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Evaluation on Structural Safety for Carbon-Epoxy Composite Wing and Tail Planes of the 1.2 Ton Class WIG

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Abstract

In the present study, structural safety and stability on the main wing and tail planes of the 1.2 ton WIG(Wing in Ground Effect) flight vehicle, which will be a high speed maritime transportation system for the next generation, was performed. The carbon-epoxy composite material was used in design of wing structure. The skin-spar with skin-stressed structural type was adopted for improvement of lightness and structural stability. As a design procedure for this study, the design load was estimated with maximum flight load. From static strength analysis results using finite element method of the commercial codes. From the stress analysis results of the main wing, it was confirmed that the upper skin structure between the second rib and the third rib was unstable for the buckling load. Therefore in order to solve this problem, three stiffeners at the buckled region were added. After design modification, even though the weight of the wing was a little bit heavier than the target weight, the structural safety and stability was satisfied for design requirements.

Key Words : WIG vehicle, Structural design, Finite element analysis, Composite material

1. Introduction

The study on WIG vehicle with lift increase effect by wing in ground effect has been underway in various sectors in a bid to develop the carrier with high transport efficiency. The structure of WIG comprises of the upper structure similar to airplane and lower structure similar to high speed vessel in shape and for efficient ground effect, it has the larger wing for its fuselage.

It takes off and lands on water and flies at proper altitude from the sea surface depending on sea weather. WIG has the mass transportation capacity at the speed between airplane and vessel, emerging as the next-generation super high speed vessel that would bring about the innovation to marine transport system. Recently, a 20-seater compact WIG to 100ton -capacity large WIG are under development in line with the relevant studies[1-3]. This study includes structural design and analysis research of main wing and tail plane of 1.2ton WIG craft.

2. Structural Design and Analysis Concept

Analysis of aerodynamic design data from design requirements was conducted to evaluate the structural safety of WIG vehicle. Structural design load was determined and mechanical properties of the material used for WIG vehicle were identified. Based on this, structural stability was evaluated to

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review the feasibility of structural design using finite element code. And satisfying the design requirements of final structural design was determined accordingly. Fig. 1 shows structural analysis process to propose in the preview study[4]. Fig. 2 shows structural configuration of main wing and tail plane.

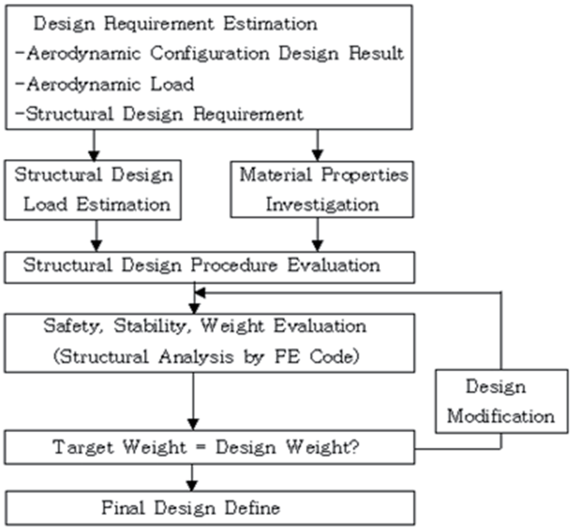


Fig. 1 Structural Analysis Process

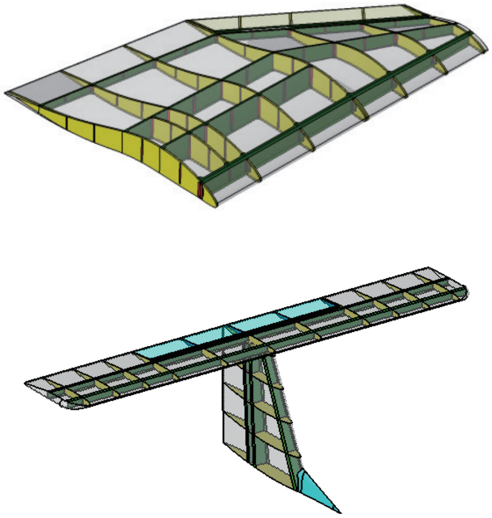


Fig. 2 Structural configuration of the main wing and tail plane

3. Design Load and Structural Design

Design load of each wing structure was estimated based on aerodynamic design data for evaluation of safety of wing structure of WIG vehicle. The load on main wing was defined in a way of distributing aerodynamic load at maximum flight speed in spar n and chord direction from load factor.

