Parametric study of composite wing box for high altitude platform using finite element analysis

Nontawat Thaiprayoon¹, Kittigorn Chalernphon², Chompunut Somtua³, Panya Aroonjarattham¹, *

¹Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakhonpathom Thailand 73170
²Geo-Informatics & Space Technology Development Agency (Public Organization), Chonburi Thailand 20230
³Department of Mechanical Engineering, Faculty of Engineering, Thonburi University, Bangkok Thailand 10160

* Corresponding Author: panya.aro@mahidol.ac.th

Abstract
This paper aims to evaluate the degree and the number of pile stack between five and six ribs wing box that created from the Eppler 397 Airfoil (e397-il) model. The model was varied three numbers of pile stack and six degrees of angle of pile stack to find the best result for the composite material to construct the High-Altitude Platform (HAP). The thickness of pile was fixed at 0.234 mm. The structure of wing box has the safety of factor 5.7 and receive load 3,052 N. The model was analysed by ABAQUS software to compute the vertical-static such as Tsai-Hill and skin defection that did not exceed 1 for Tsai-hill and 2 mm for skin defection. The results were shown that the wing box had six ribs model with the angle of pile stack as [+45/-45/90/90/0/90/90/-45/+45] was the best model in this research. It had Tsai-Hill 0.030 and skin defection 0.348 mm. The model had more ribs and number of pile stack increase the strength of wing box and the degree of pile stack between the outer and the adjacent layer should be a perpendicular direction.

Keywords: High Altitude Platform, Tsai-Hill, Skin defection.

1. Introduction
Geo-informatics and Space Technology Development Agency (GISTDA) has a project to create the High-Altitude Platform (HAP) using the composite materials that had a lightweight and stronger than aluminums. HAP can be used instead of the satellite because it can survey the resource on the earth, transmit and receive the radio signal at 20-50 kilometers over the ground with the lower operating and maintenances cost. In the maintenance process, HAP can be land and repair on the ground like a plane that easier maintain than the satellite. It uses the solar energy for work by install the solar cells on their wing. This research aim to evaluate the degree and the number of pile stack between five and six ribs wing box that created from the Eppler 397 Airfoil (e397-il) model. The results were computed the vertical-static such as Tsai-Hill and skin defection to find the best degree and numbers of pile stack that use to construct the HAP.
2. Materials and Methods

2.1 Three-dimensional model of wing box

Three-dimensional models of wing box were constructed using CATIA software. The spacing between ribs was 250 and 312.5 mm as shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** The model of wing box: (a) 250 mm of spacing rib and (b) 312.5 mm of spacing rib

Two spars of wing box as front and rear spar were used in this study. The front spar was installed at 15% from the anterior of wing box and the rear spar was installed at 60% from in front of wing box [1] as shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Position of front and rear spar of wing box [2].

2.2 Boundary condition of wing box

Wing box received the load from the wind action that analysed from CFD analysis. The angle of attack was set at 18 degree from Eppler 397 airfoil cl-alpha diagram. The wind’s particle was act in the X-axis with the speed of 21 m/s. After that the maximum force in the X-axis was 550 N and Y-axis was 400 N as shown in Figure 3 [3].

![Figure 3](image3.png)

**Figure 3.** The result of wind action on the X- and Y-axis [4].

The ultimate load act on the wing box was calculated by using the maximum force and load factor. The load factor can get from the V-n diagram that was shown the relationship between the load factor (n) and the velocity for flying (V) as shown in Figure 4.
Figure 4. The relationship between load factor and velocity.

The operating flight strength of an airplane was presented in form of V-n diagram that shown the maximum performance of aircraft without breaking [5]. From the graph, the maximum load factor did not have a damage to the structure is 3.7 and the factor of safety is 1.5 so the ultimate load as shown in Figure 5 was the load factor x safety factor x maximum load

\[
\text{Ultimate load} = 3.7 \times 1.5 \times 550 = 3,052 \text{ N}
\]

Figure 5. The ultimate load act on the wing box.

2.3 Skin-deflection

The force act on the surface of the wing box caused a point load to press the wing surface between the ribs that affect the bent of composite materials. The bendy skin of the wing box surface was called skin-deflection (\(\delta\)) as shown in Figure 6. It should not bend more than 2 mm of the total skin thickness [6].

