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Study on Properties of Pressure Vessels Based on CF/AF Hybrid Fiber Reinforced Epoxy Composites

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ABSTRACT

With epoxy resin as matrix, seven types of pressure vessels (a carbon fiber reinforced composite, an aramid fiber (AF) reinforced composites and five carbon/AF hybrid composites with different ply types and hybrid ratios) were studied. The strength and strain behavior of these vessels was investigated. The results showed that the strength of a vessel with the same kind of fibers longitudinally had a positive hybrid effect, and the strength of a vessel with different kinds of fiber longitudinally was low and had a negative hybrid effect. All hybrid fiber composite vessels had higher stiffness and lower axial strain than pure AF reinforced composites vessels.

Keywords: hybrid fiber, pressure vessel, strength-strain behavior

1. INTRODUCTION

Carbon fiber (CF) has become an important reinforcement in recent years because of its high specific strength and stiffness. The strength of CF has developed from 2500MPa to 7000MPa, and the modulus has developed from 200GPa to 580GPa. In addition, CF shows good compatibility with epoxy matrix, so it has wide applying prospects. But CF reinforced composites have great susceptibility to impact damage and are expensive /1/. Aramid fiber (AF) has good properties in engineering application; it has high strength and toughness as well as low density. However, AF composite's compressive and shear strength is low. In a word, composites based on each kind of fibers have their own advantages and disadvantages. Especially in the case of the pressure vessel, that based on pure AF reinforced composite (AFRP) has high deformation because AF has low modulus, while that based on CF reinforced composite (CFRP) has high modulus and relatively high cost. In order to combine the high modulus of CF with the high strength and low cost of AF, hybrid composites have attracted considerable attention. Hybrid composites, produced with different properties fiber, hybridization style and hybrid ratio, have special properties and meet more requirements of a competitive marketplace /5/. Moreover, they also enlarge the design freedom of composites /2-4/. It is known that some properties of hybrid composites can be predicted by the ruler of

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mixtures, but some do not obey the ruler. If a property value of hybrid composite is higher than that calculated by the ruler, which means a positive hybrid effect, when a property value of hybrid composite is lower than that calculated by the ruler, a negative hybrid effect appears /6-10/.

This paper aims to fabricate winding pressure vessels with intraply and interply modes, and investigate the effect of hybrid mode on the strength and strain of these vessels.

2. EXPERIMENTAL

2.1. Raw materials

The CF was T800 carbon fiber, produced by Toray Co. Ltd., Japan, and the AF was amarid fiber.

The matrix is a middle-curing-temperature resin system comprised of multi-functional epoxy resin and a curing agent of the aromatic amine type. Their properties are given in Table 1.

Table 1

Properties of raw materials

Materials	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Density ($g{\cdot}cm^{-3}$)	Linear density ($g{\cdot}m^{-1}$)
T800	4900	210	2.3	1.80	0.2222
AF	4300	130	3.5	1.45	0.6000
Matrix	100	4.0	4.2	1.24	---

2.2 Preparation of pressure vessels

Seven types of pressure vessels were fabricated by wet filament winding /1/; their ply modes are shown in Table 2.

Table 2. Ply type of composite vessels

Type	CFRP	HYB-11	HYB-12	HYB-13	HYB-14	HYA-11	AFRP
•·•·•·	CF	CF	AF	CF	AF	CF·AF	AF
××××	CF	AF	CF	CF	AF	CF·AF	AF
•·•·•·	CF	CF	AF	AF	CF	CF·AF	AF
××××	CF	AF	CF	AF	CF	CF·AF	AF

×longitudinal winding •hoop winding

The interply hybrid vessels were prepared based on the method used in single kind of fibers winding, that is, fibers under a certain tension were immersed into a resin tube and impregnated, and then wound on the mandrel according to a certain locus to obtain a pre-cure vessel. The mandral was removed after the vessel had been cured in the dry oven (shown in Fig.1).

Two kinds of fibers were impregnated at the same time to fabricate intraply hybrid vessels, then bundles of impregnated CF and AF were mixed and wound on the mandrel, finally, the resin was squeezed out /11/, the whole process flow chart was depicted in Fig. 2.

