Development and Validation of NDE Standards for NASA's Advanced Composites Project

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ABSTRACT

The adoption of composite materials in aircraft manufacturing for use in structural applications continues to increase but is still relatively new to the industry. Composite components have large development and certification costs in comparison to metallic structures. Traditional methods of nondestructive evaluation (NDE) used for isotropic materials such as metals may not be adequate for composite applications and therefore is a contributing factor to the cost and complexity of developing new structural composites. Additionally, the defects of interest in composite materials are significantly different from metals. Thus, good quality composite reference standards are essential to obtaining reliable and quantifiable NDE results. Ideally, reference standards contain flaws or damage whose NDE indications most closely represent those created by actual flaws/damage. They should also be easy to duplicate and inexpensive to manufacture. NASA's Advanced Composites Project, working with industry partners, developed a set of composite standards that contain a range of validated defects representing those typically found in aerospace composite materials. This paper will provide an overview of the standards fabricated, the manufacturing plans used to fabricate them, the types of defects included, and validation testing that has performed. Also discussed is an inter-laboratory "round-robin" test that is being performed on these standards. The paper will describe a guidance document being compiled to outline relevant inspection procedures for challenging and critical defects unique to composites where conventional techniques may not be appropriate.

Keywords: Composites, NDE, Standards

INTRODUCTION

In the Advanced Composites Project (ACP), NASA is collaborating with members of the aerospace industry to reduce the timeline to develop and certify composite structure for commercial and military aeronautic vehicles. NASA and industry have identified three focus areas, or technical challenges, as having major impact on the current certification timeline. One focus area, Technical Challenge (TC2) - Rapid Inspection, is concerned with increasing the inspection throughput by the development of quantitative and practical inspection methods, data management methods, models, and modeling tools. One of the objectives in TC2 is to develop tools for rapid quantitative characterization of defects. The adoption of composite materials in aircraft manufacturing for use in structural applications continues to increase but is still relatively new to the industry and has relatively large development and certification costs in comparison to metallic structures. Traditional methods of nondestructive evaluation (NDE) used for isotropic materials such as metals may not be adequate for composite applications and is a contributing factor to the cost and complexity of developing new structural composites. Additionally, the defects of interest in composite materials are significantly different from metals.

Therefore, under the ACP, TC2, NASA initiated an assessment of the current state-of-practice (SoP) in the aerospace industry for the NDE of composite structural components and a determination of what factors influence the NDE process for composites. This assessment spanned the fixed-wing, rotary-wing and propulsion segments of the aircraft industry and received input from a corresponding cross-section of the aviation industry. The assessment identified critical defect types, current inspection methods, NDE data exchange methods, processes and methods suitable for automation or improvement, and other issues associated with the inspection and certification of composite aerospace structures. Based on the results of this assessment, NASA procured from the ACP industry partners a set of composite specimens (standards) that contain a range of controlled defects representing those typically found in aerospace composite materials. Defect types included such manufacturing defects such as varying amounts of porosity (in a range typically found in autoclave cured aerospace composites) and varying degrees of fiber waviness (both in-plane and out-of-plane), as well as inserts representing delamination type defects. In addition to the composite specimens, the industry partners also provided details on the fabrication procedures and validation results.

RESULTS OF THE STATE OF PRACTICE ASSESSMENT

The goal of the survey was to assess the current SoP for NDE/nondestructive testing (NDT) of composite parts and structures, drawing from as large a cross-section of the industry as was practical. The survey sought to identify critical defect types, inspection methods, NDE data exchange methods, processes and methods suitable for automation or improvement, and other issues associated with the inspection and certification of composite aerospace structures as part of the assessment process. The results represent the responses from relevant points of contact involved in composite design, testing, fabrication, inspection, NDT equipment sales, NDT R&D, and NDT management. One hundred fifty-three individuals, representing about 1/10th of those invited to participate, took the survey. Nearly half (46%) currently work in the aerospace industry, with the remainder working in other composite related industries such as the automotive industry.

Table 1 summarizes the top survey answers to questions (listed in column headers) about composite defects. The most common composite defects addressed today are delaminations, disbonds, and weak bonds (bond integrity/strength). These three defects are of most concern, according to survey respondents, and receive the largest amount of research in the industry. The type of defects viewed as most challenging to address are microcracking, bond integrity/strength, and moisture ingress. It is important to note when separated as a group, fabricators listed porosity, foreign material, and fiber waviness, along with delaminations/disbonds, at the top of their list of most common defects they encounter.

