CHARACTERISATION OF THE TENSILE AND FRACTURE PROPERTIES OF FILAMENT WOUND CARBON FIBRE RINGS

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Abstract

The hoop strength of filament wound CFRP composite rings is obtained using the split-disk test method. During the tests three dimensional Digital Image Correlation (3D DIC) technique is used for full-field strain measurements together with strain gauges. A video camera is used to capture crack initiation and final failure. In addition, the mechanical properties of cured CFRP pre-impregnated (pre-preg) tows are experimentally measured and values were compared to the properties of composite rings.

Results show that the tensile strength and modulus of the CFRP pre-preg tow were about 20% lower than that reported on the manufacturer datasheets. The hoop strength of the composite rings increased by about 51% by reducing the number of wound layers by half. Strain values measured with DIC have been validated using strain gauge measurements. In addition, the strain value at the split was lower than that away from the split. Cracks initially appeared at the edge of the notches and propagated away from the split area due to high shear strain. Then, fracture failure is suddenly occurred at the split area.

1 Introduction

Permanent magnet rotors require containment to avoid failure due to centrifugal forces. Normally such containment is achieved using magnetic and non-magnetic metallic sleeves (such as Steel, Inconel, Titanium, Aluminium etc). As electric motor technology has advanced and with the advent of high speed, high efficiency machines, the use of metallic sleeves becomes restrictive and therefore a move to alternative technologies is required. Carbon fibre reinforced polymer (CFRP) composite sleeves are lighter and provide stronger containment than metallic sleeves, which make them an ideal solution for high speed rotors, generators and flywheels energy [1-3]. CFRP sleeves are normally produced by filament winding technology using two different methods depending on the process of resin impregnation: wet winding using dry fibres impregnated in a liquid resin bath or dry winding using pre-preg fibres with B-stage resin. Since the inertial stresses are dominant in the circumference direction, most of the fibres are usually wound in the hoop direction.

In this work, the tensile properties of pre-preg tow were measured experimentally and values are compared with data given by supplier datasheet. CFRP composite sleeves were manufactured using dry pre-preg winding method. The hoop strength of CFRP specimens was determined using the split-disk test method. 3D DIC system and strain gauge were used to measure the hoop strain at the split location. The initiation of the crack and final failure were also recorded.

2 Experimental

2.1 Composite ring specimens

CFRP composite tubes were manufactured by filament winding method. T800S carbon fibre tow with a roving size of 24000 filaments was pre-impregnated in UF3357 thermosetting epoxy resin. The UF3357 resin was used in this work as it was developed for high temperature applications with a glass transition temperature of 182°C [4].

Two different tubes thickness were manufactured by winding 4 and 8 layers in the hoop direction on a solid steel mandrel (70mm diameter and 300mm long). A consistent tension was applied on the tow while winding to achieve low void content and high fiber volume fraction ring specimens. Digestion testing method using Nitric acid was used to determine the fiber volume fraction in the composite rings, which was 62%±0.8 [5]. The CFRP tubes were precision cut into rings of two nominal widths of 15 and 25mm using 0.4mm diamond water cooled saw. The CFRP rings with large width have two notches at each side to give a nominal width in the reduced sections of 15mm (Figure 1a). The notches were created by drilling holes using D-STAD diamond coated drill (from OSG) with 6.375mm diameter. To ensure the holes were centred relative to the ring width a wooden fixture was designed for this purpose, as shown in Figure 1b. Also a wooden rod was inserted inside the CFRP tube to reduce the vibration while drilling.

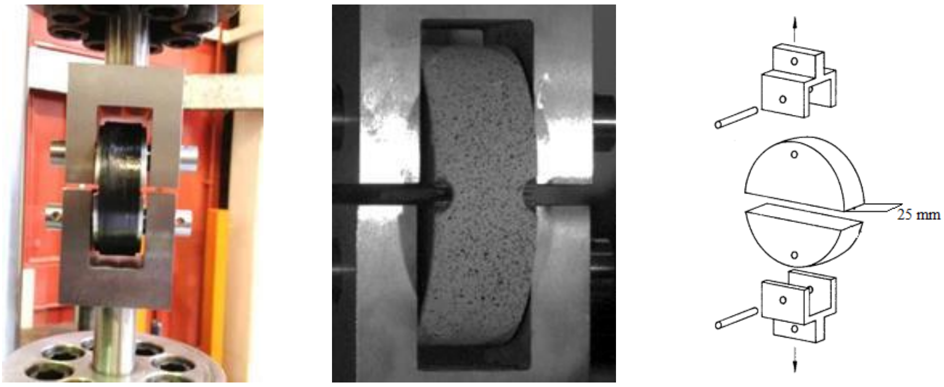
(a) (b)

