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Optimal Design of Three-Dimensional Woven Composite Aircraft Wing with Genetic Algorithm

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Abstract
The wings of aircraft should have sufficient mechanical properties and should not fail, but they should be lightweight. The three-dimensional woven composite has excellent formability and outstanding utilization by the automated manufacturing process based on the preform. In addition, it has high out-of-plane mechanical properties due to the three-dimensional fiber arrangement. In this paper, the optimal design was performed using a genetic algorithm to reduce the weight of the aircraft wing in three-dimensional woven composite. Through the optimal design, we can build a database of mechanical properties and the wing's mass according to the number of fill yarn layers.

1. Introduction

The three-dimensional woven composite has a preform-based automated manufacturing process, so the production speed is fast and the formability is good. In addition, since it has a three-dimensional fiber arrangement, the mechanical properties in the out-of-plane direction are high [1]. As aircraft wings need to have enough mechanical properties, three-dimensional woven composite can be a good material for aircraft. The weight reduction of the wing box is essential. In order to reduce the weight of the wing, an optimal design is required. However, it is difficult to optimize the wing box using differential equations because it has a complex shape. A genetic algorithm is a probabilistic search method that mimics natural selection and genetic laws [2]. It can find optimal solutions through various operators without using differential equations. There are various of research to perform the optimal design using woven composites. Axinte used genetic algorithm to optimize the geometrical parameters of satin weave fabric [3]. Whang performed the optimal design of the thickness and width of the yarns through the micromechanical model and genetic algorithm [4]. Xinwei used genetic algorithm of the yarn's gap to derive the optimal solution of the three-dimensional woven composite stiffened panel [5]. Through the research, there are a lot of optimal designs for woven composite unit cells and simple panel, but no optimal design studies for wing box have been conducted.

In this paper, the genetic algorithm was used to reduce the weight of the three-dimensional woven composite aircraft wing box. Minimizing the aircraft wing box was specified as the objective function. Design variables were the number of fill yarn layers of the wing parts skin, stringer, spar and rib. Depending on the number of fill yarn layers, the mechanical properties and mass of each part change, so this can be important design variables. Using the design variables, this paper set a population to be used for the optimal design and evaluated according to the fitness function. According to the evaluation result, the selection operator selected the chromosome to be maintained in the next generation. Selected chromosome generated the next generation by crossover operator. It is necessary to apply mutation operator so that the entire generation do not fall into the local optimum. Based on the Tsai-Wu failure theory, the presence or absence of fail was constrained through finite element analysis. Chromosomes that do not meet the constraints were excluded and repeated. Iteration progressed until converging. Through the optimal design performed in this paper, it is possible to design a wing box with an optimized mass by customizing of three-dimensional woven composite. In addition, it is possible to build a database for the mechanical properties and mass of aircraft wing according to the number of fill yarn layers.

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2. Design of aircraft wings with three-dimensional woven composite

2.1 Aircraft wing preform made of the three-dimensional woven composite

The aircraft wing is consisting of ribs, spars, skins and stringers. Those are expressed as Figure 1. Table 1 shows the number of each part. All parts are made of three-dimensional woven composites with a layer-to-layer (LTL) pattern. The LTL pattern has warp yarns and fill yarns, as shown in Figure 2. The warp yarns are placed in the x-axis direction and the fill yarns are placed in the y-axis direction. The warp yarn weaves two layers of the fill yarn. It is the basic design of the LTL pattern woven composite.

Ribs and spars are manufactured individually. The number of rib and spar's fill yarn layer is minimum one layer and maximum eight layers. Because of the set loom size, the number of fill yarn layers can't over the eight layers. The number of the warp yarn layers is changed by the number of the fill yarn layers. Since the skin and stringer are manufactured in one preform, the number of fill yarn layers is dependent. The number of skins fill yarn layers is minimum two layers and maximum six layers. The number of stringer's fill yarn layers is the total number of preform, eight layers, minus the number of skin's fill yarn layers. These parts also change the number of warp yarn layers by the number of fill yarn layers. Regardless of the number of skin and stringer layers, the number of skin+stringer's fill yarn layer is always the same with eight layers.