Table 1: Summary of top SoP survey answers to questions about composite defects.

Rank	Most Challenging Defect	Frequency of Defect	Better Standards Needed	Defects of Concern	Effect to Structure
1	Microcracking	Delaminations	Porosity	Disbonds	Disbonds
2	Bond Integrity / Strength	Disbonds	Disbonds	Delaminations	Delaminations
3	Moisture Ingress	Bond Integrity / Strength	Wrinkles / Fiber Waviness	Foreign Material	Bond Integrity / Strength
4	Heat Damage	Porosity of Laminates	Delaminations	Microcracking	Wrinkles / Fiber Waviness
5	Wrinkles / Fiber Waviness	Moisture Ingress	Bond Integrity / Strength	Bond Integrity / Strength	Porosity

Most respondents (64%) agreed that they deal with flaws that need better physical reference standards. Therefore, based on the results from the survey we chose to fabricate NDE standards to represent the top four defects listed in Table 1 under the column “Better Standards Needed.” Additionally, variations in part geometry were also included in the standards fabricated. We decided not to fabricate bond integrity/strength standards at this time, due in part to the additional difficulty of creating reference standards for this defect type (although these standards may be included in the future). In addition to the defect types identified by the SoP, we fabricated several standards that contained defects commonly occurring during the manufacture of composites using automated fiber placement (AFP) equipment, such as ply laps, gaps and twisted or folded tows.

FABRICATION OF THE NDE STANDARDS

Delamination / disbond NDE standards can be fabricated using a number of different well-known methods (1, 2). On the other hand, porosity and wrinkles are among the most challenging defects to create in a controlled manner during the fabrication of NDE standards. These two defects can arise from an array of manufacturing issues. In developing these standards, it is helpful to consider the factors that can cause porosity and wrinkling.

There are two general types of porosity, surface porosity and internal porosity (3) which can arise from a number of factors. For example, Lenoe (4) reports that advancing the cure too quickly causes the formation of voids from the vapor of the resin or solvent. Some of the resin ingredients can volatilize if the temperature steps of the cure cycle exceed the rate at which the cross-linking occurs during polymerization. Stone and Clark (5) discuss the formation of porosity due primarily to the entrapment of air during the formulation of the resin system, in resin rich areas, and Jeong (6) considers porosity from moisture absorbed during material storing and processing. In addition, inadequate values of temperature and pressure or failures in the vacuum bag during cure cycle contribute to porosity formation (7).

Likewise, many factors can cause wrinkling in composite structures. For instance, Dodwell (8) considers wrinkles caused by buckling of individual plies when parts are under compression during consolidation over complex geometries. Further, Bloom (9) discusses a number of other causes of wrinkling such as a mismatch in surface area between the ply and the tool surface, during reinforcement over complex geometries, and as a result of defects in the as-delivered prepreg material.

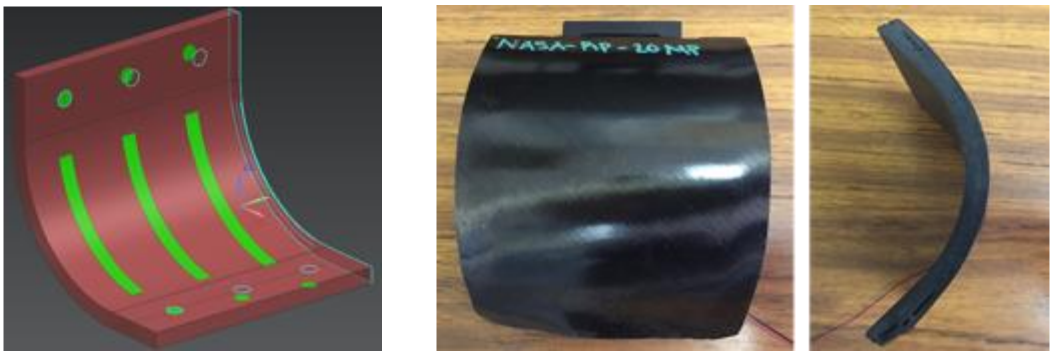
For this project, our industry partners fabricated 64 NDE standards using one of three material systems. Forty-six of the standards used an IM7/8552 or IM7/8552-1 material system with the fibers being either uni-directional, braided, woven or slit-tape. Ten standards used BMS 8-276 material system and 8 used T-800SC Triaxial Braid [0/+60/-60] with 3M AMD-825. The geometries produced include 21 flat panels, 10 S-curved panels, 9 wedges, 8 radius corner standards, 8 rotorcraft blade-spar tubes, 4 step and 4 flange standards.

