DEVELOPMENT OF PULTRUSION SYSTEM FOR FIBER HYBRID BRAIDED COMPOSITES

Toshihiro MOTOCHIKA[1*], Daisuke HATANO[1], Asami NAKAI[1]

[1]*Kyoto Institute of Technology, Goshokaidocho, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan*
**m1651026@edu.kit.jp*

Keywords: FRTP, Pultrusion, Fiber hybrid structure, Braided fabric

Abstract

The purpose of this study is to establish the pultrusion system for the pipes using hybrid braided fabric with Carbon fiber and Aramid fiber. Fiber hybrid braided composite was designed in terms of structural design of braided fabric and processing design. By using the obtained molding condition from previous research, fiber hybrid braided composite was molded and investigated by cross-sectional observation, 4-point-bending test and 3-point-bending impact test. From these results, in the case of fiber hybrid composite, essential molding time was different at each fiber bundle of different property. Therefore, pre-heating is important for the pultrusion of hybrid braided fabric because Aramid fiber become a heat shield material for Carbon fiber during pultrusion.
.

1 Introduction

Recently, continuous fiber reinforced thermoplastic composite (FRTP) is paid attention. Thermoplastic resin gives composite secondary workability and recycling efficiency. Molding-cycle of FRTP is shorter than that of FRP, so thermoplastic resin enables high-cycle-molding products. However, combination of continuous fiber and thermoplastic resin results in the difficulty in impregnation because of the high melt viscosity. To realize high-cycle-molding by solving this problem, we have been developed intermediate material which resin fiber was put nearby reinforcing fiber and pultrusion system for FRTP [1].

Hybrid composite have been researched a lot because hybrid fiber or resin gives composite great mechanical performance which composite made from single fiber or resin does not have. Hybrid composites are expected to be highly-functional because of eliminating weakness and developing merit each other. Most popular hybrid composite is hybrid fiber composite and it has different two or more reinforcing fiber like glass fiber, Carbon fiber and Aramid fiber in one composite.

In braided fabrics, the fiber bundle called middle-end-yarn (MEY) can be inserted into the braided fabrics in longitudinal direction, so that the excellent mechanical properties were expected. In addition, the braided fabrics by using various kinds of braiding fiber and MEY with different properties can be fabricated. Therefore, concept of hybrid composite can be easily applied by using braiding technology and the mechanical properties of the braided composite can be designed according to the requirements.

The purpose of this study is to establish the pultrusion system for the pipes using hybrid braided fabric with Carbon fiber and Aramid fiber. Two kinds of intermediate materials, Aramid fiber and PA66, Carbon fiber and PA66, were prepared by our developed commingled machine. By using two types of intermediate material, first, braided fabric was fabricated and used for the pultrusion

There are various parameters on pultrusion system. The design of pultrusion system was considered in terms of “material design” for intermediate material such as volume fraction and resin viscosity, “braiding design” such as filling ratio and braiding structure and “processing design” such as die temperature, pultrusion speed. In previous study, in terms of processing design, effects of processing conditions on the impregnation state of moldings were researched [2]

In this paper, the braiding design was focused. For the braiding design, combination of Aramid fiber and Carbon fiber in the structure of braided fabric was changed. After pultrusion, impregnation state was observed by cross-sectional observation. For the static mechanical properties, 4-point bending test was performed. For the dynamic mechanical properties, 3-point impact bending test was performed.

2 Materials and testing methods

2.1 Materials

Carbon fibers (T700-50C-12000 800tex, TORAY) and Aramid fibers (Kevlar29-12000 660tex, TORAY DuPont) were used as the reinforcement while the PA66 resin fibers (L-235T35B Nylon66 235dtex, melting temperature: 265 °C) were used as the matrix resin. Carbon fibers or Aramid fibers and PA66 were combined in a parallel hybrid yarn arrangement and used as the braided yarns (BYs) and MEYs. Tubular braided fabric was fabricated with 24 BYs and 12 MEYs. One commingled yarn for BYs and two commingled yarns for MEYs were combined.

