Visualization of flowing current in braided carbon fiber reinforced plastics using SQUID gradiometer for nondestructive evaluation

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Abstract. In this paper, visualization of flowing current in various braided carbon fiber reinforced plastics (CFRPs) was demonstrated using high-temperature superconductor (HTS) superconducting quantum interference device (SQUID) gradiometer, in order to study electrical properties and integrity of the braided CFRP samples. Step-by-step tensile loading was also applied to the samples, in order to study their mechanical properties and destructive mechanism. Experimental results indicated that the addition of carbon nano fibers and middle-end carbon fiber bundles attributed to modify not only the mechanical properties, but also the electrical properties of the samples. Combining the results by the both methods, a scenario of the destructive mechanism of one sample was estimated.

1. Introduction

Recently, braided carbon fiber reinforced plastics (CFRPs), in which carbon fiber bundles are interlaced in a braided textile (see Figure 1(a)), have been developed and studied to achieve superior properties compared to conventional woven CFRPs, because of the continuity of the carbon fiber bundles [1 - 3]. Furthermore, it is expected that the addition of carbon nanofillers in the matrix of the braided CFRPs (Figure 1(b)) and insertion of middle-end carbon fiber bundles in the braided textile (Figure 1(c)) would improve some braided CFRP’s properties [4, 5]. However, nondestructive evaluation (NDE) technique for the braided CFRPs is yet established, because the fine diameter of the carbon fibers and the complexity of the braided textile require a novel NDE technique having high sensitivity and spatial resolution. Since tensile loading applied to the braided CFRPs is mainly maintained by the continuous carbon-fiber bundles, it is important for the NDE technique to detect breakages of the carbon fiber bundles, whose electric conductivity can change significantly when they are broken. Thus, we have proposed a NDE technique using a high-temperature superconductor (HTS) superconducting quantum interference device (SQUID) gradiometer having extremely high sensitivity to electric current, which generates magnetic field, and sufficiently high spatial resolution for the
braided CFRPs [6]. So far, we demonstrated that the discontinuity of the braided carbon-fiber bundles in tubular-braided CFRPs could be well detected using the SQUID-NDE technique by visualizing electric current distribution in the CFRP samples while injecting ac currents into the samples.

In this study, we prepared various braided CFRP samples based on flat-braided CFRP panels. The samples included carbon nanofibers (CNFs) or the middle-end carbon fiber bundles. The mechanical properties and destructive mechanism of the samples were studied with observation and measurements of stress-strain curves, while applying step-by-step tensile loading to the samples. The SQUID-NDE technique to visualize flowing currents in the samples was tested for evaluating the integrity of the carbon fiber bundles in the samples, before, during, and after the tensile loading.

![Figure 1](image1.png)

**Figure 1.** (a) Braided textile with continuous carbon fiber bundles in flat-braided CFRPs. In actual samples, neighboring bundles are touching with each other. (b) Dispersion of carbon nanofillers in matrix and carbon fibers. (c) Inserted middle-end bundles in braided textile.

### 2. Braided CFRP samples and step-by-step tensile tests

#### 2.1 Samples

For this study, ±45° flat-braided CFRP panels with and without CNFs were fabricated. These panels contain 25 carbon-fiber bundles (HTS40, Toho Tenax) braided together at angles of ±45° into flat textiles, and epoxy resin (JER828, Japan Epoxy Resins Co. Ltd.). Each carbon-fiber bundle was composed of 12000 carbon fibers with the average diameter and specific electrical resistivity of 7 μm and $1.6 \times 10^{-3} \, \Omega \cdot cm$. The average tensile strength, tensile modulus, and elongation of the bundles were 4200 MPa, 240 GPa, and 1.8 %, respectively. Vapor grown CNFs (VGCF, Showa Denko K.K.) were dispersed throughout one panel, which was labeled as 45HTS-NF. The average diameter, length, and specific resistivity of the CNFs were about 150 nm, 10 μm, and $10^{-4} \, \Omega \cdot cm$, respectively. The dimensions of the sample 45HTS-NF were 151 mm × 41 mm × 1.0 mm. From observation of a sample of the same kind as 45HTS-NF, using scanning electron microscopy, it was demonstrated that the CNFs were distributed not only in the epoxy resin matrix, but also in between the carbon-fiber bundles as schematically shown in Figure 1b [5]. For comparison, the CFRP panel without the CNFs was prepared and labeled as 45HTS. The dimensions of 45HTS were almost same as 45HTS-NF.

