Experimental Study on Hoop Stress Affecting Braided Carbon Fiber Reinforced Plastics Subjected to Internal Pressure

Nanang Endriatno, Kawai Kento, Suehiro Takuru, Kitayama Satoshi, Sakamoto Jiro, Kinari Toshiyasu

Abstract

Braided carbon fiber reinforced plastics (CFRPs) can be employed in the construction of pressurized vessels to increase performance and reduce overall weight. However, owing to the complex braiding structures resulting from the braiding process, an analysis of the elastic modulus is important as it affects the hoop stress on the pressure vessel. In this study, braided preformed CFRP constructed on a steel cylinder subjected to internal pressure was experimentally investigated using a simple approach that involved estimating the elastic modulus and hoop stress. Five types of braided preformed CFRP with different braiding angles and number of applied layers were analyzed. The elastic modulus and hoop stress can be estimated from these measurements of the internal pressure. The differences in the braided structures result in different strain values and affect the elastic modulus. High braiding angles tend to be more stable against high internal pressure, and exhibit small strain differences and high elastic modulus in the hoop direction. Similar results were observed when additional layers were applied. Increasing the braiding angle and the number of layers can increase the average elastic modulus.

Key Words: Carbon fiber reinforced plastic (CFRP), Braid, Elastic modulus, Hoop stress

1. Introduction

Thin cylindrical pressure vessels have a variety of applications in the industry. However, many thin-walled steel structures subjected to internal stresses fail because of hoop stress. Hoop stress on pressure vessels can be reduced by increasing the wall thickness, but this will increase the weight of the component. An alternative is to add composites such as braided carbon fiber reinforced plastic (CFRP) in the pressure vessel. Braided preformed CFRP is a high strength, lightweight composite that can resist the internal pressure at the contact between the cylinders. Several studies have experimentally analyzed the use of braided structures subjected to internal pressures. These studies focused mostly on the use of different fabric structures, the use of isotropic elastic methods for composites, and analysis of hoop stress and strain.

Previous studies explored how biaxial and triaxial structures with one or more layers at different braid angles affect the mechanical properties, including the flexural properties of braided composite tubing. In particular, the braid angles, the number of laminates, and fraction volume are important parameters that influence the mechanical properties [1]. Other studies investigated the burst pressure of fiber reinforced tubing fabricated using E-glass fiber with different structures (e.g., laminated prepreg, filament wound, and braided tubes) by applying simplified modeling approaches and experimental analyses. It was found that filament wound and braided tubes provided greater potential to resist hydrostatic pressures compared to prepreg laminated tubes [2]. Methods for analyzing isotropic elastic tubes were applied to study the stress distribution of triaxial braided carbon T-700 composite tubes under internal pressure, and to calculate hoop stress; large local strain variations and large strains at the composites were noted [3]. Elastic limits in strain curves, and subsequently hoop stresses, have been determined experimentally and by using isotropic elastic tube equations developed for calculations on silicon carbide fiber reinforced matrix tubes with interlocking 3D braided preforms [4]. By utilizing the hoop stress–strain curve obtained by measuring the pressure data along with the strain, hoop tensile properties such as ultimate hoop tensile strength, proportional limit hoop stress, and
the elastic modulus in the circumferential direction can be obtained [5].

In many studies, hoop stress–strain curves are used to analyze hoop properties. However, when steel cylinders are combined with composite fiber material, hoop stress cannot be determined without knowing the elastic modulus of individual structural materials. The braiding process offers a simple manufacturing approach for many complex structures that may be very difficult to analyze theoretically within a short time. When the braided structure changes, the elastic modulus changes, and when CFRP is used in a pressure vessel subjected to internal pressure, the modulus also changes. Thus, an analysis of the elastic modulus is necessary to determine CFRP performance in terms of the internal pressure. This study aims to provide a simple method of analyzing the elastic modulus and hoop stress for a combination of thin steel cylinders and braided CFRP subjected to internal pressure. Five configurations of biaxial braided carbon T-700 were produced using a circular braiding machine. Then, a vacuum assisted resin transfer molding (VaRTM) system was used to mold the specimen. Pressure and strain data were obtained from hydraulic experiments and used to determine the elastic modulus of CFRP by applying simplified methods of combining thin cylinders so that the hoop stress of each cylinder can be calculated. Thereafter, discussions are presented on 1) the effect of braiding angles and number of layers on strain distributions, and 2) techniques for reducing hoop stress in the five types of braided CFRP used in steel cylinders.

