Attainment of High Fiber Content in Centrifugal Forming of FRP Pipes

Part 1: Experiments for the Attainment of High Fiber Content

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Abstract

The centrifugal method of a fiber reinforced plastic (FRP) pipe has been developed owing to the simple processing in the cylindrical forming, and the technique of mass-production has been established. At the next step, the improvement of the quality has been closed up and the study to enhance the fiber content has been considered to be of importance.

On the centrifugal method, only the centrifugal force is applied on fibers and other mechanical forces are not applied at the lamination process. Therefore, the high fiber content has been seemed to be difficult.^{[6]-[8]}

In this report, an experiment have been made on the effective centrifugal forming for the high fiber content by applying the forming behavior of fibers. As a result, a high fiber content of approximate 55 vol.% was achieved, although it was hitherto only 25 vol.% at its maximum.

1. Introduction

Centrifugal Forming of FRP (Fiber Reinforced Plastics) pipes established itself because it is most suited for cylindrical forming to attain a technology of high productivity.^{[1]-[5]} Subsequently attainment of high product quality particularly in the form high fiber content in the product became an important problem.

In the centrifugal forming process no force other than the centrifugal force acts on the fabric during lamination. For this reason it has been considered difficult to attain a high fiber content in this process.^{[6]-[8]}

In view of above state of the affair, experiments were carried out in the present study for the purpose of developing two auxiliary pressing devices which press against the fabrics augmenting the centrifugal force to attain a high fiber content in the product. The auxiliary pressing

devices were found to increase the fiber content from the previous 25 vol.% to as high as 55 vol.%.

2. Forming Process for High Fiber Content

2.1 Necessity of the improvement of fiber content

Figure 1(a) shows a section of anti-corrosion FRP (Fiber Reinforced Plastic) pipe formed by continuous FM (forming machine). Most currently produced FRP pipes have cross-section similar to that shown in Fig. 1(a) possessing an anticorrosion layer at bottom (inside) end and a reinforcing layer extending from the middle to the top (outside) of the picture.

On the other hand, cross-section of centrifugally formed pipes shown in the upper part of Figs. 1(b), 1(c) are irregularly shaped on the upper (inside) surface because no mold is pressed against the surface. To obtain a smooth

Fig. 1 Partial sections of various FRP pipes

finish the inside surface has to be resin filled to result in a fiber poor layers as in the upper pictures in Figs. 1(b) and 1(c). A fiber poor layer tends to crack while in use and is low in strength in spite of the heavy use of resin. The fiber poor and resin rich inside layer has been a marked drawback of the centrifugally shaped FRP pipes.^[9]

To overcome this drawback auxiliary devices has to be developed to press against the inside surface of shaped pipes but at present only a small number of papers^[10-11] are available on the subject. In view of above background new methods that enables fiber rich inside layers as the ones shown in the bottom of Figs. 1(b) and 1(c) are discussed in the present study.

2.2 Basic idea of high fiber content forming

Figure 2 shows the tensile and compressive test of fabrics used in FRP pipes. In the tensile test shown in Fig. 2(a) T_1 is tensile force, ΔL_t is elongation and ΔL_{wt} is shrinkage in width. Fig. 2(b) shows the compressive test in which T_2 is compressive force and L_c is shrinkage in thicknesswise

Fig. 2 Stress-strain testing of roving cloth

direction. Figure 3 shows the stress and strain relation in a compression test in thicknesswise direction. Two kinds of glass fiber fabrics were used in the present study: Taped roving cloth (hereinafter called RT) and chopped strands (hereinafter called CS). The compressive strain ϵ_γ versus compressive stress σ_γ curves shown in Fig. 3 usually start at a low gradient and reach a high gradient at large ϵ_γ values. Figure 4 is tensile stress versus strain curve for RT 300 1/1 fabric. The tensile strain $\epsilon_{\theta t}$ versus tensile stress σ_θ curve rapidly increases its gradient $\epsilon_{\theta t}$ grows. The compressive and tensile behavior in Figs. 3 and 4 can be summarized into the three step model shown in Fig. 5. The diagrams in the left upper corner of Fig. 5 show how the CS and RT fabrics are aligned and how they change by stressing.

