Chapter 8

Recent Development of Reused Carbon Fiber Reinforced Composite Oriented Strand Boards

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Additional information is available at the end of the chapter

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Abstract

There is a growing interest for the reused composite oriented strand board (COSB) for stiffness-critical and contoured applications. COSBs are made of rectangular shape prepreg strands that are randomly oriented within the structure. Development of this product form could markedly reduce the scrap generated during aerospace manufacturing processes. COSBs retain high modulus and drapability during processing and manufacturing. However, before any material can be deployed in industrial applications, its various properties must be well understood so that proper design analysis can be performed. Nondestructive testing (NDT) is widely used in research and industry to evaluate the quality of a variety of materials including composite materials and structures. NDT, as the name indicates, has the benefit that it does not alter or destroy the sample like other techniques, such as cross-sectional imaging. In this chapter, two nondestructive techniques, ultrasound and micro-computed tomography (micro-CT), were used to characterize carbon fiber epoxy composites, particularly comparing conventional laminates and reused COSB. The void content and morphology of samples cured using a range of materials and process parameters were determined using NDT and conventional microscopic analysis of cross sections. The mass distribution of fiber and resin within each sample was also determined. The manufacturing and NDT of COSB were introduced, and provided most detailed information on composite microstructure, including void size, void morphology, void distribution, and overall void content. Conventional micro-CT was determined to be ill-suited to scan large samples because of long scan times and large file sizes. To enhance the capabilities of micro-CT for evaluation of composite materials and structures, a micro-CT postprocessing method using stitching computer programming algorithms was developed. The method presented markedly increases the resolution that micro-CT can achieve, as well as the maximum feasible sample size, thus overcoming some of the primary drawbacks to conventional micro-CT. The primary objective of this work was to evaluate the feasibility of NDT methods in the assessment of both conventional composite laminates and the reused COSB fabricated from prepreg scrap. To this end, the advantages and limitations of ultrasound and micro-CT were discussed. The results showed that with stitching up postprocessing, micro-CT can be used

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to detect global void morphology structure wide, making the technique competitive with ultrasound, yet with greater resolution and equivalent scan size.

Keywords: composite oriented strand board (COSB), reuse, recycle, NDE, micro-CT, ultrasound computer numeric control (CNC)

1. Introduction

Production waste and end-of-life (EOL) materials from one industrial process can serve as the raw materials for another, thereby reducing the environmental impact of an industry or process [1]. This concept is drawing attention in the aerospace industry as commercial aircraft designs transition from primarily metallic structure to carbon and glass fiber composite materials reduce weight and increase durability. Over the next 20 years, approximately 12,000 aircraft currently utilized for different purposes will be at the end of service life. In 2015, Boeing projects a demand of 38,050 new airplanes at a total value of $5.6 trillion [2] over the next 20 years, an increase of 3.5% from the previous year's forecast. With current trends in aircraft design, these airplanes are likely to contain increasing quantities of composite materials. The Boeing 787 Dreamliner, for example, is about 50% composite by weight, equating to roughly 32,000 kg of carbon fiber reinforced polymer (CFRP). The increased use of composites in aerospace has benefits in terms of fuel efficiently and durability. An immediate concern, however, is the large amount of thermosetting composite scrap generated during the manufacturing process.

In current aerospace and automotive production lines, 10–20% or more of virgin carbon fiber reinforced prepreg sheets end up as production wastes (**Figure 1**), as large prepreg rolls are cut into desired shapes to manufacture parts. This production scrap accounts for a significant source of composite waste. A second waste stream is end-of-life (EOL) thermoset composites. The total combined volume of end of life and production waste generated by the thermoset composites market in Europe is expected to reach 304,000 tons by 2015 [5]. Composite waste reduction and disposal are pressing concerns worldwide. Traditional disposal routes include landfilling and incineration. The financial and environmental costs of these methods, however, are steadily increasing. The composite industries, from suppliers and part manufacturers to customers, are seeking more sustainable solutions for reusing and recycling composite materials.

Jin et al. have been actively seeking viable methods and processes to turn in-process waste into useful products and components [6–9]. Research efforts thus far have focused on the repurposing of prepreg scrap into reused composite products including consumer products like skateboards and structural materials like reused composite oriented strand board (COSB), hat stiffened panels, etc. These components are fabricated by cutting prepreg trim waste into rectangular strands and curing them using out-of-autoclave (OoA) techniques like vacuum bag only (VBO), oven cure, and hot pressing. The work presented here originated from an NSF G8 Research Council funded project on "Sustainable Manufacturing through Out-of-Autoclave Processing". The first phase of the project focused on evaluating the manufacturing feasibility and mechanical properties of components made from scrap prepreg. As part of this work, finite element analysis (FEA) was utilized to predict the mechanical properties of scrap-based composites. Jin et al. and Jain et al. [7, 8] used FEA and mean field homogenization hybrid

