Characterization of laminated structure on scarfed slope of CFRP by utilizing eddy current testing with differential type probe

Hiroyuki Kosukegawa\textsuperscript{a,}\textsuperscript{*}, Yuta Kiso\textsuperscript{b}, Yuki Yoshikawa\textsuperscript{b}, Ryoichi Urayama\textsuperscript{a} and Toshiyuki Takagi\textsuperscript{a}

\textsuperscript{a}Institute of Fluid Science, Tohoku University, Sendai, Miyagi, Japan
\textsuperscript{b}Graduate School of Engineering, Tohoku University, Sendai, Miyagi, Japan

Abstract. Laminated structure (fiber orientation and boundary of adjacent layers) on scarfed surface of CFRP is characterized by eddy current testing (ECT) with differential type probe. The fiber orientation of each layer is identified by C-scanning of ECT. The peak of eddy current signal amplitude on each layer, which is shifted toward the upper side layer due to the distribution of eddy current, indicates the boundary of the adjacent layers. Because the peak of the eddy current signal is well represented by electromagnetic numerical simulation of finite element analysis, the boundary of the adjacent layers is correctly identified by combining ECT and numerical analysis. These abilities of ECT are useful for automation of scarf adhesive repair process.

Keywords: Eddy current testing, scarf adhesive repair, automation

1. Introduction

Due to the superior characteristics such as specific elastic properties, specific strength and corrosion-resistance, carbon fiber reinforced plastic (CFRP) is increasingly employed for structural materials. Considering the aerospace industries, the airlines or aircraft makers decide the repair process of the structural materials such as main wings by following the “Structural Repair Manual (SRM).” However, the repair process of CFRP products is more complicated than metallic materials due to the complex structure. To reconstruct the structural function to nearly 100\%, “scarf adhesive repair” process is performed.

Scarface repair is mainly composed of the following 6 steps \cite{1}: (1) The defect inside CFRP is detected by proper nondestructive testing method like ultrasonic testing. (2) The CFRP is roughly grinded up to the depth of the defect. (3) The CFRP is grinded in tapered shape so that the ratio of the radius and depth is 30–50. (4) The shape and fiber orientation of the respective layer is extracted, and the prepreg patch according to the layers is cut out. (5) An adhesive film and the prepreg patches are patched on the scarfed surface so that the fiber orientations of prepreg patches are parallel to those of the parent laminates.

Corresponding author: Hiroyuki Kosukegawa, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan.
E-mail: kosukegawa@wert.ifs.tohoku.ac.jp.

1383-5416/19/$35.00 © 2019 – IOS Press and the authors. All rights reserved
to compensate the mechanical properties. (6) Curing of prepreg patches is performed by heating, and defects inside the repaired structure are inspected by nondestructive testing. If some defects are inspected, the above process is reperformed again.

Conventionally, these processes are carried out by hand of advanced repairmen. However, due to the drastic increase of the aircraft composed of CFRP, the automation of these processes is required. Automation of scarf adhesive repair can improve the performance of use of aircrafts and reduce the maintenance cost. It can also enhance the popularization of aircraft composed of CFRP. To automatize these processes, some different technologies are needed for respective process.

Eddy current testing (ECT) is one of the methods capable of contributing to the automation of scarf adhesive repair. Recently, several researchers have paid attention to ECT as the nondestructive testing method which can detect the orientation of the carbon fiber in CFRP [2–6]. The fiber orientation in CFRP can be identified by ECT due to the anisotropy in electrical conductivity. When exciting magnetic field is loaded on a flat CFRP plate using a circular coil, eddy current in CFRP stretches to the fiber direction and shrinks to the other directions [4–6]. Because the bundle of carbon fibers (tow) are arranged in one direction in each ply, insulating resin rich region exists between the neighboring bundles. This region is heterogeneously distributed in the transverse direction of fiber and induces difference in the electrical resistance and eddy current density. A differential type probe has high sensitivity to the difference of eddy current density in the transverse direction of fibers [6,8]. In addition, respective pickup coils in a differential type probe can cancel the noise of other coils. Therefore, ECT with differential type probe can detect the fiber orientation with high signal-to-noise ratio [6]. This function of ECT is usable to the process (4) of scarf adhesive repair; the extraction of the shape of prepreg patch. By identifying the fiber orientation and boundary of adjacent layers on scarfed surface, and by transferring the geometry data of the patches to the cutting machine with ECT, the process (4) can be automatized. In this paper, we investigate the application of ECT with a differential type probe for identifying the fiber orientation and boundary of adjacent layers on the scarfed surface of CFRP laminates by both experiment and numerical simulation.

