Hoop tensile strength of tubular carbon fiber reinforced silicon carbide matrix composites

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\section*{ABSTRACT}

C/SiC (carbon fiber-reinforced silicon carbide) composites are widely used in the aerospace industry and for the fabrication of high-temperature parts owing to their excellent heat and chemical resistances. In this study, the tensile properties of C/SiC composite tubes manufactured by a filament winding method were examined via hoop tensile testing, and the optimal testing conditions were determined by comparing them with the properties of a composite plate specimen. It was found that during tensile testing, bending stress was generated and the strain inside and outside of the gauge section of the composite specimen is shown as tensile and compressive, respectively; as a result, premature damage occurred, which was not observed for the plate specimen. In order to minimize this effect, tensile testing was performed under the improved conditions, at which the side of fixture was close to the side of the test specimen, and the distance between the upper and lower fixtures was small. However, the relatively low strain to failure (which is a unique characteristic of C/SiC composites) suppressed the induction of both strain inside and outside the specimen in the tensile direction, which led to lower tensile strengths of the composite tubes as compared to that of the plate specimen. Because the tensile modulus calculated in this study is very close to that of the plate specimen, the hoop tensile testing method is suitable for determining the modulus values of C/SiC composites.

\section*{1. Introduction}

Among all available engineering materials, ceramic matrix composites (CMC) offer the highest specific strength at temperatures above 1000 °C. They mainly consist of oxide and non-oxide materials, which include C/SiC, C/C-SiC, SiC/SiC, and C/C composites. C/SiC composites have attracted much attention as a structural material with potential applications in the aerospace, automotive, and other industries owing to their high strengths and relatively low density\cite{1-4}. The methods for their manufacture include chemical vapor infiltration (CVI), polymer infiltration and pyrolysis (PIP), and liquid silicon infiltration (LSI). During LSI, C/SiC composites are fabricated by infiltrating molten silicon into porous C/C composites. This method is characterized by lower residual porosity of the resulting material and shorter processing time (as compared to those of CVI and PIP) and has no thickness limitations. The LSI-fabricated C/SiC composites are commercially used in various round and tubular parts such as combustion liners, nozzles, and brake disks, owing to their excellent thermal and mechanical properties. A filament winding method is used for manufacturing tubular composite materials via continuous winding fibers in the form of a filament around a mandrel with the shape of a desired product\cite{5-7}. The obtained preform is transformed into C/SiC composite tubes through carbonization and LSI.

Because tubular composite materials are mainly used for pressure-resistant parts that are able to maintain their shapes against deformation under a specific pressure, their tensile properties must be thoroughly evaluated\cite{8,9}. In order to determine the tensile properties of tubular composite materials, various methods including elastomer loading, pressure loading, and hoop tensile testing are utilized. Jenkins et al.\cite{10} investigated the stress generated in CMC tubes via elastomer loading. This method consists of inducing damage to the tested tubular specimen by applying a load to the elastomer inside it along the vertical direction; however, it is subject to the influence of the friction of a rough surface and the amount of the load that can be applied to the specimen is limited. In addition, Cain et al.\cite{11} conducted a study, in which the pressure loading method was used for testing glass/epoxy composites in order to generate uniform radial stress in cylindrical specimens. This technique uses hydraulic pressure, which can be produced only by special equipment and has a limitation in the testing temperature. Hoop tensile testing performed by Dick et al.\cite{12} on
aluminum tubes can be used for evaluating the performance of tubular pressure-resistant parts. In this method, a load is applied to the tested specimen after its mounting on two closely-fitting D-shaped fixtures, and the testing procedure can be conducted without using special equipment [12–14]. However, because standardization of the property evaluation method via CMC hoop tensile testing has not been performed yet properly except the some studies [10,15], Yu et al. [15] had investigated the various loading behaviors on the SiC/SiC tube specimens through the results of circumferential tensile test and structural analysis. However, there was no detailed study on the effect of parameters such as the distance between fixtures on the evaluation of mechanical properties through hoop tensile test.