In this study, main wing is divided into 20 parts along the spar n and then inertia load and aerodynamic load by gravity load of main wing were calculated. Design load calculated by considering safety factor 1.5 to calculated maximum structure load was assumed for structural safety review. For the load on horizontal tail wing, the load considering checked accelerated maneuvering load to normal non-accelerated load was defined as the maximum load and for vertical tail wing load, the load considering slip stream effect by engine propeller while the rudder at maximum displacement is at neutral position and yaw up to static balance angle was defined as the maximum load. For both horizontal and vertical tail plane, design load considering safety factor 1.5 was considered for structural stability review.

Table 1-3 shows each shear force and bending moment distribution of main wing, horizontal tail and vertical tail.

The load induced engine thrust was calculated by engine power and velocity related equation (1). Where, V is velocity, η_p is propeller efficiency. H.P is engine horse power. In this study, the 102 horse power was applied to engine thrust of WIG craft.

$$\mathrm{T} = \frac{\eta_p \cdot H.P \cdot 550}{V} \tag{1}$$

Table 1 Shear force and bending moment distribution of main wing at maximum load condition

Station	Shear force[N]	Bending moment[Nm]
1	15,000	35,000
2	13,000	27,000
3	11,000	23,000
4	9,000	15,000
5	7,000	11,000
6	5,000	6,000
7	3,000	4,000
8	2,500	3,000
9	1,800	2,000
10	1,000	1,500

Table 2 Shear force and bending moment distribution of horizontal tail plane at maximum load condition

Station	Shear force[N]	Bending moment[Nm]
1	5,800	10,000
2	5,100	7,900
3	4,300	5,900
4	3,500	4,000
5	2,600	2,500
6	1,800	1,600
7	1,000	800
8	400	200

Table 3 Shear force and bending moment distribution of vertical tail plane at maximum load condition

Station	Shear force[N]	Bending moment[Nm]
1	5,500	4,800
2	4,700	3,600
3	4,000	2,700
4	3,300	2,100
5	2,600	1,400
6	2,000	900
7	1,400	500
8	900	250

The material used for structural design is composite material such as carbon-epoxy fabric prepreg used for fuselage skin, main wing, vertical and horizontal tail wing and spar and rib. Carbon epoxy UD prepreg was applied to Bulkhead and ring frame. And Glass epoxy was applied to side hull of main wing.

In designing the parts of WIG vehicle, main wing was designed, after dividing it into three parts from the point connecting to fuselage frame, the part from the root to 1/3 point to wing, part to the center of wing and the part to the tip. Over entire part, thickness of spar flange (Range) and web are designed same. Skin was designed to bear main load and thus the first compartment lengthwise receives concentrated stress severely and thus the number of layer was designed more than the second and third compartment. Rib was designed equally over entire part.

Horizontal tail plane and vertical tail plane were designed to have same thickness of skin and rib for the convenience in manufacturing.Table 4 shows material properties of the applied composite material for structural design.

