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Nondestructive evaluation of ±45° flat-braided carbon-fiber-reinforced polymers with carbon nanofibers using HTS-SQUID gradiometer

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ABSTRACT

Step-by-step tensile tests were applied to flat-braided carbon-fiber-reinforced polymers with and without added dispersions of carbon nanofibers (CNFs) and with and without sample sides cut off to study their mechanical properties and destructive mechanisms by means of in situ observation and stress–strain measurements. An ex situ nondestructive evaluation technique, using a high-temperature superconductor superconducting quantum interference device gradiometer, was also applied to the samples to study their electrical properties; the relationships between the mechanical and electrical properties by visualizing current maps in the samples during ac current injection was also studied. Clear differences were observed in the mechanical and electrical properties and the destructive mechanisms between the samples with and without CNFs and with and without cut off sides. These differences were mainly attributed to the addition of CNFs, which enhanced the mechanical and electrical connections between the carbon fiber bundles.
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1. Introduction

Carbon-fiber-reinforced polymers (CFRPs) have gathered attention from many commercial industries such as the automobile and aircraft industries for use as a material that can facilitate weight reduction and energy saving. Recently, braided CFRPs, in which carbon fiber bundles are interlaced in a braided textile and are thus continuous in the longitudinal direction, have been studied and developed to achieve superior strength and degrees of freedom in design compared to conventional woven CFRPs [1–5]. Furthermore, the addition of carbon nanofibers (CNFs) in the matrix of braided CFRPs can improve some CFRP properties. The addition of the CNFs can enhance the viscosity of matrix polymers and create mechanical and electrical connections between the fibers and bundles [6,7]. In this study, we prepared flat-braided CFRP samples, in which the bundles were braided with angles of ±45° (see Fig. 1a), with and without CNF addition. For comparison, we also prepared additional ±45° flat braided CFRP samples, with and without CNFs, with side cut off, to imitate conventional cross-woven CFRPs composed of non-continuous fiber bundles (see Fig. 1b). We applied step-by-step tensile loading to the samples to study their mechanical properties and destructive mechanism, with in situ observation and measurement of the stress–strain diagrams. Meanwhile, to study the electrical properties of the braided and imitated cross-woven CFRP samples, and the relationship between their mechanical and electrical properties, we applied an ex situ nondestructive evaluation (NDE) technique. This involved injecting ac current into the samples and visualizing the resulting current distribution, using a small high-temperature superconductor (HTS) superconducting quantum interference device (SQUID) gradiometer with high current sensitivity and spatial resolution [8–11]. Compared to conventional NDE techniques [12], this novel use of a HTS-SQUID gradiometer with ramp-edge Josephson junctions and a small baseline length [13] allowed for superior detection of defects in the braided CFRPs because it can detect small cracks in the carbon fibers, whose electric conductivities can change significantly when they are broken. The SQUID-NDE technique was also used for evaluating the integrity of the carbon fiber bundles in the samples before, during, and after tensile loading.

2. ±45° Flat-braided CFRP samples with and without CNFs and with and without sides cut off

In this study, we fabricated ±45° flat-braided CFRP panels, each containing 25 carbon fiber bundles (HTS40–12 k, Toho Tenax) braided together at angles of ±45° into a flat textile, and epoxy resin

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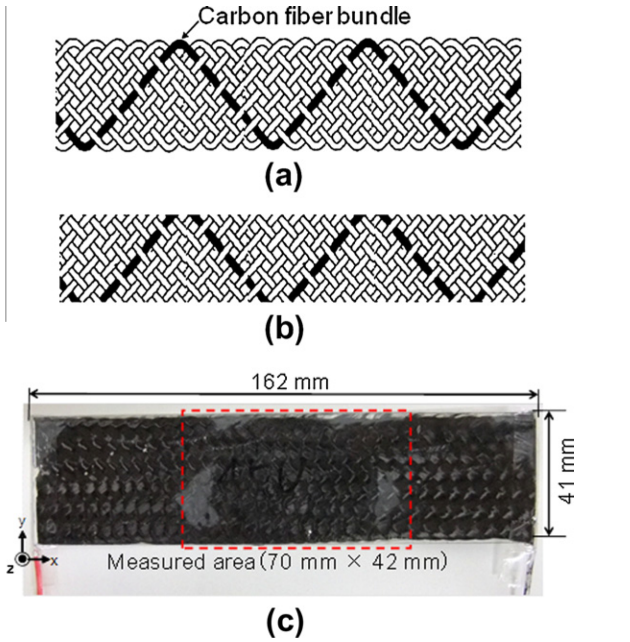

Fig. 1. (a) Schematic illustration of ±45° flat braided textile composed of carbon fiber bundles. (b) Imitated cross-woven textile with cut sides. (c) Photograph of sample A-W. Measured area by SQUID-NDE method is indicated with the dashed line.

