Simplifying the Testing and Calculation of Fracture Toughness of Thermoplastic and Thermoset Matrix Composite Materials

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James Shedden

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Project Title: Simplifying the Testing and Calculation of Fracture Toughness of Thermoplastic and Thermoset Matrix Composite Materials

Author: James Shedden

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CAL POLY STATE UNIVERSITY

Materials Engineering Department

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Prof. Blair London _____

Faculty Advisor Signature

Prof. Richard Savage _____

Department Chair Signature

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Abstract

Fracture toughness, or the ability of a material to resist fast fracture by crack propagation is an important property in the use of composite materials for structural designs. Other mechanical tests such as tensile, flexure, and compression are more established and practical than testing fracture toughness. Fracture toughness testing is less commonly used because it requires specific specimens and non-conventional test methods. In composite materials specifically, delamination of the plies of materials is tested for G_{IC} and G_{IIC} values to find the critical strain energy release rate of the two types of fracture modes. The common two tests for these values are the double cantilever beam (DCB) and the end-notched flexure (ENF) tests. Both tests require a complex loading scheme, compliance calibration, and Excel calculations to achieve the final maximum strain energy release rate values. This project aimed to simplify the preexisting testing methods and the calculations that follow. In an attempt to simplify these test methods, a USB microscope recorded the crack propagation throughout the laminate for the compliance calibration as either test method proceeded. DCB tests were run to determine average G_{IC} values of 1318 J/m^2 and 145 J/m^2 for the AS4/ PEEK thermoplastic and TR50s/TC275 thermoset material, respectively. ENF tests were also run to find average G_{IIC} values being 1428 J/m^2 for the thermoplastic matrix material and 455 J/m^2 for the thermoset matrix material. Along the way to these calculations, the USB microscope was found to be extensively useful in monitoring crack growth and a new Excel template for both tests was developed to make calculations simpler.

Key Words

Materials Engineering, fracture toughness, strain energy release rate (G), crack modes I and II, composite materials, laminate, double cantilever beam, mixed mode bending, end-notched flexure, compliance, delamination

Acknowledgements

This project was made possible only through the generous donation of time and materials given by TenCate Advanced Composites. I would like to thank Barry Meyers of TenCate for sharing his invaluable experience with composite material testing to assist me in following the test procedures and with the calculations that follow. I would also like to thank my advisor, Dr. Blair London for all of his assistance in keeping this project on schedule and his daily advice and insight. I would also like to thank Dr. Eltahry Elghandour for assisting me in cutting my specimens to the correct size, and for allowing me access to the cutting saw as I please.

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1. Introduction

1.1. Problem Statement

The use of composite materials for structural components depends on the values of the various applicable mechanical properties. One of these properties is fracture toughness, or the ability of a material to resist fast fracture by unstable crack propagation. Other mechanical tests such as tensile, flexure, and compression are more established and practical compared to fracture toughness. Fracture toughness testing is difficult because it requires specific specimens and non-conventional test methods. In composite materials specifically, delamination of the plies is tested by G_{IC} and G_{IIC} tests to find the critical strain energy release rate of the two fracture modes. These tests give acceptable values for predicting delamination; however the test procedures and data analysis methods are not practical and difficult to reach the ending values. These tests could be improved by automating where the crack length is recorded without the operator observing it. The data analysis could also have a user-friendly spreadsheet template where data placement and results are observed without the calculations visibly present. This improvement to practicality could bring testing fracture toughness to the forefront of composite material testing and design.

1.2. Background

1.2.1. Fracture Toughness Property

Fracture toughness is defined as “a property which describes the ability of a material containing a crack to resist fracture”.[1] In other words it is the ability of a material to resist a brittle-type fracture when a crack is present. Fracture toughness is a distinguished property for many structural designs and applications. The value for this property is typically denoted by the stress-intensity factor (K) when a crack begins to grow as a load is applied. The values for this property are given in either MPa$\sqrt{m}$ or ksi$\sqrt{in}$. The K value is denoted as either K_{IC}, K_{IIC}, or K_{IIIC} with respect to which cracking mode is being tested (Figure 1.1). However, in composite materials, G, the strain energy release rate is looked into more closely. As the material is being tested and the crack begins to propagate, the stiffness and force on the material begin to decrease. The decrease in the load on the material means the strain energy stored in the material is also decreasing and being released (eq. 1).

$$G = -\frac{\partial U}{\partial a} \tag{1}$$

That being the potential energy for crack growth (U) over the crack length (a).[2] The units for this value are J/m^2. Since the strain energy release rate is a variable value, G_C or the critical strain energy release rate is the reported value for interlaminar fracture toughness. This value can also be described as the strain release energy at the point when the delamination crack begins to propagate. This value of G_C must be overcome if any delamination is to occur.[3]

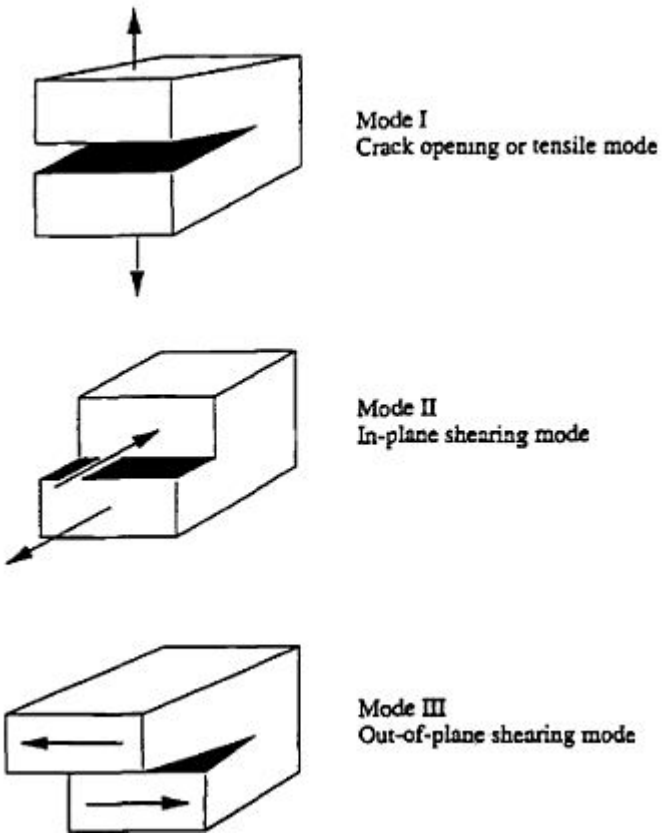

Figure 1.1: View of the various cracking modes for fracture toughness classification.[3]

G_C can also be called the fracture energy of the material as it is independent of applied loads and the dimensions of the tested material.[2] Relating K and G together gives us an equation, where E is the Young's modulus of the material (eq. 2).

$$G = \frac{K^2}{E'} \tag{2}$$

E'= E in plane stress and E'= E/ $(1-v^2)$ for plane strain. G_C is also denoted as G_{IC}, G_{IIC}, or G_{IIC} in regard to the cracking mode of the test. With respect to cracking modes, G_{IC} and G_{IIC} are found to be acceptable values in predicting delamination.[3] G_{IIIC} is however not accepted as there is no

current test method to determine the value of the beginning of delamination in pure cracking mode III. Cracking mode III is often neglected for design of structures due to this difficulty and uncommon occurrence. The scope of the project will be concerned with delamination in cracking modes I and II.

