Composite wing structure of light amphibious airplane design, optimization, and experimental testing

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A B S T R A C T

A lightweight amphibious aircraft hybrid composite wing was designed and optimized in this study. The Ansys Composite PrepPost and Ansys Mechanical Module use finite element modeling to simulate and assess the static structural test. It is possible to build a lightweight and cost-effective composite wing by balancing the amount and orientation of carbon fiber and glass fiber ply patterns. The BII2 wing design case (spar/rib/skin : [(±45)C, (0/90)C, …]25/(±45)C, (0/90)C, (±45)C, F]6/(±45)C, (0/90)C, F) is the best option of 72 cases, with a total weight of 44.96 kg and a manufacturing cost of 1,288 USD. The optimal design composite wing mock-up was built and tested on a universal test rig. The test demonstrated that the optimal wing design could withstand the maximum load (±6G and -3G) without structural collapse. The experimental structural deformation and elastic strain were consistent with the FEM model, within an acceptable error range.

1. Introduction

In the aerospace industry, composite materials are becoming more popular due to their high stiffness-to-weight and strength-to-weight ratios, and improved corrosion resistance and resistance to fatigue damage (Nurhaniza et al., 2009). Composite materials can be molded into large integrated structures such as airplane wings and fuselages (Elaldi, 2005). Traditional E-type glass fiber composites offer adequate strength at a low cost, making them excellent for interiors or small components that are not subjected to substantial loads or stress (Mili and Necib, 2009). Carbon fibers are gaining popularity in applications requiring limited flexibility. Although carbon fiber is more costly (approximately 8–10 times more expensive than E-glass) and has a lower compressive strength, glass fiber has a lower tensile modulus, a higher strain-to-failure ratio, and the capacity to bend and absorb more strain without breaking. Carbon fibers are more prone to misalignment during production. Industry and academics have taken an interest in hybrid composites that blend carbon and glass fibers (Cairns and Wood, 2009). Hybrid composites mix carbon and glass fibers into a single matrix to combine the advantages and compensate for the disadvantages of each (Mishnaevsky, 2012). Researchers are currently experimenting with different techniques to obtain the optimal blend of carbon and glass fibers to provide the best technical solution.

Hybrid composites are becoming increasingly popular among small- and medium-sized manufacturers; advanced composite technology allows rapid assembly of light airplanes. General aviation is expected to grow at an exponential rate in the coming years. Civil aviation authorities must provide instructions and regulations regarding light aircraft standards. ASTM F-2245 (Standard Specification for Design and Performance of a Light-Sport Airplane) has been approved by the Federal Aviation Administration (FAA), and has been used worldwide to demonstrate compliance for airplane structure and flight safety since it was introduced in 1982 (ASTM F2245-20, 2020).

Manders and Bader (1981) examined the hybrid effect and strain increase of a carbon/glass-fiber composite hybrid. With the superior elongation of glass fiber, the failure strain increases as the amount of glass fiber in the composite increases. According to Shan et al. (2002), hybrid composites outperform glass composites in both wet and dry conditions. Belingardi and Cavatorta (2006) demonstrated that when bending fatigue is applied to a hybrid composite, a configuration of carbon fibers on the outer surface and E-glass in the middle improved the bending fatigue characteristics. Cavatorta (2007) added that the exterior carbon fibers of the structure provide the majority of the strength. As the flexural strength is determined by the strength of the bottom layer, Hung et al. (2018) demonstrated that using carbon fibers in both the top and bottom layers may help reduce damage and deflection.

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Zhang et al. (2012 a, b) observed that the stacking sequence had no significant effect on the tensile characteristics of the material, but had a considerable impact on its flexural and compressive properties. When flexural loads are applied, hybrid composites exhibit greater matrix failure and reinforcement failure than traditional composites. Cavatorta (2007), demonstrated that hybrid composites containing 50% carbon fiber exhibited the best flexural properties when the carbon layers were located on the outside of the composite. Prabhakaran et al. (2013) reported that the tensile and compressive characteristics of hybrid composite materials are intermediate between those of conventional glass/epoxy composites and non-hybrid carbon/epoxy composites.