Filament winding was accomplished by computer controlled multi-axis winding machine. The winding tension was preset and controlled.

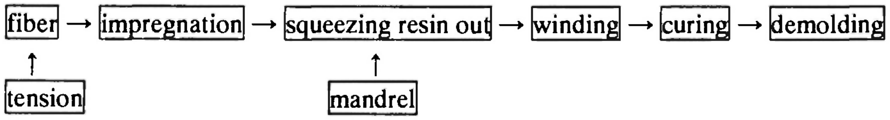


Fig. 1: Process flow chart of interply hybrid fiber winding vessel

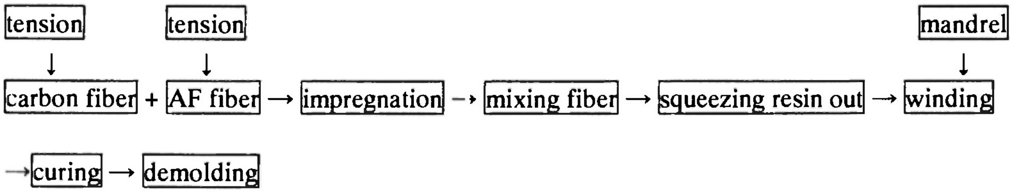


Fig. 2: Process flow chart of intraply hybrid fiber winding vessel

2.3 Measurements

The performance parameter of vessel (PF) is calculated by

$$PF = PV/W \qquad (1)$$

where P is the burst pressure of the vessels, tested on a water pressure burst device, W is the weight of vessel, V is the volume of the vessel. PF is an important parameter of vessel's material property.

Radial and axial stress-strain behavior of vessels was investigated by using data acquisition system. Radial and axial strain gages were stuck on the vessels according to Fig. 3. In this figure, gages with odd number measure axial strain, others measure radial strain.

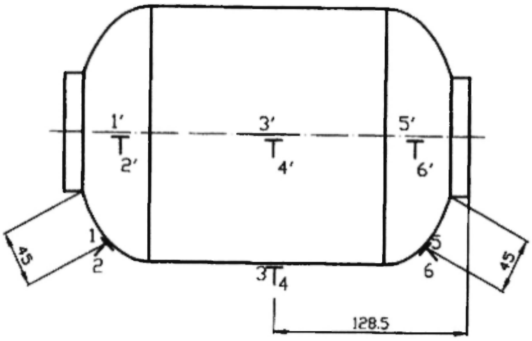


Fig. 3: Distribution of strain measuring points on Φ150mm vessel

3 PRESSURE VESSEL DESIGN

The paper studied the hybrid winding using CF and AF. CF and AF have different physical and mechanics properties, so they have different stress equivalent coefficients.

On the basis of netting theory analysis /12/, the vessel was designed to wind with two layers of longitudinal and two layers of hoop, and the hoop layer and longitudinal layer were wound alternately. The burst pressure (P) of all vessels was designed to 25MPa in order to make all kinds of vessels be comparable, that is,

$$P = 25\text{MPa} = P_h = P_l \qquad (2)$$

$$P_l = \frac{2A_0 r_l \sigma_l n_l \cos^2 \alpha}{R} \qquad (3)$$

$$P_h = \frac{2A_0 r_h \sigma_h n_h}{R(2 - tg^2 \alpha)} \qquad (4)$$

where P is the burst pressure; P_l is the burst pressure of longitudinal winding; P_h is the burst pressure of hoop winding; R is the the radius of vessel; α is the winding angle of longitudinal winding; A_0 is the fiber section area; n_l is the number of longitudinal fiber; n_h is the number of hoop placement; r_l is the placement density of longitudinal fiber; r_h is the placement density of hoop fiber; σ_l is the strength of longitudinal fiber; σ_h is the fiber design strength of hoop fiber.

For interplay hybrid vessels, the pressures are calculated respectively in each layer, and their algebraic sum should be 25MPa.

