STUDY OF DESIGN VARIABLE WITH LOADING CONDITION FOR COMPOSITE LAMINATE BICYCLE FRAME

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Keywords: composite, bicycle frame, Tsai-Wu failure index, genetic algorithms

Abstract
In this study the problem formulation and solution technique using genetic algorithms for optimization design of laminate composite bicycle frame, with respect to its stacking sequence, was introduced. Tsai-Wu Criteria was applied to be as objective functions. The stacking sequence optimization, which deals with the discrete ply-angle, was used for development of composite bicycle frame. For optimization, each frame was divided into six parts; head tube, seat tube, top tube, bottom tube, seat stay, and chain stay. As they produces different stress distribution pattern among the parts, the unique stacking sequence should be applied for each part, and optimized with finite element method in two different loading conditions, level loading and vertical loading. Then the most effective stacking sequence of composite frame was decided, having the lowest failure index. Numerical results showed that the optimal stacking sequence is found with fewer evaluations of objective function than expected with size of feasible region, which shows the algorithm can be effectively used for lay-up optimization of composite bicycle.

1 Introduction

Due to the high specific strength, high specific modulus and long fatigue life, fiber reinforced composite materials are widely used for manufacturing structures, which need weight reduction such as aircraft and cars, [1]. The bicycles are popular sports equipments or traffic tools. The frame of the bicycle is the main structure to support the external loads. Traditional materials of the bicycle frame are the steel or aluminum alloy. For the purpose of reducing weight, the carbon/epoxy composite materials are now widely used to make the bicycle frames. An example of the carbon/epoxy bicycle frame [1] only weights 1.36 kg, which is much less than the 5 kg weight of the corresponding steel frame. In the design process of the bicycle, the structural analysis of the frame, or even other parts, is very important criteria. With the aid of theoretical or numerical calculations, the strength and stiffness of the bicycle structures can be predicted and modified to the optimal design before the manufacture of the prototype and commercial products. The finite element method is one of the numerical calculations applied in various physical problems. It usually plays a major role to calculate the stress and deformation of the structures. In 1986, the finite element method was applied in the design of the steel and aluminum bicycle frames [2]. The Euler beam elements (or frame elements) were adapted to the simplified model of the whole bicycle frame. The deflection, von Mises stress and strain energy of the frame under various loading conditions were obtained. The design strength, riding performance and weight reduction of the bicycle have been considered and discussed [2]. The finite element method was also adopted to analyze the structural behaviors of the composite bicycle frames [3, 4]. The shell elements were used to model the composite bicycle frame [3]. In that study, two types of shapes of the graphite/epoxy composite frame were analyzed under three loading conditions. The 0 fiber direction corresponds roughly to a line which follows the shape of the bicycle from the front tube to the rear dropouts. The stacking sequences $[0_2/90]_s$ and $[0_2/90_2/0]_s$ were used, respectively, in the low and high loaded regions of the frame [3]. The single-layer equivalent model was adopted to simulate the multi-ply composite laminate of the bicycle frame [4]. The effective material constants of the 8-ply carbon/epoxy laminate were obtained by the mathematical transformation. Under the torsional loading, the results showed that the stacking $[0/\pm45/0]_s$ can cause the highest stiffness [4].

However, there has not been the research that suggests the optimized stacking sequence showing the highest strength. In this paper, therefore, the optimum stacking sequence design for the bicycle frame made of the carbon/epoxy composite laminates was discussed. Two different loading cases; level loading and vertical loading cases, were applied to the bicycle frame. Genetic algorithms were used for the optimization. Tsai-Wu Criteria was applied to be as objective functions. The design variables are ply orientation. The optimum stacking sequence composite bicycle frame design was suggested with lowest failure index in different loading analysis.

2 Materials and testing methods

2.1 Bicycle frame modeling

The dimension of the bicycle frame used in this study was referred to the LOOK 496 model in (Look Cycle International, Nevers, Bourgogne, France) Product. To consider practical loading condition on composite bicycle frames, the frame was composed with carbon/epoxy composite tubes.