Hybrid materials have great potential in terms of longevity and damage resistance, and should be examined experimentally and theoretically although their performance is dependent on a variety of microstructural and loading parameters (Dai and Mishnaevsky, 2014). By following a general rule of mixing (RoM), the mechanical properties required in a range of settings can be readily obtained. According to Dong (2016), hybrid effects are a possibility that contrast with what may be observed in nature at the molecular level. The flexural characteristics of carbon/glass fiber-reinforced epoxy hybrid composites differ significantly from those of other composites. Buddi et al. (2015) demonstrated that the finite element model could be used to predict the characteristics of composite materials by comparing their experimental findings to the RoM and Halpin–Tsai criteria. Dulgheru et al. (2012) discovered that the simulation inaccuracy using ANSYS APDL compared to experiments was approximately 20%.

In conjunction with optimization techniques, the FEM for structural analysis and the FDM for aerodynamic analysis can be used to find the best structural design to satisfy all design requirements, allowing for the most efficient method. In 2011, Ren et al. (2011) investigated the use of RSM in conjunction with finite element structural analysis. Venkatesh et al. (2014) used FEM in combination with RSM and the design of experiments (DoE) approach to optimize truck chassis design. Ozroy and Kurmaz (2016) developed an alternate method for identifying the three best candidates before selecting one for production. Cayiroglu et al. (2016) optimized wing aerodynamics using genetic algorithms and ANSYS Fluent to minimize drag. This method is computationally expensive, but allows the design variable to be computed within a restricted range of possible values. Rajadurai et al. (2017) used ANSYS ACP to analyze three wing models with different materials and ply. They concluded that a [0/90/+45/−45/90/0] ply sequence demonstrated the best performance of the three models. Shrivastava et al. (2018) studied the weight optimization of multi-laminated aerospace structures using a genetic algorithm with ANSYS ACP. The optimization procedure for a transport aircraft wing torsion box indicated a 29% weight reduction compared to a quasi-isotropic laminated structure, and a 54% weight reduction compared to a metallic structure. The objective of this study is to minimize the weight and cost of spars, ribs, and wing skin with the aerodynamic wing load constraint stated in the standard.
Section 2 presents the basic design and dimensions of a light composite amphibious airplane, and the material data validation method used to build the aircraft. Subsection 2.1 illustrates the failure of a polymer matrix composite material (PMC) specimen exposed to tensile load in accordance with the usual stress-strain curve of the standard. Section 3 presents the findings of a static optimization study of hybrid carbon/glass composites performed in ANSYS Composite PrepPost (ACP) and ANSYS Mechanical Module (AMM) to determine the best ply pattern to achieve a good balance of weight and cost while maintaining the required safety margins. The validation of the optimal design is presented in Section 4, through an experiment that conforms to the ASTM F-2245 standard. The dependability of the wing design in terms of wing deflection is discussed in Section 5. Section 6 presents a summary and conclusions.

2. Light amphibious airplane design and dimensions

With a maximum takeoff weight of less than 650 kg, a light amphibious airplane is classified in the light sport aircraft category. The fuselage is a monocoque design with a strut-braced high-wing monoplane, retractable landing gear, and a powerful 115 Hp Rotax 914 F piston engine with three blades of constant pitch propeller installed as a "pusher" high-wing configuration. The main airplane structure is mostly composed of composites, with the benefits of lightweight control and enhanced strength. The features and dimensions of the airplane are shown in Figure 1.

Composite materials consist of two or more elements linked together as reinforcements (fibers) and a matrix (resin). Combining the best attributes of each material, composites may exhibit improved properties that the component materials do not exhibit on their own (Potter, 1996). Individual plies of fibers are usually embedded layer-by-layer into a polymer matrix to form composite materials. The stiffness and strength of composites vary depending on the fiber orientation in the layered structure of the material. The best characteristics may be obtained by aligning the fiber direction with the main load direction (Mangalgiri, 1999).

The initial wing design is a mono-spar I-shaped design that supports static and aerodynamic loads. Eleven C-shaped ribs are distributed across the wing. Aluminum alloy struts connect the fuselage and rib #6 in the left and right wings, creating a closed-loop structure. Woven carbon fiber (TEANAXW-3136 by DIAB, Inc.), woven glass fiber (SW110C-100A by DIAB, Inc.), and foam core (H60-4PSC by DIAB, Inc.) were used as base composite materials. The matrix formed by a mixing ratio of 100:34 for...
the resin (EPOTEC YDL 579 by ADITYA BIRLA CHEMICALS, Ltd., Thailand) and hardener (EPOTEC TH 8377M by ADITYA BIRLA CHEMICALS, Ltd., Thailand), with woven carbon fiber or glass fiber, was a polymer matrix composite material (PMC) used to build the spar, ribs, and wing skin.

