

Offset-Stoichiometric Reflowable Composite Bonding Method with Adhesive for Mitigating Strict Faying Surface Tolerances

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ABSTRACT

Inherent susceptibility of adhesive bonds to miniscule quantities of contamination can cause undetectable weakened bonds. For this reason, the Federal Aviation Administration (FAA) places strict regulations on adhesively bonded joints in primary aircraft structures. To meet certification requirements aircraft manufactures resort to redundant load paths in the form of fasteners which inherently add weight to the structure and increase manufacturing time. In prior work, a secondary bonding technique called AERoBOND was developed, which utilized off-stoichiometric epoxy-matrix resins to facilitate reflow and diffusion of the resin within the joint interface during a secondary bonding/cure process, thus achieving a bond similar to a co-cured joint. However, the AERoBOND process required tight spatial tolerances between the two parts being joined. This study examined the utilization of conventional adhesive with the AERoBOND method to act as a filler in the joint line, effectively reducing the need for tight tolerances on the joining parts and serving as a flexible alternative for existing manufacturing processes. Ultrasonic inspection, optical microscopy, and ASTM International standard tests were performed to analyze the joints for defects and to quantify the mode-I and mode-II interlaminar fracture toughness and short beam strength of the proposed methodology with varying manufacturing parameters. The comprehensive results indicate that the AERoBOND+ method with and without surface preparation performs comparably to co-cured and conventional, adhesively bonded joints when secondary cured in an autoclave with 791 kPa of pressure. As an example, the AERoBOND+ panel without surface preparation bonded with 791 kPa of pressure (referred to as AB+3 throughout paper) had a mode-I fracture toughness (G_{Ic}) of 0.643 kJ/m² and a mode-II fracture toughness (G_{IIc}) of 4.000 kJ/m² in the non-precracked condition and 4.218 kJ/m² in the precracked condition at the adhesive-to-prepreg interface. These results were 96%, 142%, and 217%, respectively, of a co-cured baseline panel (referred to as C1 throughout paper).

Keywords: Composites; Reflowable Interface; Bonding; Adhesive; Fracture Toughness

1 INTRODUCTION

Carbon fiber reinforced polymer (CFRP) primary aircraft structures have flown in commercial aerospace applications for over 35 years [1], demonstrating exceptional strength-to-weight ratios and durability resulting in fuel savings and longer flight ranges. Despite this, aircraft such as the Boeing[®] 787 Dreamliner[®] still fly with thousands of redundant fasteners [2]. The use of redundant fasteners is a direct result of the inherent uncertainty associated with adhesive bonds, primarily arising from material discontinuity at the composite-to-adhesive interfaces which are prone to contamination. A lack of certifiable non-destructive techniques (NDE) for evaluating bond strength has led to the Federal Aviation Administration (FAA) certification requirements for adhesively bonded aircraft structures [3]. Fasteners are employed as the most cost-effective and straightforward solution to satisfy the FAA's mandated criteria. Nevertheless, the requirement for redundant load paths in adhesively bonded joints contributes to additional challenges such as increased aircraft weight, higher costs, and longer manufacturing times [4]. Additional factors include stress concentrations around bolts and aging of adhesive bonds. An extensive description and evaluation of bonded, bolted, and hybrid bonded-bolted structural configurations is covered in [5] and [6]. For secondary bonding, quantifiable and consistent surface preparation is required to prevent contamination and ensure proper adhesion [7, 8, 9]. On the other hand, co-cured bonds do not require surface preparation and produce predictable and certifiable aircraft structures with reduced reliance on redundant load paths.

The NASA AERoBOND project investigated reformulated aerospace epoxy-matrix resins to enable reflow and diffusion of the resin at the joint interface during a secondary bonding/cure process. By promoting the intermixing of the matrix resin at the interface, the project aimed to eliminate material discontinuity and reduce reliance on adhesively bonded joints. The AERoBOND method uses a stoichiometric offset in the hardener-to-epoxy ratio on the faying surfaces of the laminates. Assembly of the components in a subsequent “secondary co-cure” process results in a joint with no discrete interface (Figure 1). The AERoBOND process involves the preparation of composite components with epoxy-rich (ER) prepreg at the faying surfaces. The ER resin remains flowable after primary cure due to a stoichiometric offset, which limits molecular weight advancement and crosslinking. For the secondary cure, the composite parts are assembled with hardener-rich (HR) prepreg material between the ER surfaces. This arrangement enables the intermixing of ER and HR resins, leading to the formation of a conventional ratio (CR) resin. As a result, the composite assembly exhibits a seamless interface without discernible material discontinuities. This approach ensures a uniform and integrated structure, enhancing the overall performance of the component and serves as a substitute for adhesive-based secondary bonding [10, 11, 12].

The present study focused on exploring the incorporation of adhesive into the AERoBOND method, denoted as AERoBOND+ (AB+) herein. The objective of this study was to alleviate the strict manufacturing tolerances of the AERoBOND method. AERoBOND+ alleviates the strict manufacturing tolerances of the AERoBOND method with the inclusion of conventional adhesive as a gap filler. The conventional adhesive flows/conforms to the potentially non-uniform spacing

[‡] Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the hardware and materials used in this study. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified product is the best available.

between the parts while the ER and HR prepreg materials retains consistent thickness and ratio at all locations. The inclusion of conventional adhesive in the AERoBOND+ method also offers the advantage of making AERoBOND+ a drop-in replacement for existing state-of-the-art adhesively bonded composite joints. This means that AERoBOND+ can seamlessly replace current bonding methods without requiring significant modifications or changes to the manufacturing process. This compatibility and ease of implementation makes AERoBOND+ a promising option for enhancing composite bonding in various industries where composite materials are utilized.

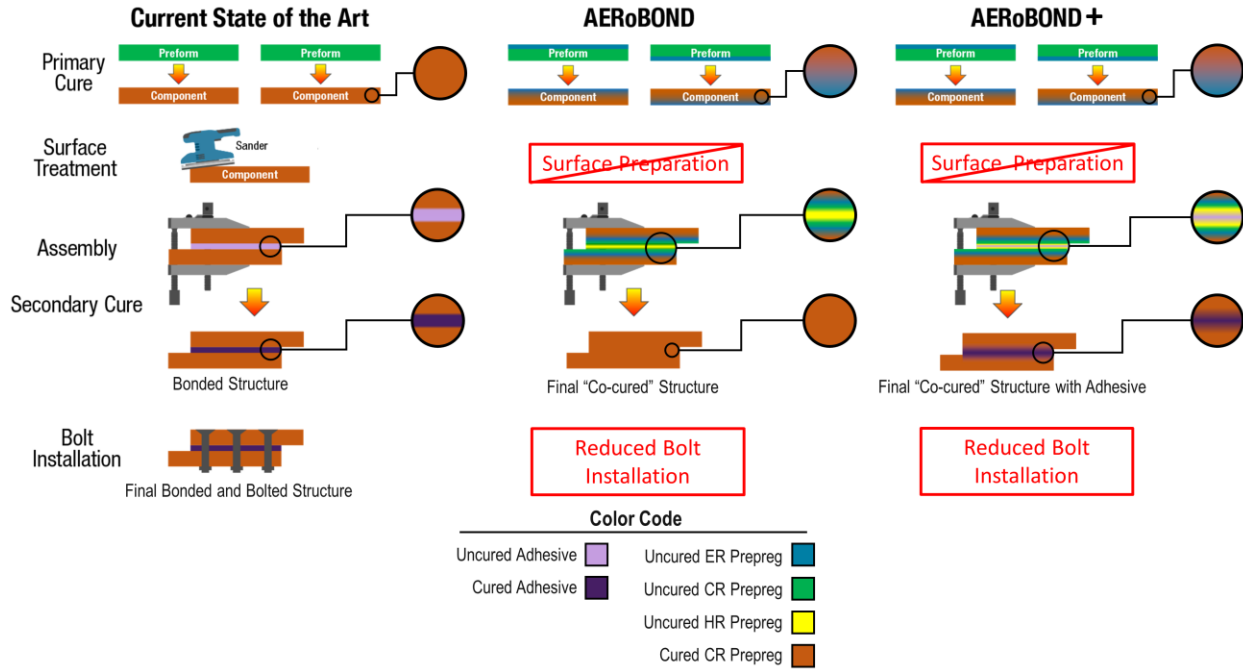


Figure 1. Composite structure bonding process comparison of the current state of the art with AERoBOND and AERoBOND+.

2 EXPERIMENTATION

Previous work at the NASA Langley Research Center led to the approximate resin compositions, bagging schemes, cure cycle parameters, evaluation methods, and chosen mechanical test types described herein [10, 11, 12, 13, 14, 15, 16].

2.1 Materials

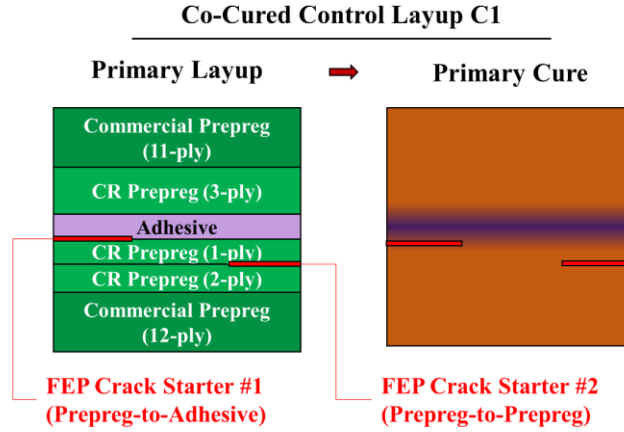
Epoxy resins were formulated using API-60[®] (part A) epoxy resin supplied by Kaneka North America[®] with an epoxy equivalent weight of 131 g/mol and diethyltoluenediamine (DETDA, part B) hardener supplied by Alpha Chemistry[®] with a hardener equivalent weight of 44.6 g/mol. ER resin, CR resin, and HR resin were formulated from part A and part B. The ER, CR, and HR resins had initial stoichiometric offsets of $r = 0.1$, $r = 0.8$, and $r = 2.5$, respectively, where r is defined in Eq. (1).

$$r = \frac{eq_H}{eq_E} \equiv \frac{\text{molar equivalents of hardener}}{\text{molar equivalents of epoxy}} \quad (1)$$

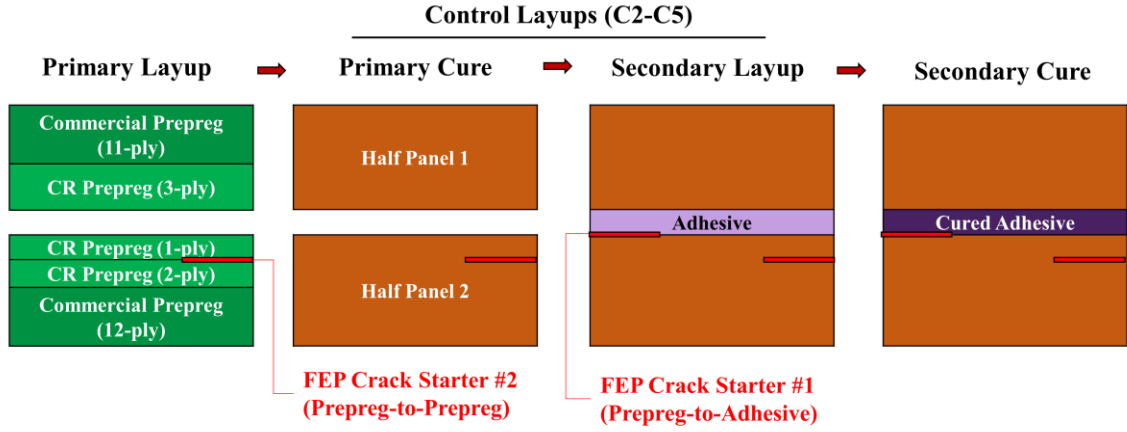
Prior research utilizing rheology and calorimetry indicated that an ER r -value less than or equal to 0.15 effectively inhibited gelation during the primary cure. An ER r -value of 0.1 was chosen for optimal mechanical performance [11]. Unidirectional Hexcel® IM7-G 12K fiber was impregnated with the ER, CR, and HR resins utilizing an in-house prepreg machine at the NASA Langley Research Center. The composite panels were manufactured utilizing the commercial prepreg Hexcel® HexPly® IM7-G/8552, unidirectional, 190 g/m² fiber areal weight (FAW), with 34 wt.% resin content. One ply of Solvay® FM209-1U® film adhesive, 146 g/m² FAW, was used to bond all the composite panels except panel C2M and AB+3M, which used FM209-1M® film adhesive with a carrier mat. Panels C2M and AB+3M were the first panels fabricated and tested. Panels C2M and AB+3M were pathfinder panels to quickly evaluate the feasibility of the AERoBOND+ method; only optical microscopy and end-notched flexure testing were performed.

2.2 Composite Panel Fabrication

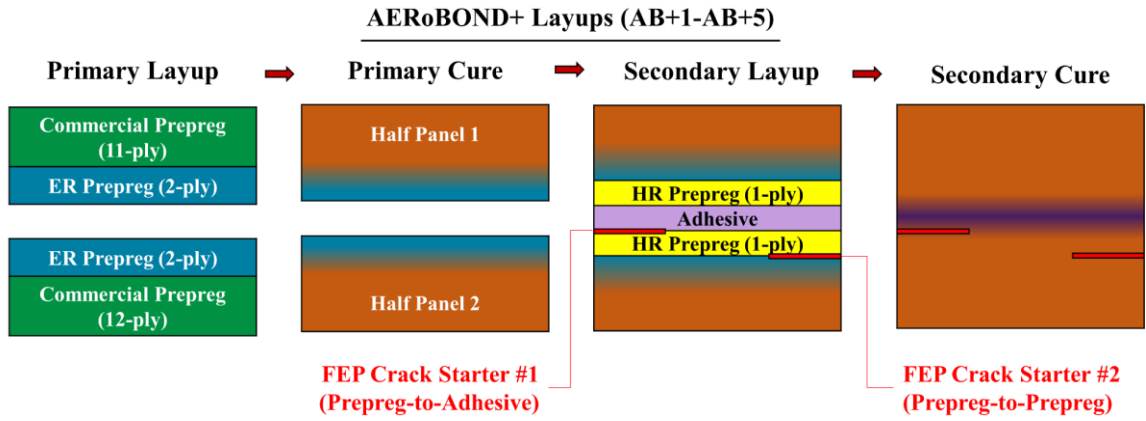
A total of thirteen composite panels were fabricated for testing. Within this set, six panels were designated as control panels, serving as a baseline for comparison, and denoted as C1, C2, C2M, C3, C4, and C5. The remaining seven panels were fabricated using the AERoBOND+ method and are denoted as AB+1, AB+2, AB+3a, AB+3b, AB+3M, AB+4, and AB+5. The material layup order for each panel is shown in Figure 2. Layup for all panels was performed at room temperature.



(a)



(b)



(c)

Figure 2. (a) Co-cured control panel C1 layup diagram, (b) control panels (C2-C5) layup diagram, and (c) AERoBOND+ panels (AB+1-AB+5) layup diagram.

Fluorinated ethylene propylene (FEP) release film (American Durafilm[®]), 12.5- μ m thick, was used during layup to create crack starters for mechanical testing. Two FEP crack starters were incorporated into each panel during the layup processes indicated in Figure 2. Crack starter #1 was positioned at the interface between the adhesive and the prepreg (adhesive-to-prepreg), while crack starter #2 was placed at the interface between the prepreg plies (prepreg-to-prepreg). These crack starters were 76.2 mm long in the fiber direction and spanned the width of each panel. The offset of one ply of IM7-G/8552 prepreg (11 plies in top half panel and 12 plies in bottom half panel) was deliberately employed to position the crack starters near the center of the panel thickness for mechanical testing. However, to locate two crack starters into a single panel offset by one ply of HR prepreg and because of different thickness values of each material (commercial prepreg, CR prepreg, ER prepreg, HR prepreg, and adhesive), each crack starter was near, but not exactly at the mid-plane. Thus, a pure mode-I or mode-II fracture may not be achieved.

Panels C2-C5 and panels AB+1-AB+5 underwent a two-step curing process. The first step was a primary cure cycle that produced two separate half panels as depicted in Figure 2b and Figure 2c. Industry standard vacuum bagging methods were used to fabricate each panel on a flat aluminum tool surface. Special considerations were taken to ensure optimal resin retention. Because the offset resins are designed to not gel during the primary cure cycle, each half panel was enclosed in an impermeable envelope made using 50 μm thick FEP (Airtech[®] A4000V) release film and 25 mm wide medium-tack, flash breaker tape (Airtech[®] Flashbreaker[®] 1). Additionally, edge dams (Airtech[®] Airdam[®] 1) were applied around the perimeters of all panels outside the FEP envelope to prevent resin bleed. The faying surface of each half panel (not applicable to Panel C1) was placed on the tool side (i.e., bottom of laminate stack) to achieve a smoother finish. Prior to sealing the vacuum bag (Airtech[®] Ippalon DP1000) with vacuum, 5-mm thick steel caul plates, permeable release fabric (Airtech[®] Release Ease[®] 234TFP), and a breather blanket (Airtech[®] Ultraweave[®] 1332) were placed over the part. The AERoBOND+ bagging scheme is shown in Figure 3.