2. Experimental Procedure

2.1 Test Specimen and Manufacturing

CFRP was added to the outside of thin steel tubes (SC400, \(E = 206\) GPa with 2 mm wall thickness and 60 mm inner diameter). The CFRP used in this study was made of carbon fiber (Toray Industries, Torayca 700SC-12000) and epoxy resin (Axson Technologies, Epolam 2031 Resin). Carbon fibers were braided in a biaxial pattern on the steel surface using a circular braiding machine (Kokubun Limited, 40Z048C) with 48 bobbins, as shown in Fig. 1.

Five types of braided preforms were applied to the thin steel cylinders. In three types of the braided preforms, three layers were applied using different braiding angles (45°, 60°, and 75°), in one type of the braided preforms, two layers were applied at a braiding angle of 45°, and in one type of the braided preforms, two layers were applied at a braiding angle of 60°. The number of strain gauges used in each type of specimen is shown in Table 1.

![Fabrication of braided composite tube specimens using braiding machine.](image)

**Table 1** Summary of specimens and strain gauge data used to evaluate the elastic modulus.

<table>
<thead>
<tr>
<th>Type of specimens</th>
<th>Sample names</th>
<th>The number of strain gauges</th>
<th>Total of strain gauges</th>
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</thead>
<tbody>
<tr>
<td>N2-60</td>
<td>N2-60-1</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>N2-60-2</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N2-60-3</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>N3-45</td>
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<td>5</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>N3-45-2</td>
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<tr>
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<tr>
<td>N3-60</td>
<td>N3-60-1</td>
<td>8</td>
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</tr>
<tr>
<td></td>
<td>N3-60-2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3-60-3</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>N3-75</td>
<td>N3-75-1</td>
<td>8</td>
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<tr>
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<td></td>
</tr>
<tr>
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<td>N3-75-3</td>
<td>8</td>
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<tr>
<td>N4-60</td>
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<td></td>
<td>N4-60-3</td>
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</tr>
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<td>SS t2-1</td>
<td>8</td>
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</tr>
<tr>
<td></td>
<td>SS t2-2</td>
<td>8</td>
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</tr>
<tr>
<td></td>
<td>SS t2-3</td>
<td>8</td>
<td></td>
</tr>
<tr>
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<td>SS t5-1</td>
<td>8</td>
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</tr>
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<tr>
<td></td>
<td>SS t5-3</td>
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</table>
angle of 60°, and in one type of braided preforms, four layers were applied at a braiding angle of 60°. Table 1 lists the specimens and strain gauge data used for the calculation of the elastic modulus of CFRP. In this research, each type of braided preform (e.g., N3-75) consists of three cylindrical specimens (e.g., N3-75-1, N3-75-2, and N3-75-3). Eight strain gauges were attached on each cylinder along the hoop (circumferential) direction, while two strain gauges were attached along the axial (longitudinal) direction. The elastic modulus was evaluated using data obtained from 24 strain gauges attached in the hoop direction of each type of braided preform. However, since some values of the strain gauges were unsuitable or had large fluctuations, values from strain gauges were not used in the calculation (N3-45-1, N3-45-2, and N3-45-3). While, the symbol of minus (-) in Table 1 shows specimen was not measured or unmeasurable so that the number of specimens for N3-60 and N4-60 is two cylinders or has 16 strain gauges, which is considered sufficient for evaluating the elastic modulus of CFRP.

Braiding angle variations were controlled by changing the revolution speed of the bobbin or the drawing speed of the mandrel according to the diameter of the steel cylinder. Layers were added by repeating the process used in creating the first layer while increasing the diameter with added CFRP.

After the braiding process, the VaRTM system was used for composite molding. The procedures for the VaRTM fabrication process include mold preparation and fabric lay-up, mold sealing and vacuuming, resin preparation at 30°C and impregnation, and keeping samples at 60°C for 3 hours. Table 2 presents a summary of the construction details of the test specimens; it indicates that the fiber volume fraction increases as the braiding angle or the number of layers increases.