Specification of tubular braided fabrics used in this study is shown Table1. In order to examine the effect of fiber hybrid structure on the mechanical property, 3 types of specimen were fabricated by changing type of fiber for BYs and MEYs. These sample names were represented by using the types of fiber for BYs and MEYs in sequence. For example, AC means braided fabric consisted from BYs of AF and MEYs of CF. All braided fabric was two-layers. In addition, in order to compare the mechanical properties between FRP and FRTP, braided pipes (PRE) were made by tape wrapping method using epoxy prepreg yarns (T700-12K SC-3 JX Nippon Oil & Energy). In PRE, one prepreg yarn for BYs and two prepreg yarns for MEYs were also combined.

Table 1. Specification of specimens

Sample name	BY	MEY	Resin	Yarn	Molding
AA	AF	AF	PA66	Commingle	Pultrusion
AC	AF	CF	PA66	Commingle	Pultrusion
CC	CF	CF	PA66	Commingle	Pultrusion
PRE	CF	CF	Epoxy	Prepreg	Tape wrapping

2.2 Pultrusion systems

The pultrusion line is shown in Figure 1. Braided fabrics were pulled into the pultrusion die having a cylindrical hole. During the passage into the die, the resin fibers of the braided fabric melted and flowed into reinforcing fibers. A preheating die and a molding die were prepared for the forming of the pipe. The braided fabrics were pre-heated in the preheating die up to near melting temperature (230 °C) of the resin fiber for easier impregnation. The molding die had the cylindrical hole with 23 mm diameter and diameter of the mandrel was 20mm, so the cylindrical tube with 1.5mm thickness was obtained by this pultrusion system.

The molding die is shown in Figure 2. The length of the molding die was 500 mm, which was separated into 4 heating zones. The temperature at each sections of the molding die was set at 300, 300, 275, 230°C from the entrance side, respectively. The mandrel had also a heater and set at 230°C during pultrusion. Generally, molding time is obtained by dividing the length of molding die by molding speed, but pressure was given only in taper zone and temperature didn't reach melting temperature in the entrance of molding die according to temperature measurement in previous research. In this study, molding time called essential molding time was defined as product set both of the time in which material was in taper zone of the molding die and the time in which material temperature was over melting temperature. The pipe was pulled out continuously by pulling system.

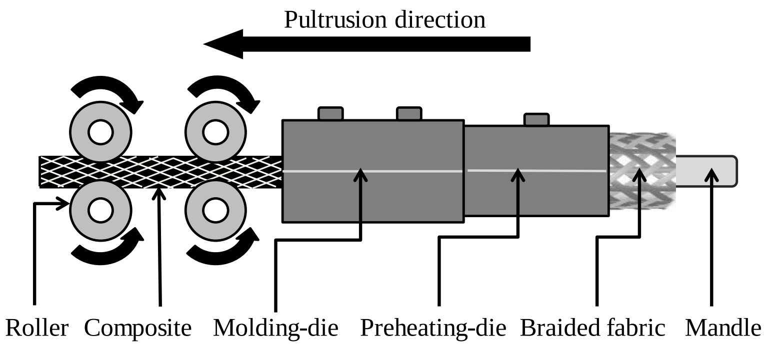

Figure 1. Pultrusion system

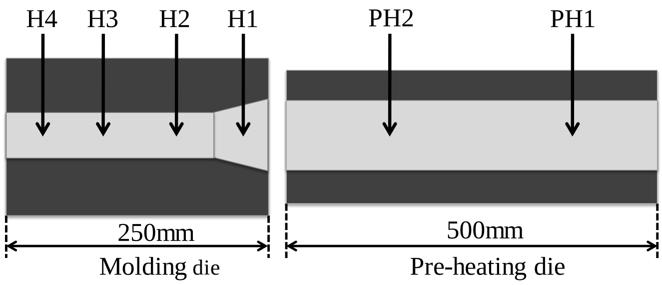

Figure 2. Dies for pultrusion

2.3 Testing methods

To investigate impregnation condition of moldings, cross-sectional observation was carried out for each moldings and un-impregnation ratio for each bundle was measured. Un-impregnation ratio is the ratio of area of un-impregnated region to the area of one fiber bundle and each un-impregnation ratio was calculated by braiding yarn and MEY.

