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1.0 **Introduction**

1.1 Background

A number of process parameters can potentially affect the performance of adhesively bonded joints in a polymer matrix composite structure. In addition to the often-extensive list of parameters associated with surface preparation, these can include (but are not limited to): adhesive age, adherend age (which can relate directly to pre-bond moisture in adherends), adhesive out-time, and cure characteristics (including ramp rates, hold temperatures, and hold durations). With respect to evaluating the effects of these potentially critical process parameters, several options exist in terms of test methods. Lap shear is perhaps the most widely considered test method, owing primarily to its ease of use. Parent panel fabrication is straightforward, though termination of the adhesive at the edges of the bonded region is known to be critical with respect to stress concentrations at the free edges of the joint [1,2]. Furthermore, testing is cost-effective, as no specialized fixturing is needed, test duration is short, and data collection needs are minimal (typically, only failure loads are recorded). However, the lap shear test verifies only short-term bond strength and is a poor indicator of long-term durability [3–6].

Hart-Smith [3,4] was among the first to detail this problem for adhesively bonded joints in composite structures. He notes that the metallic structures community recognized the shortcomings of the lap shear test and responded with the development of the Boeing wedge-crack test (once designated as ASTM D3762, which was withdrawn in 2019) to better screen for environmental effects in metal-bonded structures. Hart-Smith draws an analog to composite-bonded structures, where peel loads – as opposed to shear loads – should also be much more likely to reveal structural deficiencies in the bonded system. He qualitatively considers the relative merits and drawbacks associated with several peel-type test methods in addition to the Boeing wedge-crack test, including the double cantilever beam (DCB) test and the floating roller peel test, but does not present a quantitative experimental comparison of said test methods. Throughout his work, Hart-Smith strongly emphasizes the need to focus on failure modes in addition to failure loads, rather than simply on failure loads alone.

Davis and Bond [5] also point out the inadequacies of the simple lap shear test and advocate the use of a peel-type test in evaluating the durability of adhesive bonds. They highlight one of the drawbacks of the Boeing wedge-crack test in that the stress at the crack tip diminishes as crack length increases – which is due to the static nature of the wedge loading – and reference a modified wedge-crack test proposed by Arnott and Kindermann [7] in which a constant applied displacement peels adherends apart to ensure a more constant crack opening force as crack length increases. This is akin to the DCB test, which is supported by ASTM D5528 [8,9] and provides for the determination of Mode I fracture toughness in unidirectional, monolithic composites so long as several key parameters (as outlined in the standard) are met. While their qualitative contributions are valuable, Davis and Bond do not present an experimental comparison of test methods for assessing the performance of adhesively bonded joints in composite structures.

Bardis and Kedward [6] considered a wide range of candidate tests and considered three of them closely – the DCB test, the travelling wedge test (similar in intent to the modified wedge-crack test considered by Arnott and Kindermann, albeit without the adherends under direct displacement), and the static wedge test (akin to the Boeing wedge-crack test). Through rigorous experimental work, Bardis and Kedward present a comprehensive comparison of candidate test methods, though the supporting experimental data comparing the test methods is not explicitly reported in many cases. They reach the conclusion that the DCB test is the most useful for evaluating long-term durability in adhesively bonded composite structures. While acknowledging the relative benefits of the wedge-based tests – including ease of implementation – they ultimately valued the data quality and detailed insight into failure modes offered by the DCB test over the others. This follows Hart-Smith's thoughts with respect to the value in characterizing failure modes in addition to failure loads. It should be noted that despite the drawbacks associated with wedge-based tests, they arguably provide the most representative assessment of long-term durability in that a bond (in particular, a crack tip zone) can be subjected to sustained stresses for an extended period of time in a relevant environment. Further, it should be recognized that the term "durability" as it relates to adhesive bond testing is not used uniformly within the community. Some practitioners tend to consider fracture-based tests as indicators of durability in adhesively bonded composite structures [3–6], while others have suggested that durability-based tests (such as wedge-based tests) should be considered distinct from fracture-based tests (such as the DCB test) while recognizing that both often fundamentally utilize Mode I loading [10–13].

The TRUST (Transition Reliable Unitized Structure) program – which was an effort led by Lockheed Martin Aeronautics Company and funded via the DARPA Open Manufacturing program – carried out an extensive comparison of test methods for assessing the performance of adhesively bonded joints in composite structures [14–16]. The TRUST program considered the single lap shear test (via ASTM D3165), the double lap shear test (via ASTM D3528), the flatwise tension test (via ASTM D2095), the DCB test (via ASTM D5528), the rapid adhesion test, the notched lap shear test (via ASTM D3165), the end notched flexure test (via ASTM D7905), and a wedge crack test (via ASTM D3762) at the coupon level, along with several additional test methods at the sub-element level (primarily focused on pi-preform joints). The TRUST program concluded that the DCB test provides the most valuable insight with respect to bonding processes and how they relate to mechanical performance. However, similar to other studies in this area, the experimental data supporting this conclusion is not openly reported.

This study aims to fill the aforementioned gaps in the literature by presenting a comprehensive experimental comparison of the single lap shear test and the DCB test for the purposes of characterizing the performance of adhesively bonded joints in composite structures.

2.0 **Experimental**

2.1 Study Design

To carry out this comparison, six test groups representing a range of manufacturing process parameters were considered. Adhesively bonded joint assemblies were fabricated per said process parameters to provide for single lap shear and DCB test specimens. Table 1 shows a summary of the test groups considered herein.

Table 1. Summary of test groups considered in this study.

Test Group	Cure Temp. (°F)	Plasma Treatment	Tests Considered (with specimen counts in parentheses)
PLA-PWD-LBJ-A-085	200	No	Single lap shear (6), DCB (5)
PLA-PWD-LBJ-A-086	200	Yes	Single lap shear (6), DCB (5)
PLA-PWD-LBJ-A-087	250	No	Single lap shear (6), DCB (5)
PLA-PWD-LBJ-A-088	250	Yes	Single lap shear (6), DCB (5)
PLA-PWD-LBJ-A-089	300	No	Single lap shear (6), DCB (5)
PLA-PWD-LBJ-A-090	300	Yes	Single lap shear (6), DCB (5)

The DCB test data for each of these six test groups has been previously published by the authors as part of a broader study on the effects of manufacturing process parameters on adhesively bonded joints for composite structures [17]. This work evaluated a range of manufacturing process parameters with respect to mechanical performance and fracture behavior using the DCB test. Results from this study showed that performance of the adhesively bonded joints considered was not highly sensitive to manufacturing process parameters, with one notable exception – excessively low cure temperature (200°F) for the film adhesive used to bond adherends to one another. The effects of preparation to bond time (of up to 14 days), film adhesive out-time (of up to 40 days), and atmospheric pressure plasma treatment (APPT) were shown to be minimal if present at all. Mode I fracture toughness was shown to correlate well with percentage cohesive failure, while wide variation in Mode I fracture toughness was shown to exist for a given relative percentage of interfacial failure. The latter takeaway reinforces the notion that interfacial failure is undesirable in practice due to its tendency to yield fracture toughness values that are not only low but also difficult to predict.