2.1. Material data validation

Validation of the composite material is required prior to construction of the spar, ribs, and wing skin. PMC specimens were prepared according to ASTM D 3039/D 3039M, 2014 and ASTM D 3518/D 3518M, 2018 (Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials and Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate) and tested on an Instron 5567 universal testing machine (Instron Ltd., USA). From June 2018 to July 2020, at least three specimens were tested for each case to evaluate and verify the mechanical properties of PMC, summarized in Table 1, and the cost of raw materials received from the manufacturer, Asia Aviation and Technology Co., Ltd., Thailand. Figure 2 shows the failure type of PMC made with carbon woven fabric and woven glass fabric subjected to a tensile test. The 0/90° carbon-woven and 0/90° glass-woven fabric had linear responses under tensile load and failed with no transition region (a significant change in the slope of the stress–strain curve). The ±45° carbon-woven and ±45°

Table 2. Ply pattern of case studies: C, carbon fiber; G, glass fiber; F, foam core; S, symmetry.

| Case | Spar's Ply Pattern | No. of Plies | Case | Ribs' Ply Pattern | No. of Plies | Case | Wing Skin's Ply Pattern | No. of Plies |
|------|-------------------|-------------|------|-------------------|-------------|------|------------------------|-------------|
| A    | [(±45)_C, (0/90)_C, …] | 16          | I    | [(±45)_C, (0/90)_C, F] | 4           | 4    | [(±45)_C, (0/90)_C, (±45)_C, F] | 4           |
| B    | [(±45)_C, (0/90)_C, …] | 20          | II   | [(±45)_C, (0/90)_C, (±45)_C, F] | 6           | 5    | [(±45)_C, (0/90)_C, F] | 2           |
| C    | [(±45)_C, (0/90)_C, …] | 24          | 6    | [(±45)_C, (0/90)_C, (±45)_C, F] | 3           | 7    | [(±45)_C, (0/90)_C, (±45)_C, (0/90)_C, F] | 4           |
|      |                   |             | 8    | [(±45)_C, (0/90)_C, (±45)_C, (0/90)_C, (±45)_C, F] | 5           |
|      |                   |             | 9    | [(±45)_C, (0/90)_C, (±45)_C, F] | 3           |
|      |                   |             | 10   | [(±45)_C, (0/90)_C, (±45)_C, (0/90)_C, F] | 4           |
|      |                   |             | 11   | [(±45)_C, (0/90)_C, (±45)_C, (0/90)_C, (±45)_C, F] | 5           |
|      |                   |             | 12   | [(±45)_C, (0/90)_C, (±45)_C, (0/90)_C, F] | 6           |

Figure 5. Finite element model.
glass-woven fibers have a transition region before reaching maximum shear, per the ASTM D3518/D3518M standard.

3. Static optimization simulation analysis

The goal of this study is to reduce the weight and cost of the spar, ribs, and wing skin while meeting the conventional aerodynamic wing load requirements (Thianwiboon, 2019). The original design emphasized the strength of the spar, which was made mainly from carbon fiber to support major bending and twisting loads. The number of plies for the spar was assumed to be 16, 20, or 24 layers in cases A, B, and C, respectively (Fleuret et al., 2016). All wing ribs in an airfoil shape that support the twisting load were modeled to be four and six layers of carbon fiber and glass fiber with a foam core in the middle, denoted as cases I and II, respectively. For the upper and lower wing skin, there were a total of 72 case studies for FEM analysis consisting of carbon fiber, glass fiber, and foam core. Figures 3 and 4 show the stack-up cases of the spar and ribs, respectively. The spar, wing rib, and wing skin details are summarized in Table 2.