Figure 6. The skin-deflection of the wing box surface [6].

2.4 Tsai-Hill

Tsai-Hill was used to evaluate the failure condition of the laminated composite materials. It did not exceed than 1 for the safe condition [7].
\[ \frac{\sigma_{11}^2}{X_{11}^2} - \frac{\sigma_{22}^2}{X_{11}^2} + \frac{\sigma_{12}^2}{X_{22}^2} + \frac{\sigma_{12}^2}{X_{12}^2} < 1 \] 

Where \( \sigma \) is normal stress

\( X_{11} \) is longitudinal tensile failure

\( X_{22} \) is transverse tensile failure

\( X_{12} \) is tensile failure between longitudinal and transverse

2.5 Basic stacking sequences rule

The composite material had three conditions for layup the pile stack as follow;

- The first was the symmetry condition. The degree of pile stack should be symmetry between upper layers and lower layers from the median layer as shown in Table 1 [8].

| Layer  | Good layup pile stack | Bad layup pile stack |
|--------|------------------------|----------------------|
|        | Degree of pile stack   | Condition            | Degree of pile stack | Condition   |
| Outer  | 45                     | Symmetry             | 90                   | Symmetry    |
| Upper 2| -45                    | Symmetry             | -45                  | Asymmetry   |
| Upper 1| 45                     | Symmetry             | 45                   | Asymmetry   |
| Median | 0                      | None                 | 0                    | None        |
| Lower 1| 45                     | Symmetry             | -45                  | Asymmetry   |
| Lower 2| -45                    | Symmetry             | 45                   | Asymmetry   |
| Outer  | 45                     | Symmetry             | 90                   | Symmetry    |

- The second condition was specified the outer layer with 45 or -45 degree as shown in Table 2.

| Layer  | Good layup pile stack | Bad layup pile stack |
|--------|------------------------|----------------------|
|        | Degree of pile stack   | Condition            | Degree of pile stack | Condition   |
| Outer  | 45                     | Specify              | 90                   | Non-specify |
| Upper 2| -45                    | Symmetry             | -45                  | Symmetry    |
| Upper 1| 45                     | Symmetry             | 45                   | Symmetry    |
| Median | 0                      | None                 | 0                    | None        |
| Lower 1| 45                     | Symmetry             | 45                   | Symmetry    |
| Lower 2| -45                    | Symmetry             | -45                  | Symmetry    |
| Outer  | 45                     | Specify              | 90                   | Non-specify |

- The third condition was the close three layers should not layup with the same degree of pile stack as shown in Table 3.

| Layer  | Good layup pile stack | Bad layup pile stack |
|--------|------------------------|----------------------|
|        | Degree of pile stack   | Condition            | Degree of pile stack | Condition   |
| Outer  | 45                     | Specify              | -45                  | Specify     |
| Upper 4| -45                    | Symmetry             | 90                   | Repeated degree |
2.6 Case analysis

All models were analyzed Tsai-Hill and skin deflection on the five and six ribs wing box. The numbers of pile were varied with three values as shown in Table 4. The pile orientations were varied under three conditions for layup pile stack.

Table 4. List of case analysis.

| Cases | Number of ribs | Number of piles | Pile orientation |
|-------|----------------|-----------------|------------------|
| 1     | 5              | 7               | [+45/0/0/-45/0/0/+45] |
| 2     | 5              | 8               | [+45/0/0/-45/0/0/+45] |
| 3     | 5              | 9               | [+45/0/0/-45/90/-45/0/0/+45] |
| 4     | 5              | 7               | [-45/+45/0/90/0/+45/-45] |
| 5     | 5              | 8               | [-45/+45/0/90/0/+45/-45] |
| 6     | 5              | 9               | [+45/-45/90/90/0/90/90/0/-45/+45] |
| 7     | 6              | 7               | [+45/0/0/-45/0/0/+45] |
| 8     | 6              | 8               | [+45/0/0/-45/0/0/+45] |
| 9     | 6              | 9               | [+45/0/0/-45/90/-45/0/0/+45] |
| 10    | 6              | 7               | [-45/+45/0/90/0/+45/-45] |
| 11    | 6              | 8               | [-45/+45/0/90/0/+45/-45] |
| 12    | 6              | 9               | [+45/-45/90/90/0/90/90/0/-45/+45] |

2.7 Material properties

The material properties of unidirectional carbon fiber prepreg were used to calculate in this research was shown in Table 5.