The following sections will provide an overview of each type of defect standard fabricated, grouped by defect type, and some representative examples of the geometry, defect size, shape and location.

Delamination Standards

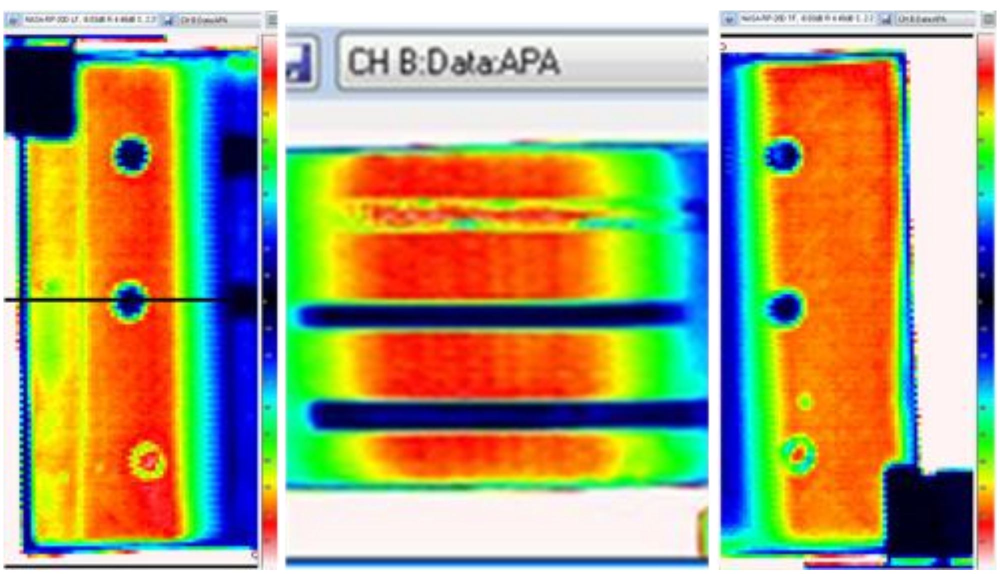
Twenty-two of the standards produced contained delamination defects. A majority of the delamination standards were fabricated by hand layup, with Polytetrafluoroethylene (PTFE or Teflon™) inserts added at various locations throughout the thickness. Most of the circular co-cured inserts are 0.25 in. (0.635 cm) diameter PTFE film. A few inserts are 0.1 in. (0.254 cm) diameter to 1 in. (2.54 cm) diameter PTFE film. In some geometries, the manufacturer used rectangular and square PTFE strips in place of circular film. In addition, a number of specimens had 0.25 in. (0.635 cm) diameter flat-bottom holes (FBH) added after cure. To simulate internal disbonds more accurately, some of the FBH's were subsequently back-filled with cured epoxy.

Figure 1 shows a drawing and photographs representative of a radius/corner delamination standard, with PTFE inserts, using an IM7/8552 material system. The standard in Figure 1 was fabricated using a quasi-isotropic stacking sequence, $[0/90/45/-45]_{3s}$. Figure 2 shows 3 through-transmission, ultrasonic c-scans of the 3 delamination regions of the standard in Figure 1. The manufacturer produced the ultrasonic c-scans in Figure 2 using a 1.0 in. (2.5 cm) diameter, 2.0 in. (5.1 cm) focal length, 2.25 MHz transducer with a scan resolution of 0.030 in. (0.076 cm). The manufacturer gated the c-scan to include the back wall reflection, thus revealing the delamination at multiple depths in a single image. Figure 3 provides another example of a delamination standard. This S-curved standard contains 29 simulated delaminations, at different ply locations through the thickness, using three different types of delamination simulators: 0.001in. (0.0025 cm) brass foil coated with Frekote® mold release agent, Air Tech International release ply fabric and American Biltrite 6782 pressure sensitive tape. The standard was fabricated BMS 8-276 carbon fiber composite. The manufacturer performed validation (Figure 3d) of the standard using 1 MHz ultrasonic through transmission inspection with 0.04 in. (0.1 cm) resolution.