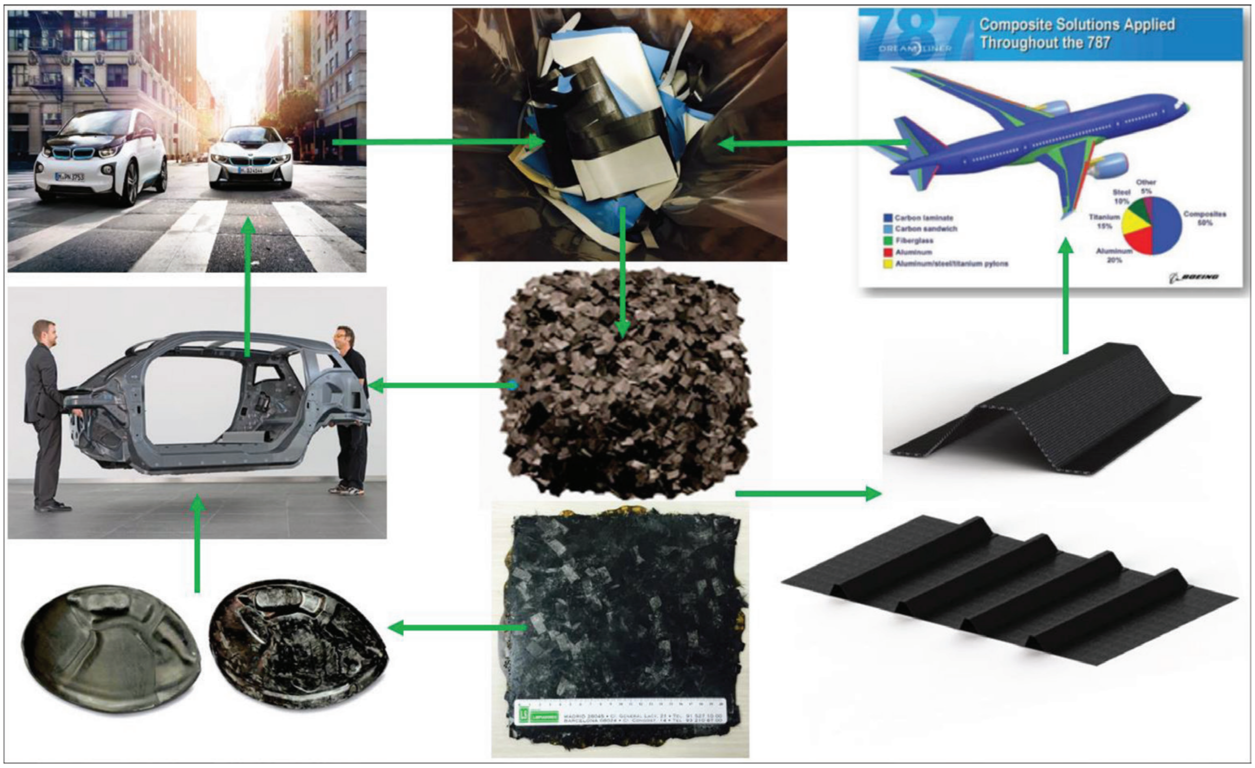

Figure 1. Motivation and potential applications of the composite oriented strand board (COSB), top middle shows the scrap generated during manufacturing, the scrap is trimmed to rectangular strands (center) and subsequently used for a variety of applications [3, 4].

methods to predict equivalent modulus of the COSB. Jin et al. [10] built a 3-D parametric FE model for random fiber composites with high volume fraction and fiber aspect ratio based on innovative 3-D spatial mathematic algorithm. In related work, Faessel et al. [11] created a finite element model on low-density wood-based fiberboards to study their local thermal conductivity, using a model based on X-ray tomography. While preliminary experimental and model results have shed light on the processing and mechanics of composites fabricated from prepreg scrap, a more detailed understanding of the microstructure of the materials is required, including voids. Details of void morphology and microstructure, as obtained through nondestructive techniques, can be utilized to build detailed and FEA models. This work describes results of NDT analysis of COSB fabricated from rectangular prepreg strands of uniform size.

2. Experiments

A reused carbon fiber epoxy COSB demonstrator panel was produced using OoA techniques [9]. The part was then analyzed for mass and void distribution using ultrasonic C-scan. After scanning, the COSB was cut down using a CNC milling machine. Void content and void morphology were investigated using both microscopic examination of polished cross sections and state-of-the-art stitched high-resolution micro-CT techniques. The results, pros and cons of the three techniques are compared and discussed later in this chapter.