Three ±25° flat-braided CFRP panels, with different middle-end carbon fiber bundles were also fabricated. These CFRP panels contained 25 carbon fiber bundles (UTS50, Toho Tenax) braided at
angles of ±25° into flat textiles, and the same epoxy resin as 45HTS. The carbon-fiber bundle UTS50 was composed of 12000 carbon fibers with the average diameter and specific electrical resistivity of 6.9 µm and 1.6 × 10⁻³ Ω·cm. The tensile strength, tensile modulus, and elongation of the bundles were 4900 MPa, 240 GPa, and 2%, respectively. In these panels, three different middle-end carbon fiber bundles were inserted: ten UTS50 bundles, ten XN05 (Nippon Graphite Fiber Corp.) bundles, and ten XN60 (Nippon Graphite Fiber Corp.) bundles, respectively. The parameters of the used carbon fiber bundles were summarized in Table 1. These three panels were labeled as 25UT-UT50, 25UT-XN05, and 25UT-XN60, respectively. We note that the electric resistivity of XN05 is highest (2.8 × 10⁻³ Ω·cm), while that of XN60 is lowest (0.7 × 10⁻³ Ω·cm). The dimensions of the samples 25UT-UT50, 25UT-XN05, and 25UT-XN60, were 250 mm × 28 mm × 1.5-1.7 mm.

### Table 1. Parameters of carbon fiber bundles used for flat-braided textiles (HTS40 and UTS50) and middle-end bundles (UTS50, XN05, and XN60).

| Grade | Filament count | Tensile strength [MPa] | Tensile modulus [GPa] | Elongation [%] | Filament diameter [µm] | Electrical resistivity [Ω·cm] |
|-------|----------------|------------------------|-----------------------|----------------|------------------------|-----------------------------|
| HTS40 | 12000          | 4200                   | 240                   | 1.8            | 7                      | 1.6 × 10⁻³                  |
| UTS50 | 12000          | 4900                   | 240                   | 2              | 6.9                    | 1.6 × 10⁻³                  |
| XN05  | 6000           | 1100                   | 54                    | 2              | 10                     | 2.8 × 10⁻³                  |
| XN60  | 6000           | 3430                   | 620                   | 0.6            | 10                     | 0.7 × 10⁻³                  |

#### 2.2 Step-by-step tensile tests

The CFRP samples were tested by step-by-step tensile loading to clarify their mechanical properties and destructive mechanisms. Tensile loading was applied to each sample in the longitudinal direction at a crosshead speed of 1 mm/min., while one surface of each sample was monitored and the stress-strain curve was measured using strain gauges. The surfaces of the samples were painted at times with white watercolor to observe surface defects. Once the initial tensile loading was applied to each sample, the loading was increased gradually. When an obvious decrease in mechanical strength was occurred, or when any defect was identified, the loading was stopped, and then released to apply below-described SQUID-NDE technique to the sample, in order to evaluate the integrity of their carbon-fiber bundles and electrical properties. We note that the stress-strain curves of the most samples did not return to the starting point after release of the loading. Therefore, after the application of the SQUID-NDE technique, we applied loading to the samples again until the measured strain reached to the maximum value at the previous loading, and thereafter, incremental quantities of strain and stress were measured, and then added to the initial stress-strain curves, for simplicity of plotting. By this process, a continuous stress-strain curve was obtained for each sample.