The wing optimization was conducted by entering all material data attributes from the previous section into ACP and AMM. The surface model was used to build the wing model, which is composed of a prominent quadrilateral element with a global size of 15 mm. To improve precision, mesh refinement was limited to 8 mm around the joint region. The model had 91,920 elements and 96,709 nodes (see Figure 5). The upper and lower wing skins were strengthened by the main spar, the
Table 3. Maximum stress on carbon fiber, glass fiber, maximum displacement, and total mass of the 72 design case studies.

| CASE | Max Stress on Carbon Fiber (MPa) | Max Stress on Glass Fiber (MPa) | Max Deformation (mm) | MASS (kg) | CASE | Max Stress on Carbon Fiber (MPa) | Max Stress on Glass Fiber (MPa) | Max Deformation (mm) | MASS (kg) | CASE | Max Stress on Carbon Fiber (MPa) | Max Stress on Glass Fiber (MPa) | Max Deformation (mm) | MASS (kg) |
|------|----------------------------------|---------------------------------|----------------------|-----------|------|----------------------------------|---------------------------------|----------------------|-----------|------|----------------------------------|---------------------------------|----------------------|-----------|
| A1   | 480.23                           | 60.02                           | 37.09                | 38.71     | B1   | 438.71                           | 40.02                           | 39.32                | 30.01     | B1   | 399.32                           | 48.06                           | 51.94                | 154.37    |
| A2   | 445.25                           | 225.23                          | 55.23                | 40.96     | B2   | 430.33                           | 177.23                          | 37.27                | 43.19     | C2   | 387.42                           | 158.34                          | 25.54                | 59.69     |
| A3   | 420.29                           | 210.23                          | 52.19                | 44.84     | B3   | 423.89                           | 173.47                          | 35.04                | 47.07     | C3   | 379.21                           | 154.37                          | 28.07                | 55.81     |
| A4   | 415.36                           | 205.18                          | 50.22                | 48.72     | B4   | 405.55                           | 170.13                          | 32.21                | 50.95     | C4   | 384.67                           | 148.92                          | 21.21                | 59.69     |
| A5   | 445.21                           | 52.12                           | 40.69                | 42.44     | B5   | 38.14                            | 42.92                           | 35.08                | 46.80     | C5   | 372.45                           | 152.17                          | 22.15                | 55.54     |
| A6   | 423.11                           | 215.56                          | 50.02                | 44.57     | B6   | 407.38                           | 168.12                          | 35.08                | 46.80     | C6   | 370.78                           | 146.78                          | 20.22                | 59.42     |
| A7   | 420.21                           | 205.56                          | 45.17                | 48.45     | B7   | 400.34                           | 165.11                          | 33.23                | 50.68     | C7   | 370.78                           | 146.78                          | 20.22                | 59.42     |
| A8   | 410.11                           | 196.95                          | 40.01                | 52.32     | B8   | 390.87                           | 162.12                          | 28.34                | 54.55     | C8   | 365.33                           | 132.02                          | 18.31                | 63.30     |
| A9   | 413.96                           | 54.23                           | 44.30                | 389.56    | B9   | 34.23                            | 46.53                           | 37.32                | 49.04     | C9   | 373.26                           | 152.29                          | 19.04                | 59.15     |
| A10  | 407.77                           | 209.98                          | 50.02                | 48.17     | B10  | 369.97                           | 155.39                          | 32.11                | 50.40     | C10  | 368.25                           | 152.29                          | 19.04                | 59.15     |
| A11  | 401.11                           | 199.91                          | 45.25                | 52.05     | B11  | 358.34                           | 151.34                          | 27.19                | 54.28     | C11  | 360.02                           | 148.88                          | 18.89                | 63.02     |
| A12  | 398.78                           | 188.66                          | 41.13                | 55.93     | B12  | 352.55                           | 148.23                          | 23.17                | 58.16     | C12  | 352.43                           | 140.22                          | 16.22                | 66.90     |
| A11  | 474.44                           | 52.21                           | 39.35                | 395.33    | B11  | 35.24                            | 41.58                           | 37.48                | 28.88     | C11  | 374.98                           | 159.56                          | 22.76                | 58.08     |
| A12  | 443.21                           | 189.49                          | 50.23                | 43.23     | B12  | 383.53                           | 148.65                          | 32.21                | 45.46     | C12  | 360.96                           | 165.23                          | 25.31                | 54.20     |
| A13  | 430.59                           | 180.23                          | 45.77                | 47.10     | B13  | 380.98                           | 142.32                          | 28.27                | 49.33     | C13  | 350.11                           | 159.56                          | 22.76                | 58.08     |
| A14  | 424.78                           | 175.11                          | 41.19                | 50.98     | B14  | 372.24                           | 134.21                          | 24.33                | 53.21     | C14  | 345.45                           | 150.04                          | 18.31                | 61.95     |
| A15  | 440.45                           | 47.23                           | 42.95                | 381.22    | B15  | 27.11                            | 45.19                           | 355.21                           | 24.51                | C15  | 353.21                           | 24.51                |
| A16  | 427.45                           | 182.13                          | 45.05                | 46.83     | B16  | 374.76                           | 140.33                          | 25.03                | 49.06     | C16  | 350.04                           | 146.23                          | 23.72                | 57.80     |
| A17  | 413.44                           | 180.03                          | 40.23                | 50.71     | B17  | 369.38                           | 134.55                          | 22.72                | 52.94     | C17  | 334.31                           | 135.66                          | 22.19                | 61.68     |
| A18  | 406.67                           | 178.81                          | 38.41                | 54.59     | B18  | 360.45                           | 125.33                          | 20.98                | 56.82     | C18  | 310.77                           | 130.61                          | 18.64                | 65.56     |
| A19  | 421.33                           | 44.92                           | 46.56                | 378.12    | B19  | 25.01                            | 48.79                           | 321.23                           | 23.66                | C19  | 321.23                           | 23.66                |
| A110 | 413.03                           | 176.12                          | 42.21                | 50.44     | B110 | 370.07                           | 136.21                          | 22.55                | 52.67     | C110 | 300.31                           | 130.27                          | 20.12                | 61.41     |
| A111 | 400.23                           | 168.12                          | 40.01                | 54.32     | B111 | 365.41                           | 130.03                          | 20.19                | 56.55     | C111 | 289.34                           | 112.19                          | 17.71                | 65.29     |
| A112 | 394.55                           | 162.76                          | 37.72                | 58.19     | B112 | 353.45                           | 125.21                          | 18.84                | 60.42     | C112 | 250.12                           | 108.24                          | 15.21                | 69.17     |
With the assumptions for structural tests, the surface of rib 1 was chosen as the fixed support, and the surface of rib 6 connecting to the wing post was chosen as the displacement support. The aerodynamic loads applied on both sides of the wing were determined according to ASTM F-2245. As the ultimate load (+6G,-3G) is determined as 1.5 times the limited load, (+4G,-2G) was the maximum loading criterion for the wing structure to comply with the standard. The ultimate load at +6G was applied to the wing model; the maximum stress in the material must
be under the stress limit. The +6G distributed load over each wing area was transformed into four point loads of 6,500 N, 6,300 N, 3,500 N, and 3,200 N applied at ribs 2, 4, 6, and 9, respectively, as shown in Figure 7.

