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Effects of the strength and precision properties of filament winding epoxy pipes

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ABSTRACT

Behavior of fiber reinforced composite pressure vessels has been analyzed and developed theoretically. Winding angle and temperature are two kinds of effect factors on filament wound composite pressure vessels. FEM method, elastic solution procedure based on Lekhnitskii's theory and thick-walled theory were employed to verify the optimum winding angles. The aim of this study was to investigate processing parameters of continuous fiber reinforced epoxy composite pipes produced by the filament winding technique. For this purpose, two kinds of tests were performed for the specimen produced with two different methods, five different winding angles and five different curing temperatures. By determining the hoop tensile strength and precision, the winding angle, thermal properties and fitting temperature were evaluated. It is found that use of winding angles greater than 55° increases the performance of the structures considerably. It is also concluded that the use of the curing temperature of 150°C can increase the precision properties during the curing processing than other temperature conditions; at the same time, time of curing course also is an important effect factor to precision quality.

Keywords: Filament winding; Composite pipes; Strength; Precision; Temperature.

1. Introduction

In a variety of industries, composite materials are now used to fabricate many components; the application of reinforced composite materials has been increasing. Pressure vessels such as reverse osmosis vessels are also fabricated from composites. Therefore, to deal with the strength and precision of these types of components so as to account for their contribution to system safety is considered. But in the case of composite materials specific problems still exist.

In general, the composite pipes are fabricated using glass fiber and polyester resin matrix by hand lay-up and also by 2-axis filament winding machine. Filament winding has emerged as the primary process for composite cylindrical structures fabrication at low cost. In this process, composite layers are successively wound on a rotating mandrel as presented in Fig. 1.

The construction of a composite cylinder by filament winding consists of three major steps [1], the first is the design, which includes the selection of materials, geometry, and fiber orientations while the second is fiber placement, the mechanical means by which the fibers are placed in their proper positions. Finally, the third is the selection and control of conditions which must be maintained during the manufacturing process.

There is now a substantial amount of literature available on probabilistic models that describe the strength of composite materials but its use in reliability formulations has been more limited. Furthermore, most of the developments have emphasized material aspects or statistical formulations.

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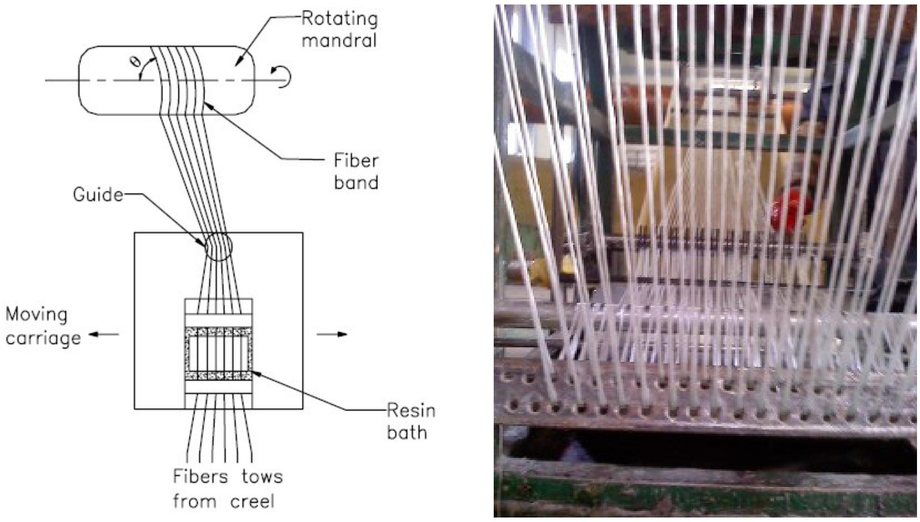

Fig. 1. Schematics of the wet filament winding process [1].

In this study, first, using the thin wall theory, we obtained the maximum pressure at a certain winding angel. Comparing with the experimental results, it was found that winding angles greater than 55° increase the performance of the structures considerably. By another method, comparing the precision on different temperature during the curing process, it is also concluded that the use of the curing temperature of 150°C can increase the precision properties during the curing process.

