Development of Percussion Diagnostics in Evaluating 'Kiss' Bonds Between Composite Laminates

INTRODUCTION

Bonding composite structures together using adhesives provides many advantages over other joining methods. These advantages include distributing the load over a large bond area, reduced weight, ability to join dissimilar materials together, higher stiffness and toughness over the bond area and in many cases lower manufacturing cost. However, one of the limitations when using adhesives is the inability to determine non-destructively if the bond joint assembled meets shear strength requirements. Unfortunately, this leads to a conservative design approach and applying fasteners through the bond to ensure joint integrity. The addition of fasteners increases cost and weight and greatly diminishes the aforementioned advantages. Furthermore, fasteners cannot be the solution to attach materials that are being bonded within composite laminates that act as toughening aids or sensors for creating multifunctional materials. In order to address this limitation, a new NDT method needs to be developed that can detect adhesive 'kiss' bonds, where the adhesive shear strength is low due to contamination on the bonding surfaces or improper handling, mixing, or curing of the adhesive. It is believed that most 'kiss' bonds result from poor surface preparation of as-molded surfaces due to excess fluorocarbons, silicones, plasticizers, etc. introduced from the manufacturing process [1,2]. If these contaminants are not removed, they will decrease the surface energy which will decrease the contact angle between the adhesive and the bonding surface causing a decrease in shear strength. As a result, the bond that is formed will not be able to carry load as both substrates will in essence be ''kissing' one another.

Currently, most of the work being done to develop 'kiss' bond NDT techniques has been in metal to metal bonding. Recently, Roach et al. from Sandia National Laboratories, explored using ultrasound and thermography to detect the presence of 'kiss' bonds between single lap shear specimens made of galvanized steel bonded together with an epoxy adhesive [3]. The authors added varying degrees of contaminants to the bonding surfaces to reproduce degradation in epoxy adhesive shear strength from 100% (no degradation) to 10% (extremely degraded). The most promising ultrasound technique was a pulse echo inspection where the ratio of the peak amplitudes between an echo through the steel adherends and an echo through the steel/steel bondline were compared. This technique was able to pick up a bond strength degradation of 50% and higher. Thermography in conjunction with flash quenching and signal to noise optimization was used to measure the differences in heat flow across the bondline of the different controlled lap shear specimens. It was found that this technique was sensitive to around 50% degradation in shear strength as well. However, quantifying the results from these NDT techniques to specific shear strengths has not been accomplished and is currently under investigation.

Vibration analysis has also been utilized to detect differences in bond integrity of metal to metal lap shear joints [4-7]. In vibration analysis, lap shear specimens are vibrated in a fixed free condition where one end of the specimen is fixed and the other end is free to vibrate. An impact force was applied to the specimen and the frequency response was measured. From the frequency response, the loss modulus can be computed dividing the resonant frequency by the half power band width. Changes in loss modulus or resonant frequency can then be compared to the shear strength of different metal to metal bond joints. Yang et al. created shear strength reductions in double lap shear joints by varying the percent bond area that was sanded. The authors found as the percent bond area that was sanded decreased, the loss modulus increased and the shear strength decreased. Paradurangan et al. investigated the effects of cyclic loading on single aluminum lap shear joints bonded with epoxy adhesive. The authors found that as the adhesive strength degraded due to cyclic loading, the loss modulus increased and resonant frequency decreased. Shiloh et al. measured the effects of aging on aluminum structures bonded with epoxy adhesive. The authors measured an increase in loss modulus with a decrease in shear strength as the structures were aged in more severe thermal environments. Lastly, Srivatsan et al. examined the effects of porosity, cure schedule and percent debond (released) area on the strength of steel double lap shear specimens bonded together with epoxy adhesive. The authors determined that the resonant frequency did not change significantly as the porosity increased or the cure time increased. The loss modulus decreased to an optimal level as the cure time increased and as the porosity decreased (increase in degassing time). However, the authors discovered as the percent debond area increases, both the loss modulus and resonant frequency showed significant changes. As the percent debond area increased, the damping capacity increased and the resonant frequency decreased, while the joint strength decreased. The authors attributed the increases in damping capacity to friction caused by the opening and closing of the debonded interfaces during the vibration test. The decrease in resonant frequency is attributed to the decrease in stiffness of the overall bonded structure due to the higher debond area. A summary of these results is shown in Figure 1.

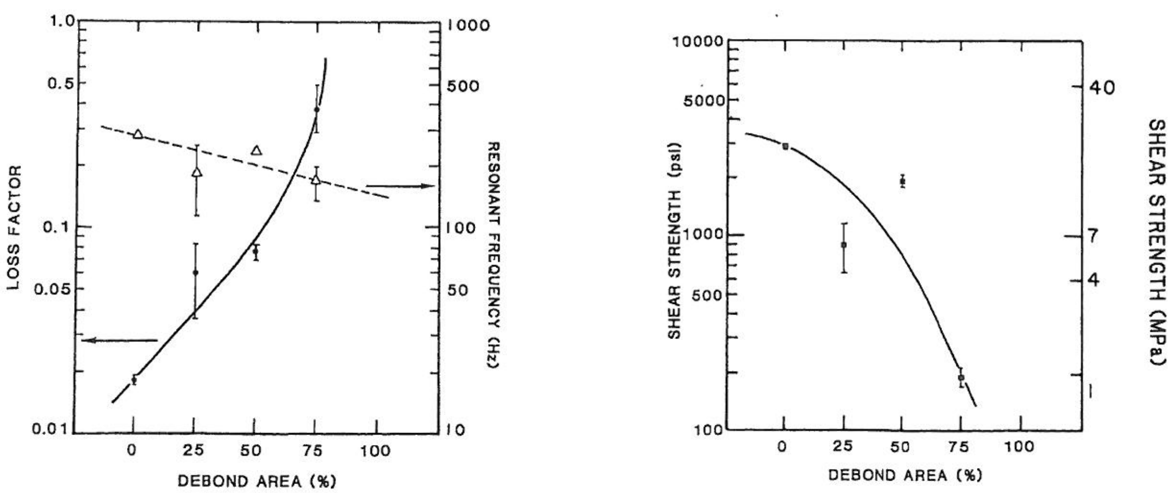

Figure 1. Loss factor and shear strength vs percent debond area of steel double lap shear specimens bonded together with epoxy adhesive [7].

All of the examples of NDT techniques used to examine bond joints provided in literature were based on metal adherends, which are typically homogenous and have high loss modulus values in the thickness direction and hence subsequently easier to examine than composite substrates. This paper describes a mechanical percussion technique that can be used to detect the difference between a well bonded composite structure (high shear strength) and a poorly bonded composite structure (low shear strength). Specifically, the loss modulus, probe force and transmitted force will be measured and compared for both well bonded and poorly bonded composite specimens. The focus of this paper is to show the potential of using mechanical percussion as a NDT method to inspect adhesive bond joints between composite substrates.

MECHANICAL PERCUSSION BACKGROUND

A cost effective legacy NDT method that has been used extensively in the past to inspect large composite components is the so-called coin tap test [8]. The coin tap test has been used in the composites industry to differentiate between a well bonded, defect-free composite part to one that has defects [8]. This method uses a coin or the back of a hammer to impact the composite part manually (a light tap). A sound of a 'good' section is very crisp and clear and radiates, while a sound from a 'bad' area has a dull thud. Distinguishing between sounds can be difficult even for a trained technician and the use of this technique over long periods of time is impractical. Also, no property information is gathered using this method that will help determine the extent of damage of the composite being inspected. Besides using sound, a tap test can be used to identify defective areas in a composite by examining different parameters controlling the impact response. An example of one such design is a mechanical percussion probe (Periometer®) designed by UCI and was originally used for determining damping capacity in dental implants [9-12]. In this design (see Figure 2) a steel rod with an accelerometer attached to the back side is driven by an electromagnetic coil to impact the specimen 16 times in four seconds. The impact of the probe onto the specimen generates a stress wave which will cause the specimen to deform both elastically and inelastically. Inelastic deformation or dampening of strain energy during impact is referred to as the loss coefficient. Software created in Labview is used to measure the input energy vs time compared to the amount of energy returned vs time for 10 of the 16 impacts based on data compiled from the accelerometer. The energy dissipated, *D,* is derived from Equation #1:

$$D = U - E_R - D_p \qquad \text{(Equation \#1)}$$

where U is the total strain energy, E_R is the energy returned and D_p is energy dissipated by sources external to the specimen [12]. An equation used to compute the loss coefficient, η, is shown by Equation #2.

$$\eta = 1/2\pi * (D/U) \qquad \text{(Equation \#2)}$$

The total strain energy, U, is equal to the total kinetic energy prior to impact from the rod ($1/2\ mv^2$). Besides displaying the loss coefficient, the output from the lab view software is a plot of the force measured by the accelerometer during the impact event (probe force) as well as the transmitted force measured by the force transducer on the back of the specimen vs time (see Figure 3). Both sets of data are useful to analyze when characterizing damaged specimens.

