INFLUENCE OF STRAND DIMENSION AND DISPERSION METHOD ON RIGIDITY AND ITS SCATTER OF HAT SHAPED SPECIMENS MADE OF RANDOMLY-ORIENTED CFRTP STRANDS

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ABSTRACT

Chopped carbon fiber tape reinforced thermoplastics (CTT), which are a type of randomly oriented strands (ROS), are a promising material for practical applications because of their high volume fraction of fibers (V_f). CTT plates were made through dispersion of tapes and compression molding. Two types of dispersion method were applied; a conventional dispersion method with just mixing tapes bulkily and putting them into the mold, and the other method using air or water to make an intermediate sheet with well dispersed tapes about in-plane direction and stocking them in the mold. The latter method can make tapes dispersed better about in-plane direction than the conventional one.

The objective of study is to make clear the effect of dispersion process and tape thickness on the mean value and scatter of the rigidity of a molded CTT. In this study, we used two kinds of tape thickness, 44 µm and 132 µm, and two different tape dispersion methods to make hat shaped specimens. We observed a flow of tapes in molded specimens, and three-point bending tests and FEA were subsequently carried out. The observation showed the difference in their appearances between specimens made of 44-µm-thick tape and 132-µm-thick tape. The test results indicated that the rigidity of specimens made of 44-µm-thick tapes was higher and less scattered than those made of 132-µm-thick tapes and the rigidity of CTT specimens with intermediate method was less scattered than those without intermediate method. It can be concluded that the hat shaped specimens made of thinner tapes have higher rigidity and lower scatter and by intermediate process, scatter of rigidity of hat shaped specimens was reduced. Hence, the application of thinner tapes and intermediate process contributes to stable quality and is expected to promote applications of carbon fiber reinforced plastics (CFRP) to the mass-production automotive.

1 INTRODUCTION

CFRP have superior specific rigidity and strength, which lead to a broad range of applications such as airplane and automobile. It has contributed to reduce energy consumption and CO_2 emission in these transportation field. In the previous applications of CFRP such as airplane and sporting goods, continuous CFRP with thermosetting resin have been widely used. On the other hand, suitability for complex-shaped components and high cycle moldability as well as superior mechanical properties are necessary for mass-produced automobiles, so discontinuous CFRP with thermoplastic resin have been actively developed in many research groups [1, 2]. Especially, CTT, which are a type of ROS [3]-[5], are a promising material for practical applications because of their high volume fraction of fibers (V_f). However, the mechanical properties of CTT fabricated by conventional dispersion method with just mixing tapes bulkily and putting them into the mold, have large scatter and are poor for their V_f. Therefore, to enhance the mechanical properties and reduce the scatter, another dispersion method has been developed [6], which uses air or water to make an intermediate sheet with well dispersed tapes about in-plane direction and stocks them in the mold. Moreover, to reduce the scatter further, thin-ply prepreg has been applied to CTT and ultra-thin CTT (UT-CTT) have been developed. In addition to the previous studies about a flat specimen of the UT-CTT [6]-[8], the suitability of the CTT for shaped components needs to be presented in order to apply the UT-CTT to a component of automobile.

The objective of this study is to make clear the effect of dispersion process and tape thickness on the mean value and scatter of the rigidity of a molded CTT. In this study, we used two kinds of tape thickness, 44 µm and 132 µm, and two different tape dispersion methods to make hat-shaped specimens.

2 EXPERIMENT AND FINITE ELEMENT METHOD (FEM)

2.1 Materials

The material used in this study was CTT, which is made from unidirectional prepreg sheets of carbon fiber reinforced polyamide 6 (CF/PA6). Carbon fiber and PA6 were provided by Mitsubishi Chemical Co. The sheets were manufactured by using tow spreading technology of Industrial Technology Center of Fukui Prefecture and their carbon fiber volume fraction is 54%. In this study, we prepared two types of prepreg sheet with different thickness, 44 µm and 132 µm, and cut them into chopped tapes with 19 mm in length and 5 mm in width, which are components of CTT.

CTT plates were made through dispersion of tapes and compression molding. Two types of dispersion methods were applied in this study. One method is a conventional method, which is just mixing tapes bulkily and putting them into the mold. This method tends to make some of tapes dispersed about out-of-plane direction. CTT made by this method is called bulk molding CTT (BM-CTT) in this study. The other method is making intermediate sheets with well dispersed tapes about in-plane direction and stocking them into the molding die. To make the intermediate sheets, the chopped tapes are dispersed by wet dispersion method and the dispersed tapes are briefly heated and compressed. CTT made by this method is called sheet molding CTT (SM-CTT). In this proceeding, BM-CTT and SM-CTT with 44-µm-thick tapes are called BM-1t and SM-1t and those with 132-µm-thick tapes are called BM-3t and SM-3t respectively.