2. Materials and methods

2.1. Preparation of scarfed CFRP laminates

A quasi-isotropic (QI) CFRP plate was fabricated by curing 48 prepreg laminates (TR380G250S, Mitsubishi Rayon Co., Ltd.) by using autoclave. The thickness of TR380G250S prepreg is 0.24 mm, the total weight of fiber is 250 g/m², and the resin content is 33 wt%. The diameter of carbon fibers in the prepreg is about 7 μm. The curing condition was 120 min in process time, 130 °C at the curing temperature, 0.5 MPa at the pressure. The dimension of the resulting CFRP plate was 220 × 110 × 11 mm³. The laminated pattern was [(45₂/0₂/−45₂/90₂)₃]s from the top layer. This CFRP was grinded in tapered shape as shown in Fig. 1(a) so that the ratio of the length and depth of removed region is 30:1. The tapered angle was 1.9°. The distance between adjacent boundaries on the scarfed slope surface was about 15 mm because each layer was composed of two prepregs having the same fiber orientation. This specimen was named as “SP-FO,” and was used for the identification of the fiber orientation.

Other four types of scarfed CFRP plates were fabricated by curing 21 prepreg laminates (P3252S-25, Toray Industries Inc.) by prepreg compression molding method. The thickness of P3252S-25 is 0.24 mm, the total weight of fiber is 250 g/m², and the resin content is 33 wt%. The diameter of carbon fibers in the prepreg is about 7 μm. The laminate patterns were [90₁/45₁/90₁], [−45₁/90₁/−45₁], and [0₁/−45₁/0₁].
The curing condition was the same as the QI laminate plate. The dimensions of resulting plates were $150 \times 75 \times 5$ (mm$^3$). After curing, these plates were grinded as well as the QI laminate as shown in Fig. 1(b). The distance between adjacent boundaries was about 50 mm. The group of these specimens were named as “SP-BAL,” and used for the identification of the boundary of adjacent layers.

2.2. **ECT system**

In this paper, ECT system with a mutual induction differential type probe was used to identify the fiber orientation of the scarfed surface layer of a grinded CFRP as shown in Fig. 2 and Fig. 3. The differential type probe was composed of one circular exciting coil and two circular pickup coils. The exciting coil and pickup coils have 27 and 305 in number of turns, 5.4 mm and 0.7 mm in inner diameter, 6.0 mm and 2.0 mm in outer diameter, respectively. The two pickup coils were arranged inside the exciting coil as shown in Fig. 4. The pickup coil closer to the surface of SP-FO and SP-BAL was “Coil R” and the other one was “Coil L.” The probe has the highest sensitivity of detection at 2 MHz. The differential angle $\Psi$ of ECT probe was defined as the angle between the $x$ axis and the differential axis binding the centers of two pickup coils. Figure 5 is the correlation of $\Psi$ and the differential signal amplitude of the differential type probe on a unidirectional (UD) ply CFRP (21 laminates of TR380G250S prepregs) that was prepared by using autoclave. The exciting current was generated by an oscillator. The differential signal of the two pickup coils was amplified by a differential amplifier and a lock-in amplifier by 20 dB. The amplified differential signal was acquired as an eddy current signal by converting from analog to digital using an A/D converter.