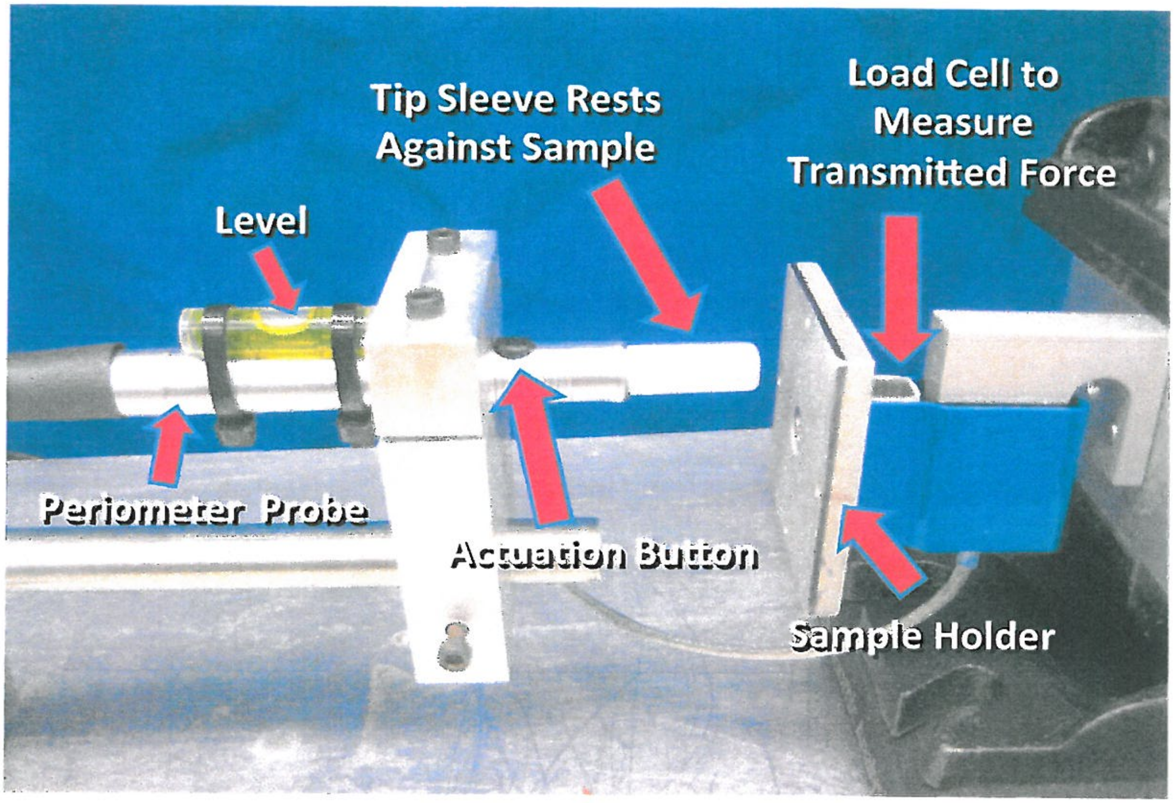

Figure 2. Schematic of mechanical percussion probe (Periometer®).

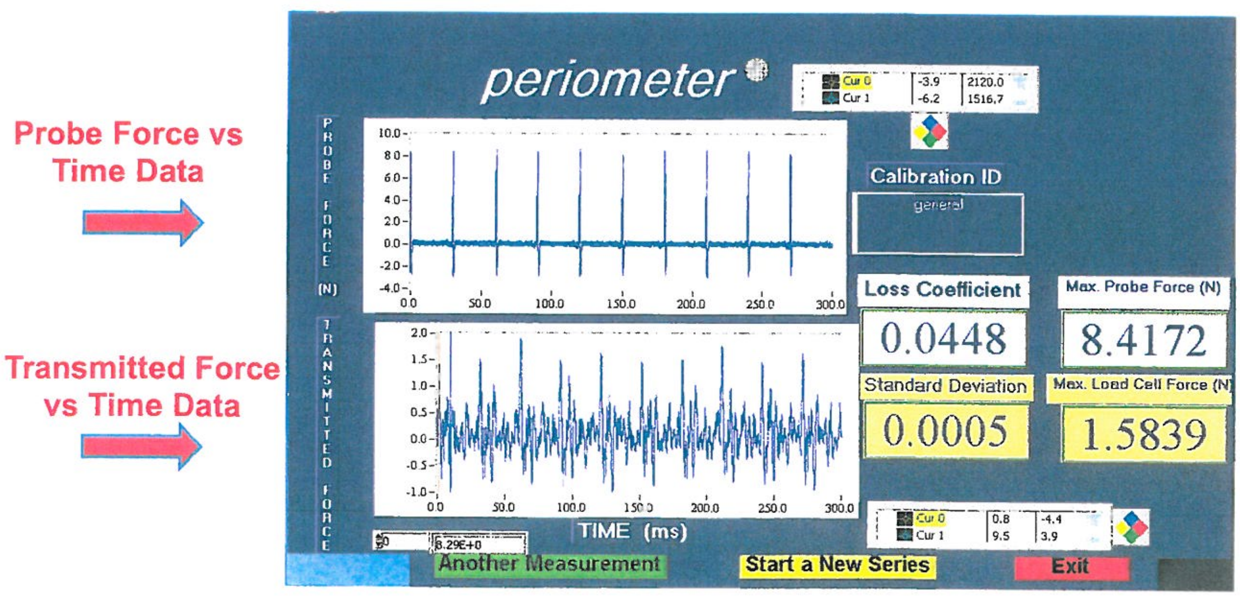

Figure 3. Data output from Labview software.

Stanley et al. previously used this device to examine damage of a carbon fiber/epoxy laminate due to an impact event [9]. The authors discovered that the loss coefficient increased as the measurement distance to the impact site decreased as shown in Figure 4. The reasoning behind this trend is that during an impact event on a reinforced composite there is internal friction caused by the movement of crack and delamination surfaces. Also, the breaking of fibers results in more stress supported by the matrix which generally results in a higher plastic deformation and more energy dissipated. Fiber sliding also can occur, which increases friction and the amount of energy dissipated as heat. Hence, a relationship between internal delamination/micro-cracking and damping capacity can be exploited to investigate internal damage in composites.

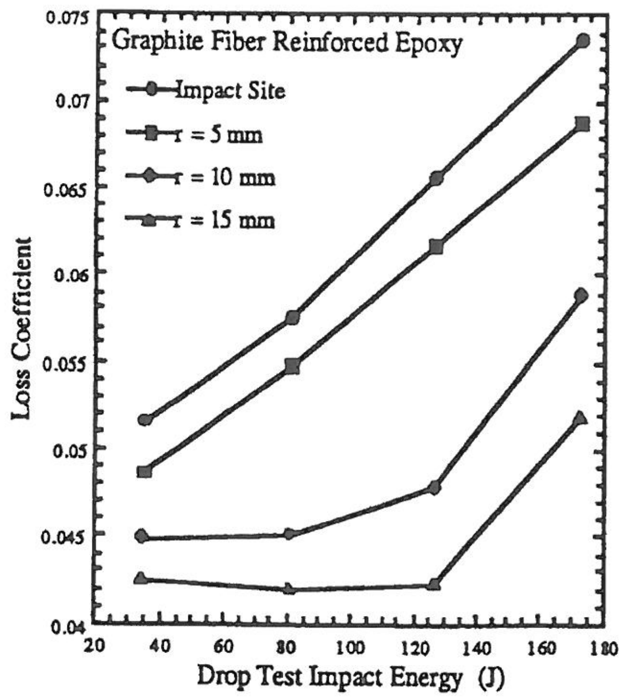

Figure 4. Loss coefficient vs drop test impact energy for fiber reinforced composite [9].