1.2.2. Cracking Mode I

Cracking mode I is considered to be the crack opening or tensile mode of delamination in composite materials.[3] It is the most common form of fracture toughness failure as it is the motion of pulling plies of material away from each other. The cracking mode is characterized by the crack face undergoing opening displacements relative to one another as the crack grows. The typical test done to determine the G_{IC} value is the double cantilever beam (DCB) test.[3] The DCB test is primarily a tensile test where one of the ends of a flat laminate is under load pulling the plies apart from each other (Figure 1.2).

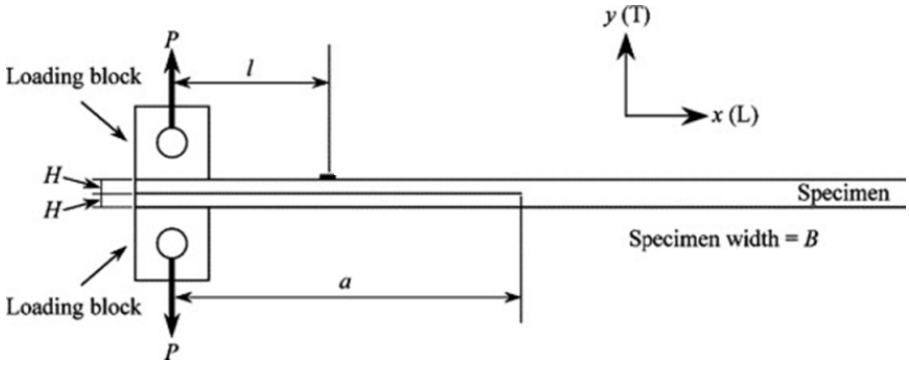

Figure 1.2: Double Cantilever Beam Test utilizing bound test blocks where the load is applied to the specimen.

This end of the laminate is attached to the either two piano hinges or bonded test blocks. There is an initial crack present when the samples are cured to allow delamination to occur in a controlled manner. This is made by curing with an insert (typically Teflon) placed in the laminate that will not melt while it is cured. Piano hinges and test blocks are then bound to the DCB specimen using a suitable epoxy adhesive that will withstand the load (P). The initial crack length (a_o) is measured from the center of where the load is applied on the specimen to the inner most end of the insert. The width (b) of these samples is typically around 1 inch. The DCB test pulls the two separated layers of the laminate away from each other until the critical elastic strain energy is reached and the crack propagates. The crack propagates through the sample and the distance of the crack is recorded. The DCB test offers a controlled load test and is a

standardized test under ASTM D5528[9] for polymer matrix composites. The DCB test is an implemented and accepted test for fracture toughness.[4]

1.2.3. Cracking Mode II

Cracking mode II is the in plane shear mode of delamination. This is classified by the two separated plies of material sliding over each other in the direction of crack growth.[3] This cracking mode is less common than the crack opening tensile mode, but it is still relevant to designs where force is not particularly down the center of a structural component. Two tests have been developed to find the value of GIIC: end-notched flexure (ENF) and end-loaded split beam (ELS) (Figure 1.3).

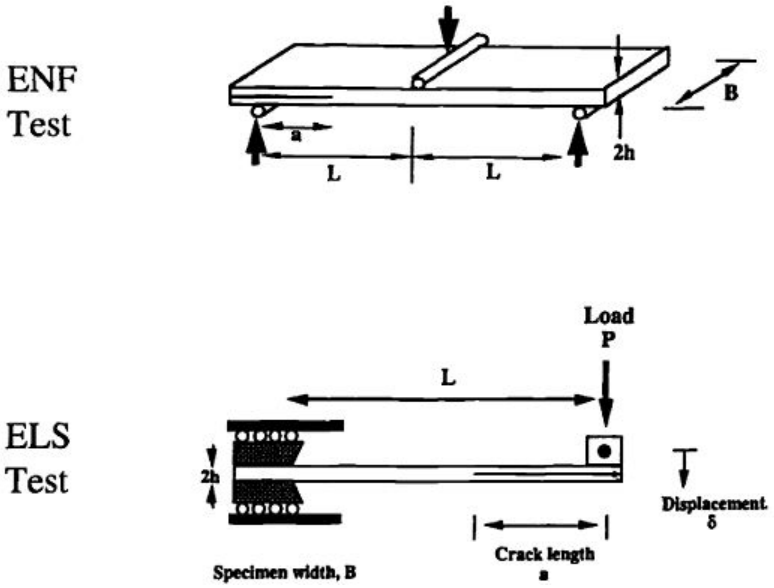

Figure 1.3: End-notched flexure and end-loaded split beam test comparison showing one as a three-point bend test, and the other utilizing a compressive load .[3]

Both tests return acceptable values, but have their pros and cons while testing. ENF requires a simple three-point bend test, but is noted to have unstable delamination growth unless controlled by a strain displacement gauge or given a long initial crack.[3] ELS requires a clamping fixture to hold one end in place while the other end experiences a force. This results in a more stable delamination growth. Both tests use 1 inch wide samples with an initial crack length present similar to the G_{IC} samples. These accepted tests of cracking mode II have been found to have pure sliding shear, however there are no available ASTM standards for either test. In comparison to G_{IC} values, G_{IIC} values should always exceed those values for the first cracking

mode.[3] There is also a trend that more brittle materials have a greater difference between the G_{IC} and G_{IIC} values, whereas tougher matrix materials have values that are closer.[3] This trend comes into play when regarding thermoplastic and thermoset matrices.

1.2.4. Thermoplastic vs. Thermoset Matrices

Thermoplastic polymers are extremely common in everyday life. Polymers such as Polyethylene terephthalate, polyethylene, polypropylene and Polyvinylchloride are all thermoplastics used in various commercial products that we use all the time.[5] However, the use of thermoplastics in composites is a newer development compared to the traditionally used thermosets. Common thermoset matrices for composite materials are made of epoxy, urethane, phenolic, and polyester resins. Thermosets are easy to work with as they are in liquid state at room temperature which allows them to impregnate various types of fibers with ease.[5] Besides this, thermosets have excellent resistance to solvents and corrosives, resistance to heat and high temperature, excellent adhesion, and excellent finishing.[5] As the thermoset matrix is cured, an exothermic chemical reaction occurs creating strong bonds between the polymer chains and it catalyzes. However, thermoplastic matrices have two major advantages over thermoset resins: increased impact resistance and the ability to be reformed. This means that they are typically tougher than thermoset matrices and that they have the ability to be repeatedly melted down and reshaped. Thermoplastics also have the capability of being recycled, while thermosets will either char or be broken down and can no longer be used. This is due to the strength of the Van der Waals bonds between the polymeric chains; the bonds being weaker in thermoplastics and stronger in thermosets.[6] The major disadvantage of using thermoplastic matrices is that they are in solid state when at room temperature and are therefore difficult to impregnate fibers. The polymer must be melted with ample pressure applied to distribute the resin throughout the fibers adequately, and must also be cooled at high pressure. Thermoplastic resin cures require a large compression mold, while autoclave can be used to cure thermoset resins (Figure 1.4).

a.) b.)

Figure 1.4: a.) Compression mold cure and b.) Autoclave cure, two techniques to cure high quality composite materials.

Applying the differences of thermoplastics and thermosets to fracture toughness, thermoplastics are tougher so they should carry a higher G_{IC} and G_{IIC} value. The difference between the G_{IC} and G_{IIC} value should be closer than the more brittle thermoset material. This is also evident due to the nature of fracture toughness tests in testing the toughness of the matrix over that of the fibers. This is solely due to the fibers being much stronger than the matrix, and also that the fibers would not be the first to fail in delamination. This is especially evident in mixed mode bend testing of both cracking modes.