(a) (b)

Figure 1: (a) Mechanical drawing and (b) photographs of one radius corner, delamination standard using an IM7/8552 material system.



(a) (b) (c)

Figure 2: Ultrasonic c-scan results from the radius corner, delamination standard shown in Figure 1 with the three scan regions indicated.

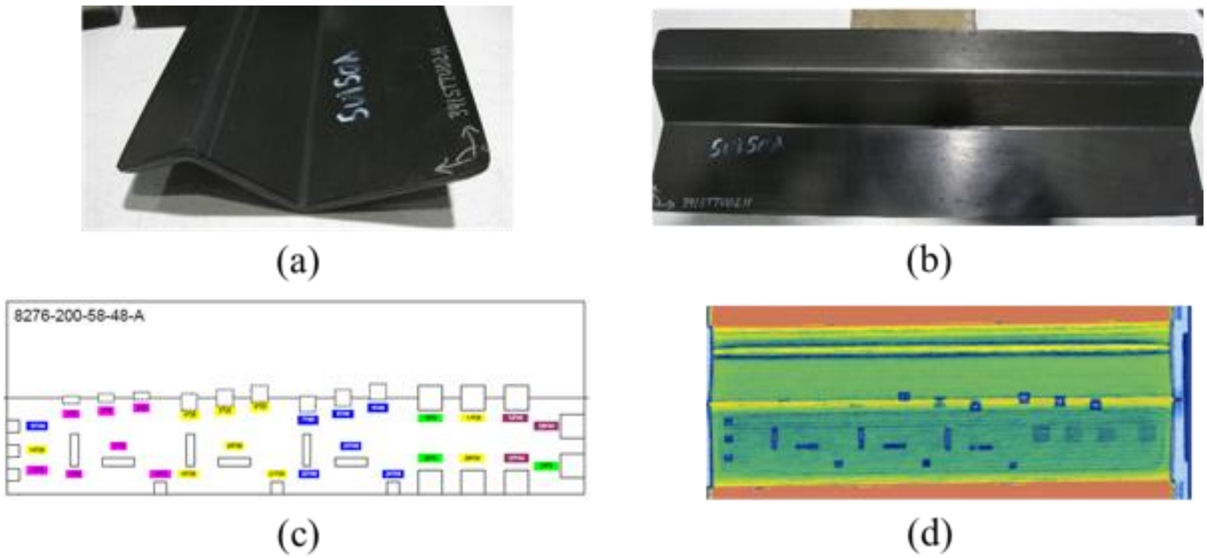


Figure 3: Photographs (a) & (b) of S-curve panels with multiple different delamination simulators. (c) Drawing of the panel with defect type, location, and (d) through-transmission ultrasound validation c-scan.

Wrinkle Standards

Seven of the standards produced contained fiber orientation defects (wrinkling), five of the standards were flat plates and two were rotorcraft blade spar tubes. The industry partners fabricated 12 in. x 12 in. (30.5 cm x 30.5 cm) wrinkle standards from BMS 8-276 composite material using one of two ply architectures $[-45/90/+45/0_2/+45/90/-45]_s$ and $[-45/90/+45/0_4/+45/90/-45/0]_s$. To produce controlled wrinkles, the manufacturer used stainless steel rods, placed perpendicular to the 0° plies during the layup at regular intervals and at different ply locations (depths) to create the wrinkle pattern. Figure 4 shows a schematic of the typical layout of the rods in the standard. Two diameters of rods were used, 0.1875 in. (0.476 cm) and 0.125 in. (0.3175 cm) as shown in Figure 4. Additionally, the rod locations alternated between the 3rd and 4th plies and between the 13th and 14th plies in the pattern shown in Figure 4. The standard was then compacted at 150°F for 1 hour, after which the manufacturer removed the rods then bagged and cured the specimen as normal. Figure 5 presents photomicrographs of the results achieved using the method of fabricating wrinkles at locations 9 (Figure 5a) and 15 (Figure 5b) in the standard. Figure 6 shows the manufacturer's verification of the wrinkling using single-sided infrared flash thermography.