### 2.2 Pressurized Oil Test Method

Figure 2 shows the hydraulic pressure test system. The schematic of the entire test equipment is shown in Fig. 2(a). Figure 2(b) shows a photograph of the output strain data, and the internal pressure was simultaneously recorded using a camera. The specimen (length = 280 mm) was placed on a high-pressure resistant jig and connected

<table>
<thead>
<tr>
<th>Name of specimen</th>
<th>Number of layers</th>
<th>Braiding angle, α [°]</th>
<th>Outer diameter, D [mm]</th>
<th>Mass of specimen, [g]</th>
<th>Fiber volume rate, Vf [%]</th>
</tr>
</thead>
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<tr>
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<td>60</td>
<td>65.2</td>
<td>870</td>
<td>33.0</td>
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<td>3</td>
<td>45</td>
<td>65.7</td>
<td>900</td>
<td>43.6</td>
</tr>
<tr>
<td>N3-60</td>
<td>3</td>
<td>60</td>
<td>66.2</td>
<td>960</td>
<td>48.6</td>
</tr>
<tr>
<td>N3-75</td>
<td>3</td>
<td>75</td>
<td>67.9</td>
<td>1020</td>
<td>51.7</td>
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<tr>
<td>N4-60</td>
<td>4</td>
<td>60</td>
<td>66.8</td>
<td>960</td>
<td>50.2</td>
</tr>
<tr>
<td>SS t2</td>
<td></td>
<td></td>
<td>64.0</td>
<td>850</td>
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</tr>
<tr>
<td>SS t5</td>
<td></td>
<td></td>
<td>70.0</td>
<td>2230</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Details of hydraulic pressure test.
(a) Schematic diagram of the measurement system.
(b) Photograph of output strain and internal pressure data recorded using a camera.
(c) Test setup.
to a hydraulic pump oil hose outlet as indicated in Fig. 2(c).

During the experiment, the pressure applied by the hydraulic pump was measured using a mechanical pressure gauge. The strain values were separately recorded by the data logger and displayed using wave logger software. In addition to the data logger, we also used a camera to record the internal pressure changes in the pressure gauges and strain data from the data logger on a personal computer simultaneously.

Strain gauges were placed along the centers and edges of the specimens to measure the distribution of the strains. After the strain gauges were connected to the computer and calibrated, oil was injected into the empty test specimens using a hydraulic pump (Hanmi Hydraulic Co., Ltd., Model: HML – 1700N) to increase the pressure inside the pipe. The experiment continued until a large fluctuation in the strain value or visible failure of the test specimen was observed. Two seals were placed at each end of the inner wall of the test cylinder and jig. Because the viscosity of oil is greater than that of air, air will be pushed out and escape through the seals as the cylinders are filled. To accommodate increases in pressure during the experiment, the seals serve as safety valves, which are sacrificially damaged at high pressures to prevent explosive releases of oil or damage to the jigs and hydraulic pumps.

For a cylinder wall thicknesses \(t\) of less than 1/20 of its internal diameter \(D\), \((t/D<1/20\) or \(D/t>20\)), the radial stress due to the pressure vessel is quite small compared to the tangential stress. Therefore, the radial stress may be neglected, and the pressure vessel is assumed to be a thin pressure vessel [6]. As shown in Fig. 3, the outer layer (CFRP) has an elastic modulus \(E_1\) and thickness \(t_1\), whereas the inner layer (steel) has an elastic modulus \(E_2\) and thickness \(t_2\). If the contact pressure \(P_m\) is defined as an indeterminate constant force, the outer cylinder has an internal pressure \(P_m\) and the inner ring receives an internal pressure \(P-P_m\). Because these are thin rings subjected to internal pressure and \(D\) is the diameter of the ring for the displacement conditions (assuming the increase in both diameters is the same, \(\delta D_1 = \delta D_2\)), the elastic modulus and the hoop stress can be calculated as:

\[
\delta D_1 = \delta D_2 = \frac{D^2}{2t_1E_1}P_m = \frac{D^2}{2t_2E_2}(P - P_m)
\]

\[
P_m = \frac{t_1E_1}{t_1E_1 + t_2E_2}P
\]

Substituting \(P_m\), the hoop stress of CFRP \(\sigma_1\) is given as:

\[
\sigma_1 = \frac{D}{2t_1}P_m = \frac{E_1}{t_1E_1 + t_2E_2} \frac{PD}{2}
\]

The hoop stress of steel \(\sigma_2\) is given as:

\[
\sigma_2 = \frac{D}{2t_2}(P - P_m) = \frac{E_2}{t_1E_1 + t_2E_2} \frac{PD}{2}
\]

where, \(E_2 = \frac{0.5PD}{t_2E_2} = \frac{\sigma_2}{\varepsilon_2}\) if \(\sigma_2 = \frac{0.5PD}{t_2}\)

Rearranging equation (2) to solve the modulus CFRP \((E_1)\) gives:

\[
E_1 = \frac{0.5PD}{t_1\varepsilon_1} - \frac{t_2E_2}{t_1}
\]

where:

\(E_1\): Elastic modulus of CFRP (GPa).