Figure 1. The Unigraphics 7.0(Siemens PLM Software, Torrance, CA, USA) CAD model of the bicycle frame in this study.

The bicycle frame was composed with six different components; head tube, seat tube, top tube, bottom bracket, seat tube, and chain stay, which were made of Carbon/Epoxy composite tubes.(Fig.2)

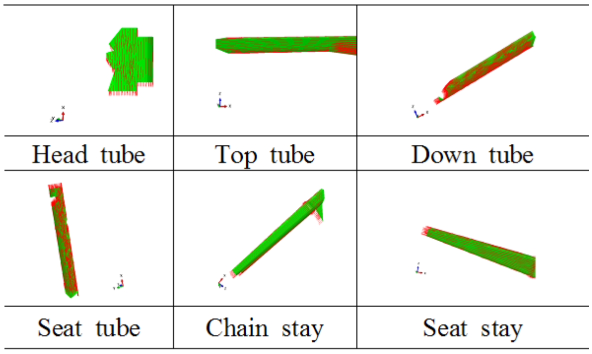

Figure 2. 6-components of the bicycle frame.

2.2 Finite element analysis

The solid model was then imported into Hypermesh 10.0 (Altair Engineering, Inc., Troy, MI, USA) to generate FE meshes. The FE mesh was analyzed with commercially available software (ABAQUS 6.6-1; Hibbitt, Karlsson and Sorenson, Inc., Providence, RI, USA). As carbon/epoxy composite material has different material properties according its direction, different x-direction in local coordinate system was applied in the frame according to the components. X-direction of each component in local coordination system was shown in Fig.3. Each component of the bicycle frame was assumed to be shell element, which was composed with 20-plys carbon/epoxy laminate layers, with 0.2 mm in thickness.[5] First order shell element was used to analyze the composite frame. 17782 nodes and 17797 elements were generated. Uni-directional carbon fiber epoxy prepreg (USN 125, SK Chemicals, Suwon, Korea) was used to composite bicycle frame.

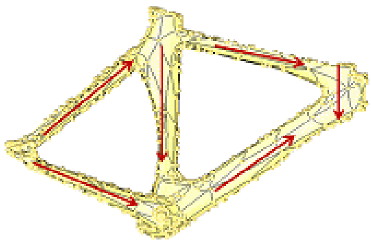

Figure 3. Directions of x-axes for each tube of the bicycle frame.

2.3 Failure criteria

This is a quadratic failure criterion, which is the most extensively used in the design of composites [1]. The failure criterion states that the lamina fails when the following condition is satisfied.

$$F_{ij}\sigma_i\sigma_j + F_i\sigma \leq 1; \quad i,j=1,2,...6. \qquad \text{(1)}$$

where F_i, F_{ij} are strength parameters and σ_i , σ_j are stress components.
In principal material coordinates (L, T), for the case of a lamina, this failure criterion is to be

$$F_{LL}\sigma_{LL}^2 + 2F_{LT}\sigma_{LL}\sigma_{TT} + F_{TT}\sigma_{TT}^2 + F_{SS}\sigma_{LT}^2 + F_L\sigma_{LL} + F_T\sigma_{TT} \leq 1 \qquad \text{(2)}$$

2.3 Optimization

In this study the optimization was conducted using DOT(Design Optimization Tool) and FEA(Finite Element Analysis). The initial stacking sequence is to be $[\pm 45]_{10}$, and the optimization was conducted to each part. The result from the different stacking for each part led to the better result in failure index, according to our previous studies [6], thus the optimization for each part was conducted separately. Optimization had been repeated until being satisfied with design variable, objective function and constraint provided in DOT. In this study, generic algorithm in DOT was used to converge to optimum value and Fig. 4 shows the flow chart of this optimization process. The objective function is to minimize the maximum Tsai-Wu failure index on the frame under the loading condition, and the values on Table 1 were applied to the value of strength. The design variable of the problem is the stacking sequence and its discrete design variable is to be 15 degree each. The limiting values of the design variables is $-180 < \theta < 180$.