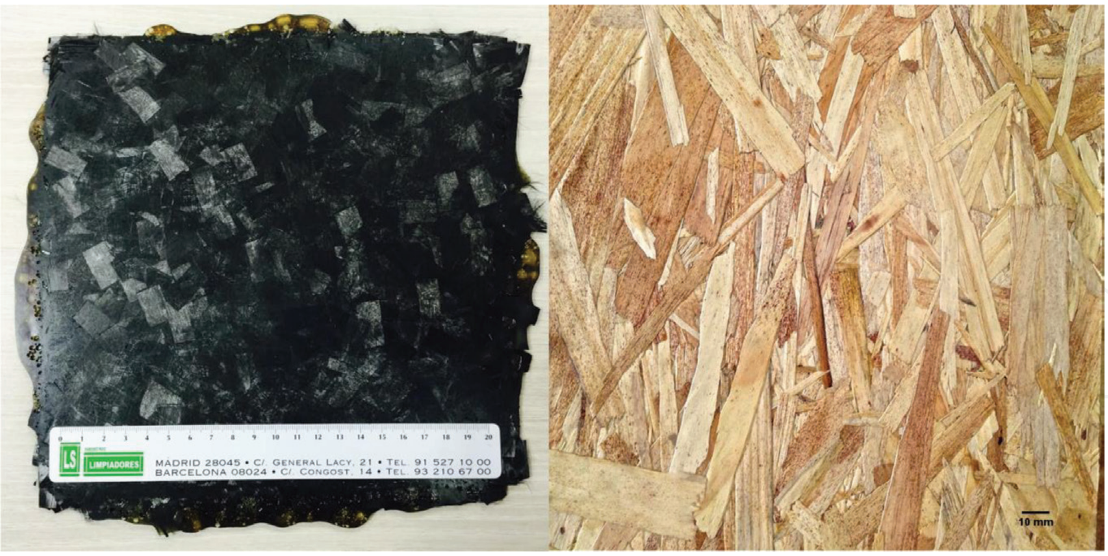

Figure 2. Composite oriented strand board (COSB, left), similar to wood OSB (right).

A demonstrator COSB panel (**Figure 2**, Left) was first manufactured. Fresh prepreg (UD Tape T40/800B with Cytec CYCOM 5320-1 epoxy resin) was manually cut into rectangular strands (10 × 20 mm) and distributed evenly on an aluminum plate. The prepreg was subsequently cured using a compression molding hot press (Wabash) into a flat COSB panel measuring 215.9 × 215.9 mm. The manufactured panel is analogous to a composite version of the ubiquitous wood-based strand board (**Figure 2**). A CNC milling machine with a diamond cutting wheel was used to section the COSB into seven individual plain tensile specimens (25 × 200 mm) in accordance with ASTM D3039 [12] standard for quasi-static tensile testing. Six coupons were tested in a loading frame (INSTRON), and elastic modulus was determined from the resulting load-displacement curve, the details of which are presented elsewhere [7].

The remaining coupons (prepared from the center of the COSB) were cut into smaller pieces (25 × 50 mm) for nondestructive evaluation (NDE) using ultrasound A and C scans, high-resolution micro-CT, as well as cross-sectional imaging analysis, that are discussed in Section 3 of this chapter.

3. Results and discussion

A commonly used nondestructive testing method used for composite materials is ultrasonic test [13]. Ultrasonic testing is a noncontact method, which typically requires a coupling agent (often water) and therefore an extensive setup. Ultrasound scans, when performed properly, enable defects such as delamination and debonding to be detected easily and accurately [14, 15].

3.1. Ultrasound scans

Ultrasonic A-scans were performed on both the demonstrator COSB sample and a reference panel. The reference laminate was an autoclave-cured Cytec 5320-1 composite panel with known low void content (<1%, by microscopic image study). To carry out the scans, the ultrasound transducer was fixed in position at the center of the specimen. A pulse-echo mode was utilized to interrogate defects within each panel. The strength of the reflected ultrasonic echoes as function of time is presented in **Figure 3**. The A-scan of the reference laminate (**Figure 3**, Upper) reveals clear top surface and back surface reflections. The region between these top and bottom surfaces (Gate 2, the interior of the panel) shows <3% signal attenuation, indicating a low void content. The A-scan of the COSB (**Figure 3**, Lower), in contrast, shows roughly 20% signal attenuation between the top and back surface reflections, indicating greater void content within the composite.

While the A-scan mode reveals critical information about the ultrasound signal attenuation, visual maps of panel quality can be produced using a C-scan mode, which is one of the most suitable method for production inspection of composites using a conventional pulse-echo or pulsed through-transmission system. In this study, a 10-MHz transducer was focused on the top surface of the specimen and gated on the echo from a glass reflector plate (**Figure 4**). The pulse passed through the specimen twice. A quantized display was used, so the various attenuation levels are presented as finite changes to tone density on a plain view of the specimen. The white regions are of lowest attenuation. There is no attenuation in the absence of a specimen, which accounts for the white border outlining each sample.

Ultrasonic C-scans were performed on the following specimens: a quasi-isotropic reference panel that was manufactured using heated platen compression molding (**Figure 5**, Left), and the demonstrator COSB (**Figure 5**, Right). These two panels are both made of same prepreg material (Cytec 5320-1). The transducer moved in two dimensions within a range in the x-y plane covering the whole flat panel area. The total time for the transducer to cover the entire laminate (215.9 × 215.9 mm) was about 6 hours. The images in **Figure 5** display the peak signal response within a time or depth interval of interest as a function of transducer position. There are two observations from the examination of the C-scan images. First, the COSB displays high signal attenuations (max ~90%) when compared to continuous fiber laminates (max ~10–20%) This confirms that, not surprisingly, COSB has a much higher overall void volume fraction compared to that of the reference panel (void volume fraction <1%). Secondly, insights into the distribution of resin and fiber in each sample are revealed in the C-scan images. We observe that the distribution of matter in COSB is significantly more uneven than in the conventional continuous prepreg laminate. The uneven distribution of the matter in COSB is probably due to less free-flowing resin as compared to the continuous prepreg plies. Also, the discontinuity and random orientation and location of the strands play an important role.