For intraply hybrid, the two kinds of fibers were wound on the mandrel simultaneously, so the burst pressure of longitudinal winding and hoop winding can be expressed as equations (5)-(6).

$$P_l = P_{lF} + P_{lc} = 25\text{MPa} \qquad (5)$$

$$P_h = P_{hF} + P_{hc} = 25\text{MPa} \qquad (6)$$

where P_{lF} and P_{lC} are AF and CF design pressure of longitudinal winding, respectively; P_{hF} and P_{hC} are AF and CF design pressure of hoop winding, respectively.

Table 3 shows the design parameters of hybrid fiber vessels.

Table 3

Design paramcters of hybrid fiber vessels

Ply type	Interply hybrid								Intraply hybrid			
	HYB-11		HYB-12		HYB-13		HYB-14		HYA-11			
	L*	H**	L	H	L	H	L	H	L-CF	L-AF	H-CF	H-AF
Design pressure (MPa)	25	25	25	25	12.5	12.5	12.5	12.5	17.79	7.21	17.59	7.41

*L-longitudinal winding **H-hoop winding

4 RESULTS AND DISCUSSION

4.1 Determination of winding tension

The winding tension of fibers influences the resin content and vessel pressure, so it is an important parameter in vessel winding process /13/.

It had been reported that the strength of a pressure vessel lost about 30% if unfit winding tension was chosen to fabricate the vessel. There are several principles on choosing the tension: (a) Fiber has proper winding tension. If the tension of fiber is too high, the resin in inner layers of a vessel is squeezed out severely and thus the resin content is low /14/. If the tension of fibers is too low, the fibers are in a relaxation state and cannot exert their strength effectively, and therefore resin cracks and vessel burst under lower pressure; (b) Fiber winding tension keeps stable. Resin content cannot keep stable if fibers lay up on the mandrel without stable tension; (c) Fiber tension reduces lay by lay. The fibers will be relaxed easily when the tension of fibers in outer layers is larger than that in inner layers. Of course, each fiber has its own tension range.

CF and AF have their own tension range in interply hybrid winding and the winding tension should be reduced lay by lay. For intraply hybrid winding, the winding tension was chosen according to the hybrid ratio of the two kinds of fibers. In the case of the HYA-11 vessel, the volume content of CF is 67%, much more than that of AF, so the winding tension was chosen as the tension of CF. Table 4 shows the winding tension of all vessels.

4.2. Strengths of pressure vessels

Strengths of intraply and interply hybrid pressure vessels were investigated and compared with the values calculated by the ruler of mixture as follows /10, 11/:

$$PF = (PF)_C V_C + (PF)_F (1 - V_C) \qquad (7)$$

where PF is the performance factor of vessel; $(PF)_C$ and $(PF)_F$ are the performance factor of CFRP and AFRP, respectively; V_c is the volume faction ratio of carbon fiber.

Table 4

Winding tension of Φ150mm hybrid fiber vessels

Sample No.	Item	L* (1)	H** (1)	L (2)	H (2)
HYB-11	Pay type	AF	CF	AF	CF
	Tension (N)	60	40	55	35
HYB-12	Pay type	CF	AF	CF	AF
	Tension (N)	40	40	35	35
HYB-13	Pay type	AF	AF	CF	CF
	Tension (N)	60	40	60	40
HYB-14	Pay type	CF	CF	AF	AF
	Tension (N)	40	40	60	60
HYA-11	Tension (N)	40	40	35	35

*L-longitudinal winding **H-hoop winding

The properties of pressure vessels with different ply types are different. The strengths of vessels in which only one kind of fiber is wound in a longitudinal layer (HYB-11, HYB-12) are higher than the value calculated by the mixture ruler; this indicates that a positive hybrid effect occurs. The strengths of vessels (HYB-13, HYB-14) in which two different types of fiber are wound in longitudinal layers are much lower than the values by the mixture ruler and those of CFRP and AFRP; this suggests a negative hybrid effect. The reason leading to the above results is that the same kind of fibers wound in longitudinal layers could transmit the stress effectively, while different kinds of fibers wound in longitudinal layers could not distribute stress well, and thus the deformations of two layers of fibers could not work in coordination with others, with the result that fibers could not increase their strength. In the case of HYB-14, CF, having a low elongation, is an inner layer, while AF, having a high elongation, is an outer layer, so the strength of HYB-14 shows a negative hybrid effect. The strength of an intraply hybrid vessel is lower than that of CFRP and AFRP.

