Design of High Altitude Long Endurance UAV: Structural Analysis of Composite Wing using Finite Element Method

Khodijah Kholish Rumayshah *, Aditya Prayoga, and Dr. Ing. Mochammad Agoes Moelyadi
Faculty of Mechanical and Aerospace Engineering, Bandung Institute of Technology, Indonesia
*kkrumayshah@gmail.com

Abstract. Research on a High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV) is currently being conducted at Bandung Institute of Technology (ITB). Previously, the 1st generation of HALE UAV ITB used balsa wood for most of its structure. Flight test gave the result of broken wings due to extreme side-wind that causes large bending to its high aspect ratio wing. This paper conducted a study on designing the 2nd generation of HALE UAV ITB which used composite materials in order to substitute balsa wood at some critical parts of the wing’s structure. Finite element software ABAQUS/CAE is used to predict the stress and deformation that occurred. Tsai-Wu and Von-Mises failure criteria were applied to check whether the structure failed or not. The initial configuration gave the results that the structure experienced material failure. A second iteration was done by proposing a new configuration and it was proven safe against the load given.

1. Introduction
In recent decades, the use of Unmanned Aerial Vehicles (UAV) in both military and civilian applications have been increased. The potential to substitute satellite to High Altitude Long Endurance (HALE) as a relay for communications is one such application. Indeed, to achieve the same capability as an orbital satellite which can cover a large area, the aircraft must be able to stay aloft for a long time in a very high altitude.

Bandung Institute of Technology (ITB) is now doing research on HALE UAV. In order to achieve low drag and long flight endurance, an aircraft must be designed having high aspect ratio wing. The 1st generation of HALE UAV ITB has been done developed with 12 m wing span. Most of its structure used balsa wood and polyurethane foam [1]. Hasan [2] had performed numerical analysis on its structure and gave many alternative designs on it. However, even though finite element analysis and static test had proven that the structure could withstand the designed load, flight test showed otherwise due to unforeseen strong side wind and wrong launch technique.

Castellani et al [3] stated that high aspect ratio wing is susceptible to many structural drawbacks. Its large span results in heavy structural weight. To overcome this problem, a very lightweight structure is needed, which in turn leads to a very flexible structure so that a large displacement cannot be neglected anymore. Romeo [4] found that a good structural wing solution to enhance bending stiffness could be represented by an opportunely reinforced high modulus carbon fiber leading edge, besides, the main spar could be subdivided into some parts which could be connected to each other. The structural configuration of the 2nd generation of HALE UAV ITB is expected to solve the problems that occurred in the previous generation. It is expected that by replacing some parts originally made from balsa wood to composite may strengthen the wing structure.
but by considering the target mass not to be too heavy. Many airframe structures currently using composites due to its ideal strength to weight ratio [5].

For the 2nd generation, HALE UAV ITB is designed having 16 m wing span with 0.4 m chord length. The wing is built modular with the length of each segment is 2 m. Every wing segment will be joined using a glass-fiber joiner at the front spar. The structural configuration is shown in Figure 3. It has a rectangular front spar which is located at 36% chord and made from a composite carbon fiber. The rear spar is an aluminum hollow tube located at 70% chord. There are 42 ribs which are made from carbon fiber along one-half span wing. Hasan [2] suggestion was to use a non-structural skin for a wing with large deformation in order to avoid buckle at the upper skin. So the 2nd generation of HALE UAV ITB is designed having skin made from plastic film, except skin at leading edge region which is strengthened using carbon fiber and a rectangular beam made from balsa.

Numerical analysis will be conducted for predicting the response of the structure to the loads given, i.e. the lift force which is distributed along wing span following non-linear Prandtl lifting line theory, the structural weight which is uniformly distributed, and the weight of the motor propeller which is located at a distance of 2 m from the airplane’s axis of symmetry. Since its symmetric geometry, the numerical analysis will be conducted only for one-half wing span in order to reduce the computing time [5]. The desired output is ensuring whether the whole structure can withstand the given loads. There will be improvements in some critical parts so as to obtain a more optimal performance.