3.2. Microscopy study of void contents

To gain more insight into void morphology and assess the validity of NDT analysis, the void contents of test laminates were also evaluated using optical microscopy. To investigate a method for reducing void content in COSB, two samples with smaller sizes (50 × 50 mm) were fabricated from prepreg aged for 14 and 28 days at room temperature, in addition to the demonstrator COSB made of fresh prepreg strands. The samples for cross-section imaging were prepared from the center of each panel, and measured 50 mm in length and 3 mm in thickness. Cross sections were prepared via mechanical polishing with silicon carbide abrasive papers on a grinder-polisher (Struers), at successive grits of 150, 240, 400, 600, 1200, and 2400. Cross-sectional images were acquired using a digital microscope (Keyence) at a magnification of 100×. Approximately, 20 images were obtained from each sample to assemble a full-scale

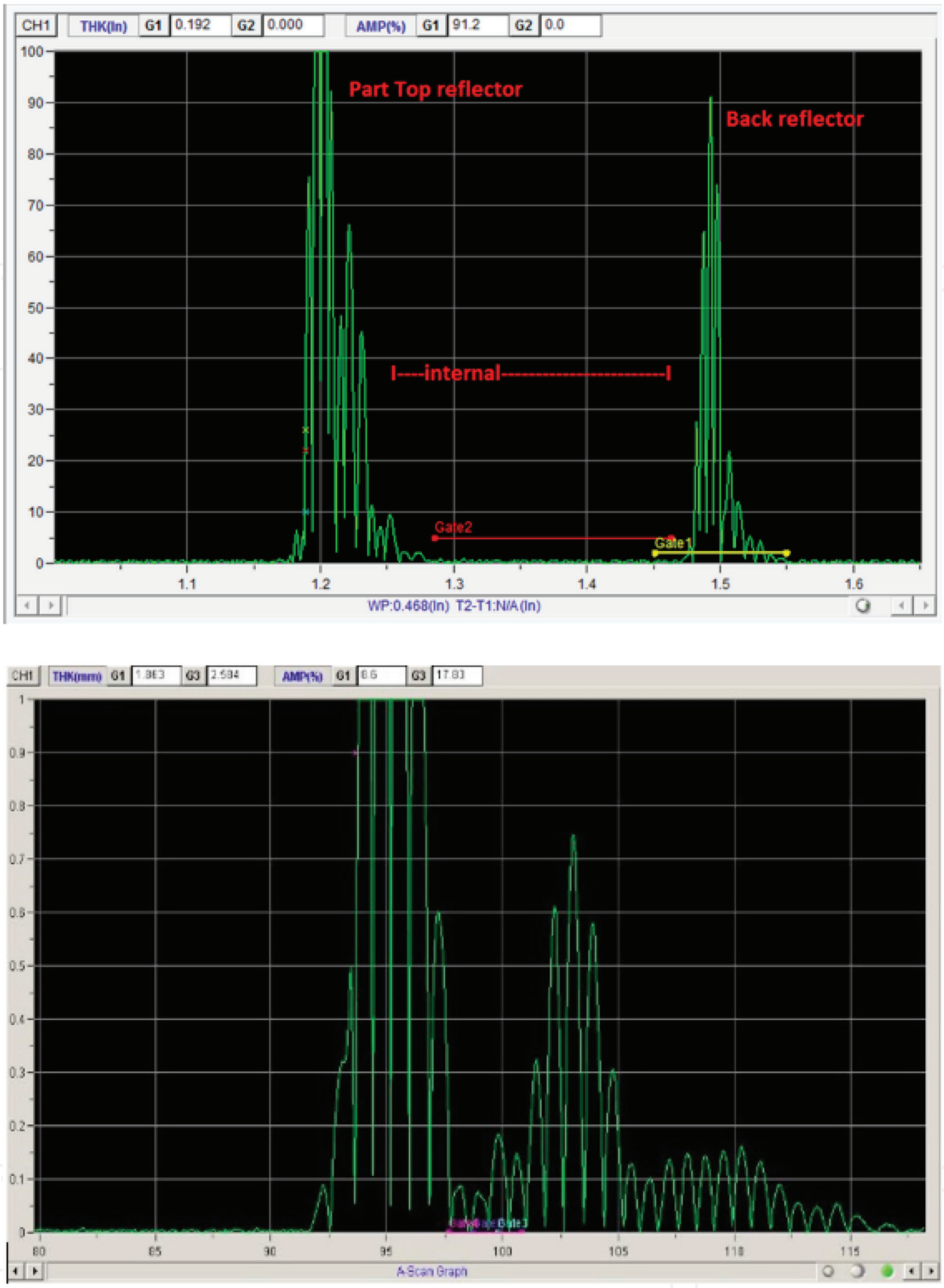

Figure 3. Upper: ultrasonic A-scan plot of the referenced autoclave cured composite laminates: void content <1%. Lower: the A-scan result of a COSB, indicating greater signal attenuation compared to the referenced laminate: void content ~6%.