In this study, we investigated the effect of specimen and fixture size parameters on tensile properties of C/SiC composite tubes manufactured by the filament winding method via hoop tensile testing. Furthermore, the optimal test conditions were determined by comparing the obtained data with the results of the tensile testing of a plate composite material specimen.

2. Experimental method

2.1. Specimen preparation

The materials utilized in this work consisted of tubular C/SiC composites and carbon fibers (PYROFIL TR30S) used as the reinforcement. First, a carbon fiber impregnated with phenol resin (KRD-HM2, Kolon Chemical, Korea) was wound on the mandrel with a diameter of 110 mm and length of 900 mm. As was previously reported by Srebrenkoska [16], the hoop tensile strength of the fiber-reinforced composite tubes for pressure resistant parts prepared by filament winding depended on the winding angle with an optimal value of 45°. Therefore, in this work, a carbon fiber-reinforced plastic tube with an inner diameter of 110 mm and thickness of 1.8 mm was manufactured at a winding angle of ± 45° and cured inside an oven at a temperature of 120 °C. Afterwards, it was carbonized in a N₂ atmosphere at 1000 °C, and C/SiC composite tubes having a fiber volume fraction of 0.49 were obtained through the impregnation/reaction process of molten silicon in vacuum at a temperature of 1600 °C. The size of tested specimens and fixtures for hoop tensile testing were manufactured in accordance with the ASTM D2290-16 standard [17]. Although this standard was developed for the polymer composites, the final standard of the hoop tensile test for the ceramic composite material does not exist yet. Therefore, in this study, the initial test conditions were prepared according to procedure A of ASTM D2290-16 standard (Fig. 1). Each specimen involves two sections of reduced area, which were located 180° apart from each other. Whereas, the plate specimens were fabricated by the same filament winding method using a regular octahedron mandrel with sides of 100 mm and length of 900 mm (see Fig. 2).

2.2. Finite element (FE) analysis

As a result of the initial test using the manufactured tubular specimens, the bending behavior of the test specimen resulted the strains in different directions inside and outside. In order to minimize the bending behavior of the specimen, a parametric study of the fixture shape was conducted, while the configuration of the test specimen remained intact. In particular, a static load structural analysis was performed using the ABAQUS, a representative commercial finite element (FE) analysis code, where the gap between the inner side of the specimen and the outer side of the fixture as well as the distance between the fixtures served as the main parameters (see Fig. 1). By varying the gap between the inner side of the specimen and the outer side of the fixture (0.5 mm, 0.1 mm, or 0 mm) and distance between the fixtures (20 mm, 15 mm, or 10 mm), two sets of analytical data depending on the fixture configuration were obtained.
2.3. Hoop tensile testing

In order to prevent the stress concentration caused by the non-uniform thickness of the test specimen that was in close contact with the fixture, a silicon pad with a thickness of 0.5 mm was attached to the fixture before conducting the experiment [18]. A hoop tensile testing procedure was performed using an MTS-370 Landmark Servohydraulic testing system, which represented a hydraulic universal testing machine. A uniform tensile load was applied to the test specimen at a speed of 0.5 mm/min and room temperature using the fixture until failure occurred. In order to ensure accurate measurement of the strains inside and outside gauge section of the test specimen, separate strain gauges were attached to the corresponding areas. The tensile test of the plate specimen was also performed on five specimens under the same conditions. The tensile strengths of tubular C/SiC composites were calculated using the following equation:

$$\sigma = \frac{F}{2A}$$  \hspace{1cm} (1)

where $\sigma$ is the tensile strength (MPa), $F$ is the maximum failure load (N), and $A$ is the area of the gauge section (mm$^2$). The tensile modulus was determined from the slope of the stress-strain curve in the strain range of 0.1–0.3% corresponding to the mean values of the strains measured inside and outside the test specimen [19].

