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# Characteristics Evaluation of CFRP Structure using Simple Lamination Model for New Product Design Method

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***Abstract*—There are many design products which has difficulty to commercialize by conventional method and technique from a restriction of strength and weight even if it has wonderful shape and function. In this study, we propose a new product design method integrated with strength evaluation and styling for effective use of high strength composite material. Here, strength property of CFRP lamination structure is evaluated using the simple model by means of FEM analysis. The material characteristics are expressed as a combination of several simple element models. And its possibility to use for new design product that has excellent styling, enough strength and stiffness is examined. Based on the application of analysis results to product design for wheelchairs, CAD modeling of outdoor wheelchairs was performed and stress analysis was carried out. Based on this result, we will examine the method which uses CFRP effectively.**

***Index Terms*—CFRP, elastic modulus, fiber direction, product design.**

## I. INTRODUCTION

Existing product developments tend to separate product design from product planning. After planning of shape and style of product by designer, its strength is evaluated by engineering analysis, and then the product will be finally designed. However there are many design products which has difficulty to commercialize by conventional method and technique from a restriction of strength and weight even if it has wonderful shape and function.

The composite material that are typified by carbon fiber reinforced plastic (CFRP) has very high specific strength and it is light compared with metals. So, it becomes possible to produce complex and lightweight products by using these materials. In addition, it will enable many designs to become actual products, and designer will be able to design with more creativity. However, it is difficult to use composite material for structural design, because this material has strong anisotropy and laminate structure.

Using these materials' characteristics, Zig-Zag Chair, which had the refined style designed by Thomas Rietvelt in 1934, was redesigned in 2014 by Haruhiko Iida. In this redesign process, the engineering point of view was used as a new proposed design method as shown in Fig. 1. The re-designed Zig-Zag Chair was manufactured by hand lay-up molding of CFRP according to analytical results, and its styling and strength were evaluated [1]. In addition, the stiffness of the chair was improved by engineering analysis using simple model of laminated structure [2]. Now, such new design method is required by product designer to apply new material for new design made of new material.

**Fig. 1: Original and re-designed Zig-Zag Chair**

## II. METHODS

In analyzing the structure made of CFRP, it is necessary to represent the characteristics on CAD modeling. At first, three-point bending test was performed to get the basic material characteristic of CFRP which has strong anisotropy. Then we propose a simple modeling method which represents the characteristics of CFRP on CAD modeling. This modeling method from CFRP to represent the result obtained by previous three point bending test must be examined. Finally, bending test simulation of the structure made from CFRP using this modeling method was preformed, and the strength of the structure was evaluated.

### *A. Representation of CFRP structure for easier CAD modelling*

To get the basic material characteristic of CFRP which has anisotropy, three-point bending test was performed. In this experiment, two types of specimens which have different fiber direction of plain weave CFRP cloth were used as shown in Fig. 2.

Based on this experimental result, the characteristic of CFRP were represented using simple model of cloth on CAD. The actual fiber cloth is shown in left side of Fig. 3. In this study, it is represented by a pair of unidirectional layers laminated orthogonally, as shown in right side of Fig. 3. Using this model, three point bending test simulation was performed for CFRP lamination structure. The simulations

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were performed in cases of 0 deg. and 45 deg. fiber directions, as same as actual three point bending test. The material constants of two orthogonal directions were identified by comparing of experimental and simulation results. Then the simulation with proposed model can well represent the material behavior to experimental result [3].

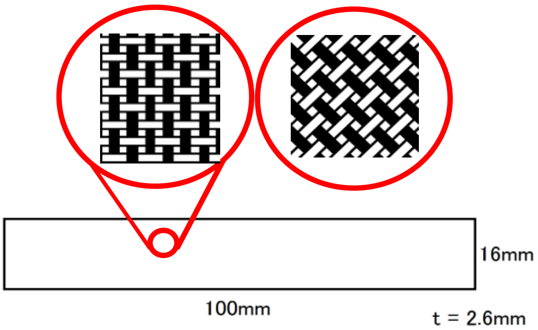



**Fig. 2: Fiber direction and dimension of specimen**

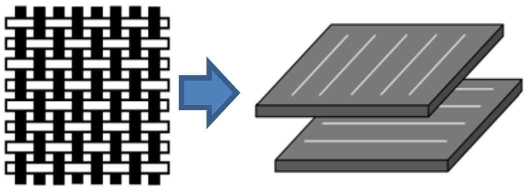


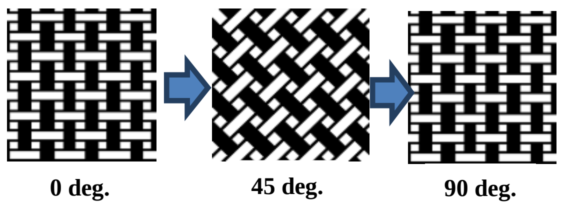
**Fig. 3: Representation of CFRP cloths**

