STRUCTURAL DESIGN ON WING OF A SMALL SCALE WIG VEHICLE WITH CARBON/EPOXY AND FOAM SANDWICH COMPOSITE STRUCTURE

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Abstract

This present study provides the structural design and analysis of main wing, horizontal tail and control surface of a small scale WIG(Wing-in-Ground Effect) craft which has been developed as a future high speed maritime transportation system of Korea. Weight saving as well as structural stability could be achieved by using the skin-spar-foam sandwich and carbon/epoxy composite material. Through sequential design modifications and numerical structural analysis using commercial FEM code PATRAN/NASTRAN, the final design structural features to meet the final design goal such as the system target weight, structural safety and stability was obtained. In addition, joint structures such as insert bolts for joining the wing with the fuselage and lugs for joining the control surface to the wing were designed by considering easy assembling as well as more than 20 years service life.

1 Introduction

When a wing is closely flying on the ground or on the water surface within a couple of meters height, the lift force is greatly increased due to the ground-effect. Therefore if a vehicle uses the wing with the ground effect, it is called as a WIG(Wing-in-Ground Effect) craft. The WIG vehicle has a special feature which has much wider wing than the conventional airplane wing and the hull type fuselage like a high speed boat. The WIG craft borrows some merits from both airplane and ship which can transport quickly many passengers or heavy payload. Since 1960s, many types of WIG crafts have been vigorously developed by Russia for military or civil uses[1, 2].

In Korea, recently study on the WIG craft is lively progressing as a new generation maritime transportation system. For instances, KORDI(Korea Ocean Research & Development Institute) and some relating industries have developed several classes of WIG crafts such as the 4 seats, 6 seats and 20 seats small scale WIG crafts and the 100 tons large scale one.

This study carried out a preliminary structural design and analysis on main wing, horizontal tail, control surface and joint parts of the 20 seats small scale WIG vehicle. Structural configuration adopted the skin-spar type structure with foam sandwich, and main material took up the carbon/epoxy composite. Initial design was performed using the netting rule and the rule of mixture. Structural safety and stability evaluation on the design features was done by a commercial FEM code NASTRAN. Through several times modifications, the final structural design features were obtained to meet the design requirements such as the system target weight, structural safety and stability.

2 Preliminary Structure Design

2.1 Design Outline

The structural design proof load of main wing and horizontal tail was defined through the small scaled WIG vehicle's design requirements and load case analysis, and also the carbon/epoxy composite material was selected by reviewing how mechanical property of the selected composite material will be reacted on the adopted structure[6].

The initial structural configuration adopted the skin-spar structural type which is based on the defined proof load. The netting rule and the rule of

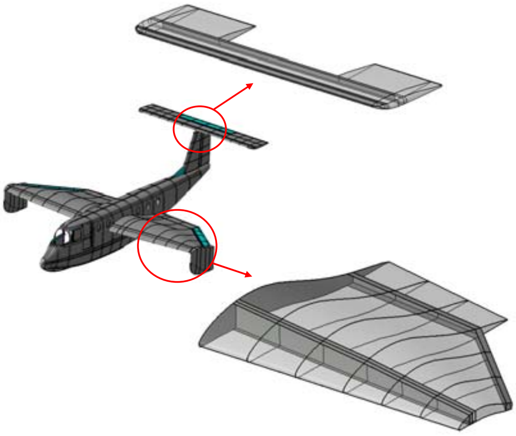

Fig. 1. 3-D model for whole WIG craft, main wing and horizontal tail structure

mixture was used for initial structural designing. In order to confirm the structural safety of the initial structural design result, structural analysis was performed by using FEM code. From the structural analysis on the first design configuration, some modifications were drawn due to weak area on buckling and a bit heavier than the target weight. The final structural configuration was fixed through several repeated design modifications and analyses. Figure 1 shows the 20 seats small scale WIG craft's aerodynamic configuration and the initial structural feature with the skin-spar foam sandwich type wing and tail.

2.2 Definition of Structural Design Load

The 20 seat small scale WIG craft's design requirements are payload of 2 tons, maximum cruising speed of 150 km/h in ground effect zone, maximum cruising speed of 170 km/h out of ground effect zone, cruising altitude of 2 meters, and range of 1000 km. Chord lengths at wing root and tip are 7.5 meters and 3.0 meters, respectively, and half span is 9.0 meters. Horizontal tail has chord length of 2.3 meters and span of 12.96 meters. Target weights of the half span wing and the full span horizontal tail are 383 kg and 180 kg, respectively.

