Development of Joining Method by Cylindrical Pin Using Thermal Expansion of CFRTP

Yuya KODAIRA1, Nobuhiro KOBAYASHI1, Naofumi KODAIRA1, 
Atsuko TAKE1 and Noboru NAKAYAMA2

1Taiyo industry Co., Ltd., Suwa 392-8585, Japan
2Faculty of Engineering, Shinshu University, Nagano 380-8553, Japan

(Received 15 January 2020; received in revised form 30 April 2020; accepted 6 May 2020)

Abstract: This study is focused on the expansion properties of CFRTP plate in thickness direction when it is heated at a temperature near the melting point of matrix resin. The purpose of this study is to investigate the usefulness of homo- and hetero-junctions with pins utilizing these expansion properties. In the study, two steel plates with a straight or tapered hole were heated to an appropriate temperature, and a cylindrical pin made of a laminated CFRTP was inserted into the hole on the plates stacked each other so as to align the positions of each hole. By heating the pin through the heated steel plates so as to generate volumetric expansion force against the wall of each hole, we have developed a new joining method of metal pieces with CFRTP pin. Experiments were performed on the new joining method. Moreover shear strength and tensile strength were evaluated. In this evaluation, it was confirmed that there is a relationship between volumetric expansion of CFRTP by heating and joint strength. It was further found that high joint strength was obtained by application of tapered hole on the steel plates.

Keywords: Dissimilar joining, Structural joining, Thermoplastic, CFRTP, Carbon fiber

1. Introduction

In the field of transportation equipment such as automobiles and aircrafts, there is a movement to reduce fuel consumption and environmental impact by weight reduction through adoption of new materials [1, 2] and new structures [3-5]. With regard to joint of structural members for transportation equipment, new joining methods with sufficient joint strength but without weight increase have been studied [6,7], because conventional methods using bolts and rivets bring weight increase while they have high joint strength. Bonding using an adhesive is free of weight increase, but it has problems such as dispersion in quality and much time to cure [8-11]. Welding is another joining method, but it also has problems such as requiring welding machine and for some metal elements high pressure and high current, as well as difficult removal after welding [12-14]. Therefore, a joining method using a lightweight, removable carbon fiber reinforced with a thermoplastic material (CFRTP) has been developed [15]. This is focused on volumetric expansion properties of CFRTP in the thickness direction when it is heated at a temperature near the melting point of the matrix resin. In the method, a CFRTP plate is inserted into a groove on a heated A5052 specimen, and the heat is transmitted to the CFRTP plate to volumetrically expand and melt surface layer. Both of the expansion and the melting contribute to strong joint strength.

This study is focused on volumetric expansion properties of CFRTP plate in the thickness direction when it is heated at a temperature near the melting point of the matrix resin. The purpose of this study is to examine the usefulness of homo- and hetero-junctions with pins utilizing these expansion properties. Volumetric expansion properties of CFRTP pin on heating have also been evaluated.

2. Experimental Method

2.1 Materials

A 5.5 mm thick stampable sheet made of 25-layered 3K plain weave carbon fiber impregnated with PA 6 as matrix resin (CFRTP, made by Ichimura Sango Co., Ltd.) was used for the material of pins. Cylindrical pins having outer diameter of 5.3 mm and length of 6.0 mm were cut out of the sheet in parallel with the lamination direction, as shown in Fig. 1.

Rolled steel for general structural applications (SS400) was used as the material for joint, and possibility of joint was first confirmed. Using this material, steel plates were prepared for (a) tensile shear test and (b) cross tension test, as shown in Fig. 2. All steel plates were 3 mm thick, but some of them had a straight hole of φ5.35mm and others had a tapered hole extending from φ5.35mm. The tapered hole was intended to increase the tensile stress when the CFRTP pin expands within the hole on each steel plate. The angle of the taper was set to 3 °, and the steel plates were joined so as to face the surfaces with thinner hole each other, so that the surfaces with thicker hole were outward each other, when they were joined. On the surface of each steel plate for (b) cross tension test, two φ20mm holes were further drilled to attach to a test jig. The number of specimens for each test was 5.
In the joining, the steel plates for the tensile shear test were stacked in parallel but in opposite direction each other, but the steel plates for the cross tension test were stacked orthogonally each other. The portions of the pin protruded over the surfaces of the steel plates were removed with a grinder. Figure 4 shows a typical example of joined specimen with a straight hole for each of (a) tensile shear test and (b) cross tension test.