Figure 2 shows the stress-strain curves of the samples 45HTS-NF and 45HTS, with photographs of sample surfaces at certain damage stages. In the case of 45HTS-NF, the stress increased nonlinearly with increasing strain from the virgin stage, indicated by “a”. When the stress and strain reached 340 MPa and 0.055, cracks occurred on the right side of the sample (indicated by the dotted oval), although no corresponding decrease in stress was measured (“b”). This means that the cracks were only matrix cracks on the matrix-rich side, and not accompanied by carbon-fiber fracture or delamination. Just before the strain reached about 0.06, the final fracture suddenly occurred at the maximum measured stress of 350 MPa (“c”).

In the case of 45HTS, the stress also increased nonlinearly with the strain, similarly to 45HTS-NF, from the virgin stage (“d”). When the strain reached 0.056, at the maximum stress of 275 MPa, the stress dropped with the occurrence of a crack in the right-lower area with an angle of about 30° (“e”). After this first drop in stress, slight increases and drops repeated with propagation of new zigzag cracks along the first crack. This repeated increase and drop indicated that delamination between the
carbon-fiber bundles and relocation of the bundles, occurred in turn. The final fracture occurred with 
the carbon-fiber fracture when the strain reached over 0.072 (“f”). The results demonstrated that the 
addition of CNFs could give greater mechanical tensile strength to the braided CFRP, although the 
measured maximum strain was smaller than that of the braided CFRP without CNFs.

Figure 2. Stress-strain curves of samples 45HTS-NF and 45HTS. Photographs of the samples at 
certain damage stages are shown together. Some cracks are indicated with dotted ovals. 
Photographs at “a” and “d” were taken before they were painted by white watercolor.

Figure 3 shows the stress-strain curves of the samples 25UT-UT50, 25UT-XN05, and 25UT-XN60, 
with photographs of sample surfaces at certain damage stages. In the case of 25UT-UT50, the stress 
increased linearly with the strain, with the initial tensile modulus of about 59 GPa. When the stress 
and strain reached 1055 MPa and 0.0178, the final fracture suddenly occurred near the center of the 
sample (“o”). We note that any cracks did not occur until the final fracture. It was interesting that 
slanting zigzag cracks at an angle of about 45° was observed on the lower part of the sample. These 
cracks were thought to be caused by reaction of the final fracture. Vertical zigzag cracks were 
observed along some middle-end bundles.

In the case of 25UT-XN05, the stress increased almost linearly with the strain, with the initial 
tensile modulus of about 58 GPa, similarly to 25UT-UT50. When the stress and strain reached 700 
MPa and 0.012, small horizontal cracks occurred (“l”). After the occurrence of the cracks, the tensile 
modulus slightly decreased, and when the stress and strain reached 800 MPa and 0.0145, the final 
fracture occurred in the upper part, concomitantly with occurrence of slanting zigzag cracks at an 
angle of about 45° in the bottom part, similarly to 25UT-UT50 (“m”). However, vertical zigzag cracks, 
which occurred in 25UT-UT50, were not observed.

In the case of 25UT-XN60, the stress increased linearly with the strain, with the higher initial 
tensile modulus of about 104 GPa, than those of 25UT-UT50 and 25UT-XN05. When the stress and strain reached 255 MPa and 0.0025, small horizontal cracks occurred (“h”). After the occurrence of 
the cracks, the tensile modulus slightly decreased. Occurrence of new cracks and slight decrease in the 
modulus repeated a few times such as indicated by “i”, and when the stress and strain reached 550 
MPa and 0.009, the final fracture occurred in the center part of the sample (“j”). Slanting zigzag cracks 
at an angle of about 25° occurred in both the top and bottom parts. Vertical zigzag cracks, which
occurred in 25UT-UT50, were not observed, but peeling-off of the watercolor paint was observed in relatively wide parts on 25UT-XN60.

From those results, it was shown that 25UT-UT50, in which the same carbon fiber bundles were used in the textile and middle-end bundle, had the greatest destructive strength and strain among the samples. 25UT-XN05, in which XN05 with much smaller tensile modulus and the same elongation was used as the middle-end bundles, had the same initial tensile modulus, although the destructive strength and strain were smaller than those of 25UT-UT50. This should be because of the 4 times smaller tensile strength of the XN05 than that of UTS50. 25UT-XN60, in which XN60 with higher tensile modulus and smaller elongation was used as the middle-end bundles, had the highest initial tensile modulus among the samples. The destructive strength and strain of 25UT-XN60 were smallest probably because of the smallest elongation of XN60.