Compression molding was conducted by a mold with 125 mm × 250 mm. CTT plates were molded under the condition that temperature of the mold was up to 255 °C and molding pressure was up to 5 MPa. Figure 1 shows cross-section of BM- and SM-1t plates observed with an optical microscope. It was observed that SM-1t tapes orientated to more in-plane direction than BM-1t tapes.

Hat shaped specimens were molded from BM-CTT and SM-CTT plates respectively by stamping molding. CTT plates were cut into plates with 145 mm × 48 mm for stamping molding and they were preheated in IR heater and a little melted. After that, preheated CTT plates were moved rapidly to stamping press and compressed by press machine. The molding temperature was 170 °C and the molding pressure was 20 MPa and these conditions were maintained for two minutes.

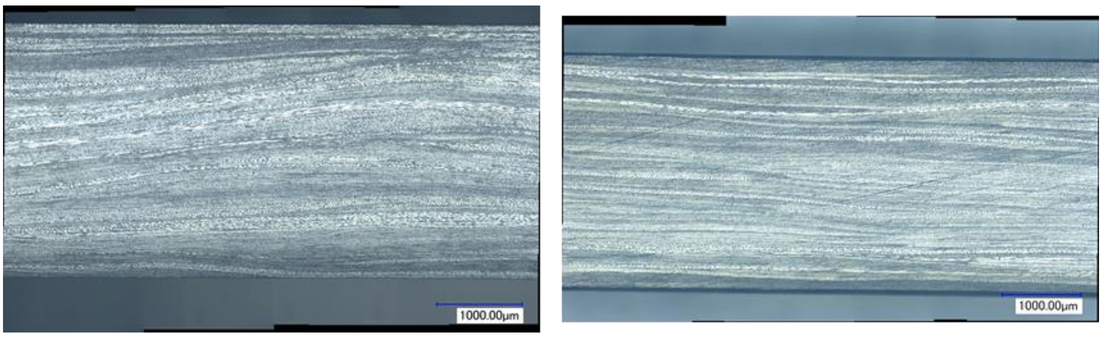

Figure 1 : Cross-section of BM-1t (left) and SM-1t (right) plates.

2.2 Experimental method

Hat shaped molding was cut into the specimen for flexural test. The width of specimen was 40 mm, the length was 114 mm and the heights was 25 mm (Figure 2). Thickness of specimen was 2 mm. In this study, six hat shaped specimens of BM-CTT and SM-CTT with each thickness (44 µm and 132 µm) were used for three-point bending test shown in Figure 3**.** For three-point bending test, the span length was 90 mm and the stroke speed was 6.75 mm/ min. This stroke speed was calculated by below equation based on JIS K7074 [9]. Since there is no standards for flexural test of hat shaped specimens, to determine the stroke speed, we adopted this standard, which is the standard for flexural test of flat specimens. In this study, 0.01 is assigned to the value of S_r.

$$V = \frac{S_r L^2}{6h} \tag{1}$$

V : stroke speed, S_r : strain rate, L : support length, h : specimen thickness

To investigate flexural rigidity of hat shaped specimen, load-deflection curves were obtained from the results of the flexural test and the value of P/δ was calculated (P is the value of load and δ is the value of deflection). In this study, the value of P/δ was calculated in the δ range of 1-2 mm, 4-5 mm and 7-8 mm.

