Evaluation of Low Viscosity Epoxy Repair Resins for Delamination Injection Repair

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Abstract. A common failure that occurs on polymer matrix composites (PMC) is delamination which can be induced by various phenomena including manufacturing defects and damage incurred during service and maintenance. Resin injection is an industry-standard technique used to repair delaminated composite materials using laminating resins EA9396 and EA956. This repair method is lower cost, less invasive, and faster than patch repairs, making it appealing for reduction of labor and material costs. However, the efficacy of this method is undercut by the difficulty of filling small cracks (< 1 micron) due to the laminating resin viscosity (~3500 cP at 25°C). Current injection repair processes are considered nonstructural due to repetitive drilling and incomplete crack filling. An investigation is ongoing on epoxies that have significantly lower viscosity and provide suitable service temperature. Testing is conducted to characterize the epoxies' material and mechanical properties such as shear strength, glass transition temperature (Tg), viscosity, and porosity. Evaluation of two downselected epoxies has been done using a modified End-Notched Flexure (ENF) specimen made with carbon/epoxy. Ultrasonic pulse-echo C-scans were taken of the coupons post-repair to discern the area filled and provide feedback on the parameters of the injection process. The repair resins' restoration of Mode II interlaminar fracture toughness (G_{IIc}) and stiffness show a marked increase in G_{IIc}, even approaching full recovery.

Keywords: Composite Injection Repair, Composite Delamination Repair, Epoxy Evaluation

1 Introduction

Polymer matrix composites (PMCs) are being heavily integrated into military aircraft structures due to their high strength and stiffness coupled with their relatively low weight, and corrosion and fatigue resistance. The manufacturing process of ply lamination makes composites susceptible to lower transverse moduli and strengths in comparison to their in-plane properties. Delamination of composite plies occur as a result of causes including impacts incurred from operational incidences, maintenance, or environmental factors and manufacturing errors. Interlaminar defects or cracks can lead to

premature failure if the cracks propagate through the structure under operational loading.

The Naval aircraft maintenance and repair manuals currently state resin injection as one of the potential repair methods for delamination. The purpose of resin injection would be to fill the interlaminar cracks and prevent them from propagating further. The two resins outlined for this repair method are Henkel's EA9396 and EA956. The problem with using either resin is that their relatively high viscosity (over 3000 cP at 77°F) makes it difficult to fill small cracks, especially those smaller than one micron. Leaving the cracks unfilled allows a path for crack propagation, diminishing the strength restoration from the repair to the structure. The Navy currently does not rely on resin injection repair for significant strength restoration to delaminated composite structures.

2 Objective

The approach of this study is to test commercially available repair resins that can potentially fill micro-cracks and subsequently restore strength to composite structures. This research is part of a larger effort to increase the efficacy of the current resin injection delamination repair process. This paper will outline the characterization of various epoxies' material and chemical properties and the testing performed to determine the fracture toughness restoration of carbon/epoxy End-Notched Flexure (ENF) coupons.

3 Resin Selection

Prior studies were conducted to improve the resin injection process for delaminations by examining and modifying process parameters that would maximize the likelihood of resin fill and subsequent restoration of mechanical properties. Russell et al. [1] parameterized the percentage of resin fill using factors including resin viscosity and injection pressure. They had additionally formulated a proprietary resin with a viscosity of 650 cP that had successfully filled most of the delamination [1].

Massey et al. [2] explored the impact of common aircraft contaminants such as lubricating oil or hydraulic fluid on the bond between the injected resin and the parent laminate. They had developed a novel cleaning process using acetone to clean the delaminated area, nitrogen to expel residual fluid, and atmospheric plasma to activate the surface; this preparation process was replicated in the subject studies. Massey et al. [2] had also studied various dilutions of EA9396 with solvents to achieve a convenient method to decrease viscosity. Diluting EA9396 with 10 percent acetone by weight lowered the viscosity from approximately 3500 cP to 500 cP. The success of diluting EA9396 prompted an exploration into further lowering its viscosity with 15 percent acetone by weight.

The following criteria were developed to select low viscosity off-the-shelf resins that can also sustain the operational environmental envelope that naval aircraft are exposed to. The epoxies listed in Table 1 were selected as they met the following critiera:

- Viscosity at room temperature $\leq$ 650 cP

- Glass transition temperature (T_g) $\geq$ 121°C (250°F)
- Pot life $\geq$ 20 minutes

The viscosity criterion was drawn from the success of the experimental resin in the studies conducted by Russell et al [1].The glass transition temperature requirement was drawn from the service temperature of naval aircraft and the minimum pot life is to ensure adequate time for the repair resin to be injected before gelation.