4.3. Stress -strain behavior of pressure vessels

4.3.1 Interply hybrid pressure vessel

Figures 4 and 5 give the stress-strain behavior of interply hybrid vessel barrels, and AFRP vessel barrels.

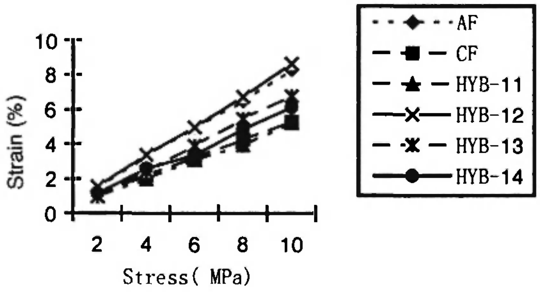


Fig. 4: Axial stress-strain curves of interply hybrid vessel barrels

The HYB-11 vessel was wound by AF in longitudinal and CF in hoop layers; its axial strain under a stress is higher than that of AFRP vessel (Fig. 4), indicating that the hoop winding layer of CF does not limit the barrel axial deformation. The HYB-12 vessel was wound by CF longitudinally and AF in hoop; its axial strain is lower than that of CFRP vessel. For HYB-13 and HYB-14, two types of fibers were wound in different layers, and their axial strain is similar, both of them are between that of AFRP and CFRP.

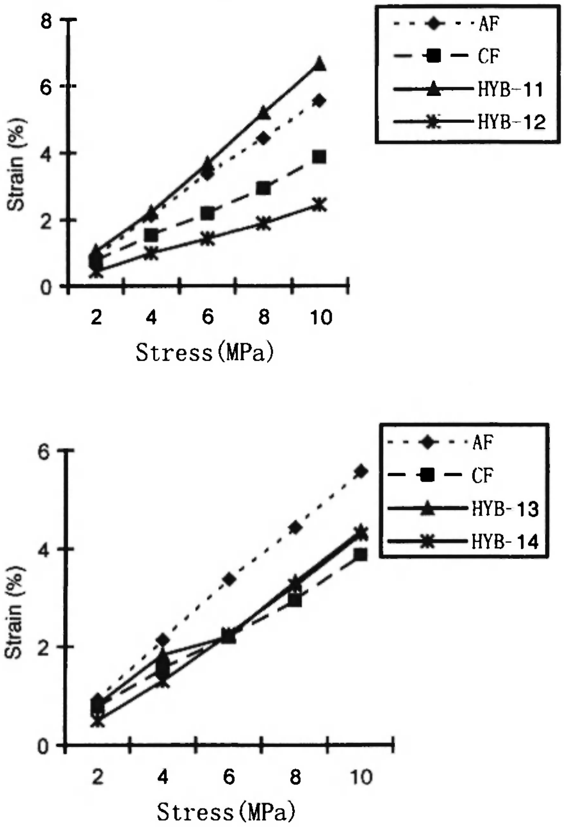


Fig. 5: Radial stress-strain curves of interply vessel barrels

It can be seen from Fig. 5 that the radial strain of HYB-11 under a stress is similar to that of CFRP, while the radial strain of HYB-12 under the stress is highest among all the interply hybrid vessels, and is equal to that of AFRP. This suggests that, for a composite with more CF in axial direction, axial strain is lower, and for a composite with more CF in radial direction, radial strain is lower. HYB-13 and HYB-14 have similar stress-strain curves, and their strain values under the same stress are between that of AFRP and CFRP.

The dome stress-strain curves of all interply vessels are shown in Fig. 6 and Fig. 7. Because CF has higher modulus than AF, all interply hybrid vessels have almost equal axial strain to CFRP (Fig. 6), and AFRP has the highest dome axial strain value. HYB-11 which is wound with AF in longitudinal layer, but with CF in hoop layer, has a great effect on strain, and thus greatly decreases the dome axial strain of the vessel. The stress-strain curves of HYB-13 and HYB-14 dome are between those of CFRP and AFRP, as shown in Fig. 6.