In the next development plan, HALE UAV ITB is going to be featured with a solar panel system as its additional energy source. By innovating this hybrid fuel, the aircraft is expected can stay aloft for a longer time (up to months) since it will be automatically charged its battery by the solar energy at day and it will use its reserve energy stored in its battery at night.

2. Finite Element Method and Simulation Setup
The finite element method (FEM) is a tool for analyzing certain structural response which comes to overly complex analytical hand-calculation. FEM divides the structures that being analyzed into finite numbers of elements each associated with some nodal points. The compatibility equations of each
element are then combined so that being appropriated for each node [6]. The static structural analysis in this simulation is performed using finite element software ABAQUS/CAE. ABAQUS is chosen since it has pre-processing features that make composite material property definition become easier.

2.1. Geometry Model
The CAD model was first generated using CATIA V5 in solid 3D. The geometry is translated into ABAQUS/CAE per part and simplified into shell 2D using mid surface technique. Broekaart [7] and Wysocki et al [8] explained why creating a mid-surface shell model is still favorable compared to analyze the whole model in solid 3D.

![Figure 5 Simplified geometry model using shell element (full model).](image1.png)

![Figure 6 Simplified geometry model using shell element (zoom-in).](image2.png)

2.2. Material Properties
The wing structure of HALE UAV ITB consists of various materials on each part. For composite materials, the ply stacking sequence is defined by firstly predicting the major load direction acting at a certain region. Then the fiber orientation can be adjusted to its direction so that the load transfer can take place optimally. Rajadurai [9] states that [0/90/45/-45/90/0] is the best ply arrangement for aircraft composite wing.

| Part        | Material          | Ply Orientation | Thickness (mm) |
|-------------|-------------------|-----------------|----------------|
| Upper Skin  | Plastic Film      | -               | 1              |
| Lower Skin  | Plastic Film      | -               | 1              |
| Front Spar  | Woven Carbon Epoxy| [90/0/45/-45]_w | 0.2 @ply       |
| Joiner      | Woven S-Glass Epoxy|[90/0/45/-45]_w | 0.2 @ply       |
| Rear Spar   | Aluminum 6061 T6  | -               | 2              |
| LE (curved)| Woven Carbon Epoxy|[90/0/45/-45]_w | 0.2 @ply       |
| LE (flat)   | Balsa             | -               | 5              |
| Ribs        | Woven Carbon Epoxy|[90/0/45/-45]_w | 0.2 @ply       |

The mechanical properties of each material are obtained from various references. The properties of woven carbon epoxy and woven s-glass epoxy are obtained from Performance Composites Ltd. website [10]. The aluminum tube is manufactured using drawing technique with the mechanical properties obtained from Military Handbook [11]. The mechanical properties of balsa wood are obtained from Wood Handbook [12]. WS Hampshire Inc. [13] provides data for plastic film.
Table 2 Mechanical properties of balsa wood.

| Property          | Value          |
|-------------------|---------------|
| Young’s Modulus E | 3 GPa         |
| Poisson Ratio ν   | 0.38          |
| Density ρ         | 0.13 gr/cm³   |

Table 3 Mechanical properties of aluminum 6061 T6.

| Property          | Value          |
|-------------------|---------------|
| Young’s Modulus E | 9.90E+03 ksi  |
| Poisson Ratio ν   | 0.33          |
| Density ρ         | 0.098 lb/in³  |

Table 4 Mechanical properties of woven carbon epoxy.

| Property          | Value          |
|-------------------|---------------|
| Young’s Modulus E₁₁ | 70 GPa       |
| Young’s Modulus E₂₂ | 70 GPa       |
| Shear Modulus G₁₂ | 5 GPa        |
| Poisson Ratio ν   | 0.1          |
| Density ρ         | 1.6 gr/cm³   |
| Tensile Strength σₜ | 600 MPa     |
| Compressive Strength σ_c | -570 MPa |
| Shear Strength τ₁₂ | 90 MPa       |