In order to clarify the static mechanical property of moldings, 4-point-bending test was conducted with pulley jig. In order to prevent buckling of specimen leading by dropping indenter, metal round bar was inserted into 50mm region from the edge of specimen at both sides. Conditions of the experiment were as follows: span length was 300mm, the distance between each pulley jig was 100mm, specimen length was 200mm, and testing speed was 1mm/min. Strain gage was attached onto the specimen at the center of the bottom side.

In order to investigate dynamic mechanical property of specimen, 3-point-bending impact test was carried out. Specimens for the impact test were same as the specimens for 4-point bending test and metal round bar was inserted into 50mm region. In the span of 300mm, load was applied onto the center of the specimen with the hemisphere indenter whose face diameter was 22mm. Applied energy was 100J.

3 Results

3.1 Cross sectional observation

Un-impregnation ratio of each bundle was shown in Figure 3. The un-impregnation ratio of CC was lower than that of AA. The dispersion ratios of reinforcement fiber in commingled yarns were 58.6 % (CF) and 68.7% (AF). Dispersion ratio is the characteristic of commingled level of fibers in one bundle and calculated by Eq.1 and Figure 4.

$$\text{Dispersion ratio (\%)} = 1 - \left(\frac{\sum_{i=1}^{n} a_i \ or\ b_i}{n} \cdot \frac{1}{\sum_{i=1}^{n} a_i, b_i} \right) \cdot 100 \qquad (1)$$

If the dispersion ratio is high, impregnation property is improved because of short impregnation distance, so FRTP can be molded with smaller pressure and shorter time. Compared with AA to CC, though AA had the higher dispersion ratio of intermediate material, the BYs and MEYs of CC still showed lower un-impregnation ratio. Since thermal conductivity of AF (2~4(W/mK)) is lower than that of CF (80~800(W/mK)), AA needs longer time to reach to the melting temperature. It is considered that this difference in each thermal conductivity produces the difference in essential molding time for each fiber bundle. On the other hand, MEYs had higher un-impregnation ratio than BYs in both AC and AA. It was found that un-impregnation ratio of AA at MEYs was lower compared to AC at MEYs. The BYs of AA and AC located outside of the MEYs performed as heat insulating material, so that the essential molding time of MEY became shorter correspondingly. In the case of AC, compared CF to AF, dispersion ratio of CF is lower than that of AF, so that the un-impregnation ratio of MEYs of AC were higher than AA.

From these results, to mold tubular braided fabric with fiber hybrid structure consisted of AF for BYs and CF for MEYs by pultrusion, it is important to design longer essential molding time for each fiber bundle by applying pre-heating die because of the difference in essential molding time.