Table 1. Selected Epoxy Resin Candidates

Product Name	Manufacturer	Initial Viscosity at 25°C/ 77°F (cP), Brookfield	Tg (°C)	Tg (Elevated Temperature-Wet, °C)	Pot Life (hrs)
SUP112 (Supreme 112)	Master Bond	50-200	287.8 (Service temperature)	N/A	48-72
Araldite LY 5052-1/ Aradur 5052 Hardener	Huntsman	600-700	120-133.9	N/A	4
Kaneka SR6400	Kaneka	80	127.8	92.8	0.33 (20 mins)
Kaneka IR6030	Kaneka	370	135	N/A	1.5

4 Characterization of Selected Epoxy Resins

The epoxy resins shown in Table 1 were evaluated for their efficacy in meeting the criteria outlined in Section 3. Procurement lead times and cost were included to generate a holistic evaluation of the resins.

4.1 Viscosity

The viscosities of the epoxy resins were tested using Spindle 1 on a Brookfield DV-E Viscometer. Approximately 300 grams of each epoxy were mixed into a 450 mL beaker; the spindle was placed within the epoxies before taking readings. The data was sampled every 30 seconds for approximately 10 minutes, where the initial reading is considered the time where mixing the resin and hardener had concluded. The viscosity curves are depicted in Figure 1, where the orange line indicates the 650 cP threshold.

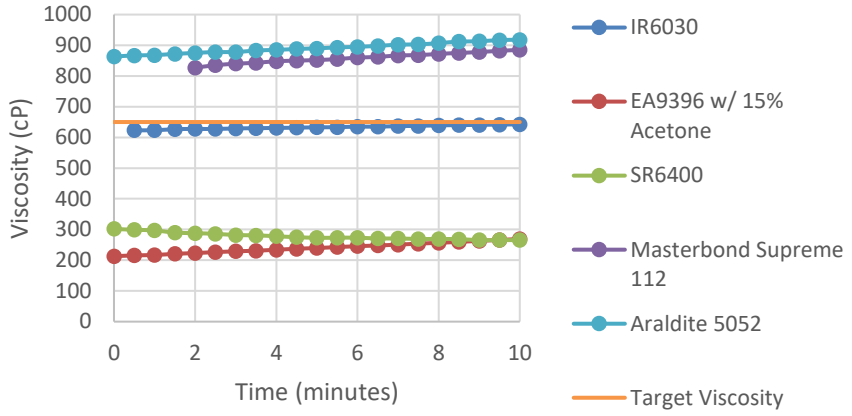

Fig. 1. Comparison of Brookfield Viscosities

The two Kaneka resins and the diluted EA9396 achieved viscosities lower than the threshold; the Supreme 112 and Araldite 5052 were more viscous at approximately 800-900 cP. All of the epoxies did not exhibit a significant increase in viscosity over the course of 10 minutes. However, the viscosity values are discrepant in comparison to what is advertised in the manufacturers' technical datasheets. One possible explanation for this is that the ambient conditions in the lab were different than the manufacturers' test data (20°C versus 25°C). This would innately result in lower viscosity due to the lower molecular kinetic energy and decrease in entropy. Another reason may be that the test method does not completely replicate the one employed by the resin manufacturers. The datasheets do not always explicitly state parameters including the amount of resin used and spindle type, which would have a significant impact on the viscosity readings.

4.2 Shear Strength

The shear strength of the epoxy resins were discerned through single lap shear testing in accordance with ASTM D1002. Aluminum alloy 2024-T3 panels were prepared in advance of bonding by grit blasting and then sol-gel and primer application. The panels were bonded together using a fixture to restrict movement and prevent misalignment. Nylon scrim cloth was employed to ensure uniform bondline thickness. The panel was subsequently cut post-cure into three coupons that were approximately 304.8 mm by 25.4 mm (length by width) with a bond overlap length of 12.7 mm.

Two environmental conditions were tested: room temperature, dry (RTD) and elevated temperature, wet (ETW). The latter condition involved placing the specimens into the humidity cabinet at 60°C and 90-100 percent relative humidity (RH) until moisture equilibrium was achieved per ASTM D5229 Procedure D. Traveler coupons were created to be weighed for moisture absorption. The coupons were weighed weekly to

track the change in moisture content. Figure 2 indicates the curve for the change in moisture content of Araldite 5052 as an example.