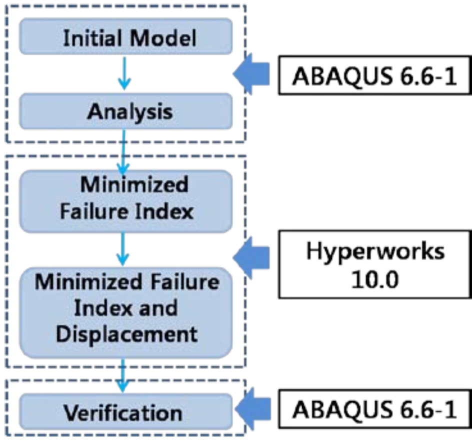

Figure 4. Flow chart of the optimization procedures.

Moreover, the validation of optimum stacking sequence was considered with the different initial design condition. For validation the initial stacking sequence was set to be $[0/90]_{10}$ in optimization process. In order to compare the effect of the optimiazation with respect to stacking sequence, the initial model is to be with sequence $[0/\pm45/90]_5$.

2.4 Boundary and loading conditions

Bicycle frames are exposed in different loading conditions according to the different driving circumstances. However, it is hard to evaluate all loading conditions occurred by all driving circumstances. Therefore, loading conditions used in this study were referred to European and Korean test standard of bicycle frame. [7, 8] Two different loading cases, vertical loading and level loading cases, were applied to the bicycle frame. For the level loading case (Fig.5), the rear part of chain stay was fixed in all direction, except the degree of freedom for rotation with respect to the y-axis. Moreover, the bottom of head tube was fixed using kinematic coupling with the reference point 400 mm apart from and was fixed in the y and z-direction, but was allowed for translation in x-direction and rotation. Then the force of 1200N was applied horizontally at the reference point in x-direction. For the vertical loading case (Fig. 5), the same boundary condition was considered to the rear part of chain stay and seat tube, but the force of 1200N force was also applied vertically to top of seat tube in the z direction, more specifically at the point 70mm apart from the reference point.

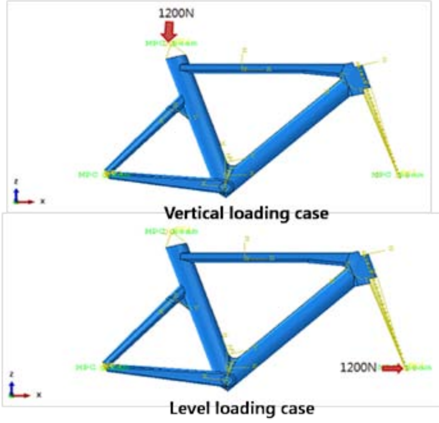

Figure 5. Boundary conditions for each loading case.

3 Results

3.1 Material Test

The tensile, compressive, and shear properties of the uni-directional carbon fiber epoxy prepreg were measured according to ASTM D 3039, ASTM 3210, and ASTM D 3518, respectively, using a static universal testing machine (MTS 810). Table 1 shows the mechanical properties of the composite bicycle frame.

Property	Symbol	Carbon/Epoxy
Longitudinal modulus	E_1	141GPa
Transverse modulus	E_2	8.7GPa
In-plane shear modulus	G_{12}	5.6GPa
Out–of-plane shear modulus	G_{13}, G_{23}	3.7GPa
Poisson's ratio	v_{12}	0.30
Longitudinal tensile strength	F_{1t}	1925MPa
Transverse tensile strength	F_{2t}	76Mpa
Longitudinal compression strength	F_{1c}	1725Mpa
Transverse compression strength	F_{2c}	228Mpa
Out-of-plane shear strength	S_{12}	70MPa

Table 1. Material properties of SK carbon/epoxy composite material

3.2 Initial design

Fig. 6 shows the failure index of $[0/90]_{10}$ and $[0/\pm45/90]_5$ models in vertical loading condition. For vertical loading ondition, the greatest value of failure index was found in the second ply of seat and tube in $[0/90]_{10}$ model whereas for $[0/\pm45/90]_5$ model, it was found to be in the first ply of seat stay.