1.2.5. Mixed-Mode Bending

Mixed-Mode Bending (MMB) is a complicated testing method used to cause both cracking modes I and II to be tested concurrently.[7] This means that a combined G_{IC} and G_{IIC} value is given from this test, in the form of a G_{IC}/G_{IIC} ratio. The MMB test requires a complex test fixture that can control the G_{IC}/G_{IIC} ratio by varying the load point location along the lever (Figure 1.5).

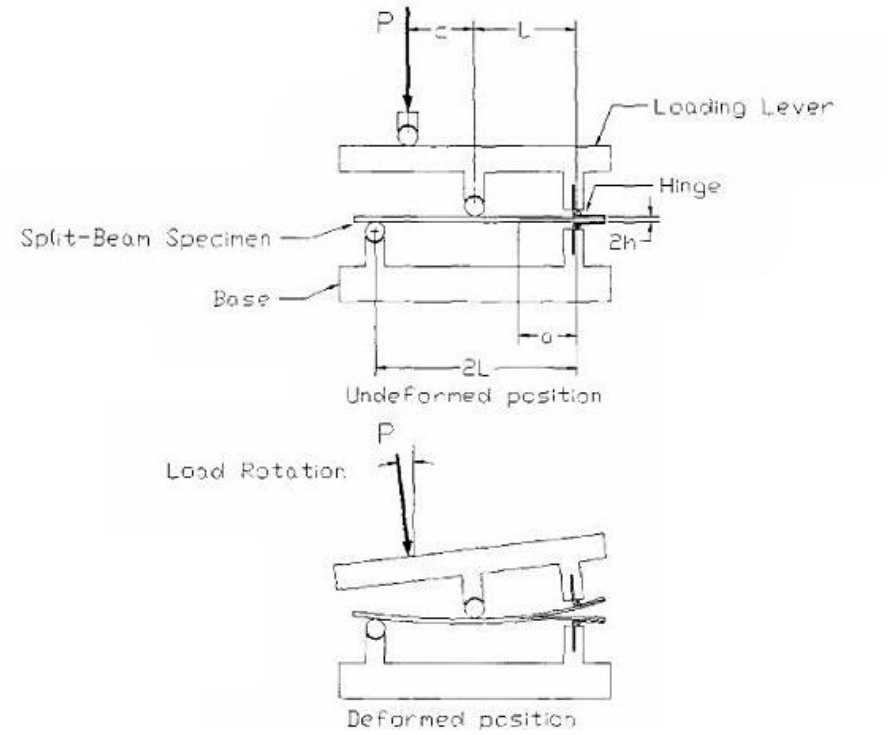

Figure 1.5: Mixed-Mode Bending Apparatus inducing a combined load of crack mode I and II to cause deformation[7]

The MMB fixture combines both cracking modes by using hinges similar to the DCB test and a three point bend induced similar in the ENF test. Acting force (P) is applied to the loading lever offset from the center of the three-point bend test component. The distance of force P from the center point (c) controls the ratio of G_{IC} and G_{IIC}. In other words, the shorter the distance c is, the more pure mode II is tested, and vice versa for mode I testing. However to produce pure mode I loading with this fixture, the entire loading arm is removed and the acting force P is focused at the hinge in similar fashion to DCB testing.[7] Purer mode II testing or, when the G_{IC}/G_{IIC} ratio is low, tends to cause unstable crack propagation and is difficult to track similarly to the ENF test.[7] MMB test is not standardized yet, but it is a versatile method as both modes of fracture can be tested to return comparable values anywhere between pure mode I and pure mode II testing. The test fixture is modifiable to analyze any combination of a specific cracking mode of interest. The MMB fixture is probably the best means to test fracture toughness in composite materials. However, since the fixture is so unique, they are not readily available and not practical to industry except in focused research situations.

2. Experimental Procedure

2.1. Initial Setup and Conditions

TenCate Advanced Composites in Morgan Hill, CA donated two carbon-fiber reinforced composite test panels to be tested for G_{IC} and G_{IIC} values. Both panels were composed of 36 plies of material with a fiber orientation of (+2˚/(0˚)16/-2˚/+2˚/(0˚)16/-2) with the fibers running perpendicular to the length of the laminate. One of the panels was composed of AS4/PEEK thermoplastic matrix material and the other of TR50s/TC275 thermoset matrix material (Figure 2.1). Both laminates utilized a similar type of carbon fiber for reinforcement that would have near identical mechanical properties, but where they would differ would be determined in the differences of matrix material. The thermoplastic panel was originally fabricated with dimensions of 12'' by 18'' and the thermoset panel was 12'' by 24''.

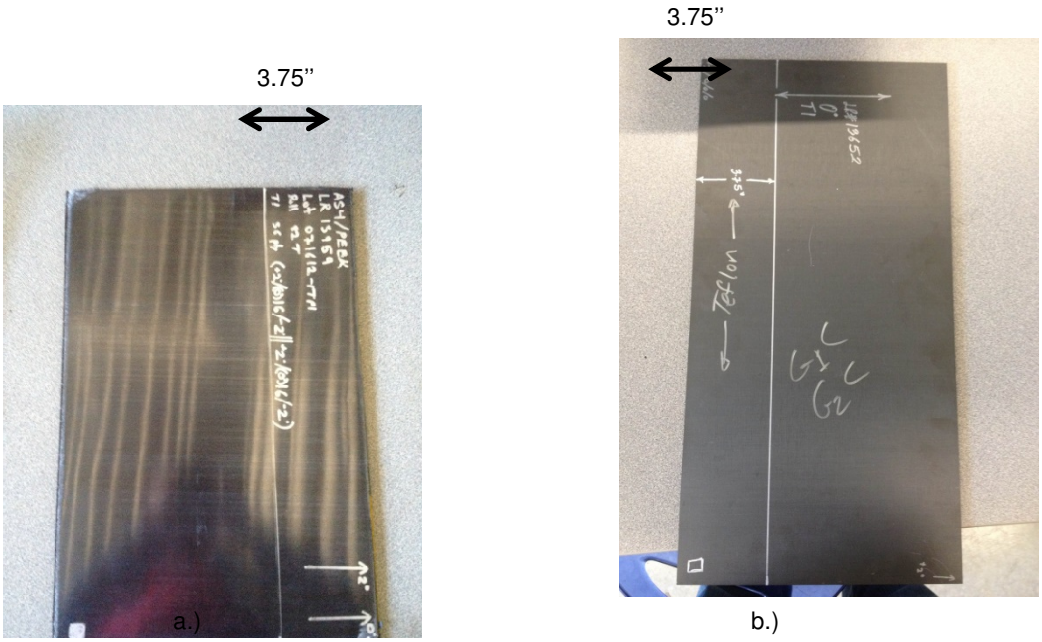

Figure 2.1: a.) AS4/PEEK laminate and b.) TR50s/TC275 laminate was the starting point for testing as generously provided by TenCate Advanced Composites.

Also from TenCate Advanced Composites were test procedures for a DCB and ENF tests and Excel templates for calculations originally designed by the Boeing Company in August of 2005. Each procedure had items such as an introduction to the testing and calculations, applicable documents, key word definitions, and other useful information to accompany the test procedures. These test procedures were laid out well to design the experiment with specific instructions and gave information as to the specimen size requirements. Specimens for both tests were required to be 10'' by 1'' with an insert length of 3.25'' (Figure 2.2).