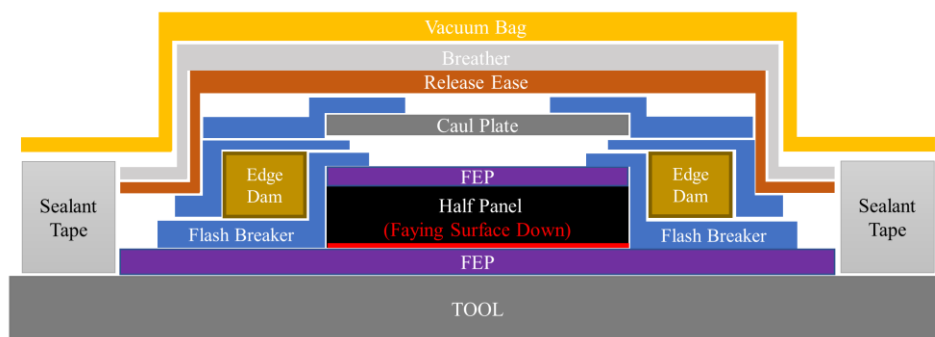


Figure 3. AERoBOND+ bagging scheme.

After vacuum bagging, the panels underwent the following primary cure cycle in the autoclave. Panel C1 underwent the cure cycle below while fully laid up as depicted in Figure 2a resulting in a co-cured panel.

1. Apply vacuum to vacuum bag (VB)
2. Heat to 107°C (225°F) with a ramp rate of 2.8°C/min (5°F/min)
3. Apply 689 kPa gauge (100 psig) pressure
4. Hold for 60 minutes (C1-C5) or 165 minutes (AB+1-5)
5. Heat to 177°C (350°F) with a ramp rate of 2.8°C/min (5°F/min)
6. Hold for 120 minutes (C1-C5) or 30 minutes (AB+1-5)
7. Cooldown with a ramp rate of -2.8°C/min (5°F/min)
8. Release pressure at 60°C (140°F)

Following primary cure, the faying surface r -value of each AB+ half panel was estimated using Fourier transform infrared spectroscopy. Characterization methods were developed previously in [10]. Resin chemistry was characterized by IR spectroscopy using a Thermo-Nicolet[®] iS5 Infrared Spectrometer equipped with an iD7 ATR diamond optic accessory. The r -values were calculated based on the relative peak heights at 907 cm^{-1} (epoxy-specific; epoxide ring) and 1450 cm^{-1} (hardener-specific; N-substituted aromatic C-C of DETDA), normalized against 1514 cm^{-1} (strongest peak in most spectra; aromatic C), using an empirical calibration curve developed from a series of resin samples of known r -values (in the range of 0.1–7). The calibration curve indicated

a linear correlation in the entire r -value range between $\log_{10}(r)$ and the difference of the normalized peak intensities at 907 cm^{-1} and 1450 cm^{-1} given in Eq. (2) [10]. The coefficients were determined by least squares, linear regression. Eq. (3) [10] was used to estimate the r -value of cured resins of unknown composition based on IR spectral data (r_{IR}). The estimated faying surface r_{IR} -values of each AB+ half panel are in Table 2.

$$-0.463 \log_{10}(r) - 0.067 = 3I_{907\text{cm}^{-1}} - I_{1450\text{cm}^{-1}} \quad (2)$$

$$r_{IR} = 10^{\frac{3I_{907\text{cm}^{-1}} - I_{1450\text{cm}^{-1}} + 0.067}{-0.463}} \quad (3)$$

Surface preparation was performed for the half panels of C3, C4, C5, AB+4, and AB+5 prior to secondary layup, which involved hand sanding of the faying surface with 220 grit garnet until it achieved a uniform grey, matte appearance. Afterward, the surface was thoroughly wiped multiple times with isopropyl alcohol (IPA) coated tech wipes until it was free of any residue. All panels (excluding C1, which was co-cured) were then assembled and bonded during a secondary cure cycle. A summary table of the panel descriptions and processing parameters are included in Table 1. A complete detailed panel description and processing parameters are included in Table 2 in the appendix.

Table 1. Panel description overview.

Panel Type	Control					AB+				
Bond Type	Co-Cured	Secondary Bonded				Secondary Bonded				
Surface Preparation (SP)	No SP		SP			No SP			SP	
Curing Equipment	Auto-clave	Auto-clave	Press	Oven	Auto-clave	Press	Oven	Auto-clave	Oven	Auto-clave
Bonding Pressure (kPa)	791 kPa	791 kPa	35 kPa	101 kPa	791 kPa	35 kPa	101 kPa	791 kPa	101 kPa	791 kPa
Panel Name	C1	C2 & C2M	C3	C4	C5	AB+1	AB+2	AB+3a, 3b & 3M	AB+4	AB+5

2.3 Test Specimen Fabrication

Each panel was machined into two types of test specimens. The first type was for double cantilever beam (DCB) and end-notched flexure (ENF) tests, while the second type was for short beam strength (SBS) testing. The DCB/ENF test specimens were cut using a waterjet and were nominally 203 mm (8.0 in.) in length and 20 mm (0.8 in.) in width with fibers running along the direction of the length. Half of the DCB/ENF specimens from each panel contained a crack starter at the adhesive-to-prepreg interface and the remaining half contained a crack starter at the prepreg-to-prepreg interface. The SBS test specimens were cut using a wet saw with a diamond coated tip blade and were nominally 30.5 mm (1.20 in.) in length and 10.2 mm (0.40 in.) in width. The test specimen cutting diagrams are illustrated in Figure 4.

specimens received a final surface polish using 0.05-micron colloidal silica on a felt pad. The polished surfaces were then imaged on a Reicher MEF4M inverted microscope shown in Figure 5. Each sample was imaged with 100 $\times$ magnification at the bondline and 500 $\times$ magnification at the adhesive-to-prepreg interface.

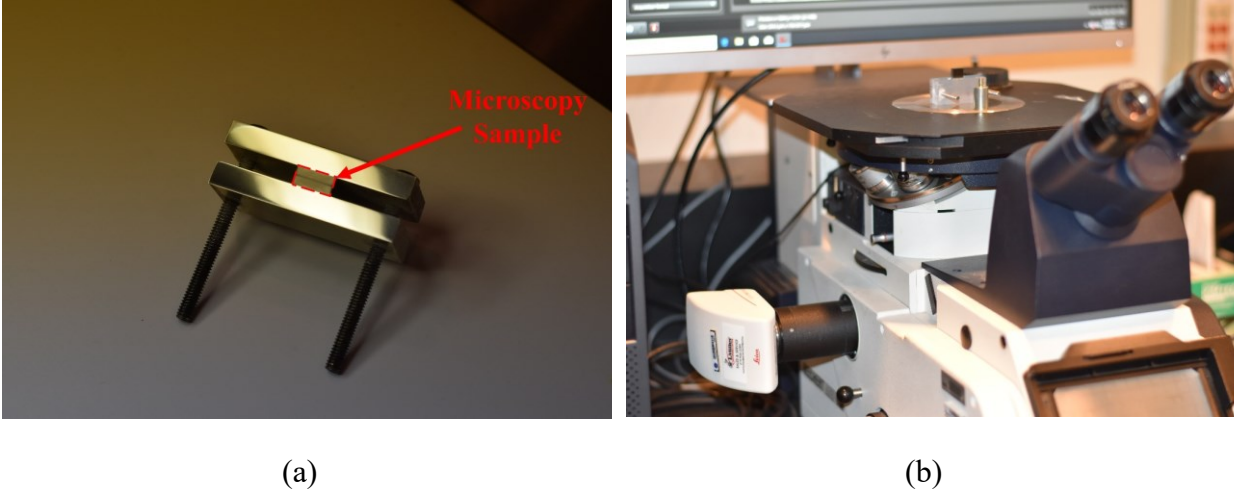


Figure 5. (a) Polished microscopy sample, and (b) Reicher MEF4M microscopy setup.

2.6 Mechanical Testing

2.6.1 Double Cantilever Beam

Double cantilever beam (DCB) tests were conducted in accordance with ASTM D5528-13 using modified beam theory (MBT) data reduction [17] to measure mode-I interlaminar fracture toughness. Specimen edges were wet sanded to reduce out-of-plane stress concentrations (i.e., defects caused by the waterjet), which could lead to premature failures at the edges. The DCB test specimen and experimental setup is shown in Figure 6.

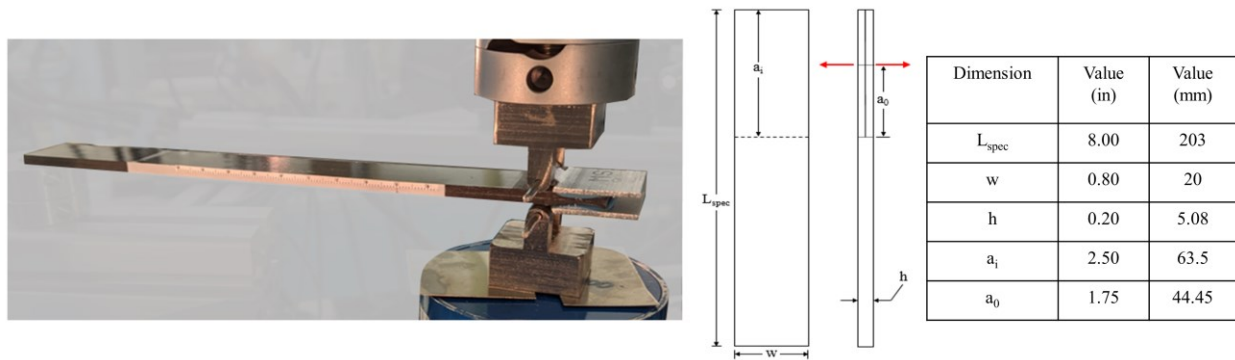


Figure 6. Double cantilever beam test setup and test specimen specifications (modified from [11]).

For load introduction, aluminum piano hinge grips were bonded to the specimen arms using Loctite® EA 9395 two-part epoxy cured in an oven at 66°C for one hour. The specimen edges were spray painted white to facilitate crack visualization, and an adhesive measurement scale in

millimeters was applied to measure crack growth. Specimens were pin mounted to clevis hardware and loaded monotonically in displacement control at a rate of 0.51 mm/min. The loading profile, as per ASTM 5528, included an initial load/unload segment intended to extend the crack tip approximately 1-3 mm beyond the inherent resin pocket that forms behind the FEP insert during curing. The initial loading sharpens the microscopically blunt crack tip formed by the FEP creating a more natural crack tip and rendering it suitable for a subsequent loading with more conservative results. The specimen underwent secondary loading until the crack length reached approximately 50 mm, at which point unloading occurred. The fracture toughness values reported in this paper were obtained during the second loading phase, representing the lowest and most conservative values. Throughout the loading process, two 5-megapixel cameras (one on each side) equipped with 35 mm lenses captured images of the specimen edges every 3 seconds. The images allow each fracture toughness value (i.e., crack growth resistance) to be correlated with a specific crack length, resulting in a delamination growth resistance curve (R-curve).

2.6.2 End-Notched Flexure

End-notched flexure (ENF) tests were conducted in accordance with ASTM D7905 [18] to measure mode-II interlaminar fracture toughness. Each ENF test specimen received the same wet sanding as described previously for DCB testing. The ENF test specimen and experimental setup is shown in Figure 7.

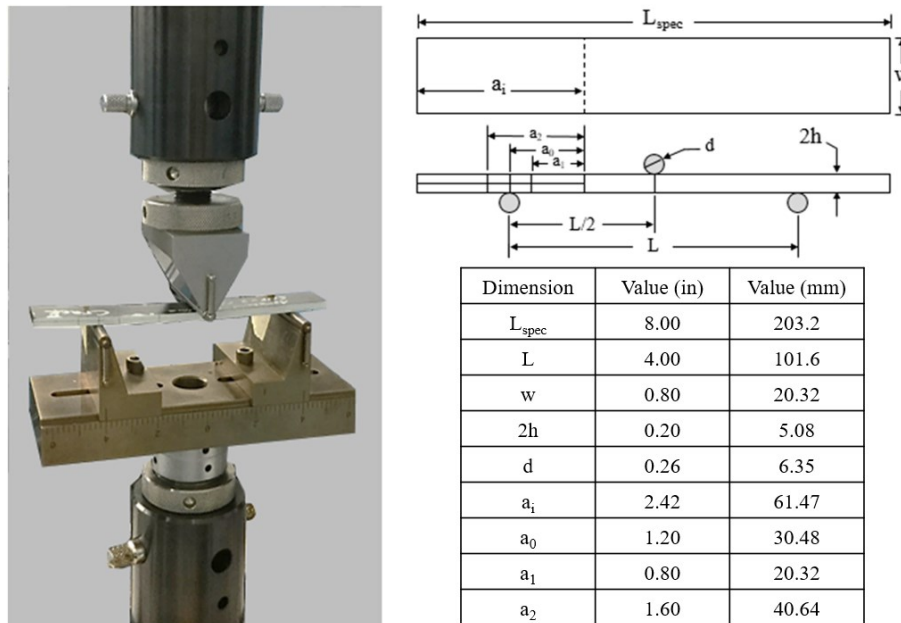


Figure 7. End-notched flexure test setup and test specimen specifications. Modified from [11].

Similar to DCB testing, each ENF specimen underwent two loading procedures. In the first loading, the delamination was initiated from a microscopically blunt crack tip formed by the FEP insert. Due to this bluntness, the stress concentration at the crack tip is lower compared to that of a sharp crack tip. Consequently, a greater crack driving force is required to propagate the delamination, leading to non-conservative fracture toughness values obtained from the initial loading. However, as the delamination progresses from the initial loading, the crack tip naturally sharpens at the microscopic level, rendering it suitable for the subsequent test. In the second

loading, the specimen is considered to be precracked (PC) due to the crack propagation from the first loading. Consequently, for the initial loading the specimen is designated as non-precracked (NPC). Due to the inherent variability in the FEP fabricated crack tip, NPC test results generally exhibit higher fracture toughness values with greater variability, while PC tests tend to yield more consistent results with more conservative fracture toughness values.

To ensure the integrity of the test results, each specimen underwent ultrasonic scanning before and after both NPC and PC tests. Invalid results were identified if the delamination migrated to another interface or if the crack front exhibited severe non-uniform growth. This validation process ensures the reliability and accuracy of the fracture toughness measurements reported in this paper.

2.6.3 Short Beam Strength

SBS tests were conducted in accordance with ASTM D2344-16 [19] to measure short beam strength. The SBS test specimen and experimental setup is shown in Figure 8.

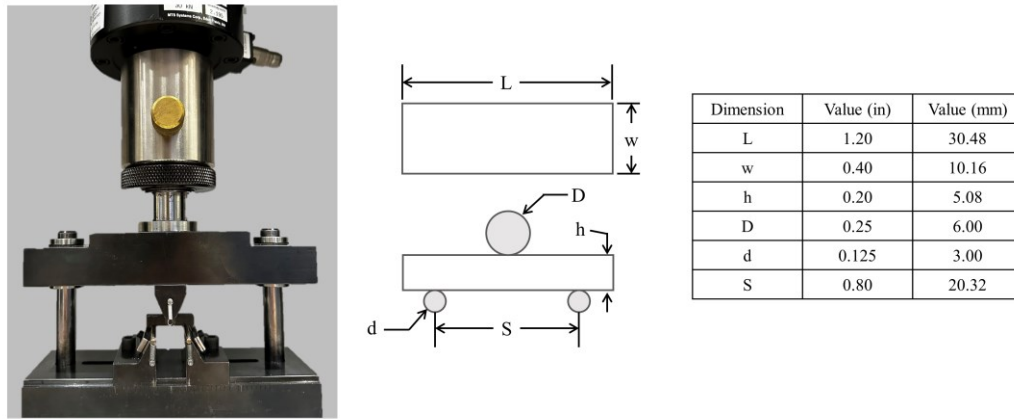


Figure 8. Short beam strength test setup and test specimen specifications.

3 RESULTS AND DISCUSSION

3.1 Ultrasonic Inspection

Ultrasonic results of the control and AERoBOND+ panels are shown as C-scan images in Figure 9 and Figure 10, respectively. C-scan images were generated using the highest amplitude signals reflected from the joint line in each pixel (0.5 mm × 0.5 mm area). In these C-scan images, strong acoustic reflections can indicate the presence of voids, disbonds, or foreign debris, while weak reflections indicate more subtle variations. In this configuration, a higher ultrasonic amplitude at the joint line indicates more significant material property change (i.e., a lower amplitude is preferred). The FEP crack starters are easily identifiable by their strong acoustic reflection and appear as two 76-mm wide dark red strips spanning the width on each side of the panels.