In order to carry out the objectives of this study, single lap shear test data was gathered to supplement the DCB test data previously published in the aforementioned broader study. Though separate bonded assemblies were fabricated for the two test types, adherends used for single lap shear and DCB bonded assemblies were taken from the same parent panel to provide for continuity between the two datasets. The single lap shear data presented herein has not been previously published.

2.2 Material Selection and Surface Preparation Approach

Hexcel IM7/8552-1 unidirectional tape was used for the laminate adherends. Solvay FM 209-1M epoxy film adhesive, which is a 250°F curing adhesive (though it is also compatible with 350°F curing systems), was used for bonding. Solvay FM 3500 EZP (epoxy with glass fabric carrier) prepreg peel ply was used to facilitate surface preparation. Where plasma treatment was considered, surfaces to be bonded were exposed to automated APPT following removal of FM 3500 EZP and prior to bonding with FM 209-1M. Figure 1 shows the automated APPT system at NASA Marshall Space Flight Center (MSFC) used in this study (see reference [17] for further details on automated APPT as carried out in this work). The following fabrication approach was used in this study:

1. Co-cure FM 3500 EZP on surfaces to be bonded during IM7/8552-1 adherend cure.
2. Immediately prior to bonding, remove FM 3500 EZP from IM7/8552-1 adherend surfaces to be bonded. Perform plasma treatment on adherend surfaces as applicable.
3. Apply FM 209-1M and secondarily bond adherends.

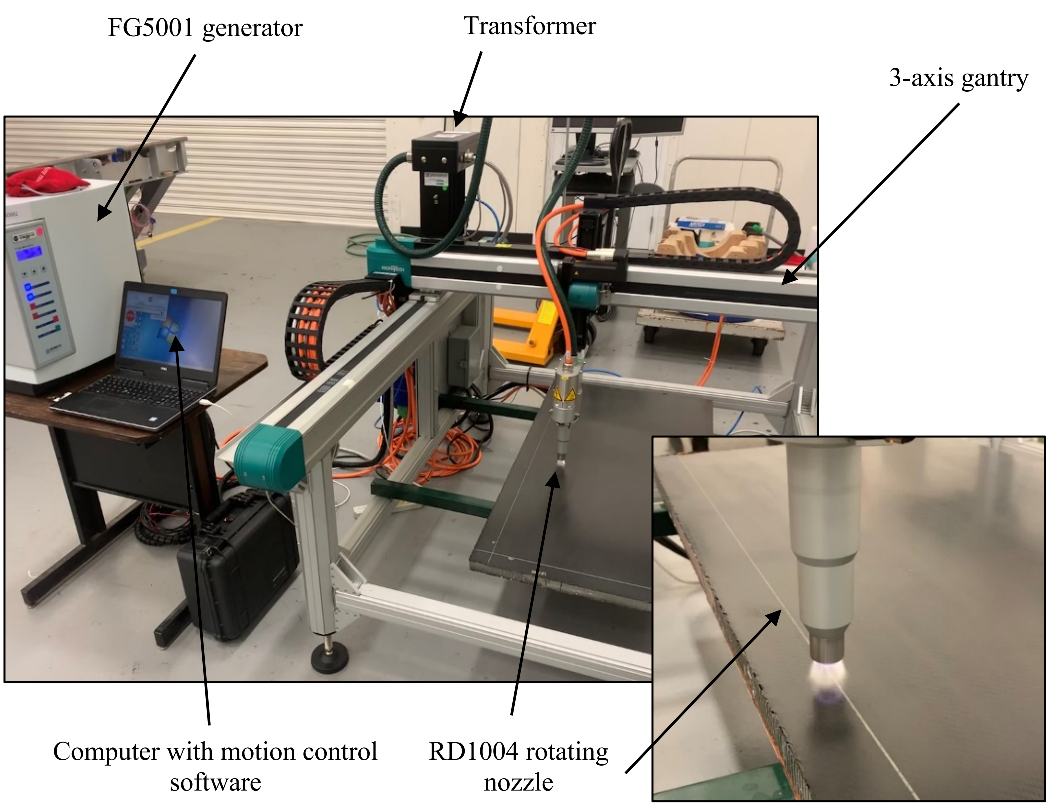
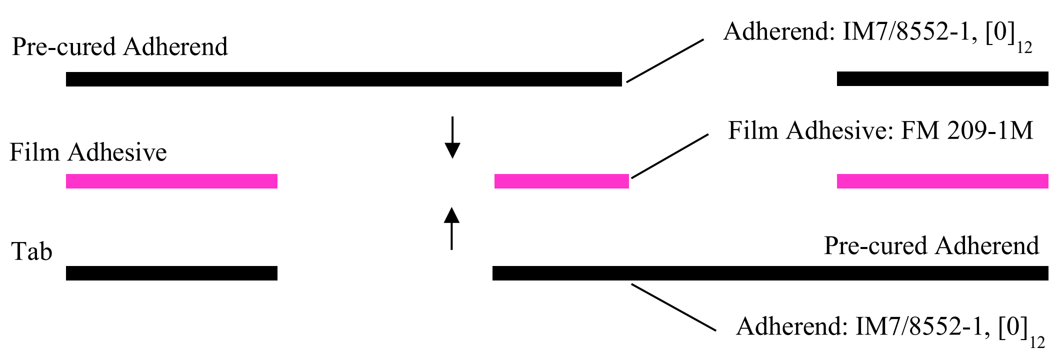


Figure 1. NASA MSFC automated system for atmospheric pressure plasma treatment (APPT).

2.3 Bonded Assembly Fabrication

A single parent panel (IM7/8552-1; $[0]_{12}$; 96 in. x 48 in. in size) was manufactured in order to facilitate fabrication of the single lap shear and DCB bonded assemblies considered in this study. This approach helped ensure that the single lap shear and DCB bonded assemblies would reflect the same parent materials and processing conditions. Parent panel layup was carried out via automated fiber placement (AFP). Care was taken in AFP programming to stagger course start points such that course-to-course seams would not be stacked through the thickness. FM 3500 EZP was placed on the tool side and on the bag side of the parent panel laminate. The parent panel was cured on a release-coated Invar tool with a release-coated composite caul sheet on the bag side of the layup (Loctite Frekote 700-NC^{TM} release agent was used on the Invar tool surface and composite caul sheet). Following autoclave cure at 350°F and 50 psi, with a 120 minute hold at said temperature and pressure, sub-panels were machined from the parent panel and stored in sealed bags.