Table 4 Material properties of the applied carbon-epoxy fabric prepreg

HPW193/RS1222 carbon-epoxy fabric		Unit
Longitudinal Modulus	63.4	GPa
Transverse Modulus	58	GPa
Axial Shear Modulus	56.2	GPa
Poisson's Ratio	0.17	-
Longitudinal Tension	635	MPa
Longitudinal Compression	527.9	MPa
Transverse Tension	411.7	MPa
Transverse Compression	304.4	MPa
In-Plane Shear	114.5	MPa
Inter-laminar Shear	61.9	MPa
Density	1.58	g/cm^3
1 Ply Thickness	0.2	mm

4. Structural Analysis Results and Design Modification

Based on structure design, structural stability was reviewed using finite element analysis. In this study, commercial finite element code was used for static strength analysis and buckling analysis and Tsai-Wu fracture theory was used as fracture standard for safety evaluation. As a result of grid generation for finite element analysis, main wing comprises of 46,134 elements, horizontal plane 10,923 elements, vertical tail plane 13,766 elements and aileron 3,307 elements. For load, distributed load by compartment was applied and for boundary condition, fixed boundary condition was applied to connection to fuselage as well as to horizontal and vertical tail wing.

According to linear static analysis of main wing, weight of wing excluding aileron was 98kg, maximum compressed stress of skin was 64.9MPa, tensile stress 59.4MPa, maximum compressed stress of spar 51.0MPa, tensile stress 64.0MPa and maximum displacement 13.7mm. Margin of safety according to Tsai-Wu failure criterion was 7.1 for skin and 12.4 for spar which is designed stably in terms of strength. But safety factor 0.5 appeared insignificantly on connection to fuselage which requires reinforcement on connection. Compressed stress on engine mount was 15.2MPa and tensile stress 9.6MPa proving to have sufficient safety factor.

Fig. 3 shows stress distribution of skin and spar of main wing. Fig. 4 showsdeformed configuration of main wing. The margin of safety by Tsai-Wu failure criterion was shown in Fig. 5[5]. The bucking analysis result was shown in Fig. 6. The bucking load factor is 0.3. Therefore, the rear skin region between second and third rib from wing root is unstable.