The differential type probe scanned the scarfed surface of SP-FO and SP-BAL by a pitch of 0.1 mm with a liftoff of 0 mm. A two-dimensional scan (C-scan) was performed in the range from $x = 0$ mm to 60 mm, $y = 0$ mm to 15 mm as shown in Fig. 2 for the identification of fiber orientation by using SP-FO, and a line scan (A-scan) was performed across the boundary for the identification of the boundary of adjacent layers as shown in Fig. 3 by using SP-BAL. The exciting voltage was $5.0 V_{p-p}$ for the identification of fiber orientation and $3.0 V_{p-p}$ for the identification of the boundary of adjacent layers, respectively. For the identification of fiber orientation with SP-FO, the exciting frequency of 10 MHz, which is the highest frequency and the restriction level on use of the experimental setup, was adopted to remove the influence of lower layers. On the other hand, the exciting frequency of 2 MHz, which is the highest sensitivity of detection for the probe, was adopted for the identification of the boundary of adjacent layers with SP-BAL. Since SP-BAL has the thick layers of the same fiber orientation, the influence of lower layers is
Fig. 2. (a) Schematic image of ECT to identify the fiber orientation by using SP-FO. (b) Scanned two-dimensional area of the scarfed surface of SP-FO.

Fig. 3. (a) Schematic image of ECT to identify the boundary of adjacent layers at the case using SP-BAL of [−45°/90°/−45°]. (b) Scanned line of the scarfed surface of SP-BAL.

Fig. 4. Schematic image and dimensions of differential type probe of ECT from the top view.

not as much as the case of SP-FO. Therefore, the exciting frequency was set at 2 MHz for identifying the boundary.

3. Numerical simulation

To discuss the results obtained from ECT scan of scarfed CFRP, electromagnetic numerical simulation of eddy current distribution and the differential signal amplitude in scarfed CFRP was performed with finite element analysis (FEA) using edge elements. A commercial FEA software PHOTO-Series EDDY jio (Photon Co., Ltd.) was employed for numerical simulation in this paper. The simulation was performed
by $A\cdot \Phi$ method with the following governing equation:

$$\nabla \times \frac{1}{\mu} \nabla \times A = J_0 - \sigma \frac{\partial A}{\partial t} - \sigma \Delta \Phi$$

where $\mu$ is the magnetic permeability, $A$ is the magnetic vector potential, $J_0$ is the current density of the exciting coil, $\sigma$ is the electrical conductivity and $\Phi$ is the electric scalar potential.

The full model was diagonal shape with a dimension of 30 mm in a length, 60 mm in a width, 1.44 mm in a height. Two layers with different fiber orientation had 15 mm in a length and are connected to each other at the boundary of adjacent probe (Fig. 6). Each layer had diagonal shape in $x$-$z$ plane, and the bevel angle to $x$-axis was 1.9°. The number of isoparametric elements and edges of the full model were 345,600 and 1,068,708, respectively. CFRP has anisotropy in the electrical conductivity, and the tensor of $\sigma$ of CFRP was converted by Eq. (2) [7]:

$$\{ \sigma \} = \begin{pmatrix}
\sigma_L \cos^2 \theta + \sigma_T \sin^2 \theta & \frac{\sigma_L - \sigma_T}{2} \sin 2\theta & 0 \\
\frac{\sigma_L - \sigma_T}{2} \sin 2\theta & \sigma_L \sin^2 \theta + \sigma_T \cos^2 \theta & 0 \\
0 & 0 & \sigma_{cp}
\end{pmatrix}$$

where, $\sigma_L$ is the electrical conductivity of CFRP in the fiber direction, $\sigma_T$ is the electrical conductivity of CFRP in the transverse direction, $\sigma_{cp}$ is the electrical conductivity of CFRP in the thickness direction. $\theta$ is the angle between the fiber direction and the reference axis (R-direction) shown in Fig. 6 which was angled by 1.9° to the $x$-axis in the $x$-$z$ plane. The electrical conductivities of CFRP, $\sigma_L$, $\sigma_T$, and $\sigma_{cp}$ were 14860 S/m, 3.8 S/m, and 0.63 S/m, respectively, which were referred from the work of Cheng et al. [5]. The geometry and coil turns of the exciting coil and pickup coils were the same as the experiment setup. The liftoff of the probe was 0 mm. The origin of the calculation coordinate was the boundary of upper layer and lower layer.

To investigate the eddy current distribution on scarfed surface, the differential type probe was set on $x = 5$ mm, which means the site on the upper layer away from the boundary of adjacent layers by 5 mm (Fig. 6(a)). The eddy current density on the scarfed surface and the interface between the upper and lower layers was calculated. The exciting frequency was 10 MHz and the exciting current was $5.7 \times 10^{-2}$ A/turn, which were the same condition as the experiment of identification of the fiber orientation by using SP-FO.