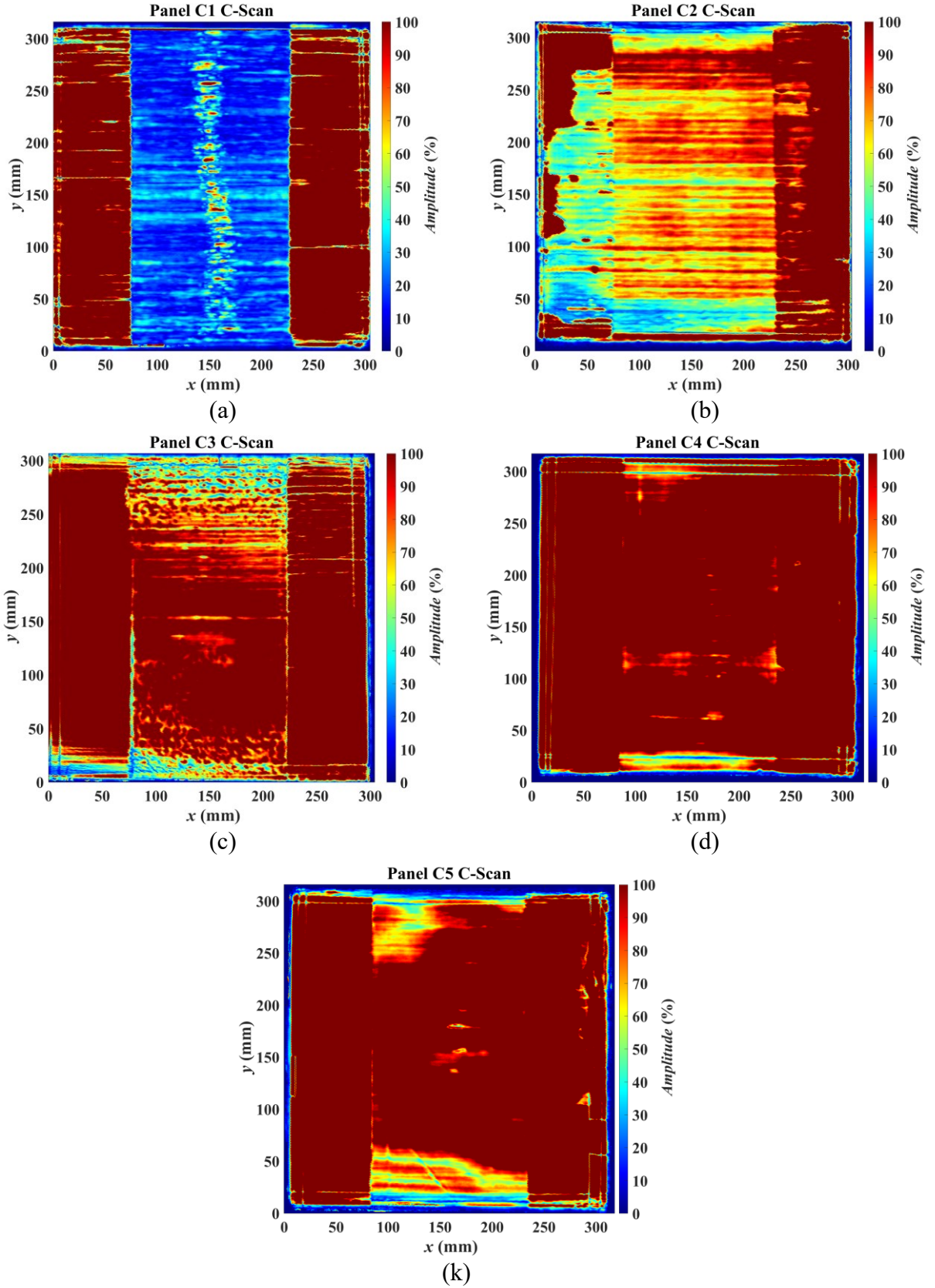


Figure 9. Maximum ultrasonic amplitude from the joint line within control panels (C1-C5).

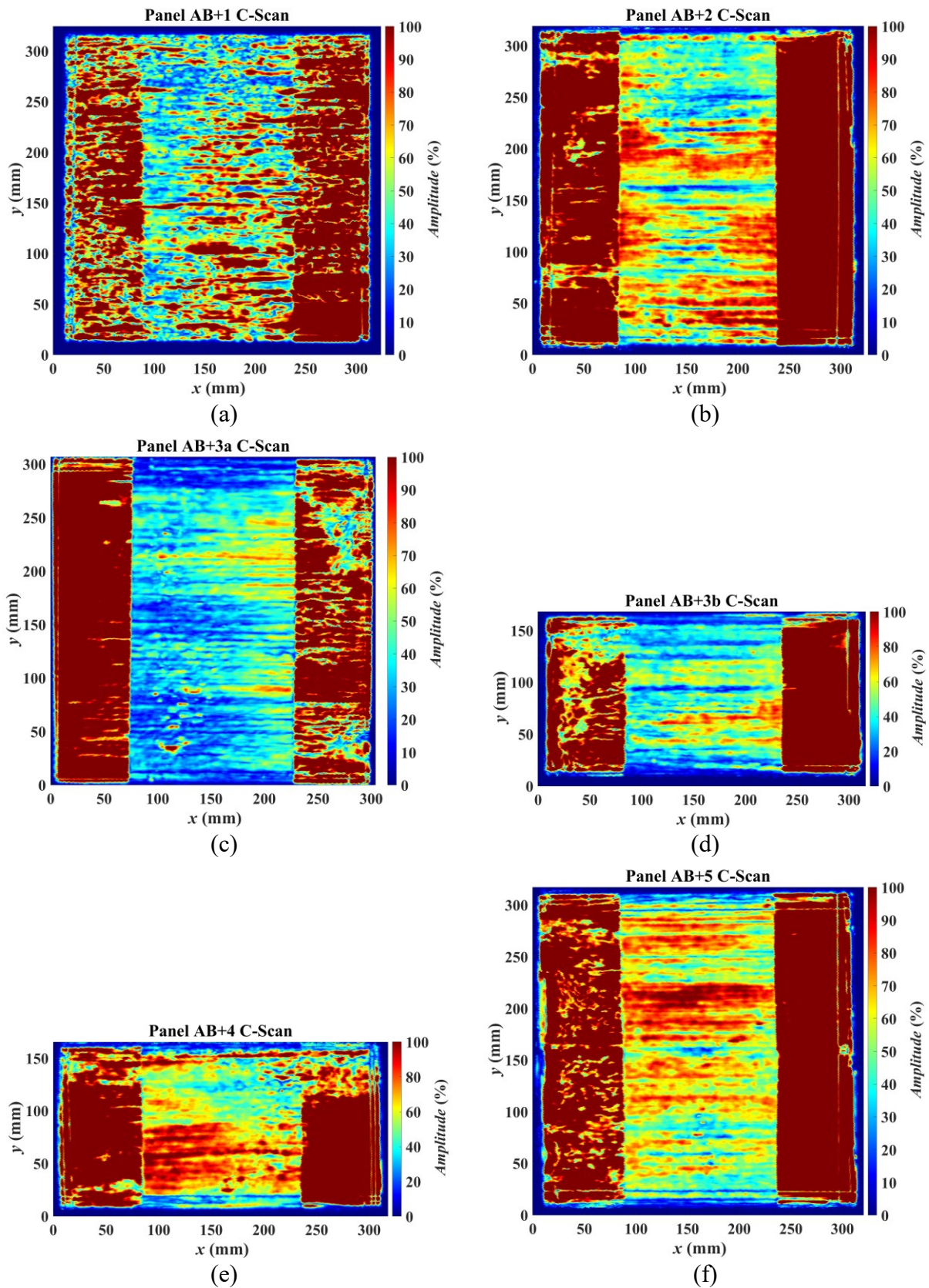


Figure 10. Maximum ultrasonic amplitude from the joint line within panels AB+1-AB+5.

From Figure 9 and Figure 10, a qualitative assessment of each panel can be made by observing which panel(s) had the lowest amplitude values between the crack starters [e.g., Panel C1 in Figure 9(a) and AB+3a and 3b in Figure 10(c) and (d), respectively]. To perform a quantitative assessment, the average amplitude of the pixels located between the crack starters was calculated (Figure 11). Panel C1, the co-cured panel, exhibited the most favorable performance (lowest amplitudes from the joint line between the crack starters). AB+3 (combined results from AB+3a and 3b) had the next lowest joint line amplitude. The AB+ panels exhibited lower amplitude values compared to the secondary bonded control panels, indicating an improved material property gradient at the joint line due to reflow and mixing in each interface.

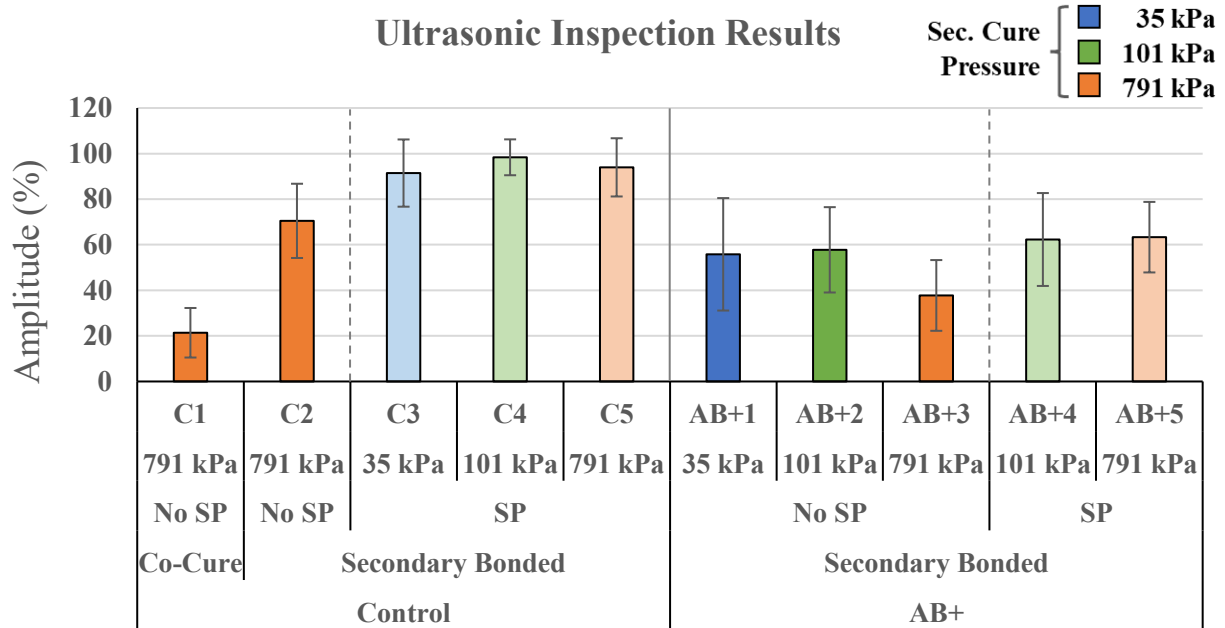


Figure 11. Average maximum joint line amplitudes between crack starters from ultrasonic inspection (Note: Lower amplitudes are preferred).

The data from each panel is color coded according to the total pressure it experienced during secondary cure (Blue: 35 kPa, Green: 101 kPa, Orange: 791 kPa).

3.2 Microscopy

Microscopy results for each panel are located in the appendix of the paper [Figure 28 (control panels) and Figure 29 (AERoBOND+ panels)]. Each panel was imaged with 100× magnification at the bondline (left) and 500× magnification at the adhesive-to-prepreg interface (right). A distinct material discontinuity between the prepreg and adhesive can be observed in the secondary bonded control panels. The carrier mat can be seen in the adhesive of panel C2M and AB+3M. The AB+ panels exhibit a bondline comparable to the co-cured control panel C1. There are no discernable discontinuities or variations in the AB+ bondlines indicating effective mixing between the ER, HR, and adhesive interfaces occurred. This mixing/diffusion at the interface results in a bondline that is not susceptible to contamination since the contaminants are not concentrated at the bonding interface. The AB+ images also show that fibers (white circles) migrated across the ER, HR, and

adhesive interface during secondary cure indicating that the bondline remained flowable. Voids were observed in the HR prepreg in both AB+1 and AB+2. The HR prepreg, which was only in the laminate stack for the secondary cure cycle, was cured under only 35 kPa for AB+1 and 101 kPa for AB+2. Although not observed at the imaging location for AB+4, it is possible that voids similar to those observed in AB+2 were present in AB+4, since AB+4 was also bonded at 101 kPa.

3.3 Mechanical Testing

3.3.1 Adhesive-to-Prepreg Interface

3.3.1.1 Double Cantilever Beam

Mechanical loading curves from DCB tests are shown in Figure 12. From the control panels, only the co-cured panel exhibited stable crack growth behavior typical in polymer matrix composite (PMC) specimens. All other control panels, regardless of secondary cure pressure or surface preparation, exhibited unstable “stick/slip” behavior rendering them invalid for calculating fracture toughness. This stick/slip behavior in panels C3-C5 is a product of adhesive failure (sudden crack extension) combined with fiber bridging (sudden crack arrest). All specimens from panel C2 experienced catastrophic adhesive failure with no fiber bridging. Evidence of this adhesive failure was observed in the fracture surfaces post-test as exemplified in Figure 13a (C2), where one surface is lighter than the other due to the adhesive mainly remaining on the lighter surface. In contrast, the majority of the AB+ specimens exhibited stable crack growth during testing, which is evidenced by few or zero major sudden drops in force shown in Figure 12f-j. For each test coupon of the AB+ panels, the post-test fracture surfaces, shown in Figure 13b, appear quite similar or identical (consistent quantities of adhesive on each side of the fracture surface), indicating cohesive failure within the adhesive.

Sudden unstable crack growth in the secondary-bonded control panels demonstrates how unpredictable failure in secondary bonded structures can be, and why redundant fasteners are required for flight certification. With the AB+ panels (especially AB+1-3 without surface preparation) demonstrating a greater propensity to produce stable crack growth than the secondary-bonded control panels, it follows that failure in the AB+ material would be more predictable, potentially allowing for significantly fewer redundant fasteners to become certifiable for flight.

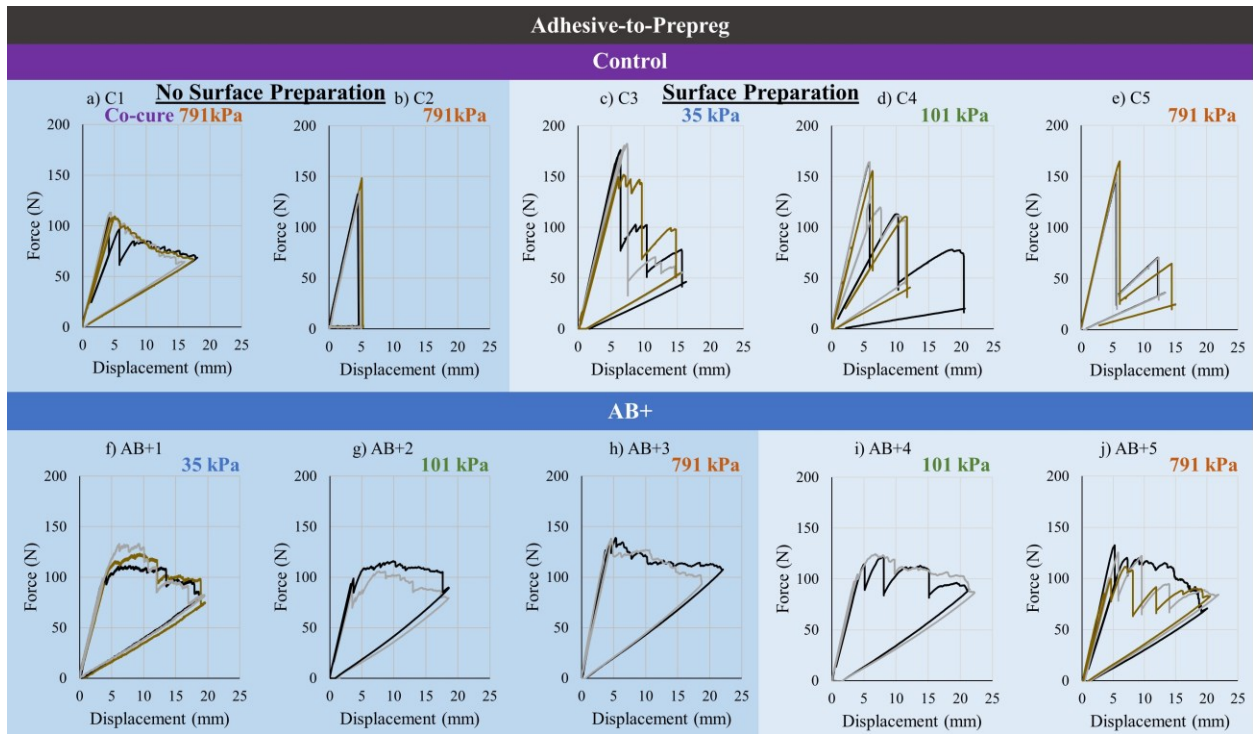


Figure 12. Mechanical loading curves from DCB tests of the adhesive-to-prepreg interface.