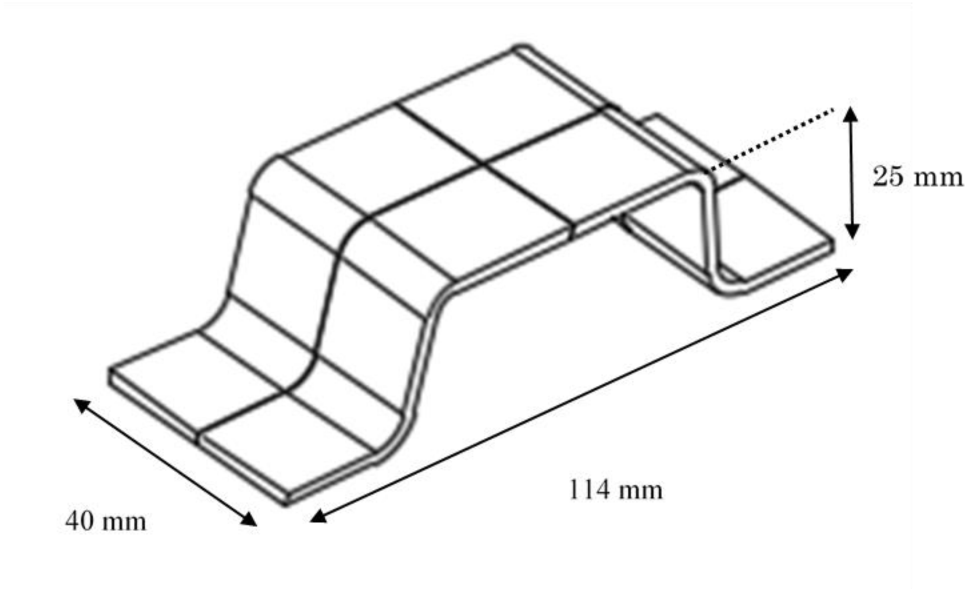

Figure 2 : Hat shaped specimen.

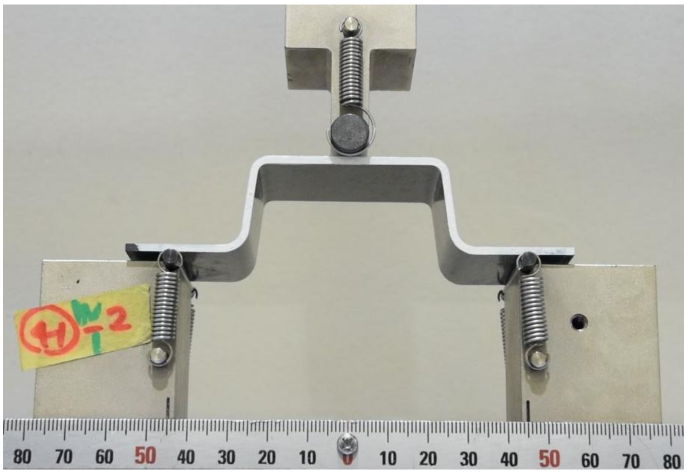

Figure 3 : Picture of three-point bending test for hat shaped specimen.

Dimensions of specimen			Span length	Stroke speed	Number of specimen
Length [mm]	Width [mm]	Thickness [mm]	[mm]	[mm/ min]	
114	40	2	90	6.75	6

Table 1 : Condition of three-point bending test for hat shaped specimen.

2.3 FEM analysis method

FEM analysis of the hat shaped specimen of BM-CTT and SM-CTT was conducted by Abaqus/Standard 6.14-5. The hat shaped specimen was modeled by solid element. The x and z axis was set to longitudinal and width direction respectively and the y axis was set to stroke direction (Figure 4). The loading nose was set to move only about y direction and two supports were restricted completely. The mesh size of hat shaped model was 0.5 mm × 0.5 mm × 0.5 mm. The parameter of mechanical properties of the material was shown in Table 2.

It is assumed that E_1 and E_2, G_{23} and G_{13}, and ν_{23} and ν_{13} are equal because CTT are considered to be in-plane isotropy.

E_3 was used by literature value of E_2 of the unidirectional material in the 90-degree direction. To obtain E_1 and ν_{12} of CTT, tensile tests were conducted according to ISO527-4 [10]. For the tensile tests, setting of specimens is shown in Figure 5. To obtain G_{13} of CTT, we adopted the method with three point bending tests proposed by Yamashita [11] according to below equation.

$$\frac{1}{E_b} = \frac{1}{E_1} + \frac{3}{2}\left(\frac{h}{L}\right)^2 \frac{1}{G_{13}} \tag{2}$$

E_b : flexural modulus, E_1 : tensile modulus, h : thickness of specimen, L : support length, G_{13} : out-of-plane shear modulus

For this method, E_b are obtained by three point bending tests with some types of support length and by finding the relationship of value of $1/E_b$ and $(h/L)^2$, G_{13} is determined. G_{12} is calculated by below equation.