Structural design load of main wing was defined from relationship between main wing's lift, horizontal tail's lift and inertia load at maximum cruising speed. The main wing load distribution was applied using the chordwise and spanwise distributed load equations proposed by reference 3 in considering the load factor of 2 which was given by the system design requirement. In this study the main wing load was calculated with 20 segments divided into spanwise in consideration of inertia load due to dead weight[3]. The design proof load was defined as 1.5 times as the calculated structural load. Because two engines are installed on main wing by the engine mounting frame, the load due to propeller thrust was calculated using relationship between break horsepower and propeller efficiency. Figure 2 shows shear force and bending moment diagrams of main wing.

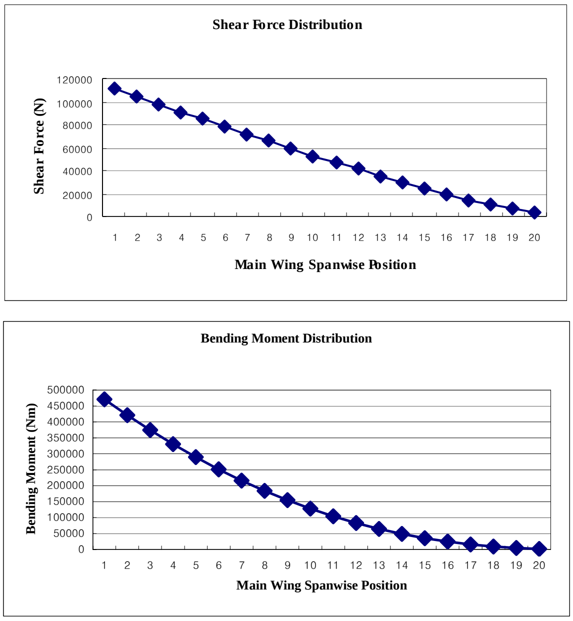

Fig. 2. Shear force and bending moment diagram of main wing

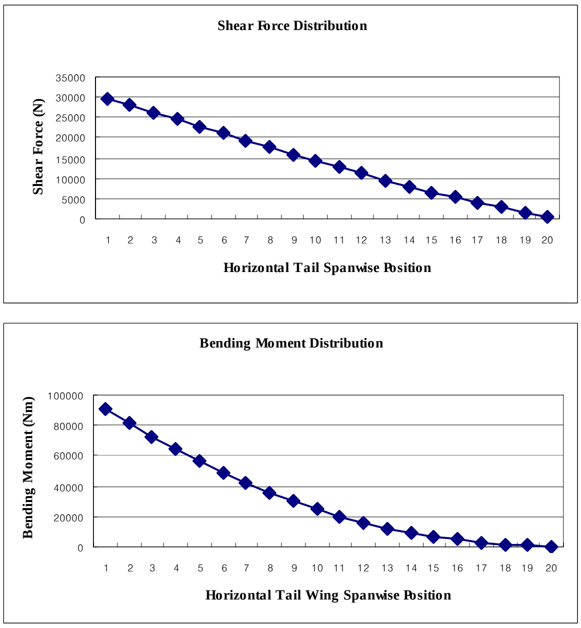

Fig. 3. Shear force and bending moment diagram of horizontal tail

The structural design load of horizontal tail was calculated from the steady state maximum load in consideration of the checked maneuver acceleration load in symmetric pitching maneuver. The proof design load also was defined as 1.5 times as the calculated horizontal tail's structural load, and the span wise distributed loads were calculated using the same equation applied at main wing. Figure 3 shows shear force and bending moment diagrams of horizontal tail.

2.3 Structural Design of Main Wing

The structural configuration was initially composed of 'I' type front spar and channel('⊏') type rear spar including flange and web to avoid complexity of manufacturing of the selected carbon/epoxy composite laminate. Preliminary structural design was initially performed by the netting rule and the rule of mixture[4, 5]. According to the netting rule, the principal load directional thickness of main spar flange and web can be sized by the crippling buckling strength 'σ_{crip}' as follows;

$$\left|\frac{F_x}{A} + \frac{M_z(\pm y)}{I_z}\right| \le \left|\frac{X_t}{S.F}, \frac{\sigma_{crip}}{S.F}\right| \tag{1}$$

$$\left|\frac{F_y}{A}\right| \le \left|\frac{X_t}{S.F}, \frac{\sigma_{crip}}{S.F}\right| \tag{2}$$

where F_x = spanwise load, F_y = chordwise load, A= flange's cross sectional area, M_z = bending moment, X_t = fiber directional tensile strength, σ_{crip} = crippling buckling strength, I_z = area moment of inertia, and S.F = safety factor(fix as 1.5).