Figure 1. CFRP specimen (a) and drilling guidance fixture (b).

2.2 Testing method

To evaluate the hoop strength of CFRP rings, the hydro-burst test method is one approach. However, this method is not straightforward and requires extensive preparation. Alternatively, split-disk test method is used to obtain the apparent hoop tensile strength of filament wound composites [6-7]. The drawback of the split-disk test method is the lower failure strain due to local bending of the composite ring at the location of the split [8].

Photo of the split disk test fixture is shown in Figure 2a. The split-disk test fixture was fabricated from high strength steel. The CFRP ring is mounted in a split disk where the reduced widths are located in front of the split (Figure 2b). The specimen is loaded through two high shear strength pins with 25.4mm diameter to compensate any misalignment, as shown in the sketch in Figure 2c. The test procedure was performed in according with ASTM D2290 standard using 200kN testing machine at a constant displacement rate of 1mm/min.



(a) (b) (c)

Figure 2. Photo of split-disk test set up (a), CFRP ring with reduced area sprayed and ready for DIC, and Sketch of split-disk fixture (c) [6].

2.3 Instrumentation

Full field strain distribution was measured using DIC at one of the reduced area (Figure 2b). DIC is an optical method to measure the displacement field at the surface of an object by comparison of surface digital images before and after deformation [9-11]. The method tracks the gray value pattern in small areas with multiple pixel points during deformation. This area is usually called subset and has unique light intensity distribution. It is assumed that the subset light intensity does not change during deformation. Thus, the displacement of the subset on the image before deformation is obtained in the image after deformation by searching the area of the same light intensity distribution. As the CFRP specimen is curved, out-of-plane deformation is recorded using three dimensional (3D) DIC system [12, 13]. This can be achieved by using two digital cameras in stereo setup. Prior to the test the CFRP ring surface is sprayed with white and black paints to produce a speckle pattern with highest possible contrast.

In addition to the strain measurement using DIC, linear pattern strain gauges were used to measure strain values on the opposite side of the split where another reduced area located at 180^{o} from the area analysed with DIC. The load and strain data were recorded using Vishay system 8000 data logger at a scanning rate of 100 data per second. In addition, a video camera is used to capture cracks initiation and the final failure.

3 RESULT AND DISCUSSION

3.1 Fibre properties

The supplier datasheet gives the mechanical properties of the composite materials made from T800S fibre and an epoxy resin different to that used in this study [14]. Therefore, tensile test was carried out on cured CFRP pre-preg tows to define their tensile strength and modulus. It is worth mentioning that there is no standard method for preparing and testing pre-preg tows. Thus, the tows were laminated on aluminum plate and cured in the same procedure as the CFRP tubes. Cured tows showed some voids and uneven stretching of the filaments. Each tow was glued with glass fibre end tabs to be hold in the tensile testing machine (Figure 3).

Figure 3. CFRP pre-preg tow cured specimens

Test results show that the average tensile strength and modulus are about 20% lower than those of suppliers (Table 1). These lower values are believed to be due to defects in the cured tows. Also, the supplier carried out tests on composite specimens with another epoxy resin using different manufacturing and testing methods than those carried out in this work.

Properties	Supplied	Average measured
Tensile strength [MPa]	2950	2304±145
Tensile modulus [GPa]	154	121±10

Table 1. Measured T800S pre-preg tow properties compared to supplier datasheet.