Lincoln et al. utilized the Periometer® to measure the damping capacity of composite honeycomb structures with damping treatments at different layer thicknesses [11]. The authors were able to show that as the damping layer was placed farther away from the surface of the structure, the damping capacity decreased. Lincoln et al. also examined the effect of specimen dimensions on the measurements from the Periometer® and found that as the specimen size decreased, the damping capacity increased. This was most likely due to edge effects from the clamping force used to secure the specimens. Finally, a depth of 4 mm and radius of 5 cm from the impact probe was determined to be the measurement limitations on composite honeycomb structures.

EXPERIMENTATION

Two sets of experiments were performed to assess the validity of using mechanical percussion to detect 'kiss' bonds in composite structures. The first set of experiments involved bonding small 102 mm x 102 mm (4 in. x 4 in.) composite laminates together using a 250F cure supported epoxy film adhesive (thickness ~ 0.20 mm). All specimens were cured using a heated press at 45 psi. A description of the specimens tested is summarized in Table 1.

Table 1. Description of 102 mm x 102 mm (4 in. x 4 in.) Bonded Specimens Tested.

Specimen Description	**Total Thickness (mm)**
Carbon Fiber/Epoxy-Released-Specimen # -Hand Held Test	1.65
Carbon Fiber/Epoxy-Not-Released-Specimen # -Hand Held Test	1.65
Kevlar Fiber/Epoxy-Released-Specimen # -Hand Held Test	1.57
Kevlar Fiber/Epoxy-Not Released-Specimen # -Hand Held Test	1.63
Carbon Fiber/Epoxy-Released-Specimen # -Hand Held Test	4.5
Carbon Fiber/Epoxy-Not Released-Specimen # -Hand Held Test	4.5
Glass Fiber/Epoxy-Released-Specimen # -Hand Held Test	1.65
Glass Fiber/Epoxy-Not-Released-Specimen # -Hand Held Test	1.52

Each specimen type was fabricated with and without release agent applied to the bonding surfaces. The release agent used was Chemlease 41-90-EZ purchased from Chem-Trend. The specimens with release agent represented a 'kiss' bond while the specimens without release agent represented a 'good' bond. Impact vs time curves were measured for all specimens at center locations of the panels using the Periometer®. Before testing, the Periometer® was turned on and left idle for 15-30 minutes to eliminate electronic drift effects during testing. Next, the Periometer® was calibrated using two different materials with known loss coefficient values; aluminum and Teflon. The loss coefficient was measured three separate times on each of these materials and the data was used to calculate the effective elastic modulus of the rod and the amount of energy dissipated by external sources (not the specimen) such as the probe [9]. Once these values were computed, the system was calibrated and testing could begin. The test specimens were held by hand to measure the loss coefficient and probe force. An illustration of this technique is shown in Figure 5.

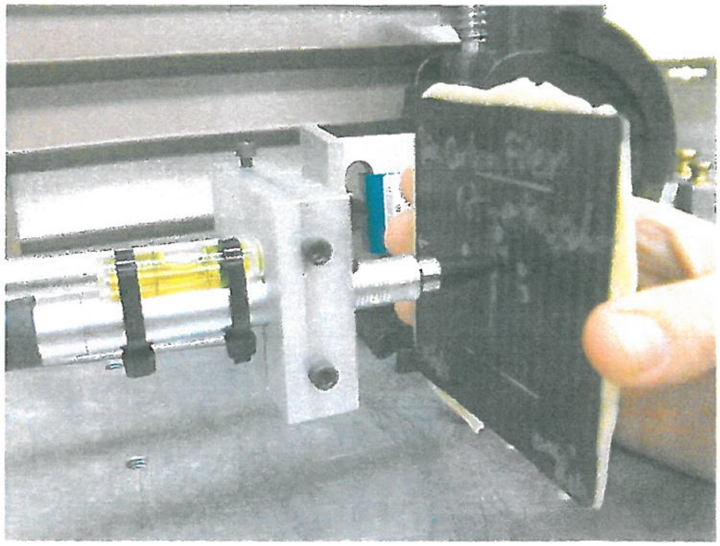

Figure 5. Illustration of hand held testing of 102 mm x 102 mm (4 in. x 4 in.) bonded laminates using the Periometer®.

The second set of experiments involved bonding large 305 mm x 305 mm x 1.59 mm (12 in. x 12 in. x 0.0625 in.) pre-cured carbon fiber/epoxy matrix laminates together with a 121°C (250°F) cure supported epoxy film adhesive. One specimen had release agent applied in a 152 mm x 152 mm (6 in. x 6 in.) area in the center of the laminate, which simulated a 'kiss' bond while the other bonded laminate had no release agent applied. To ensure the release agent created a poor bond, it was baked onto the laminate surface prior to bonding. Mechanical percussion was used to measure the impact/time curves for both specimens on locations in the center of the panel. The loss modulus and probe force were measured using the fixture shown in Figure 6. A 44.5 N (10 lbf) force transducer was added to the back of the panel to measure the transmitted force.

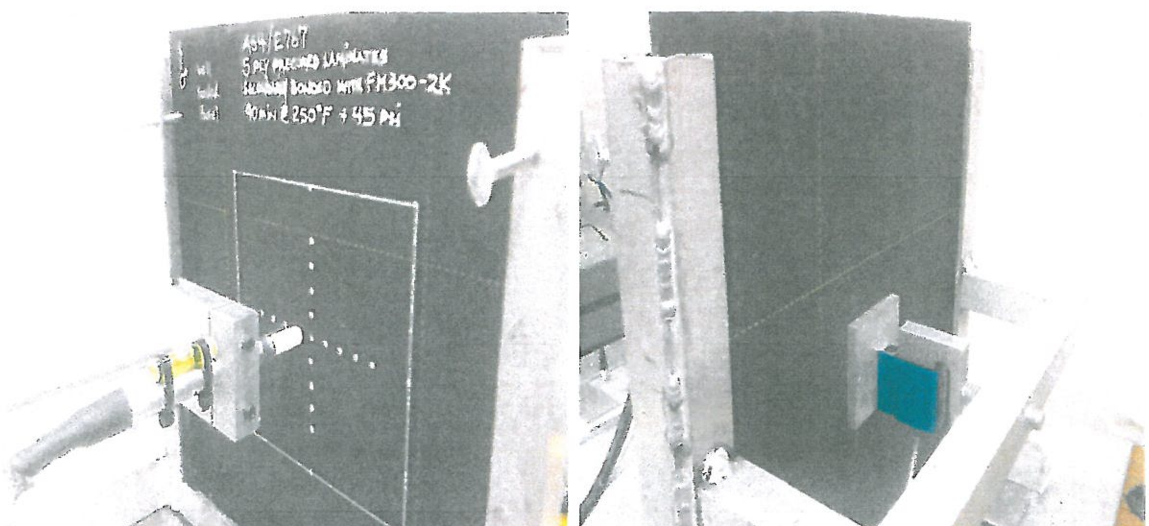

Figure 6. Illustration of fixture holding the 305 mm x 305 mm (12 in. x 12 in.) bonded laminates tested using the Periometer®.

RESULTS AND DISCUSSION

Loss Coefficient and Probe Force Measurements

First, the loss coefficient and maximum probe force for the 102 mm x 102 mm (4 in. x 4 in.) bonded laminates was measured by holding the specimens by hand in front of the Periometer®. Measurements were taken at the center location only because of the small size of the specimens. It was found during preliminary testing that a large scatter of data was seen when examining too many locations away from the center of the panel. Each measurement was repeated 4-6 times over the location and tested three times to ensure its repeatability. A summary of the data is shown in Figures 7 and 8.