image of the cross section. Images were processed and merged using image-processing software for void content analysis. The images were first converted to gray scale. Voids were manually selected and filled to distinguish from solid phases. An image analysis program (ImageJ [16]) was used to convert each image into a binary map of voids (black pixels) and solid (white pixels). The areal void contents was then calculated and used as a representation of void volume fraction (**Figure 6**).

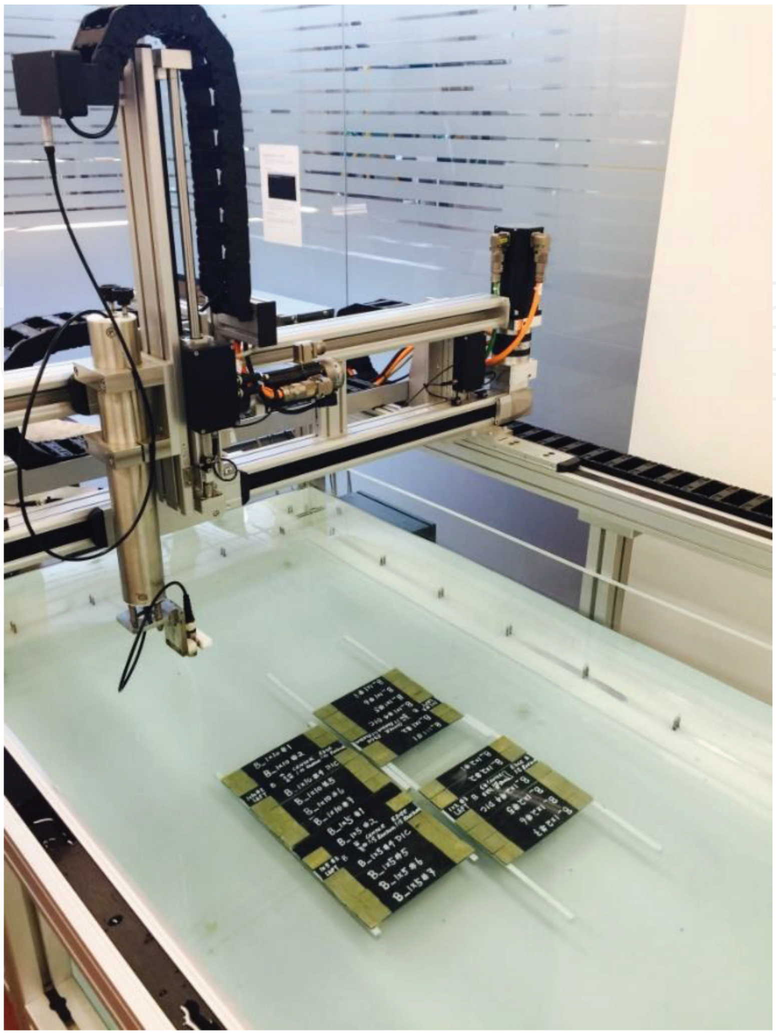

Figure 4. Ultrasonic scan setup. At the top is the arm with a 10-MHz transducer installed. The samples are placed in the water pool underneath.

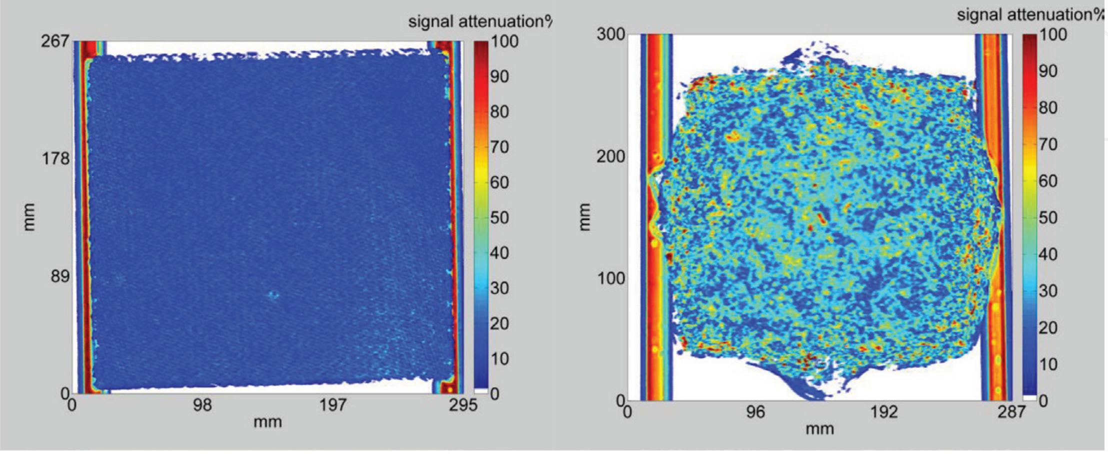

Figure 5. Ultrasonic C-scan results. Left: reference panel, quasi-isotropic layup, heated platen compression molding cured. Right: the demonstrator COSB.