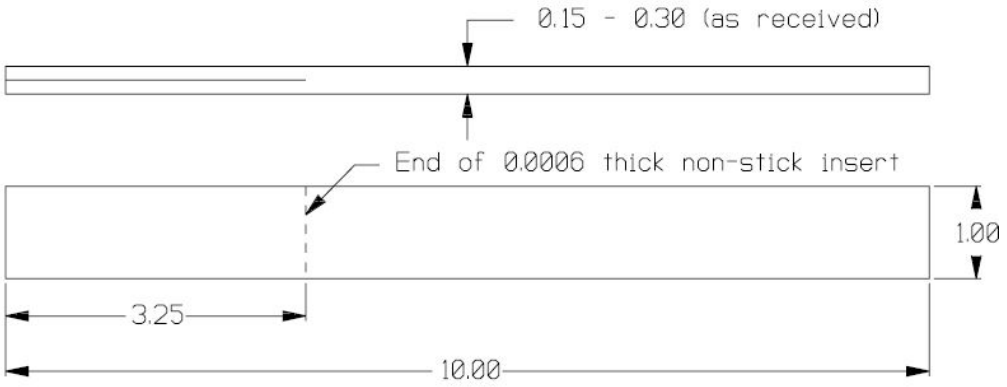

Figure 2.2: Individual specimen size dimensions where the plies are stacked to make a thickness of 0.15'' to .30'' (note: all dimensions are in inches).

Since these laminates were required to be in a smaller specimen size than the original laminate given, they were required to be cut to the appropriate size. To do this, accessibility was obtained to use one of the saws owned by the Aerospace department in their composites lab. Specimens were cut to the correct size using a tile saw that was water cooled (Figure 2.3). Once cut to the correct size, specimens were outlined with a white permanent Sharpie paint pen along the side and the distance from the extent of the original crack was marked spanning 0 to 50 mm distance.

Figure 2.3: Using the tile saw to cut the laminate to sample size.

In looking at testing specifically, training using the Instron 3369 and appropriate fixtures was received and taken note of for both test types (Figure 2.4). In working with what was learned from this, test methods were developed for my specific tests. The “test profiler” option in

Instron's Bluehill software was made use of due to the requirement of both tests inducing a load at a certain extension rate and unloading at another extension rate while still collecting data. By collecting data in this fashion, the test produced an integral shape visual for the energy being the area under the curve. With regard to this test method, the machine was instructed to reach a certain amount of extension at one speed, then to return back to the 0 extension position once that amount of extension was reached. The way the test would finish was determined by the time it would take to complete both extension rates and return to 0 extension position. Data would stop being collected once this time period was exceeded and the test would conclude.

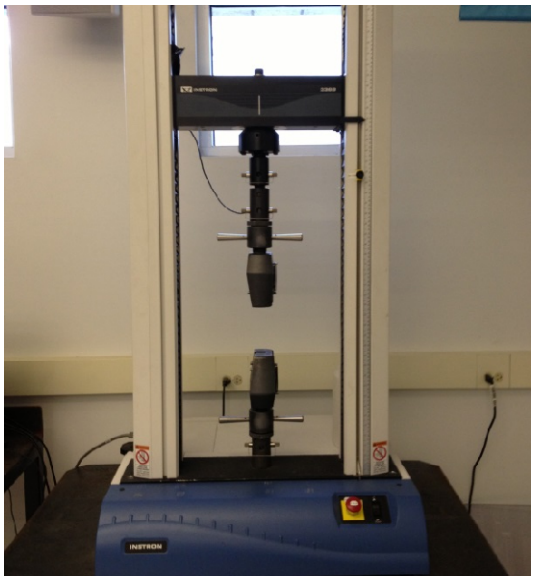

Figure 2.4: Instron 3369 Testing Machine used for the bulk of the mechanical testing.

While the tests were in motion, crack propagation was required to be monitored while the test was ongoing. Originally, a simple optical microscope lens was found to view this. This was quickly improved to a USB microscope capable of recording a video of the crack propagation for each test while also displaying it on the screen of a laptop (Figure 2.5). The quality of the videos was found to be ample for observing the crack and presented a clear focused image. The crack distance was taken account of by using a stopwatch to record the time when the crack crossed through the marked distance.

Figure 2.5: Image of the propagating crack view from the USB microscope recorded video.

2.2. DCB Testing Procedure

Test specimens from both test laminates were machined to the correct size using the tile saw. However, before they could be tested they had to be outfitted with test blocks bound with an adhesive. The adhesive used was Hysol EA 9394 which has a primary purpose of bonding composite materials to metal. This adhesive was purchased in a 50 ml dual cartridge quantity and applied using a twin mini cartridge mix ratio manual epoxy applicator. Following the Hysol surface preparation guide[8], specimens were cleaned and abraded using medium grit sandpaper before the adhesive was applied. Once applied, the adhesive was left for 3-5 days at room temperature to be allowed to cure completely as instructed by the product description by Hysol. Since the number of test blocks was limited, the first batch was created over this time frame, and the second was cured at an elevated temperature of 72˚C for a period of over an hour due to time constraints. The two batches produced were either five or six specimens (Figure 2.6).

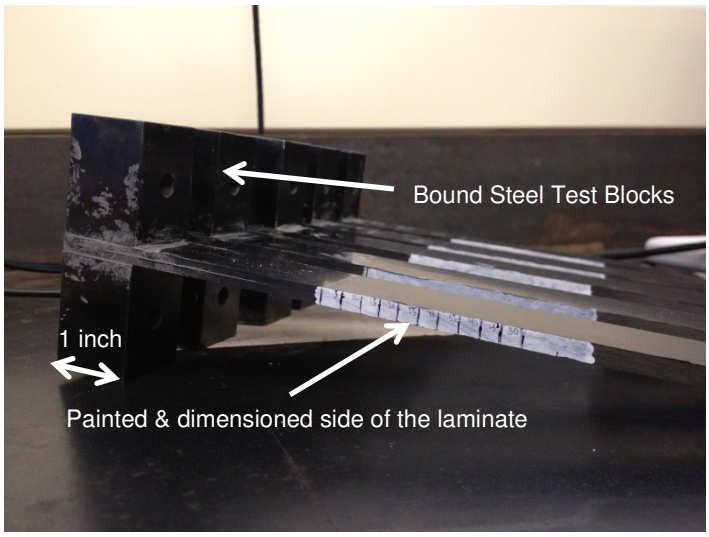

Figure 2.6: Batch of DCB samples with bonded test blocks and side markings.

Looking into the procedure of the DCB G_{IC} test specifically, the primary function of the test is similar to that of any basic tensile test. Using the tensile "test profiler" method, the load of the test was set at a rate of 0.1 inches/minute and unloading at a rate of 1.0 inches/minute. The crosshead extension for the majority of tests was set to 1.2 inches for a total test time of 13.2 minutes. The test blocks were placed into the 1 inch sized "Sandwich Panel Flatwise Tensile Test" fixture by Wyoming Test Fixtures, Inc. The USB microscope was placed near the specimen being tested and the test proceeded to induce crack propagation (Figure 2.7). The time was recorded every millimeter between 0 and 10 mm and every 5 mm until 50 mm was reached by the propagating crack.

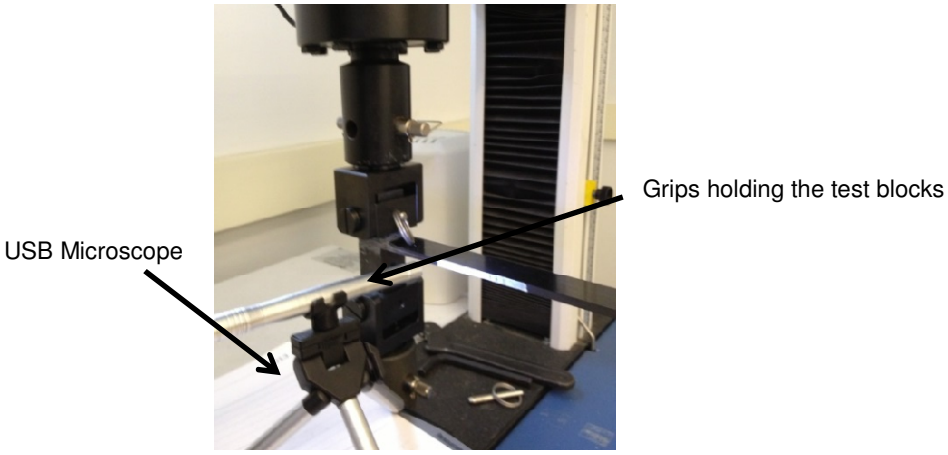

Figure 2.7: DCB test setup using appropriate grips and USB microscope.