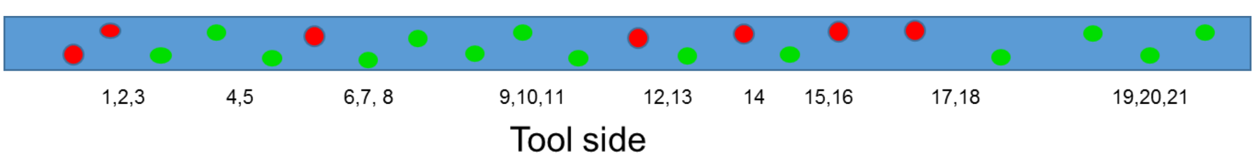
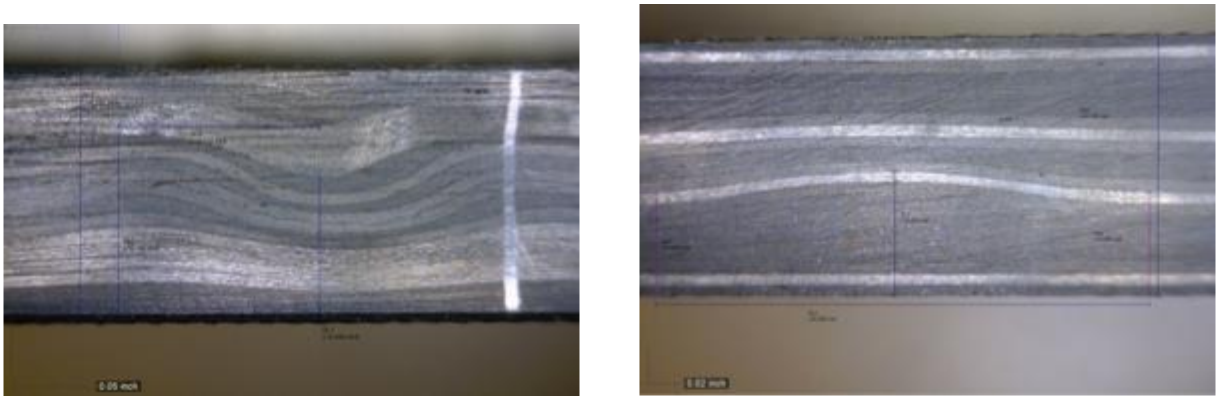


Figure 4: Schematic of the typical layout and numbering of the rods used to create wrinkling in the flat plate standards. The diameter of the rods shown in red are 0.1875 in. (0.476 cm) and the ones shown in green are 0.125 in. (0.3175 cm). Rod locations alternated between the third and fourth plies and between the 13th and 14th plies.



(a) (b)

Figure 5: Photomicrographs of two wrinkle locations as indicated in Figure 4, (a) is location 9 and (b) is location 15. A through-thickness view is shown in the images.

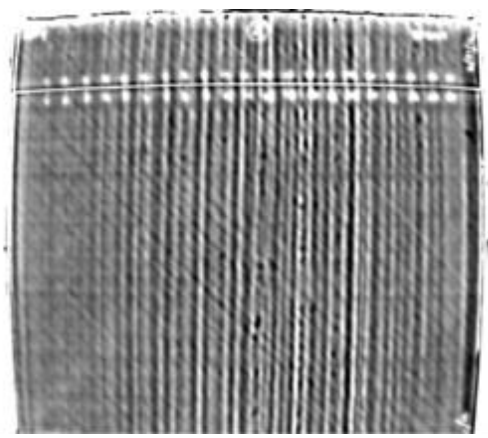


Figure 6: Verification results using flash thermography. The image is an instantaneous time derivative calculated 1.6 seconds after flash heating. Data corresponds to an area view of the specimen.