However the rule of mixture can consider approximately 10% additional load in off-loading directions at other inclined fiber directional plies. Therefore the initially sized 0° ply flange thickness by the netting rule was modified by the rule of mixture with the added ±45°and 90°plies. The initial structural design results were shown in Table 1.

Skin thickness can be sized by the following equation in consideration of shear flows q_i of skin and web.

$$q_i = \frac{Q_y I_z - Q_z I_{yz}}{I_y \cdot I_z - I_{yz}^2}\sum A_i y_i - \frac{Q_z I_y - Q_y I_{yz}}{I_y \cdot I_z - I_{yz}^2}\sum A_i z_i + q_0 \tag{3}$$

$$\tau_{allow} = \frac{q_i}{t} \tag{4}$$

where q_i = shear flow, Q_y = y axis component shear force, Q_z = z axis component shear force, I_z , I_y and I_{yz} = 2nd area moment of inertias in z, y, and y-z axes, $\Sigma A_i y_i$ = 1st area moment of inertia in y axis, $\Sigma A_i z_i$ = 1st area moment of inertia in z axis. Figure 4 shows the shear flow on skin and spar webs.

Table 1. The initial structural design results of main wing

Station	Front spar flange thickness(mm)	Stacking sequence
1	7.00	$[\ 2(\pm45,0_4,90,\pm45,0_4,90)\ ]s$
2	5.25	$[\ \pm45,0_4,90,\pm45,0_4,90,\pm45,0_4,90\ ]s$
3	2.75	$[\ \pm45,90,0_4,\pm45,90,0\ ]s$
4	1.75	$[\ \pm45,0_4,90\ ]s$
5	1.25	$[\ \pm45,0_2,90\ ]s$
6	1.25	$[\ \pm45,0_2,90\ ]s$
Station	Rear spar flange thickness(mm)	Stacking sequence
1	11.50	$[\ 2(\pm45,90,0_4,\pm45,90,0_4,\pm45,90,0_4,\pm45)\ ]s$
2	7.75	$[\ 2(\pm45,90,0_4,\pm45,90,0_4),\pm45,90\ ]s$
3	5.25	$[\ \pm45,0_4,90,\pm45,0_4,90,\pm45,0_4,90\ ]s$
4	3.50	$[\ \pm45,0_4,90,\pm45,0_4,90\ ]s$
5	1.25	$[\ \pm45,0_2,90\ ]s$
6	1.25	$[\ \pm45,0_2,90\ ]s$
Station	Spar web thickness(mm)	Stacking sequence
all	4.00	$[\ 2(\pm45,0,90,\pm45,0,90)\ ]s$
		※ Front and rear spar flange width : 225mm

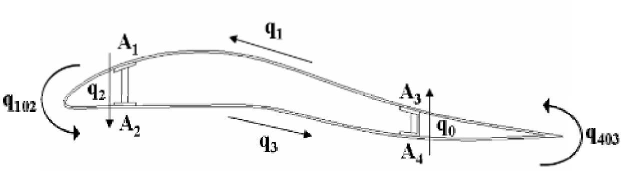

Fig. 4. Shear flow of skin and spar web

2.4 Structural Design of Horizontal Tail

Horizontal tail was designed using similar way with the main wing. Structural feature was composed of 'I' type front spar and channel type rear spar to accommodate easily the control surface such as elevator. Initial structural design was performed by the netting rule and the rule of mixture in the same way as the main wing design. Table 2 shows initial structural design results of horizontal tail.