3. Results and discussion

3.1. Results of initial test

The initial hoop tensile testing procedure was conducted at an inner diameter of the tested specimen with 110 mm, outer diameter of the fixture with 108 mm, and distance between the fixtures was 10 mm. As a result, failure of specimens occurred in the gauge section during hoop tensile test. The morphology of the failure surface was analyzed by scanning electron microscope (SEM: HITACHI S-4800) as shown in Fig. 4. Since the fibers were reinforced at $\pm$ 45°, a proper pull-out phenomenon is observed in the overall failure surface. This shows that the damage of reinforcing fiber did not occur seriously during specimen production, and that the fiber damage parameter was not reflected in the evaluation of mechanical properties. During the initial tensile testing, nonlinear behavior was observed as shown in Fig. 3(a) due to the generation of tensile and compression strains inside and outside the specimen, respectively. The stress-strain curve using mean strain is plotted in Fig. 3(b).

Because it is not possible to apply the same tensile load to the internal and external areas of the tested specimen, the difference in their strains caused its premature damage. Hence, the value measured during initial testing was not the actual tensile strength, but an apparent tensile strength resulting from the bending behavior in the gauge section of the test specimen [17]. As a result, the measured tensile strength of the tubular composites was only about 65% (32 MPa) of the tensile strength of the plate test specimen (49.5 MPa).

According to the study conducted by Yu [15], the generation of bending stress occurred because the fixture was smaller than the test specimen, and a distance existed between the upper and lower fixtures.

Fig. 3. (a) Inside and outside strains measured during the initial test of tubular specimen. (b) Stress-strain curves recorded in initial test of tubular specimen.

Fig. 4. Fiber pull-out SEM observation at fracture surface of the specimen.

Fig. 5. A diagram describing the distance(C) from the point of contact between the fixture and test specimen to the outermost point of the test specimen.

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Therefore, the actual tensile strength can be obtained via the application of a true tensile load that is achieved by modifying the fixture configuration to reduce the difference in strain and minimize the bending stress. The effect of fixture modification on the bending stress (σ) caused by load application can be described using the following equation:

$$\sigma = (M \cdot C) / I$$

(2)

where \(M\) is the bending moment [N·mm], \(C\) is the distance [mm] from the point of contact between the fixture and test specimen to the outermost point of the test specimen, and \(I\) is the moment of inertia [mm\(^3\)] of the area (Fig. 5). The latter parameter can be expressed as \(I = bh^3/12\) (where \(b\) and \(h\) are the width and length of the area, respectively), and \(M\) is the product of the load and the distance \((F \cdot C)\). By using this equation, the bending stress [MPa] can be expressed as \(\sigma = (F \cdot C^2) / I\). Because its value is directly proportional to the square of distance \(C\), the magnitude of the bending stress can be varied by adjusting the testing geometry (such as the gap between the test specimen and the fixture). Therefore, in this study, we attempted to minimize the bending stress by reducing the difference in strain via fixture modification in accordance with Eq. (2) and [15].

3.2. Results of FE analysis

Fig. 6 shows the bending stress generated in the test specimen during its contact with the fixture under the tensile load. As shown in the figure, we could find the compressive stress outside the test specimen at the point of contact between the specimen and the fixture (792 N), but thereafter the compressive stress decreased due to the

![Fig. 6. Results of strain analysis conducted at different loads.](image-url)
tensile load. Therefore, in order to determine the effect of their interaction on the strain, its distributions inside and outside the test specimen were obtained at various distances between the inner diameter of the test specimen and the outer diameter of the fixture. Fig. 7(a) shows the dependence of the strain on the gap between the inner side of the test specimen and the outer side of the fixture under tensile load. In this experiment, the distance between the upper and lower fixtures was fixed at 10 mm, and the gap between the inner side of the specimen and the outer side of the fixture was varied between 0.5, 0.1 and 0 mm. The larger the gap between the specimen and the fixture, the larger the strain difference between the inside and outside of the specimen because it is not possible to apply the same tensile load to both sides of the test specimen, and the larger nonlinear region of the strain-load plot originated at early loading stage.