Table 5 Mechanical properties of woven s-glass epoxy.

| Property          | Value          |
|-------------------|---------------|
| Young’s Modulus E₁₁ | 25 GPa       |
| Young’s Modulus E₂₂ | 25 GPa       |
| Shear Modulus G₁₂ | 4 GPa        |
| Poisson Ratio ν   | 0.2          |
| Density ρ         | 1.9 gr/cm³   |
| Tensile Strength σₜ | 440 MPa     |
| Compressive Strength σ_c | -425 MPa |
| Shear Strength τ₁₂ | 40 MPa       |

Table 6 Mechanical properties of plastic film.

| Property          | Value          |
|-------------------|---------------|
| Young’s Modulus E | 125000 psi    |
| Poisson Ratio ν   | 0.3           |
| Density ρ         | 0.93 gr/cm³   |

2.3. Loads and Boundary Conditions

Silitonga et al [14] had done a comparative study of wing lift distribution for HALE UAV ITB. It came up to the conclusion that the use of Non-linear Prandtl Lifting Line Theory (NLLT) is recommended for preliminary analysis of HALE UAV ITB. Figure 7 shows the spanwise lift distribution along one-half wing span by following NLLT. Besides lift force, there are also gravity force and any other concentrated loads working on the wing structure. The weight of the structure is automatically calculated by considering the material density input into ABAQUS pre-processing. While the concentrated force comes from 2 kg motor propeller which is located at a distance of 2 m from the aircraft’s symmetry axis. ENCASTRE (fixed support) boundary condition is applied to the ribs at the wing root which will prevent translation and rotation in all direction. While the wing tip is free from constraint in all degree of freedoms. Overall loads and boundary conditions acted on the model is shown in Figure 8.
2.4. Meshing
The global mesh seed is generated for the whole model with the size of approximately 5 mm. Mesh control is activated for regulating the shape of the element and the meshing technique which is being used. For all of the parts except ribs, quad-dominated shape element and structured meshing technique is used. While for ribs, since the airfoil shape gives many curved edges, the meshing technique is free. The mesh result is shown by Figure 9 below.

3. Failure Criteria
Failure criteria are used to ensure the ability of a structure standing to the loads given, whether it fails or not. There are many different kinds of failure criteria based on the material characteristic. In this paper, the authors use Tsai-Wu failure criterion for parts made of composite materials and use Von-Mises failure criterion for isotropic or homogeneous materials.

Numerous failure criteria have been proposed to examine a composite material. Rajanish [15] conducted a study on it and found that Tsai-Hill, Tsai-Wu, and Hashin failure criterion give the best fit with the experimental result compared to the other failure criteria widely used. Further, Kaw [16] stated that Tsai-Wu failure criterion is more general than the Tsai-hill failure criterion since it distinguishes between compressive and tensile strength of a lamina. Tsai-Wu failure criterion is developed based on Beltrami failure theory concerning strain energy. Lamina (composite layer) in a structure is called fail if it does not satisfy Equation 1 as follows [16].

\[
H_1\sigma_1 + H_2\sigma_2 + H_6\tau_{12} + H_{11}\sigma_1^2 + H_{22}\sigma_2^2 + H_{66}\tau_{12}^2 + 2H_{12}\sigma_1\sigma_2 < 1
\]

Equation 1

Which \(\sigma_1\) is stress in fiber direction, \(\sigma_2\) is stress in transverse direction, and \(\tau_{12}\) is shear stress. While the value of \(H_1\), \(H_{11}\), \(H_2\), \(H_{22}\), \(H_6\), and \(H_{66}\) can be obtained using Equation 2 up to Equation 7 as follows.

\[
H_1 = \frac{1}{(\sigma_1^T)_{ult}} - \frac{1}{(\sigma_1 C)_{ult}}
\]