The differential signal amplitude was also calculated as the differential type probe was moved every 1 mm from $x = -5$ mm to 5 mm on the scarfed surface as shown in Fig. 6(b) and (c). In this simulation, the differential angle $\Psi$ was 0°, and the exciting frequency was 2 MHz and the exciting current was $5.7 \times 10^{-2}$ A/turn, which were the same condition as the experiment of identification of the boundary of
Fig. 6. Schematic image of numerical simulation model: (a) the case of setting the probe on the surface of scarfed upper layer, the exciting frequency was 10 MHz, (b) the case of scanning the eddy current signal on the scarfed surface with a scan pitch of 1 mm, the exciting frequency was 2 MHz, (c) the isometric view of the case (b).

Fig. 7. (a) C-scan image of ECT amplitude of scarfed surface of SP-FO, (b) the image of 90° layer scanned by setting the off-set of the signal at \((x, y) = (15 \text{ mm}, 0 \text{ mm})\).

adjacent layers using SP-BAL. The position of the peak of the differential signal amplitude was compared to the value obtained by the experiment.

4. Results and discussion

4.1. Identification of fiber orientation of scarfed QI CFRP

The C-scan image of SP-FO is shown in Fig. 7(a), when \(\Psi\) is 0°. From this result, it is possible to discriminate the fiber orientation of 45°, 90° and −45°. When the differential axis is parallel to the fiber orientation of 0°, it is difficult to recognize the fiber orientation because the signals of two pickup coils are nearly equal. Around the boundary of adjacent layers (e.g., \(x \approx 15 \text{ mm}, 30 \text{ mm}\)), the ECT signal amplitude exhibits higher value.

By scanning the region from \(x = 15 \text{ mm}\) to 30 mm by setting the off-set of the signal at \((x, y) = (15 \text{ mm}, 0 \text{ mm})\), it is possible to recognize that the information of two fiber orientations 90° and 45° are included in one image (Fig. 7(b)). Fig. 8 shows the results of numerical simulation of eddy current distribution on the surface and subsurface of scarfed slope of CFRP [45°/90°] at the condition of Fig. 6(a). From Fig. 8,
when the exciting coil is on the upper layer, the path of the eddy current on the scarfed CFRP is explained as following. On the surface of the upper layer, the eddy current strongly flows along the direction of the fiber of the upper layer near the boundary (Fig. 8(c)). The eddy current flows down toward the lower layer around the boundary (Fig. 8(e)) and goes half around below the exciting coil on the interface of [45°/90°] along the direction of the fiber of the lower layer (Fig. 8(d)). After that, the eddy current flows up toward the surface along the direction of the fiber of the lower layer on the interface as going half around below the exciting coil (Fig. 8(f)), and returns to Fig. 8(c). The previous research also describes that the eddy current density in CFRP tends to be large on the interface and the eddy current changes the direction on the interface of the layers with different fiber orientation [5, 8]. Therefore, the eddy current on the interface can affect the result of the C-scan image.

To extract the information of only the surface layer, it is necessary to cancel the signal of the fiber orientation of the lower layer. The method setting $\Psi$ of the differential type probe parallel to the fiber orientation of the lower layer is effective because the two pickup coils cancel the signal from the lower layer. Figure 9 shows the C-scan images of the 90° layer on the scarfed surface of SP-FO when $\Psi = 0^\circ$ and 45°. When $\Psi$ is parallel to the fiber orientation of the lower layer (45°), the signal from 45° layer is lowered, and the fiber orientation of the surface layer becomes easier to be discriminated. This result means that it is required to scan the surface with several settings of differential angle to extract the fiber orientation of only the surface layer.