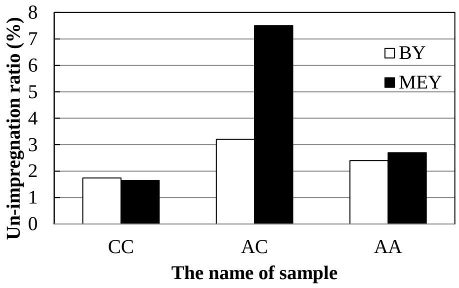

Figure 3. Un-impregnation ratio of each specimen

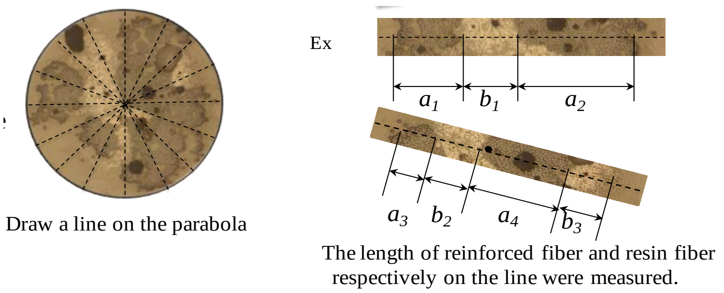

Figure 4. Each parameter of dispersion ratio

3.2 4-point-bending test

Results of 4-point bending test were shown in the Table 2. Elastic modulus and max bending stress were represented as E_e and σ_{max} respectively. Achievement ratio is the percentage of elastic modulus obtained from experiments to the theoretical elastic modulus calculated by laminate theory. Referring to Fig.1 and Table 2, achievement ratio was increased with decrement in the un-impregnation ratio. These results mean it is important to decrease the un-impregnation ratio for higher elastic modulus.

Though AC with fiber hybrid structure has only 40% volume fraction of Carbon fiber compared to CC, its elastic modulus showed almost the same value with CC and significant increment than AA because appropriate alignment of CF yarns can be achieved by using braiding technology. It is considered that high ratio of un-impregnation, especially for CF yarns of AC, was the reason for lower bending strength.

Additionally, even though the same reinforcing fiber was adopted, yet the CC showed the lower bending strength than PRE. Not only the ratio of un-impregnation, property of matrix resin, interface property and thermal degradation of the PA66 during pultrusion process were also assumed to be the reason of the weakness of CC compared to PRE.

Table 2. Results of 4-point bending tests

Sample name	E_e (GPa)	Achievement ratio (%)	σ_{max}(MPa)
AA	18.1	83.3	111
AC	42.6	77.7	102
CC	54.7	94.9	170
PRE	51.4	99.6	244

3.3 3-point-bending impact test

Max load and each absorbed energy were shown in Table 3. In this table, Energy was represented as E and total E was divided into two E; the energy before Max Load and the energy after Max Load. All result was higher in the order of PRE, CC, AC and AA.

Photographs of the cross-section of each specimen after impact test and the schematic drawing of fracture morphology were shown in Figures 5(a), (b), (c) and (d). Fracture morphology of AA was mainly interface fracture inside of MEYs and a little debonding around MEYs. In order of AC and CC, interface fractures inside of MEYs were decreased and fiber fractures at MEYs were increased. The fracture morphology of PRE was mainly fiber fractures both at Bys and MEYs. The absorbed energy for crack propagation is higher in fiber fracture than interface fracture inside of fiber bundle. The fracture mode was changed from fiber fractures to interface fractures inside of fiber bundle with increase in the un-impregnation ratio. Therefore, it is considered that the interface fractures inside of fiber bundle were caused by the un-impregnation regions. Consequently, impact properties were higher in the order of PRE, CC, AC and AA according to the un-impregnation ratio.

Table 3. Results of 3-point-bending impact tests

Sample name	**Max Load (kN)**	**E to max load (J)**	**E after max load (J)**	**Total E (J)**
AA	1.68	0.5	31.8	32.3
AC	1.64	0.55	27.2	28.5
CC	1.7	0.53	43.7	44.2
PRE	1.93	0.58	55.6	56.2