(JER828, Japan Epoxy Resins Co., Ltd.). Each fiber bundle was composed of 12,000 carbon fibers. The average diameter and specific resistance of a single carbon fiber were 7 μm and $1.6 \times 10^{-3}\ \Omega$ cm, respectively. The tensile strength of each bundle was 4200 MPa. Vapor grown CNFs (VGCF, Showa Denko K.K.) were dispersed throughout one of the samples, which was labeled as A-W. The dimensions of the sample A-W were 151 mm × 41 mm × 1.0 mm. The average diameter, length, and specific resistance of the CNFs were about 150 nm, 10 μm, and $10^{-4}\ \Omega$ cm, respectively. From observation of the sample containing CNFs, using scanning electron microscopy, it was demonstrated that the CNFs were distributed not only in the epoxy resin, but also in between the carbon fiber bundles [7]. For comparison, a sample without CNFs was also prepared, which was labeled as A-W/O. The dimensions of the sample A-W/O were 162 mm × 41 mm × 1.0 mm.

Fig. 1c shows a picture of the sample A-W. Because the braided textiles of the samples were manually impregnated with epoxy resin, their resulting widths were not completely identical. The average width of a single fiber bundle was about 2 mm. For comparison with conventional cross-woven CFRPs, and additional pair of identical braided CFRP panels, with and without CNFs was fabricated, and both sides of each panel were cut off to imitate cross-woven CFRPs. These cut samples with and without CNFs were labeled as B-W and B-W/O, respectively. The dimensions of samples B-W and B-W/O were 151 mm × 30 mm × 1.0 mm and 161 mm × 32 mm × 1.0 mm, respectively. At both ends of the samples, electric terminals were attached with silver paste for applying voltage to the samples to induce currents in the longitudinal directions of the samples for measurement using the HTS-SQUID gradiometer.

3. Step-by-step tensile tests

The braided and imitated cross-woven CRFP samples were tested by step-by-step tensile loading to clarify their destructive mechanisms, as well as to evaluate the integrity and electrical properties of the samples at certain damage stages by using below described SQUID-NDE technique. Tensile loading was applied to each sample in the longitudinal directions at a crosshead speed of 1 mm/min., while the surface of each sample was monitored and the stress–strain curve was measured using strain gauges. The surfaces were painted with white watercolor to observe the surface defects easier. Once the initial tensile load was applied to each sample, the loading was increased gradually. When there was an obvious decrease in mechanical strength, or when any defect was observed, loading was stopped and then released to

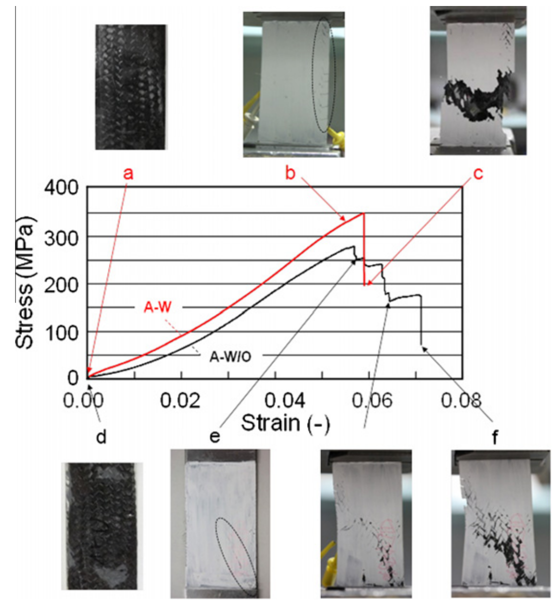

Fig. 2. Stress–strain diagrams of samples A-W with CNFs and A-W/O without CNFs. Photographs of the samples at certain damage stages are shown together. Some cracks are emphasized with dotted ovals. The photographs corresponding to "a" and "d" were taken before the watercolor was painted onto the surfaces.

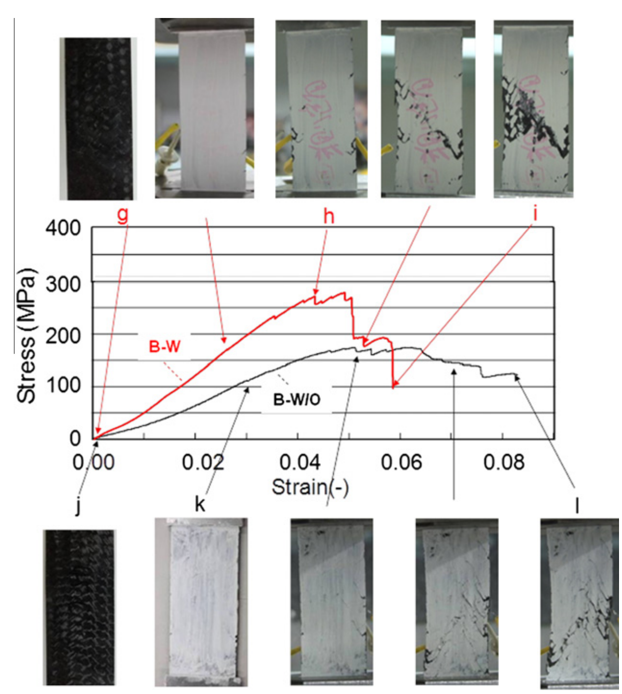

Fig. 3. Stress–strain diagrams of samples B-W with CNFs and B-W/O without CNFs. Photographs of the samples at certain damage stages are shown together. The photographs corresponding to "g" and "j" were taken before the surfaces were pointed with watercolor.

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