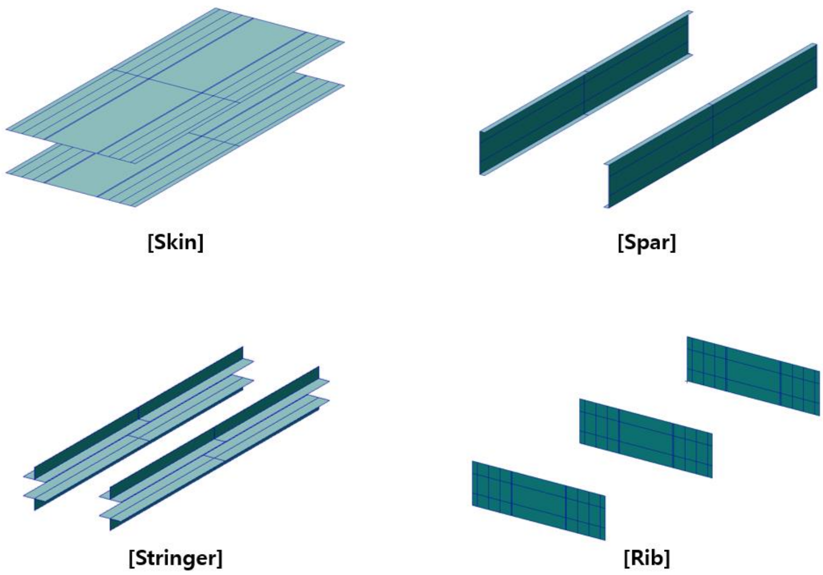

Figure 1: The parts of aircraft wing

Table 3: Length, width and height of wing box and each part

N_{skin} **[ea]**	N_{spar} **[ea]**	N_{rib} **[ea]**	$N_{stringer}$ **[ea]**
2	2	3	4

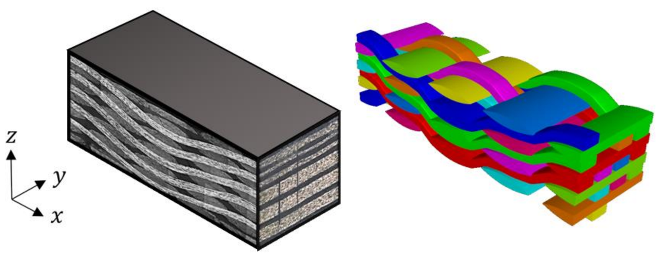

Figure 2: Layer-to-layer pattern

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2.2 Geometric modelling and finite element analysis of the aircraft wing box

To analyse the three-dimensional woven composite patterns of each part, we took a cross-section of the specimen by electron microscope. Figure 3 is x-z section of the three-dimensional woven composite and Figure 4 is y-z section of the three-dimensional woven composite. We observed the section and path of the yarns and measured the geometrical parameters, as shown in Table 2. w_f and w_w are the width of fill yarn and warp yarn. t_f and t_w are the thickness of fill yarn and warp yarn. g_f is the gap between fill yarns and warp yarns.
The wing box for optimal design are designed as follows. The woven composite wing box model with a constant rectangular cross-section along the wingspan. The wingspan length considered was 1600 mm, while the cross-section was characterized by a height of 201 mm and a width of 667 mm. The wing box presented four T-shaped stringers located two on the top and two on the bottom panel and its wingspan was divided in to three bays by two rectangular ribs [6].