Bonded assemblies were fabricated by secondarily bonding sub-panels together using FM 209-1M film adhesive. Figure 2 shows schematics of the single lap shear and DCB bonded assemblies. In the case of the single lap shear bonded assemblies, tabs (shims) were bonded to the adherends to facilitate tensile loading (this practice also provides for ease of manufacturing). Note that the tabs used in the single lap shear bonded assemblies were taken from the same parent panels as the adherends, such that thickness and layup matched that of the adherends. In the case of the DCB bonded assemblies, 0.0005 in. fluorinated ethylene propylene (FEP) was placed between the film adhesive and one adherend as a non-adhesive insert to create an initiation site for delamination growth.



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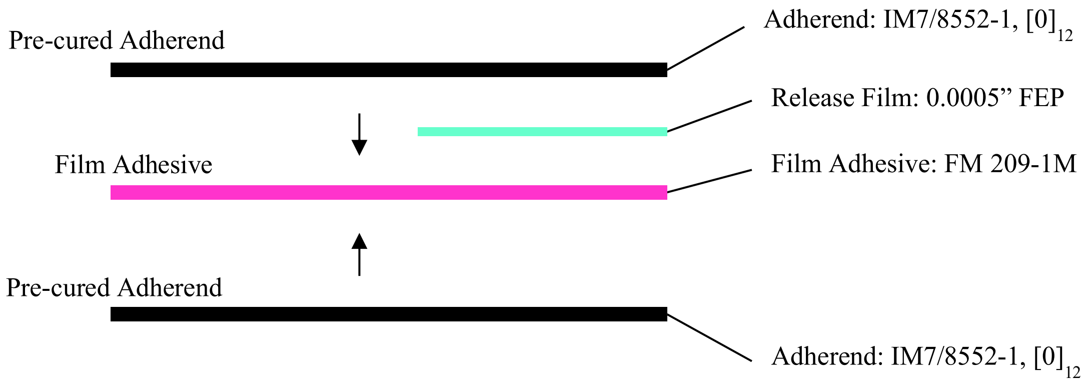


(b)

Figure 2. Overview of bonded assemblies fabricated to yield (a) single lap shear test specimens and (b) double cantilever beam (DCB) test specimens.

To better ensure consistency among the test groups, each assembly was bonded with the tool side of the adherends oriented toward the film adhesive. Though both laminate adherend surfaces (tool side and bag side) were tooled and released, the authors preferred to avoid any potential interferences associated with considering a mix of tool side and bag side surfaces at the bonded interfaces. With respect to this concern, it should be noted that the aforementioned broader study previously carried out by the authors [17] shows that the use of Frekote 700-NC™ on the tool and the caul sheet did not play a role at the bonded interface – which is to be expected given that the use of the sacrificial FM 3500 EZP layers precludes the potential transfer of any contaminants to from the release agent to the IM7/8552-1 bonding surfaces. Each assembly was bonded under full vacuum (> 27 in. Hg) using the following cure profiles:

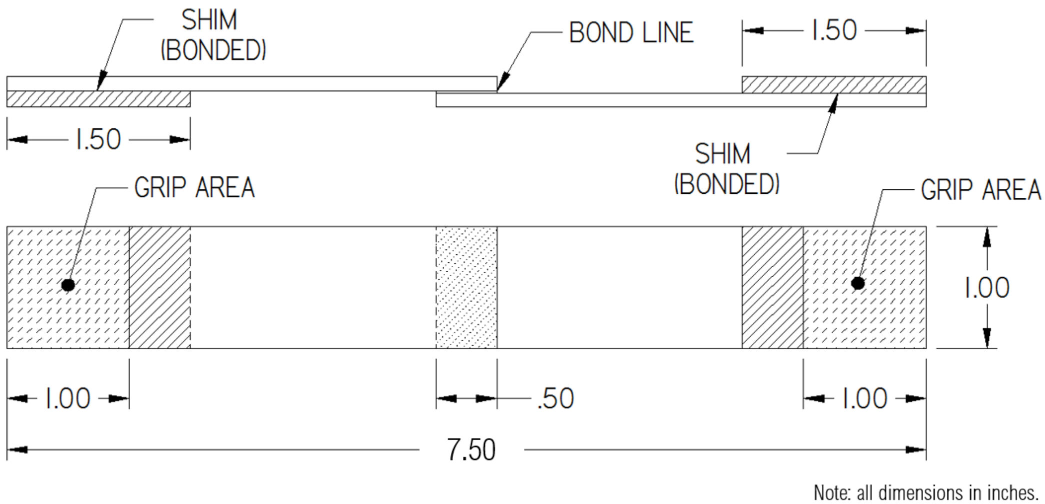
- For 200°F cure groups: Heat to 200°F at 3-5°F/minute, hold at 200°F for 90 minutes, then cool to below 150°F at no greater than 5°F/minute.
- For 250°F cure groups: Heat to 250°F at 3-5°F/minute, hold at 250°F for 90 minutes, then cool to below 150°F at no greater than 5°F/minute.
- For 300°F cure groups: Heat to 300°F at 3-5°F/minute, hold at 300°F for 90 minutes, then cool to below 150°F at no greater than 5°F/minute.

As was the case in the previously published study [17], cure profiles were selected with the specific intent of evaluating the effects of hold temperature given the wide variations in cure temperature often encountered in practice when using a hot bonder/heat blanket cure approach (as would be the case for adhesively bonded joints in a large scale structure that cannot be placed into an autoclave or oven due to size, logistical, or other engineering constraints). In taking this approach, test results can be used to establish acceptable process windows for hold temperature at a given hold duration (in this case, 90 minutes). It is recognized that where hold temperature is insufficient in practice, hold duration could be extended to increase degree of cure and associated mechanical properties of the adhesive. While this is worthy of pursuing in future work, the present study (and the authors' previously published study) focuses on establishing process windows for hold temperature at a given hold duration – hence the cure profiles selected for use herein.

Bonding operations were carried out in a composites fabrication facility (large volume high bay) at NASA MSFC. This facility is climate controlled and continuously monitored for temperature, relative humidity, and airborne particulates. The facility is also regularly monitored for the presence of airborne silicones via aluminum fallout plates that are checked via benchtop Fourier-transform infrared (FTIR) spectroscopy. Over the period that this study was carried out, these regular checks via FTIR showed no evidence of silicones.