The loss coefficient measured for carbon, Kevlar and glass fiber bonded laminates at ~1.52 mm thicknesses were similar in value for both the released (R) and not-released (NR) specimens. It appears that the impact force used is too strong to pick-up differences in the adhesive bond strength for the thin specimens. However, the carbon fiber bonded laminates at roughly twice the thickness (~4.5 mm) showed a higher loss coefficient and a lower maximum probe force for the released specimens compared to the not-released specimens. To determine if this trend is repeatable, two more trials were performed focusing only on the thick carbon fiber specimens. Also, the sleeve used to house the impact rod was changed from a narrow, black tip to a slightly wider, white Teflon tip to help ensure the specimen is perpendicular to the Periometer® during testing (a white sleeve on a shiny black carbon surface provides better contrast). The results are summarized in Figure 9.

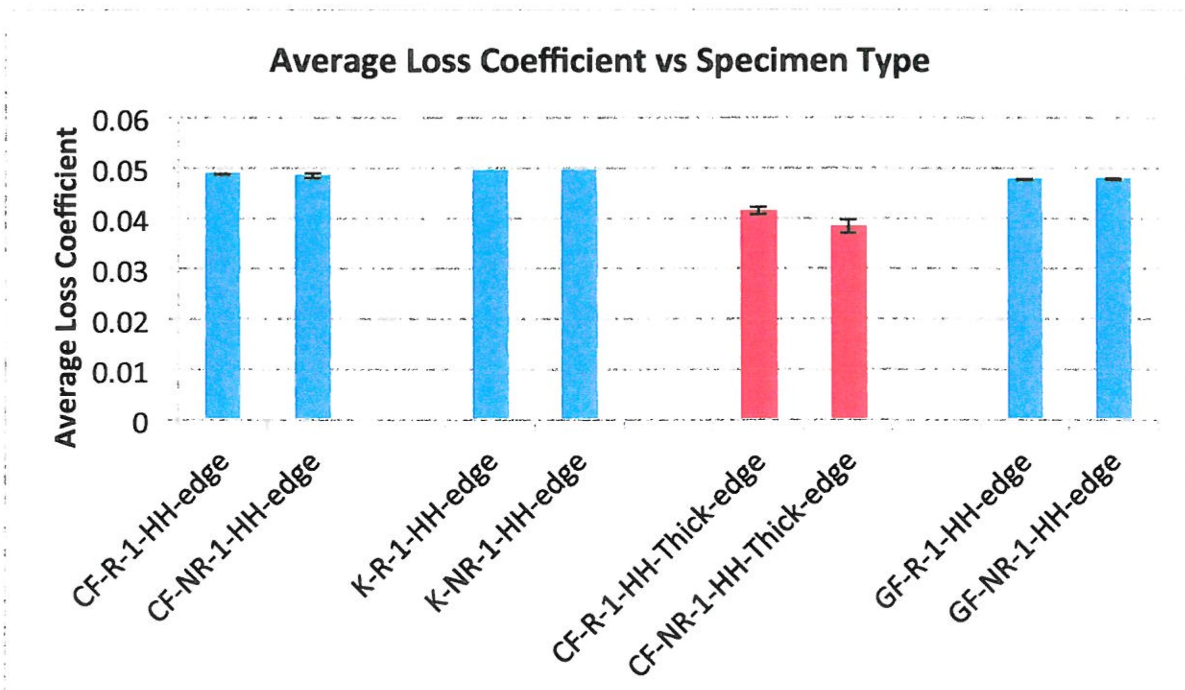

Figure 7. Average loss coefficient measurements for 102 mm x 102 mm (4 in. x 4 in.) released (R) and not-released (NR) bonded laminates.

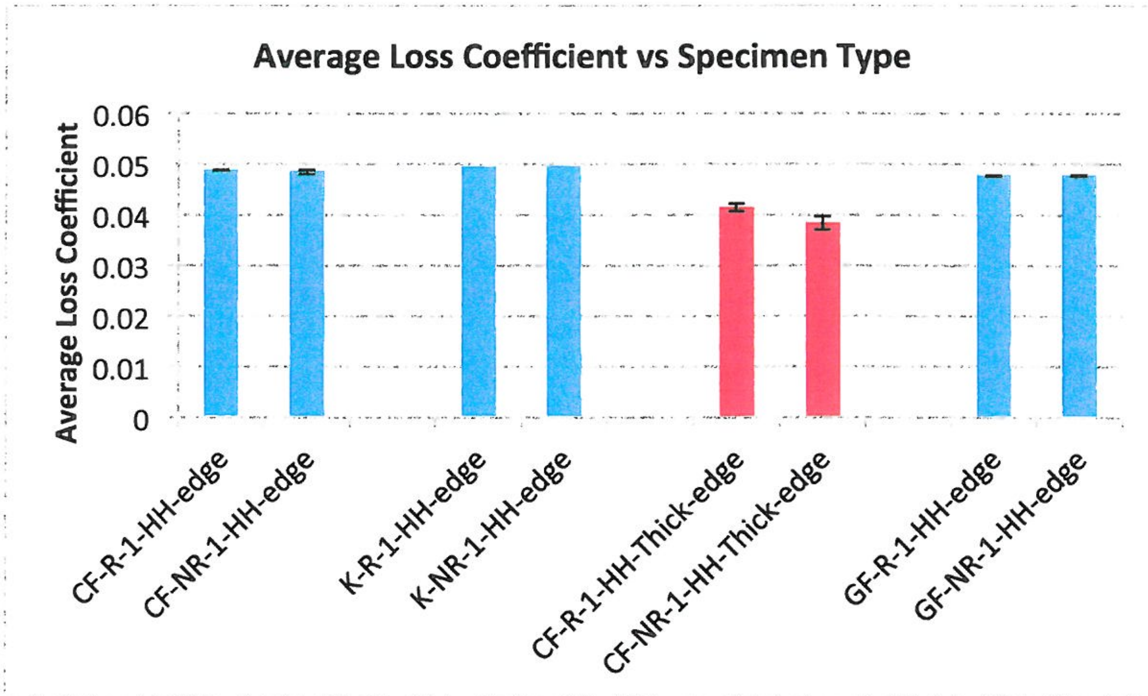

Figure 8. Average maximum probe force measurements for 102 mm x 102 mm (4 in. x 4 in.) released (R) and not-released (NR) bonded laminates.