The rotorcraft blade spar tubes specimens are generic elliptical airfoil shaped tubes that are representative of main and tail rotor blade spar structures. Figure 7 shows a photograph of one of these specimens. These specimens were fabricated by hand layup of IM7/8552 over a 3D printed acrylonitrile butadiene styrene mandrel. After layup, the industry partner used an aluminum clamshell to maintain the outer mold line dimensions. Wrinkles were produced by over sizing the layup mandrel, minimizing debulking of the preform (15 minute vacuum at room temperature per debulk cycle), using best practice for pleating the internal vacuum bag, and using a high pressure cure cycle (100 psi). There was one unintended consequence; some of the inner mold line wrinkles entrapped the fluorinated ethylene propylene release film, therefore some wrinkles contain foreign object damage (FOD). Figure 8 shows several example photomicrographs of the cross section of the rotocraft blade spar tubes with wrinkles and FOD.

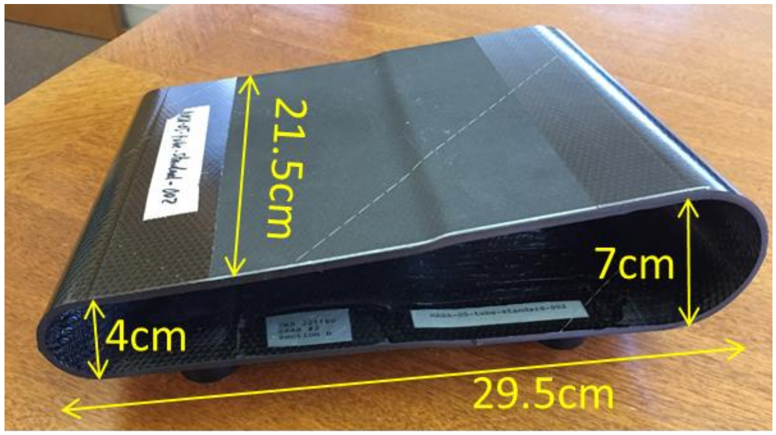


Figure 7: Photograph of a typical rotocraft blade spar tube specimen.

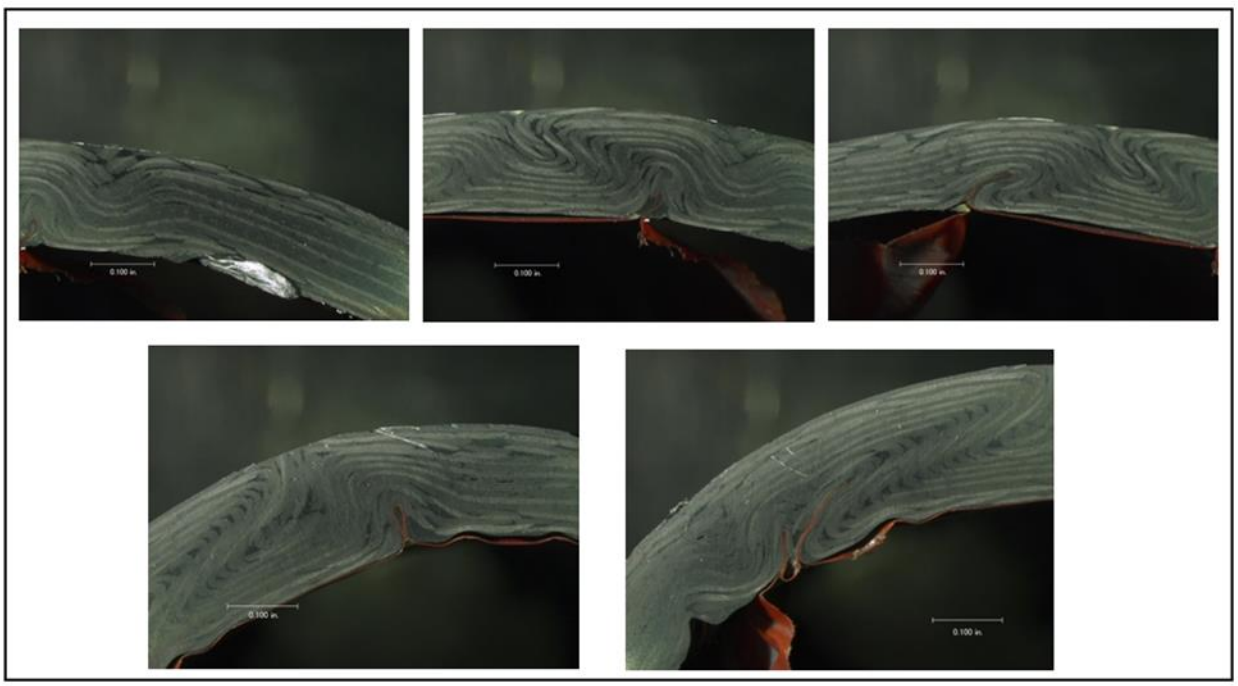
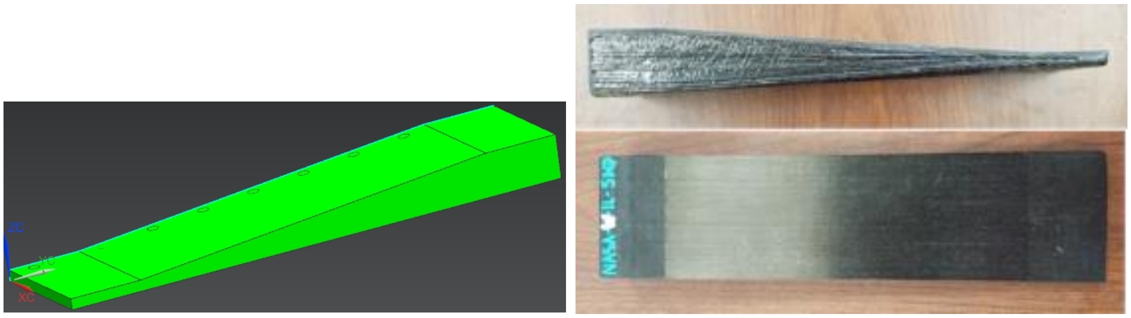