Table 2. The initial structural design results of horizontal tail

Station	Front spar flange thickness(mm)	Stacking sequence
1	7.5	[2(±45,90,0_4,±45,90,0_4),±45]s
2	5	[±45,0_4,90,±45,0_4,90,±45,0_3,90]s
3	2.5	[±45,0_3,90,±45,0,90]s
Station	Rear spar flange thickness(mm)	Stacking sequence
1	5	[±45,0_4,90,±45,0_4,90,±45,0_3,90]s
2	2.5	[±45,0_3,90,±45,0,90]s
3	2.5	[±45,0_3,90,±45,0,90]s
Station	Spar web, skin thickness(mm)	Stacking sequence
all	3	[±45,0_3,90,±45,0_3,90]s
※ Front and rear spar flange width : 97mm		

2.5 Evaluation of Structural Safety and Stability

In order to investigate structural safety and stability on the initially designed main wing and horizontal stabilizer, structural analysis was performed using the well-known commercial finite element code, PATRAN/NASTRAN. The element type used for this composite analysis was the laminated composite shell element ‘PCOMP’.

Through stress analysis for structural safety using Tsai-Wu failure criterion and structural stability analysis using the buckling load factor, it was found that the upper skin between front spar and rear spars of main wing was unstable in buckling at the given design load. Maximum stresses, which maximum compressive stress is 67MPa and maximum tensile stress is 65MPa, were found around the joint part between wing and fuselage. The estimated weight of the initially designed wing was 395 kg which is a bit heavier than the target weight of 383 kg, and the wing tip deflection was 259 mm.

From stress analysis it was found that for the initially designed horizontal tail is a bit lighter than the target weight. However the upper skin between front and rear spars of horizontal tail was unstable in buckling. At the initially designed horizontal tail, maximum compressive stress and maximum tensile stress are 128MPa and 110MPa, respectively.

Because not only the initially designed main wing’s weight exceeds the target weight but also upper skins of main wing and horizontal tail were unstable in buckling, so in order to meet the design requirements it should be modified. Therefore, through several iterative modifications from the initial design features of wing and stabilizer the final design features added the middle spar and the urethane foam sandwich at skin and web.

3 Design Modifications

3.1 Design Modifications of Main Wing

In the first design modification, a middle spar was added between front spar and rear spar. Through buckling analysis, it was found that the upper skin between middle and rear spars was unstable again even though the first deign modification.

Therefore, in the second to the fourth design modifications ribs were gradually added to remove the buckling. According to structural analysis results, because the first load factor of buckling was found as 0.9, structural stability of the modified wing feature with ribs was obtained. However the fourth modified wing feature’s weight was 1.3 times as the target weight.

For both weight reduction and structural stability the skin-spar type feature with foam sandwich was finally adopted. According to structural analysis results for the final design feature, it was found that weight of the finally designed wing was a bit less than the target weight, and the structural safety was confirmed by safety factor evaluation using Tsai-Wu failure criterion. In this calculation, it was found that the total weight of main wing was 351.4kg. As shown in the figure 5, maximum compressive stress on the upper skin is 120MPa, maximum tensile stress on the lower skin is 114MPa, and the first buckling load factor is 2.78. Figure 6 shows the deformed configuration and the first buckling mode shape of the finally modified main wing, and as shown in figure 7 the final modification feature of main wing is composed of three spars and skin with the foam sandwich. Figure 8 shows the design modification flow of main wing.

Table 3 shows the sized thicknesses of spar flange, web and skin, and their laminate stacking sequences.

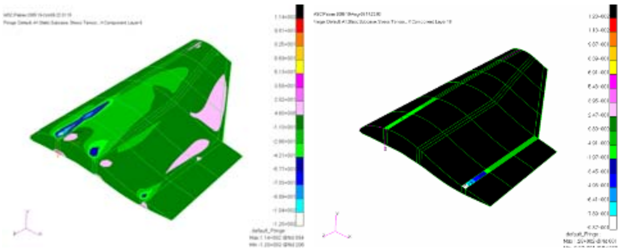

Fig. 5. Stress contour on skin and spar of final modified main wing

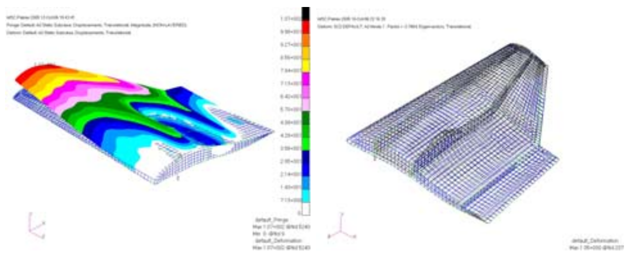

Fig. 6. Deformed configuration and first buckling mode shape of final modified main wing