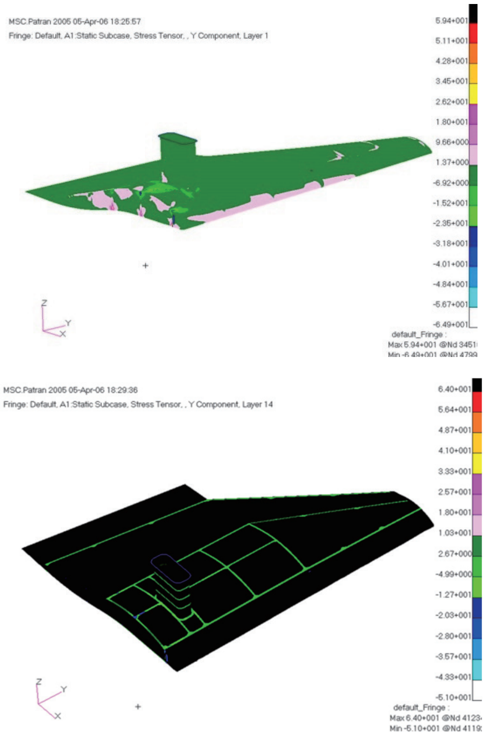


Fig. 3 Stress contour on skin and spar of main wing

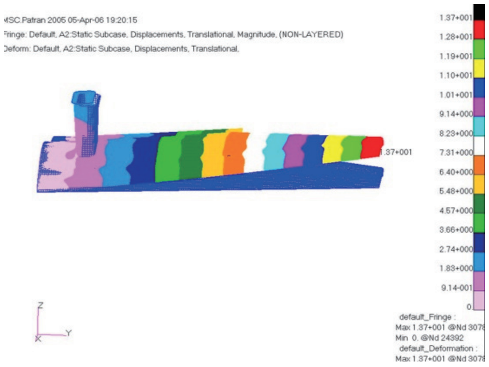


Fig. 4 Deformed configuration of main wing

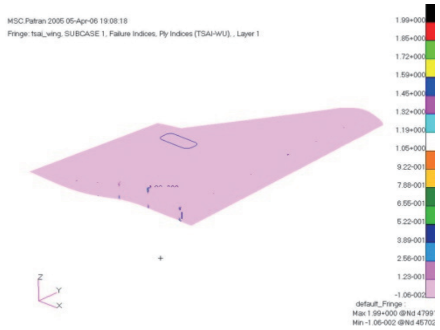


Fig. 5 Safety factor distribution of main wing by Tsai-Wu failure criterion

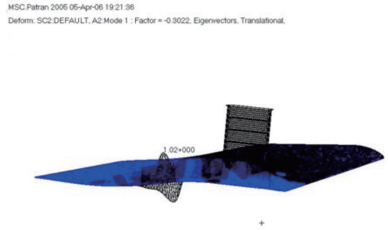
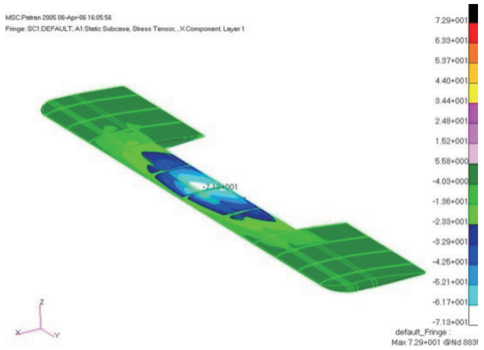


Fig. 6 First buckling mode shape and load factor of main wing

According to linear static analysis of horizontal tail plane, weight of the structure excluding elevator was 25kg, maximum compressed stress of skin and spar was 71.3MPa and 49.3MPa and maximum tensile stress was 72.9MPa and 41.6MPa, respectively, proving to have sufficient safety factor. According to buckling analysis, buckling load factor was 0.09, indicating the upper skin part between wing root and the first rib was vulnerable to buckling. Partial reinforcement is needed to ensure sufficient buckling strength is secured.

Fig. 7 shows stress distribution of skin and spar of horizontal tail. Fig. 8 shows deformed configuration of horizontal tail. The margin of safety by Tsai-Wu failure criterion was shown in Fig. 9. Fig. 10 shows first buckling mode shape and load factor of horizontal tail.



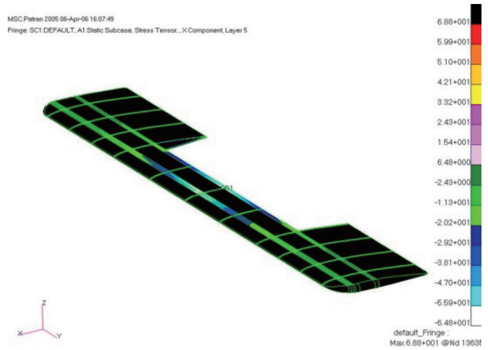


Fig. 7 Stress contour on skin and spar of horizontal tail

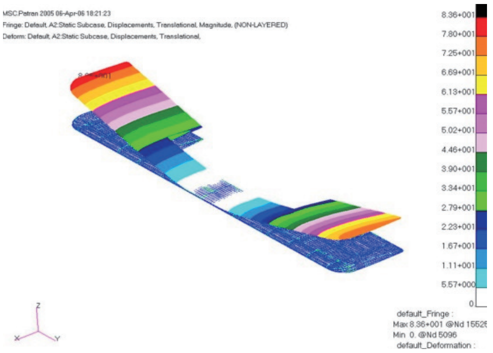


Fig. 8 Deformed configuration of horizontal tail

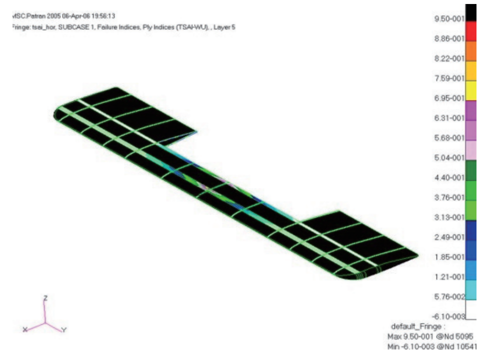


Fig. 9 Safety factor distribution of horizontal tail by Tsai-Wu failure criterion