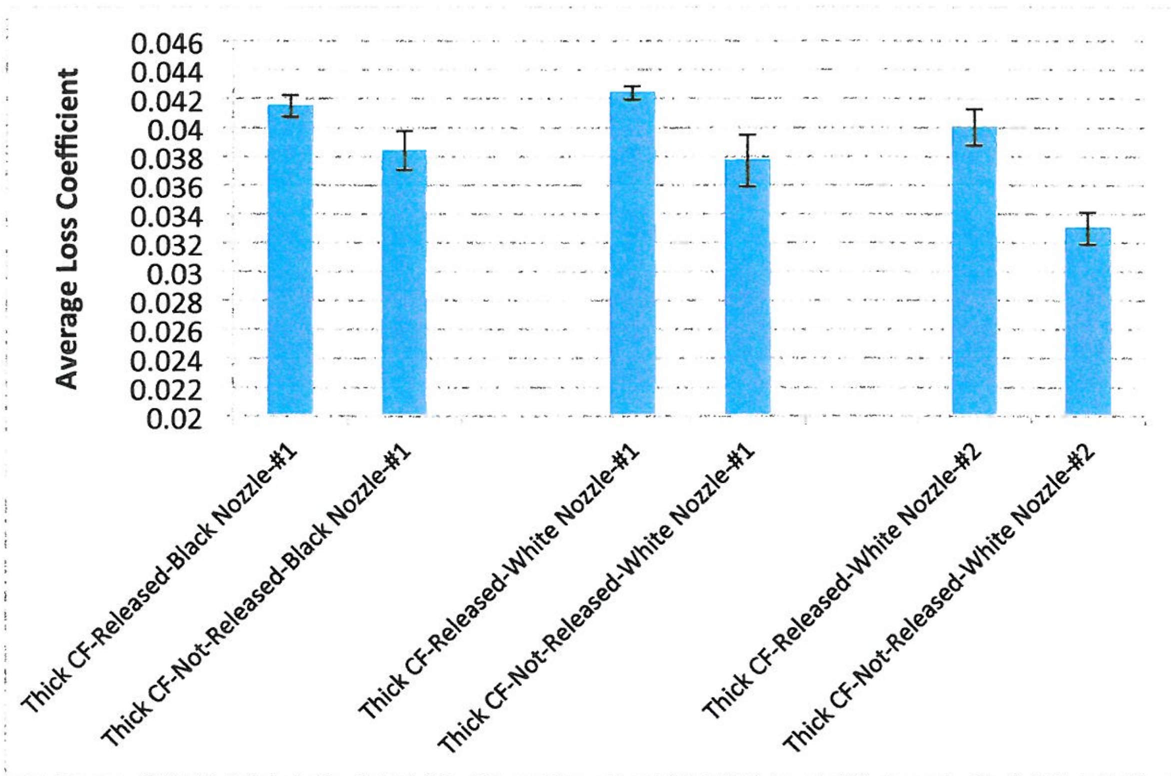

Figure 9. Average loss coefficient measurements for 102 mm x 102 mm (4 in. x 4 in.) released (R) and not-released (NR) thick carbon fiber bonded laminates.

A single factor analysis of variance (ANOVA) was completed for the loss coefficient and probe force data collected for the thick carbon fiber laminate specimens. The p values obtained for loss coefficient and probe force data were approximately 0.05 (5%) which further validates there is a significant difference between the released and not-released laminates.

The next set of data gathered was the probe force vs impact time data. Each impact test on a specimen records 10 sets of probe force vs time data. Five tests were recorded for each trial. The first set of data from the 'fifth' test for each released and not-released specimen was analyzed. A plot of the probe force data for all three trials of the thick carbon fiber specimens is illustrated in Figure 10. Although the shapes of the curves are similar, the released specimens all had measurably lower maximum probe acceleration values.

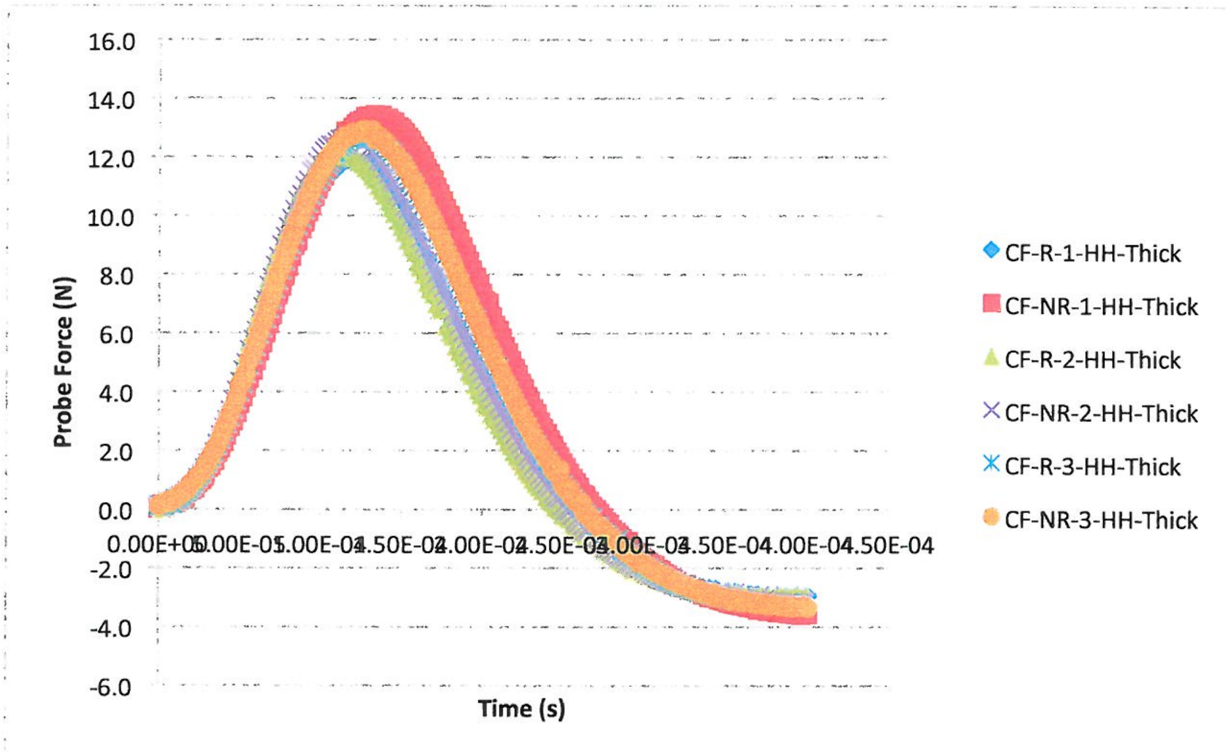

Figure 10. Probe force vs time measurements for 102 mm x 102 mm (4 in. x 4 in.) thick carbon fiber laminates (3 released, 3 not-released).

After evaluating the 102 mm x 102 mm (4 in. x 4 in.) specimens, larger 305 mm x 305 mm x 1.59 mm (12 in. x 12 in. x 0.0625 in.) carbon fiber/epoxy laminates were bonded together and evaluated with the Periometer® using the previously described fixture. Impact measurements were taken at seven different locations horizontally across the middle of the laminates as shown in Figure 11. A summary of the results for this testing is illustrated in Figures 12 and 13. The loss coefficient was found to be higher at every location tested for the released ('kiss' bond) panel when compared to the not-released (well bonded) panel. The maximum probe acceleration (shown in Figure 13) is also lower for all locations located on the released ('kiss' bond) panel. A single factor analysis of variance (ANOVA) was completed for the loss coefficient and maximum probe force data collected for both specimens The p values obtained for loss coefficient and probe force data were between 6 to 8 x 10^{-5}. These very low values confirm there is a statistical difference between the released and not-released panels. The increase in loss coefficient and decrease in probe force are thought to be due to an increase in internal friction within the laminate during the impact event for poorly bonded specimens as noted in literature for metal adherends [6,7].

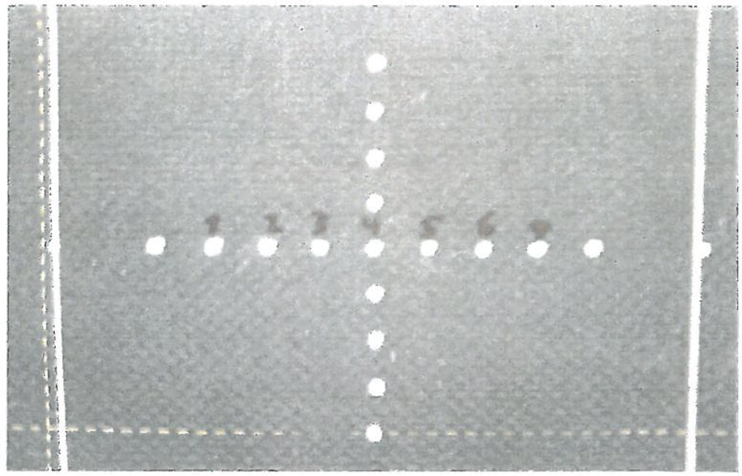

Figure 11. Locations where impact measurements were taken on 'kiss' bond panel (KBP).