3. Visualization of flowing current using HTS-SQUID gradiometer

3.1 Visualization method
At the certain damage stages before, during, and after the tensile loading, ex-situ SQUID-NDE technique was applied to the samples, using a HTS-SQUID gradiometer with current injection. A planar first-order HTS-SQUID gradiometer, with small differential pickup coil and a small baseline, functions as a current detector with high spatial resolution when a liftoff between the gradiometer and a conductive panel sample is short enough such that the liftoff is comparable to the baseline, as described elsewhere [7]. In this study, we put electrical terminals on both ends of each sample to induce an ac current in the longitudinal direction, while applying an ac voltage across each sample. In such case, distribution of the resultant flowing current in the sample depended on distribution of
electrical resistivity in the sample. The distribution of the electrical resistivity was determined by the geometry of the braided textile, and contacting resistivity between the bundles in the braided CFRPs. The CNFs existing in between the bundles, and the middle-end carbon-fiber bundles interlaced in the braided textile would also attribute to the current distribution. When such a sample, in which an ac current is being induced, is set on the \(x-y\) plane, the induced current densities \(J_x\) and \(J_y\) in the sample have similar distributions as the magnetic field gradients \(dB_z/dy\) and \(-dB_z/dx\) in an \(x-y\) plane near the sample. These relationships \(\mu_0 J_x \approx dB_z/dy\), and \(\mu_0 J_y \approx -dB_z/dx\), between the currents and the field gradients, can be derived from the Maxwell’s equation, \(\nabla \times \mathbf{H} = \mathbf{J}\) \[7\].

Based on this principle, we employed a SQUID-NDE system using a small HTS-SQUID gradiometer and an automated \(xy\)-stage, whose details were described elsewhere \[6\]. Schematic diagram of the NDE system is shown in Figure 4. An HTS-SQUID gradiometer with a differential pickup coil, composed of two square coils with size of 1 mm x 1 mm, was used. DC bias current of about 170 \(\mu A\) was applied to the SQUID to drive the gradiometer. We set each sample on the \(xy\)-stage, and induced an ac current of 7 mA at 800 Hz in the longitudinal directions in the cases of 45HTS-NF and 45HTS. In the cases of 25UT-UT50, 25UT-XN05, and 25UT-XN60, the induced currents were 2.6 mA, 4.2 mA, and 10.8 mA at 800 Hz, respectively, which depended on the electrical resistivity of each sample. The distributions of the field gradients \(dB_z/dy\) and \(dB_z/dx\) above each sample were scanned with a liftoff of 2–3 mm, while changing the direction of the gradiometer to measure \(dB_z/dy\) at first, and then \(dB_z/dx\) next. The scanning intervals in the \(x\) and \(y\) directions were 1 mm. The measured area above the samples was the area shown in the photographs in Figures 2 and 3. We converted the field gradient distributions of \(dB_z/dy\) and \(-dB_z/dx\) into the distributions of current components \(J_x\) and \(J_y\) based on the field gradient to current conversion scheme \[7\]. In this paper, the units of the converted current distributions were shown with those of the measured field gradients \(dB_z/dy\) and \(-dB_z/dx\).

![Figure 4. Schematic diagram of NDE system using HTS-SQUID gradiometer.](image-url)