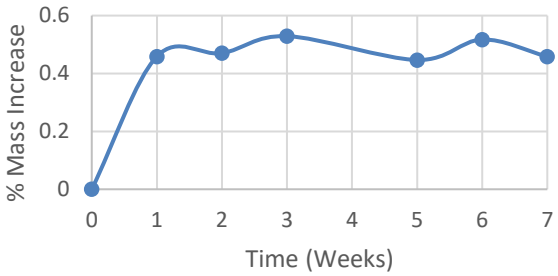

Fig. 2. Change in Moisture Content Example-Araldite 5052

The conditioned samples were tested in an insulated heated chamber with a thermocouple placed in proximity of the bondline. The samples were thermally soaked at 121 ±3°C for 10 minutes to account for any degradation from exposure to the expected service temperature. The thermally-soaked samples were subsequently tested at the elevated temperature. See Figure 3 for the test setup of the ETW testing.

Fig. 3. Testing of ETW Specimens Within Heated Chamber

Figure 4 and Table 2 summarizes the single lap shear test results for all of the epoxies under both the RTD and ETW conditions. All of the epoxies exhibited a decrease in shear strength as a result of the exposure to moisture and heat. The neat EA9396 and Araldite 5052 were sensitive to moisture intrusion, losing 42.6% and 55.7%, respectively of their shear strength. The SR6400 and IR6030 resins comparatively did not witness an appreciable decrease in shear strength.

The EA9396 diluted with 15% acetone by weight was observed to be the most sensitive to moisture, suffering an 87% decrease in shear strength from the RTD value. The diluted EA9396 also lost mass through moisture exposure, contrasting the other

epoxy resins that had expectedly gained mass. This behavior has been studied by Loos et al. [3] in which various concentrations of acetone were added to an unnamed epoxy resin. The effect was deleterious for the mechanical properties of the epoxy. The initial mass lost between 40-140°C was also surmised to be solvent evaporation [3]. This could be linked to the current study's mass loss of the acetone-diluted EA9396 coupons at 60°C.

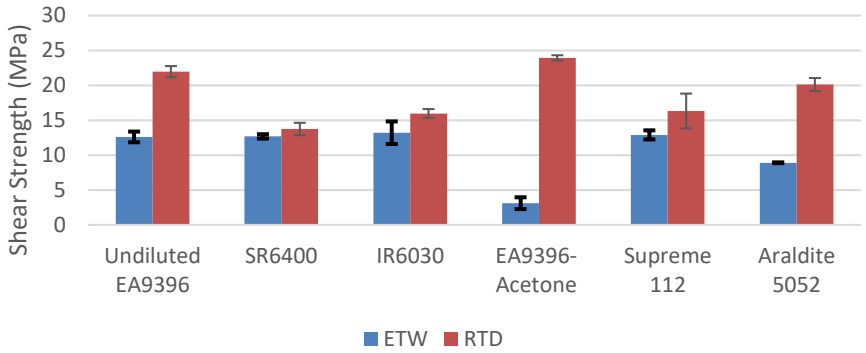

Fig. 4. Single Lap Shear Strength Results Comparison

Table 2. Single Lap Shear Strength Data Comparison

	EA9396	SR6400	IR6030	EA9396-15% Ace	SUP112	Araldite 5052
% change from original to final mass*	1.74	1.52	0.57	-1.32	0.27	0.46
RTD shear strength (MPa)	22.0	13.7	16.0	23.9	16.3	20.1
ETW shear strength (MPa)	12.6	12.7	13.2	3.1	12.9	8.9
% difference from average RTD results	-42.6	-7.7	-17.3	-87.0	-21.0	-55.7

*change in mass of process monitoring coupons

4.3 Glass Transition Temperature

Dynamic Mechanical Analysis (DMA) was performed to determine the glass transition temperature of the epoxy resins. The cure cycles were derived from the technical datasheets; they were examined using Differential Scanning Calorimetry (DSC) to determine the degree of cure. The degree of cure was calculated with Equation (1):

$$Degree\ of\ Cure\ (\%) = \frac{-\Delta H_{cured}}{-\Delta H_{not\ cured}} x\ 100 \quad (1)$$

Where:

$-\Delta H_{cured}$ = residual exotherm of cured sample (J/g)
$-\Delta H_{not\ cured}$ = residual exotherm of raw sample (J/g)

All epoxy samples had exceeded the threshold value of 90% degree of cure which allows the reasonable conclusion that the samples were sufficiently cured. The DSC testing was performed on a NETZSCH DSC Polyma 214 using ASTM D7426 as a guideline. A heating rate of 20K/min was utilized instead of the 10K/min to improve the detectability of the signal. Aluminum pans with pierced lids were employed to mitigate pressure-induced deformation of the pan which would likely impact the results.