![Image](image.png)

Fig. 4 Image of specimen of straight hole

### 2.3 Tensile shear test method

The test was conducted in accordance with JIS Z3136. Table 1 shows the test apparatus and the condition.

<table>
<thead>
<tr>
<th>Apparatus</th>
<th>AG-50KNDX by Shimadzu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosshead speed</td>
<td>1mm/min</td>
</tr>
</tbody>
</table>

Figure 5 shows the detail of holes drilled on the steel plates ((b): straight, (c): tapered) as well as the schematic diagram of the tensile shear test (a). A support plate of $3.0 \times 70 \times 50$ mm$^3$ was bonded on each end of each specimen with an epoxy adhesive.

![Image](image.png)

Fig. 5 Detail of holes on steel plate and schematic diagram of tensile shear test
A load cell was used to measure the load in the tensile shear direction $F_t$, and the mean shear stress defined as the shear strength $\tau$ was calculated from the measured maximum load $F_{t\text{max}}$ using Eq. (1):

$$\tau = \frac{4F_{t\text{max}}}{\pi d^2}$$

(1)

Where $d$ is the diameter of the CFRTP pin.

2.4 Cross tension test method

The test was conducted in accordance with JIS Z3137. The test conditions shown in Table 1 were as well as in Section 2-3. Figure 6 shows a schematic diagram of the cross tension test.

In the test, a specimen made of two steel plates joined orthogonally was fixed on the upper and lower jigs with bolts, and a static tensile load was applied in the vertical direction so as to peel off two plates. A load cell was used to measure the load in the tensile axis direction $F_t$, and the mean tensile stress defined as the tensile strength $\sigma$ was calculated from the measured maximum load $F_{t\text{max}}$ using Eq. (2):

$$\sigma = \frac{4F_{t\text{max}}}{\pi d^2}$$

(2)

3. Experimental Results

3.1 Tensile shear test

The results of the tensile shear test for specimens with straight hole (a) and tapered hole (b) are shown in Fig. 7. The horizontal axis is the stroke of crosshead on the tester, and the vertical axis is the load $F_t$ measured with the load cell. It was identified that when both plates were pulled horizontally, the pin was finally taken off from the hole on either plate, through gradual deformation. Figure 7 shows the relationship between tensile load and crosshead stroke, and it is found on each of (a) straight hole and (b) tapered hole that each curve shows gradual increase and decrease without sharp changes except in the beginning and at the end. It is thought that slight gap between the pin and the hole and deformation of voids in the pin is the reason why the load doesn’t change quickly in the stroke range between 0 and 0.5 mm. For the reason why the load decreases rapidly from about 100 N to 0 N at the end of each curve, it is considered that the CFRTP pin took off the hole.

Figure 8 shows the values of the shear strength calculated from the maximum load $F_{t\text{max}}$ measured in the test using Eq. (1), together with the values of the shear strength for the lap joint of SS400 with epoxy adhesives A and B [16]. Each error bar shows the data range of the measured shear strength values. It is identified that the shear strength for the specimen with tapered hole is about 30% (11MPa) higher than that for the specimen with straight hole.

---

Y. KODAIRA, N. KOYASHI, N. KODAIRA, A. TAKEI and N. NAKAYAMA
3.2 Cross tension test

Figure 9 shows the results of the cross tension test (relationship between tensile load and crosshead stroke); (a) for straight hole and (b) for tapered hole. The horizontal axis denotes the stroke of crosshead of the tester, and the vertical axis denotes the load 

\[ F_c \]

measured from the load cell. It was identified that when both plates were pulled horizontally, the pin was finally taken off from the hole on the wall of the holes through volumetric expansion. As well as in the tensile shear test, slight gap between the pin and the hole and deformation of the voids in the pin may be the reason why the load doesn’t change quickly in the stroke range between 0 and 0.5 mm. On each curve, the load gradually decreases in the final stage. They are presumed to be the effect of frictional force between the pin and the walls of the holes after adhesion of the pin is lost. For the specimens with tapered hole, higher values of load between 300 and 550 N were obtained. They are presumed to be due to anchor effect in addition to the effect of pin adhesion. To separate two steel plates after pin adhesion is lost, the pin solidified along with the tapered shape of the holes is considered to further deform so as to pass through the thinnest part of the holes. It is thought that the deforming force becomes resistance in the tensile direction, so that load values for 4 specimens rise again.