2.3. ENF Testing procedure

The ENF testing procedure followed a similar technique to that of the DCB test. Test specimens were cut

from both laminates, and painted and marked on the sides. There is no other specimen preparation necessary and the specimens are ready to be tested. The test was done using a 3-point bend test fixture in conjunction with a compressive “test profiler” method in Bluehill software. The method was programmed to place a load with an extension rate of 0.05 inches/minute and unload at a rate of 0.2 inches/minute. The crosshead extension was set to unload after reaching 0.38 inches, requiring exactly 9.5 minutes before completing each test. The support span of the 3-point bending fixture was adjusted to be 4 inches between the lower two points with the top middle point placed 1 inch away from the extent of the initial crack (4.25 inches from the beginning of the initial crack). The USB microscope was utilized in a similar manner as the DCB test setup being placed next to the specimen for viewing the continued crack propagation (Figure 2.8).

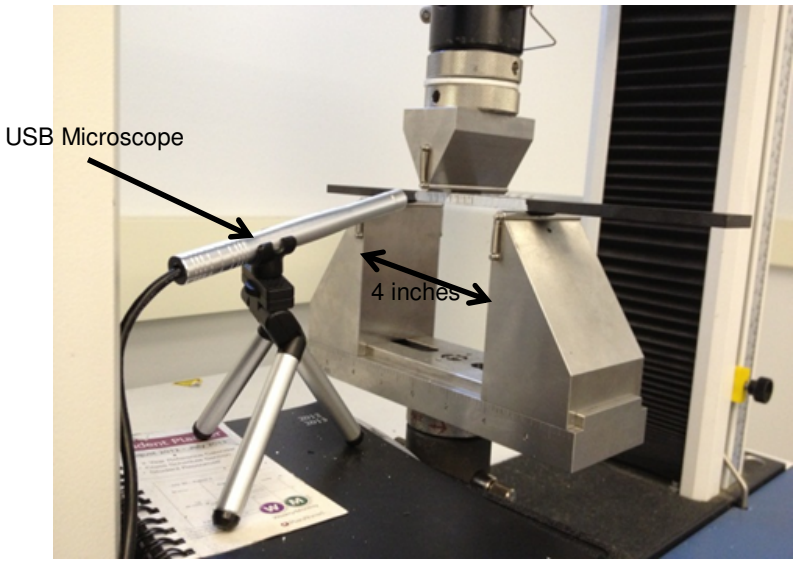

Figure 2.8: ENF test setup using appropriate 3-point bending fixture and USB microscope.

2.4. Realistic Constraints

Manufacturing:

By performing any of these tests described, the fracture toughness of either pure mode I, pure mode II or a mixture of both modes can be labeled with a specific G_C value for any set of reinforcing fibers and matrices. This allows the possibility of comparing the fracture toughness property between not only thermoplastic and thermoset matrices, but any polymer matrix available. The major constraint of defining a G_C value to a matrix is that the values tend to fluctuate in almost every test. Also since there is no specific ASTM test specification for ENF, ELS and MMB testing, values cannot be organized under a repeatable test until that is

assembled. Concerning this project in particular, pure mode I and pure mode II will be tested to receive values for a thermoplastic and thermoset matrix by being DCB and ENF tested. This limits the more in depth comparison between cracking mode I and II produced by using MMB. With this as a constraint, pure mode test results will be compared to one another of the same material, and compared with the other matrix material. Pure mode testing should be able to yield values of G_C to be comparable to determine which matrix is less prone to delamination.

Economic:

There was also the constraint of the sample size I could test due to the amount of material provided. As these materials are expensive, a modest supply is not expected for a donation toward a senior project. However, since the sample size is smaller, there is less room for error than if there were a larger supply of specimens. That being said, preliminary tests to ensure adequate crack propagation had to be well thought out beforehand to not waste material.

3. Results

3.1. G_{IC} Analysis and Calculation

Results were taken from the Bluehill .raw data file and placed into Excel to create a plot of tensile load vs. tensile extension showing each specimen tested (Figures 3.1 and 3.2). Both materials were tested using five specimens for the DCB testing. However, the thermoplastic sample only consists of three specimens that were analyzed for G_{IC} data due to poor adhesion between the block and composite on one of the tests (Specimen 4), and strange delamination on another (Specimen 2). Video recordings for each specimen's crack propagation were recorded and labeled with the corresponding material and specimen number. Delamination was found to occur when the initial slope of the load over extension began to decrease.

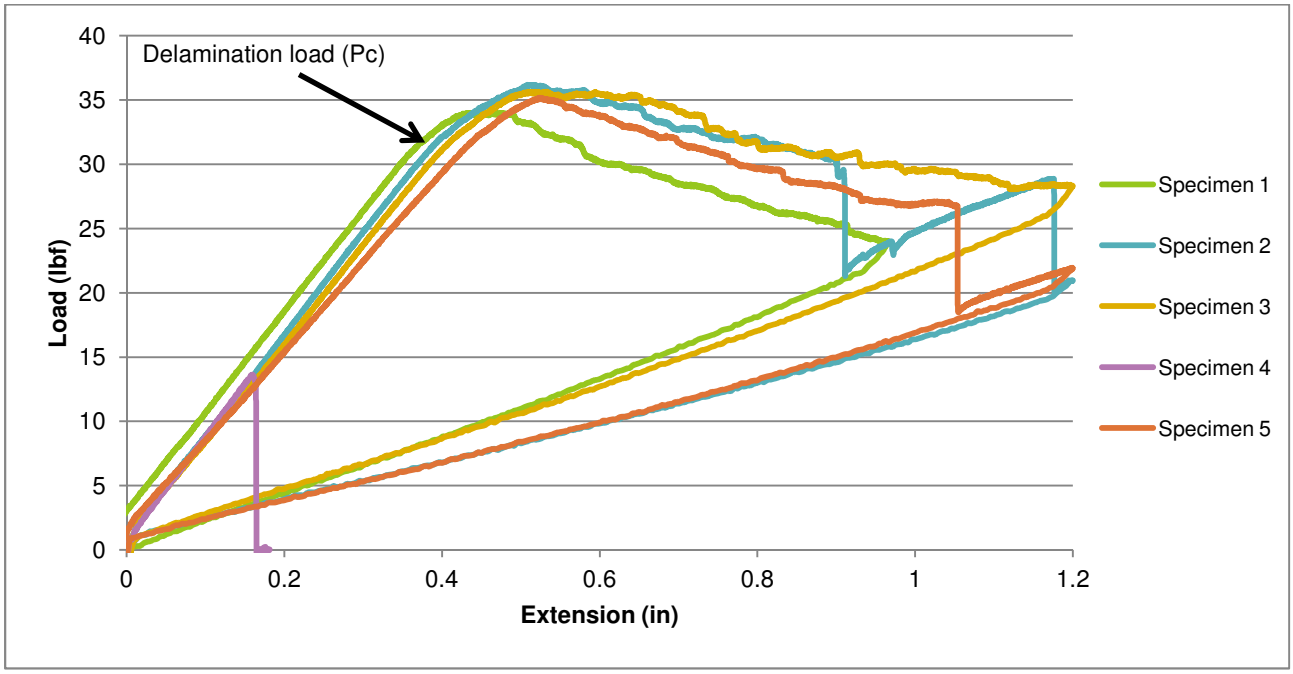

Figure 3.1: Thermoplastic Matrix Tensile Load vs. Tensile Extension Plot.