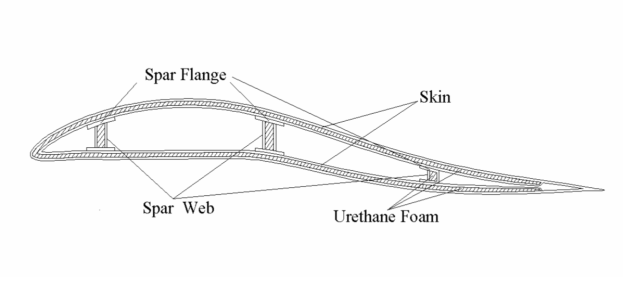

Fig. 7. Final modification of main wing structure with three spars and foam sandwich

Table 3. Final modification results of main wing structure

Station	Front spar flange thickness(mm)	Stacking sequence
1	4.25	[±45,0_4,90,0_4,±45,0_3,90]s
2	3.75	[±45,0_4,90,±45,0_3,90,±45]s
3	2.00	[±45,0_3,±45,0]s
4	1.75	[±45,0_3,90,0]s
5	1.75	[±45,0_3,90,0]s
6	1.75	[±45,0_3,90,0]s
Station	Middle spar flange thickness(mm)	Stacking sequence
all	2.00	[±45,0_3,±45,0]s
Station	Rear spar flange thickness(mm)	Stacking sequence
1	6.00	[±45,90,0_4,±45,90,0_4,±45,0_4,±45,0_2]s
2	4.25	[±45,0_4,90,0_4,±45,0_3,90]s
3	3.75	[±45,0_4,90,±45,0_3,90,±45]s
4	2.00	[±45,0_3,±45,0]s
5	1.75	[±45,0_3,90,0]s
6	1.75	[±45,0_3,90,0]s
Station	Spar web and skin thickness (mm)	Plying sequence
all	16.75	(±45,0,90,±45,0),foam,(0, ±45,90,0, ±45)
		※ Front and rear spar flange width : 225mm ※ Foam sandwich thickness of web and skin : 15mm

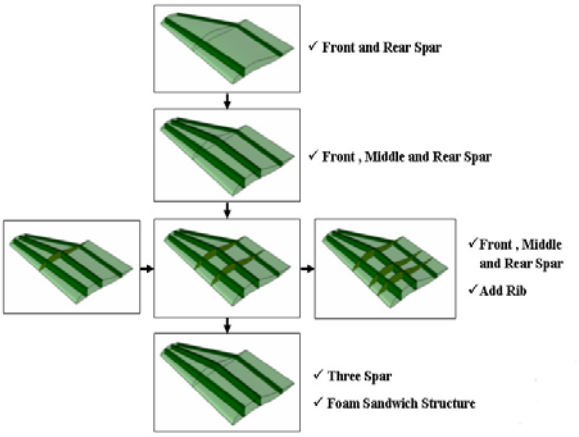

Fig. 8. Design modification flow of main wing

3.2 Design Modifications of Horizontal Tail

In the initial structural design and analysis, it was found the upper skin between front and rear spars was unstable in bucking. In order to solve this buckling problem, the foam sandwich was added at upper skin and spar web like the main wing design modification.

By stress analysis of the modified design feature, it was found that maximum compressive stress and tensile stress on the skin are 97.0MPa and 97.1MPa respectively, compressive stress and tensile stress at the spar are 141MPa and 101MPa respectively, and the structure is stable in bucking.

Figure 9 shows stress contour on skin and spar of the modified horizontal tail, and figure 10 shows the deformed configuration and the first buckling mode shape. Table 4 shows final design modification results.

Table 4. Final modification results of horizontal tail structure

Station	Front spar flange thickness(mm)	Stacking sequence
1	7.5	[2(±45,90,0_4,±45,90,0_4),±45]s
2	5	[±45,0_4,90,±45,0_4,90,±45,0_3,90]s
3	2.5	[±45,0_3,90,±45,0,90]s
Station	Rear spar flange thickness(mm)	Stacking sequence
1	5	[±45,0_4,90,±45,0_4,90,±45,0_3,90]s
2	2.5	[±45,0_3,90,±45,0,90]s
3	2.5	[±45,0_3,90,±45,0,90]s
Station	Spar web, skin thickness(mm)	Stacking sequence
all	16.75	(±45,0,90,±45,0),foam,(0, ±45,90,0, ±45)
		※ Front and rear spar flange width : 97mm ※ Foam sandwich thickness of web and skin : 15mm