\(E_2\): Gradient (slope) of hoop stress–strain curve \((\sigma_2, \varepsilon_2)\) of steel or elastic modulus of steel (GPa)

\(\varepsilon_2\): Strain of CFRP applied to steel cylinder subjected to internal pressure of CFRP-steel \((P)\) obtained from experiment.

\(P\): Internal pressure of CFRP-steel obtained from experiment (MPa).

Data from the eight strain gauges in the hoop direction of the specimen and pressure were plotted in a pressure–strain curve to determine the gradient at linear region of the curve. The average modulus of CFRP was evaluated from the eight pressure–strain curves for each specimen (some specimens have less than eight curves). The two strain gauges in the axial direction were not used for thin cylindrical calculations. \(E_2\) is the elastic modulus of steel SC400, and the theoretical steel modulus is 206 GPa, which agrees with the average elastic modulus of steel when calculated using the hoop stress–strain curve obtained from experimental data.

The elastic modulus of CFRP \((E_1)\) was calculated using simplified methods of combining thin cylinders. First, the pressure–strain \((P, \varepsilon_1)\) curve was plotted using the pressure \(P\) and strain \(\varepsilon_1\) values obtained from experiment using CFRP-steel specimens. Using this curve, the gradient of the pressure \(P\) and strain \(\varepsilon_1\) at the linear region of the curve can be obtained.

Second, by using the other specimen (steel), a hoop stress–strain \((\sigma_2, \varepsilon_2)\) curve for steel (without CFRP) was plotted using the hoop stress \(\sigma_2\) and strain values \(\varepsilon_2\) of steel (SS t2). Using this curve, the gradient of the curve for steel \((E_2)\) can be obtained. The hoop stress \(\sigma_2\) was calculated using the internal pressure data of steel \((P)\).

Finally, the elastic modulus value of CFRP \((E_1)\) was calculated using equation (4). The verification of this result can be carried out graphically by finding the residue of the internal pressure of
CFRP–steel and steel without CFRP at the same strain condition to determine the value of the contact pressure ($P_m$). Then, the elastic modulus of CFRP can be obtained from the gradient of the hoop stress–strain curve.

3. Results and Discussion

3.1 Effect of the braiding structure on the distribution of strains and the elastic modulus of CFRP

Figure 4 shows the relationship between the applied internal pressure and the average strain. The strain value variation in the specimen due to high internal pressure produces the different gradients on the pressure–strain curve obtained from the strain gauges on the specimen. As a result, the specimens exhibit different elastic modulus. Other studies have also reported that composites have a highly sensitive mechanical response to the distinct variations that affect the distribution of strains [7]; they found that increased pressure causes micro mechanism failures in multiple regions, and that the damage sequences do not necessarily occur at the same time [8,9].

As the braiding angle increases, the thickness of the CFRP increases and the direction of the fibers becomes closer to the hoop stress direction; on the other hand, the fiber volume fraction increases when the braiding angle is large, so that many fibers can distribute the load [1]. Figure 5 shows the test specimens after being subjected to internal pressure. As shown in Fig. 5(b), the braiding angle was measured from the long axis of the tube. Figures 5(g)–

![Graph showing relationship between applied internal pressure and average strain.](image)

**Fig. 4** Relationship between applied internal pressure and average strain.

![Test specimens after hydraulic pressure testing.](image)

(a) SS t2  (b) N2-60-2  (c) N3-45-3  (d) N3-60-1  (e) N4-60-1  (f) N3-75-2  

![Enlarged views of damage sequences.](image)