3.2 Apparent hoop strength

The apparent hoop strength of CFRP ring specimen is calculated by equation (1)

$$\sigma_{hoop} = \frac{P}{2A_g} \tag{1}$$

Where P is the failure load and A_g is the cross-sectional area of the ring where the strain gauge is located at the split line. Table 2 summaries the testing results of all CFRP ring specimens. The failure strains at the split location were measured using DIC technique on one side of the ring and using strain gauge (SG) on other side.

The average hoop strength for thin (4 layers) and thick (8 layers) CFRP rings is 2316±24MPa and 1535±143MPa, respectively. According to Lame's equation for thick wall cylinder, the hoop strength relates to the diameter to thickness (D/t) ratio [15], and the hoop strength increases with an increase in the D/t ratio. Thus, thinner rings have higher hoop strength than thicker ones.

specimen	No. of layers	Width (mm)	Thickness (mm)	Hoop strength (MPa)	Strain (μ)
CFRP1.1*	8	14.76	2.53	1518	/
CFRP1.2*	8	15.2	2.57	1426	4582 (DIC)
CFRP1.3*	8	15.72	2.62	1335	/
CFRP1.4	8	15.03	1.98	1564	6884 (SG) 6802 (DIC)
CFRP1.5	8	15.06	2.03	1733	6645 (SG) 8032 (DIC)
CFRP1.6	8	15.07	2.13	1636	7698 (DIC)
CFRP9.1	4	15.04	0.99	2286	11179 (SG)
CFRP9.2	4	14.91	0.99	2314	11800 (SG)
CFRP9.3	4	15.05	0.99	2318	11115 (DIC)
CFRP9.4	4	15.05	1.00	2346	11529 (DIC)

* Drilled holes to reduce the width,

Table 2. Measured hoop strength of filament wound CFRP rings.

The stress-strain curves for thick and thin rings (without holes) are shown in Figure 4. The figure shows that the curves are non-linear at lower applied load and then become linear up to failure. This non-linearity is due to slack in the loading system and due to straightening of the CFRP ring at the split location. The elastic modulus was calculated in the linear part of the stress-strain curve from strains of 0.3% and 0.5%, respectively. The average value of elastic modulus for thick rings is 267±15GPa, which is higher than that for thin rings of 181±0.4GPa. Both values are higher than those given by the supplier and measured using pre-preg tows (Table 1). Comparing the measured tensile strength of pre-preg tow and CFRP ring shows that the tensile strength of thinner rings is closer to that of the CFRP pre-preg tows, as shown previously in Table 1.

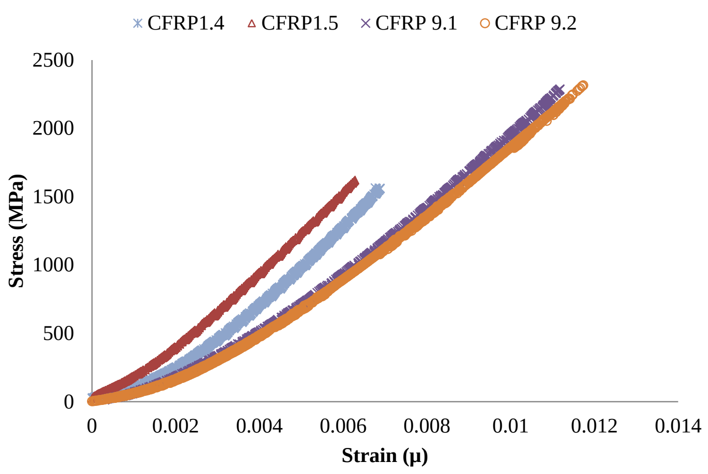


Figure 4. Stress versus strain curves for CFRP rings

3.3 Strain distribution

Figure 5 compares the strain data acquired by DIC and strain gauges at the split location for CFRP1.5 specimen. The figure shows that strain data measured by both techniques agree well up to 0.4% tensile strain, and then the strain measured by DIC diverges slightly from the strain measured by strain gauges. This is due to formation of damage in the ring at the side of the DIC.