2.4 Single Lap Shear Testing

Single lap shear tests were carried out at NASA MSFC. ASTM D1002 and D3165 were used as guides for specimen configuration. Figure 3(a) details the specimen configuration used in this study. Test specimens were loaded to failure in tension at a rate of 0.05 in./min. Upon failure, maximum loads were recorded and adherends were packaged so as to protect failure surfaces. Figure 3(b) shows a typical single lap shear test in the load frame. Following mechanical testing, failure surfaces for each test specimen were imaged using an optical microscope.



(a)

(b)

Figure 3. Single lap shear testing: (a) specimen configuration and (b) typical single lap shear test at NASA MSFC.

2.5 Mode I Fracture Toughness Testing

Mode I fracture toughness tests were carried out at the National Institute for Aviation Research (NIAR) in accordance with ASTM D5528-13 [20]. While ASTM D5528 is intended for use with monolithic unidirectional composite laminates with single-phase matrices, the standard acknowledges that the test method can be applicable to other configurations so long as potential interferences are taken into account [8]. In the case of this study, the potential for multiple apparent fracture toughness values due to the presence of multiple materials and bonded interfaces is noted. This potential interference is accounted for by considering as-measured Mode I fracture toughness values in accordance with associated failure modes and failure locations, as this precludes the possibility that fracture toughness values by themselves are improperly interpreted. Furthermore, the data reduction methods identified in ASTM D5528 do not directly account for a dissimilar adhesive layer, as is present in the DCB coupons considered in this study. However, Bardis and Kedward [6] have shown that adhesive layer effects can be neglected as long as certain conditions are met with respect to delamination length, adherend thickness, and adhesive thickness. The authors have previously shown [17] that the DCB test specimens considered in this study meet the aforementioned conditions; therefore, the presence of the adhesive layer is neglected in this study for the purposes of calculating Mode I fracture toughness values. Though additional considerations must be made (as detailed in this section), the Mode I fracture toughness test using the DCB specimen is commonly used to evaluate assemblies where two composite adherends are bonded using a dissimilar adhesive [6,14–16,18–21].

ASTM D5528 was updated in 2021 – the same year that the authors published the broader study on manufacturing process parameters that heavily leveraged the DCB test [17] (the authors' previous work entered the publication review cycle prior to the release of the updated standard, and as such, leverages ASTM D5528-13). The updated ASTM D5528/D5528M-21 [9] differs from ASTM D5528-13 [8] in several key areas, including the points where fracture toughness values associated with delamination onset are to be calculated (including changes in terminology for these points) and the method recommended for data reduction. In particular, ASTM D5528/D5528M-21 recommends the compliance calibration (CC) method for data reduction, as opposed to the modified beam theory (MBT) method recommended by ASTM D5528-13. ASTM D5528/D5528M-21 states that the CC method is recommended because it is consistent with the data reduction method in ASTM D7905/D7905M [22] (which addresses Mode II fracture in polymer matrix composites), while also stating that the MBT method can be used instead of the CC method if desired. In order to maintain consistency with the authors' previously published broader study, the present study also relies on ASTM D5528-13 and uses the MBT method for Mode I fracture toughness data reduction. In addition to the initiation fracture toughness values called for by ASTM D5528-13, mean Mode I propagation fracture toughness values were determined for each specimen. As noted in reference [17], this value was calculated over a delamination length range (approximately 1-2 in.) where delamination growth was principally stable. This same delamination length range was used to evaluate and quantify failure modes, such that Mode I fracture toughness values and corresponding failure modes can be considered in direct relation to one another. Figure 4 shows this concept in reference to a typical delamination resistance curve (R-curve) generated in this study.

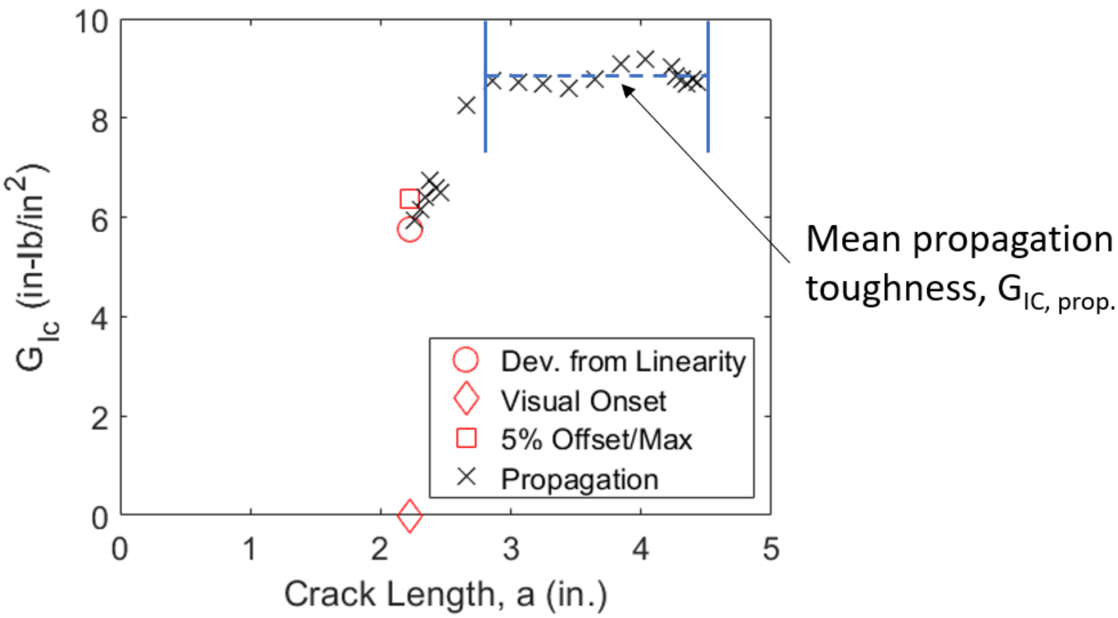


Figure 4. Typical delamination resistance curve (R-curve) as observed in this study, with delamination length range over which mean propagation toughness was determined. Note that terminology used for initiation fracture toughness values reflects that of ASTM D5528-13.

DCB specimens were initially loaded at 0.08 in./minute to advance the delamination 0.12-0.20 in. from the tip of the non-adhesive insert. Specimens were then unloaded at a rate of 1 in./minute, then reloaded at 0.08 in./minute to advance the delamination an additional 2-3 in. Delamination length was tracked via a visual camera and correlated to the load-displacement record. Upon test completion, specimens were loaded at 1 in./min to completely separate the two adherends to facilitate failure surface analysis. As was done for the single lap shear test specimens, failure surfaces for each test specimen were imaged using an optical microscope.

3.0 **Results and Discussion**

3.1 Test Results

Single lap shear and Mode I fracture toughness test results are presented in detail in Table 2 and are shown graphically in Figure 5.