### *B. Application of proposed CFRP model*

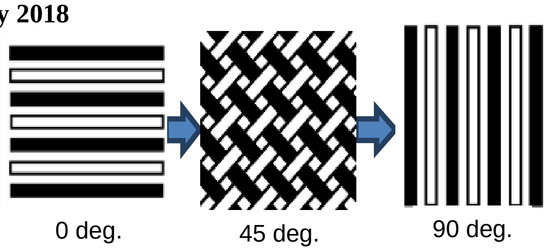
Using proposed model, simulation of flat plate and pipe model were performed to represent the characteristics of laminated CFRP. For example, the drastically changes of elastic modulus depending on fiber angle and direction were examined. Using the flat plate model, three point bending test simulation was performed, in the case that fiber direction is changed from 0 to 90 deg. (Fig. 4 (1)), and fiber angle is also changed from 0 to 90 deg. (Fig. 4 (2)).

## III. SIMULATION RESULTS OF BASIC SHAPE MODEL

The results of simulation of flat plane model are shown in Fig. 5 and Fig. 6. Fig. 5 shows that when three point bending test of flat plate model changing direction of fiber, the elastic modulus becomes the lowest in 45 deg. fiber direction and it's symmetry with respect to 45 deg. In the case of changing angle of fiber, the elastic modulus becomes the highest at 0 deg.; that is called Uni-Direction structure, and it drastically decrease from 10 deg. to 60 deg. with increasing of angle of fiber, as shown in Fig. 6.




**(1) Fiber direction changed 0 – 90 deg.**




**(2) Fiber angle changed 0 – 90 bisymmetrical**

**Fig. 4: Changing of Analysis conditions of fiber**

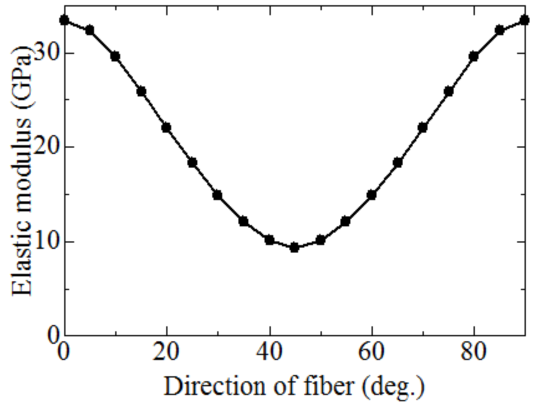



**Fig. 5: Elastic modulus vs. direction of fiber**

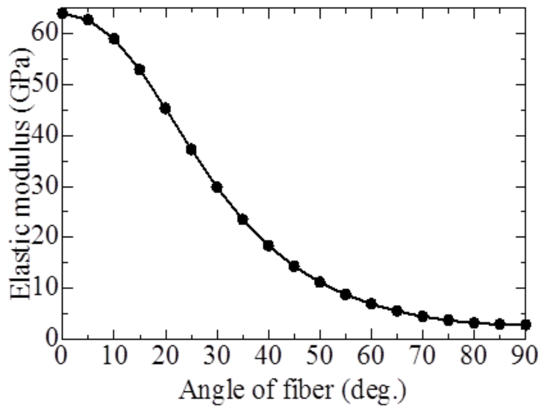



**Fig. 6: Elastic modulus vs. angle of fiber**

Next, bending test and torsion test simulation was performed for pipe model. The bending elastic modulus from the simulation and the modulus of transverse elasticity from torsion test simulation are shown in Figs. 7 and 8 respectively. The modulus of transverse elasticity is calculated using equation (1) based on the result of torsion test simulation.

$$G = \frac{Tl}{\theta I_p} \quad \left( I_p = \frac{\pi}{32}\left(d_{out}{}^4 - d_{in}{}^4\right) \right) \qquad (1)$$

Here, $T$ is torque, $l$ is length of specimen, $\theta$ is angle of torsion and $I_p$ is polar moment of inertia of area.