$$G_{12} = \frac{E_1}{2(1+\nu_{12})} \tag{3}$$

G_{12} : in-plane shear modulus, E_1 : tensile modulus, ν_{12} : Poisson's ratio

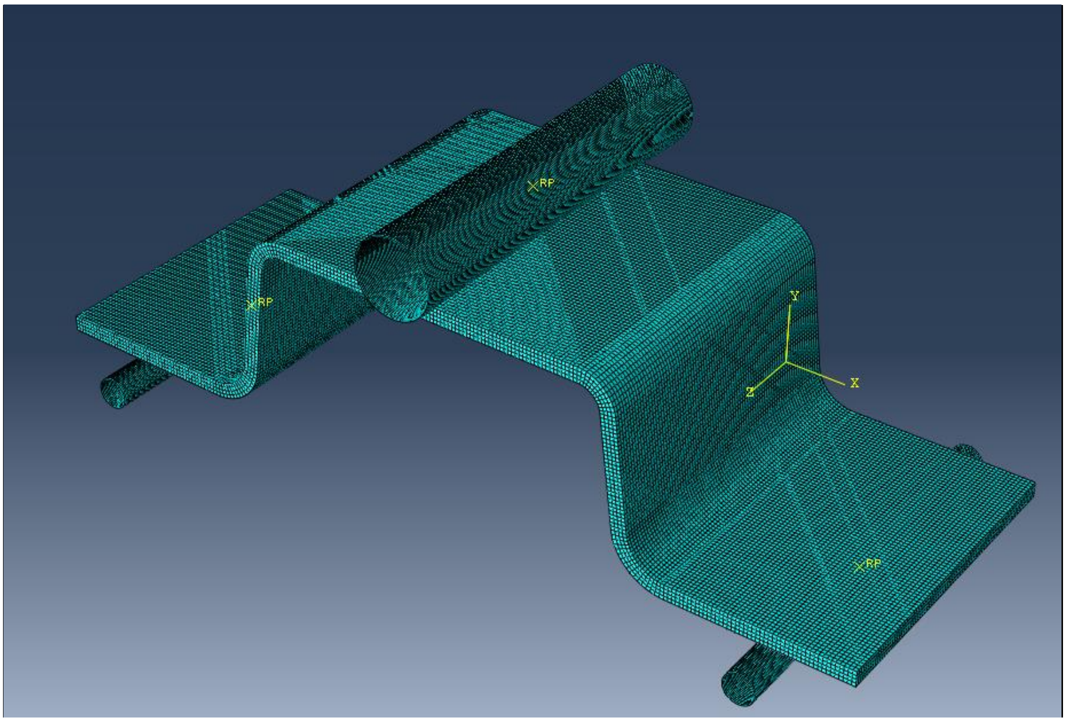

Figure 4 : Hat shaped FEM model.

	E_1, E_2		E_3	G_{12}	G_{23}, G_{13}	v_{12}	v_{23}, v_{13}
	μ [GPa]	σ [GPa]	μ [GPa]	μ [GPa]	μ [GPa]	M [-]	μ [-]
BM-1t	38.1	4.5	7.33	15.4	0.84	0.24	0.345
BM-3t	35.5	1.8		14.5	1.73	0.22	
SM-1t	44.8	2.3		16.7	1.08	0.34	
SM-3t	36.7	1.8		14.1	1.17	0.30	

μ: average, σ: standard deviation

Table 2 : Mechanical properties of materials for FEM.

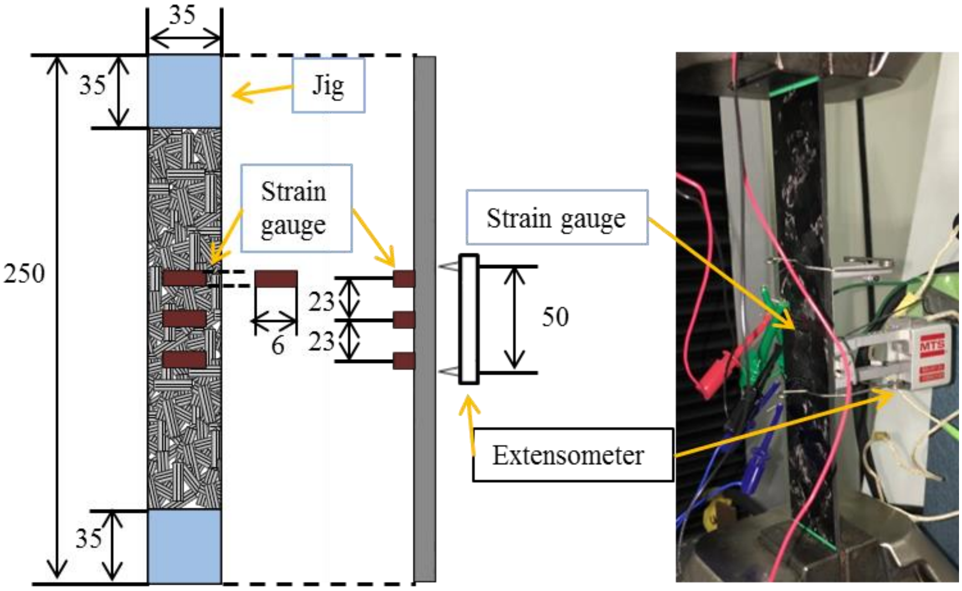

Figure 5 : The setting of tensile test for getting E_1 and v_{12} of CTT.