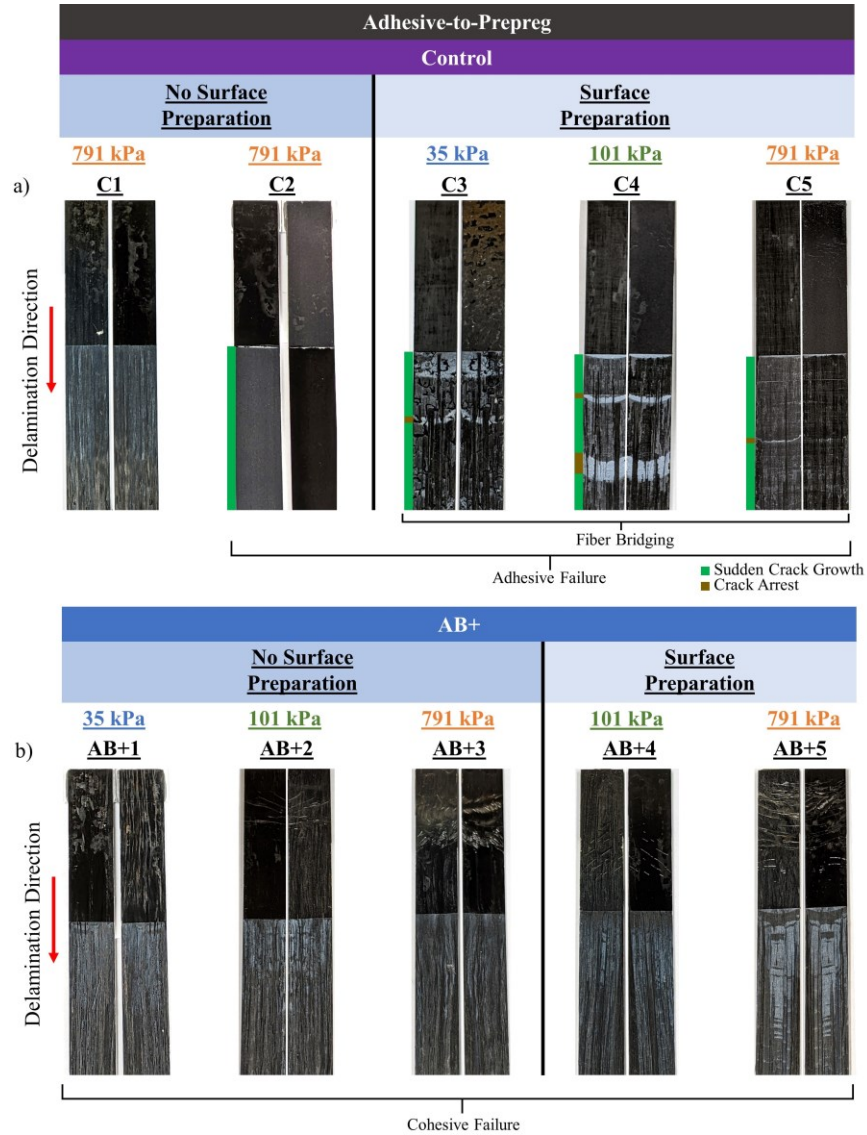


Figure 13. Failure surfaces following DCB testing for (a) Control and (b) AB+ panels of the adhesive-to-prepreg interface.

Mode-I interlaminar fracture toughness (G_{Ic}) results from the DCB tests for the adhesive-to-prepreg interface are reported in Figure 14. As previously mentioned, the values reported are the valid fracture toughness values at the initiation (init) of damage. The initiation values reported in this study were determined MBT data reduction according to when onset of crack growth was first observed visually. The results from AB+3 and AB+5 demonstrate that, with a process pressure application of 791 kPa, the AB+ method exhibits interlaminar fracture toughness comparable to the co-cured joint (C1). However, under oven plus vacuum bag only (VBO) (101 kPa), the performance of the AB+ panels decreased (AB+2 and AB+4). The trend of decreasing fracture toughness in the AB+ panels with reduced pressure during secondary cure did not continue with AB+1 (35 kPa). Values for control panels C2-C5 are shown for reference but are overestimates due to the significant unstable load drops as seen in Figure 12b-Figure 12e and should therefore not be considered as valid results. Note, however, that even with the overestimated values from

panels C2, C4, and C5, their AB+ counterpart panels, respectively AB+3, AB+4, and AB+5, either matched or were superior in performance.

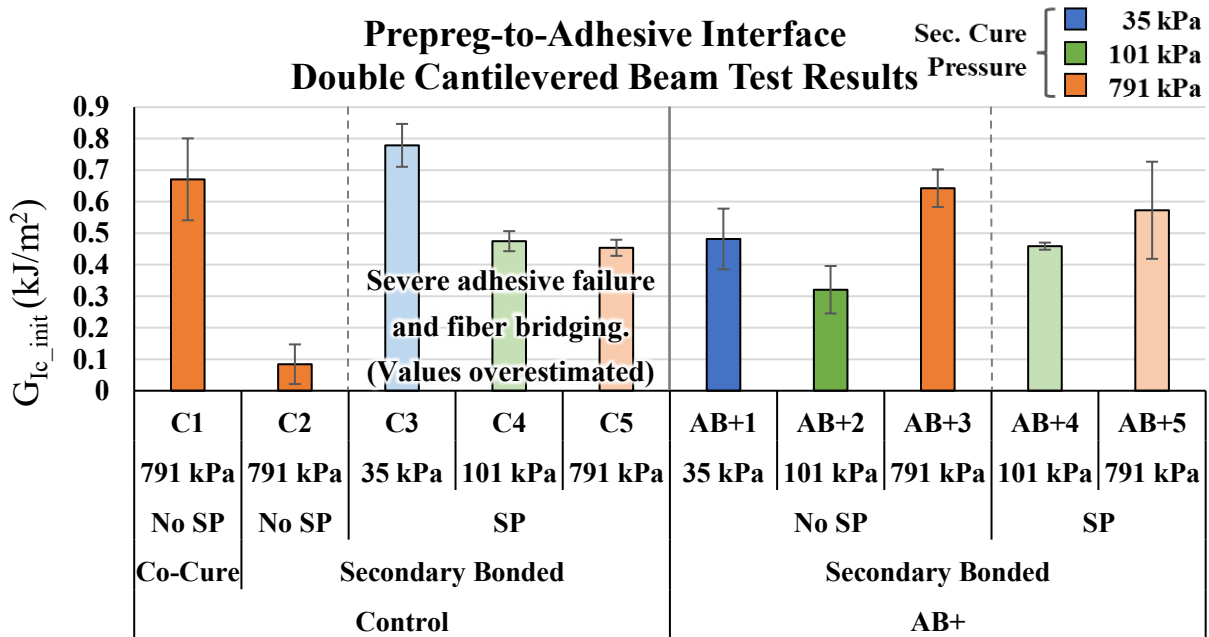


Figure 14. Mode-I interlaminar fracture toughness properties from DCB tests of the adhesive-to-prepreg interface.

3.3.1.2 End Notched Flexure

Mechanical loading curves from the ENF tests in the PC condition are shown in Figure 15. While most specimens exhibited stable crack growth, only specimens from panels C2 and C2M experienced sharp load drops upon failure. Inspection of the fracture surfaces (Figure 16a) show that panels C2 and C2M exhibited adhesive failure and C3 had partial adhesive failure. Only the secondary bonded control panels that received surface preparation and were cured under the medium or high pressure (C4 and C5, respectively) produced cohesive failure. In contrast, all of the AB+ panels tested, regardless of surface preparation or cure pressure, produced cohesive failure (see Figure 16b).

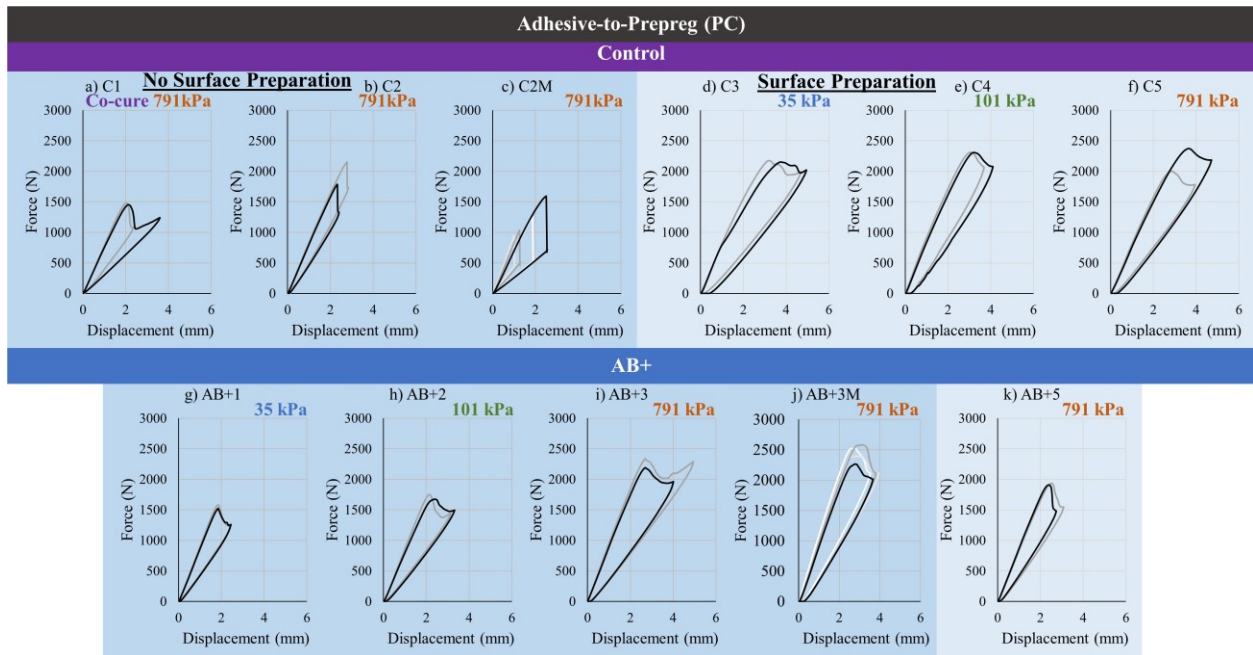


Figure 15. Mechanical loading curves from precracked ENF tests of the adhesive-to-prepreg interface.

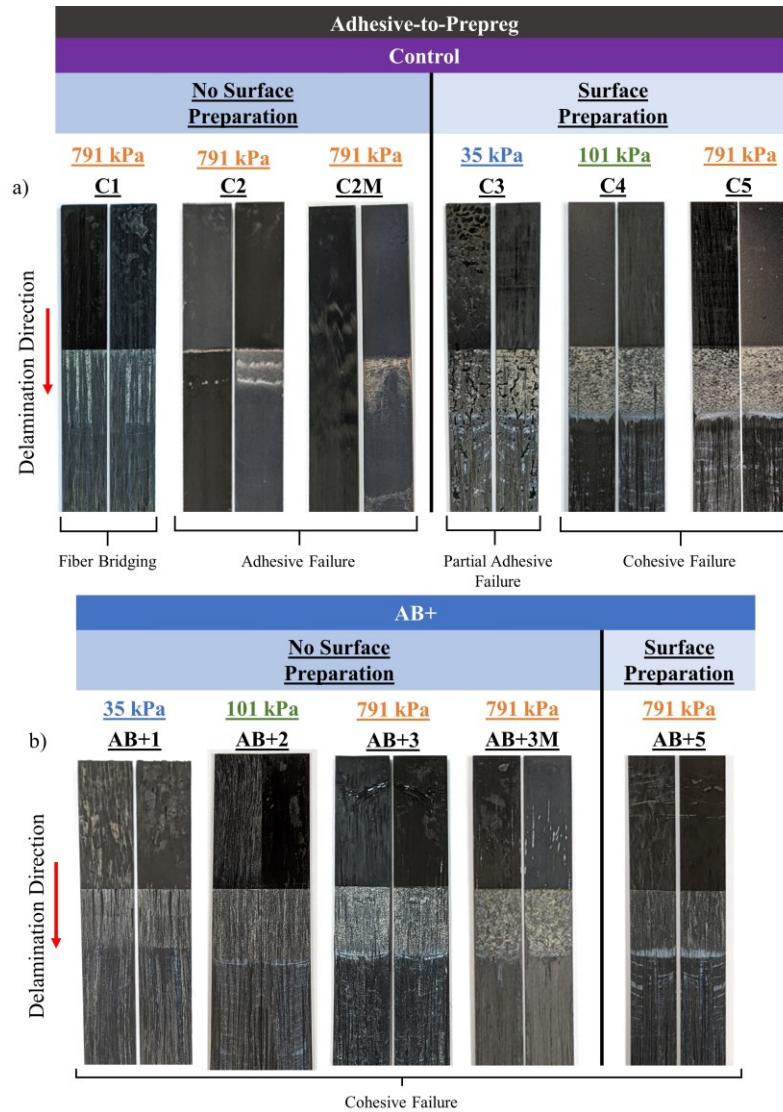


Figure 16. Failure surfaces following ENF testing for (a) Control and (b) AB+ panels of the adhesive-to-prepreg interface.

Mode-II interlaminar fracture toughness (G_{IIc}) results from the NPC condition of valid ENF test specimens for the adhesive-to-prepreg interface are reported in Figure 17. The subsequent valid ENF data in the PC condition are presented in Figure 18. Specimens from panel AB+4 were not ENF tested; due the panel's smaller size all of its specimens were devoted to DCB tests.

Panel AB+3 and AB+3M exhibits comparable mechanical properties to the secondary bonded control panels with surface preparation (C3-C5) and higher properties than C1 (co-cured control panel). Under mode-II loading, as pressure during the secondary cure process decreased, mechanical properties in the AB+ panels also decreased. However, the control panels appear to be unaffected by a reduction in secondary cure pressure. If a HR adhesive layer was implemented instead of the HR prepreg, the challenges associated with reduced pressure during secondary cure could be addressed since adhesive systems typically require less pressure to consolidate compared to prepreps. Another alternative would be to design the HR prepreg as an out-of-autoclave prepreg

that can adequately consolidate under reduced pressure. This could lead to improved mechanical properties and performance of the AB+ panels.

The poor performance of C2M (secondary bonded control panel without surface preparation) in the ENF PC test is particularly noteworthy, especially when compared to AB+3 and AB+3M, which were bonded under identical conditions. C2 and C2M both display adhesive failure at the bondline between the adhesive and prepreg as shown in Figure 16a. Additionally, the comparison between AB+3/3M (no surface preparation) and AB+5 (with surface preparation) in both the DCB and ENF tests, highlights that the AERoBOND+ method is resilient to contamination; therefore, eliminating the need for surface preparation which is required in conventional secondary bonded joints.

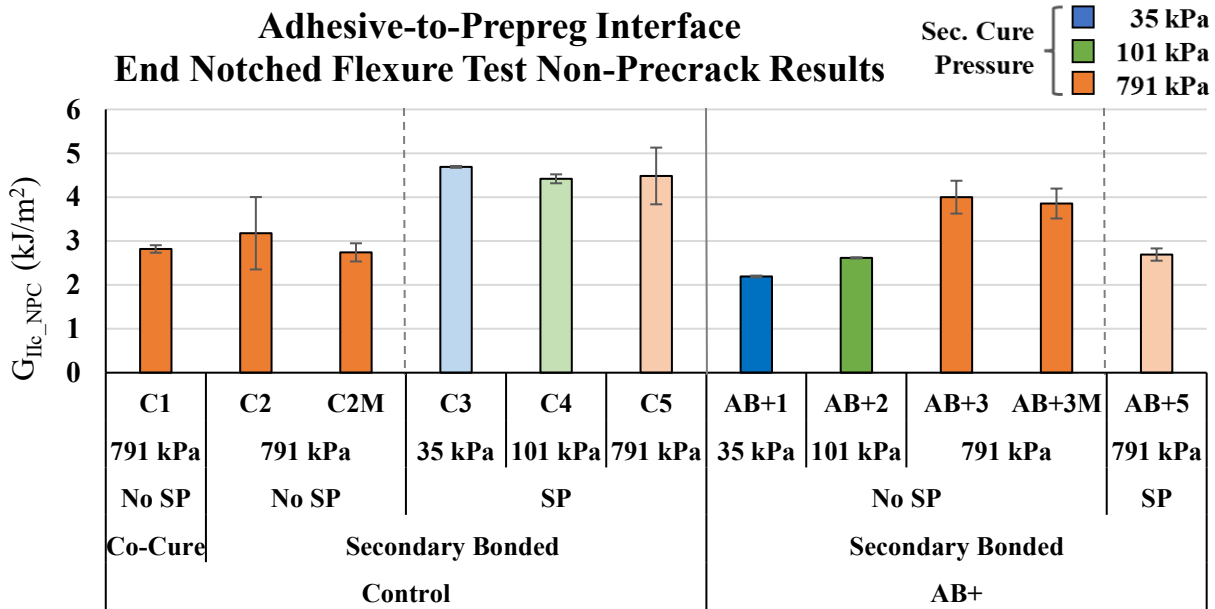


Figure 17. Non-precracked mode-II interlaminar fracture toughness properties from ENF tests of the adhesive-to-prepreg interface.