Table 2. Single lap shear and Mode I fracture toughness test results. Coefficients of variation are shown in italics.

Test Group ID	Cure Temperature (°F)	APPT[1]?	Single Lap Shear Strength (psi)	Mode I Fracture Toughness[2] ($in\text{-}lb/in^2$)
PLA-PWD-LBJ-A-085	200	No	3662 ± 779 *(21%)*	3.98 ± 1.09 *(27%)*
PLA-PWD-LBJ-A-086	200	Yes	3542 ± 381 *(11%)*	3.01 ± 0.51 *(17%)*
PLA-PWD-LBJ-A-087	250	No	3905 ± 471 *(12%)*	8.65 ± 0.43 *(5.0%)*
PLA-PWD-LBJ-A-088	250	Yes	3781 ± 228 *(6.0%)*	8.60 ± 0.31 *(3.6%)*
PLA-PWD-LBJ-A-089	300	No	3978 ± 506 *(13%)*	9.48 ± 0.35 *(3.7%)*
PLA-PWD-LBJ-A-090	300	Yes	4402 ± 62.5 *(1.4%)*	8.94 ± 0.27 *(3.0%)*

[1] Atmospheric pressure plasma treatment.

[2] Mean propagation fracture toughness.

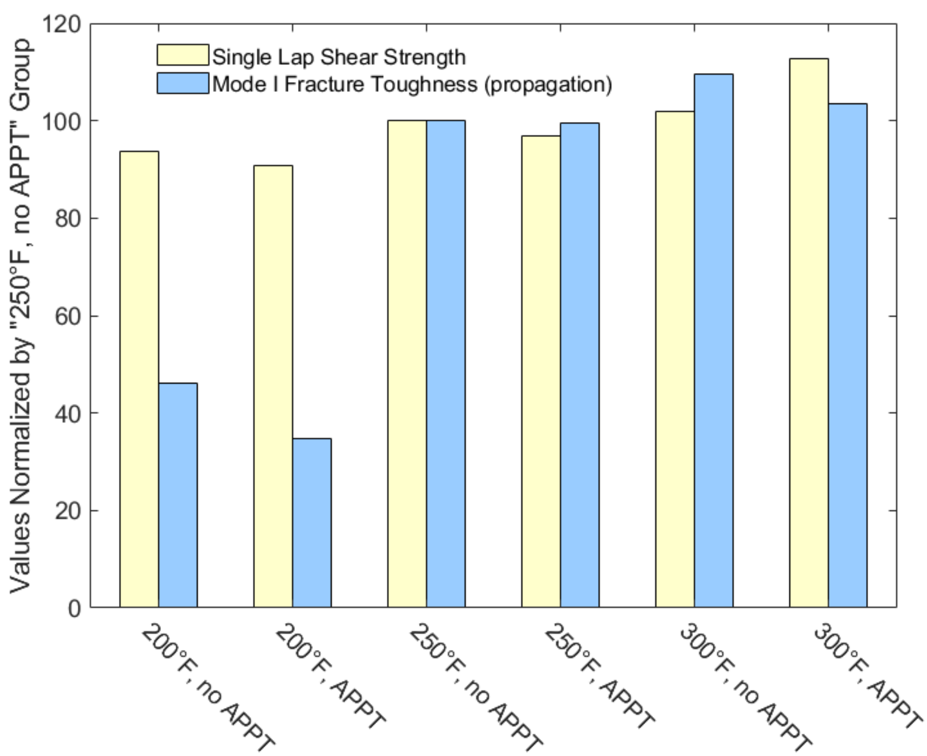
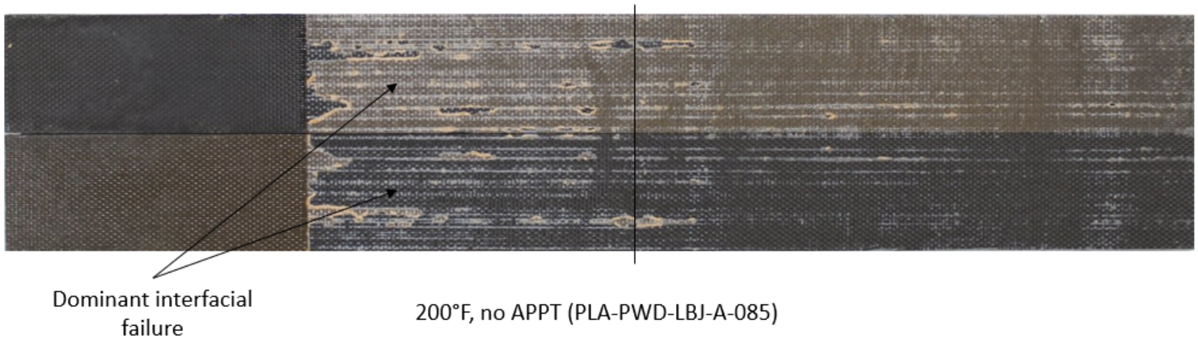


Figure 5. Graphical representation of single lap shear and Mode I fracture toughness results. Note that values are normalized by the 250°F cure temperature/no APPT group.

Large relative differences can be observed in Table 2 and Figure 5 with respect to the 200°F cure temperature groups. Considering the 250°F cure temperature groups as the baseline, the 200°F cure temperature groups show declines of less than 10% in single lap shear strength and more than 50% in Mode I fracture toughness. Differences relative to the baseline are reasonably comparable for the remaining test groups. Taken by itself, the trend observed with respect to the 200°F cure temperature groups is telling and significant; however, further context can be gleaned from failure surface analysis as presented in the following section. In the interest of completeness, detailed test data comparisons among the single lap shear strength and Mode I fracture toughness datasets using the Student's t-test are shown in Appendix A.

3.2 Failure Mode Analysis

Representative failure surfaces for each test group and both test methods considered in this study are shown in Figure 6 (200°F cure temperature groups), Figure 7 (250°F cure temperature groups), and Figure 8 (300°F cure temperature groups). Note that for the failure surfaces that resulted from the DCB tests, the vertical black lines separate the regions where fracture propagated during the test (to the left of the vertical black lines) and the regions where fracture propagated after the test (to the right of the vertical black lines; where specimens were separated post-test to allow for failure surface analysis).