3 RESULTS AND DISCUSSION

3.1 Evaluation of flexural rigidity of BM-CTT and SM-CTT with each thickness

Figure 6 shows that the results of three-point bending test of hat shaped specimens. In Figure 6, blue and green bars indicate flexural rigidity and red mark indicates coefficient of variation (CV) of P/δ.

Concerning tape thickness, both BM-1t and SM-1t have higher rigidity and lower scatter than BM-3t and SM-3t respectively. This trend is similar to those of E_1 (Table 2). Cross sections of BM- and SM-CTT with 44-µm- and 132-µm-thick tapes were observed with an optical microscope (Figure 7-8). It was shown that 44-µm-thick (1t) tapes orientated to more in-plane direction than 132-µm–thick (3t) tapes. Considering the results of the cross section observation, it is assumed that the 3t tape was more out-of-plane oriented than the 1t tape. Therefore, it is assumed that the rigidity of the hat three-point bending tests were decreased.

Concerning dispersion method, BM-CTT have higher rigidity and larger scatter than SM-CTT with every thickness. Cross sections of BM-CTT and SM-CTT with 44-µm-thick (1t) tapes were observed (Figure 9-10). It was observed that tapes of BM and SM-1t orientated to in-plane direction. Difference of tape orientating was not shown by observation.

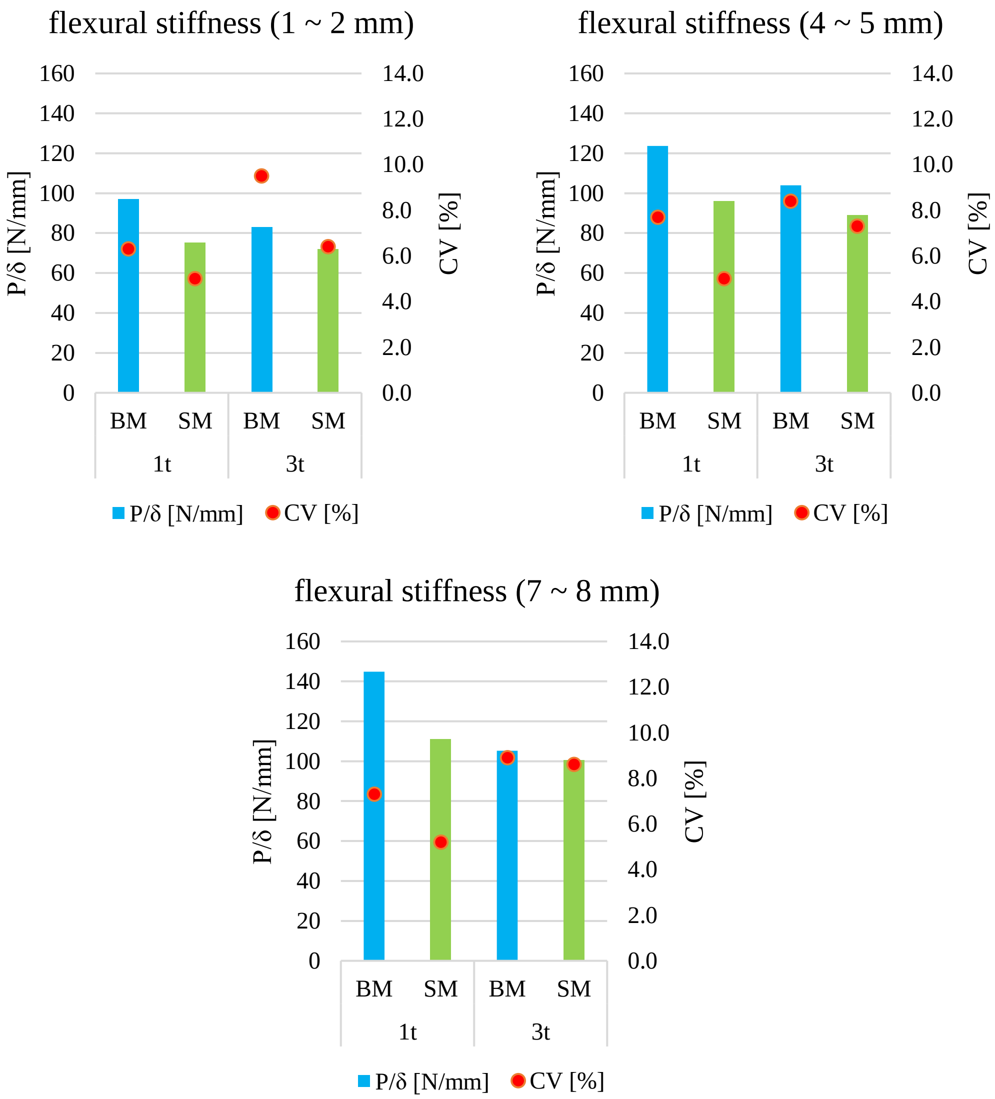

Figure 6 : Results of three-point bending test for hat shaped specimens.