3.2 Measurement results of 45HTS-NF and 45HTS

Figures 5 and 6 show the measurement results of the converted \(J_x\) and \(J_y\) distributions in 45HTS-NF and 45HTS. The left-upper and left-lower current maps in Figure 5 show the \(J_x\) and \(J_y\) distributions at the virgin stage “a” with a liftoff of 2 mm. In the current map of \(J_x\), two peaks were measured along both sides, whereas the current was weaker in the middle area of the sample. Conversely, a stripe pattern along the braided bundles was clearly visible in the current map of \(J_y\). The same stripe pattern can be hardly seen in the \(J_x\) map because the peaks along the sides were dominant. From the stripe patterns, it could be seen that the currents flowed mainly along the ±45° bundles continuously. The patterns of the same kind were also observed in the case of 45HTS at the virgin stage “d”, as shown in Figure 6. However, the peak along the edges observed in 45HTS was weaker and narrower, and the
stripe pattern was less uniform than those of 45HTS-NF. It is inferred that these differences were attributed to the addition of CNFs in 45HTS-NF, because it is thought that CNFs in between the bundles should decrease the contacting electrical resistivity between the bundles, thereby averaging (or smoothing) the current density among the bundles and increasing the $J_x$ component, which should flow in the $x$ direction through neighboring bundles owning to the assistance of the CNFs [4]. The current distributions shown in the middle-upper and middle-lower maps of Figure 5 (at “b”) did not quite differ from those at “a”, with the exception of less spatial resolution owning to the longer liftoff of 3 mm. In the tensile test, 45HTS-NF broke suddenly, and most of the bundles were fractured. This damage mechanism was quite different from that of 45HTS and was likely due to the presence of the CNFs, which increased the maximum stress of the sample, as shown in Figure 2. Because of the CNFs, not only the strength of the matrix, but also the strength of the mechanical connection between the bundles should be increased. Thus, delamination between the bundles and relocation of the bundles, which occurred in 45HTS, did not occur in 45HTS-NF. This led to the firm transmission of stress between neighboring bundles fixed with the strengthened matrix, resulting in the sudden final fracture. At the final stage “c”, only several bundles were not broken in 45HTS-NF, as shown in the right-upper and right-lower maps of Figure 5, because several strong current appeared.

In the case of 45HTS, it appears that the first crack did not cause a clear change in the current distribution, as shown in the middle-upper and middle-lower maps of Figure 6 (“e”). As mentioned, it was estimated that the crack, which caused the drop in stress, should cause the delamination and relocation of the bundles. However, because the mechanical and electrical connections between the neighbouring bundles in 45HTS should be weaker than those of 45HTS-NF, the delamination and relocation did not seriously affect to the current distribution. After the final fracture, it was estimated that most bundles in the right-side area of the first crack line, which is indicated by the dotted line in Figure 6, were broken, whereas those in the left-side area of the line were almost not damaged, from observation of the current distribution. We note that there was a low current density area on the first crack line even at the virgin stage “d”, which is indicated by the dotted line. This may indicate a possibility to predict the location of the final fracture by this NDE technique.

![Figure 5](image1.png) ![Figure 6](image2.png)

**Figure 5.** Measured $J_x$ (upper) and $J_y$ (lower) maps of 45HTS-NF at damage stages “a”, “b”, and “c”.

**Figure 6.** Measured $J_x$ (upper) and $J_y$ (lower) maps of 45HTS at damage stages “d”, “e”, and “f”. 
3.3 Measurement results of 25UT-UT50, 25UT-XN05, and 25UT-XN60

Figure 7 shows the measurement results of the converted \(J_x\) and \(J_y\) distributions in 25UT-UT50 at “n” and “o” in Figure 3, 25UT-XN05 at “k” to “m”, and 25UT-XN60 at “g” to “j”, respectively. The scales of the current maps in Figure 7 were normalized according to the currents induced in the respective samples. In the case of \(J_x\) distributions, white region means large current toward the \(+x\) direction. Black regions above both the samples’ edges in the figures are the edge effects [7]. In the case of \(J_y\) distributions, white region means current toward the \(+y\) direction, while black region means current toward the \(-y\) direction. At the respective virgin stages (“g”, “k”, and “n”), the current distributions were quite different. In the case of 25UT-XN60 with the middle-end bundles of the lowest resistivity, the current in the \(x\) direction was dominant compared to the other results, while the current in the \(\pm y\) directions, which appeared along the braided textile, was weakest relative to the other results. These indicate that the induced current flowed mainly in the middle-end bundles XN60, and partially in the braided textile made of UTS50. In the rest of the samples, the current in the \(x\) direction in 25UT-UT50 was more dominant relative to that in 25UT-XN05. These results well agreed with the fact that the resistivity of UTS50 was lower than that of XN05. From the results shown in Figure 7, it was shown that the observed cracks before the final fractures, which occurred in 25UT-XN60 at “h” and “i”, and in 25UT-XN05 at “l”, caused the reduction of the samples’ tensile modules, but did not change the current distributions significantly. It indicates that the surface cracks occurred in 25UT-XN05 and 25UT-XN60 were likely due to rupture of small number of the middle-end bundles in the respective samples, and/or debonding between the middle-end bundles and the braided textile. It is thought that the energy of the rupture or the debonding was transmitted to the surface, resulting in the observed surface cracks.