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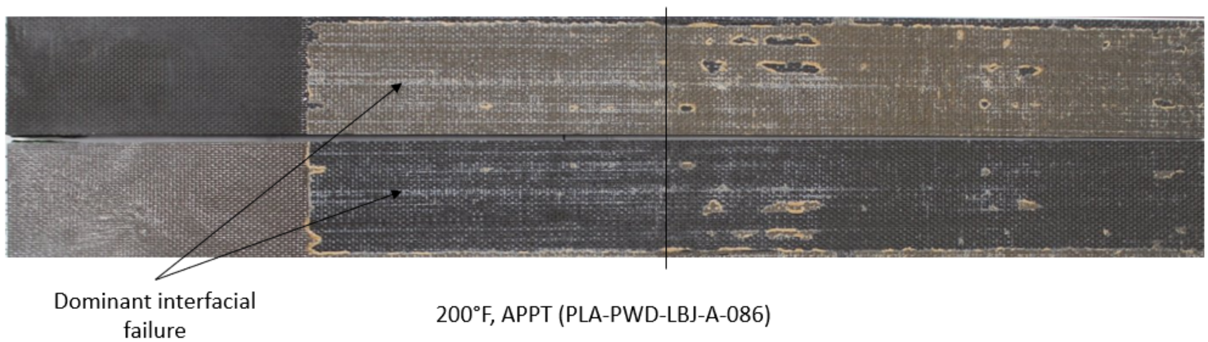

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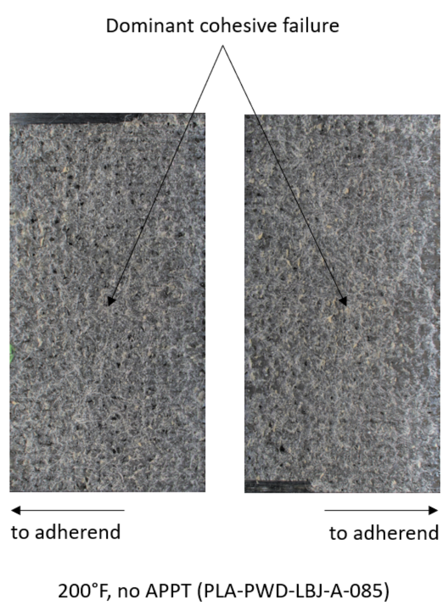

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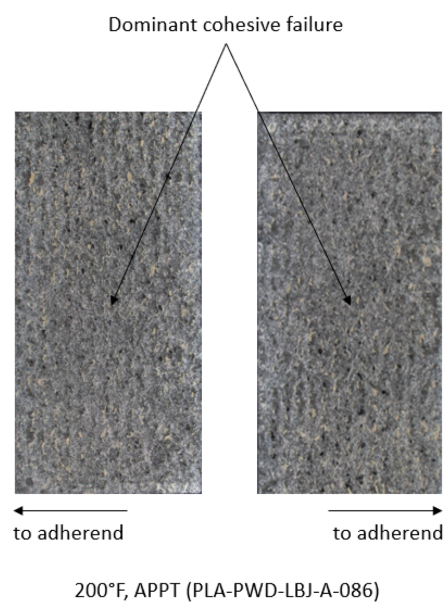

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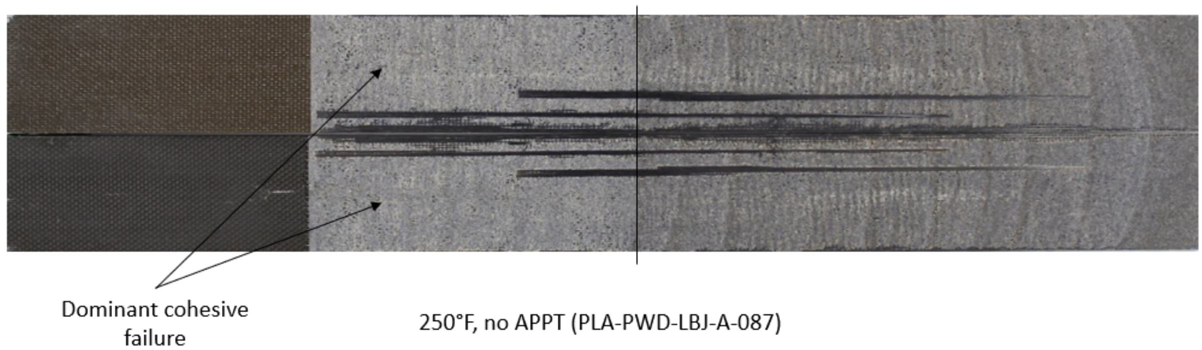
Figure 6. Comparison of failure surfaces for 200°F cure temperature groups: (a) DCB/200°F/no APPT, (b) DCB/200°F/APPT, (c) single lap shear/200°F/no APPT, and (d) single lap shear/200°F/APPT. Note that bond areas shown are 7.5 in. x 1.0 in for DCB specimens and 0.5 in. x 1.0 in. for single lap shear specimens.



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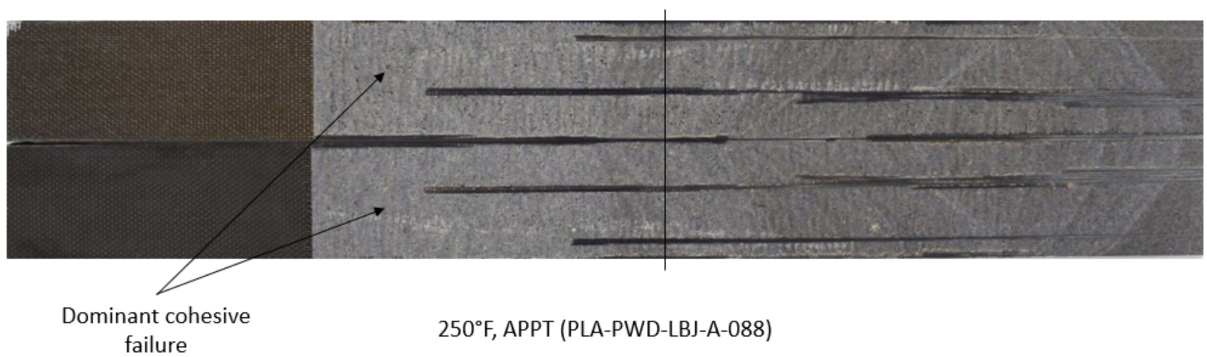

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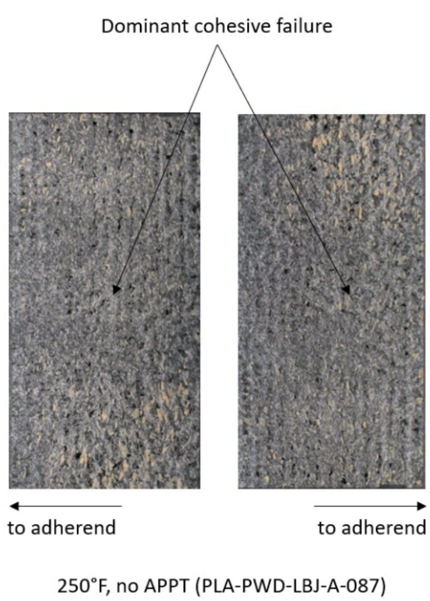