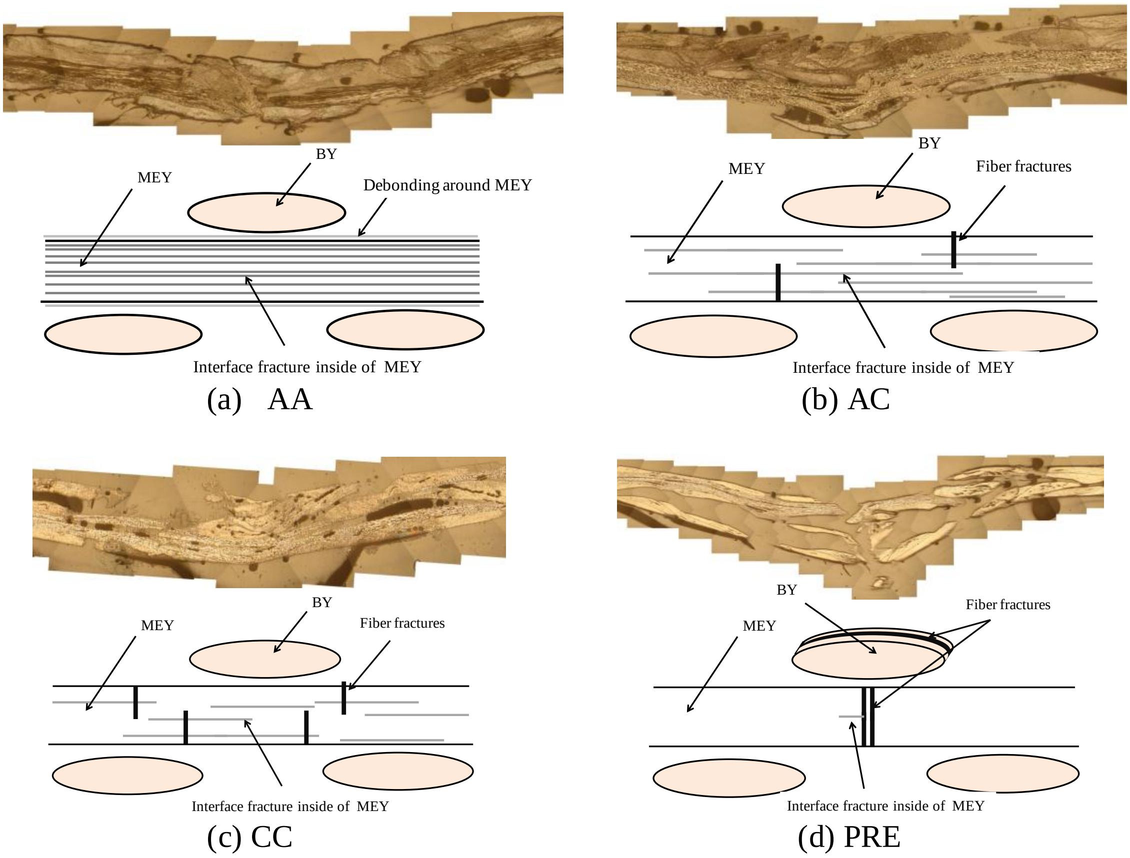

Figure 5 Photographs and fracture morphology after 3-point bending impact test

4 Conclusions

In this study, pultrusion system for continuous fiber reinforced thermoplastic composite was proposed. In fiber hybrid structure consisted of Carbon fiber adopted as BY and Aramid fiber adopted as MEY, essential molding time of braided fabrics was determined by molding condition, but each bundle had different essential molding time according to cross-sectional observation and researching un-impregnation ratio. By pre-heating, each fiber bundle's essential molding time was controlled by decrement of un-impregnation. Fiber hybrid structure made by pultrusion must be researched molding condition reducing un-impregnation ratio in order to increase stiffness and strength of the composite.

5 References

[1] Toshihiro Motochika, Daisuke Hatano, Asami Nakai, Akio Otani. Pultrusion of Fiber Tubular Braided Thermoplastic Composites. B-10, 56th FRP CON-EX2011 (2011)

[2] Toshihiro Motochika, Daisuke Hatano, Asami Nakai, akio Otani. Pultrusion of Fiber Tubular Braided Thermoplastic Composites. 1134, JSCM2012/JCOM-41 (2012)