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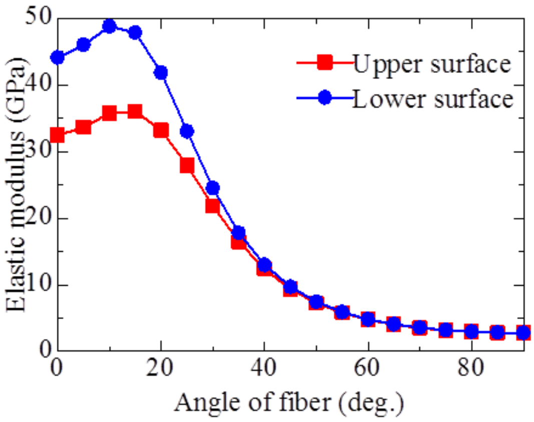


Fig. 7: Elastic modulus of pipe structure

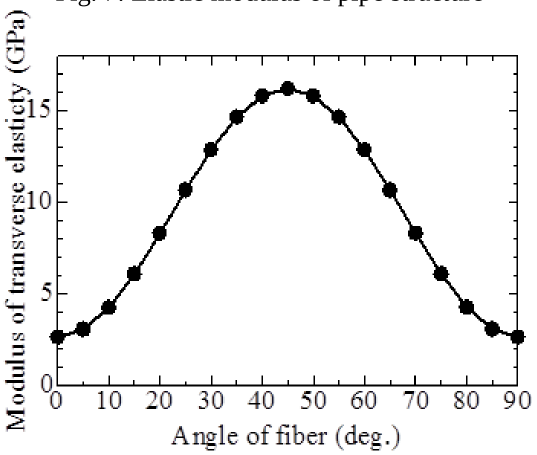


Fig. 8: Modulus of transverse elasticity of pipe structure

In the bending test simulation, displacement at upper surface where is loaded differs from lower free surface. Then the apparent bending elastic moduli calculated from both displacements are different. From the result shown in Fig. 8, torsional rigidity of pipe will become the highest at 45 deg. angle of fiber, and it shows symmetry with respect to 45 deg. in the other angles.

## IV. APPLICATION

### *A. Target of application for new product design*

By applying the above consideration and verification by simulation, new product design is expected by using characteristics of CFRP effectively. As a trial, we are going to design a structure of product that is used with touching to human body. In this study, we chose a wheelchair as the target. Wheelchair is mainly categorized into two kinds. They are electric wheelchair and manual wheelchair. Among them, the manual wheelchair is classified into a self-propelled wheelchair that the users drive and operate by themselves, and an attendant-controlled wheelchair that the attendant operates instead of user. For self-propelled and attendant-controlled wheelchair, there are a standard type which is generally used most commonly and a sitting position changeable type which has a tilt function and a reclining function. Besides those wheelchairs, there is sports type wheelchair used in various sports as a kind of self-propelled type. On the other hand, there is a bathroom type which is a kind of attendant-controlled wheelchair for bathroom use.

### *B. Modelling of wheelchair*

n this study, we chose wheelchair for outdoor use as a design target. At first, we researched existing product of wheelchair for outdoor use. The HIPPO campe$^{TM}$ is a kind of outdoor wheelchair which is commonly used [4]. For the strength analysis, we made 3D-CAD model of a wheelchair. The wheelchair was modified for self-propelled by our design team based on the HIPPO campe. The structure and dimensions of each part were estimated from several photographs on the web site. The each part and completed assemble model of the wheelchair are shown in Fig. 9.

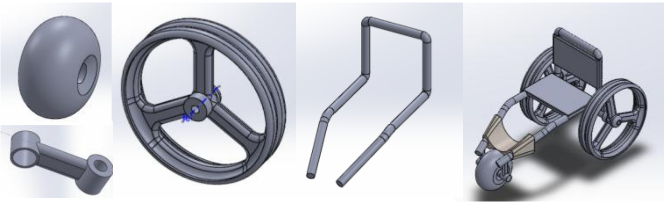

**Fig. 9: CAD model of parts and assembled wheelchair**

### *C. Analysis using model of wheelchair*

In the modeling, material of each part was assumed as below. Front and rear tires are made of natural rubber, frame and connecting parts are made of alloy steel, and seat, backrest part and footrest part are made of plastics. As a loading condition, it was assumed by sitting of a person of 60 kg, and that 80% of the body weight; estimated as 470N was applied to the seat. Therefore, 20% of the body weight; estimated as 118N was applied to the footrest part. A parts as the ground of rectangular board was put under the model in order to make the fixing condition as well as actual wheelchair. Then, simulation was performed under condition that two wheels were fixed on the ground.