The stressing at first deforms just the looped part of CS & RT to result in an increased fiber content in the finished FRP pipe. This is called the first-stage deformation. The second stage is the deformation of the whole CS and RT fabric layers to result in a further increase in fiber content. In the third stage fiber content reaches saturation and further deformation requires a great force because individual fibers are strongly deformed. Fiber content in FRP pipes increases at each above three stages. The unloading behavior is indicated as broken lines in Fig. 5. Evidently the strain does not return to zero in unloading to develop an irreversible deformation. In view of above,

Fig. 3 Compression properties in thickness direction

RT300 1/1: Tape of roving cloth, 300 g/m²,
Strength in length : in width = 1 : 1
CS 25 mm: Chopped strand cut in 25 mm length

Fig. 4 Tensile properties of RT300 1/1

Fig. 5 Stress-strain behavior of fiber glass

subjecting the fiber layers to tensile or compressive stress can be expected to result in an increased fiber content in the finished produce.

Next we discuss the centrifugal force acting on the fabrics while in pipe forming. Figure 6 shows qualitatively

Fig. 6 Centrifugal force acting on fabrics RT-1 and RT-2

the centrifugal force acting on the RT-1 fabric on an outside layer and the RT-2 fabric on an inside layer at each step of lamination (1) to (6) during the formation of FRPM (Fiber Reinforced Plastics Mortar). RT-1 is laid out at step (1) and RT-2 at step (4). Centrifugal forces due to layers (1)–(5) acts on RT-1 fabric while forces due to (4)–(5) acts on RT-2. Both RT-1 and RT-2 show peak values in centrifugal force, for example at stages (2) and (5) on RT-1. These peaks develop because centrifugal force builds up as resin is fed and subsequently recedes as the resin penetrating into the fabric decreases the apparent density of the fabric. Moreover, RT-1 is acted upon by a large centrifugal force while RT-2 is acted by a small centrifugal force. As a result fiber content of the pipe at RT-1 layer becomes necessarily high that at RT-2. Now, the problem is how to get a large fiber content of the inner layer RT-2. There are two possible solutions to this problem: One is to roll-press the layers from inside during forming. The other is to press against the fabric layers by means of a cylindrical balloon (film bag).

The two measures can both be used in combination whenever possible. Fig. 7 shows the basic idea for the

Fig. 7 Strain of laminated material and suitability of various forming methods

attainment of high fiber content derived from the principle shown in Fig. 5. Fiber strain ϵ is taken on the x axis and stress σ acting on the fibers on the y axis. Point A shows strain ϵ_A due only to the centrifugal pressure σ_A . Point B shows strain ϵ_B of fiber due to the centrifugal pressure and roll pressure σ_B . Point C shows strain ϵ_C of fiber caused by centrifugal pressure, roll pressure and balloon pressure σ_C . The idea is to realize the conditions in points B and C by pressing against the fabric layers using rolls and a

balloon to attain a high fiber content. Discussed in subsequent sections are experiments on roll pressing and balloon pressing of fiber layers for a high fiber content based on the principles shown in Figs. 6 and 7.