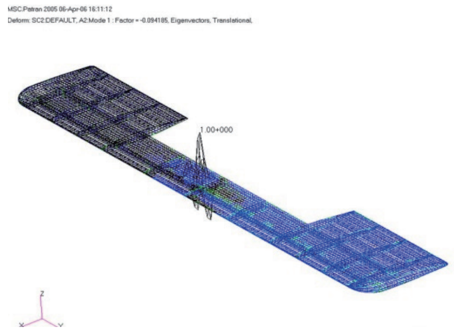


Fig. 10 First buckling mode shape and load factor of horizontal tail

According to linear static analysis of vertical tail wing, weight of the vertical tail wing excluding Rudder was 9.54kg, maximum compressed stress of skin and spar was 26.9MPa and 13.7MPa and maximum tensile stress was 34.1MPa and 28MPa, respectively. According to displacement analysis result, it's 2.75mm on tip of the wing, indicating to have the sufficient safety factor. According to buckling analysis, buckling load factor was 0.5, indicating the skin part between wing root and the first rib was vulnerable to buckling.

Fig. 11 shows stress distribution of skin and spar of vertical tail. Fig. 12 shows deformed configuration of vertical tail. The margin of safety by Tsai-Wu failure criterion was shown in Fig. 13. Fig. 14 shows first buckling mode shape and load factor of vertical tail.