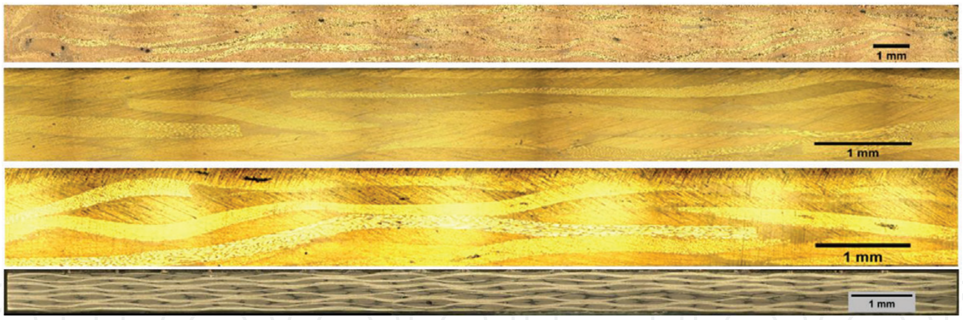

Figure 6. Microscopic scan results of (from top to bottom): (a) the demonstrator COSB (made of fresh prepreg strands). Void content = 2.07%, (b) COSB sample made from prepreg strands aged in room temperature for 14 days. Void content = 0.81%, (c) COSB sample made from prepreg strands aged in room temperature for 28 days. Void content = 2.41%, (d) an autoclave-cured reference sample with continuous prepreg fibers.

COSB made from fresh prepreg strands, 14-day room-temperature-aged-, and 28-day room-temperature-aged prepreg strands yielded void contents of 2.07, 0.81, and 2.41%, respectively. The COSB sample made from prepreg with 14 days of out time had the lowest void content. This is because prepreg is partially cured during room temperature aging time, resulting in decreased tack and easier manipulation during layup and more efficient air removal during cure. This aging process can have beneficial results in the short term, but when prepreg is aged over its shelf life (28 days), viscosity increases such that resin flow is hindered and flow-induced voids are formed.

3.3. Micro-CT analysis

X-ray CT is an effective nondestructive technique for studying the details of internal defects. This technique was first applied in designing medical CT device. Because nonmetal composite materials have a similar composition to human bodies, the medical CT devices were well suited to imaging of carbon fiber epoxy composite materials. The device can be used for 3-D image reconstruction to detect defects (microcracks, inclusions, voids, delamination and debonding), determine distribution of mass, and accurately measure and display internal structural configurations. Previous studies [14] have indicated that the resolution of micro-CT is well suited to the detection of internal and surface defects in carbon fiber epoxy composites. In this work, a Phoenix Nanotom Tomographic machine (General Electric) with a Hamamatsu C-7942 detector and an Mo anode was utilized to perform micro-CT scans on the demonstrator COSB. A micro-CT sample (25 × 50 × 3 mm, **Figure 7**, Left) was prepared from the center of COSB. Electric tensions between 30 and 55 kV and current intensities between 190 and 220 μA were used. Spatial resolutions between 2.5 and 14.5 μm/px were attained from the above setup.

Initial scans showed that clear boundaries between strands cannot be resolved using X-ray absorption tomography, even at the highest resolution. However, when viewing continuous frames of scanned images, an animation reveals strand boundaries. This observation was helpful in identifying the shape of deformed strands and stitching multiple volumes for further postprocessing and analysis. The technique proved to be valuable for estimating void content. Thus, all samples were scanned in sets of 3–4 simultaneous samples to optimize available tomography time. Updated settings used were 80 kV and 150 μA, with a 500 ms exposure time. The attained resolution was 13.04 μm/px.

Figure 7. Left: a micro-CT sample prepared from the center coupon of COSB. Right: a 2-D micro-CT image of cured COSB sample (resolution: 2.5 μm/px). Deformed prepreg strands and their curvature were observed. Morphology of the voids was also presented.