3. Methods and Apparatus of Experiments

3.1 Apparatus

Figure 8 is the photograph of experimental set up with its specification listed below the figure. Figure 9 shows six different press rolls Nos. 1–6. The reason of using different kinds of press rolls is that the shape of roll seems to have an important bearing on the stirring of fiber surface and on an effective compression of fabric layers at a high

Fig. 8 CW-O apparatus fundamental experiment

- Specifications:
- Mould diameter: $\phi 174$ mm
 - Mould length: 110 mm
 - Rotation speed: 0–300 rpm
 - Heating: Room temperature–120°C

Fig. 9 Press rollers used in the experiment

- No. 1: Metallic type (with irregular surface)
- No. 2: Metallic type (with grooves in axial direction)
- No. 3: Metallic type (with grooves in circumference direction)
- No. 4: Tail fiber type
- No. 5: Cotton type
- No. 6: Rubber type

Fig. 10 Experimental apparatus for press roller

Specifications:

Mould diameter: $\phi 174$ mm

Mould length: 1000 mm

Rotation speed: 0–1500 rpm

Heating: Room temperature–100°C

Fig. 11 Cylindrical balloon

speed. Fig. 10 shows the centrifugal forming installation equipped with press roll assembly having three press rolls. The movement of the rolls relative to the forming surface draws a parabola. Fig. 11 is the picture of the cylindrical balloon which presses against the surface of the lamination face. The outermost film of the balloon has many small holes. Air is supplied through a rubber tube at the center of the balloon passes a fiber layer surrounding the rubber tube to reach the outermost film.

3.2 Experiments on the effects of centrifugal pressure, resin viscosity and order of lamination upon fiber content.

Materials used in the the experiments and common experimental conditions are as follows; thickness of formed product is approx. 3 mm, fiber content is 10–50 vol.%, resin viscosity is 5–10 p, length of fiber cut is approx. 12 mm, duration of resin feed is approx. 20s.

Experiments on the effect of centrifugal force on product fiber content was performed under the conditions listed in Table 1. Experiments on the relation between resin viscosity and product fiber content was performed under the conditions of Table 2. Two different methods of resin feed were used. In the wet-out method fiber was laid over the resin pool while in the wet-through method resin was poured over the fiber layer. At times the two methods were used in combination. Product fiber content was obtained by burning the formed product at 700°C for 5 hours and divide the residual weight by initial specimen weight.

Table 1. Conditions of centrifugal forming

	Experimental conditions
Rotation speed in forming (rpm)	200, 500, 1200, 2600
Resin feeding	Fiber onto resin, resin onto fiber, fifty-fifty
Curing	Gelling in 30 minutes
Used resin	NIHON SHOKUBAI G103 600 g/piece
Used catalyst	PERMEK N 1.5% 9 g/piece
Used glass	NITTOBO 128SB, 480 g/piece
Temperature	60°C

Table 2. Conditions of experiments on resin viscosity and fiber content

*acceleration of gravity

	Experimental conditions
Glass content (wt%)	10, 20, 25, 30, 35, 40, 45, 50
Resin viscosity (P)	4, 7.3, 8.3, 9, 11
Used catalyst	N1%
Used accelerator	Cobalt 0.15%
Used thickness to be formed	about 3 mm
Used resin	NIHON SHOKUBAI G103
Used fiber	NITTOBO RS128SB
Centrifugal force in forming	180 g*
Temperature	80°C

3.3 Experiments on the effects of press rolls

To evaluate the effects of roll pressing different rolls 40 mm in diameter and 50 mm long shown in Figs. 9 and 10 were pressed against the laminated layers at a fixed load. Common experimental conditions are as follows; 1000 revolutions per minute, both wet-out and wet-through resin feed. Other conditions are as listed in Table 2.

3.4 Experiments on the effects of balloon pressing

Uncured lamination layers immediately after centrifugal forming (hereinafter laminated layers are meant to consist of fiber and resin) are pressed by means of the balloon shown in Fig. 11 with the mold stopped. Figure 12 shows the construction of the balloon. From the top down, the balloon is composed of surface layer, fiber layers and rubber tube for air supply. The fiber layers consist of alternating layers of fiber and film whose combinations are listed in Table 3. The circles show the materials used. Holes of 0.1 mm diameter at a spacing of 20–30 mm were made on the film. Figure 13 shows the fiber webs used in the balloon.