2. Theory

The theory used in this research is based on thin wall theory [2–6]. The thickness ratio is defined as the ratio between external and internal radii of the pressure vessel. For pressure vessels of thickness ratios more than 1.1, the thin wall analysis can satisfactorily be used. In this theory, the radial stress is assumed to be zero in addition to hoop and axial stress to be constant through the thickness. The hoop and the axial stresses of a pressure vessel subjected to internal and external pressure, and an axial force can be calculated, respectively, as shown in Eq. (1):

$$\sigma_{\theta\theta} = \frac{\left(P_{\text{int}} - P_{ext}\right) r_{\text{int}}}{t}$$
$$\sigma_{zz} = \frac{\left(P_{\text{int}} - P_{ext}\right) r_{\text{int}}}{2t} + \frac{F_A}{2\pi r_{\text{int}} t} \qquad (1)$$

where t is the wall thickness of the vessel. According to the pipes used in this study, the results are shown in Fig. 2.

In Fig 2, the burst pressure, P_{burst}, by using both thin and thick walled solution techniques are plotted vs. winding angle. Both thick and thin-wall solutions predict almost the same burst pressure. The winding angles are between 48° and 64°.

Since the curing temperature is the stress free state for composite materials, the operation temperature affects the failure of the composite depending on whether it is below or above the curing temperature. If the operation temperature is less than zero or if it is less than the cur-

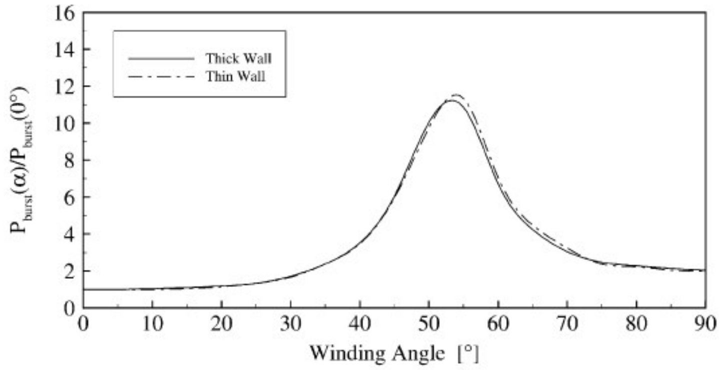

Fig. 2. Variation of burst pressure with increasing the winding angle.

ing temperature, the burst pressure is increased since the thermal strains and mechanical strains for pure internal pressure case work in opposite senses. It should be pointed out that the negative temperature for constant moisture content also causes an increase in the mechanical properties of the composite material. It can be concluded that if the operation temperature is less than the curing temperature, the burst pressure is increased.

Comparing with the results from the FEM method and experimental methods used for determining the burst pressure of composite pressure vessels [7], the same results have been given. The optimum winding angle for filament wound composite pressure vessels is given by the netting analysis as shown in Fig. 3, and similar experimental results are also given in Fig. 4. The optimum winding angle is obtained as 55° in the composite pressure vessels.

Fig. 3. Variation of burst pressure with increasing the winding angle for a single lamina [7].

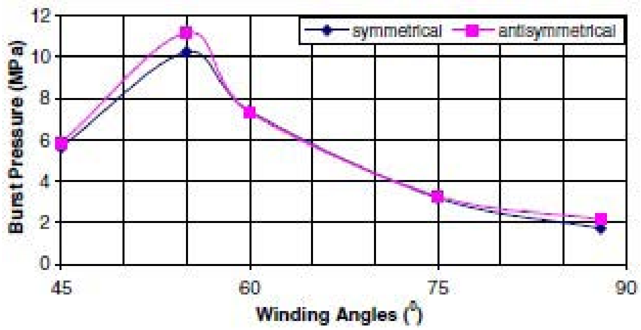

Fig. 4. Experimental results of burst pressure with increasing the winding angle for test specimens [7].

3. Experimental

3.1. Winding system and specimens

The auto-winding system is made up of a winding machine, cutting machine, stripper machine, drying structure and other parts. First, the filament winding epoxy pipes were manufactured from the winding system with different winding angles, then pipes were dealt with thermal treatment, etc., then, the FRP pipes used for the reverse osmosis vessels system were half-finished. After that, using the cutting equipment and fixing ports, the pipes used for the pressure test were prepared. In order to finish the stress-stain testing, as shown in Fig. 4, with the especial cut tool, the test sheet specimens have been manufactured.