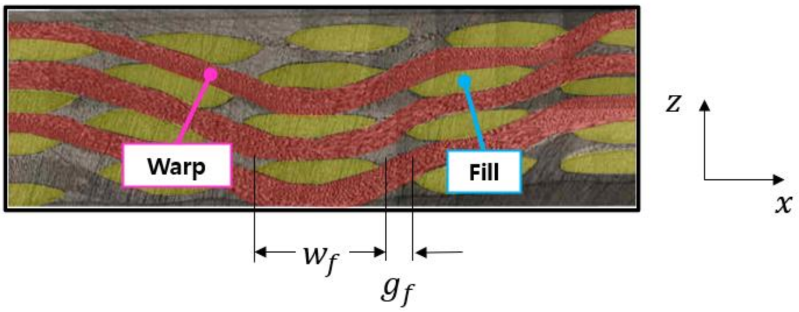

Figure 3: x-z plate

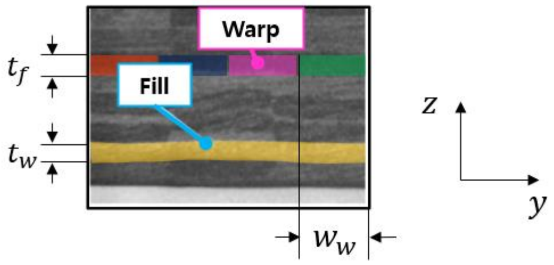

Figure 4: y-z plate

Table 2: Geometric parameters of yarns

	Thickness(t_f, t_w)	**Width(w_f, w_w)**	**Gap(g_f)**
Fill [mm]	0.28	2.65	0.37
Warp [mm]	0.24	2.62	-

3. Optimal design method of aircraft wing

3.1 Genetic algorithm for optimal design

We choose genetic algorithm for securing structural stability and reducing weight of the aircraft wing box using three-dimensional woven composite. The genetic algorithm has gene, chromosome and generation. The genetic algorithm is performed in following order. It can be expressed in flowchart with Figure 5.

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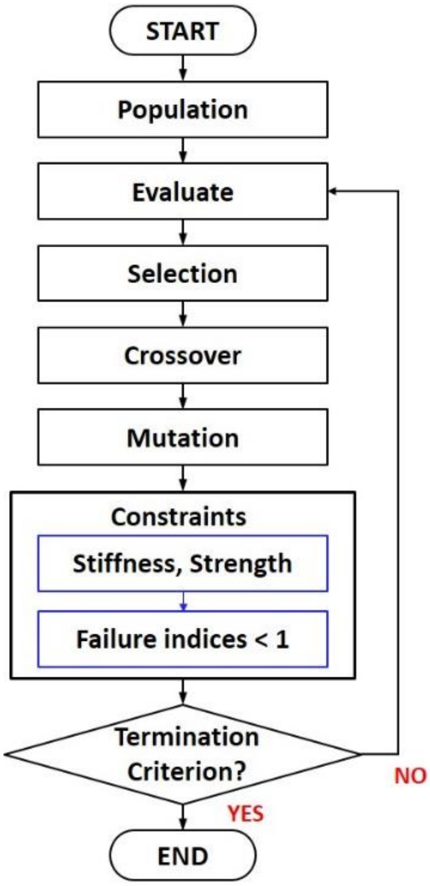

Figure 5: Optimal design flow chart of aircraft wing

① Population

N initial chromosomes are randomly generated by a combination of several design variables. At this time, the diversity of the population should be maintained. In addition, the optimal population size should be determined by considering the speed and accuracy of the algorithm. In this paper, 10 initial chromosomes were generated.

② Evaluation

The fitness of each chromosome is evaluated as shown in Equation 1.

$$f\left(Ch_i\right)=\left(C_w-C_i\right)+\frac{\left(C_w-C_b\right)}{\left(k-1\right)} \tag{1}$$

Where C_b, C_w and C_i denote the cost(mass) of the best chromosome, the worst chromosome and chromosome i. The best chromosome has a high fitness and the worst chromosome has a low fitness. If the value of k is raised, the difference in probability of choosing the best chromosome and the worst chromosome increase. In general, the most used k value is three to four and three is used in this paper.