3.1. Simulation results

A total of 72 wing hybrid composite structures were analyzed; the maximum stress on the carbon fiber layer, glass fiber layer, and total displacement associated with the mass are presented in Table 3. With the maximum stress limit criteria and a weight limit on each wing of 50 kg, seven candidate cases (BII9, BII2, BII3, BII15, BII16, BII19, CI1) were identified and finalized to the optimum design according to cost criteria. The simulation sample of the equivalent stress on the carbon fiber layer, the glass fiber layer, the equivalent stress on the carbon fiber layer, particularly on the spar, and the total displacement for case BII2 are shown in Figures 8, 9, 10, and 11, respectively. Figure 12

Figure 11. Total deformation at +6G.

Maximum Stress in Carbon Fiber, Glass Fiber, and Mass in 72 Case Studies

Figure 12. 3-D plot of all case studies concerning weight, carbon-fiber stress, and glass-fiber stress (optimal design case BII2 is highlighted in feasible region).
shows a 3-D plot of all cases associated with the maximum stress limit and weight.

3.2. Optimum design solution

Of the candidate cases that met the stress limit and weight criteria in Table 4, the minimum weight occurs in case BII5, and the lowest material cost occurs in case BII2. Thus, there are different optimum design solutions for the objectives of mass and cost. However, when we consider these two candidates closely, BII2 is a better choice for the final design because the material cost can be reduced by up to 11.8% (152.85 USD) with a weight gain of only 0.6% (0.27 kg).