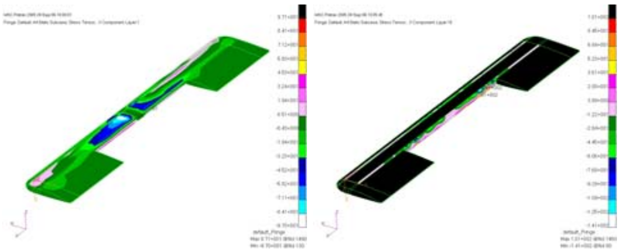

Fig. 9. Stress contour on skin and spar of the modified horizontal tail

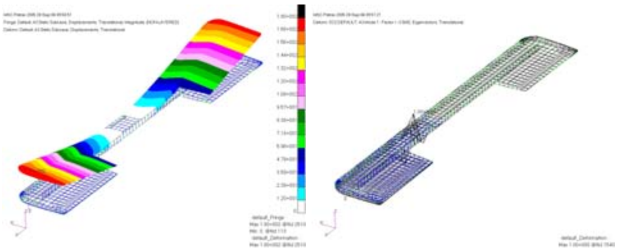

Fig. 10. Deformed configuration and the first buckling mode shape of the modified horizontal tail

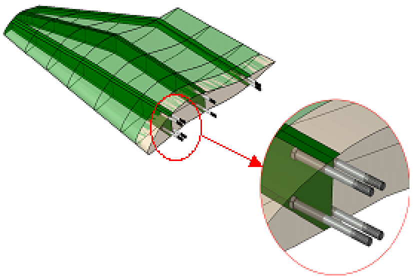

Fig. 11. Joint part configuration of main wing

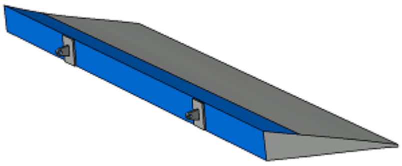

Fig. 12. 3-D CATIA model for control surface

4 Design on Joint Part and Control Surface

4.1 Joint Design between Main Wing and Fuselage

For the wing root joint to fuselage, the insert type bolts were adopted through reinforcing root spar flanges. By considering principal stresses and allowable strength of the insert bolt, the Titanium based steel alloy M30 bolt was selected for anti-corrosion against sea water environmental condition.

In the first design four bolts were applied to root flanges of the front and rear spars. The safety factor was calculated as 2.48 for the maximum static load in this case. By considering the dynamic load which may occur in flight and the fatigue limit load for more than 20 years fatigue life, 6 insert bolts including 4 bolts at the front root spar flange and 2 bolts at the rear root spar flange were decided. However because the final design modification feature of main wing has 3 spars, 2 more bolts were added at the middle root spar flange. Therefore 8 insert bolts including 4 bolts at the front root spar flange and 2 bolts at the middle root spar flange and 2 bolts at the rear root spar flange were finally decided[7]. Figure 11 shows joint part configuration of the final design feature.

4.2 Control Surface Design

For structural design on aileron and elevator, similar method with the main wing and horizontal tail design was used, for instance the channel shape spar was selected for easy joint shape with the wing or the horizontal tail, and for calculating structural design load distribution the control surface was longitudinally divided into 20 sections. The initially designed laminate stacking sequences for the aileron skin and spar were [±45°, 0°, 90°]s, respectively. Through structural analysis, it was found that the spar was unsafe in strength and the upper skin was locally unstable in buckling. For modifying the first design feature, some more plies of the spar flange were added, and the foam sandwich was added to the skin. Therefore the modified stacking sequence was [±45°, 0°, 90°, 0°, ±45°, 0°]s and the added foam thickness was 15mm. In other word, the final laminate stacking sequence was decided as [±45°, 0°, 90°, Foam, 90°, 0°, ±45°]s. According to stress analysis, it was found that not only the final feature was safe in strength because maximum compressive stress on the upper skin and maximum tensile stress on the lower skin are 52.8Mpa and 33.0MPa respectively, but also was stable in buckling because the first buckling load factor is 1.03.