③ Selection

This operator is used to select the target chromosomes of the crossover operator. There are various selection operators and the probability of the best chromosome selection should be high. A roulette wheel selection operator is the most representative selection operator and uses it to select chromosomes. The roulette wheel selection operator is a selection operator that throws darts while roulette is rotating. The roulette is divided into several zones. The proportion of the area occupied by chromosome ($P(Ch_i)$) can be expressed as follows:

$$P\left(Ch_i\right)=\frac{f\left(Ch_i\right)}{\sum_{j=1}^{N} f\left(Ch_j\right)} \tag{2}$$

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where N is the number of chromosomes. Chromosomes considered to be superior due to high fitness occupies a large area and chromosomes consider to be inferior due to low fitness occupies a small area. Therefore, the probability that the superior chromosome will be selected as the parent increase.

④ Crossover

Crossover operator is an operator to create offspring generation by crossover two parent chromosomes. The operator is repeated until the number of objects in the offspring generation becomes the numbers of parent objects. It is difficult to predict that offspring's chromosomes will be formed, because it is random from which parent the gene will be inherited. Two points crossover, one of the representative crossover operators, is used.

⑤ Mutation

Through the mutation operation, the search space can be expanded by putting properties that do not exist in the parent generation. As a result of the mutation, the ill-formed gene disappears over time and the well-formed gene contributes improving the quality of the population. In this paper, one gene of the entire chromosome is mutated at random numbers. This happens with a low probability of 0.05%.

⑥ Replacement

New genes created through evaluation, selection, crossover and mutation are formed in the offspring generation. Then, chromosomes that degrade structural stabilities are screened out and replaced by the number of deleted chromosomes.

⑦ Loop

Repeat steps ② to ⑥ until the mass converges minimum. In this case, the constrain must be satisfied.

⑧ End

Check whether the obtained design variables have the optimal value and exit.

3.2 Optimal design of aircraft wing with three-dimensional woven composite

3.2.1 Objective function

The purpose of the optimal design is structural lightweight. For optimal design, we set objective function (y) to mass minimization. The objective function is obtained with density of material, volume of each part and the number of parts in the wing box. the objective function can be expressed as below in Equation 3.

$$y = N_{skin}V_{skin}\rho_{skin} + N_{rib}V_{rib}\rho_{rib} + N_{spar}V_{spar}\rho_{spar} + N_{stringer}V_{stringer}\rho_{stringer} \tag{3}$$

N_{skin}, N_{rib}, N_{spar} and $N_{stringer}$ are the number of each part. Then V_{skin}, V_{rib}, V_{spar} and $V_{stringer}$ are the volume of the skin, rib, spar and stringer. To obtain the volume of the aircraft wing box, the length, width and height of each part (L, W, H) is calculated using Table 3 and Figure 6,7 as follows.

Table 3: Length, width and height of wing box and each part

$L_{wingbox}$ **[mm]**	$W_{wingbox}$ **[mm]**	$H_{wingbox}$ **[mm]**	W_{spar} **[mm]**	W_{web} **[mm]**	$W_{skinstringer}$ **[mm]**	W_{flange} **[mm]**
1,600	667	201	25	56	56	113

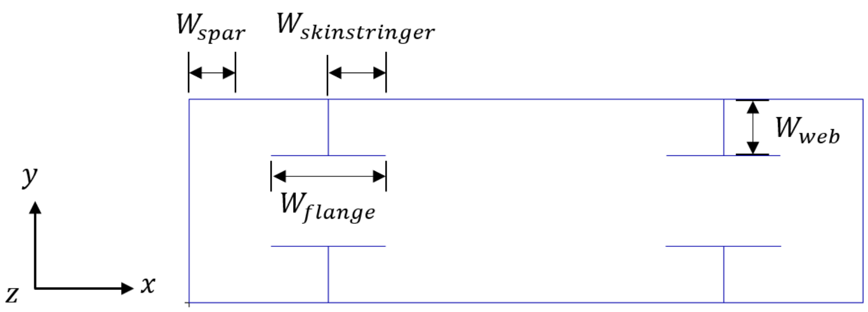

Figure 6: Dimension information for each part

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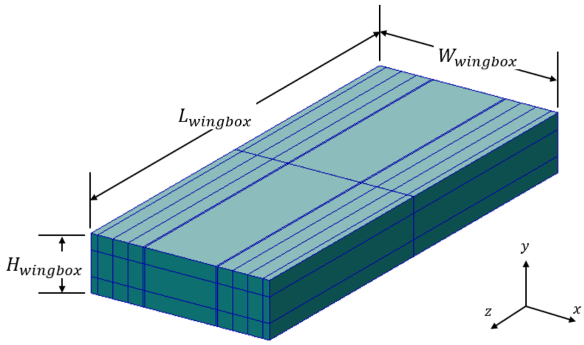