Specimen	Rigidity (stroke: 1 mm – 2 mm) Average [N/mm]	CV [%]	Rigidity (stroke: 4 mm – 5 mm) Average [N/mm]	CV [%]	Rigidity (stroke: 7 mm – 8mm) Average [N/mm]	CV [%]
BM-1t	79	3.9	102	3.7	108	8.3
BM-3t	95	5.7	123	6.3	144	6.3
SM-1t	72	4.4	92	6.1	104	6.1
SM-3t	73	3.5	96	3.9	111	4.2

Table 3 : Results of three–point bending test.

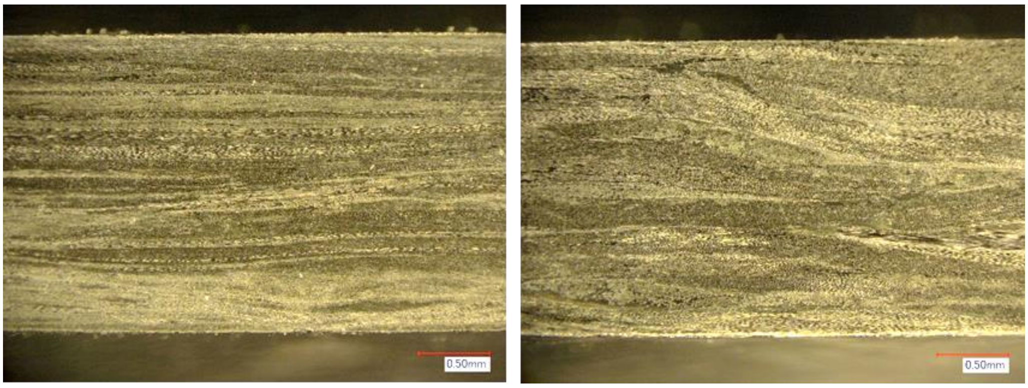

Figure 7: Cross-section at the center of hat shaped specimens made of BM-1t (left) and BM-3t (right).

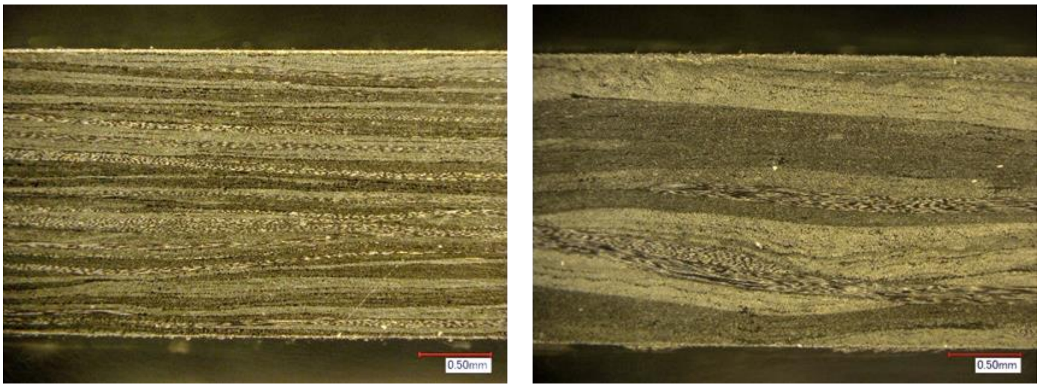

Figure 8 : Cross-section at the center of hat shaped specimens made of SM-1t (left) and SM-3t (right).

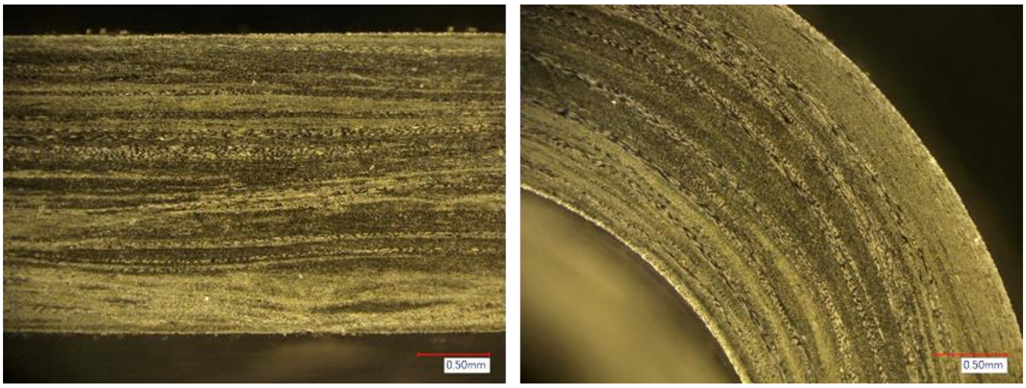

Figure 9 : Cross-section at the center (left) and at the corner (right) of hat shaped specimens made of BM-1t.