4. Experiment setup

A universal test rig was built to verify the strength of the aircraft structure (Dongming et al., 2014), as shown in Figure 15. The test rig consisted of the main platform covering the entire aircraft wingspan, three ring fixtures for holding the aircraft body, and a frictionless sliding mechanism connected with the ring fixtures for drop test purposes. Eight hydraulic jacks powered by a 5.0 HP hydraulic pump, shown in Figure 16, were used to apply the upload and download to the main wing. Three additional hydraulic jacks were used for stabilizer upload and download and side-load testing; two hydraulic jacks were used for fuselage torsion tests. All forces from the hydraulic jacks were measured through a load cell installed at the tip of each jack. The pressure and stroke of each jack were controlled and adjusted by a modular pressure control module consisting of a hydraulic directional control valve, a pressure-reducing valve, a modular pilot-operated check valve, and a hydraulic solenoid valve to achieve the desired load pattern on both sides of the wing. This is semi-manual control as there is no automatic controller in this setup; the accuracy and performance of the test system are satisfactory.
All loads were applied through wooden shrouds wrapped around the wing to avoid skin damage during application of test loads. The set of National Instruments data acquisition systems includes a 2.7 GHz Dual-Core Processor PXIe-8840 Embedded Controller, a PXIe-4330 strain/bridge input module, and a PXIe-4302 analog input module to collect the necessary parameters including displacement, force, and strain. Strain gauges for composite types and light sensors were used to measure the strain and deflection at the assigned locations (Chinvorarat et al., 2019). Figure 17 shows the light amphibious airplane in the universal test rig, ready for the test to verify the strength of the airplane structure.

4.1. Wing load test verification

The purpose of static testing is to validate the strength and safety of the airplane structure design (Petrašinović et al., 2017). According to ASTM F-2245, the test program is performed in several parts of the airplane including the main wing with symmetric and asymmetric loads, vertical fin loads, horizontal fin loads, flap loads, aileron loads, engine loads, drop tests, and water load conditions. ASTM F-2245 states that the structure must be able to support limit loads without detrimental, permanent deformation, and the structure must be able to support the ultimate load without failure for at least 3 s to comply with the standard.

A mock-up airplane with a BII2 ply pattern composite wing was used to verify and demonstrate the ASTM F-2245 standard. The aerodynamic wing distributed load is usually formulated using Schrenk's method (Schrenk, 1940). Based on an elliptical lifting coefficient distribution span-wise hypothesis on the wing, the aerodynamic wing distribution load is computed and transformed into four points of loading location, as shown in Figure 18. Each point load acts on the wing spar associated with four rib positions; thus, loading transfer to the wing structure can be performed perfectly. Before wing test loading, the fixture rings were fixed to the column of the test rig by four spacers at each column, and all gears (main and nose gears) were fixed to the platform by locked chains to ensure that the applied forces at the main wing were transferred through the airplane structure, especially the main wing and the wing box. Two
strain gauges were attached to the wing skin at ribs 6R and 6L to measure the strain of the wing. Two additional strain gauges were attached at the center of the left and right struts. These strain gauges verified the strain direction associated with positive and negative loads, and the strain limit of the wing skin and struts. Eight laser sensors installed on two side stands were used to measure wing deflection, both positive and negative. All measured data were collected and stored in the data logger of the data acquisition system.
The test started with a 1G positive load as a baseload, followed by a 2G positive load, observing the change of the structure for at least 3 s before returning to the baseload. This loading pattern (apply-observe-release) continued with 3G, 4G (limit load), 5G, and 6G (ultimate load), followed by -1G, -2G (limit load), and -3G (ultimate load). The weights of the wooden shrouds were considered while applying positive and negative loads. Table 5 shows a comparison between Shrenk’s load pattern and the actual applied load, and the error at different load factors. The error between the target load and the application load is low due to the high efficiency of the hydraulic power and control units, which ensured that the correct amount of force was applied to the wings (Paswan et al., 2014).