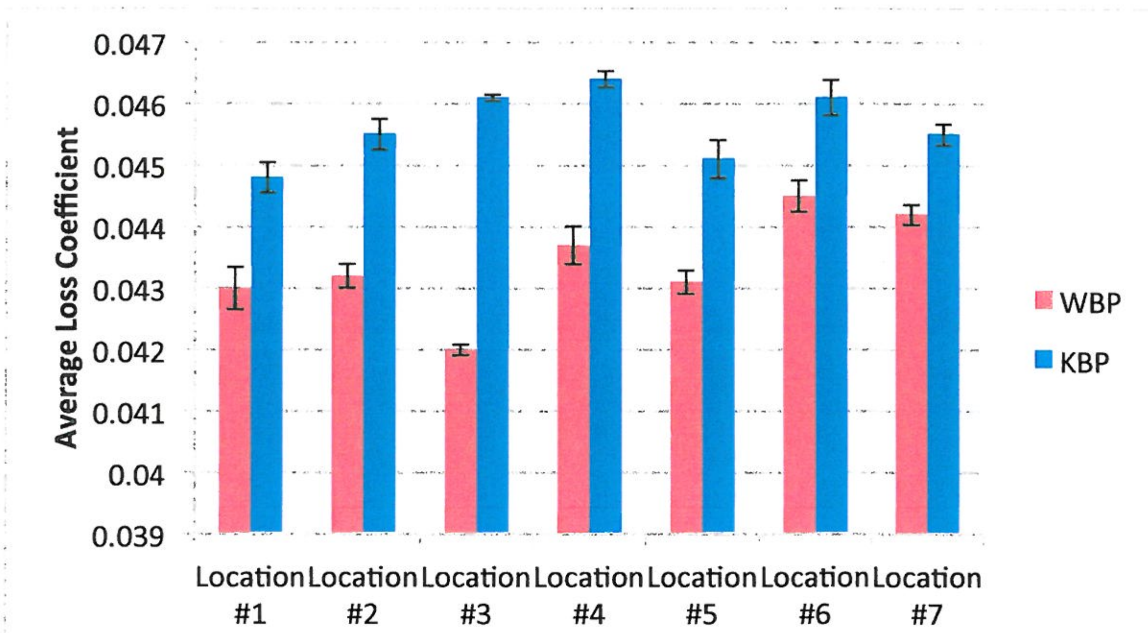

Figure 12. Loss coefficient measured at different locations for the well bonded-not-released panel (WBP) and the released 'kiss' bond panel (KBP).

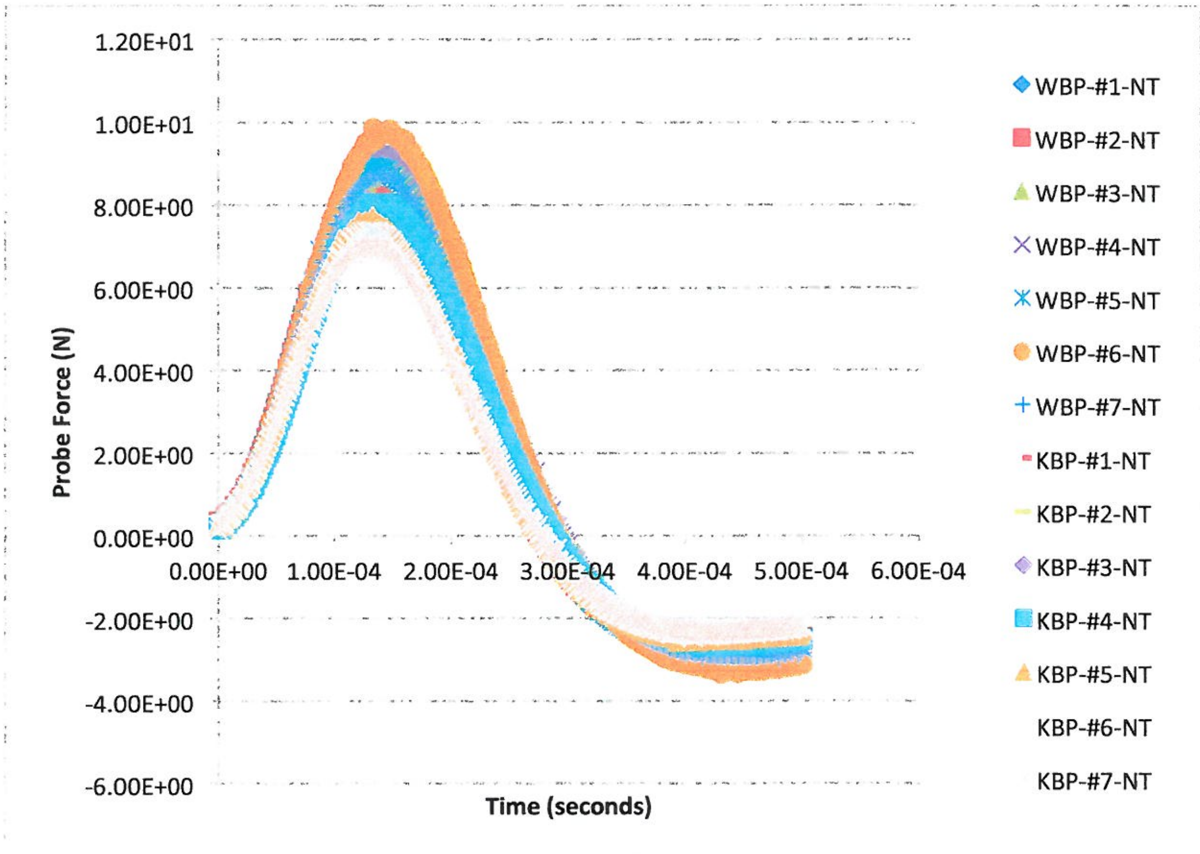

Figure 13. Probe force vs time measured at 7 different locations for the well bonded not-released panel (WBP) and the released 'kiss' bond panel (KBP).

Transmitted Force Measurements

The last series of tests performed on the 305 mm x 305 mm x 1.59 mm (12 in. x 12 in. x 0.0625 in.) carbon fiber specimens was measuring the changes in transmitted force between the released and not-released specimens using a force transducer on the opposite side of the impact event. The force transducer is attached to a 50.8 mm x 50.8 mm (2 in. x 2 in.) backing plate which helps transmit the impact force from the transducer to the specimen. In order to center the backing plate on the test panel using the test fixture, an inch was machined off the end of each panel. An illustration of where the backing plate was located relative to the impact locations is illustrated in Figure 14.

A pre-load is needed to ensure good intimate contact between the backing plate and specimen. However, the pre-load may have an effect on the transmitted force measurement. To understand this effect, one set of measurements was taken using a low pre-load around 3-4 newtons and another set of measurements was taken using a large pre-load around 12-13 newtons. A summary of both data sets is shown in Figures 15 and 16. For low pre-load data, most maximum transmitted force measurements were higher on the not released (well bonded) panel compared to the released ('kiss' bonded) panel. This was especially true for the three middle locations where the well bonded panel recorded significantly higher transmitted force values. The explanation for this trend could be that the impact energy will have a harder time moving through the thickness of two laminates that are poorly bonded at the interface. The well bonded laminates should be able to transmit force easier from the front to back surface. The p-value calculated in a completed analysis of variance for the middle three locations was 0.0013.

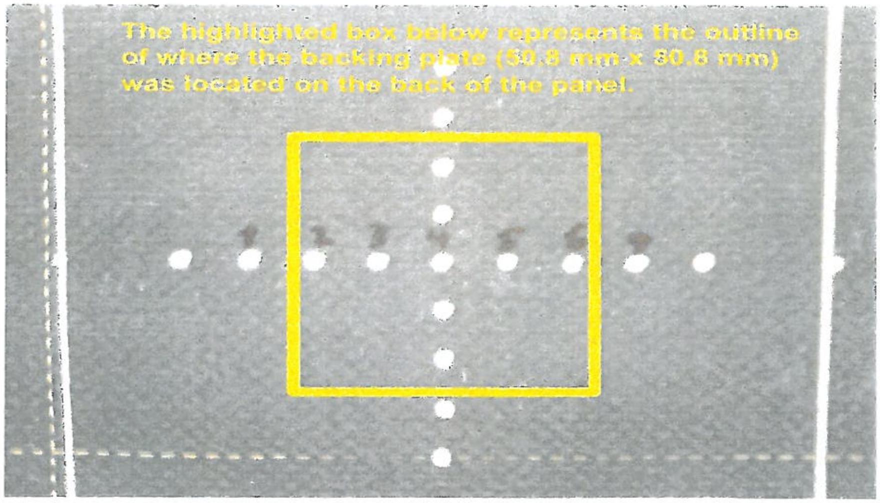

Figure 14. Probe force vs time measured at 7 different locations for the well bonded-not-released panel (WBP) and the released 'kiss' bond panel (KBP).