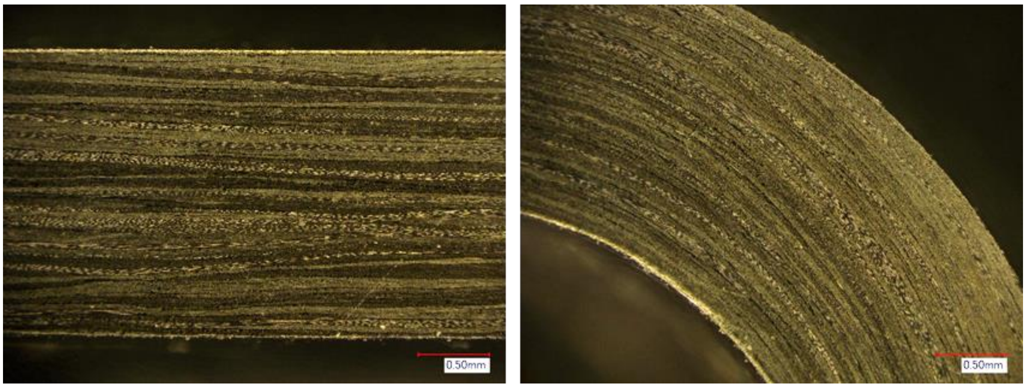

Figure 10 : Cross-section at the center (left) and at the corner (right) of hat shaped specimens made of SM-1t.

3.2 Comparison of experimental results and FEM results

Figure 11-12 show comparisons of experimental results and FEM analysis results of hat shaped specimens three-point bending test made by BM-CTT (1t) and SM-CTT (1t). In both graphs, a black curve indicates the FEM result based on mechanical properties of each kind of CTT and other color curves indicate the experimental results. In Figure 11, a curve of broken line indicates the FEM result based on mechanical property of SM-1t.

Concerning BM-CTT, experimental rigidity of hat shaped specimen was higher than FEM result as shown in Figure 11. Compared cross-section of CTT plates (Figure 1) and hat shaped BM-1t (Figure 9), it was observed that hat shaped tapes orientated to more in-plane direction than BM-1t plates tape but the tape orientating of hat shaped BM-1t is similar to that of SM-1t plates (Figure 1). This is assumed to be the reason why the hat shaped FEM result based on mechanical property of SM-1t plate is closer to the experimental result of BM-1t than that based on mechanical property of BM-1t plate. On the other hand, in the case of SM-CTT, experimental rigidity was lower than FEM result based on mechanical property of SM-1t plate. Although the difference of tape orientating of SM-1t plates (Figure 1) and hat shaped SM-1t (Figure 10) was not observed, there is possibility that hat shaped SM-1t had molding failure.

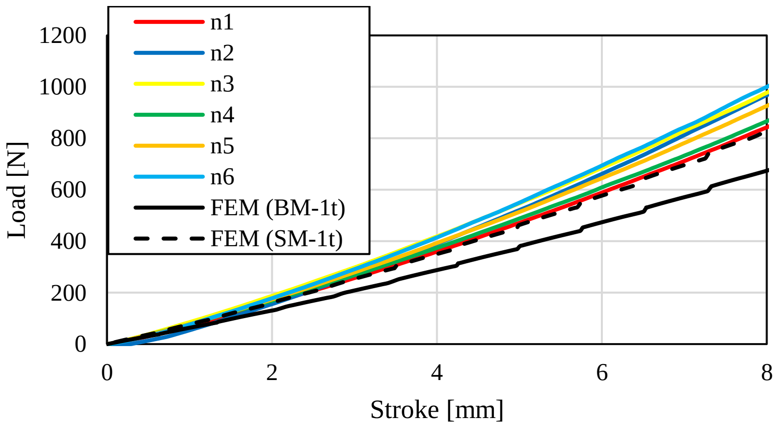

Figure 11 : Comparison between experimental results and FEM result of three point bending test for BM-CTT (1t).