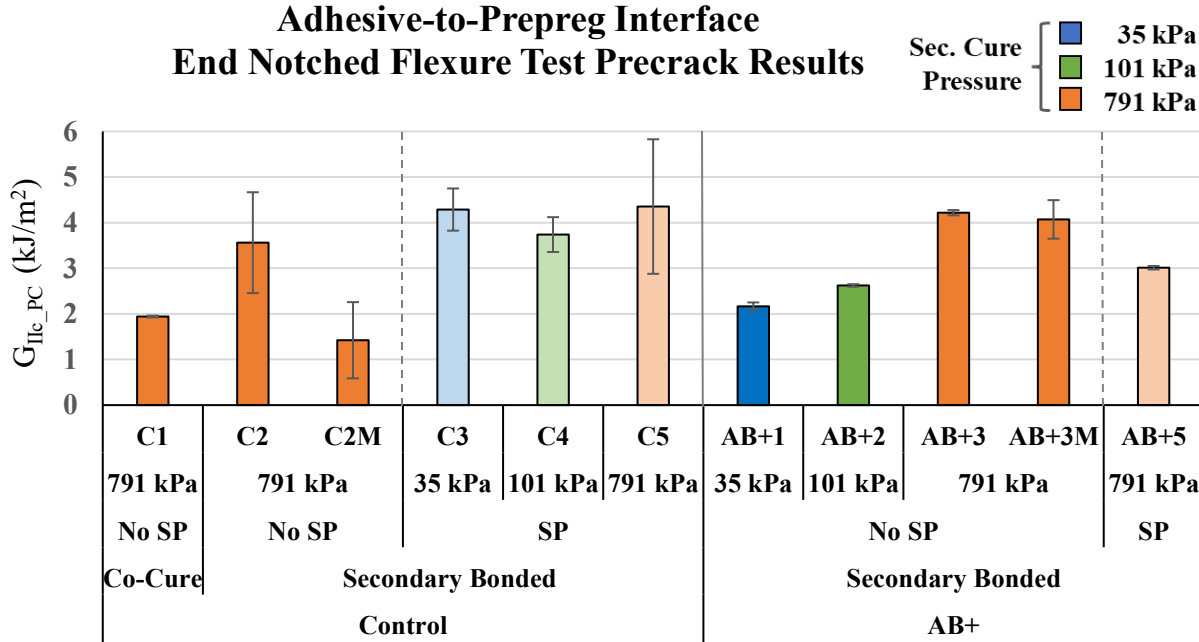


Figure 18. Precracked mode-II interlaminar fracture toughness properties from ENF tests of the adhesive-to-prepreg interface.

3.3.2 Prepreg-to-Prepreg Interface

3.3.2.1 Double Cantilever Beam

Mechanical loading curves from DCB tests targeting the prepreg-to-prepreg interface are shown in Figure 19. During the tests, fiber bridging was observed in all specimens; however, specimens from panels C3, AB+1, and AB+4 exhibited bridging to the greatest extent which is reflected in the loading curves. The failure surfaces in Figure 20 show that panels C3 and AB+1 possessed non-uniform fiber patterns with more voids than the others; these two panels were cured at the extremely low pressure of 35 kPa.

Mode-I interlaminar fracture toughness (G_{Ic}) from the DCB tests for the prepreg-to-prepreg interface are reported in Figure 21. The same test procedure as described earlier for the adhesive-to-prepreg interface was also employed for DCB testing of the prepreg-to-prepreg interface. The co-cured control panel (C1) produced performance that doubles any other panel. The G_{Ic_init} of 0.490 kJ/m² measured for C1 more than doubles the previously measured G_{Ic_init} of the prepreg-to-prepreg interface of IM7G/API-60 (0.18 kJ/m²) [11] as well as IM7/8552 (Panel 1: 0.221 kJ/m² and Panel 2: 0.204 kJ/m²) [20]. A possible explanation for the improved prepreg-to-prepreg properties is that perhaps a portion of the adhesive one ply away diffused through the single ply of CR prepreg (Figure 2a) resulting in a fracture toughness less than the adhesive-to-prepreg interface (0.670 kJ/m²), but greater than previously measured prepreg-to-prepreg properties. The mode-I fracture toughness at the prepreg-to-prepreg interface of the AB+ panels were comparable to the control panels which were secondary bonded (C2-C5). The AB+ panels showed a slight reduction trend in G_{Ic} as the secondary cure pressure decreased. The observed decrease in properties of the AB+ panels under reduced pressure supports the idea that the HR prepreg may be experiencing inadequate pressures for consolidation in the secondary cure cycle.

As mentioned previously, a potential solution to address this issue could involve replacing the hardener-rich prepreg with a hardener-rich adhesive layer designed for lower pressure cure cycles.

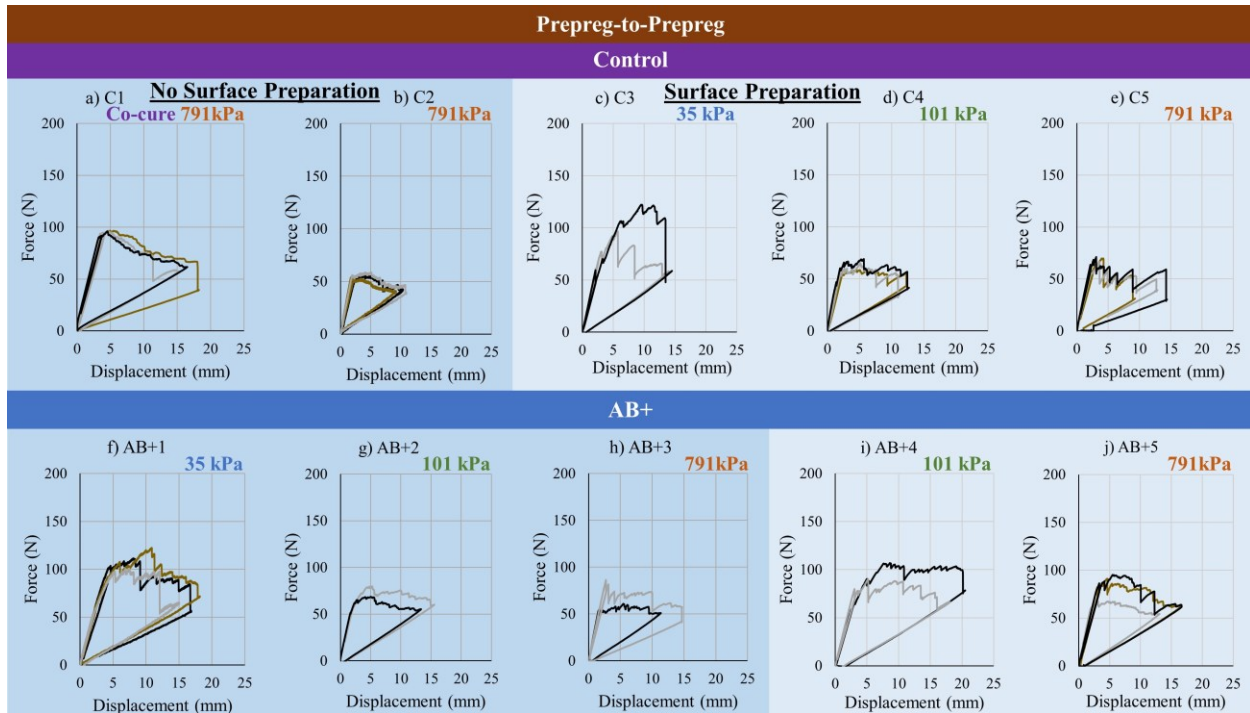


Figure 19. Mechanical loading curves from DCB tests of the prepreg-to-prepreg interface.

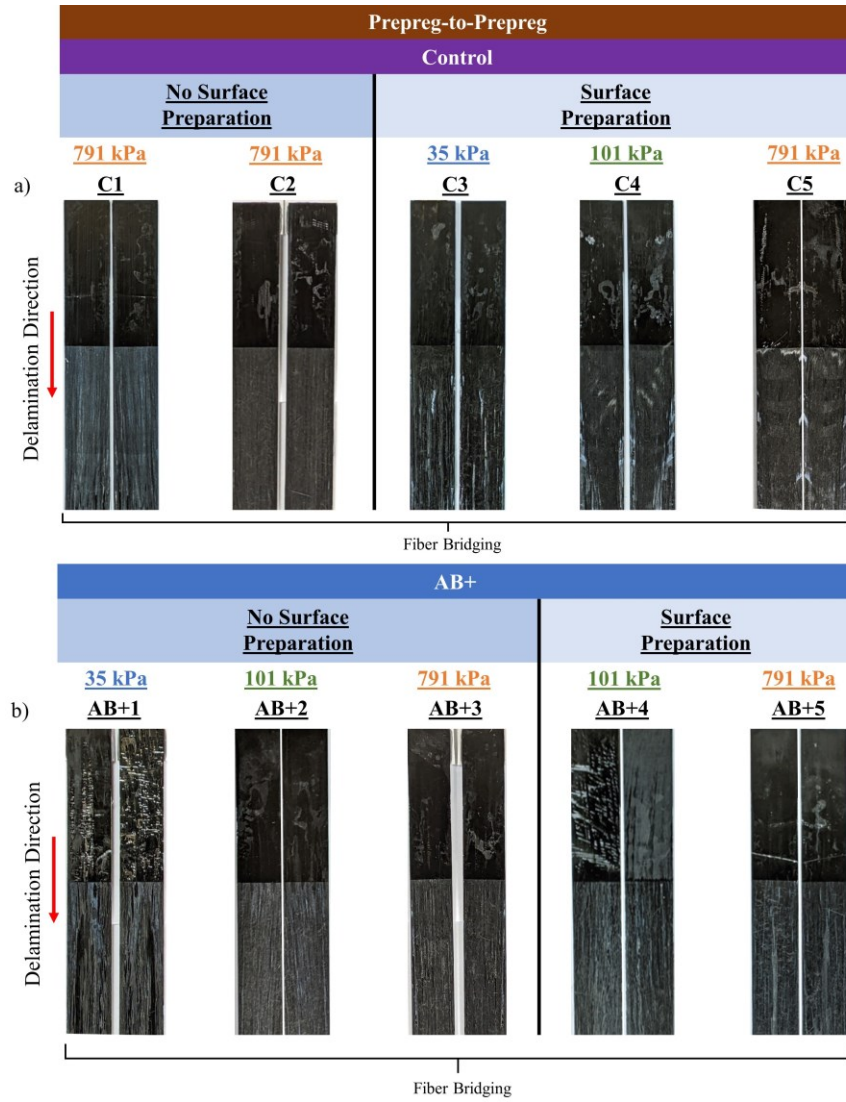


Figure 20. Failure surfaces following DCB testing for (a) control and (b) AB+ panels of the prepreg-to-prepreg interface.

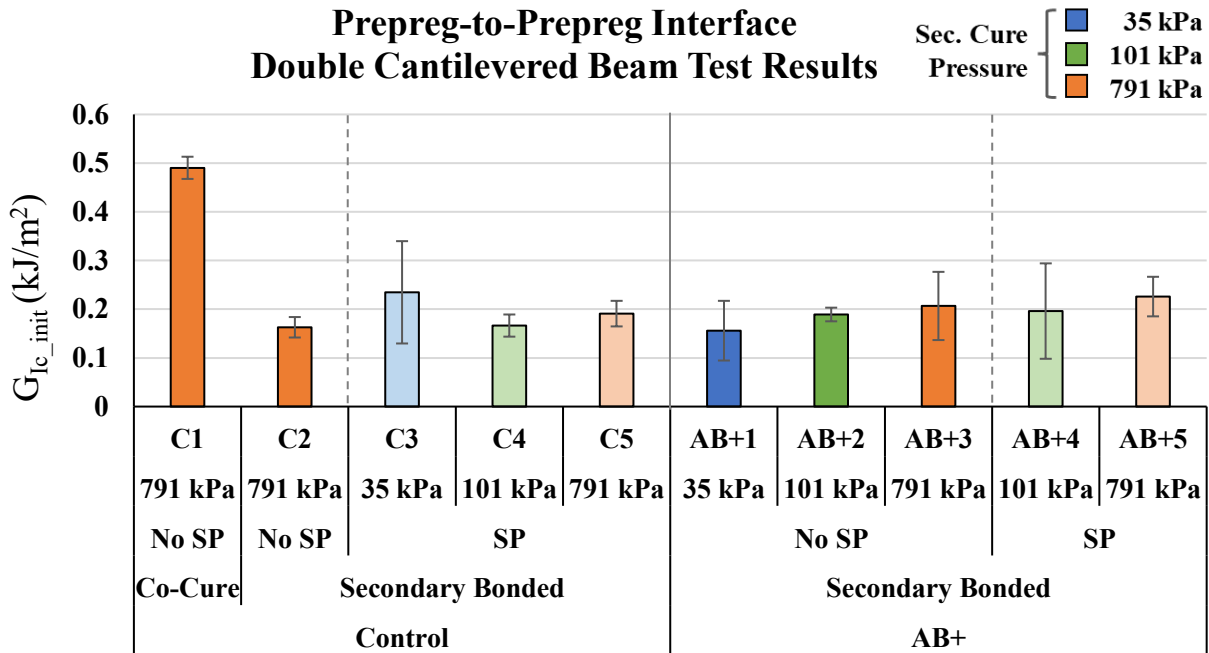


Figure 21. Mode-I interlaminar fracture toughness properties from DCB tests of the prepreg-to-prepreg interface.

3.3.2.2 End Notched Flexure

Mechanical loading curves from ENF tests in the PC condition are shown in Figure 22. While most specimens exhibited the typical sudden load drop at failure, specimens from panel C3 experienced severe fiber bridging and even delamination migration (see Figure 23) which caused a continual increase in load even after onset of damage in the NPC test. The failure surface of C3 appeared to exhibit signs of the adhesive interacting in the damage, which would explain the relatively higher mechanical loads in both the NPC and PC tests. Again, similar to what was observed in the failure surfaces from the DCB tests, the fracture surfaces from panels C3 and AB+1 possessed wavy, non-uniform fiber patterns, which could be attributed to the extremely low secondary cure pressure.

Mode-II fracture toughness from the NPC condition of valid ENF test specimens for the prepreg-to-prepreg interface is reported in Figure 24. The subsequent valid ENF data in the PC condition are presented in Figure 25. In the NPC and PC test condition, AB+3 was the best performer. In the PC condition, all the AB+ panels outperformed the co-cured control C1, which outperformed all the secondary bonded control panels (C2-C5). As with previous tests, a reduction in pressure during secondary cure decreased the mode-II fracture toughness of the AB+ panels (AB+1 vs. AB+2 vs. AB+3). In addition, across all DCB and ENF tests, AB+3 (in all but one case) outperformed AB+5 which indicates that surface preparation decreased the interlaminar fracture toughness of the AB+ panels. This finding is congruent with that of [7] in which the interlaminar properties were highly sensitive to the thickness of the ER ply material. A surface preparation step would reduce the thickness of the ER ply to below the optimum thickness.