(g) N3-45-3  (h) N3-60-1  (i) N3-75-2  (j) N2-60-2  (k) N3-60-1  (l) N4-60-1

**Fig. 5** Test specimens after hydraulic pressure testing. In Fig. 5(b), angle $\alpha$ shows how the braiding angle was measured. Fig. 5(g), 5(h), 5(i) are enlarged views of Fig. 5(c), 5(d), 5(f), respectively.
5(i) depict the deformation on the specimen, which is indicated by the gap between the specimen and the ruler line. At low braiding angles (e.g., ~45°), larger deformations of the specimen occur than at high braiding angles (e.g., ~60° and 75°). This increases the difference between the strain value and the elastic modulus when the specimen is braided with CFRP at 45°; owing to the lower braiding angle, the CFRP has a small thickness and the fiber is not close to the hoop stress direction. In contrast, at a higher braiding angle (e.g., ~75°), in which the thickness of the CFRP increases and the fiber closely follows the hoop direction, the specimen tends to be stable and able to resist the internal pressure; in other words, the CFRP has greater capability to withstand the internal pressure. Therefore, the elastic modulus deviation decreases as the braiding angle increases. The relationship between the elastic modulus of the specimens and the variation of the braiding angle is illustrated in Fig. 6(a). Calculation results show that specimens braided at 75° had the highest elastic modulus value, followed by those braided at 60° and at 45°.

In terms of the difference in the number of layers for the 60° angle braided specimens, as the thickness and fiber volume fraction of the specimen increase, it is expected that, the elastic modulus value increases as the number of layers increases [10]. The fractures of the test specimens after the hydraulic pressure test are shown in Fig. 5(j)–5(l). As shown in Fig. 5(j), the results of the pressure test indicate that CFRP with two layers (N2-60) had greater damage compared to specimens with three or four layers, with fiber breaks occurring due to large local deformation. In terms of specimens with three or four layers, as shown in Fig. 5(k) and 5(l), the local deformations decreased, although a crack occurred in the matrix along the specimen. The relationship between the elastic modulus of the specimens and the variation of the number of layers is shown in Fig. 6(b). The average modulus value increases as the number of layers increases. In other words, the addition of layers can increase the elastic modulus owing to the increased thickness of the CFRP and fiber volume fraction. The same trend occurs in cases where the elastic modulus deviation decreases when the number of layers is increased from two layers to three and four layers. The highest elastic modulus value occurred at four layers, followed by that for three layers and two layers.

### 3.2 Effects of adding CFRP on the hoop stress of steel cylinder/braided CFRP combinations

From the elastic modulus results, it can be observed that the modulus of CFRP is lower than that of steel; however, as shown in Fig. 4, when CFRP is added to a steel cylinder, the strain distribution changes and the hoop stress value is affected. It is

![Diagram](image-url)
known that increasing the braiding angle and the number of layers result in increase in the average elastic modulus of CFRP owing to the cylinder combination, the hoop stress value decreases.

A summary of the relation between the hoop stress and specimens when the internal pressure is 20 MPa in the elastic region is presented in Fig.7 and Table 3. When the elastic modulus of CFRP ($E_1$) and steel ($E_2$) are known, the hoop stress of CFRP can be determined using equation (2). While, the hoop stress of SS $t_2$ is determined using equation (3).

The hoop stress on the thin cylinder with CFRP is smaller than that of the single steel cylinders. The addition of CFRP can provide effective pressure contact to withstand internal load from inside the pipe. In the high CFRP elastic modulus, it can be observed that the hoop stress received by the CFRP cylinder is larger, while the hoop stress received by the steel is smaller.

It can be concluded that increasing the braiding angle from 45° to 60° and then to 75° increases the ability of the cylinder to withstand hoop strains at each pressure increase. On the other hand, increasing the number of layers from two to three and four also reduces the hoop stress on a cylinder under internal pressure.

4. Conclusions

This study analyzed the elastic modulus and hoop stress on combinations of steel cylinders and CFRP subjected to internal pressure. Differences in CFRP braiding patterns caused the strain on the steel cylinder/CFRP combinations to vary significantly, and affected the deviation of the elastic modulus value. When the direction of the fibers was closer to the hoop stress direction, the ability of the specimen to withstand high internal pressure increased because it has a small strain difference and a high elastic modulus in the hoop direction, and consequently, it can withstand large local deformations. The same phenomenon also occurred when CFRP layers were added. The internal pressure test results indicated that the elastic modulus can be estimated using a simplified method based on a thin cylindrical formula. Results also show that increasing the braiding angle and the number of layers can increase the average elastic modulus of CFRP. It was also found that the addition of CFRP on cylindrical steel can decrease the value of the hoop stress. The largest decrease in the hoop stress occurred at a braiding angle of 75°, and among the different layer combinations, the minimum hoop stress value occurred with four layers of CFRP.

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References