Once the cure cycles were verified to provide a sufficient degree of cure, DMA testing was performed in accordance with ASTM D7028 to ascertain the glass transition temperatures of the epoxies. The epoxy samples were fabricated in a silicon negative mold and cured. The samples were sanded to correct defects and ensure that they met the correct size: 25.4 ± 2 mm x 6.35 ± 2 mm x 2.00 +0/-0.5 mm. This sample size was generated from the geometric parameters set by ASTM D7028 coupled with the size of the fixture.

The testing was conducted on a NETZSCH DMA 242 E Artemis with a 3-pt bend fixture. A study was conducted to converge upon a heating rate that would balance the trade-off between accuracy and time efficiency. 2°C/min was converged upon due to its accuracy being within 1% difference of the 1°C/min heating rate. Using the empirically-derived heating rate of 2°C/min and the stated parameters from ASTM D7028 for amplitude (100 µm for amplitude, 5 Hz for frequency), the glass transition temperatures were derived for all of the resins. Three samples per epoxy resin were tested for repeatability of results. Figure 5 demonstrates sample DMA curves from the Kaneka SR6400. Figure 6 depicts the curves for Henkel neat EA9396 and diluted with 15% acetone by weight, respectively.

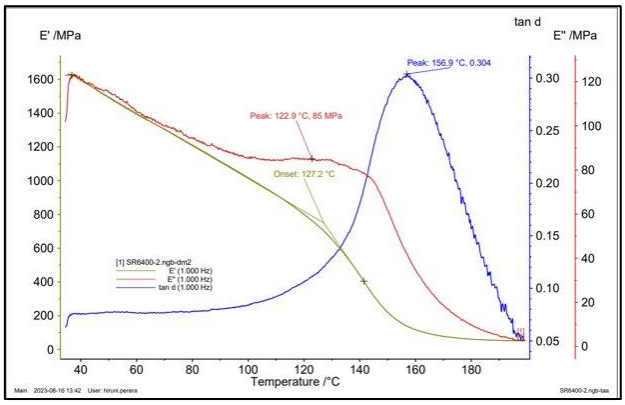

Fig. 5. DMA Curve- Kaneka SR6400

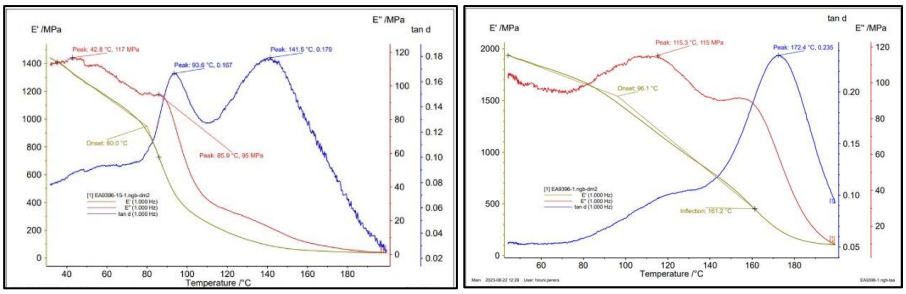

Fig. 6. DMA Curve- Henkel EA9396 (left) and EA9396 with 15% Acetone by Weight (right)

The storage modulus curve for the SR6400 demonstrates a large uncertainty in the onset glass transition temperature due to the distinct slope decrease from the starting temperature before the inflection. The glass transition range is not well defined which indicates that the epoxy is likely more amorphous. The neat EA9396 exhibit a similar storage modulus curve albeit with a less defined transition. Where the transition ends seems less discernible. The storage modulus curve of the diluted EA9396 more closely mimics the SR6400, with a more apparent inflection point where the transition region's endpoint is defined. More notably, the blue tan delta curve sports two transition peaks. The first peak is surmised to be caused by the presence of uncured material from the integration of acetone into the epoxy. This would align with the behavior Loos et al. had found [3]. The addition of acetone has clear deleterious effects on the glass transition temperature of EA9396, provoking an earlier transition in comparison to the neat resin.

Due to the difficulty in discerning the glass transition temperature from the storage modulus curves of the more amorphous epoxies, the loss modulus was reported to easily pinpoint an average for each epoxy. ASTM D7028 denotes the peak of the loss modulus as a transition temperature. Table 3 summarizes the results derived from the

DMA testing. The SR6400, IR6030, and Araldite 5052 exceeded the 121° threshold outlined in Section 3.