Fig. 12 Structure of balloon

Table 3 Tested combinations of fibers and films in balloon
(thick): approx. 400 g/m²; others: approx. 150 g/m²

Film \ Cotton	Thickness (mm)	Acryl	Acryl (thick)	Acryl (sliver)	Cotton	Cotton (thick)	Polyester	Polyester (thick)
PE	0.1	○	—	○	○	○	○	—
PE	0.2	○	○	○	—	○	○	○
PP	0.05	—	—	—	○	—	—	—
Polyester	0.05	—	—	—	○	—	—	—
Urethane	0.01	—	—	—	○	○	○	—
Urethane	1.0	—	—	—	—	○	○	○
Vinylon	0.05	—	○	—	—	—	—	—
PVDC	0.01	—	○	—	—	—	—	—
Poval	0.1	—	○	—	—	—	—	—

a) Cotton: flat web

b) Cotton: silver-like web

Fig. 13 Fiber sheets used in balloon

4. Results of Experiments

4.1 Effects of centrifugal force (mold revolution) and lamination order

Figure 14 shows the effects of centrifugal force and

Fig. 14 Fiber content versus mould speed

lamination order on product fiber content. Three kinds of lamination order were tested: wet-out, that is to put fabric on resin, wet-through that is to pour resin on the fabric and the combination of wet-out and wet-through. First of all it is evident in Fig. 14 that product fiber content increases with increasing centrifugal force but lamination order does not seem to have a consistent effect. The “⊗ cavities present” indicate formed product contained cavities. The sensitivity of fiber content to centrifugal force tends to decrease with increasing centrifugal force. This is equivalent to the upward bend of the σ versus ϵ curves in Figs. 5 and 7. In conventional FRP forming processes the nondimensional centrifugal force α shown in Fig. 14 take the value of about 100. At this α value product fiber content is as low as 20 vol.% in Fig. 14 to give a quantitative support to the current belief that centrifugal forming results in low fiber content. Figure 14 shows further that fiber content does not exceed 27 vol.% even at very high α values. The FW (filament winding) forming known for its high fiber content attains about 50 vol.% while hand layup ranges 20–30 vol.% in fiber content, about the same as in centrifugal forming. In summary of above centrifugal forming of about 3 mm thick FRP pipes using CS (chopped strands) fiber content attained ranges from about 10 vol.% to 27 vol.%. Changes in lamination order unfortunately does not bring improvements in this respect.

4.2 Effect of resin viscosity

Figure 15 shows the effect of resin viscosity and product fiber content on void content. The fiber content values shown in Fig. 15 are actual measurement and the void

Fig. 15 Effect of resin viscosity and fiber content on void content

Experimental conditions: $\alpha \approx 180$, resin is fed twice by using both wet-out and wet-through procedures

content is calculated using the theoretical layer thickness and the measured layer thickness. When the measured thickness is more than the theoretical thickness the layer contains voids. The negative void content observed in Fig. 15 is most probably due to the neglect of the evaporation of styrene monomer.

Figure 15 suggest that about 5 wt.% styrene monomer evaporated while in centrifugal forming. The considerable scattering of void content values in Fig. 15 was because the uneven inside surface of the pipe made the measurement of pipe thickness difficult in spite of the carefully conducted experiments. When the fiber content was less than about 25 vol.% void content was approximately zero (0) for all resin viscosity and gas bubbles were not observed in formed product. The range of fiber content up to 25 vol.% is about the same as the range covered in Fig. 14. Figures 14 and 15 may be interpreted to show that fiber content below 15 vol.% is not affected appreciably by resin viscosity variation in the range 5 p–11 p. In contrast to above void content above 25 vol.% increases sensitively with increasing resin viscosity. The data shown in Fig. 15 however find little practical use unless void content is desired.