Equation 2
\[ H_2 = \frac{1}{(\sigma_2^T)_{ult}} - \frac{1}{(\sigma_2^C)_{ult}} \]  
\[ H_{11} = \frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}} \]  
\[ H_{22} = \frac{1}{(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}} \]  
\[ H_6 = 0 \]  
\[ H_{66} = \frac{1}{(\tau_{12})_{ult}^2} \]  
\[ \text{Equation 3} \]  
\[ \text{Equation 4} \]  
\[ \text{Equation 5} \]  
\[ \text{Equation 6} \]  
\[ \text{Equation 7} \]  

Which \((\sigma_1^T)_{ult}\) is tensile strength in fiber direction, \((\sigma_1^C)_{ult}\) is compressive strength in fiber direction, \((\sigma_2^T)_{ult}\) is tensile strength in transverse direction, \((\sigma_2^C)_{ult}\) is compressive strength in transverse direction, and \((\tau_{12})_{ult}\) is shear strength. While the value of \(H_{12}\) can be obtained from Mises-Hencky criterion as follows.

\[ H_{12} = -\frac{1}{2} \sqrt{\frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}}} } \]  
\[ \text{Equation 8} \]  

Whereas to examine homogeneous material parts, Von-Mises failure criterion is used. The magnitude of Von-Mises stress can be obtained from general Von-Mises equation as follows [17].

\[ \sigma_{VM} = \frac{1}{\sqrt{2}} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{\frac{1}{2}} \]  
\[ \text{Equation 9} \]  

Which \(\sigma_1\), \(\sigma_2\), and \(\sigma_3\) respectively are normal stresses that occur in the x-axis, y-axis, and z-axis. Plane stress assumption is used in the analysis so that \(\sigma_3\) can be neglected and the equation comes into

\[ \sigma_{VM} = \sqrt{\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2} \]  
\[ \text{Equation 10} \]  

The comparison between Von-Mises stress \((\sigma_{VM})\) and allowable stress of the material (yield stress/\(\sigma_Y\)) is defined as safety factor (SF).

\[ SF = \frac{\sigma_Y}{\sigma_{VM}} \]  
\[ \text{Equation 11} \]  

The structure is safe if the safety factor is greater than 1. Otherwise, safety factor less than 1 means the structure has performed a plastic deformation which is unpreferable [18].

4. Results and Discussion

Figure 10 to Figure 15 below provides visualization of the numerical simulation results.
The numerical calculation of Tsai-Wu failure criterion gives the result as shown in Table 7 below. The structure is failed since the calculation of Tsai-Wu equation gives the number of 63.68 so that Equation 1 is not fulfilled. The most critical part is leading edge since it gives the highest number of Tsai-Wu failure criterion.

| Tsai-Wu Criteria | Conclusion |
|------------------|------------|
| Front Spar       | 9.656      | Fail       |
| Joiner           | 4.117      | Fail       |
| LE (curved)      | 8.075      | Fail       |
| LE (flat)        | 63.68      | Fail       |
| Ribs             | 5.632      | Fail       |

The safety factors of homogeneous parts are calculated in Table 8 below. Von-Mises failure criterion gives the result that the structure is failed since the value of safety factor is less than 1 in the entire model which means the stress that occurs in the structure has caused the material to be yielding. The most critical part is rear spar since it has the lowest value of safety factor.
Table 8 Von-Mises failure criterion for parts using homogenous material.

| Part          | Von-Mises Stress (Pa) | Material       | Yield stress (Pa) | Safety Factor | Conclusion |
|---------------|-----------------------|----------------|-------------------|--------------|------------|
| Upper Skin    | 1.06E+08              | Plastic Film   | 2.14E+07          | 0.2016       | Fail       |
| Lower Skin    | 1.46E+08              | Plastic Film   | 2.14E+07          | 0.1468       | Fail       |
| Rear Spar     | 2.13E+09              | Aluminum 6061 T6 | 3.0E+08        | 0.1297       | Fail       |

The second iteration is then conducted in order to achieve a better structural configuration. The principle is to strengthen parts that receive high load either by means of material replacement or part thickening. Changing the ply orientation also quite helpful in doing this optimization. Outward wing (4th segment from wing root) only accepts small portions of load, so that parts of this segment can be reduced in strength in order to reduce weight until a satisfactory result is reached. Table 9 and Table 10 below show the new configuration offered.