Two lugs which are located at 1/4 position from the end of the control surface respectively was selected for joint between aileron and wing as shown in Figure 12. The lug design load was estimated from control surface movement in slant direction, and aluminum alloy 7075-T6 material was selected for light weight

Lug can be sized by the following equation (5) and (6) and the proper safety factor on the design load.

$$P_{tru} = K_{tru} f_{tux} dt \tag{5}$$

$$S.F = \frac{P_{tru}}{P_a} > 1 \tag{6}$$

Where, P_{tru} = allowable critical load, K_{tru} = efficiency factor, F_{tux} = tensile strength of material, d = diameter of lug hole, t = lug thickness and P_a = applied load on control surface.

5 Structural Test

Before manufacturing the full scale WIG prototype, in order to evaluate structural design and analysis procedure the structural test was performed by a sub-scale main wing with the scaling ratio of 1/17. The subscale wing configuration is slightly different form the full scale one due to the manufacturing difficulty and the laboratory autoclave size. The sub-scale static structural test was performed under the simulated aerodynamic loads at three positions. The manufactured carbon/ epoxy composite wing was set on the test rig and loaded by three steel weights. Figure 13 shows the experimental test setup of the sub-scale wing. Table 5 shows comparison results between the measured value and the predicted value on the stresses at the 0.2r/R station.

Fig. 13. Static structural test setup of the sub-scale wing loaded by the simulated aerodynamic load with three steel weights

Table 5. Comparison between the tested and predicted stress results

Item	Analysis results	Test results
Upper surface stress	- 20.7 MPa	-17.2 MPa
Lower surface stress	+6.81 MPa	+5.32MPa

Table 6. Comparison between the measured and predicted natural frequencies

Item	Analysis results	Test results
First flap mode	5.53Hz	4.12Hz

In order to find the natural frequency of the sub-scale wing, the experimental test was carried out by the impulse hammer, and the natural frequencies were found by the FFT analyzer. Table 6 shows the measured and predicted first mode natural frequencies.

In this comparison, it was inferred that the differences between the test results and the predicted values are caused by the incorrect test specimen due to a bit excessive coating and adhesive treatment

6 Conclusion

In this study, a structural conceptual design and analysis for wing and horizontal tail of a 20 seats small scale WIG craft considering weight minimization was performed. Basic structural feature adopted the skin-spar type structure, and especially the foam sandwich composite was applied on upper and lower surfaces of the wing to improve buckling behavior and vibration absorption capability. The front spar adopted ‘I’ type beam and the rear spar adopted channel type beam to accommodate control surface structure. In order to improve strength weight ratio as well as stiffness weight ratio the carbon/epoxy composite material which is mostly used in aerospace vehicle design was selected.

Through investigation of various load cases, the aerodynamic load including inertia load at the maximum cruising speed was defined as a structural design load. For light structural design concept the carbon/epoxy composite material was selected, and for initial structural design of the spar flange and web of main wing and horizontal stabilizer the netting rule and the rule of mixture design methods were used. In this design, it was assumed that front and rear spar flanges endure mainly bending load, and skin and the spar webs endure the shear load. Through FEM analysis for evaluating structural safety and stability, several times of structural modifications were repeatedly carried out to meet the given target weight of 383kg.

From structural stability analysis results of the initially designed main wing, it was found that the upper skin structure between front and rear spars was weak against buckling. Therefore in order to solve this problem, a middle spar and the foam sandwich at the upper skin and the web were added. After several design modification structural safety and stability of the final design feature was reconfirmed. An insert bolt type wing joint structure with eight high strength bolts to fix the designed wing to fuselage was adopted for easy assembly and removal as well as in consideration of more than 20 years fatigue life. The final wing design feature's weight was 371.4 kg which is 11.6 kg less than the target weight.

Horizontal stabilizer was designed by a similar structural feature with main wing. From buckling analysis of the initially designed horizontal stabilizer, it was found that the upper skin was a bit weak against buckling like the initially designed wing. Therefore the foam sandwich structure was added at upper skin and spar web. Structural safety and stability of the final design feature was reconfirmed from the FEM analysis. The final horizontal tail design feature's weight was 150 kg which is 30 kg less than the target weight.

Structural design of control surface including joint structure between main wing and control surface was performed. A structural feature with a channel type spar, the foam sandwich-carbon/epoxy composite skin structure and two lug joints was adopted for aileron design.

Before manufacturing the full scale WIG prototype, the structural test was performed by a sub-scale main wing for evaluation of the proposed structural design and analysis procedure. Through this comparison, even though there were some differences between them, it was confirm that the proposed design method is appropriate for the WIG's composite wing structure.

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