Figure 8: Photomicrographs showing the cross section of wrinkle defects and FOD in rotocraft blade spar tubes.

Porosity Standards

Twenty of the standards produced contained porosity introduced by using a modified cure cycle with either low (1/2 the recommended) or zero autoclave pressure but constant vacuum. Figure 9 shows a drawing and photograph of one of the wedge standards fabricated with process induced porosity. This five degree wedge standard was laid up using a quasi-isotropic stacking sequence, $[0/90/45/-45]_{ns}$, where n varied depending on the thickness. The manufacturer interleaved ply drops forming the wedge along the slope, alternating short plies and longer plies in the stacking sequence, then completed the stack by placing a full set of plies, one complete stacking sequence, as a cover layer over the exposed ply drops. To validate the integrity of the specimen, the manufacturer acquired through-transmission ultrasonic attenuation data (Figure 10) using a 2.25 MHz, 3.0 in. (7.62 cm) focal length transducer that was 1.5 in. (3.81 cm) in diameter. From the ultrasonic validation data shown in Figure 10, the manufacturer calculated the porosity of the standard to be between 2 and 4% by volume.



(a) **(b)**

Figure 9: (a) Mechanical drawing and (b) photographs of an example porosity standard with a 5° wedge.

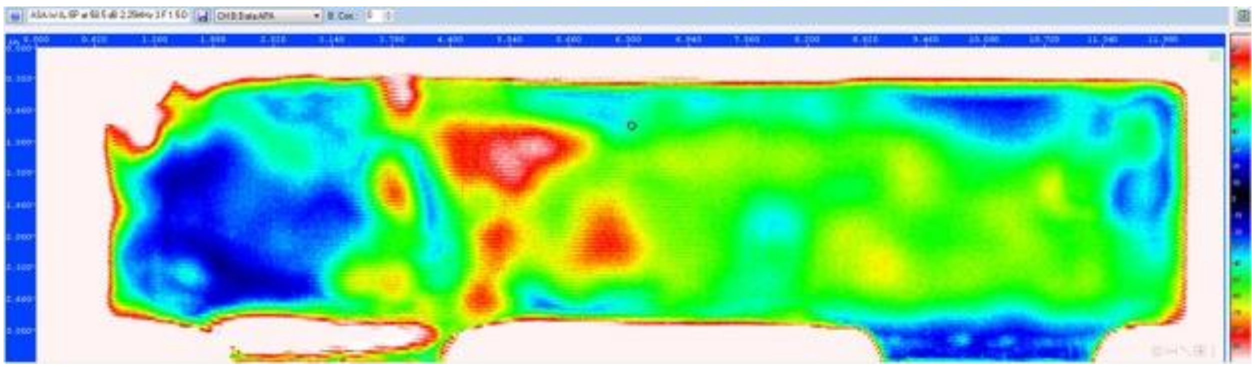
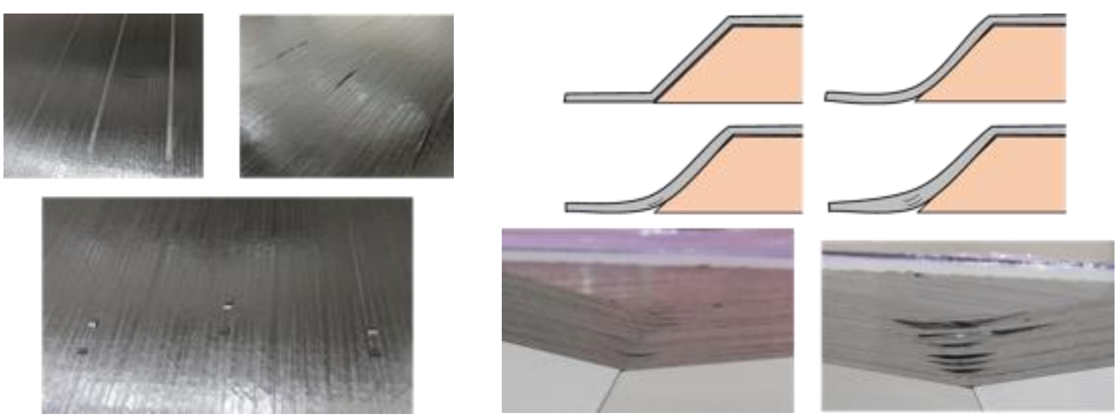


Figure 10: Example verification results for the standard shown in Figure 7 using through-transmission ultrasound. From the attenuation of the ultrasonic signal and the known thickness of the specimen the porosity was calculated to vary between 2 and 4% by volume.

Other Standards

A few standards were fabricated to simulate defects that can be found when composite components are manufactured using AFP equipment. These defects include fiber bridging, twisted, folded and missing tows. Figure 11a shows several photographs of these types of defects during the lay-up process and Figure 11b show a graphic of how fiber bridging occurs (top) and photographs (bottom) of fiber bridging defects.



(a) **(b)**