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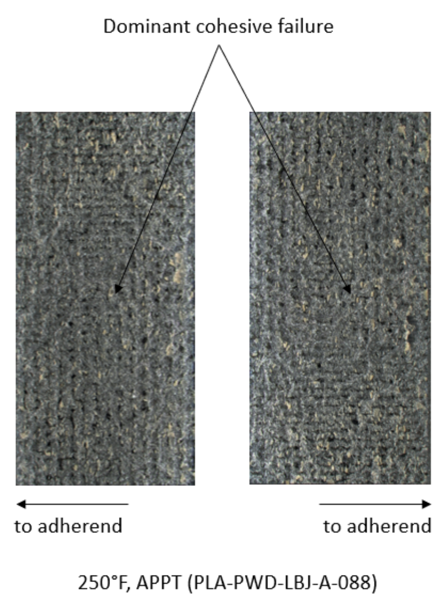

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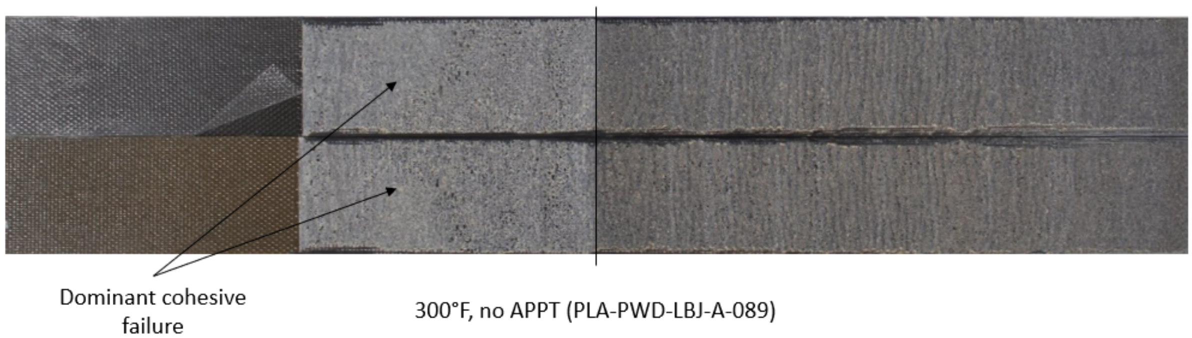
Figure 7. Comparison of failure surfaces for 250°F cure temperature groups: (a) DCB/250°F/no APPT, (b) DCB/250°F/APPT, (c) single lap shear/250°F/no APPT, and (d) single lap shear/250°F/APPT. Note that bond areas shown are 7.5 in. x 1.0 in for DCB specimens and 0.5 in. x 1.0 in. for single lap shear specimens.



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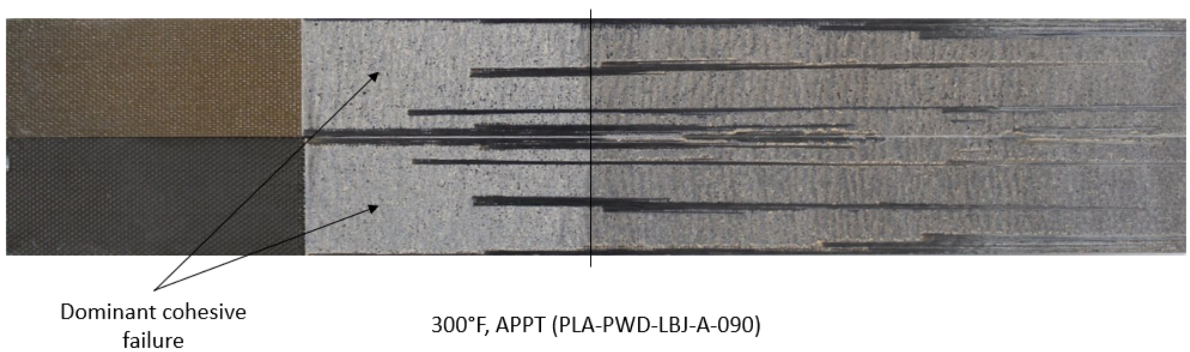

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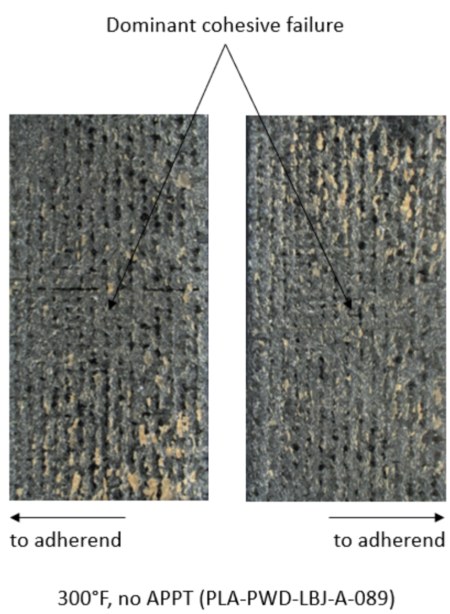

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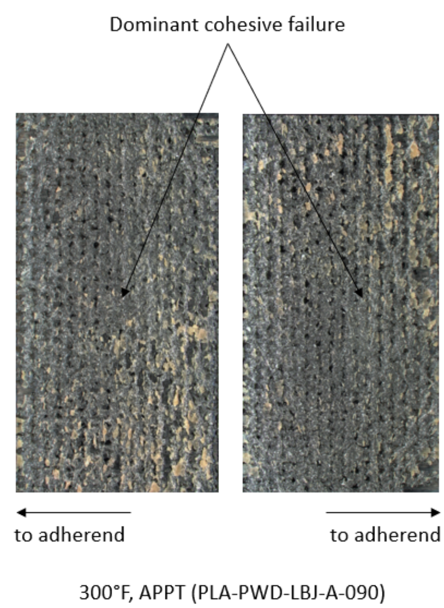

(d)

Figure 8. Comparison of failure surfaces for 300°F cure temperature groups: (a) DCB/300°F/no APPT, (b) DCB/300°F/APPT, (c) single lap shear/300°F/no APPT, and (d) single lap shear/300°F/APPT. Note that bond areas shown are 7.5 in. x 1.0 in for DCB specimens and 0.5 in. x 1.0 in. for single lap shear specimens.