Five kinds of specimens were cut from the filament winding epoxy pipes manufactured by way of a filament wet winding method. During their manufacture, the winding angles were selected from 30° to 70° in order to compare the strength power during the winding processing. Fig. 5 shows the pictures of the specimens used in this experiment. The specimens were prepared for the pressure and thermal testing.

3.2. Experimental methods

3.2.1. Strength testing

According to the thin–thick wall theory, a strength test has been done at five different winding angle pipes.

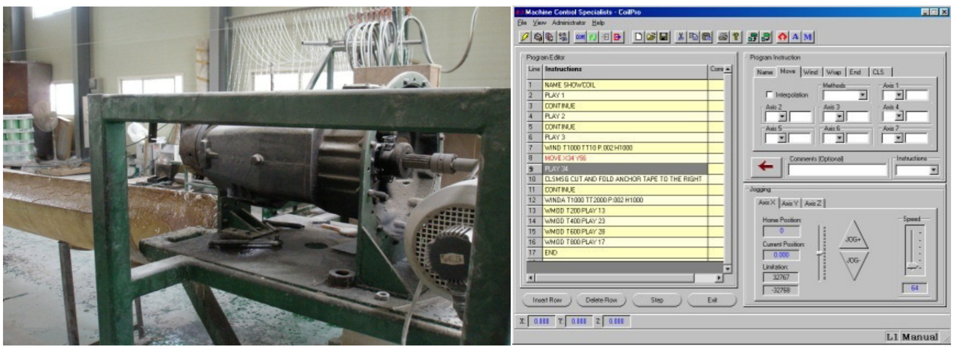

Fig. 5. Schematics of the auto-winding machine system.

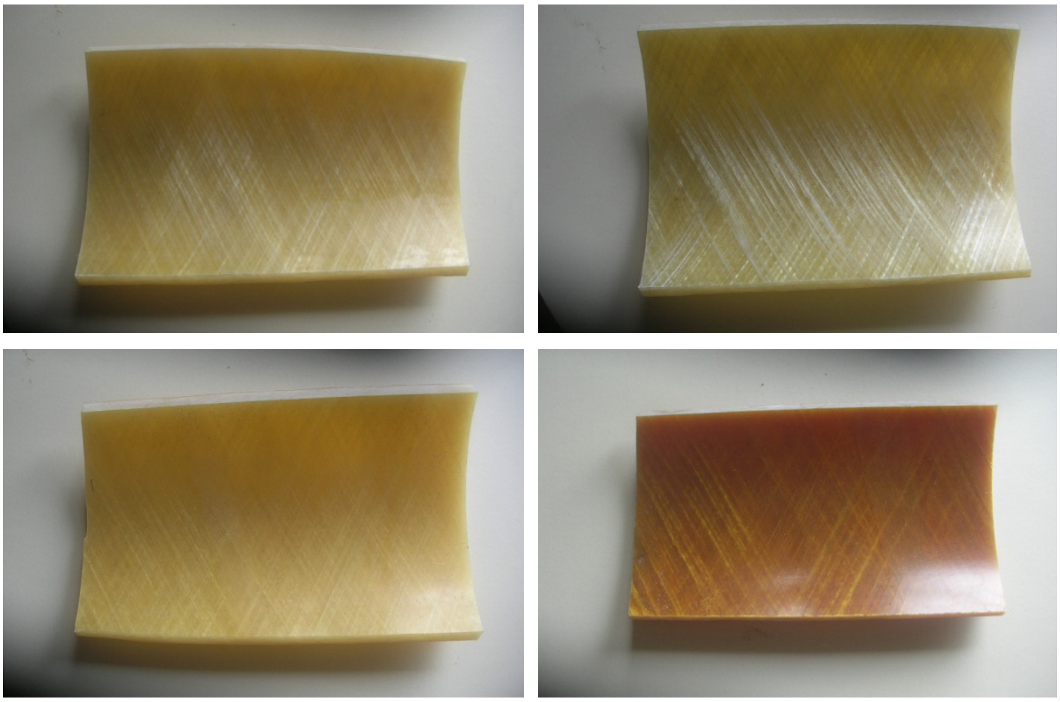

Fig. 6. Sheet specimens made from different winding pipes.

Input pressure on different parts and different pipes to find which winding angle can give out the maximum pressure value, at the same time, the effect of the thermal curing also has been studied to find the best-fit winding angle for ensuring to the normal manufacture processing in our factory. As shown in Fig. 6, different specimens have been selected in this testing.