Figure 11: (a) Photographs of AFP type defects. Upper-left: missing tows; upper-right: twisted-tows; lower: folded tows; and (b) graphics and photographs of fiber bridging defects.

CONCLUSIONS AND FUTURE DIRECTIONS

In response to a state-of-the-practice survey that identified the need for better composite NDE standards, NASA's ACP in partnership with industry has developed a set of 64 composite standards. This paper has provided an overview of a majority of the standards fabricated. The standards include 22 with various types of simulated delaminations, 20 with varying amounts of porosity, nine with AFP tow defects, seven with fiber wrinkling, two with microcracking and two with bond integrity or weak bond defects. A majority, 46, of the standards used an IM7/8552 or IM7/8552-1 material system with the fibers being either uni-directional, braided, woven or slit-tape. A few of the standards, 10 in total, used BMS 8-276 material system and 8 used T-800SC Triaxial Braid [0/+60/-60] with 3M AMD-825. The geometries produced include 21 flat panels, 10 S-curved panels, 9 wedges, 8 radius corner standards, 8 rotorcraft blade-spar tubes, 4 step and 4 flange standards.

NASA has developed a complete database documenting all of the standards fabricated. Further, NASA has begun a process of inter-laboratory round robin testing of these standards among the members of the NASA Advanced Composites Consortium (ACC) (10). The ACC is a public-private partnership with five organizations to advance knowledge about composite materials, reduce the certification timeline and improve the performance of future aircraft. The NDE techniques to be used in the round-robin testing will include, but are not limited to ultrasound, laser based ultrasound, thermography, and x-ray CT. NASA will compile the data from all of the inspections into a publicly available "handbook" documenting the recommended protocols for detecting and characterizing these common flaw types in complex composite structures. Finally, at the conclusion of the ACP, these NDE standards will be available for use on a loan basis to the NDE community in general.

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