Figure 7: Dimension information for wing box

3.2.2 Design variable

The design variables are the number of fill yarn layers in skin, spar and rib. The number of fill yarn layers in stringer is not included as it is dependent with the number of fill yarn layers in skin. The preform of skin and stringer has eight fill yarn layers. Due to the preform branching, the number of fill yarn layer in skin is minimum of two and maximum of six. The number of fill yarns layer in stringer is same with the value obtained by subtracting the number of fill yarn layer in skin from the total. The number of fill yarn in rib and spar is minimum of one and maximum of eight.

3.2.3 Constraints

As the constraint for the optimal design, we consider the failure among structural instabilities. Apply Tsai-Wu failure theory to check whether wing box is broken or not. When the Tsai-Wu failure index is greater than 1, the wing box is broken. The Tsai-Wu failure theory can be expressed as below in Equation 4. The optimal design algorithm is linked with NASTRAN and it repeatedly calculated the failure index.

$$F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\sigma_1\sigma_2 = 1 \tag{4}$$

3.2.4 Optimal design result

The optimal design was performed using the developed optimal design algorithm. As shown in Figure 8, the optimal design result is derived through 13 generations. When the failure index is 0.3863, the minimum mass is 27.01kg. The number of fill yarn layer of the skin, rib and spar, which is design variables, were 6, 2 and 8 for each. Original model has 4 layers of skin and stringer fill yarns and 8 layers of rib and spar fill yarns. The mass of the original model is 33.67kg and the mass of the optimal design model is 27.01kg. It decreased about 6.66kg.

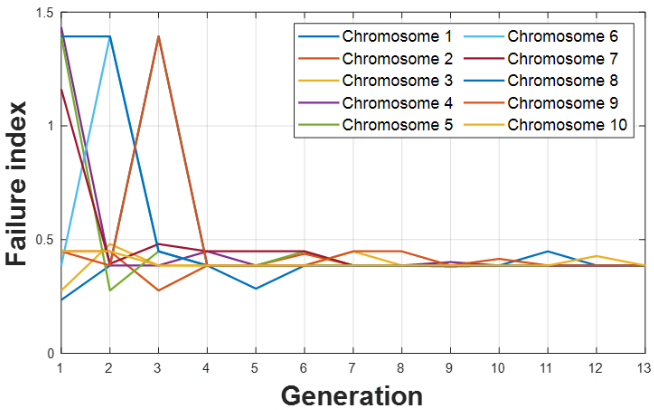

Figure 8: Optimal design result

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4. Conclusions

In this paper, we preformed the optimal design of the three-dimensional woven composite aircraft wing box by genetic algorithm. Aircraft wing box has skins, stringers, ribs and spars. They are designed by LTL pattern three-dimensional woven composite. The objective function is structural lightweight. The design variables are the number of fill yarn layers in each part. We set the constraint by Tsai-Wu theory. Using these optimal design conditions, genetic algorithm was performed. In one generation, there are 10 chromosomes generated randomly by combination of several design variables. We evaluated the fitness of the chromosomes and selected the superior ones by roulette wheel selection operator. The selected chromosomes create offspring generation by crossover operator. Some chromosomes are modified with a low probability to increase diversities. Through these processes new chromosomes are replaced. We repeated all the processes 13 times, the number of times until convergence is reached. The difference in weight with original wing box model and optimal design model is 6.66kg. We get the optimal mass of the three-dimensional woven composite through this process. It can be a good database for wing design using three-dimensional woven composite.

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