3.2.2. Water–pressure testing

As shown in Fig. 7, the water–pressure has been put into the FRP pipes, usually 2–3 times of the rated value has been used in order to assure the strength and precision to defend service failure. Using the damage mechanics method, the pressure will be tested at different strength and precision conditions.

3.2.3. Thermal curing testing

Using the equipment shown in Fig. 8, the thermal curing processing has been controlled and tested. With different curing times and temperatures, the pressure, content of glass fiber and bachol-precision values can be obtained, and the best-fit thermal curing temperature and best-fit curing time also can be determined by evaluating the results obtained from the different test results.

4. Results

4.1. Strength affected with the winding angle and temperature

The strength experimental results are shown in Fig. 9. From the results we can see that with increasing the

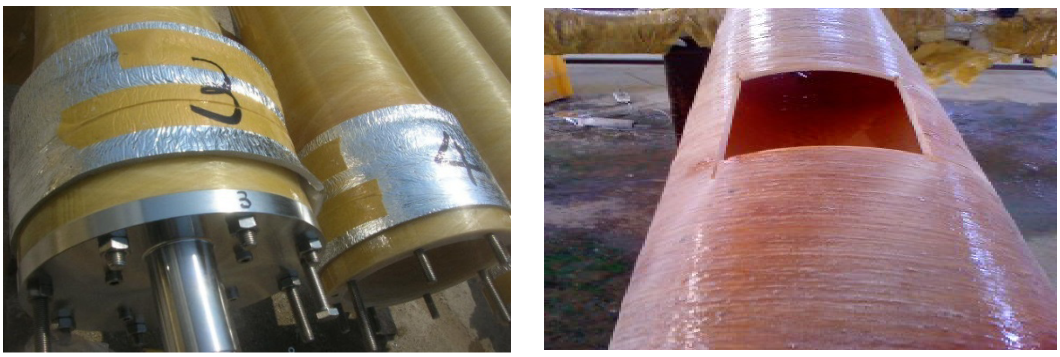

Fig. 7. Pipes made by different winding angles.

Fig. 8. Schematics of the drying system.

winding angle from 30° to 70°, the strength has changed greatly and at the angle of 55° the maximum value can be obtained. That means that in order to get the best FRP pipes, according to the change of the winding angle; we should select the winding angle about 55° during the manufacture process.

Comparing with the effect of the winding angel, thermal curing temperature has little effect on the strength during the winding processing. These results are shown in Fig. 10.

4.2. *Damage pressures affected with temperature and thermal curing time*

At different thermal-curing temperatures, the damage pressures variation is shown in Tables 1 and 2. With increasing the curing time and temperature, the pressure has increased obviously. At any thermal temperature conditions, long time curing will increase the damaged pressure.

4.3. *Precision affected with temperature and thermal curing time*

Much like the effect on the damage pressure, the precision also was affected with two kinds of factors, precision treated is an important factor to estimate the quality of the FRP pipes, a constant and long thermal condition will increase the precision of the pipes. These results can be seen in Tables 3–7.

The content of glass fiber changed with varying the amount of glass roving. When the amount of the glass

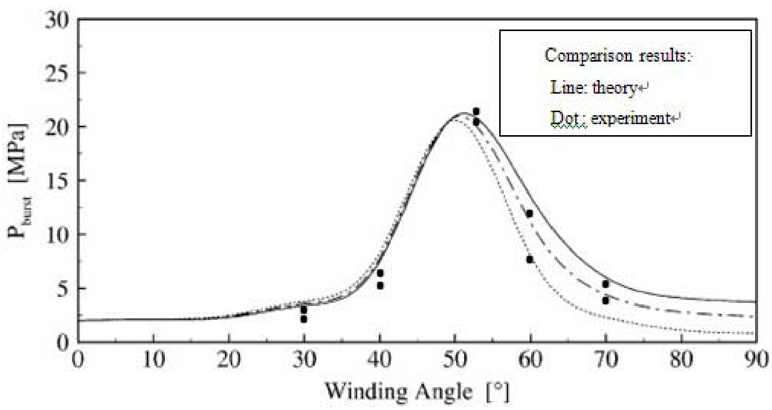

Fig. 9. Pressure variation of theory and experiment caused by winding angles.