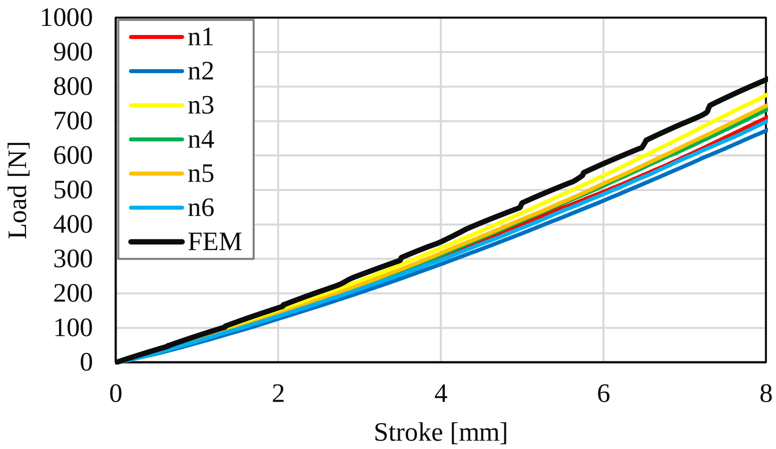

Figure 12 : Comparison between experimental results and FEM result of three point bending test for SM-CTT (1t).

4 CONCLUSIONS

In this study, it was investigated that influence of dispersion method and tape thickness on rigidity and its scatter of molded CTT. The following conclusions were obtained.

- By sheet molding process, rigidity is not improved but its scatter is reduced.
- CTT made of thinner tapes have high rigidity and low scatter. The reason is that thinner tapes tend to be dispersed about in-plane direction.
- Hat shaped BM-1t have higher mechanical property than BM-1t plates. The reason is assumed that hat shaped BM-1t tapes were orientated to in-plane direction.

Based on the results, hat shaped CTT made of thinner tapes have high rigidity and low scatter and hat shaped SM-CTT have low scatter and hat shaped BM-CTT have high rigidity and its scatter is higher than SM-CTT a little. Therefore, CTT with thinner tapes and inter mediate process are thought to be applicable to components requiring stable quality. Moreover, BM-CTT with thinner tapes are also thought to be applicable to shaped components because hat shaped BM-CTT have high rigidity and its scatter is not too high.

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REFERENCES

[1] F. Rezaei, R Yunus, N.A. Ibrahim and E.S. Mahdi. "Development of short-carbon-fiber-reinforced polypropylene composite for car bonnet". *Polymer-Plastics Technology and Engineering*, 47, (2008), 351-357.

[2] K. Friedrich and A.A. Almajid. "Manufacturing aspects of advanced polymer composites for automotive applications". *Applied Composite Materials*. 20, (2013), 107-128.

[3] M. Selezneva and L. Lessard. "Characterization of mechanical properties of randomly oriented strand thermoplastic composites". *Journal of composite materials*, 50, 20 (2016), 2833-2851.

[4] M. Selezneva, S. Roy, L. Lessard and A. Yousefpour. "Analytical model for prediction of strength and fracture paths characteristic to randomly oriented strand (ROS) composites". *Composites Part B*, 96, (2016), 103-111.

[5] A. Levy and P. Hubert. "Interstrand void content evolution in compression moulding of randomly oriented strands (ROS) of thermoplastic composites". *Composites Part A*, 70, (2015), 121-131.

[6] H. Suganuma, S. Yamashita, X. Zhang, K. Hashimoto, I. Ohsawa and J. Takahashi, "Influence of dispersion method to dispersibility and mechanical properties of ultra-thin carbon fiber tape reinforced thermoplastics", *Proceedings of ICCM-20*, Copenhagen, July 2015.
[7] S. Yamashita, K. Hashimoto, H. Suganuma and J. Takahashi. "Experimental characterization of the tensile failure mode of ultra-thin chopped carbon fiber tape-reinforced thermoplastics". *Journal of Reinforced Plastics and Composites*, 35, 18 (2016), 1342-1352.
[8] Y. Wan and J. Takahashi. "Tensile and compressive properties of chopped carbon fiber tapes reinforced thermoplastics with different fiber lengths and molding pressures". *Composites Part A*, 87 , (2016), 271-281.
[9] JIS K 7074 (Testing Methods for Flexural Properties of Carbon Fiber Reinforced Plastics)
[10] ISO527-4:1997.Plastics –Determination of tensile properties –Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites.
[11] S. Yamashita, I. Ohsawa, T. Matsuo, X. Zhang and J. Takahashi. "Evaluation of Young's Modulus and Out of Plane Shear Modulus of Carbon Fiber Reinforced Thermoplastics by Three Point Bending Test". Journal of the Japan Society for Composite Materials 39, 6 (2013), 221-230.