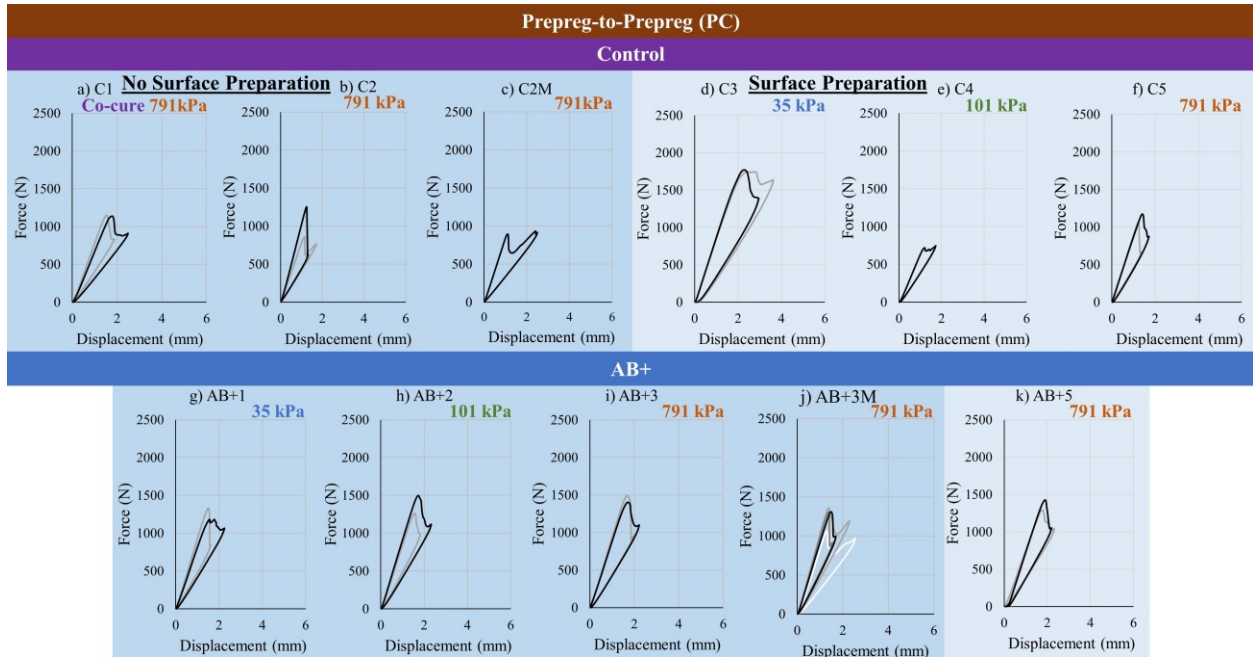


Figure 22. Mechanical loading curves from precracked ENF tests of the prepreg-to-prepreg interface.

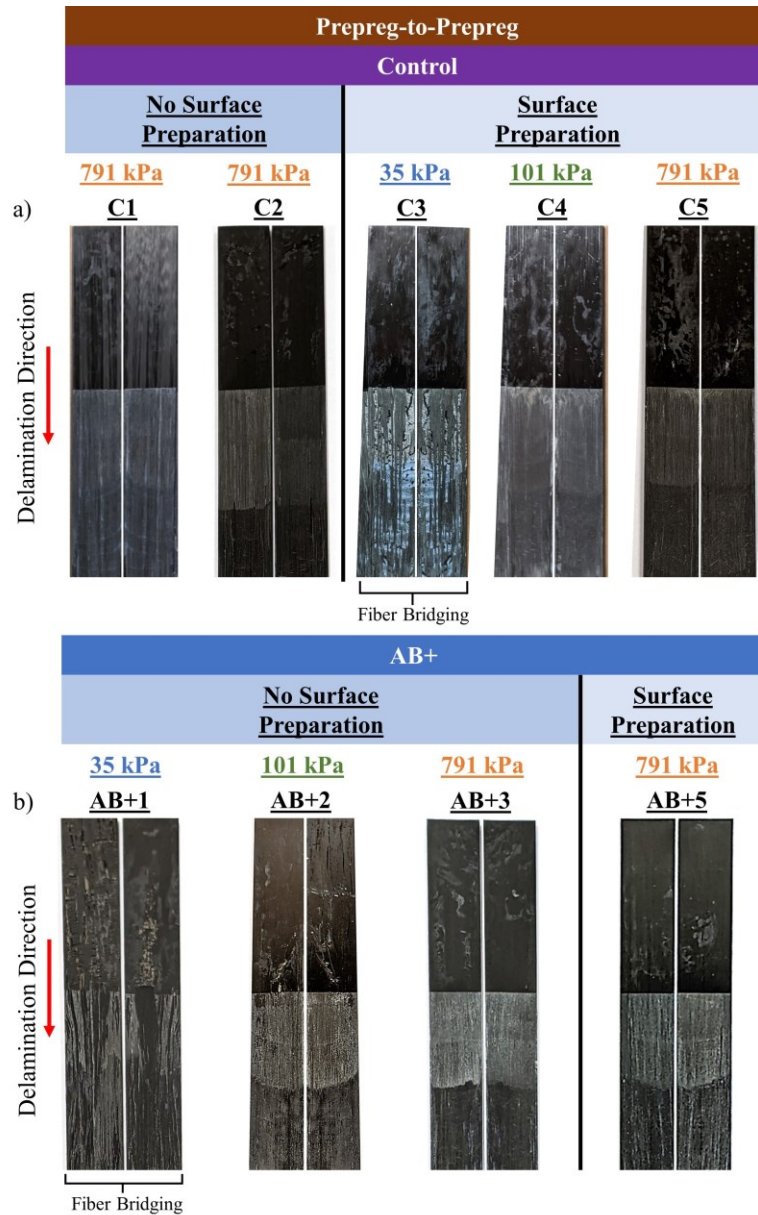


Figure 23. Failure surfaces following ENF testing for (a) control and (b) AB+ panels of the prepreg-to-prepreg interface.

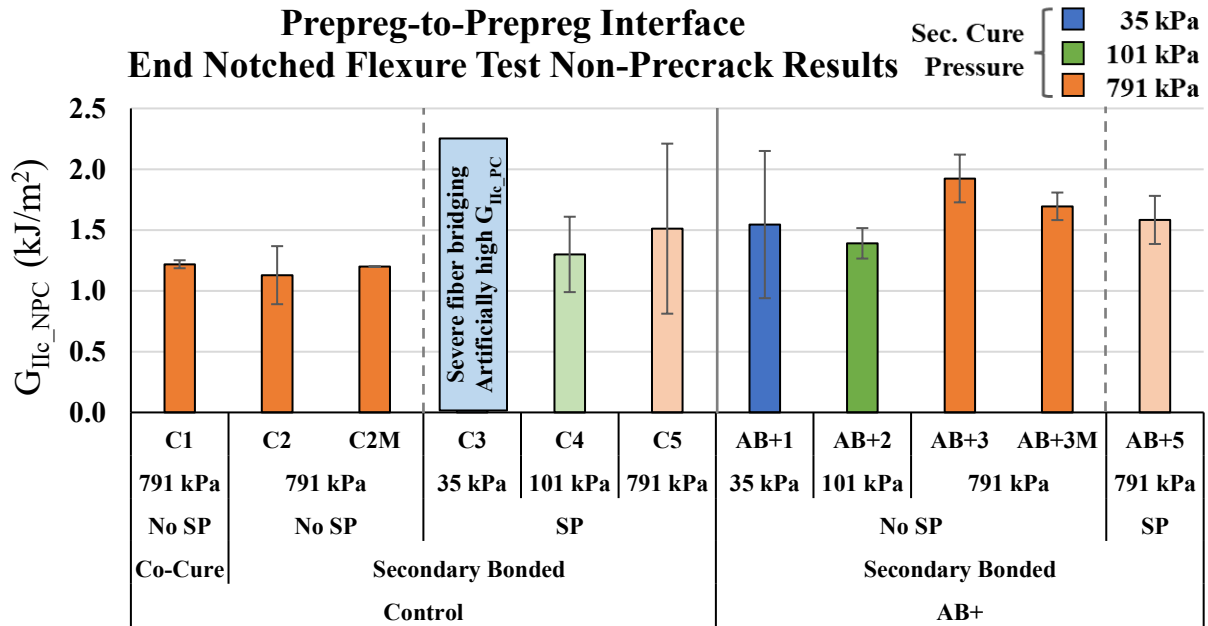


Figure 24. Non-precracked mode-II interlaminar fracture toughness properties from ENF tests of the prepreg-to-prepreg interface.

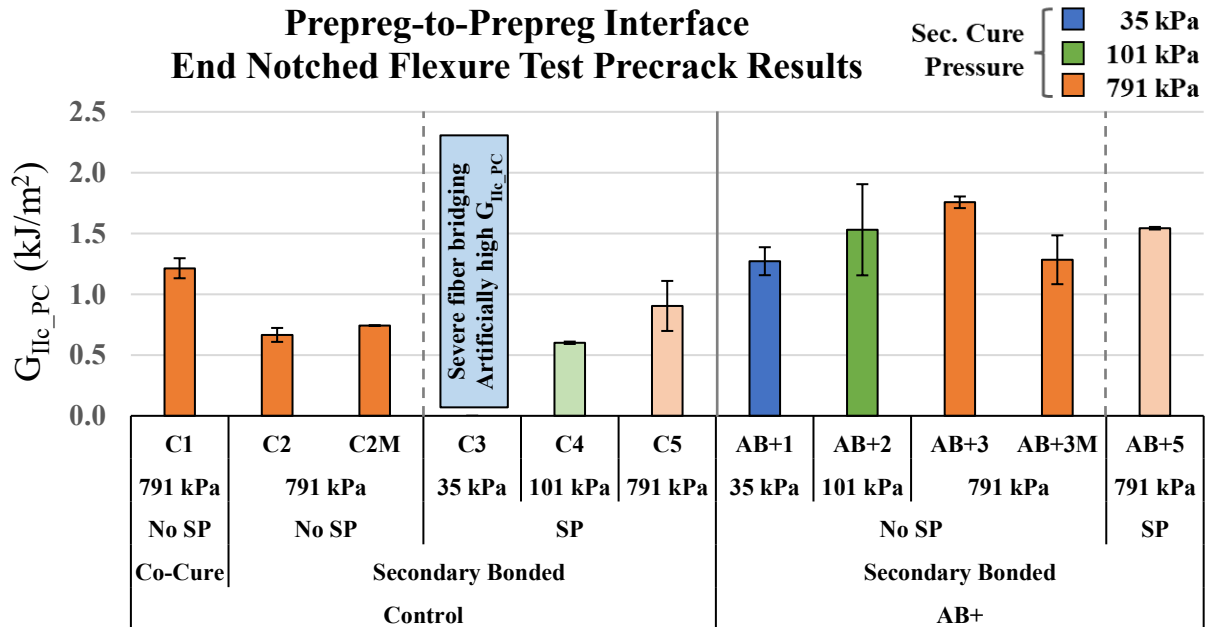


Figure 25. Precracked mode-II interlaminar fracture toughness properties from ENF tests of the prepreg-to-prepreg interface.

3.3.3 Short Beam Strength

The average short beam strength of each panel is reported in Figure 26. The results of the SBS tests revealed consistent failures at an IM7/8552 prepreg interface(s) for all panels with VBO or

autoclave consolidation during secondary cure (C1-2, C4-5, and AB+2-5) resulting in SBS values of 104-115 MPa. A representative failure is shown in Figure 27a from AB+3a. The results from these panels (C1-2, C4-5, and AB+2-5) suggest that both the adhesive-to-prepreg and prepreg-to-prepreg interfaces exhibited comparable or greater strength than the IM7/8552 prepreg interface in terms of short beam strength. However, a direct comparison between the SBS of the adhesive-to-prepreg and prepreg-to-prepreg interfaces between these panels cannot be made based on this data alone. Both panels bonded under reduced pressure (35 kPa) in the press (C3 and AB+1) exhibited slightly lower average SBS (96 MPa and 90 MPa, respectively). A SBS failure at the ER/HR prepreg interface as well as at one of the IM7/8852 interfaces from panel AB+1 is shown in Figure 27b.

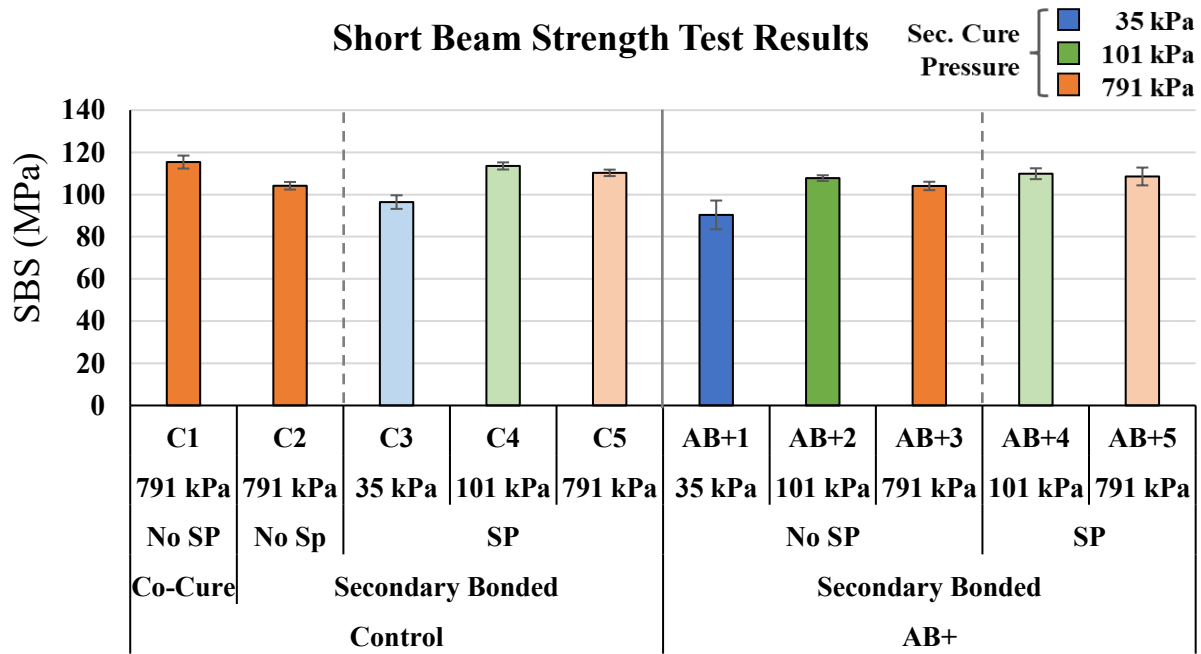


Figure 26. Short beam strength (SBS) properties.

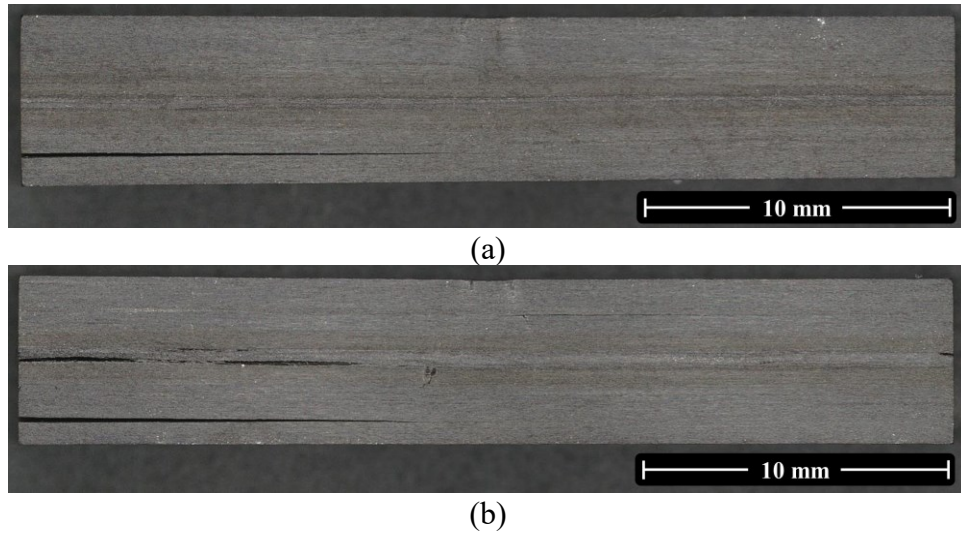


Figure 27. Post-failure SBS coupon from (a) AB+3a and (b) AB+1.

3.4 Comprehensive Results Summary

The results obtained from each test conducted are consolidated and presented in the appendix (Table 3). The table utilizes color-coded data with a qualitative scale to facilitate easy visual interpretation of the results. The average values for each test type are provided for every panel, and a comparison is made between the AB+ panels and the control panels. The color scheme is as follows: red signifies a poor comparison, yellow indicates an adequate comparison, green represents a good comparison, and blue signifies an excellent comparison. In the case of the ultrasonic data, n represents the number of pixels, while in the mechanical tests n represents number of test specimens. The table reveals a noticeable trend of improved performance in the AB+ panels as the bonding pressure increases. Of the AERoBOND+ panels, AB+3 (high pressure with no surface preparation) exhibits the best performance overall with comparable or improved results for all evaluation methods when compared to the control panels. Additionally, the results indicate that the AB+ panels that did not receive surface preparation exhibit comparable results to their counterpart AB+ panels that did receive surface preparation. This highlights that the AERoBOND+ method eliminates the need for extensive surface preparation performed for traditional secondary bonded joints.