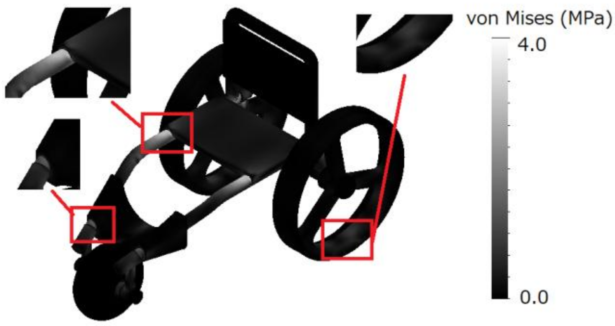


**Fig. 10: Result of stress distribution**

The result is shown in Fig. 10. High stress is generated in frame near the seat and footrest, and the contact part of wheels with ground. The maximum stress is caused in axle of rear wheel. In this analysis, alloy steel was assumed as frame material. Based on this result, we will examine the method which uses CFRP effectively. As the next step we can improve the strength of frame and axle of wheelchair with CFRP.

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### *D. Characteristics of various cross section models*

Next, various cross section model is simulated in order to design product parts using material characteristics of CFRP effectively. Here, simulation of bending test using a pipe model with elliptic and rectangular cross sections (Fig. 11) were performed. Using the pipe model with these cross sections, simulation of bending tests were performed changing fiber angle from 0 deg. to 90 deg., as well as the above analysis. The results of elliptic cross section model of two different lengths are shown in Fig. 12. The graph (a) of short length model shows that the bending elastic modulus becomes the highest at around 10 deg. as well as the result of Fig. 7, but it does not increase much between 0 deg. and 10 deg. in compare with Fig. 7. However, the length of models are different, the circle cross section pipe used in Fig. 7 the length was 100mm. However, elliptic cross section model here is 200mm. Further, elliptic cross section pipe of 700mm length model (Fig.12 (b)) shows almost same tendency in comparing with flat plane model shown in Fig. 5. As for rectangular cross section model, the same and a little stronger tendency is observed as shown in Fig. 13.

For considering of strange behavior of bending elastic moduli of pipe structure, longitudinal and transversal strains were obtained from three point bending test of flat plate model, and Poisson's ratio of CFRP cloth on each fiber angle was calculated by using these results.

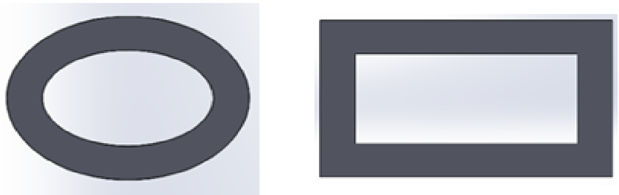
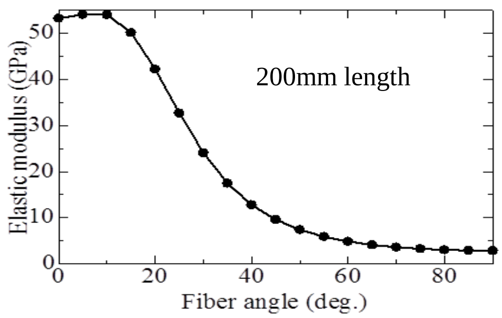
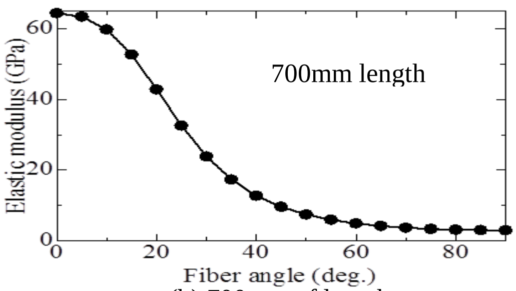


Fig. 11: Elliptic and rectangular cross-section




(a) 200mm of length




(b) 700mm of length

**Fig. 12: Bending elastic modulus of elliptic cross-section**

The result is shown in Fig. 14. In bending test of flat plate model, the elastic modulus becomes the highest in 0 deg. angle of fiber (Fig. 6), but in pipe model it becomes highest in around 10 deg. (Figs. 7 and 11). Poisson's ratio of CFRP is about 0.33 in 0 deg. and becomes about 1.12 which is the highest in around 25 deg., finally it decreases to about 0 at 90 deg. It is thought that the strange behavior of bending elastic moduli is caused by this characteristic change of Poisson's ratio of CFRP structure, and it will be used as effective function using CFRP for structural parts.