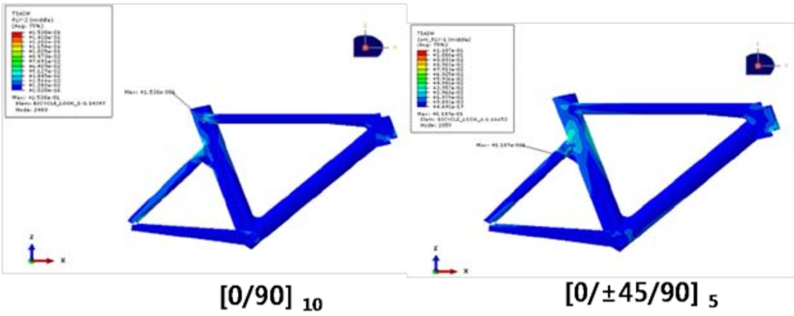

Figure 6. Tsai-Wu failure indexes of the $[0/90]_{10}$ and $[0/\pm45/90]_5$ stacking sequence models under vertical loading case.

Fig. 7 shows the failure index of $[0/90]_{10}$ and $[0/\pm45/90]_5$ models in level loading condition. In level loading condition, the greatest value of Tsai-Wu failure index was seen in the area of head tube and they all caused failure in the initial design models. For level loading condition, the failure was found to be in the second ply in head tube for $[0/90]_{10}$ model and it was found in the first ply in head tube in $[0/\pm45/90]_5$ model. According to the result above, even though the bicycle tube was designed along the fiber direction usinjg local coordinate, due to the complexity of loading condition, the failure location and stacking sequence are all different in each model. Thus the optimization process is needed and important.

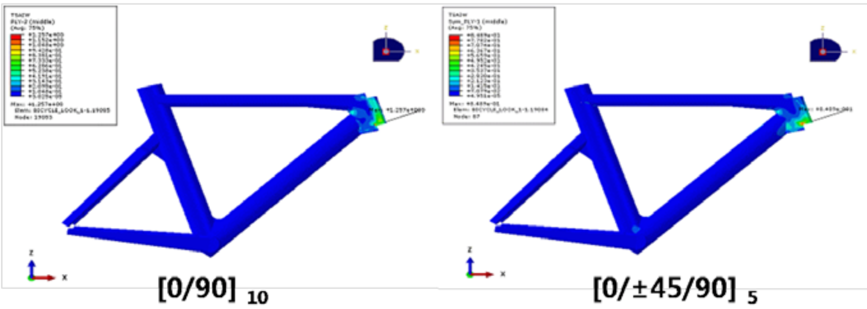

Figure 7. Tsai-Wu failure indexes of the $[0/90]_{10}$ and $[0/\pm45/90]_5$ stacking sequence models under level loading case.

3.3 Optimum design

Table 2 and 3 show the each stacking sequence with the maximum Tsai-Wu failure index corresponding to each load condition. Table 4 shows the failure index for initial and optimum designs. Table 4, 5 shows the failure index values found when the optimum sequence in vertical loading case was applied in level loading case, and vice versa. In Table 4, 5 it is shown that optimum design is to be more effective compared with the initial design. However, as shown in Table 2 and 3, the stacking sequences for each frame part are not consistent with different two loading conditions. Therefore, the optimization was reconsidered using two loading conditions at once. Table 6 shows the stacking sequence having these two loading together and Table 7 shows the failure index of initial and re-optimized model designs. Moreover difference of initial value between $[0/90]_{10}$ and $[\pm45]_{10}$ have made identical optimization results, which proves the validity of optimization. For vertical loading of

optimum model, the greatest value of failure index was found to be in seat stay for 60 degree layer whereas for level loading, it was found to be in head tube for 30 degree layer.
In vertical loading, 32% of Tsa-Wu failure index value was reduced whereas 23% of that was reduced in level loading, compare with the initial model.