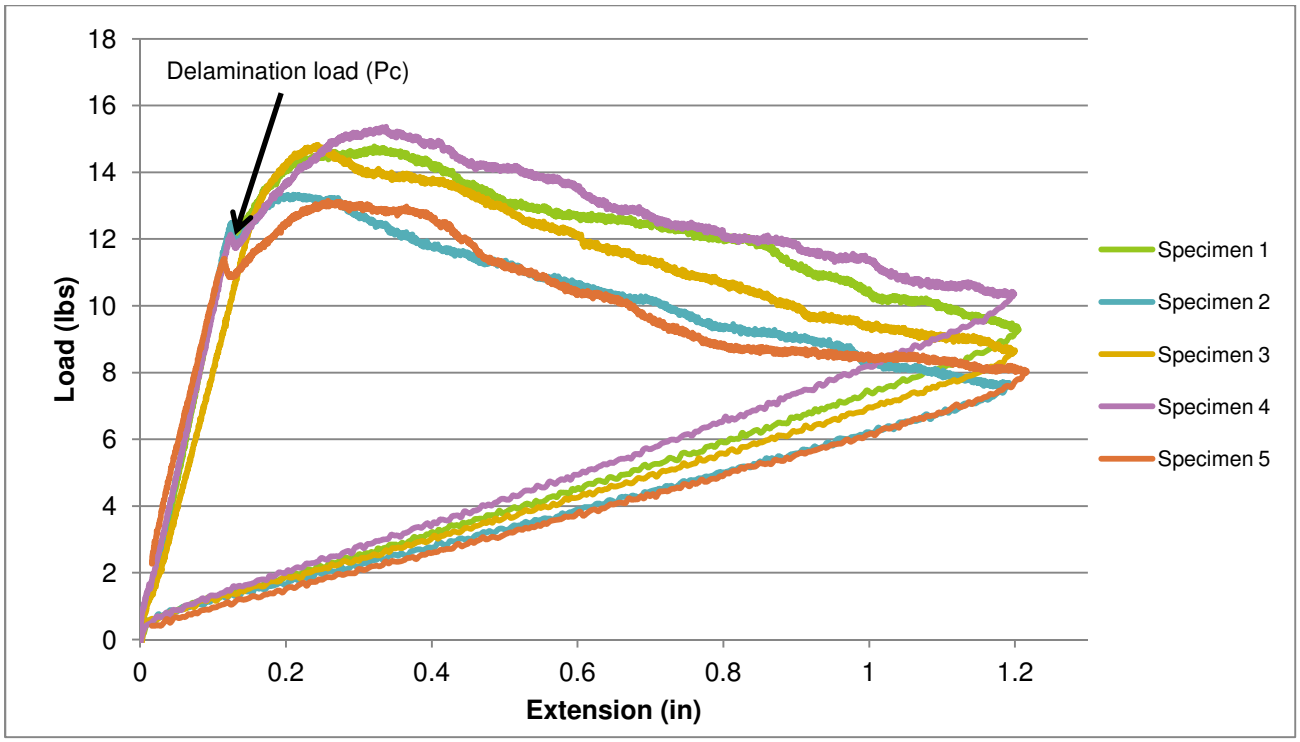

Figure 3.2: Thermoset Tensile Load vs. Tensile Extension Plot.

The key traits of each specimen that were noted before crack propagation was recorded were the width, thickness and initial crack length. The initial crack length (a_0) was consistent for every specimen being around 2 inches or 50 mm. As delamination began to propagate, the initial load and extension of this was recorded and extracted from the .raw data by finding the time when crack propagation began as noted by the operator. This data was taken for every specimen with the exception of thermoplastic specimen 4 (Tables I and II). The width was found to be around 25.02 mm and 25.18 mm and thickness around 4.79 mm and 5.58 mm for the thermoplastic and thermoset materials, respectively.

Table I: Thermoplastic DCB Delamination Data

Specimen ID	Delamination Load (N)	Delamination Extension (mm)
1	150.53	10.87
2	150.39	11.049
3	153.15	11.89
4	-	-
5	145.63	11.658
Average	149.93	11.37

Table II: Thermoset DCB Delamination Data

Specimen ID	Delamination Load (N)	Delamination Extension (mm)
1	58.98	4.191
2	54.62	3.683
3	58.81	4.242
4	53.29	3.556
5	48.47	3.3274
Average	54.83	3.80

Continuing to use the raw data led to finding more corresponding forces and extensions for the recorded time when the propagating crack moved passed the marked distances. These time recordings were matched with the forces and extension for a compliance calibration. This calibration was accomplished by placing these values into an Excel spreadsheet template and measuring a slope. For mode I testing, there are actually three ways to calculate the G_{IC} value: Modified Beam Theory (MBT), Compliance Calibration (CC), and Modified Compliance Calibration (MCC). For my analysis and comparison between mode II testing, I used the CC method as my results for the G_{IC} values (Eq. 3).

$$G_{Ic}=\frac{mPc\delta}{2ab} \tag{3}$$

M is the slope of the compliance, Pc is the delamination load, δ is the delamination extension, a is the initial crack length, and b is the width. By inputting the forces and extensions of the crack's propagation, the compliance (C) was determined to equal δ/P with units of mm/N. The logarithmic value was taken of these values was plotted against the logarithmic value of a, or the crack's propagation where $a= a_o$ + the crack's distance traveled (Figure 3.3). This returned the slope, of this plot which is used for the final G_{IC} value. (Table III and IV).

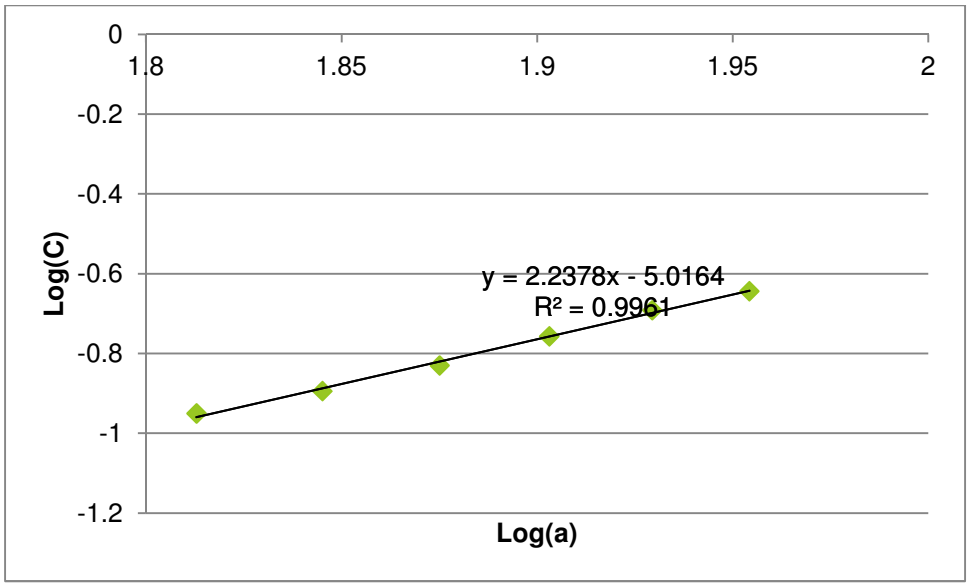

Figure 3.3: Compliance Calibration graph for a DCB test which returns the slope, in this case being 2.2378 for the G_{IC} calculations.