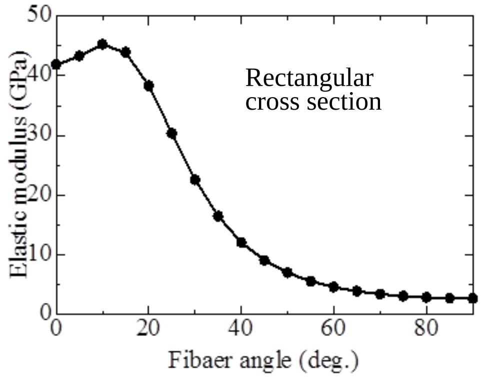



Fig. 13: Result of rectangular cross section

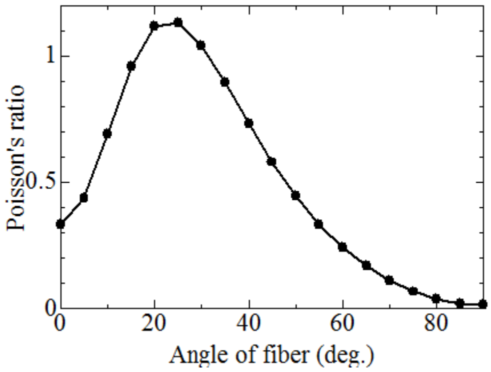



**Fig. 14: Poisson's ratio of CFRP structure**

### *E. New proposal for product design of wheelchair*

Next, we describe structures of wheelchair which uses CFRP as a new proposal. We will compare the strength of original structure and three kinds of CFRP structural models, which are rib structure, hollow structure and fold structure as well as design of CFRP Zig-Zag Chair as shown in Fig. 15 [1]. The first one is reinforced by rib at the edge of plate. Laminate structure does not have rigidity in plate thickness direction because of its thinness. Therefore this structure is reinforced by existence of rib for the purpose of strength for bending load. It is expected that this structure has strength and rigidity for human sitting on the seat. The next one is composed of hollow CFRP plate members. This structure has high rigidity because of its box form. However this structure is difficult to make by integral molding of CFRP. The last one consists of fold CFRP plate members. As for this structure, a flexible design is possible from the aspect of the styling. The structure can increase rigidity by having folds to each surface. For these reasons, fold structure can have both high design

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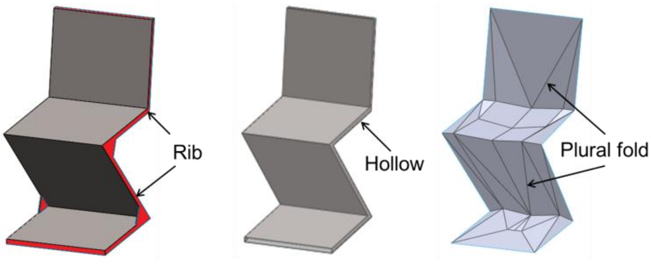
quality and rigidity. However this structure does not have enough rigidity for torsion. Therefore it is needed to increase torsional rigidity. As the future work, we will propose new structure of wheelchair for outdoor use using CFRP. We aim to realize small displacement structure utilizing high rigidity of CFRP.



Rib structure Hollow structure Fold structure

**Fig. 15: Three kinds of CFRP structural models**

## V. CONCLUSIONS

In this study, CFRP of composite material widely used which has very high specific strength and elastic modulus was targeted. Then we proposed a new product design method integrated with strength evaluation and styling. For the purpose, we examined CFRP lamination structure characteristics and developed simple simulation method for strength evaluation for optimum shape and design. The results obtained in this study are described below.

1) We proposed a simplified CAD model of CFRP laminated structure which has high anisotropy, and it can well represent the material characteristics in CAE analysis.
2) The representation of CFRP was applied to the basic shape and characteristic and behavior of lamination structure were examined. And we confirmed the behavior caused by anisotropy of CFRP can be represented on simulation using proposed model.
3) Based on the application of analysis results to product design for wheelchairs, CAD modeling of outdoor wheelchairs was performed and stress analysis was carried out. Based on this result, we will examine the method which uses CFRP effectively.

By using this modeling method, the behavior of CFRP structure with various complex shape proposed by product designer can be well represented, and we can estimate its strength and stiffness of CFRP structure by simulation. Therefore, the product designer can get its material characteristics and structural behavior before styling, and will be able to pursue the optimum structure design and styling effectively by considering the characteristics and behavior of original shapes he designed.

## ACKNOWLEDGMENT

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