Table 3. Average Glass Transition Temperature Results

Epoxy	Average Tg ,°C (°F)
Masterbond Supreme 112	111.4 (232.5)
Kaneka SR6400	132.5 (270.6)
Kaneka IR6030	134.5 (270.0)
Henkel EA9396-15% Acetone	84.2 (182.6)
Henkel EA9396	107.4 (225.3)
Huntsman Araldite 5052	122.2 (252.0)

4.4 Porosity

Excess voids within a laminate poses a significant concern as it generally begets reduced mechanical properties. Injecting resin into the delaminated composite can result in bubbles becoming trapped within the small cracks, solidifying into voids upon cure. The voids are also sources for moisture ingress which could compromise the bond between the injected resin and the parent laminate. The introduction of porosity into the resin is a key concern tied to the use of solvent to dilute epoxies. Hakim et al. [4] cited that the interlaminar shear strength decreased by 34% for carbon/epoxy specimens with an increase in porosity from 0.55% to 5.6%. Their own research underscored the inverse relationship between Mode II fracture toughness of composite/epoxy specimens and the areal porosity percentage. Thus, characterizing the amount of porosity generated through the mixing, curing, and usage of epoxy resins was critical.

The study involved developing a quantitative method to capture porosity when the epoxy fills a thin bondline using glass slides and the aforementioned Keyence microscope. The epoxies were first mixed by hand before being injected via a 200 µL pipette in between two microscope glass slides. The epoxies were mixed by hand rather than an automatic mixer due to the assumption that in most cases, the Navy fleet repair facilities will not have access to the latter equipment. Dispensing the epoxy via pipette was done to mimic the actual scenario where resin would be injected into a laminate. The glass slides were subsequently taped together on three sides (the fourth side was left exposed) and the epoxy was cured. This would replicate the restrictive amount of free volume that the injected resin would have to outgas while curing. Additionally, the clear slides allowed for inspection under the microscope. A built-in function within the Keyence microscope software calculated areas based on contrast in hues or brightness. The resulting areal porosity percentage is a function of the total area presented by the voids divided by the total area chosen for inspection.

Two slides per epoxy were examined at 20x magnification to yield a more global view of the sample. Figure 7 demonstrates a micrograph of an EA9396 sample containing the identified pores in red within the analyzed area. The average areal porosity for each epoxy resin is summarized in Table 4.

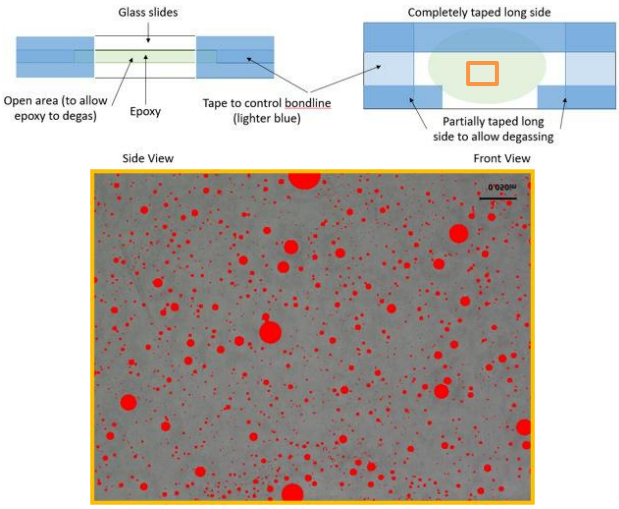

Fig. 7. Experimental Setup and Micrograph of EA9396 (x20 Magnification)

Table 4. Average Areal Porosity

Epoxy	Average Areal Porosity (%)
EA9396	8.32
EA9396 w/ 15% Acetone	6.61
SR6400	0.22
IR6030	1.42
SUP112	2.80
Araldite 5052	2.03

4.5 Discussion of Results

The results from the Brookfield Viscometer testing demonstrated that the EA9396 diluted with acetone and the two Kaneka formulations yielded the lowest viscosities. Although the Kaneka resins also exhibited the lowest shear strengths, their sensitivity to moisture was decidedly lower than the other epoxies. The Kaneka resins had comparatively suffered the least knockdown in shear strength for the ETW condition. This can be correlated with the areal porosity results depicted in Table 4, where the Kaneka resins yielded the lowest values amongst the samples. Conversely, the EA9396 and Araldite solutions exhibited the largest reductions in strength. Although the Araldite did not correspondingly have the largest areal porosity, the EA9396 resin combinations had a significantly larger average areal porosity value than the remainder of the resins.

One suggestion for this phenomena would be that an increase in void content increases avenues for moisture intrusion via the open pores. In the case of a bonded joint,

moisture could plasticize the bondline as the water molecules bond to hydrophilic polymers and weaken the intermolecular bonding. The weakened bonding would promote increased chain mobility and the accompanying effects including a reduction in strength. This would pose a significant concern for the long-term bond integrity between the injected resin and the parent laminate of an aircraft that needs to frequently fly in humid environments.