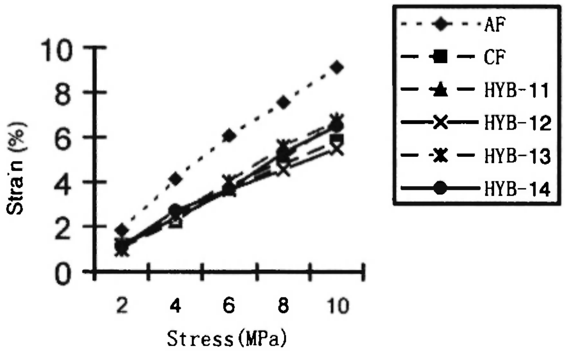


Fig. 6: Axial stress-strain curves of interply hybrid vessel domes

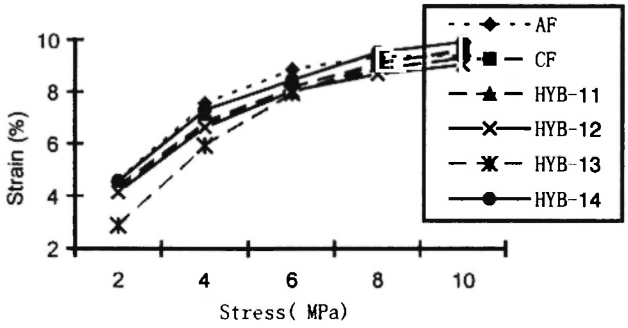
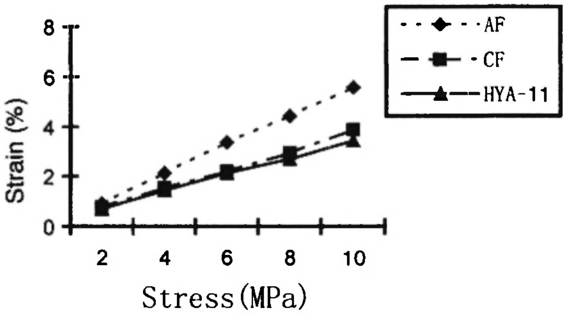


Fig. 7: Radial stress-strain curves of interply hybrid vessel domes

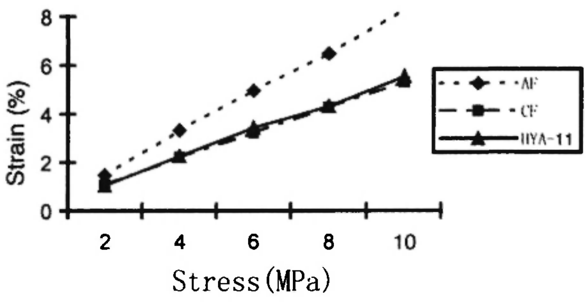
Figure 7 shows that four interply hybrid vessels, CFRP and AFRP, have similar dome radial strain values under any stress, which are different from that of their barrels. In addition, all strains under a stress lower than 0-8MPa have linear relationship with stress, when the stress is higher than 8MPa, corresponding strains do not change greatly with the stress.

4.3.2 Intraply hybrid pressure vessel

Figure 8 shows that the barrel's axial and radial strains of intraply hybrid vessel are close to that of CFRP, but lower than that of AFRP. In the case of axial strain, the strain of HYA-11 under the stress of 10MPa is only 61% of AFRP.



Axial



Radial

Fig. 8: Radial stress-strain curves of intraply hybrid vessel barrels

5. CONCLUSIONS

The ply type of interplay hybrid vessel has an important effect on strength. The strength of a vessel with the same kinds of fibers longitudinally has a positive hybrid effect, and the strength of a vessel with different kinds of fibers longitudinally is low and has a negative hybrid effect.

The ply type of CF has an important effect on barrel stress-strain behavior. The vessel with CF in hoop has low radial deformation, its axial deformation is close to AFRP, while the vessel with AF in hoop is the opposite. The strain of vessels with different fibers in different layers is between that of AFRP and CFRP. Interply vessels have no apparent difference on dome stress-strain curves, and are close to CFRP.

The intraply hybrid vessel has lower strength than CFRP, but its strain under the stress is close to CFRP.

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