### 4.2. Identification of boundary of adjacent layers of scarfed CFRP

Figure 10 shows the profile of the signal amplitude from $x = 0$ mm to 35 mm at the arbitrary $y$ position. The probe crosses the two boundaries of [45°/90°] and [90°/−45°] of SP-FO and $\Psi$ is 0°. There are three peaks of signal amplitude around the true boundary positions. The broken lines of I ($x = 15.4$ mm) and II ($x = 29.2$ mm) are the true positions of the boundary of [45°/90°] and [90°/−45°], respectively. The left peak in Fig. 10 indicates the mixed signal of the boundary of [0°/45°] and the fiber of the 45° layer. From Fig. 10, the peak of ECT signal amplitude seems a good indicator for determining the boundary position of adjacent layers. However, the peaks are a little shifted toward upper layer from the true boundary position, and the difference of the peak and the true position is sometimes several millimeters which are not negligible. The peak of ECT signal indicating the boundary of [45°/90°] is shifted by 2.3 mm, while that of [90°/−45°] is shifted by 1.3 mm from the true position. The shift of the peak of eddy current signal amplitude is due to the distribution of eddy current around the diagonal interface between the lower and upper layers [9].

To quantitatively evaluate the difference between the true boundary position and the position of the shifted eddy current signal amplitude, an A-scan of ECT with simpler specimen (SP-BAL) and numerical simulation at the condition in Fig. 6(b) were carried out. There are three boundary patterns; [45°/90°], [90°/−45°], and [−45°/0°]. Figure 11 shows the distribution of the eddy current density and its evolution in accordance with the position of the exciting coil. The upper figures show the distribution of eddy current on the surface, and the lower figures show that on the interface. In common among these three boundary patterns, the eddy current hardly flows when the exciting coil is located on the lower layer. After that exciting coil passes over the boundary toward the upper layer, the eddy current becomes to flow and the eddy current density increases. This phenomenon is caused by the existence of the interface of two adjacent layers which have different fiber orientations. With a circular exciting coil, the eddy current in CFRP can flow on the interface by changing the direction [5,8].
Fig. 8. The contour of eddy current density $J$ (A/m$^2$) of CFRP [45°/90°] obtained by numerical simulation: (a) top view of the scarfed surface, (b) the projection view of the interface of 45° and 90° layer. The vector of $J$ (A/m$^2$) around the exciting coil of (c) top view of the scarfed surface and (d) the projection view of the interface of 45° and 90° layer. The contour of $J_z$ (A/m$^2$) around the exciting coil of (e) top view of the scarfed surface and (f) the projection view of the interface of 45° and 90° layer.

Considering around the boundary [45°/90°], the eddy current concentrates at the boundary on the surface when the exciting coil is on the upper 90° layer. On the interface of [45°/90°], the eddy current mainly flows toward 90° direction, because the boundary interrupts the current toward the directions other than 0° direction. On the other hand, about the boundary [90°/−45°], the eddy current on the surface hardly flows on the upper −45° layer even though the exciting coil is on the upper layer. However, the
eddy current on the interface of \([90^\circ/−45^\circ]\) can flow toward \(90^\circ\) direction and \(−45^\circ\) direction. The reason that the eddy current on the surface hardly flows toward \(−45^\circ\) direction is because the boundary interrupts the eddy current toward the directions other than \(90^\circ\) and the eddy current cannot change the direction. On the contrary, the eddy current on the interface of \([90^\circ/−45^\circ]\) can flow toward \(−45^\circ\) because of the \(90^\circ\) lower layer.

The distribution of the eddy current around the boundary \([−45^\circ/0^\circ]\) is much different from the other cases. The eddy current on both the surface and interface is weaker compared with that of \([45^\circ/90^\circ]\) and \([90^\circ/−45^\circ]\). This tendency is caused by the boundary and the existence of the \(0^\circ\) layer. In the cases of \([45^\circ/90^\circ]\) and \([90^\circ/−45^\circ]\), the eddy current flows through the \(90^\circ\) layer whose current is not interrupted by the boundary. On the other hand, the eddy current on the \(0^\circ\) layer is interrupted by the boundary and the eddy current density does not become as high as that of the other cases even on the interface.