Multiple scans were performed on different regions from a single sample in order to cover the entire sample volume. The obtained volumes were reconstructed using a user-defined computer program. By stitching and cropping, an individual volume containing the complete sample volume was obtained. Results are displayed in **Figure 8**. Detailed void content and void morphology information was extracted from the stitched volume, as presented in **Figure 9**. In the demonstrator COSB made of fresh prepreg strands, voids mostly appear as

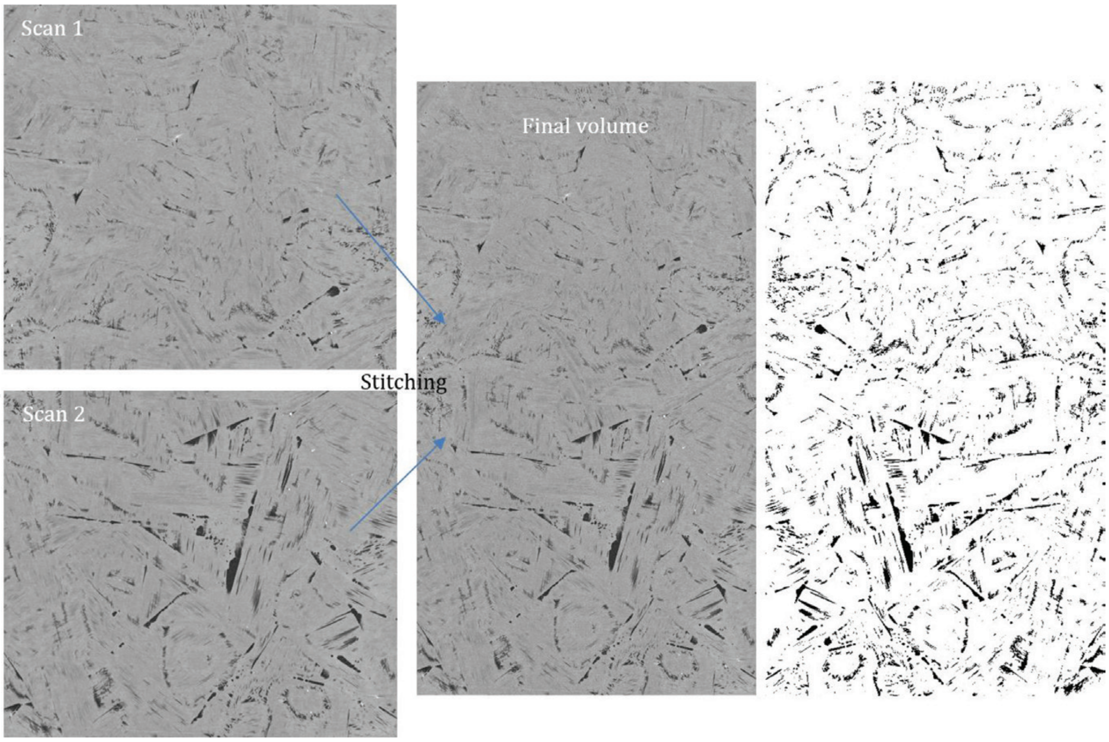

Figure 8. Stitching of multiple scanned volumes to obtain completed final micro-CT scanned volume.

needle shapes, and void content was determined to be 8.55%. This is considerably higher than the 2.07% void content determined via microscopic analysis. This is not surprising, as the void content from micro-CT is obtained from a 3-D volume, while the void content concluded from microscopic imaging is obtained from 2-D images. There is a difference of one spatial degree between two sources of data. Because micro-CT can reveal void information in 3-D, it has advantages compared to 2-D techniques such as microscopic images of polished sections.

The curvature of the deformed strands is a critical parameter when trying to predict and optimize the modulus and strength [7, 8] of COSBs using FEA techniques. Micro-CT allows for examination of this critical parameter. Several shapes of deformed strands (10 × 20 mm), extracted from the micro-CT data, are displayed in **Figure 10**. Strands have various deformed shapes after being cured within the COSB, due to the randomness and complex geometry of the material (**Table 1**).

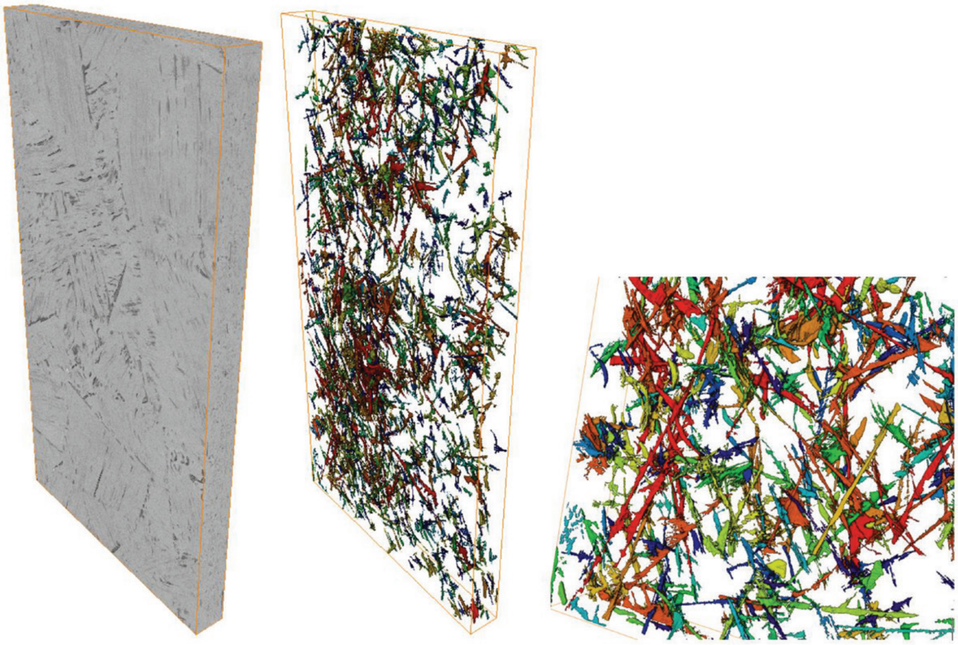

Figure 9. Extracted void content (8.55% voids) and void morphology of COSB (left and middle). Close-up view of void morphology (right).