The two Kaneka resins (IR6030, SR6400) and the Araldite 5052 do comply with the expected service temperature, yielding glass transition temperatures above 121.1°C. The other three candidates fell short of this threshold, with the diluted EA9396 garnering the lowest glass transition temperature. Considering the findings from Loos et al. [3], the result was expected.

A decision matrix summarizing the aforementioned assessments is shown in Table 6. The multipliers for each category were determined based on their criticality to the performance of the laminate post-injection repair. Low viscosity, shear strength, and glass transition temperature are essential characteristics that would predict the short and long-term performance of the repaired laminate. Table 5 also demonstrates an explanation for the scoring criteria and the category weights. Logistical characteristics were added to the technical topics to provide a holistic evaluation of the potential epoxy candidates for a common naval fleet repair. The scoring was derived from a relative comparison of the epoxies to each other.

Table 5. Decision Matrix Scoring Criteria

Score Rating	RTD SS* (MPa)	ETW SS* (MPa)	Viscosity (cP)	Tg, E'' (°C)	Porosity (%)	Pot Life (hrs)	Cost/qt. kit ($)	Procurement (months) **
1	<13.8	<12.1	>700	<104.4	>5	<0.5	>1000	>2
2	13.8-20.7	12.1-13.8	300-700	104.4-121.1	3-5	0.5-1.5	500-1000	1-2
3	>20.7	>13.8	<300	>121.1	<3	>1.5	0-500	<1

*Shear strength

**Months from time order was placed

Table 6. Decision Matrix of Potential Epoxy Candidates

Category	Category Weights	EA9396	SUP112	SR6400	IR6030	EA9396 -15% Ace	Araldite 5052
RTD SS*	0.1	3	2	1	2	3	2
ETW SS*	0.1	2	2	2	2	1	2
Viscosity	0.2	1	1	3	2	3	1
Tg	0.2	1	2	3	3	1	3
Porosity	0.15	1	3	3	3	1	2
Pot Life	0.05	3	1	1	3	3	2
Cost	0.1	3	1	2	3	3	3
Procurement	0.1	3	2	3	3	3	1
Total	1	1.90	1.80	2.80	2.60	2.10	2.00

*SS = shear strength

The Kaneka SR6400 and IR6030 received the largest ratings by a wide margin, totaling 2.80 and 2.60 points, respectively. Their lack of sensitivity to moisture, low porosity generation, viscosity, and high glass transition temperature makes them suitable candidates to converge upon for coupon-level injection repair and mechanical testing.

5 Mode II Fracture Toughness

The efficacy of the selected Kaneka resins in preventing delamination crack propagation were evaluated in restoring fracture toughness to IM7/977-3 adherends. The chosen test standard was ASTM D7905 which measures the Mode II interlaminar fracture toughness of unidirectional PMCs. The End-Notched Flexure (ENF) test arguably represents aircraft loading of delaminations under Mode II shear. The coupons are manufactured with a PTFE insert to create an initial crack. The propagation of the crack under transverse loading resembles the advancement of delaminations that can occur during operation. All elements of the fracture toughness testing for this study were derived from the novel methodology developed by Massey et al. [2].

The coupons are composed of 24 plies of unidirectional IM7/977-3 tape with a total nominal thickness of 3.175 mm. The layup schedule consists of only 0° plies. The width

of the coupons used for this study were increased from the nominal 25.4 mm stated by ASTM D7905 to 50.8 mm to make the features of the fracture surface more apparent [2]. The length of the PTFE insert, or the pre-crack length, was set to 63.5 mm. Baseline testing was conducted to discern the laminate fracture toughness, in which the length of the crack propagation met or exceeded 50.8. This served as the "repair area" where resin would be injected through drilled holes and was marked accordingly on the coupon. Figure 8 demonstrates the nominal coupon dimensions.

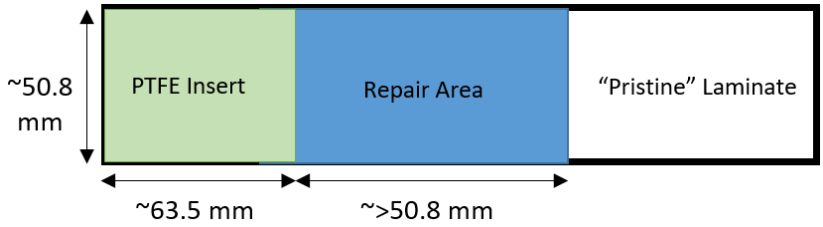

Fig. 8. ENF Coupon Nominal Dimensions

Post-baseline testing, the coupons were processed with the following steps and parameters [2]:

1. Drill two holes 12.7 mm from the boundaries of the repair area.
2. Remove the old insert and apply a second 63.5 mm x 50.8 mm insert into the coupon. Seal the exposed edges of the coupons with Henkel EA9394 to prevent leakage.
3. Inject 3 mL of MIL-PRF-83282 hydraulic fluid (HF) by hand into the holes with a syringe and an 18-gauge needle to simulate the infusion of the worst-case contaminant. Allow coupons to sit for 7 days to ensure that HF has thorough pervaded the coupon.
4. Inject 10 mL acetone per hole with the same equipment to flush out the HF. Allow coupons to sit for 24 hours to allow residual acetone to dissipate.
5. Purge coupons with nitrogen for 5 seconds on one of the holes.
6. Plasma treat with Surfx Atomflo 500L to treat the bonding surfaces with atmospheric oxygen plasma for 20 minutes on each hole.
    a. Gas outflow was monitored with Hiden Analytical Quantitative Gas Analyzer (QGA) to ensure reduction of elements intrinsic to HF.
7. Inject 15 mL of resin with a syringe and 18-gauge needle iteratively to ensure complete fill and cure at 121.1°C after allowing coupons to sit for 24 hours.
    a. Sealant tape was adhered to the edge of the repair area to trap the resin over the injected holes.
8. Sand away the excess injected resin and the EA9394.

Ultrasonic pulse-echo C-scans were performed on the repaired coupons to discern the effectiveness of the injected Kaneka resin in filling the delaminations. The coupons were submerged in a water tank and the scans were conducted with a 10 MHz trans-

ducer at a scan rate of 30 mm/s and a resolution of 0.250 mm. The data was post-processed in the software, UTWin, to correct the velocity of the wave going through the 3.175 mm thick coupon. Two C-scans from the SR6400 and IR6030-injected coupons were shown in Figure 9 to contrast the differences between the two resins in their capability in filling the delaminated region. The voids in the repair region are outlined by white boxes.

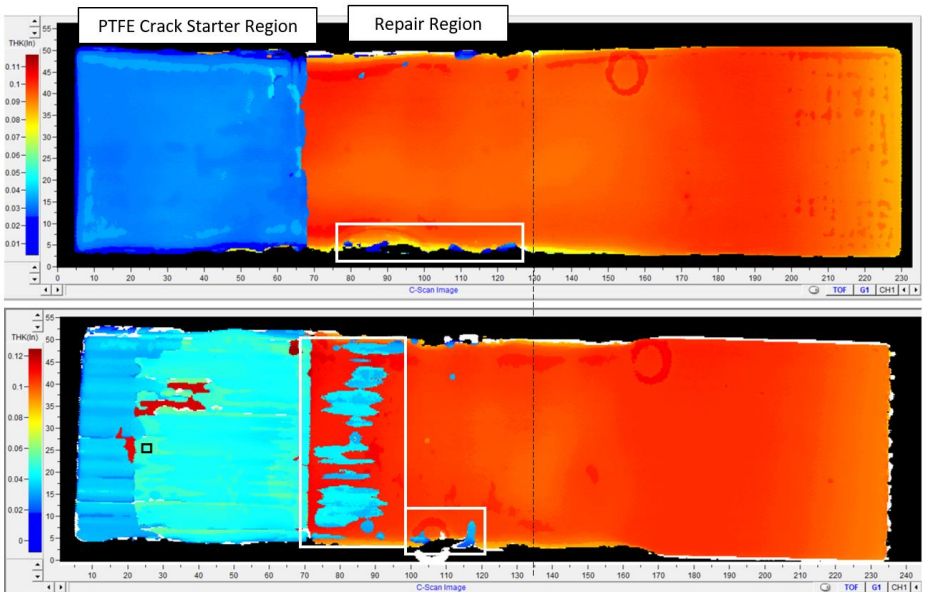

Fig. 9. C-Scans of Coupons with Injected SR6400 (Top) and IR6030 (bottom)

The coloring in the C-scan is generated through the individual waveforms and scaling to reflect the correct wave velocity through 3.175 mm coupon. The blue coloring represents waves that were reflected earlier than the back surface of the coupon, whereas the orange-red hues are to signify larger time-of-flight (TOF) values for reflection off of the back surface. There is a larger number of voids in the Kaneka IR6030 coupon than the SR6400. Moreover, the size of the voids in the former are significantly larger than that of the latter. The SR6400 has a viscosity of approximately 250 cP compared to the 650 cP IR6030 which could explain the differences in the fill of the repair region. The IR6030 was observed to require more exertion to inject into the holes than the less viscous SR6400.

