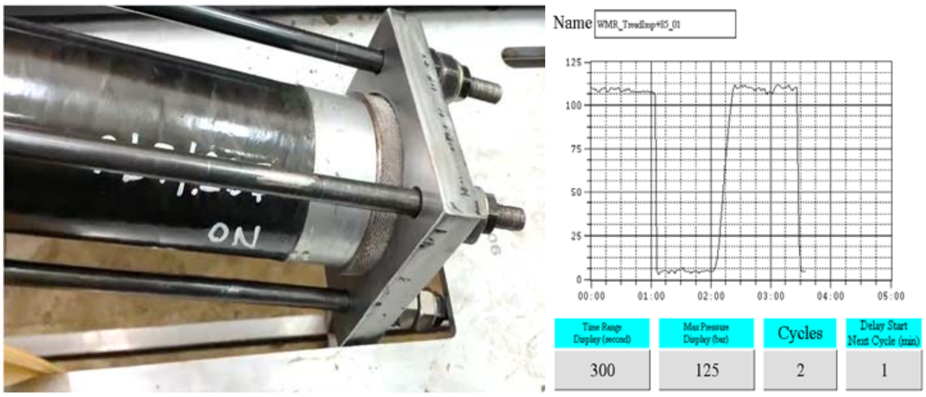


Figure 18 Hydro-static testing results

4. Conclusions

In this work, Ansys workbench components was used for CFRP winding angle and structural analysis for the hybrid composite-aluminum rocket motor case. The motor case was designed in order to hold the rocket motor working pressure, which is about 10.4 MPa without losing the benefit of weight gain given by composite material over metallic material. The weight of the composite-aluminum tube was around 61% of the metallic tube. The filament winding angle design and structural analysis was used to find the safety ply angles, which minimize the inverse reserve factor (IRF) for CFRP and Safety factor grater than 1 for aluminum. The results shown that the ply sequence for circumferential filament winding angle $\geqslant 60^\circ$ (± 60, ± 75, ± 85) provide a safety for all parts. A prototype with winding angle $\pm 85°$ was chosen and produced for the properties test including mechanical properties and hydro-static pressure test. Upon examining the properties of the prototype, it was found that CFRP has a density of 1.485 g/cm3, according to ASTM D792 standards. Upon inspection, it was confirmed that the adhesion between the resin matrix and the fibers in the CFRP material is complete, supported by SEM analysis. Elemental analysis via EDS revealed carbon content at around 83.33%, oxygen at 15.86%, and chlorine at 0.81%. The hoop tensile strength test conducted per ASTM D2290 standards yielded an average strength of 738.91 MPa from five samples, with a standard deviation of 64.04 MPa. SEM examination of fractured fiber surfaces indicated brittle fracture characteristics. Hydrostatic testing affirmed the motor case's ability to withstand designed pressure, utilizing fixed jig fixtures to prevent longitudinal movement, demonstrating pressure resistance in the radial direction (Hoop) only. Notably, the hybrid composite-aluminum motor case weighed approximately 38.9% less than an aluminum tube, aligning with expectations.

5. Acknowledgments

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