Figures 19 and 20 show the wing deflection versus wingspan and the measured strain at four locations from the experiment. It can be concluded that the designed composite wing can support the limit load and ultimate load in both positive and negative directions because there is no damage or permanent deformation, and the measured strain returns to the initial value when the load is released. All four hinges between the wing box and

### Table 5. Positive and negative wing load versus wingspan.

| Load Factor | Computed/Actual Load | Applied Load Locations | Total | %Error |
|-------------|----------------------|------------------------|-------|--------|
|             |                      | Rib#9R | Rib#6R | Rib#4R | Rib#2R | Rib#2L | Rib#4L | Rib#6L | Rib#9L |
| 1G          | Shrenk Tested Load (kgf) | 55.00  | 60.00  | 100.00 | 110.00 | 110.00 | 100.00 | 60.00  | 55.00  | 650.00 |
|             | Actual apply load (kgf) | 51.65  | 58.98  | 102.67 | 107.22 | 103.03 | 59.34  | 52.23  | 641.89 |
|             | Error (kgf)           | -3.35  | -1.02  | 2.67   | -3.23  | -0.66  | -2.77  | 1.25   |        |
| 2G          | Shrenk Tested Load (kgf) | 80.00  | 100.00 | 230.00 | 240.00 | 240.00 | 230.00 | 100.00 | 80.00  | 1300.00|
|             | Actual apply load (kgf) | 75.23  | 98.45  | 224.78 | 238.45 | 222.89 | 99.43  | 79.63  | 1273.42|
|             | Error (kgf)           | -4.77  | -1.55  | -5.22  | -1.55  | -0.57  | -0.37  | 2.04   |        |
| 3G          | Shrenk Tested Load (kgf) | 135.00 | 160.00 | 330.00 | 350.00 | 350.00 | 330.00 | 160.00 | 135.00 | 1950.00|
|             | Actual apply load (kgf) | 127.68 | 148.33 | 325.33 | 353.56 | 326.12 | 150.34 | 129.57 | 1911.15|
|             | Error (kgf)           | -7.33  | -11.67 | -4.67  | 0.23   | -3.88  | -9.66  | 5.43   | 1.99   |
| 4G          | Shrenk Tested Load (kgf) | 190.00 | 230.00 | 430.00 | 450.00 | 450.00 | 430.00 | 230.00 | 190.00 | 2600.00|
|             | Actual apply load (kgf) | 175.02 | 220.77 | 430.12 | 452.11 | 432.56 | 223.56 | 176.07 | 2566.45|
|             | Error (kgf)           | -14.98 | -9.23  | 0.12   | 2.11   | 6.23   | 6.44   | 13.93  | 1.29   |
| 5G          | Shrenk Tested Load (kgf) | 255.00 | 280.00 | 530.00 | 560.00 | 560.00 | 530.00 | 280.00 | 255.00 | 3250.00|
|             | Actual apply load (kgf) | 232.23 | 278.87 | 512.34 | 540.12 | 520.31 | 280.45 | 238.48 | 3163.14|
|             | Error (kgf)           | -22.77 | -1.13  | -17.66 | -19.88 | -9.69  | 0.45   | 16.52  | 2.67   |
| 6G          | Shrenk Tested Load (kgf) | 320.00 | 350.00 | 630.00 | 650.00 | 650.00 | 630.00 | 320.00 | 3900.00|
|             | Actual apply load (kgf) | 287.32 | 332.34 | 580.98 | 620.23 | 625.56 | 581.92 | 340.34 | 298.25 | 3666.94|
|             | Error (kgf)           | -32.68 | -17.66 | -49.02 | -29.77 | -24.44 | -48.08 | -9.66  | -21.75 | 5.98   |
| -1G         | Shrenk Tested Load (kgf) | -55.00 | -60.00 | -100.00 | -110.00 | -110.00 | -100.00 | -60.00 | -55.00 | -650.00|
|             | Actual apply load (kgf) | -51.00 | -59.10 | -105.77 | -107.32 | -108.45 | -106.34 | -59.23 | -52.05 | -649.26|
|             | Error (kgf)           | -4.00  | -0.90  | 5.77   | -2.68  | -1.55  | 6.34   | -0.77  | 2.95   | 0.11   |
| -2G         | Shrenk Tested Load (kgf) | -80.00 | -100.00 | -230.00 | -240.00 | -240.00 | -230.00 | -100.00 | -80.00 | -1300.00|
|             | Actual apply load (kgf) | -80.11 | -108.55 | -214.44 | -229.23 | -232.31 | -215.91 | -112.34 | -82.45 | -1275.35|
|             | Error (kgf)           | 0.11   | 8.55   | -15.56 | -10.77 | -7.69  | -14.09 | 12.34  | 2.45   | 1.90   |
| -3G         | Shrenk Tested Load (kgf) | -135.00 | -160.00 | -330.00 | -350.00 | -350.00 | -330.00 | -160.00 | -135.00 | -1950.00|
|             | Actual apply load (kgf) | -124.94 | -152.94 | -293.19 | -316.49 | -320.28 | -295.24 | -164.22 | -128.58 | -1795.87|
|             | Error (kgf)           | -10.06 | -7.06  | -36.81 | -33.51 | -29.72 | -34.76 | 4.22   | -6.42  | 7.90   |
root ribs can withstand bending and shear at the ultimate load without any sign of permanent bending or deformation. The designed composite wing has an adequate margin of strength to achieve the limit load stated in the ASTM F-2245 standard.