4.3 Effect of roll pressing

Figure 16 show the effectiveness of pressing the laminated pipe wall layers various press rolls. The x axis shows fiber content and y axis shows void content as in Fig. 15. The broken curve in Fig. 15 is the void content without the roll pressing for the resin viscosity of 5 P reproduced from Fig. 15. The double dotted broken curve shows the average results for press rolls Nos. 3, 4 & 5 which effectively reduced the void content. While the data in Fig. 16 are considerably scattered they roughly form two groups: data for roll Nos. 1, 2 and 6 and those for roll Nos. 3, 4 and 5. The dotted curve for roll Nos. 1, 2 and 6 is

Fig. 16 Effectiveness of various press rolls
Resin viscosity 5P {0.5 Pa·s}, conditions other than roll pressing are same as in Fig. 15

almost identical to the curve for the 5 P resin without roll pressing shown in Fig. 15. Whereas the double dotted broken curve for roll Nos. 3, 4 and 5 is about 10% more in fiber content than the above former curve. Put in other words the pressing effect is influenced considerably by the shape of press rolls. Brush covered rolls (Nos. 4 and 5) and rolls with circumferential grooves (No. 3) effectively improved the product fiber content. Whereas roll Nos. 1, 2 and 6 tended to raise the fabric surface to make it fuzzy. As a result more resin was required to cover the fuzzy

surface to bring the product fiber content down. In summary use of adequate press rolls can improve the fiber content by about 10 vol.%.

4.4 Effect of balloon pressing

Figure 17 shows product fiber content plotted against balloon air pressure. The upper curve in Fig. 17 denoted

Fig. 17 Internal pressure of balloon and fiber content
Centrifugal force in the forming operation: $\alpha \approx 100 \text{ g}^*$
Formed thickness: 1–3 mm
Balloon film: Polystyrene 0.1 mm

“whitening limit” shows the lower limit of void formation. The lower curve denoted “uniform thickness limit” is the lower limit of the resin in which excess resin flows into the balloon through the small holes on its surface to prevent resin rich product. Increasing the balloon air pressure was clearly effective in improving the product fiber content. The upper limit air pressure in the present was about 1.0 kgf/cm² due to the use of rubber hose resulting in a maximum fiber content of about 55 vol.%. The results shown in Fig. 17 are consistent with the ideas shown in Fig. 7. Shown in Fig. 18 is the effect of balloon air pressure on

Fig. 18 Fiber content versus balloon pressure on RT lamination
Multiple laminated layer: Laminated structure of external layer RT about 1.5 mm, intermediate mortar about 10 mm, and internal layer CS about 2.0 mm.
Centrifugal force in the forming: 100 g*

product fiber content when the fiber used is the roving cloth denoted RT-1 in Fig. 6. The lamination process was the FRPM shown in Figs. 1(b) and 1(c). Balloon pressing is totally ineffective on roving cloth (RT) probably because the RT is well deformed by the centrifugal pressure exerted by the mortar layer (Fig. 6) while in forming.

Listed in Table 4 are how different combinations of the films and fibers used inside the pressing balloon affect the balloon pressing process. In Table 4 (A) shows that the evaporation of styrene monomer resulted in a swelling and wrinkling of the film covering the balloon. (B) shows the pressing effect was insufficient because of poor air supply and (C) denotes insufficient degassing from lamination layers due to the clogging of the small holes on the film and other causes. (D) shows unsatisfactory separation of the film from the lamination surface and (E) denotes satisfactory results. (E) marks are found on poly-urethane film of 1.0 mm thickness, vinylon film of 0.05 mm thickness, PVdc and poval films. Experiments were not carried out on unmarked combinations. Varieties of fibers do not seem to affect the process appreciably. Thick fiber layer, however, brings better results. As for the thickness of urethane film, thin films tend to wrinkle resulting in poor finish. Since thick urethane films do not wrinkle product finish was satisfactory. However, the lack of extension in thick films caused inferior degassing from lamination layers. Evidently the thick films were unable to follow the uneven surface of the lamination layers. Polyester film was thin and flexible but lacked elongation to also result in insufficient degassing. In summary of above films about 0.1 mm thick and are not swelled by styrene monomer within about 1 hour are suitable for use as outside cover to the balloon. Free fiber in the balloon should at least be 0.2 mm thick while in use and fiber denier should better be large for a better degassing effect.