3.5 Current Limitations

AERoBOND/AERoBOND+ is a thermoset material, thus is only applicable to the bonding of thermoset composites. Further, the AERoBOND/AERoBOND+ methods are currently limited to scenarios with elevated-temperature primary and secondary cure cycles due to the requirement for reflow and diffusion. In its current form, AERoBOND/AERoBOND+ would not work with room-temperature cure thermoset material systems. In addition, a complete study has not been performed to determine the out-time requirement between primary and secondary cure. The maximum amount of time between cure cycles has been approximately two weeks. Lastly, the AERoBOND/AERoBOND+ epoxy-rich and hardener-rich materials are formulated using aerospace-grade precursors; however, they have not been produced by commercial material suppliers. For widespread adoption, an industrial partner would likely be needed to scale-up manufacturing.

4 SUMMARY AND CONCLUSIONS

The performance and bonding characteristics of the AERoBOND+ method under varying cure cycle parameters and surface preparations were evaluated. The AERoBOND+ method utilized conventional adhesive as a gap filler in the joint line effectively reducing the need for tight tolerances on the joining parts. The inclusion of conventional adhesive as a gap filler in the AERoBOND+ method also offers the advantage of being a drop-in replacement for existing adhesively bonded composite joints. Therefore, AERoBOND+ could potentially replace current bonding methods without requiring significant modifications or changes to the manufacturing process.

Ultrasonic inspection of AB+ panels consistently revealed reduced reflections from the joint due to reflow and mixing of the materials at each interface. Microscopy indicated that the AB+ bondline structure is comparable to that of the co-cured panel (C1) showing no discernable material discontinuities between ER, HR, and adhesive layers. DCB and ENF tests were conducted to assess the mode-I and mode-II interlaminar fracture toughness of both the adhesive-to-prepreg interface and the prepreg-to-prepreg interface of each panel. SBS tests were used to measure the short beam strength. Overall, the results revealed that AB+ panels, when subjected to 791 kPa of bonding pressure during secondary cure, exhibited comparable mechanical properties to the control panels. However, reduced pressure during secondary cure of AB+ panels resulted in lower mechanical properties, highlighting the importance of proper pressure application for achieving optimal bonding. Surface preparation had no (or detrimental) impact on the mechanical properties of the AB+ panels, suggesting that the AERoBOND+ method is resilient to standard surface contaminants, therefore eliminating the need for extensive surface preparation.

The implementation of a hardener-rich adhesive layer is proposed as a potential solution to address the issue of inadequate process pressure with HR prepreg, which could allow for lower pressure secondary bonds using the AERoBOND+ method and eliminate the reliance on expensive (both capital and operational) autoclaves. The use of a hardener rich adhesive layer facilitates the retention of a stoichiometric offset and mobility in the faying surface resin during the secondary cure without the additional pressure needed to consolidate the HR prepreg.

In future work, there is an intention to investigate the application of both the AERoBOND and AERoBOND+ methodology in a co-bonding scenario. A co-bonding method would also address the issue of inadequate pressure distribution in the prepreg material experienced in the secondary bonding scenario. Overall, the study of AERoBOND and AERoBOND+ in a co-bonding scenario can provide valuable insights into its applicability in broader manufacturing applications.

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6 FUNDING

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7 DATA AVAILABILITY STATEMENT

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study. Portions of the raw/processed data can be made available upon request to the corresponding author (tyler.b.hudson@nasa.gov).

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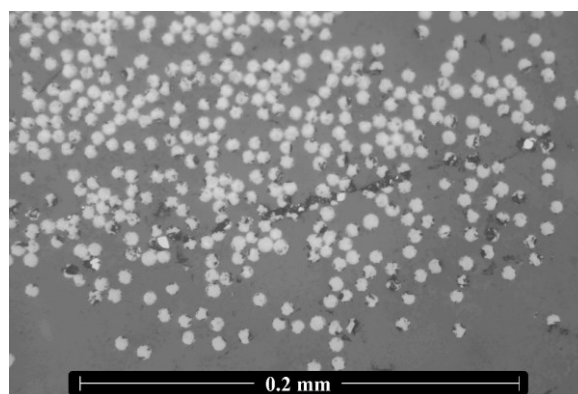
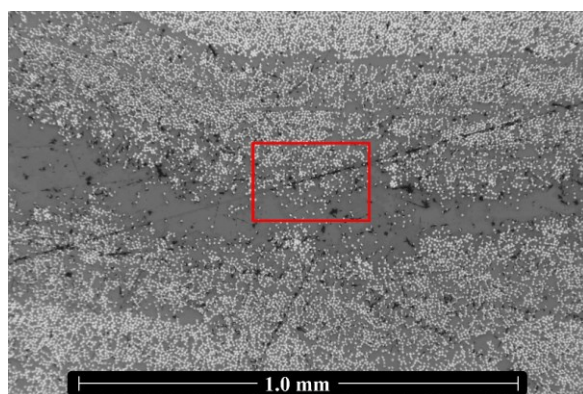
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9 APPENDIX

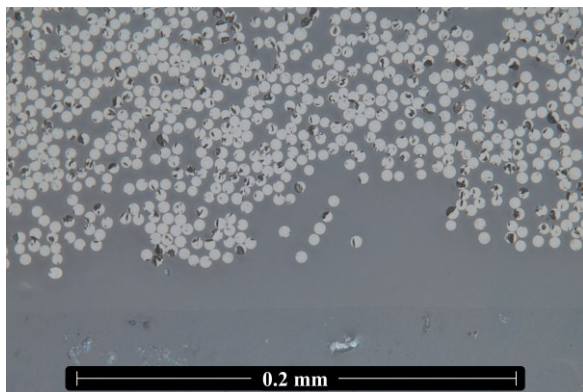
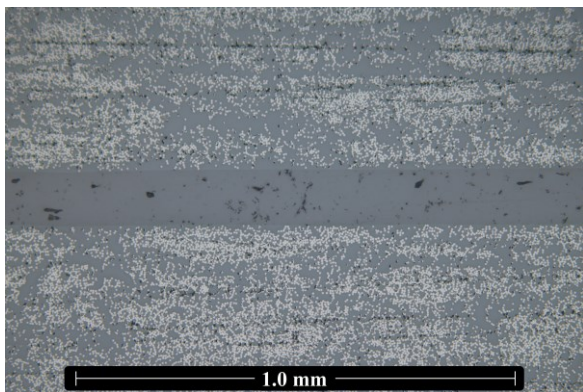
Table 2. Detailed panel description and processing conditions.

Panel	C1	C2	C2M	C3	C4	C5	AB+1	AB+2	AB+3a AB+3b	AB+3M	AB+4	AB+5
Panel Properties												
Length (mm)	305	305	305	305	305	305	305	305	305	305	305	305
Width (mm)	305	305	305	305	305	305	305	305	305 ^(a) 152 ^(b)	305	152	305
Surface Prep (SP)	No SP	No SP	No SP	SP	SP	SP	No SP	No SP	No SP	No SP	SP	SP
Bond Type	Co- Cure	Sec. bond	Sec. bond	Sec. bond	Sec. bond	Sec. bond	Sec. bond	Sec. bond	Sec. bond	Sec. bond	Sec. bond	Sec. bond
Adhesive (FM209-)	1U	1U	1M	1U	1U	1U	1U	1U	1U	1M	1U	1U
Primary Cure Cycle Processing Conditions												
Equipment	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave	Auto-clave
Equipment Pressure (kPa gauge)	689	689	689	689	689	689	689	689	689	689	689	689
VB Pressure (kPa gauge)	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101
Total Pressure (kPa)	790	790	790	790	790	790	790	790	790	790	790	790

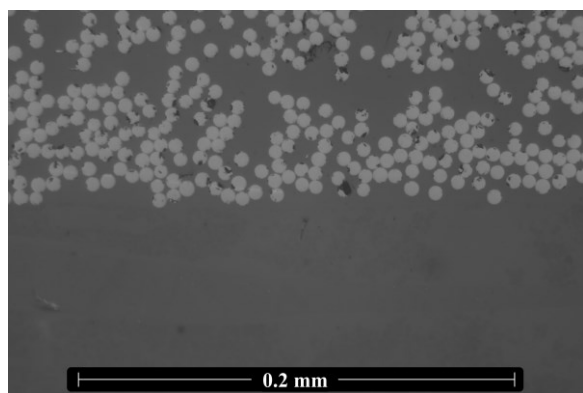
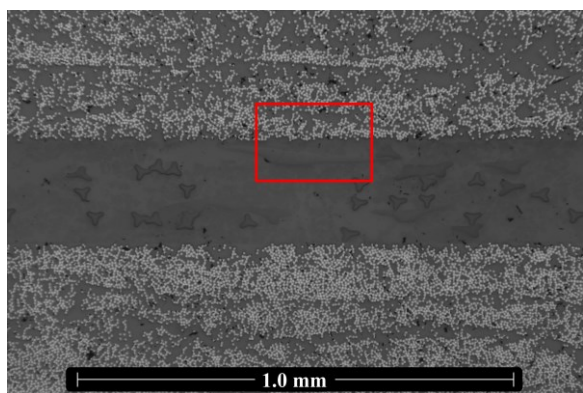
Ramp Rate (°C/min)	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Hold 1 (°C)	107	107	107	107	107	107	107	107	107	107	107	107
Hold 1 (min)	60	60	60	60	60	60	165	165	165	165	165	165
Hold 2 (°C)	177	177	177	177	177	177	177	177	177	177	177	177
Hold 2 (min)	120	120	120	120	120	120	30	30	30	30	30	30
r _{IR} Half Panel 1	-	-	-	-	-	-	0.14	0.10	0.10 _(a)	-	0.11	0.10
r _{IR} Half Panel 2	-	-	-	-	-	-	0.11	0.11	0.10 _(a)	-	0.10	0.10
Secondary Cure Cycle Processing Conditions												
Equipment	N/A	Auto-clave	Auto-clave	Press	Oven	Auto-clave	Press	Oven	Auto-clave	Auto-clave	Oven	Auto-clave
Equipment Pressure (kPa gauge)	N/A	690	690	35	0	690	35	0	690	690	0	690
VB Pressure (kPa gauge)	N/A	-101	-101	N/A	-101	-101	N/A	-101	-101	-101	-101	-101
Total Pressure (kPa)	N/A	791	791	35	101	791	35	101	791	791	101	791
Ramp Rate (°C/min)	N/A	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Hold 1 (°C)	N/A	107	107	107	107	107	107	107	107	107	107	107
Hold 1 (min)	N/A	60	60	60	60	60	60	60	60	60	60	60
Hold 2 (°C)	N/A	177	177	177	177	177	177	177	177	177	177	177
Hold 2 (min)	N/A	240	240	240	240	240	240	240	240	240	240	240



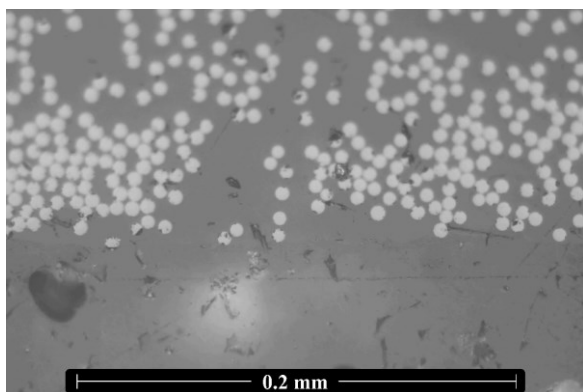
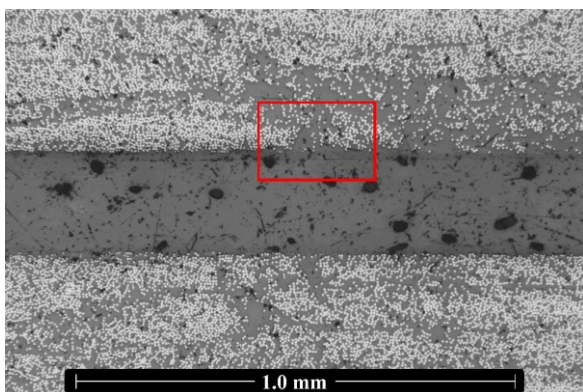
(a) C1



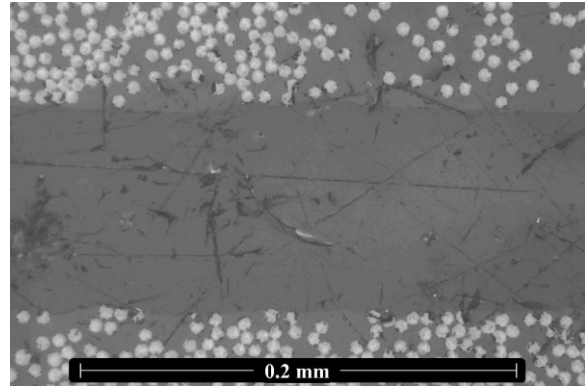
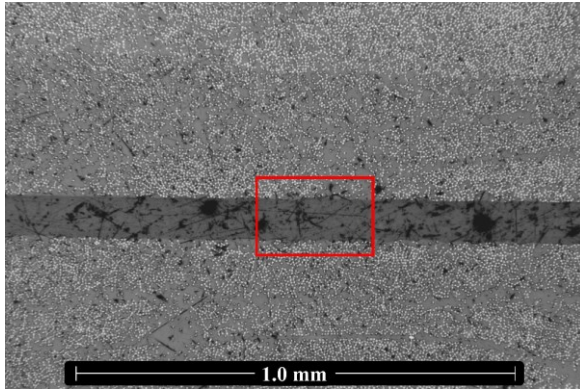
(b) C2



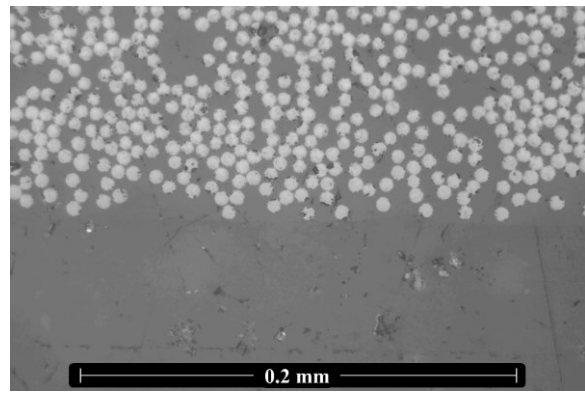
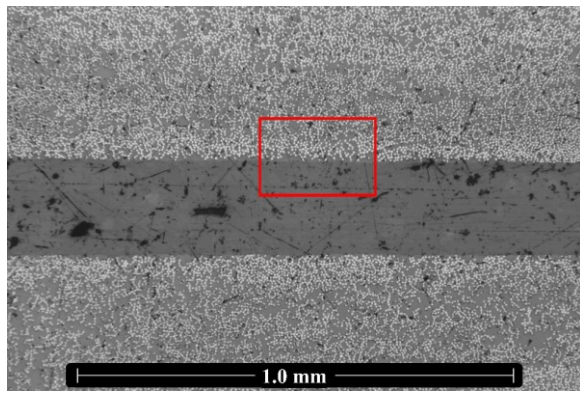
(c) C2M



(d) C3

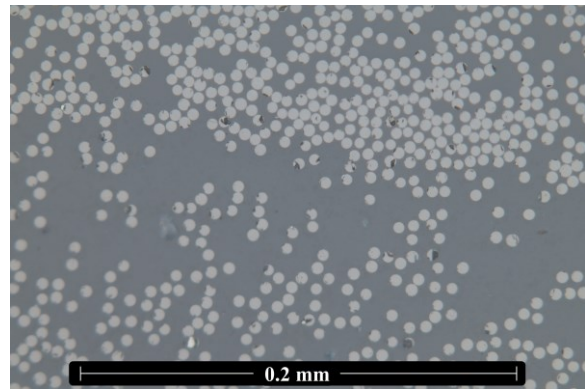
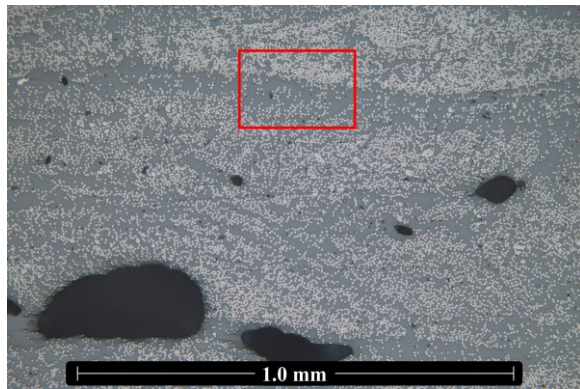