The repaired coupons were labelled with the nomenclature shown in Figure 10. Compliance calibration data was generated for each repaired specimen as variation in the calculated fracture toughness to account for variation between specimens. The testing was conducted akin to the baseline coupons in that non pre-cracked (NPC) and precracked (PCC) data were collected for comparison. The Mode II interlaminar fracture toughness for both datasets was calculated with Equation (2).

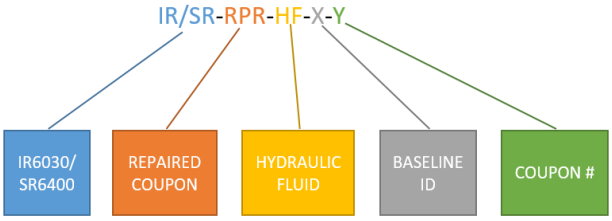

Fig. 10. Coupon Labelling Nomenclature

$$G_{IIc} = \frac{3mP_{max}^2 a_0^2}{2B} \quad (2)$$

Where:
G_{IIc} = Mode II interlaminar fracture toughness (J/m^2)
m = slope of the linear fit between the compliance calibration versus the cube of the crack length
P_{max} = maximum force on the force-displacement curve (N)
a_0 = length of delamination used in the test (m)
B = coupon width (m)

The results of the ENF testing conducted on the repaired coupons are summarized in Figure 11. Although the NPC dataset was included in the plot, the PCC dataset was used to draw conclusions about the repair resins' performance due to the natural crack propagation versus the artificial initial pre-crack. The IR6030 and SR6400 resins increased the laminate fracture toughness by a minimum of 120% and 143%, respectively, compared to the baseline average. The testing demonstrates that both repair resins are capable of restoring fracture toughness and by proxy, strength, to a delaminated laminate.

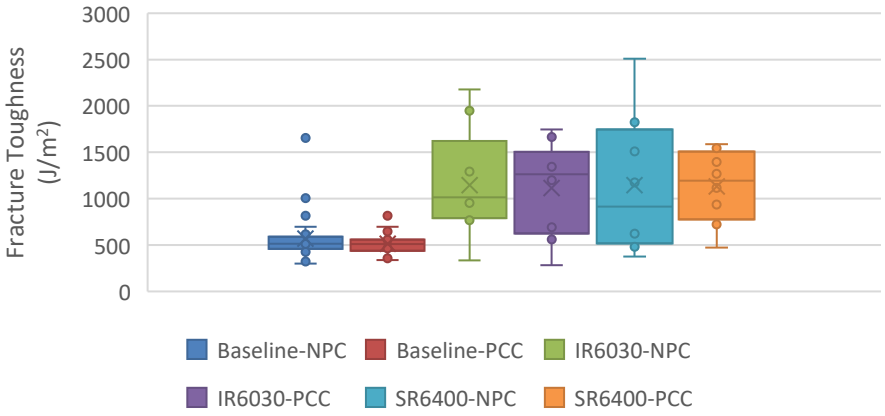

Fig. 11. Mode II Fracture Toughness Test Results

6 Conclusion

Off-the-shelf epoxy resins were holistically evaluated for the purpose of improving the delamination injection repair process currently used for Naval PMCs. The resins were tested to determine their mechanical and thermomechanical properties including viscosity, shear strength, and glass transition temperature in both dry, room temperature and wet, elevated temperature environments. The acetone-diluted EA9396 yielded the lowest Brookfield viscosity at 200 cP, whereas the Araldite 5052 and Masterbond Supreme 112 exceeded the mandated threshold of 650 cP. However, the viscosity advantage of the diluted EA9396 was offset by an 87% reduction in shear strength correlated to the high porosity qualitatively and quantitatively witnessed. Ultimately, the two Kaneka resins were converged upon due to the combination of their satisfactory glass transition temperatures, low porosity generation and viscosity.

The Kaneka resins were further evaluated using the ASTM D7905 ENF test method for Mode II interlaminar fracture toughness determination. The IM7/977-3 coupons underwent an initial round of ENF testing to discern their baseline toughness. The coupons were subsequently drilled, cleaned, and injected with resin in accordance with the process developed by Massey et al. [2]. Ultrasonic pulse-echo testing was implemented to generate C-scans that would visually demonstrate how well filled the delaminated region was by the repair resins. The test results revealed an increase in fracture toughness by 120% and 143% when the coupons were repaired with the IR6030 and SR6400 resins, respectively, compared to the average baseline value. Thus, the conclusion can be drawn that the Kaneka IR6030 and SR6400 are viable candidates for further investigation on repairing delaminated PMCs.

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