![Load vs. Stroke](image)

**Fig. 9 Relationship between tensile load and crosshead stroke**

Figure 10 shows the tensile strength \( \sigma \) calculated from the maximum load \( F_{t_{\text{max}}} \) measured in the test using Eq. (2). Each error bar shows the data range of the measured tensile strength values. It is identified that the tensile strength for the specimen with tapered hole is about 2.6 times (13MPa) as much as one for the specimen with straight hole.

![Tensile strength comparison](image)

**Fig. 10 Comparison of tensile strength values**

4. Discussion

In the observation during the tensile shear test, steel plates gradually moved in opposite directions each other when load is applied. CFRTP pin begins to deform then, and finally takes off either hole. Figure 11 shows micrographs of CFRTP pins after the test; (a) a pin applied to straight holes and (b) a pin applied to tapered holes. It is identified that each pin is deformed compared to the original shape before the test. The pin applied to the tapered holes is deformed significantly. It is presumed that the CFRTP pin deformed due to the force in the shear direction so as to reduce joint area between the pin and the holes. It is then considered that the deduction of the joint area decreased joining force to take the pin off from the holes. On the specimen with tapered hole, it is considered that the CFRTP pin expanded along with the tapered shape continues to deform until it passes through the thinnest part of the holes. Therefore the degree of deformation on this pin is presumed to be higher than that for the pin on the specimen with straight hole.

![Micrographs of CFRTP pins](image)

**Fig. 11 Image of CFRTP pin after tensile shear test**

From Figs. 7 and 9, it was found that the values of tensile load for the specimens with tapered hole were higher than the values for the specimens with straight hole both in the tensile shear test and the cross tension test. The reason is thought that the pin (carbon fiber and matrix resin) expanded due to the heat transferred from the heated steel plates, and solidified along with the tapered shape, so that the resistance load to take off the holes was higher. To verify it, joined specimens were cut in the center to observe the cross-section with a microscope (VHX-6000, by...
Figure 12 shows cross section micrographs of the specimens ((a): straight hole, (b): tapered hole). On each micrograph, voids and delamination are seen between carbon fiber layers. The sections enclosed with white frame are presumed to be voids generated during expansion.

(a) Straight hole

(b) Tapered hole

Fig. 12 Cross section micrographs of joined specimen

Much more and bigger voids are identified on the specimen with tapered hole (b) than on the specimen with straight hole (a). Voids are dispersed in the tapered hole in (b). It is presumed that the voids generated in the tapered gap moved when the pin extended in the axial direction. In the specimen with tapered hole, the pin (carbon fiber and matrix resin) expanded to fill the gap with the wall of the hole. It is thought that the resultant tapered shape of the CFRTP pin, produced through volumetric expansion and solidification, became the resistance to forces in the shear direction or the tensile direction. It is so-called anchor effect.

Then, thermal expansion of single CFRTP pin was investigated. A CFRTP pin was heated in an electric furnace and the values of outer diameter in two directions were measured before and after the heating (φ $d_p$: diameter parallel to carbon fiber layers, φ $d_v$: diameter perpendicular to the layer, Figure 13). Increasing rates $\alpha_d$ for the outer diameter were obtained from Eq. (3). In the increase rates, the rate in the direction parallel to the carbon fiber layers is determined as $\alpha_d$, and the rate in the direction perpendicular to the layers is determined as $\alpha_d$. $d_{ph}$ denotes the outer diameter parallel to carbon fiber layers before the heating and $d_{ph}$ after the heating. On the other hand, $d_{vh}$ denotes the outer diameter perpendicular to carbon fiber layers before the heating and $d_{vh}$ after the heating.