(e) C4

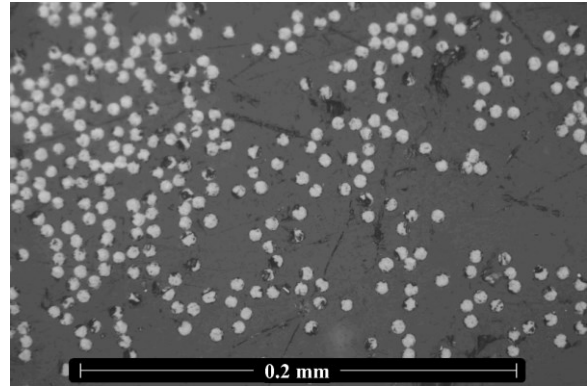
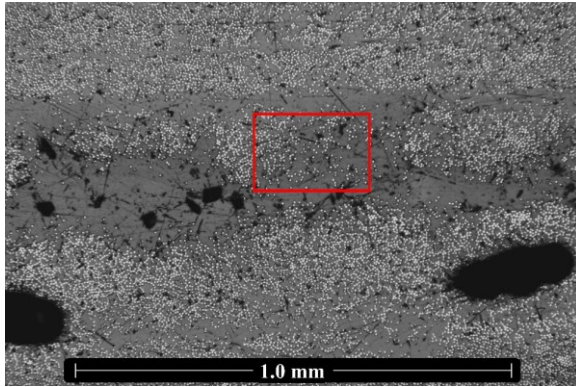


(f) C5

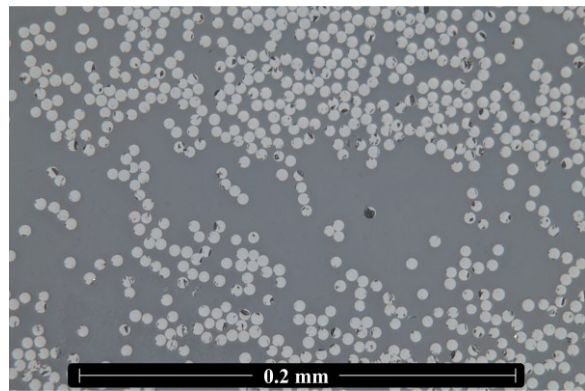
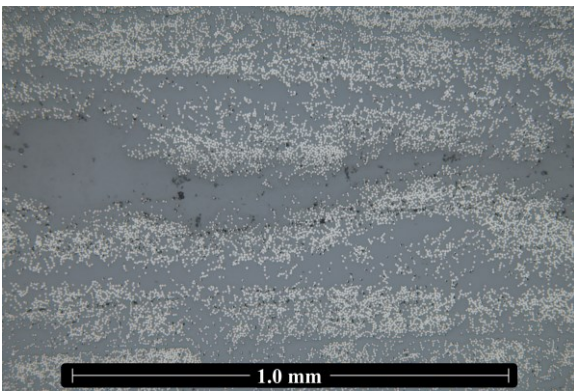
Figure 28. Microscopy images of joint line at 100 $\times$ and 500 $\times$ magnification of the control panels (C1-C5).



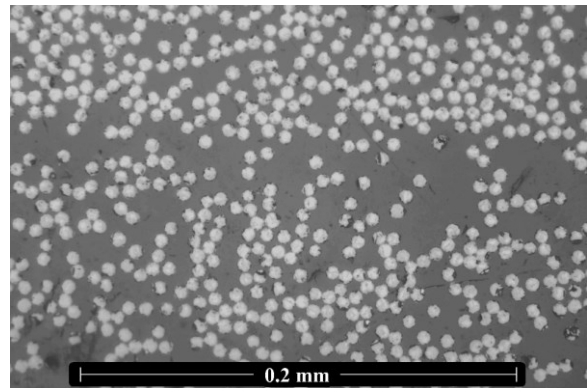
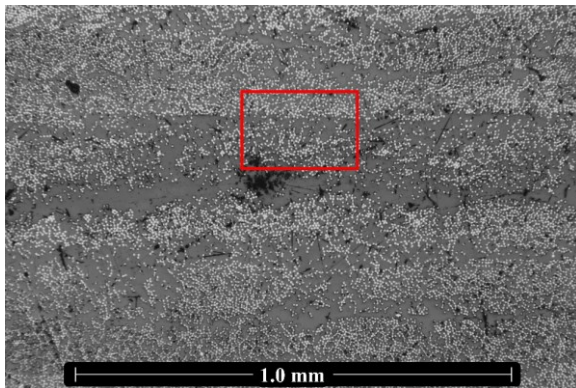
(a) AB+1



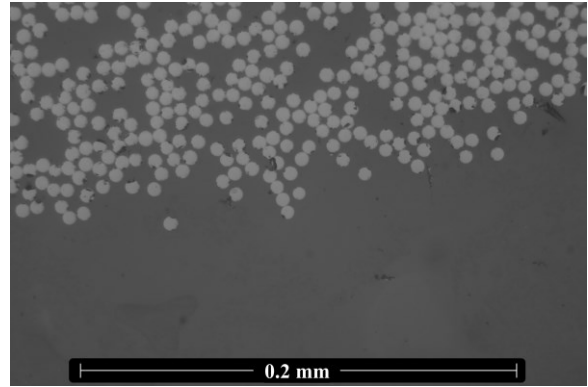
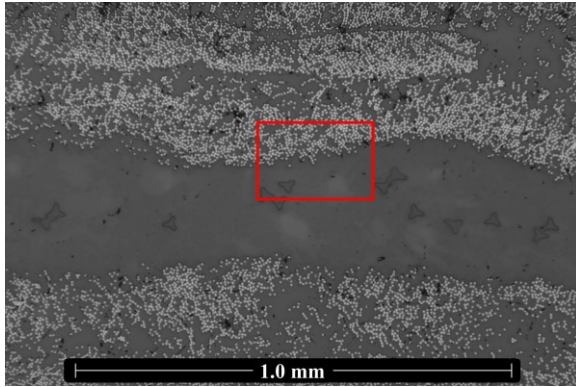
(b) AB+2



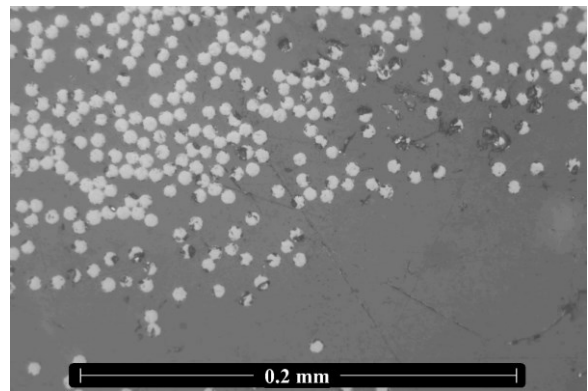
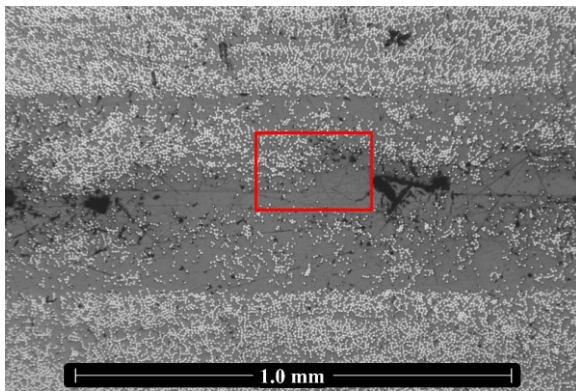
(c) AB+3a



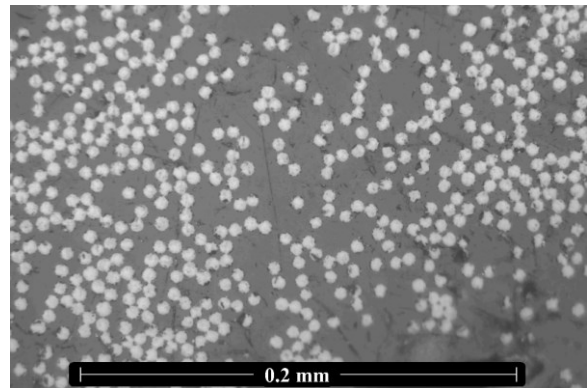
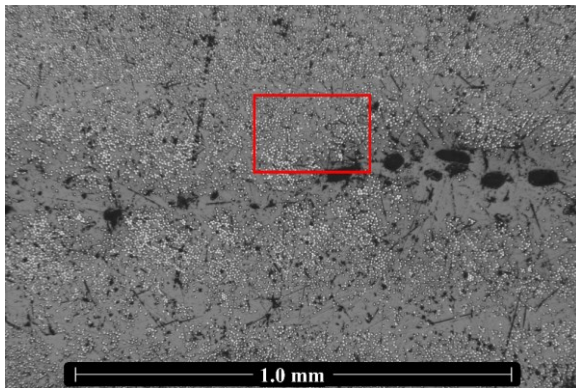
(d) AB+3b



(e) AB+3M



(f) AB+4



(g) AB+5

Figure 29. Microscopy images of joint line at 100 $\times$ and 500 $\times$ magnification of the AERoBOND+ panels (AB+1-AB+5).

Table 3. Experimental results summary table.

Panel Properties						Ultrasonic Amplitude (%)	Prepreg-to-Adhesive			Prepreg-to-Prepreg			SBS (MPa)								
Panel Type	Bond Type	Surface	Preparation (SP)	Curing Equipment	Bonding Pressure (kPa)		G _{Ic} _init (kJ/m²)	G _{Ic} _NPC (kJ/m²)	G _{Ic} _PC (kJ/m²)	G _{Ic} _init (kJ/m²)	G _{Ic} _NPC (kJ/m²)	G _{Ic} _PC (kJ/m²)									
Control	Co-Cure	No SP				Autoclave	791	C1	Mean	21.4	0.671	2.820	1.942	0.490	1.219	1.214	115.4				
									n	166440	3	2	2	3	2	2	11				
						CV	51%	2%	3.0%	1.0%	5%	2.7%	6.8%	2.7%							
						Secondary Bonded	Autoclave	791	C2	Mean	70.5	0.084	3.178	3.562	0.163	1.129	0.665	104.2			
										n	161240	3	2	3	2	2	2	11			
							CV	23%	1.1%	26.0%	31.0%	12.9%	21.1%	8.6%	0						
	SP	Press	35	C3	% C1		330%	13%	113%	183%	33%	93%	55%	90%							
					Mean		NA	NA	2.742	1.423	NA	1.200	0.742	NA							
		n	NA	NA	6		6	NA	1	1	NA										
		Oven	101	C4	CV	NA	NA	7.5%	58.7%	NA	0.0%	0.0%	NA								
					% C1	NA	NA	97%	73%	NA	98%	61%	NA								
		Auto-clave <td rowspan="2">791<td rowspan="2">C5<td>Mean</td><td>91.5</td><td>NA</td><td>4.690</td><td>4.287</td><td>0.235</td><td>NA</td><td>NA</td><td>96.4</td></td></td>	791 <td rowspan="2">C5<td>Mean</td><td>91.5</td><td>NA</td><td>4.690</td><td>4.287</td><td>0.235</td><td>NA</td><td>NA</td><td>96.4</td></td>	C5 <td>Mean</td> <td>91.5</td> <td>NA</td> <td>4.690</td> <td>4.287</td> <td>0.235</td> <td>NA</td> <td>NA</td> <td>96.4</td>	Mean	91.5	NA	4.690	4.287	0.235	NA	NA	96.4								
	n				141687	NA	2	2	2	NA	NA	11									
	AB+	Secondary Bonded					Press	35	AB+1	CV	16%	NA	0.4%	10.8%	45%	NA	NA	3.3%			
										% C1	428%	NA	166%	221%	48%	NA	NA	84%			
							Oven	101	AB+2	Mean	98.4	NA	4.418	3.739	0.166	1.299	0.601	113.5			
										n	146025	NA	2	2	3	2	2	11			
										CV	8%	NA	2.3%	10.2%	14%	23.9%	1.6%	1.5%			
										% C1	460%	NA	157%	193%	34%	107%	49%	98%			
										Autoclave	791	AB+3	Mean	94.0	NA	4.483	4.354	0.191	1.511	0.904	110.3
													n	151200	NA	2	2	3	2	2	11
							CV	14%	NA				14.4%	33.9%	14%	46.3%	22.8%	1.4%			
							% C1	439%	NA				159%	224%	39%	124%	74%	96%			
							SP	Oven	101				AB+4	Mean	55.8	0.482	2.193	2.165	0.156	1.545	1.271
n														159159	3	2	2	2	2	2	11
CV										44%	10%	1%		4%	39%	39%	9%	7%			
% C1										261%	72%	78%		111%	32%	127%	105%	78%			
% C2										79%	447%	69%		61%	96%	137%	191%	87%			
% C2M										NA	NA	80%		152%	NA	129%	171%	NA			
Autoclave							791	AB+3M	% C3	61%	NA	47%	51%	66%	NA	NA	94%				
									% C4	57%	NA	50%	58%	94%	119%	212%	80%				
									% C5	59%	NA	49%	50%	82%	102%	141%	82%				
									Mean	57.8	0.320	2.616	2.623	0.189	1.391	1.530	107.8				
									n	163868	2	2	2	2	2	2	11				
									CV	32%	8%	0.5%	1.1%	7.4%	9.0%	24.5%	1.3%				
SP							Autoclave	791	AB+5	% C1	270%	48%	93%	135%	39%	114%	126%	93%			
										% C2	82%	298%	82%	74%	116%	123%	230%	103%			
	% C2M	NA	NA	95%	184%	NA				116%	206%	NA									
	% C3	63%	NA	56%	61%	81%				NA	NA	112%									
	% C4	59%	NA	59%	70%	114%				107%	255%	95%									
	% C5	61%	NA	58%	60%	99%				92%	169%	98%									
Oven	101	AB+4	Mean	37.8	0.643	4.000	4.218	0.207	1.924	1.756	104.1										
			n	247069	2	2	2	5	0	2	19										
			CV	41%	6%	9.4%	1.4%	33.9%	10.2%	2.7%	2.0%										
			% C1	177%	96%	142%	217%	42%	158%	145%	90%										
			% C2	54%	298%	126%	118%	127%	170%	264%	100%										
			% C2M	NA	NA	146%	296%	NA	160%	237%	NA										
Autoclave	791	AB+5	% C3	41%	NA	85%	98%	88%	NA	NA	108%										
			% C4	38%	NA	91%	113%	124%	148%	292%	92%										
			% C5	40%	NA	89%	97%	108%	127%	194%	94%										
			Mean	NA	NA	3.855	4.071	NA	1.695	1.284	NA										
			n	NA	NA	4	4	NA	0	6	NA										
			CV	NA	NA	0.0%	0.0%	NA	18.0%	10.0%	NA										
SP	Autoclave	791	AB+5	% C1	NA	NA	137%	210%	NA	139%	106%	NA									
				% C2	NA	NA	121%	114%	NA	150%	193%	NA									
				% C2M	NA	NA	141%	286%	NA	141%	173%	NA									
				% C3	NA	NA	82%	95%	NA	NA	NA	NA									
				% C4	NA	NA	87%	109%	NA	130%	214%	NA									
				% C5	NA	NA	86%	94%	NA	112%	142%	NA									
Oven	101	AB+4	Mean	62.3	0.459	NA	NA	0.196	NA	NA	109.9										
			n	83220	2	NA	NA	2	NA	NA	10										
			CV	33%	1%	NA	NA	50.0%	NA	NA	2.3%										
			% C1	291%	68%	NA	NA	40%	NA	NA	95%										
			% C2	88%	298%	NA	NA	120%	NA	NA	105%										
			% C3	68%	NA	NA	NA	84%	NA	NA	114%										
Autoclave	791	AB+5	% C4	63%	NA	NA	NA	118%	NA	NA	97%										
			% C5	66%	NA	NA	NA	103%	NA	NA	100%										
			Mean	63.3	0.573	2.692	3.012	0.226	1.583	1.543	108.6										
			n	144900	3	2	2	3	2	2	11										
			CV	24%	15%	5.2%	1.3%	17.8%	12.5%	0.7%	3.9%										
			% C1	296%	85%	95%	155%	46%	130%	127%	94%										
SP	Autoclave	791	AB+5	% C2	90%	447%	85%	85%	139%	140%	232%	104%									
				% C2M	NA	NA	98%	212%	NA	132%	208%	NA									
				% C3	69%	NA	57%	70%	96%	NA	NA	113%									
				% C4	64%	NA	61%	81%	136%	122%	257%	96%									
				% C5	67%	NA	60%	69%	118%	105%	171%	98%									

Qualitative Assessment

Excellent

Good

Adequate

Poor

Ultrasonic Inspection

0-66% Control

66-125% Control

125-200% Control

>200% Control

Mechanical Testing

>150% Control

80-150% Control

50-80% Control

0-50% Control