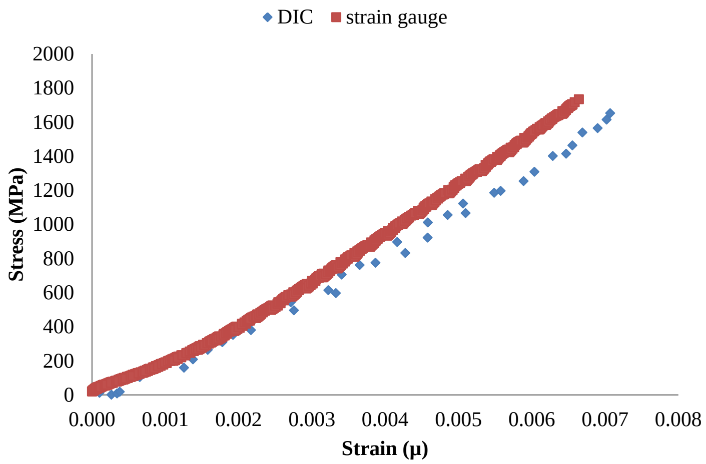


Figure 5. Comparison of strain data measured by strain gauge and DIC for CFRP1.5 specimen.

The hoop strain at the split (R0=0.0067) is lower than that at a distance away from the split (R1=0.0076 and R2=0.0079), as shown in Figure 6. This is because the fibres in the ring specimen at the split location are orientated at 0^{o} with respect to the load direction and their elastic modulus (E_1) is higher for this orientation.

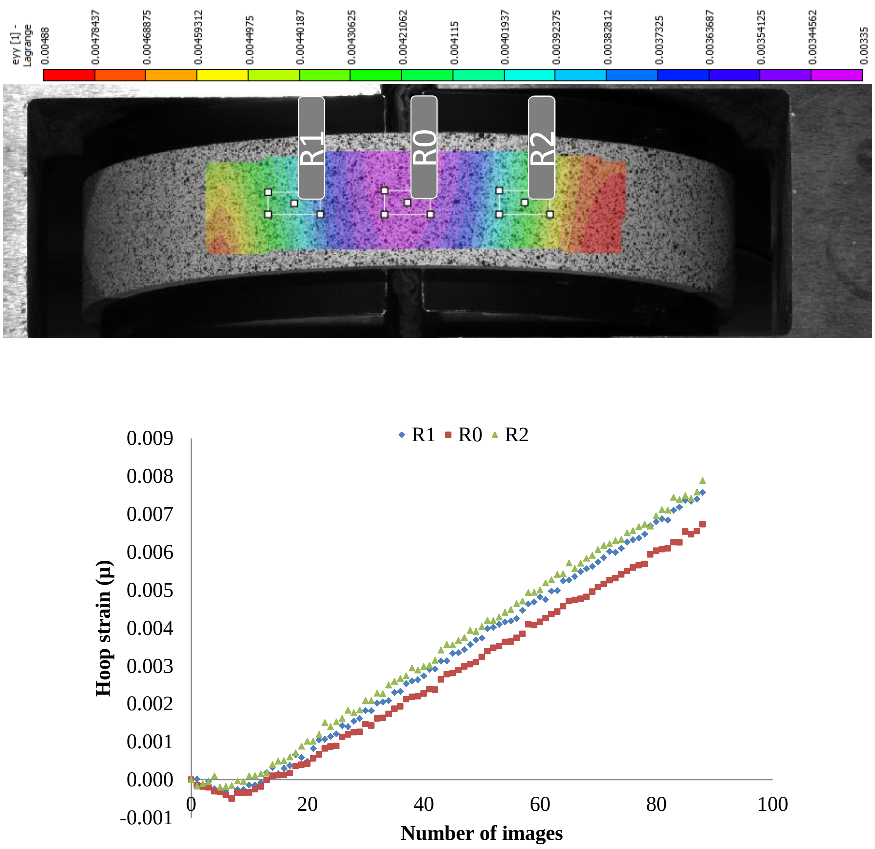
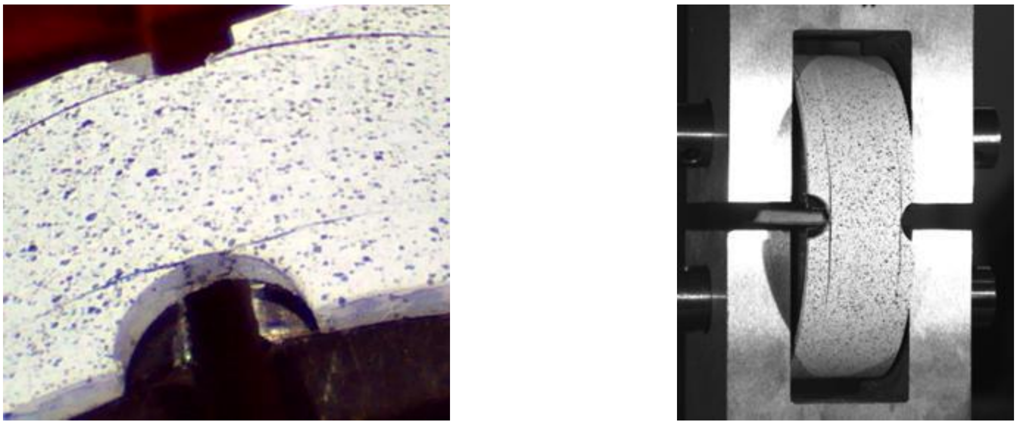