$$\alpha_d = \frac{d_{ph} - d_{vh}}{d_{ph}}, \quad \alpha_d = \frac{d_{ph} - d_{ph}}{d_{vh}}$$  \hspace{1cm} (3)

The heating temperature was set to 523 K which is in the middle between 498 K as the melting point and 573 K as the thermal decomposition temperature of PA6 (matrix resin of the CFRTP) [15]. The heating time was set to 2 min so as to avoid fraying of carbon fibers, considering the results of preliminary experiments. Five pieces of the CFRTP pin were used to the investigation. Figure 14 shows the results.

![Fig. 13 Diameter measurement direction](image)

**Fig. 13 Diameter measurement direction**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$d_p$ (mm)</th>
<th>$d_v$ (mm)</th>
<th>Increase rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample1</td>
<td>1.0%</td>
<td>17.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Sample2</td>
<td>11.8%</td>
<td>1.4%</td>
<td>10.8%</td>
</tr>
<tr>
<td>Sample3</td>
<td>1.3%</td>
<td>12.4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Sample4</td>
<td>1.3%</td>
<td>13.0%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Sample5</td>
<td>1.3%</td>
<td>13.0%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

**Fig. 14 Outer diameters of CFRTP pin before and after heating**

On every pin, expansion was large in the direction perpendicular to carbon fiber layers, and the values of the increasing rate in the direction ($\alpha_d$) were 10 to 13%. On the other hand, expansion of the pins in the direction parallel to carbon fiber layers ($\alpha_d$) was as small as about 1%. Carbon fibers generated under a high pressure condition expand in the direction perpendicular to the fiber layers and voids are generated between the layers through melting of the matrix resin, when a CFRTP pin is heated. Therefore, it is considered that the values of the increasing rate in the direction perpendicular to carbon fiber layers ($\alpha_d$) became large. The average increasing rate calculated from all data is 7.11%, which is enough to fill the gap with hole wall and the volume increase in the tapered portion as much as 3.9% (Figure 15).

![Fig. 15 CFRTP pin and tapered holes on steel plates](image)

**Fig. 15 CFRTP pin and tapered holes on steel plates**
CFRTP stampable sheet is formed by heating and compressing carbon fiber sheets and resin, and further cooling to solidify. Heating it again melts the resin and releases stress within the carbon fibers, so that the sheet expands in the thickness direction (parallel to the carbon fiber layers) [15]. Small compressive stress is left within the pin once expanded in the direction perpendicular to the carbon fiber layers even after cooled down, but it is much smaller than the joining strength with the steel plates through melting. It is supported by the results that the values of tensile load in the cross-tension test drop rapidly after the peak, as shown in Fig. 9.

5. Conclusion
The purpose of this study is to examine the usefulness of the bonding using a pin utilizes the expansion properties of CFRTP. Volumetric expansion properties of CFRTP pin during heating have been evaluated. The results are as follows:

1. The jointed specimens with tapered hole had higher values of tensile load both in the tensile shear test and the cross tension test than the specimens with straight hole.
2. The pin inserted into the specimen with tapered hole expands and fills the gaps with tapered wall of hole on steel plates in the heating joint process, and solidifies as it is. Then the specimens with tapered hole had higher values of tensile load in both tests than the specimens with straight hole.
3. In the tensile shear test, it was found that the CFRTP pin takes off the hole on either steel plate to separate the plates before they are sheared.
4. Single CFRTP pin expands its outer diameter by 10 to 13% in the direction perpendicular to carbon fiber layers when it is heated.

Examining the above results, it was found that steel plate joint with higher joining strength is obtained by this method inserting CFRTP pin into holes on stacked and heated plates. Steel plates with tapered hole improve joint strength against the plates with straight hole due to the anchor effect of the pin by volumetric expansion and pressurization. Tensile shear stress of this joint is nearly double as high as that of joint with an epoxy adhesive. Therefore, it has been identified that heating joint with CFRTP pin is useful as a homo- and hetero-junction technology.

References