Table 5. Material properties of carbon fiber T700/M21.

| Variable | Values | Unit |
|----------|--------|------|
| $E_1$    | 131.100| GPa  |
| $E_2 = E_3$ | 8.200  | GPa  |
| $G_{12}$ | 3.930  | GPa  |
| $G_{23} = G_{13}$ | 4.300  | GPa  |
| $X_t$    | 2.489  | GPa  |
| $X_c$    | 1.254  | GPa  |
| $Y_t$    | 53.000 | MPa  |
The results were evaluated Tsai-Hill and skin defection on the wing box of twelve cases analysis as shown in Table 6.

**Table 6. The result of Tsai-Hill and skin-defection of 12 cases analysis.**

| Cases | Tsai-Hill | Skin-defection (mm) |
|-------|-----------|---------------------|
| 1     | 0.149     | 1.434               |
| 2     | 0.111     | 1.072               |
| 3     | 0.084     | 0.826               |
| 4     | 0.097     | 1.160               |
| 5     | 0.083     | 0.886               |
| 6     | 0.042     | 0.616               |
| 7     | 0.095     | 0.869               |
| 8     | 0.074     | 0.661               |
| 9     | 0.056     | 0.518               |
| 10    | 0.065     | 0.702               |
| 11    | 0.053     | 0.533               |
| 12    | 0.030     | 0.348               |

The best wing box was a case no.12 that had the smallest Tsai-Hill and skin-defection. The contour of Tsai-Hill on the wing box was shown in Figure 8 and skin-defection was shown in Figure 9.
Figure 9. The contour of skin-defection on mesh model.

All wing boxes constructed by composite material was safe in all cases analysis because all values of Tsai-Hill did not exceed 1 and skin-defection did not exceed 2 mm in all cases.

In case of five ribs, case no.6 was the best case because Tsai-Hill and skin-defection are lower than the other cases. It was shown more number of pile stack increase the strength of wing box. The case no.3 has a same number of piles as case no.6 but there are more Tsai-Hill and skin-defection than case no.6 that shown the degree of pile stack between upper 4 and outer layer and lower 4 and outer layer should be a perpendicular direction.

In case of six ribs, case no.12 was the best case because Tsai-Hill and skin-defection are lower than the other cases. It was shown more number of pile stack increase the strength of wing box same as five ribs case and the degree of pile stack between the outer and the adjacent layer should be a perpendicular direction.

4. Conclusion
This study aims to evaluate the parameters as number of ribs, number of pile stack and the degree of pile stack of wing box constructed by composite material by finite element analysis. The results were shown more ribs and number of pile stack help to increase the strength of wing box and the degree of pile stack between the outer and the adjacent layer should be a perpendicular direction. The next step is to validate the finite element result with the mechanical testing machine as shown in figure 10 to confirm the best model for construct the High-Altitude Platform (HAP).

Figure 10. The mechanical testing machine for wing box testing.

Acknowledgments
The author wishes to thank the Geo-informatics and Space Technology Development Agency (GISTDA) and Biomechanical Analysis and Orthopaedic Device Design Laboratory (B-AODD Lab), Faculty of Engineering, Mahidol University for their kind support of the facilities.

5. References
[1] Annabel R 2009 M.S. Thesis (Guildford: Department of Physics, University of Surrey)
[2] Niu M C Y 1992 Composite airframe structures: practical design information and data, 3rd ed (USA: Adaso/Adastra Engineering Center)
[3] Gregoire A Gabriel D 2016 J Mech Phys Solids 97 168-196
[4] Jarukit S 2019 B.E. Project, (Nakhon Pathom: Department of Mechanical Engineering, Mahidol University)
[5] UAVNavigation In Depth: Flight Envelope 2019
   https://www.uavnavigation.com/company/blog/uav-navigation-depth-flight-envelope,
   accessed 23 November 2019

[6] Edward A B Benjamin K S Keejoo L Curt S K Norman M W 2010 *J Intel Mat Syst Str* 21(17)
   1699-1717

[7] Engineering Sciences Data Unit 1995 *Elastic direct stresses and deflections for flat rectangular
   plates under uniformly distributed normal pressure, 71st ed* (England: Engineering Sciences
   Data Unit)