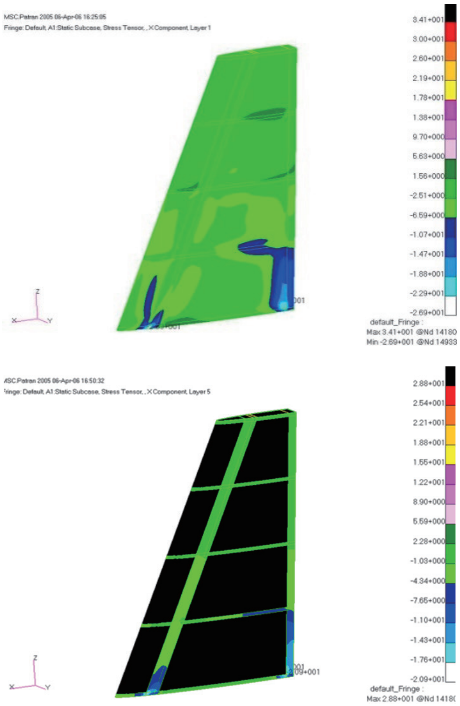


Fig. 11 Stress contour on skin and spar of vertical tail

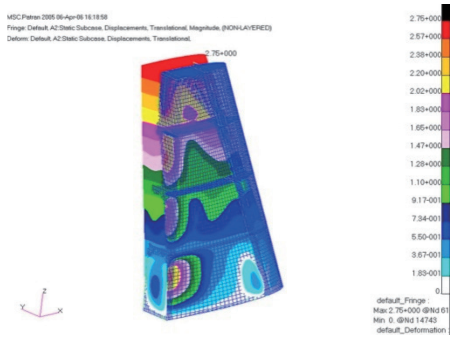


Fig. 12 Deformed configuration of vertical tail

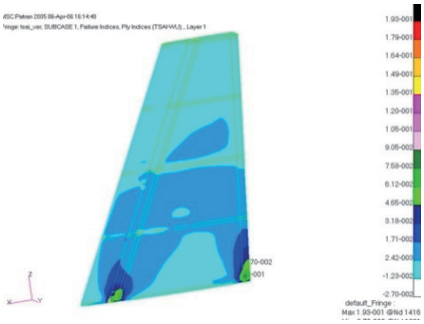


Fig. 13 Safety factor distribution of vertical tail by Tsai-Wu failure criterion

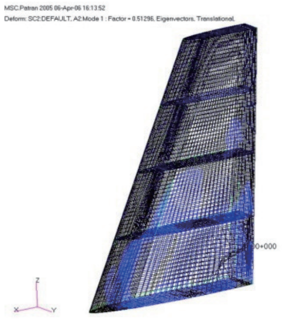


Fig. 14 First buckling mode shape and load factor of vertical tail

According to structural safety analysis of aileron of main wing based on load on aileron, compressed stress on skin part was 98.6MPa and tensile stress was 71.3MPa but the safety factor on skin load was slightly lower. According to buckling analysis result, buckling load factor was 0.2 indicating partial buckling occurred on skin.

According to strength result, structural design requirements were mostly satisfied but it reached 1.3 times of design target weight as seen in Table 5. Thus, change of laminating layer depending on stress and lightweight design technique are needed.

And the parts vulnerable to buckling such as the skin between the second rib and the third rib and the part between the first rib add second rib on horizontal tail wing and vertical tail wing need to be improved in design.

Table 5 Comparison between target weight and designed weight of wing

Part	Target weight[kg]	Design result[kg]
Main wing	54	98.85
Horizontal tail	31	25
Vertical tail	18	9.54
Total	103	133.39

As a result of structural stability review after reinforcing the thickness of skin and spar from wing root to 200m lengthwise to improve the connection on main wing, sufficient safety factor was obtained. And to improve the parts vulnerable to buckling, design to reinforce with three 30mm wide and 0.8mm (8 plies) thick channel stiffeners lengthwise were proposed and structural analysis was conducted. Consequently, buckling load factor 1.01 was obtained, securing the structural stability.

Fig. 15 shows safety factor distribution of main wing by Tsai-Wu failure criterion. Fig. 16 shows first buckling mode shape and load factor of modified main wing.

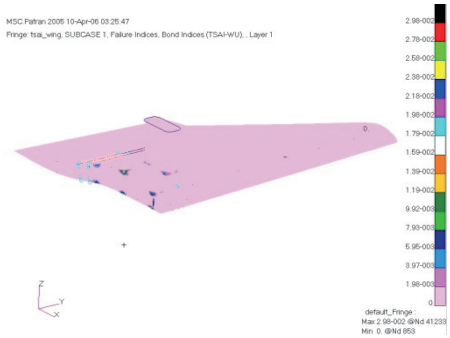


Fig. 15 Safety factor distribution of main wing by Tsai-Wu failure criterion

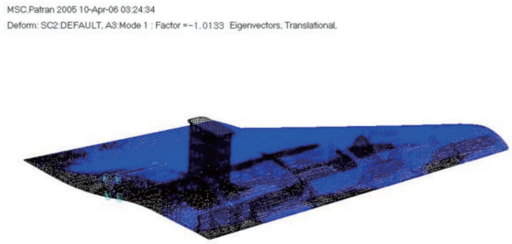


Fig. 16 First buckling mode shape and load factor of main wing

As part of the way to improve the safety factor on aileron skin, skin laminating was increased by 2plies and 1 rib was added to the parts between existing ribs and as a result of structural stability review, the structure was reinforced stably and buckling factor was increased to 2.

5. Conclusions

In this study,safety and stability review of main wing, vertical and horizontal tail plane of small high speed WIG vehicle was conducted. Carbon epoxy composite material was used to realize lightweight, high strength and high performance and structure design of each wing was made to bear the main load by skin based on design concept, skin - spar - rib. According to structural analysis, it proved to be safe at maximum load condition but the weight exceeds the target weight by 30%. According to buckling analysis, the part between the second rib and the third rib was vulnerable to buckling and partial buckling appeared also on tail wing skin and design improvement measure was proposed.

In this study, the measure to design the wing of WIG vehicle was proposed and based on this study, lightweight design technology using composite material was proposed which is expected to be useful in designing the structure of various carriers in future.

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