Figure 12 exhibits the variation of simulated induced electromotive force of the two pickup coils according to the position of the exciting coil at the cases of \([45^\circ/90^\circ]\), \([90^\circ/−45^\circ]\) and \([−45^\circ/0^\circ]\). The position of the boundary is \(x = 0\) mm. The differential signal between the two pickup coils becomes large after the exciting coil passes through the boundary \((x > 0)\). At the cases of \([45^\circ/90^\circ]\) and \([90^\circ/−45^\circ]\), the difference in signal amplitude between two pickup coils exhibits the maximum value in the range from \(x = 1\) mm to \(2\) mm. However, at the case of \([−45^\circ/0^\circ]\), the difference in signal amplitude does not expand.
Fig. 11. Evolution of the distribution of simulated eddy current density $J$ (A/m$^2$) around the boundary of $[45^\circ/90^\circ]$, $[90^\circ/−45^\circ]$, and $[−45^\circ/0^\circ]$ at the condition shown in Fig. 6(b). $x$ is the position of the exciting coil. $x = 0$ means that the center of the coil is just located on the boundary (white line). The upper figures are the distribution of $J$ on the surface and the lower figures are that on the interface of the adjacent layers. The left side of the boundary is the lower layer and the right is the upper layer.

as much as those at the other cases. From Fig. 11, this tendency is explained as the eddy current on the interface of $[−45^\circ/0^\circ]$ does not concentrate on the boundary and is averagely distributed toward the $0^\circ$ direction.

Figure 13 shows the experimental and simulated results for the line profile of eddy current differential signal on the boundaries of $[45^\circ/90^\circ]$, $[90^\circ/−45^\circ]$ and $[−45^\circ/0^\circ]$. The true boundary position is $x = 15$ mm in Fig. 13. For the results of numerical simulation, the coordinate is converted so that the boundary position of $x = 0$ mm in Fig. 12 becomes $x = 15$ mm in Fig. 13. The peaks of the experimental and simulated eddy current differential signal are always shifted toward the upper layer side by several millimeters from the true boundary position. The difference of the peak shift of the eddy current signal between the experiment and simulation is less than 1 mm, which is the pitch distance of the position of exciting coil in simulation, in any cases of layer settings. From Fig. 13, the numerical simulation well represents the experimental data of ECT signal for all cases of layer settings. From these results, the true boundary position can be precisely estimated by comparing the data of ECT with that obtained by the simulation as far as the fiber orientations of both lower and upper layers are identified in advance.

In addition, with a differential type probe, the sensitivity of ECT decreases when $\Psi$ is parallel to the fiber orientation. These results indicate that it is better to multiply plural data to determine the fiber orientation


Fig. 12. Variation of simulated induced electromotive force of two pickup coils corresponding to the position $x$ of the exciting coil at the condition shown in Fig. 6(b). “Coil R” is the pickup coil closer to the surface of the laminate and “Coil L” is the pickup coil further from the surface. The center line ($x = 0$ mm) is the true boundary of the adjacent layers. (a) $[45°/90°]$, (b) $[90°/−45°]$, (c) $[−45°/0°]$.

Fig. 13. A-scan profile of ECT signal amplitude obtained by experiment with SP-BAL and numerical simulation at the condition shown in Fig. 6(b). The center line ($x = 15$ mm) is the true boundary of the adjacent layers and equivalent to $x = 0$ mm in Fig. 12 for the simulation results. (a) $[45°/90°]$, (b) $[90°/−45°]$, (c) $[−45°/0°]$.

and the boundary of adjacent layers by setting several pickup coils with various differential axis for one scan.

5. Concluding remarks

The results obtained in this paper indicate that eddy current testing (ECT) using a differential type probe can identify the fiber orientation and boundary of the adjacent layers on the scarfed slope surface of CFRP. Because the sensitivity of ECT decreases when the differential axis is parallel to the fiber orientation, it is better to apply several settings of differential axis by adding sequence of scanning or by using a multi-axial probe with plural pickup coils. The boundary of the adjacent layers is identified by measuring the peak position of the eddy current signal amplitude. The peak position of eddy current signal is shifted to the upper side layer by several millimeters from the true boundary position, and this is well represented by numerical simulation. Therefore, the boundary position of adjacent layers is identified by comparing ECT scan and numerical analysis. From these abilities, ECT with a differential type probe can be helpful for automating the technique to determine the geometry of prepreg patch in scarf adhesive repair process.
Acknowledgements

This study was supported by JSPS Grant-in-Aid for Exploratory Research “15K14143” and JSPS Core-to-Core Program, A. Advanced Research Networks, “International research core on smart layered materials and structures for energy saving.” The fabrication of SP-FO was supported by Dr. Motoi Fujishima (Akita Industrial Technology Center).

References