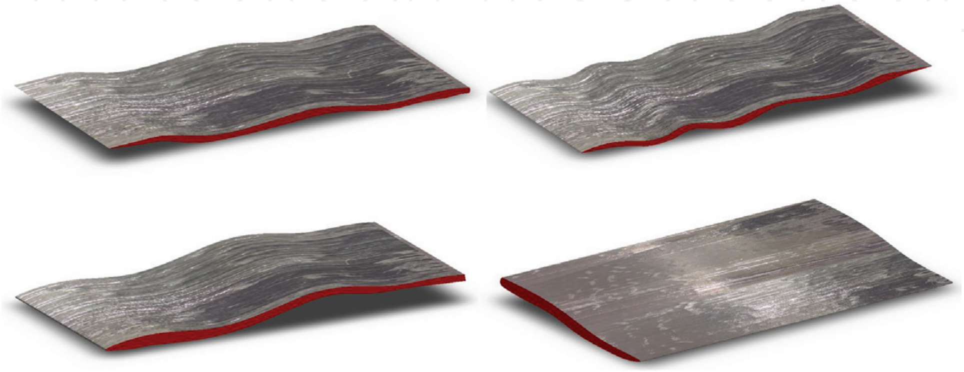

Figure 10. Extracted shape of deformed strands in COSB.

Technique	**Approximate processing time**	**Maximum sample size**
Ultrasonic scan (3-D)	4–6 hours	1 × 1 m by sample thickness
Microscopic image (2-D)	1–2 hours	5 × 5 cm
Micro-CT (3-D)	6–12 hours	3 × 5 cm × 5 mm by sample thickness

Table 1. Comparison of different techniques: approximate processing time and sample size.

3.4. Comparison of NDE techniques

In this chapter, the void content, void distribution, void morphology and deformed strand shapes of carbon fiber epoxy composite panels were examined. Microscopic cross-sectional analysis and NDE techniques (ultrasound and micro-CT) were employed. Traditional laminates and reused COSB were examined using these techniques. Conclusions on the pros and cons of each technique are discussed below:

3.4.1. NDT ultrasonic scans

a. Ultrasonic scans evaluate the overall void distribution in a panel-level scale. Macrolevel information such as void cluster regions, and distribution of matter, can be revealed by this technique. Ultrasound scans can also evaluate relatively large sample sizes.

b. Signal attenuation level does not directly link to void content. Ultrasonic scans cannot offer a void content number quantitatively and accurately without the use of reference panels. Overall relative panel level void content can be estimated when compared to ultrasonic image of a reference panel with low void content.

3.4.2. Microscopic image study

a. Microscopic imaging of cross sections is one of the most convenient methods in evaluating composite void content. The process of sample preparation including cutting, polishing and image postprocessing are relatively straightforward and less time consuming compared to other methods.

b. However, it is not nondestructive. Samples need to be cut and polished. Extra-damages are possible to be introduced during sample preparation procedure. Also, void content is only investigated in the area of the cross-sectional cut, which is a 2-D area but not a 3-D volumetric study. The results vary based on location within the sample.

3.4.3. Micro-CT

a. Micro-CT is a nondestructive method. It yields accurate void content values, and reveals void morphology. However, it is time consuming and requires a large amount of image-processing work. One high-resolution micro-CT scan can take up to dozens of hours and engage dozens of GBs of data space in computer system.

b. Limitation of the sample size cannot be ignored. Due to the limitation of scanning time and storage, the sample size of micro-CT is relatively small, normally within a few millimeters in length and width. As a result, some materials could potentially loose representativeness when examined via a micro-CT scan.

c. Due to this limitation of the sample size, overall void distribution in panel size level cannot be obtained. So, this technique does not work well for large panels with none-even mass distribution.

4. Conclusions

The void contents of COSB made of reused production scraps as well as conventional composite laminates were studied using different NDE methods, including ultrasonic C-scan, micro-CT scan, and microscopic image analysis of polished cross sections. Results were reported and the general pros and cons of the different techniques as well as specific observations relative to the COSB material have been identified. The void content, void distribution, void morphology and curvature and geometries of the deformed strands obtained by the NDE techniques in this study are valuable information for future COSB design and optimization. With these information, methods such as FEA [7] and hybrid methods using analytical solutions and homogenization schemes [8] can be used to predict various mechanical responses of such material. Future work will be focused in these directions.

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