Table 9 A new configuration in the use of material for 1st to 3rd wing segment.

| Part          | Material       | Ply Orientation | Thickness (mm) |
|---------------|----------------|----------------|----------------|
| Upper Skin    | Skin Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
|               | Core Balsa     |                | 4              |
| Lower Skin    | Skin Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
|               | Core Balsa     |                | 4              |
| Front Spar    | Horizontal Surface Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
|               | Middle Splitter Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
|               | Vertical Surface Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
| Joiner        | Hor& Ver Surface Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
| Rear Spar     | Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
| LE (curved)   | Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
| LE (flat)     | Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |
| Ribs          | Woven Carbon Epoxy | [90/0/45/-45]s | 0.2 @ply      |

Table 10 Material changing for 4th wing segment.

| Part          | Material       | Ply Orientation | Thickness (mm) |
|---------------|----------------|----------------|----------------|
| Front Spar    | Hor, Mid, & Ver Surface Woven Carbon Epoxy | [-45/45]   | 0.2 @ply      |
| Joiner        | Hor&Ver Surface Woven Carbon Epoxy | [-45/45]   | 0.2 @ply      |
| Rear Spar     | Woven Carbon Epoxy | [-45/45]   | 0.2 @ply      |
| LE (curved)   | Woven Carbon Epoxy | [-45/45]   | 0.2 @ply      |
| LE (flat)     | Woven Carbon Epoxy | [-45/45]   | 0.2 @ply      |
| Ribs          | Woven Carbon Epoxy | [90/0/45/-45] | 0.2 @ply      |

The numerical analysis results of the new configuration offered are shown by Figure 16 up to Figure 20. It is proven that the structure succeeds as it does not experience failure against the given load. The Tsai-Wu failure criterion for the overall model has the value of 0.865. In the new configuration, there is no part using homogeneous material anymore so as Von-Mises failure criterion is no longer used.
The maximum displacement is 3.265 m occurs at the wing tip. It can be reduced by locating the concentrated load to a point further away from wing root. The 2 kg motor propeller is previously located at a distance of 2 m from wing root. Simulation has been done to put the motor propeller at a distance of 6 m and give a result of 3.217 m maximum deflection at wing tip. This changing in motor propeller location needs further consideration including the flight control aspect.

However, the use of woven carbon epoxy in almost all of the parts makes this configuration heavier than the initial configuration. In the actual model, ribs have holes which are not modeled in this simulation. The existence of holes in ribs can reduce the mass of ribs by 53% in comparison with ribs without holes. It is an important consideration for an overweight problem that arises. The further suggestion offered is to make the 4th wing segment become tapered.

![Figure 16](image1.png) Deformation (U) plot for the new configuration with motor propeller located at 2 m from root.

![Figure 17](image2.png) Deformation (U) plot for the new configuration with motor propeller located at 6 m from root.

![Figure 18](image3.png) Stress plot in fiber direction (S11) for the new configuration.

![Figure 19](image4.png) Stress plot in transverse direction (S22) for the new configuration.
5. Conclusions

Structural analysis on the 2nd generation of HALE UAV ITB is done using finite element software ABAQUS/CAE. The results prove that the initial configuration fails as evidenced by Tsai-Wu failure criterion for composite parts is 63.68 and Von-Mises failure criterion for homogeneous parts is less than 1 for the entire model. The second iteration is made by proposing a new configuration which done some changes of the material, ply direction, and thickening in some parts. This new structural configuration is proved succeeds against the given loads with Tsai-Wu failure criterion is at the value of 0.865.

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