We further investigated the samples after their final fractures to elucidate the destructive mechanisms of the samples. We cut out the samples such that cut-out parts did not have visible damage, to study the inside of the broken samples. Only in the case of 25UT-XN60, the cut-out sample had a visible damage, which occurred at the final fracture. The measured areas are shown on the photographs in Figure 3 by dotted lines. The field gradient distributions above the cut-out parts were measured by the same visualization method, and they were converted into the current distributions. The measurement results are also shown in Figure 7. In the most results, the current distributions in the cut-out parts look similar to those in the samples before the final fractures, especially concerning the flowing current in the braided textile as seen in the \(J_y\) distributions. In the case of 25UT-TU50 at “o”, the edge effects are clearly seen in the both ends of the cut-out sample because the sample was short. Concerning the flowing currents in the middle-end bundles, the \(J_x\) current distributions in 25UT-UT50 and 25UT-XN60 “j” have some areas with lower current density, which are indicated by dotted circles. Especially, in the case of 25UT-XN60 at “j” with less influence of the edge effect, the current decrease along the middle-end bundles are more evident. Figure 8 shows the line scan results of \(J_x\) at “g”, “i” and “j” in Figure 7. The scanned lines are indicated with broken lines in the figure. As shown in Figure 8, the current density around 10 mm in the \(y\)-axis decreased with the propagation of the damage stages. The current density decrease in the area from 16 – 27 mm in the \(y\)-axis after the final fracture must be originated in the visible slant zigzag crack near the bottom.

Considering that the distribution of the current \(J_y\) flowing in the braided textile of 25UT-XN60 changed little between before and after the final fracture, the destructive mechanism of 25UT-XN60 is thought to be following: first, debonding between the braided fabric and the middle-end yarns should occur at the damage stages such as “b”, and “c” in Figure 2, because of the difference in the elongation characteristics between UTS50 and XN60. From the current visualization results, it is indicated that the base textile was not damaged even at the final fracture except for the final fracture part. At the final fracture, not only at the fracture part but also in some parts of the sample, the middle-end bundles broke inside the sample. Taking account of this scenario, it can be said that the debonding between the base textile and the middle-end bundles is the key factor in the destructive mechanism.
Figure 7. Measured $J_x$ (upper) and $J_y$ (lower) maps of 25UT-XN60 at “g” to “j”, 25UT-XN05 at “k” and “m”, and 25UT-UT50 at “n” and “o”.

Figure 8. Line scan results of $J_x$ distribution on 25UT-XN60 at “g”, “i”, and “j” in Figure 7.
4. Conclusions
Destructive test of the step-by-step tensile loading and current visualization method using HTS-SQUID gradiometer were applied to the braided CFRP samples with the CNFs and the different middle-end fibers. The experimental results indicated that the addition of the CNFs and the different middle-end bundles attributed to modify not only the mechanical properties, but also the electrical properties of the samples. Combining the results by the both methods, a scenario of the destructive mechanism of 25UT-XN60 was also estimated. It is expected that the current visualization method using HTS-SQUID gradiometer will be a useful tool to assist for study of destructive mechanism of new advanced composites like braided CFPR. For practical applications, in-situ NDE method without contact to a sample is desirable. We are studying an eddy-current-based NDE method for the composites by improving the SQUID-NDE system.

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