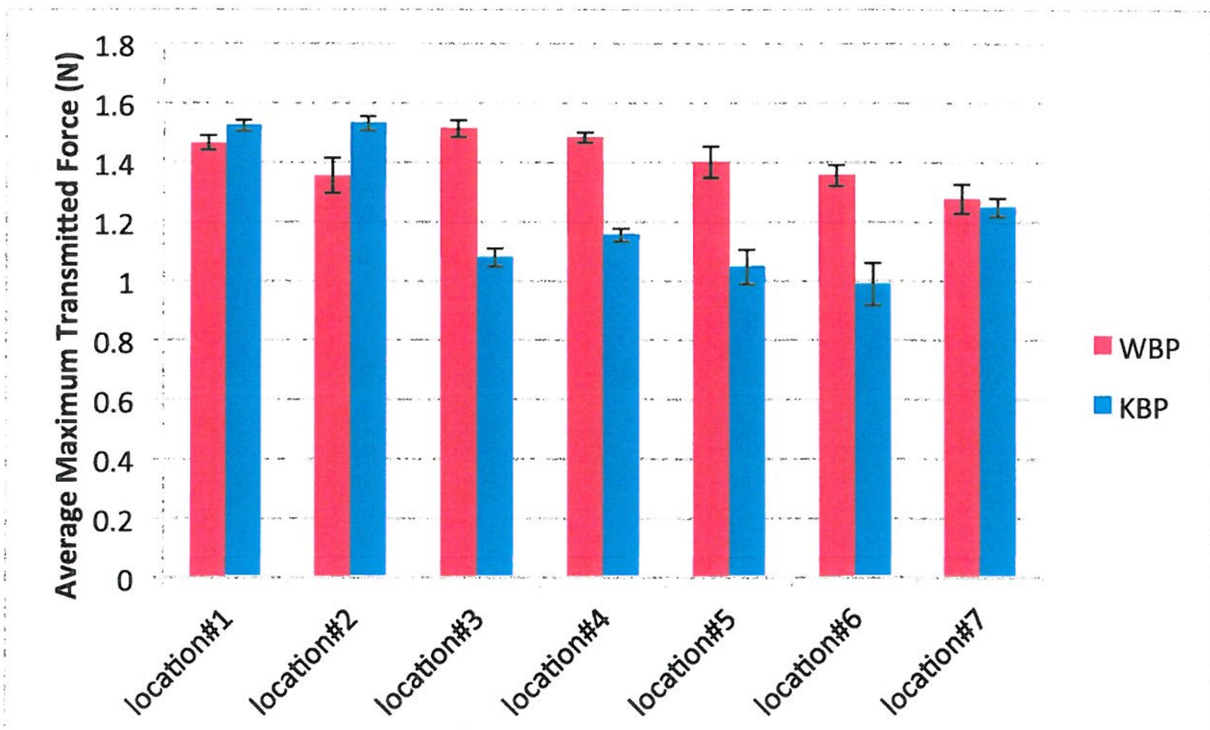

Figure 15. Average maximum transmitted force measured at 7 different locations using a low pre-load (3 N-4 N) for the well bonded-not-released panel (WBP) and the released 'kiss' bond panel (KBP).

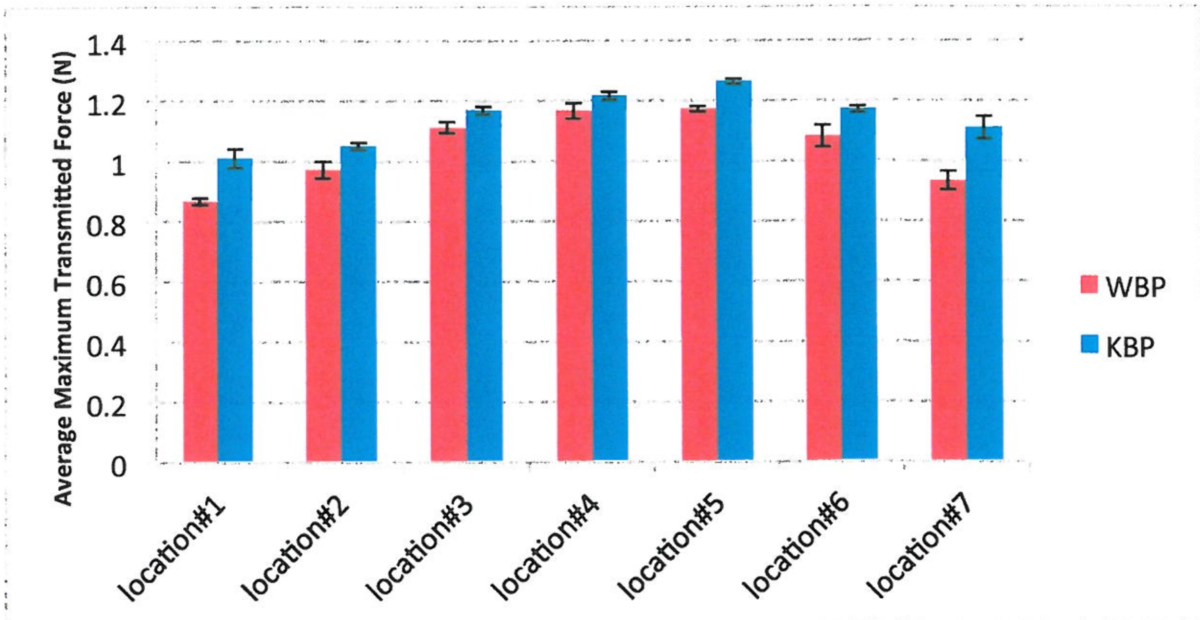

Figure 16. Average maximum transmitted force measured at 7 different locations using a high pre-load (13 N-14 N) for the well bonded-not-released panel (WBP) and the released 'kiss' bond panel (KBP).

For hjgh pre-load data, the maximum transmitted force was very similar for both released and not-released bonded panels. The explanation for this change is that the bonded surfaces are compressed together more at a high pre-load and should be able to transmit energy through the bonded interface similarly.

Also, as shown in Figures 15 and 16, the maximum transmitted force varies depending on the location of the impact test with respect to the backing plate. For the high preload testing a 'bell' shape trend reaches its peak when the impact location is closer to the middle of the backing plate. However, for the low preload testing the transmitted force was higher at locations #1 and #2 for the KBP when compared to the middle locations (#3, #4, #5). This trend was not observed for the WBP's or the KBP tested at a high pre-load. On explanation for this difference is that locations #1 and #2 are off the backing plate and when impacted create a cantilever effect which increases the transmitted force. However, this increase in transmitted force would only occur if the specimen is not stiff which the KBP is not due to the poor bonding. The WBP did not show this trend presumably because of its high stiffness. In order to verify if this was the case, the maximum transmitted force was measured on a solid aluminum plate of similar dimensions to the composite panels. The maximum transmitted force measured at location#1 (off the backing plate) on the aluminum plate was 1.18 N while the maximum transmitted force measured at location #4 (center of backing plate) on the aluminum plate was 1.31 N. The stiff aluminum plate as expected did not experience the cantilever effect as the center location recorded a higher transmitted force measurement than location #1 off the backing plate. Finally, the KBP tested at high preload did not experience the cantilever effect because of the high force keeping the panel in contact between the Periometer® probe and backing plate.

The last set of data analyzed was a comparison plot of the transmitted force and probe force for both released and not-released bonded panels at low and high pre-loads. The force vs time plots for the low pre-load (location #4) data are shown in Figure 16.