Figure 6. Comparison of strain data at different locations from the split.

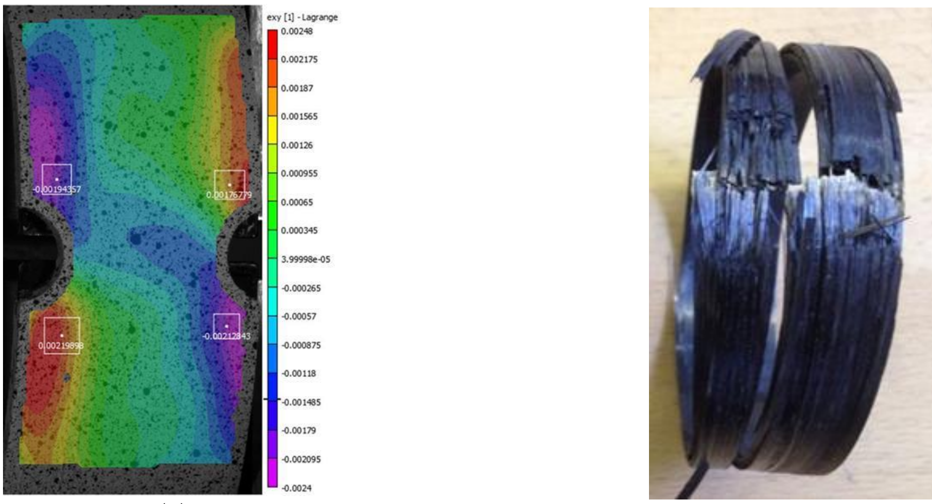
3.4 Rings failure

A video camera was used to capture crack initiation and propagation. Figures 7a and 7b show that the drilled holes initiated cracks at the notch tip and propagating along the fibres direction in CFRP rings. These cracks appeared at low load because of fibres discontinuity at the edge of the notches, as the ring was wound in the hoop direction. The propagation of these cracks progressively isolated the two notches from the rest of the specimen with the load then carried by the ligament which eventually failed at the split location. The shear strain map recorded by DIC prior the appearance of the cracks along the fibre direction shows local strain values of about 0.2% close to the initiation site (Figure 8a). Final failure occurred by rupturing the fibres at the split location with delamination across the ring thickness, as shown in Figure 8b.



(a) (b)

Figure 7. Initiation of the crack (a), and CFRP ring after shear delamination (b).



(a) (b)

Figure 8. Localised shear strain at the sides of the notches (a) CFRP rings final failure (b).

4 Conclusion

An experimental procedure has been developed to characterize the failure process of composite rings wound along the hoop direction by monitoring the evolution of full-field strain distributions measured by 3D DIC. The strength of the composite rings doubled when reducing the number of wound layers by a factor of two. Strain values measured using DIC has been validated using strain gauges. High shear strain was recorded prior to the early appearance of circumferential cracks initated at the tip of drilled notches aimed at localizing the failure of the ring. CFRP ring failed by rupturing the fibres at the split location coupled with through thickness delamination.

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