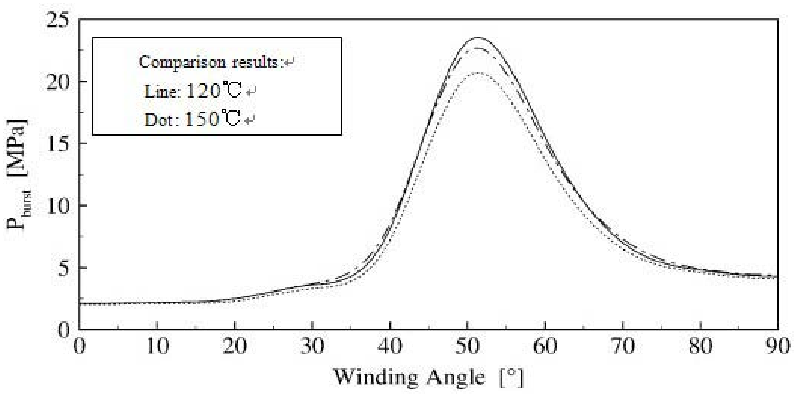

Fig. 10. Pressure variation caused by winding angles and curing temperatures.

Table 1
Pressure and bachol precision variation with the curing time and temperature (120°C)

Curing time (h)	Internal diameter	Thickness (mm)	Pressure	Bachol precision
2	202	7	47	48
3	202	7	70	57
5	202	7	103	65

Table 2
Pressure and bachol precision variation with the curing time and temperature (150°C)

Curing time (h)	Internal diameter	Thickness (mm)	Pressure	Bachol precision
2	202	7	82	60
3	202	7	101	64
5	202	7	117	70

Table 3
Bachol precision variation with the curing time and temperature (120°C)

Curing time (h)	Internal diameter	Thickness (mm)	Strands of roving	Bachol precision
3	404	32	32	48
3	404	32	25	49
3	404	32	18	52

Table 4
Bachol precision variation with the curing time and temperature (120°C)

Curing time (h)	Internal diameter	Thickness (mm)	Strands of roving	Bachol precision
5	404	32	32	52
5	404	32	25	55
5	404	32	18	57

Table 5
Bachol precision variation with the curing time and temperature (150°C)

Curing time (h)	Internal diameter	Thickness (mm)	Strands of roving	Bachol precision
7	404	32	32	60
7	404	32	25	60
7	404	32	18	62

Table 6
Bachol precision variation with the curing time and temperature (150°C)

Curing time (h)	Internal diameter	Thickness (mm)	Strands of roving	Bachol precision
9	404	32	32	62
9	404	32	25	65
9	404	32	18	66

Table 7
Bachol precision variation with the curing time and temperature (150°C)

Curing time (h)	Internal diameter	Thickness (mm)	Strands of roving	Bachol precision
12	404	32	32	63
12	404	32	25	65
12	404	32	18	68

roving is smaller, the content of glass fiber is larger, that means that if the distance between the glass roving is increased with increasing the content of the glass fiber, the bachol-precision can be increased, but the production efficiency will be reduced. With a comprehensive consideration during the production process, a proper number of the strands of roving should be selected during the production process.

Curing time changes with the variation of the pipe thickness, usually 8 inch and 16 inch pipes are used, for the 16 inch ones, although the bachol precision and burst pressure is higher with the thickness increasing, the curing time is longer than that for 8 inch ones. The experimental results show that if the curing time is too long the thermo effect can cause quick reduction of the bachol-precision. 7 h is a fit curing time for 8 and 16 inch pipes. Of course, different material components will give different curing times. Experimental testing is needed before the curing course.

Although curing time, thickness, strands of roving, internal diameter and temperature are effective factors during the curing process, curing time is the most important factor compared with other factors. In order to increase the precision during the production process, a proper selection of curing time and temperature is very important.

5. Conclusions

In this study, two kinds of works have been done.

First, the effect of the winding angle on the strength of the FRP pipes was studied, based on the theoretical and experimental study, it was found that the best-fit winding angle is about 55° and the thermal curing time and temperature has little effect on the strength during the winding process.

At the same time, the damage pressure and precision have also been studied. Long thermal curing time and high temperatures are factors increasing the precision and the damaged pressure, there are also the important factors during the FRP pipe manufacture process.

With the experimental method, curing time and temperature are found as the important factors during the curing process. The right selection of these two important factors should be done according to the properties of the materials of the pipes.

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