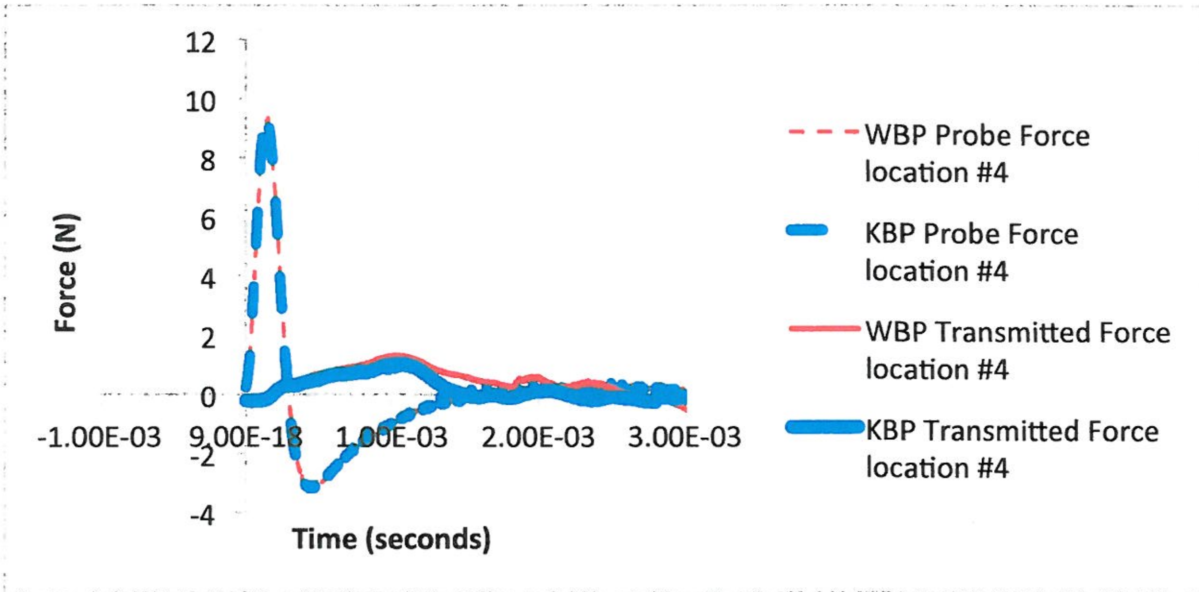

Figure 16. Probe and transmitted force vs time measured at location #4 using a low pre-load (3N-4N) for the well bonded panel (WBP) and the released 'kiss' bond panel (KBP).

No change was observed in the probe force plots. However a change in the behavior of the transmitted force curves was observed after 0.001 seconds. The transmitted force for the WBP was slightly higher than for the KBP after 0.001 seconds until both force curves oscillated to zero around 0.003 seconds. The change in transmitted force between panels was expected as the WBP should record a higher transmitted force.

The force vs time plots for the high pre-load (location #4) data are shown in Figure 17. No significant shape changes were observed when comparing the released and not-released specimens for the probe force curves. However there was again a difference between the transmitted force curves after 0.001 seconds. The transmitted force curve decreased more rapidly for the KBP panel from 0.001 seconds until 0.002 seconds where both curves began to follow a similar trend. This change in transmitted force shows that even at a high pre-load a difference between the WBP and KBP curves can be observed although the initial maximum transmitted force values are similar.

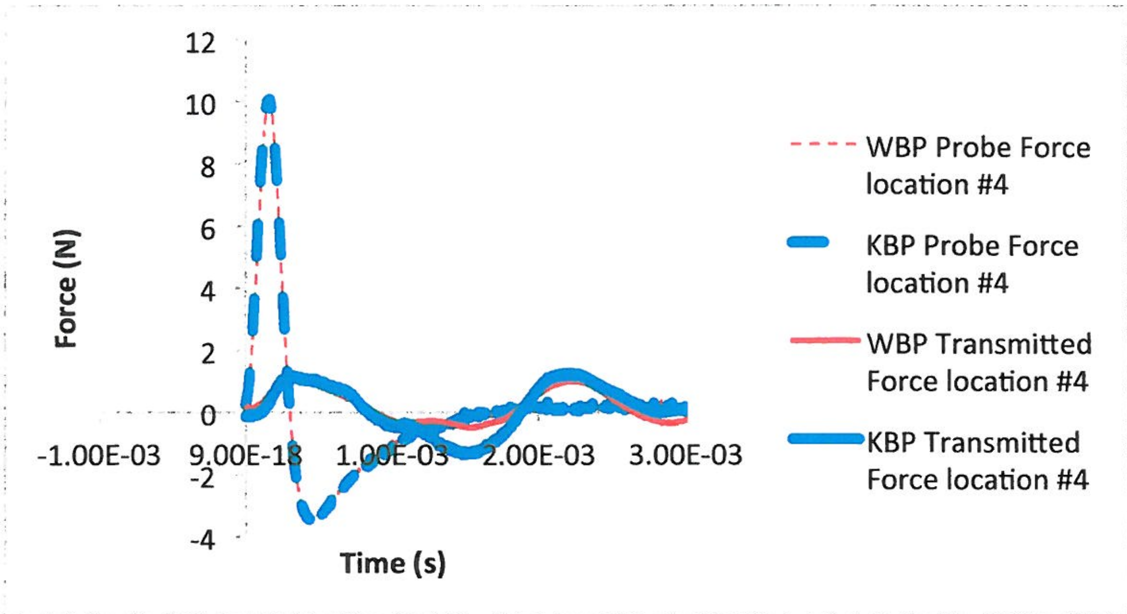

Figure 17. Probe and transmitted force vs time measured at location #1 using a high pre-load (13N-14N) for the well bonded panel (WBP) and the released 'kiss' bond panel (KBP).

SUMMARY AND CONCLUSIONS

In the first set of experiments (102 mm x 102 mm laminates), a significant **increase** in the loss coefficient was observed for the released 4.5 mm thick carbon fiber bonded laminates compared to the unreleased bonded laminates Also, a significant **decrease** in the maximum probe force was observed for the released 4.5 mm thick carbon fiber bonded laminates compared to the unreleased bonded laminates. The impact force used in the current test set-up is too strong to pick-up differences in the adhesive bond strength for the other 'thin' composite specimens tested.

In the second set of experiments (305 mm x 305 mm carbon fiber/epoxy laminates), a significant **increase** in the loss coefficient was observed for the 'kiss' bonded panel compared to the well bonded panel. Also, a significant **decrease** in the maximum probe force was observed for the 'kiss' bonded panel compared to the well bonded panel. The increase in loss coefficient and decrease in probe force are thought to be due to an increase in internal friction during the impact event for poorly bonded specimens as noted in literature for metal adherends [6,7].

Using a low pre-load force, a significant **increase** in the maximum transmitted force was observed for the well bonded panel compared to the 'kiss' bonded panel when using the force transducer and 50.8 mm x 50.8 mm backing plate. For a low pre-load force the maximum transmitted force was higher for locations off the backing plate when compared to being centered on the backing plate. The increase in transmitted force observed off the backing plate for the 'kiss' bonded panel may be attributed to a lower overall stiffness of this panel. The lower stiffness could cause a cantilever effect during impact of the specimen which would increase the transmitted force. This cantilever effect was not observed for the well bonded panel or solid aluminum sheet as both panels have a large stiffness.

For a large pre-load force, **<u>no change</u>** was observed in the maximum transmitted force for the well bonded panel compared to the 'kiss' bonded panel when using the force transducer and 50.8 mm x 50.8 mm backing plate. The increase in transmitted force for the well bonded panel at a low pre-load probably is the result of the two bonded substrates having a greater ability to transmit load across the interface when compared to the 'kiss' bonded panel.

For future work, in order to improve the measurement accuracy of the Periometer® on bonded composite laminates, the impact force should be varied and optimized for specific composite laminate materials and thicknesses. Also, to improve the sensitivity of the transmitted force measurements, a 3D full-field velocity measurement of the back side of the specimens during impact should be examined. Finally, different bonded composite architectures should be tested (honeycomb, solid laminate, metal to composite, etc.) using the Periometer® to help determine how different sandwich geometries and materials affect the measurement accuracy.

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