Given the critical differences observed in mechanical testing with respect to the 200°F cure temperature groups, the failure mode analysis presented herein focuses on these test groups. Figure 6 shows that for the 200°F cure temperature groups, cohesive failure is dominant (though instances of substrate and interfacial failure are present) in the single lap shear specimens while interfacial failure is dominant (though instances of cohesive failure are present) in the DCB specimens. The significant degree of interfacial failure – which is known to correspond to poor mechanical performance in adhesively bonded joints [3,5,6] – observed in the 200°F cure temperature groups explains the reduction in Mode I fracture toughness compared to the baseline 250°F cure temperature groups.

Figures 7 and 8 show that failure modes are similar for the 250°F and 300°F cure temperature groups regardless of test method. While instances of substrate failure (in the case of the DCB specimens) and interfacial failure (in the case of the single lap shear specimens) are present, cohesive failure is dominant.

The contrast in failure modes presented herein – which correlates to the previously presented differences in mechanical performance – illustrates the value of the DCB test compared to the single lap shear test. The DCB test clearly shows that a cure temperature of 200°F (where 200°F is held for 90 minutes) is insufficient for the material systems (primarily, FM 209-1M) considered in this study. In these groups, failure occurs primarily at the adherend-adhesive interface, which corresponds to a reduction in Mode I fracture toughness of over 50% compared to the baseline groups. The single lap shear test – considering the same test groups with specimens manufactured from the same parent materials under the same processing conditions – provided no suggestion that a cure temperature of 200°F could lead to a critical shift in failure mode or a significant reduction in mechanical capability.

These observations with respect to failure modes can be related to the variability (i.e., standard deviations and coefficients of variation) measured for each test group to provide further insight into the relative merits of the single lap shear and DCB tests. Since Mode I fracture toughness values correspond to observed failure modes, the variability associated with the Mode I fracture toughness data can also be correlated to observed failure modes. Dominant interfacial failure – which is present in both of the 200°F cure temperature groups evaluated via the DCB test – corresponds to relatively high variability (17% to 27%), where dominant cohesive failure – which is present in the 250°F and 300°F cure temperature groups – corresponds to relatively low variability (≤ 5%). This reinforces the well-established knowledge that interfacial failure is undesirable for its tendency to yield not only poor mechanical performance, but also relatively unpredictable mechanical performance. Since each of the six test groups tested via single lap shear showed dominant cohesive failure, with little change in failure mode characteristics from test group to test group, the same insight cannot be gleaned from the single lap shear test.

Note that quantitative representations of failure modes (i.e., % cohesive failure, % substrate failure, and % interfacial failure) are not reported in this study. The failure surfaces that resulted from the DCB test lend themselves to image thresholding such that subsequent analysis can be used to determine relative percentages of the aforementioned three principal failure modes. This process is carried out in the broader study by the authors [17], which reports relative percentages of the three principal failure modes for each DCB test group considered herein. However, the failure surfaces that resulted from the single lap shear test did not provide for reliable image thresholding. Although the principal failure modes in the single lap shear test specimens are discernible via visual inspection, their interspersed nature complicates the image analysis process (i.e., does not allow for objectivity) to the extent that the authors are not comfortable reporting quantitative data for failure surfaces that resulted from the single lap shear test.

4.0 **Conclusions**

This study presents an experiment-based comparison of two test methods commonly used to characterize adhesively bonded joint performance – the single lap shear test and the DCB test. Single lap shear and DCB tests were carried out on six test groups representing a range of manufacturing process parameters. Mechanical test results were supplemented with failure surface analysis to more comprehensively evaluate the two test methods considered. Results show that the DCB test provides a more complete evaluation of adhesively bonded joint performance as compared to the single lap shear test. The DCB test proved capable of screening for insufficiencies in the bonded system that led to undesirable interfacial failure, while the single lap shear test effectively masked these same insufficiencies. Where the DCB test showed mechanical property knockdowns along with a critical shift in failure mode (from cohesive to interfacial failure), the single lap shear test showed no relative changes. As such, this study proves through experiment that the DCB test is considerably more reliable than the single lap shear test with respect to the evaluation of adhesively bonded joints in composite structures. Although the simplicity of the single lap shear test is appealing, it can introduce significant risk in a structural substantiation program due to its ineffectiveness in screening for critical insufficiencies in bonding processes and resulting mechanical performance. The DCB test should be considered as a primary tool in evaluating and substantiating adhesively bonded joints in composite structures.

Appendix A – Detailed Test Data Comparisons

Tables A1 and A2 show detailed test data comparisons for single lap shear strength and Mode I fracture toughness datasets, respectively. Values reported in the tables represent p-values calculated upon comparing datasets using a two-sample, two-sided Student's t-test where variances are unequal (heteroscedastic). By considering a two-sided test, no assumptions are made with respect to the direction of change (i.e., increase or decrease) between any two datasets. The null hypothesis is taken as "the property of Dataset A is the same as the property of Dataset B". If the p-value returned by the t-test is less than an established significance level, commonly taken as 0.05 [23], then the null hypothesis is rejected and the property of interest is deemed to be different between Dataset A and Dataset B. Care should be taken in interpreting the results of the Student's t-test (and hypothesis tests in a more general sense); in particular, p-values and the chosen significance level should not be considered in a binary manner. That is, if a significance level of 0.05 is chosen, it should be recognized that there is little difference between p-values of 0.048 and 0.052 even though these two results – when strictly interpreted – would yield different conclusions about the null hypothesis.

Table A1. p-values calculated per Student's t-test for single lap shear strength test data.

			200°F		250°F		300°F	
			No APPT	APPT	No APPT	APPT	No APPT	APPT
			-085	-086	-087	-088	-089	-090
200°F	No APPT[1]	-085	1.000	0.743	0.531	0.732	0.428	0.067
	APPT	-086		1.000	0.174	0.223	0.125	0.002
250°F	No APPT	-087			1.000	0.579	0.802	0.049
	APPT	-088				1.000	0.414	0.001
300°F	No APPT	-089					1.000	0.095
	APPT	-090						1.000

[1] Atmospheric pressure plasma treatment.

Table A2. p-values calculated per Student's t-test for Mode I fracture toughness test data[1].

			200°F		250°F		300°F	
			No APPT	APPT	No APPT	APPT	No APPT	APPT
			-085	-086	-087	-088	-089	-090
200°F	No APPT[2]	-085	1.000	0.121	0.000	0.000	0.000	0.000
	APPT	-086		1.000	0.000	0.000	0.000	0.000
250°F	No APPT	-087			1.000	0.837	0.010	0.238
	APPT	-088				1.000	0.003	0.098
300°F	No APPT	-089					1.000	0.027
	APPT	-090						1.000

[1] Mean propagation fracture toughness.

[2] Atmospheric pressure plasma treatment.

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