Table III and IV: (III) Thermoplastic and (IV) Thermoset G_{IC} Values and Averages

Specimen ID	m	G_{IC} ($J/m^{2)}$
1	2.2378	1456.146
2	-	-
3	2.0448	1480.747
4	-	-
5	1.4914	1017.207
Average	1.925	1318

Specimen ID	m	G_{IC} (J/m^2)
1	2.0551	167.9532
2	2.0395	136.402
3	2.0458	169.4291
4	1.945	119.541
5	2.0395	132.4678
Average	2.025	145

3.2. G_{IIC} Analysis and Calculation

The data returned from the ENF tests was obtained in a similar manner to the DCB test data. The .raw files were taken and data was organized to produce graphs of compressive load vs. compressive extension (Figures 3.4 and 3.5). Both materials were tested to have more than five specimens due to issues with the paint coming off of the laminates during this type of testing.

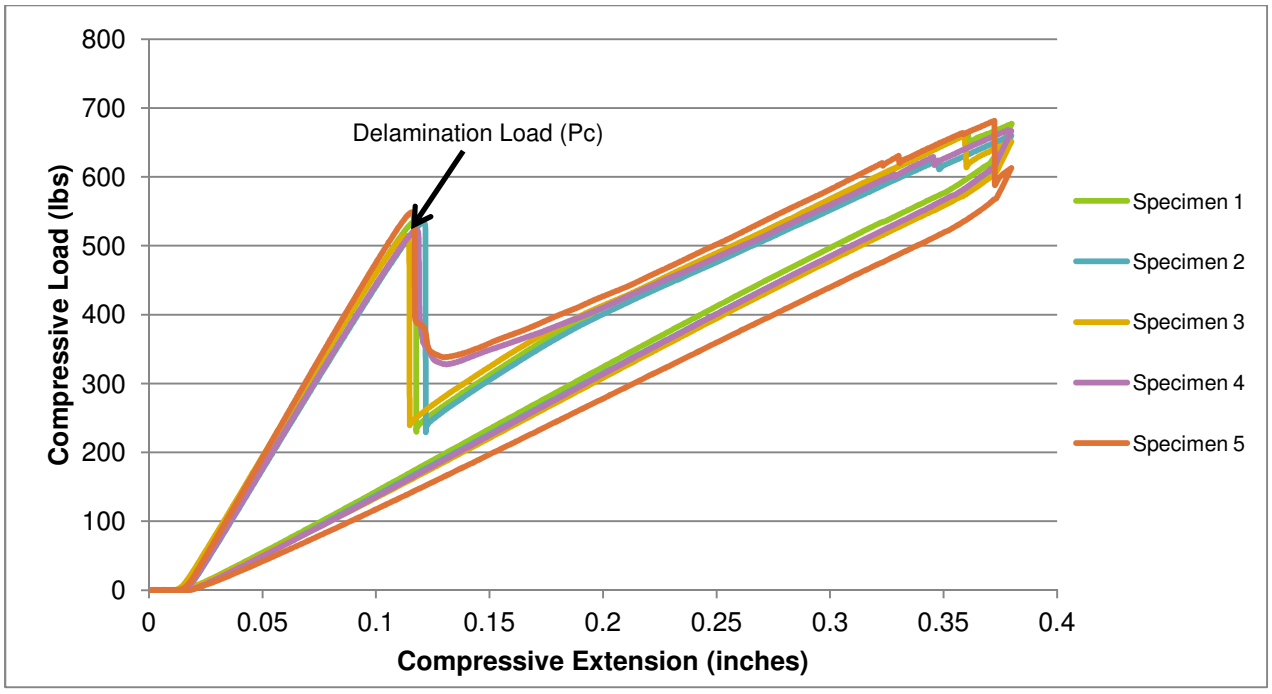

Figure 3.4: Thermoplastic Compressive Load vs. Compressive Extension Plot.

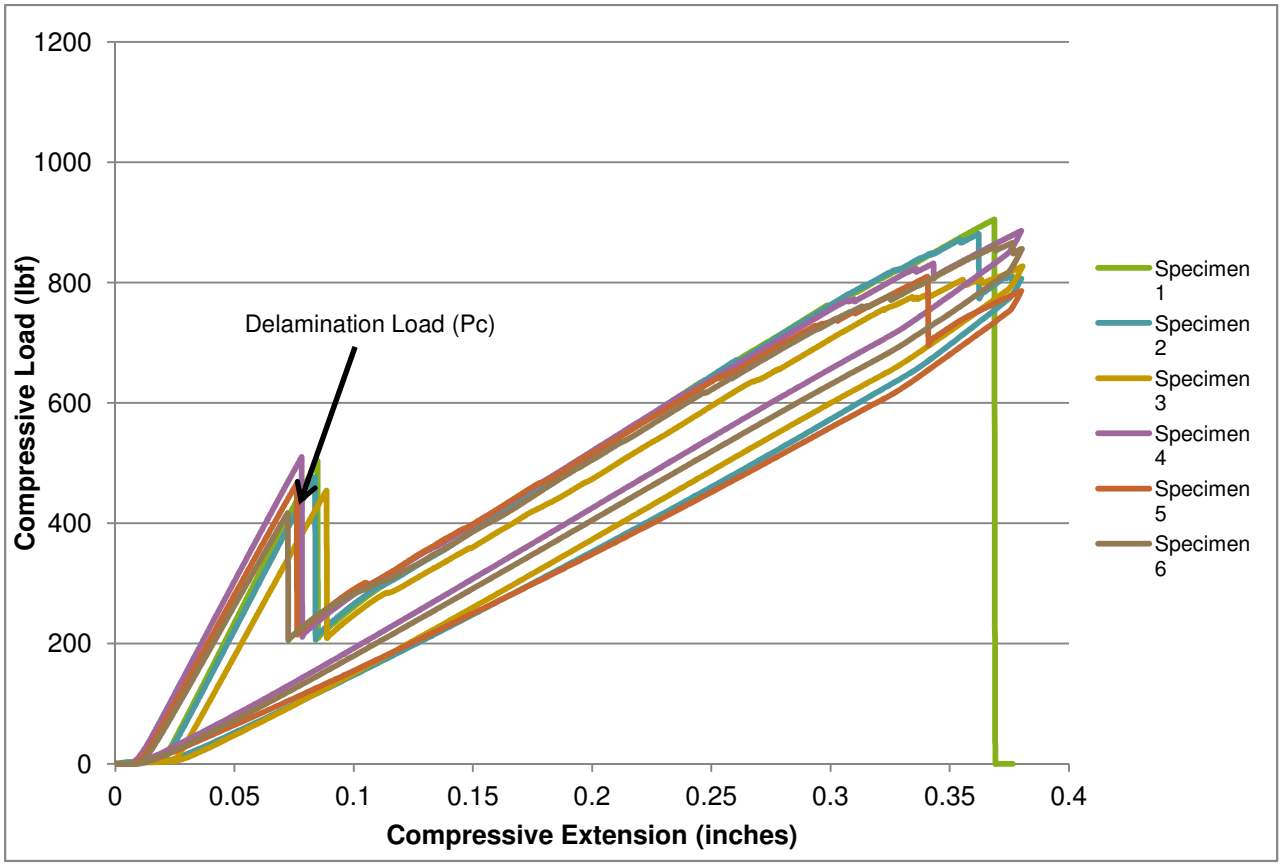

Figure 3.5: Thermoset Compressive Load vs. Compressive Extension Plot.