5. Discussion

For the purpose of verifying the design dependability, a comparison of vertical displacement between the experiment and the FEM analysis is presented in Figure 21, along with a discussion. The average percent error of the inner ribs (ribs numbers 2, 4, and 6) is 0.70% for the ultimate positive load and 8.65% for the ultimate negative load. The average percent error of the outer rib (rib number 9) is 8.73% for the ultimate positive load and 14.26% for the ultimate negative load. One can observe that the deflection error at the outer rib is larger than the inner rib; it might be because of the strut-braced high wing configuration that the inner structure loop is more rigid than the structure at the wingtip. However, the overall percent error of the wing deflection is acceptable and ensures that the wing design optimization is satisfactory and successful. This leads to the design and optimization of other parts of the airplane (fuselage, empennage, stabilizer, etc.) but is not illustrated in this paper.
6. Conclusion

The design and optimization of the hybrid composite wing of a light amphibious airplane are presented in this study. The objective was to minimize the weight and cost of the wing structure subjected to the weight limit and ultimate load in the ASTM F-2245 standard. The hybrid composite wing consists of a spar, ribs, and wing skin made of a number of layers of carbon-woven fiber and glass-woven fiber as the main material. The finite element analysis using ANSYS Composite PrepPost (ACP) and ANSYS Mechanical Module (AMM) was conducted using 72 ply-pattern cases. The discoveries of this study are presented as follows.

- The analysis revealed that the strength of the wing increased significantly when the number of carbon-fiber layers was increased, the cost of production was also increased.
- The main spar with at least 20 carbon layers and ribs with six hybrid carbon-fiber and glass-fiber layers can support the ultimate static load without any damage or permanent deformation.
- With the maximum stress of the carbon- and glass-fiber layers within the safety limit and the weight limit of 50 kg, the BII2 design case (spar/rib/skin: \((\pm 45)^{20}/[\pm 45]_{c}, (0/90)c_{c}, (\pm 45)_{F}, F]\) produces the lowest material cost (1,288.29 USD); the BII5 design case (spar/rib/skin: \((\pm 45)^{20}/[\pm 45]_{c}, (0/90)c_{c}, (\pm 45)_{F}, F]\) produces the minimum weight of 45.19 kg. BII2 is a better compromise because the material cost is reduced by up to 11.8% (152.85 USD) with a weight gain of only 0.6% (0.27 kg).
- From the hybrid carbon/glass fiber composite wing analysis, a compromise between the strength limit, weight, and manufacturing cost was achieved using an optimization approach, resulting in the best hybrid composite wing engineering solution.
- The mock-up light amphibious airplane was built with the BII2-case wing and placed in the universal test rig to demonstrate compliance with the standard. The experiment showed that the hybrid composite wing design could support the limit and ultimate load stated in ASTM F-2245 without any damage or structural failure.
- A comparison of structural deformation and equivalent elastic strain in the FEM model and the experiment showed good agreement with an acceptable error, particularly in the inner wing loop structure. Thus, we were successful in applying optimization approaches to this design challenge.
- This design and optimization method, incorporating ACP and AMM, can be used for any composite component of the airplane. For larger airplanes, the test rig for engineering verification may be significantly more expensive, and may encounter difficulties during mechanical and measurement setup. To meet the requirements of ASTM F-2245 for airworthiness certification, further FEM studies on the fatigue load may be required to cover the entire structural test section.

Declarations

Author contribution statement

Sinchai Chinvorarat: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

The data that has been used is confidential.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.
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