Part	Stacking sequence
Head tube	$[30/-30/30/-30/30/-30/30/-30/30/-30/30]_s$
Top tube	$[60/-60/60/-45/0/-60/45/-45/60/-45]_s$
Down tube	$[30/-30/30/-45/30/-30/30/-45/30/-30]_s$
Seat tube	$[60/-60/60/-45/0/-60/45/-45/60/-45]_s$
Seat stay	$[30/-45/45/-60/45/-45/45/-45/45/-45]_s$
Chain stay	$[60/-45/60/-45/45/-60/30/-45/30/-45]_s$

Table 2. The stacking sequences under vertical loading case.

Part	Stacking sequence
Head tube	$[30/-30/30/-30/30/-30/30/-30/30/-30/30]_s$
Top tube	$[60/-15/90/-15/0/0/45/0/45/-15]_s$
Down tube	$[15/-15/90/-15/30/-15/90/-15/30/-15]_s$
Seat tube	$[45/-15/45/-15/45/-15/45/-15/45/-15]_s$
Seat stay	$[45/-45/45/-30/45/-30/60/-45/45/-45]_s$
Chain stay	$[75/-30/75/-15/30/-30/75/-30/75/-30]_s$

Table 3. The stacking sequences under level loading case.

Loading condition	$[0/90]_{10}$ model	$[0/\pm45/90]_5$ model	Optimized model
Vertical case	0.154	0.118	0.102
Level case	1.257	0.849	0.833

Table 4. Comparison the maximum Tsai-Wu failure indexes of the initial models with those of the optimized model under vertical loading case.

Loading condition	$[0/90]_{10}$ model	$[0/\pm45/90]_5$ model	Optimized model
Vertical case	0.154	0.118	0.117
Level case	1.257	0.849	0.668

Table 5. Comparison the maximum Tsai-Wu failure indexes of the initial models with those of the optimized model under level loading case.

Part	Stacking sequence
Head tube	$[30/-30/45/-30/15/-30/30/-15/15/0]_s$
Top tube	$[75/0/75/-15/0/-15/60/-30/45/-30]_s$
Down tube	$[90/-15/75/-15/75/0/75/-15/75/-15]_s$
Seat tube	$[75/-75/60/-105/45/-45/75/-45/75/-60]_s$
Seat stay	$[75/-75/60/-105/45/-45/75/-45/75/-60]_s$
Chain stay	$[60/-45/60/-45/45/-60/30/-45/30/-45]_s$

Table 6. The stacking sequences for complex loading case.

Loading condition	$[0/90]_{10}$ model	$[0/\pm45/90]_5$ model	Optimized model
Vertical case	0.154	0.118	0.080
Level case	1.257	0.780	0.601

Table 7. Comparison the maximum Tsai-Wu failure indexes of initial models with those of the optimized FE model under complex loading case.

4 Conclusions

This paper uses a GA to find the optimal stacking sequence of laminated composite bicycle frame under various loading and boundary conditions, optimized of maximum strength. The main objective of stacking sequence optimization in composite bicycle is to maximize the strength of the laminate for loading, having the best efficiency in its weight. For optimum model, the strength increased 32% and 23% in vertical and level loading, respectively, with 36% reduction in weight. In addition to its high strength and stiffness properties, it is the versatility of carbon fiber which makes it to be an excellent material for lightweight structures. Bicycle frames are an excellent example of successful application of this material.

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