The result of structural analysis conducted at a 0.5 mm gap between the specimen and the fixture (Fig. 7(b)) revealed that both the tensile strain of inside of the test specimen and compression strain of outside of specimen were generated even under the maximum load. In contrast, when the gap between the test specimen and the fixture was smaller, the strain started to exhibit linear behavior at a relatively early stage from the moment of load application, and the difference in strain between the inside and outside the test specimen decreased as well. When this gap was 0.1 mm (Fig. 7(b)), both regions of the test specimen exhibited tensile strain under the maximum load.

Hence, it can be concluded that by reducing the gap between the inner side of the test specimen and the outer side of the fixture, the magnitude of bending behavior can be minimized. Furthermore, after the load was applied under the described conditions, tensile strain was generated both inside and outside the specimen, which was consistent with the linear region on the corresponding plot.

Fig. 8(a) shows the dependence of the strains measured inside and outside the test specimen on the distance between the upper and lower fixtures when there is no gap between the specimen and the fixture. At larger distances between the fixtures, bending stress was generated in the gauge section while the strains measured inside and outside the specimen exhibited significant differences (Fig. 8(b)). In contrast, when the distance between the upper and lower fixtures decreased, the difference in strain decreased as well.

### 3.3. Results of hoop tensile testing

From the results of structural FE analysis, it was found that the

<table>
<thead>
<tr>
<th>Inner diameter of the test specimen (mm)</th>
<th>Initial test</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter of the fixture (mm)</td>
<td>110</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Distance between the fixtures (mm)</td>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
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Table 1

Experimental conditions used during the initial test as well as case I and case II studies.
difference between the strains inside and outside the specimen decreased when the gap between the specimen and the fixture as well as the distance between the fixtures were small because the bending behavior under tensile load was minimized. Using these parameters, two separate studies were conducted with six test specimens respectively (see Table 1). As shown in Fig. 9, it was estimated that the bending stress occurring to the test specimen can be minimized by reducing the distance C.

Fig. 10 shows the differences between the inside and outside strains measured in experimental case I and II. The obtained results excluding the specimens failed at loads below 1500 N show that the average difference between the inside and outside strains of the test specimens at the loading point of 1500 N was reduced to 0.32%ε in case I and 0.27%ε in case II, as compared to the average strain difference of 0.55%ε observed during the initial tests. In contrast to the results of the initial test (Fig. 3(a)), the strain exhibited a linear dependence on the applied load during the initial testing stage. As a result, it was experimentally confirmed that the change in the fixture configuration affects difference between the inside and outside strains as predicted in the FE analysis results.

Fig. 11 shows the stress–strain curves plotted in cases I and II. The deviations between the data points obtained for different test specimens were caused by such factors as the alignments of the test specimen and fixture observed after the load application as well as the non-uniform thickness of the specimen. It was found that in case I (Fig. 11(a)), the deviations caused by the differences between the test specimens were
in the gauge section was minimized by applying the ASTM standard; however, its occurrence could not be prevented completely, which was the main reason for the observed decrease in the material strength [20]. On the contrary, the modulus of the tubular test specimen in Case II was very close to that of the plate test specimen. Therefore, hoop tensile testing can be generally used for evaluating the tensile modulus of CMC tubes; however, the tensile strength evaluation should be considered to be low due to the bending stress generated in the specimen.

4. Conclusion

In contrast to plate test specimens, tubular test specimens exhibit early damage caused by the generation of bending stress during tensile testing due to the difference between the inside and outside strains. To resolve this issue, the fixture geometry was modified; however, it was not possible to apply the same tensile load to both the inside and outside regions of the test specimen. As a result, the measured tensile strength was lower than that of the plate test specimens by about 26%. In contrast, the moduli of the tubular CMC specimens were close to that of the plate test specimens within the range of about 8%. Therefore, hoop tensile testing can be potentially used for evaluating the tensile properties of tubular CMC materials if it is considered that the strength is evaluated to be lowered by the bending stress.

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References