5. Conclusions

Deformation of glass fiber fabrics used in FRP pipes exhibits three distinct stages. The first stage is the defor-

mation of fiber loops exclusively, the second stage is the deformation of the whole fabric and the third stage sees an excessive deformation of individual constituent fibers.

Improvements in product fiber content are brought about by the irreversible plastic deformation of the glass fabrics in the above first and second stages. Glass fabrics layers close to the outside surface of FRP pipes tend to be well compressed by the centrifugal force but compression is insufficient on layers close to the inner surface of pipe to result in a low fiber content. This drawback can be remedied by making best use of the above irreversidle plastic deformation of the glass fabrics.

First of all in the present experimental study it was shown that under practical conditions of centrifugal forming timing of resin feed and resin viscosity have little effect on product fiber content since they influence only the low stress initial deformation of the glass fabrics. This is the reason why minor improvements on existing centrifugal forming can attain only up to 25 vol.% fiber content.

Pressing rolls against lamination layers while in centrifugal forming was found to fully attain the first stage fabric deformation shown in Fig. 5. An approximately 10 vol.% increase in product fiber content was obtained by the roll pressing but it failed to attain the second stage fabric deformation.

It was found necessary to remove the excess resin contained in fiber layers as the layers are compressed for a second stage deformation to be attained. For this purpose a cylindrically shaped balloon was developed to press against the lamination layers. The balloon pressing was found increase the product fiber content up to about 55 vol.% but it was inaffective on pipes using roving cloth (RT) because RT does not develop second stage deformation. In most other fabrics, however, combination of roll pressing and balloon pressing was found to attain the fabric deformation in the second stage.

Shown in Fig. 19 are levels of product fabric content attainable by different processes tested in the present study. Simple centrifugal forming of CS was about 25 vol.% in fiber content. When roll pressing added to this

Table 4 Evaluation of the combinations of films and fibers used in the balloon
A: Wrinkling of film
B: Insufficient film extension
C: Insufficient degassing of layers
D: Balloon sticking to pipe
E: Smooth surface finish

Film	Cotton	Thickness (mm)	Acryl (sliver)	Acryl sliver (thick)	Acryl (flat)	Cotton	Cotton (thick)	Polyester	Polyester (thick)
PE		0.1	Ⓐ	—	Ⓐ	Ⓐ	Ⓐ	Ⓐ	—
PE		0.2	ⒶⒸ	Ⓐ	Ⓐ	—	Ⓐ	ⒶⒸ	Ⓐ
PP		0.05	—	—	—	Ⓐ	—	—	—
Polyester		0.05	—	—	—	ⒷⒺ	—	—	—
Urethane		0.01	—	—	—	Ⓐ	Ⓐ	Ⓐ	—
Urethane		1.0	—	—	—	—	ⒸⒺ	ⒸⒺ	ⒸⒺ
Vinylon		0.05	—	Ⓔ	—	—	—	—	—
PVDC		0.01	—	ⒹⒺ	—	—	—	—	—
Poval		0.1	—	Ⓔ	—	—	—	—	—

Fig. 19 Fiber content attained under different laminating methods
Centrifugal force in the forming operation: $\alpha \cong 100 \text{ g}^*$
Formed thickness: 1–3 mm
CS: Chopped Strand
RT: Roving cloth Tape

fiber content increased to 35 vol.% and further addition of balloon pressing attained 55 vol.% with RT the maximum fabric content reached was about 45 vol.%

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