The key traits of each specimen that were noted before crack propagation was recorded were the width, thickness and initial crack length. Also required for the compliance calibration was the initial delamination load for each specimen. The initial delamination was found to occur between 25 and 35 mm passed the initial crack's length and this seemed to happen randomly. This delamination load was found in the .raw data by matching it up with the time of initial delamination. The average width of specimens was found to be on average 25.32 mm and 25.45, and thickness was found to be on average 5.618 mm and 4.83 mm for the thermoset and thermoplastic laminates, respectively. In calculating the G_{IIC} values, the equation was utilized in a similar fashion to the DCB test where m is the slope of the compliance, Pc is the delamination load, a is the initial crack length, and b is the width (eq. 4).

$$G_{IIc}= \frac{3mPc^2a^2}{2b} \quad (4)$$

The forces and extensions were taken from each noted time of the crack's distance traveled, typically being from 25 to 45 mm for each specimen. From there a slope was developed by plotting the compliance value (C) against a, the distance that crack had traveled. From there the G_{IIC} value was determined for each sample. (Table V and VI)

Table V: ENF G_{IIC} Thermoplastic Data and Averages

Specimen ID	m	Pc (N)	GIIc (J/m^2)
1	6.04E-09	2364	1243.41
2	6.86E-09	2327	1368.36
3	9.49E-09	2188	1673.57
4	-	-	-
5	-	-	-
Averages:	7.46E-09	2293	1428

Table VI: ENF G_{IIC} Thermoset Data and Averages

Specimen ID	m	Pc (N)	GIIc (J/m^2)
1	2.05E-09	2268	388.44
2	3.1E-09	2067	487.89
3	4.16E-09	1853	526.17
4	2.1E-09	2268	399.96
5	2.98E-09	2068.2	471.81
Averages:	2.878E-09	2104.84	454.9

4. Discussion

4.1. Crack Propagation Analysis

In comparing the crack propagation of both tests, the DCB test gave a more uniform delamination rate and was much easier to track compared to that of the ENF test. This being noted, going back and viewing the ENF videos was difficult to follow the crack to adjust the compliance calibration in a better way after that initial test. The slope of the compliance was also found to be slightly less consistent in the ENF test specimens than that of the DCB test specimens. In regard to the DCB test, viewing the crack propagation video again was simple to modify the compliance calibration if the operator was unsure with the time recordings taken the first time around. This showed that the use of the USB microscope in this test was significantly beneficial for watching tests run again to witness the crack propagating.

4.2. DCB Sample Set

Looking at the data shown by the DCB test, there was a significant difference between the G_{IC} values of the thermoplastic material and the thermoset material. The thermoplastic material having an average value of 1318 J/m^2 is more than 9 times greater than that of the thermoset material having an average value of 145 J/m^2. This is evident in the force required to induce crack propagation; being 149.9 N and 54.83 N on average for the thermoplastic and thermoset materials, respectively. It is also evident in the extension required from the crosshead to begin delamination, being 11.37 mm and 3.980 mm on average for the thermoplastic and thermoset materials, respectively. The differences in these values are great showing that the thermoplastic matrix material requires more energy to be dissipated for crack propagation to occur and continue, therefore being the tougher material.

4.3. ENF Sample Set

The ENF sample set showed a similar trend as the DCB test, however was not as severe in the results. Looking at the initial delamination load of both materials, the thermoplastic material required a greater force to cause this, being 2293 N and 2105 N for thermoplastic and thermoset, respectively. However, since the crack certainly propagated at a slower rate in the thermoplastic material, the slope of the compliance was greater causing the G_{IIC} values to also be higher, being 1428 J/m^2 on average over the thermoset's 454.9 J/m^2 average. This shows that the two materials followed a similar trend, even in another type of cracking mode. The thermoplastic matrix material was found to be difficult to view crack propagation, even amongst so many samples making the compliance calibration difficult to produce. Comparing this data with that of the G_{IC} values, the values agree well with the statement that G_{IIC} values should

always be higher than G_{IC} values and that tougher material should have values more close together than that of brittle materials. That being said, the thermoplastic matrix material is clearly the tougher material.

4.4. Excel Template Redesign

While in the process of calculating the G_C values for both tests, the Excel templates donated were determined to be disorganized and difficult to use. The newly designed templates followed a format of using fewer tabs than the version before and to be organized in the order of inputs, graphs/calculations, and summary. The ENF template was organized to have only three tabs in this format accounting for a total of five specimens, while the DCB template was organized to have four tabs with graphs/calculations split into separate tabs. (Figure 4.1) Once these templates were made, the data was entered into them to ensure that the connections between tabs were set up correctly and that it gave similar results as the original template.

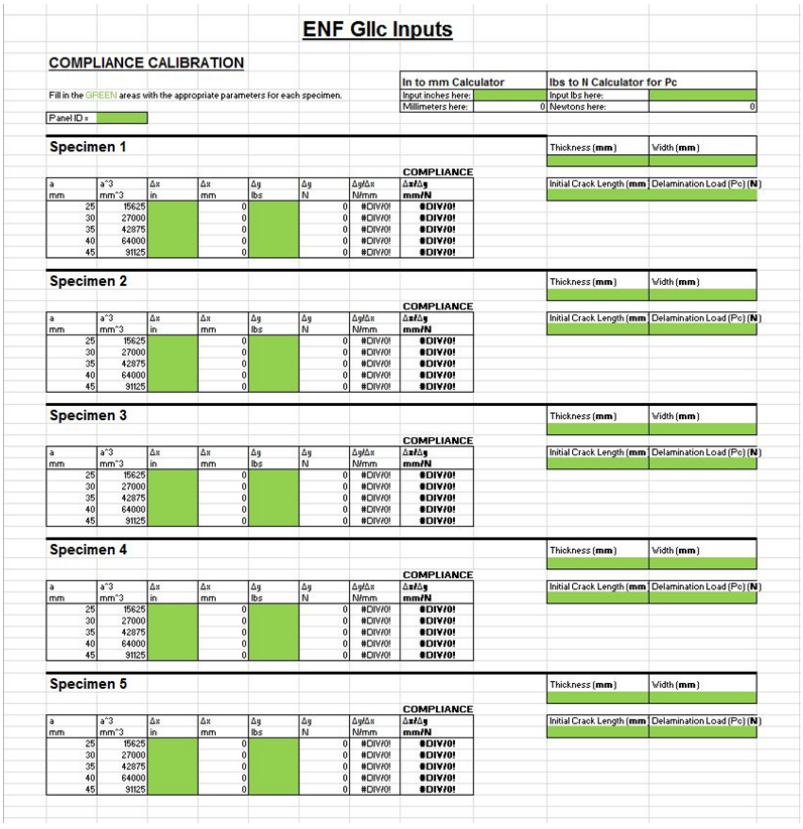

Figure 4.1: ENF Template Inputs tab showing five specimens. The DCB Template was made to look in a similar fashion to this.

5. Conclusions

1. G_c values show that the thermoplastic matrix required more energy dissipated for continued crack propagation (G_{IC} requiring 1318 J/m^2 and G_{IIC} requiring 1428 J/m^2) compared to the thermoset matrix (G_{IC} requiring 145 J/m^2 and G_{IIC} requiring 455 J/m^2). This agreed with the original idea and statement that the thermoplastic material is indeed tougher than the thermoset material due to its increased resistance to crack propagation.
2. The USB microscope was useful for recording crack propagation footage for playback. This made it capable for one operator to operate the test and monitor what the camera was doing without paying constant attention to the crack propagation during that one instance of viewing the crack during the test.
3. A reformed spreadsheet was developed to simplify the calculation process of the G_c values. This new template has been found to work just as well as the old one and is modifiable to include more samples if desired.

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