DETERMINING MODE I FRACTURE TOUGHNESS OF ADHESIVE COMPOSITE JOINTS: AUTONOMOUS CRACK TRACKING USING MATLAB DEVELOPED PROGRAM

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ABSTRACT

Characterizing the fracture toughness of composite material joints is essential to informing design safety factors. ASTM D5528 defines how to calculate the Mode I fracture toughness of an adhesive using a double cantilever beam peel test. The standard specifies visual markers on the sample be inspected during the experiment to measure the crack length, which is needed to calculate the fracture toughness. While this method allows one to determine the fracture toughness, the process is extremely time consuming, tedious, and prone to human error when marking the sample and again when visually inspecting the crack growth relative to those markers. A MATLAB toolbox was written to automatically analyze crack propagation from digital images, create compliance plots, and export the fracture toughness using the modified beam theory method, the compliance calibration method, and the modified compliance calibration method. Rather than using 18 points of data as defined in the traditional method, the program computes the fracture toughness using hundreds of points, reducing noise and error. Different test types are compared i.e. ductile adhesive, brittle adhesive, crack jumping, inhomogeneous surface, etc.; and the results calculated using the ASTM standard method are compared to those exported by the MATLAB program.

Keywords: DCB, Fracture Toughness, MATLAB, ASTM D5528, Crack Propagation, Image Analysis
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1. INTRODUCTION

Adhesive bonds are commonly used to join fiber reinforced polymer composites for the wind and aerospace industries. Understanding of the failure mechanics of adhesive joints enables the design of safe, reliable composite structures. Fracture mechanics are typically characterized using three failure modes: 1) mode I, which describes peeling, 2) mode II, which describes shearing, and 3) mode III, which describes tearing [5]. The most common cause of failure of adhesively bonded fiber reinforced composites is delamination, which is predominantly a mode I failure [1]. This type of failure is governed by the interlaminar fracture toughness of the joint, which is used in delamination failure models including the cohesive zone model (CZM) [1]–[3] and virtual crack closure technique (VCCT) [4]. Without accurate fracture toughness values, models cannot accurately be used to design and predict the failure of adhesively bonded composite structures.

A double cantilever beam (DCB) test is often used to determine the interlaminar (mode I) fracture toughness of adhesive joints as it is relatively easy to fabricate and test such specimens [6], [7]. The fracture toughness of a material is a measure of the critical energy release rate of a propagating crack through the material. A DCB test can be used to determine the fracture toughness of a material as a function of load, displacement, crack length, and specimen dimensions as established through various theories [8]–[14]. The ASTM standard to determine fracture toughness of composite materials (ASTM D5528) [6] suggests the use of three methods; the modified beam theory (MBT) [15], compliance calibration method (CC) [16], and the modified compliance calibration method (MCC) [17] to calculate the mode I fracture toughness.

While the current ASTM method provides a means to determine the mode I fracture toughness of adhesive joints, advances in digital image acquisition and processing that have been made in recent years can improve the use of the standard, especially in terms of improving the certainty of the measurements and simplifying the sample preparation. Specifically, as the test requires measurement of crack length during the delamination failure, the ASTM standard indicates that markings should be made on the sample in 1mm increments, and then visual inspection should be used to note the load and displacement each time the crack advances 1 mm. The accuracy of this visual inspection technique is limited by the accuracy of the marker placement on the sample and the use of only 19 data points. Furthermore, if the crack suddenly advances past more than 1 marker at a time, the data is skewed, and the fracture toughness value will be incorrectly reported. ASTM suggests using a microscope to measure the crack length as it passes the markings and record the force and displacement at that crack length. This process takes 30 minutes to an hour for each side of the sample, thus not only is the testing tedious, but also time consuming.

In this paper, toward addressing these limitations, we present the development of a digital image processing code to automatically measure the crack length and export the fracture toughness values of a DCB test using hundreds-to-thousands of data points in the form of digital images that are continuously acquired during the test. We also provide discussion of the suggested sample preparation method and camera setup. To verify and benchmark the code, multiple cases of crack propagation are demonstrated and a comparison of the code to traditional visual inspection-based calculations is given.

2. MATLAB CODE METHODOLOGY/EXPERIMENT SETUP

2.1 Program Methodology

The purpose of the software is to improve the process used to calculate mode I interlaminar fracture toughness from DCB tests. The program imports the test load and displacement data from a Microsoft Excel file, analyzes a series of images, and locates the edge of the crack in each image. Once the crack length has been determined throughout the test, the program then generates the required compliance plots and calculates the fracture toughness using the modified beam theory as described in ASTM D5528. The fracture toughness is calculated using the three methods found in the standard (MBT, CC, and MCC). The fracture toughness and flexural modulus are exported to the Excel file where the force and displacement data are obtained.

2.1.2 Required Inputs

An Excel file with the axial force and axial displacement as shown in Figure 1 must be placed in the same folder as the images. The force data should start in A4 and the displacement data should start in B4. It is imperative that the data rate be synced for the force, displacement, and images to ensure accurate results (the number of images should match the number of force/displacement data points). Image recording should stop once the crack is at its maximum length.

	A	B
1		
2	Axial Force	Axial Displacement
3	N	mm
4	0.147354126	0.040035695
5	0.372039795	0.083059072
6	0.757476807	0.127678737
7	1.158096313	0.169729814
8	0.908874512	0.211285427
9	1.434158325	0.251406804
10	1.522949219	0.294798985
11	1.560073853	0.338345766
12	2.049987793	0.380361453

Figure 1 - Excel data example

The other required inputs of the program are: initial crack length in mm, specimen width in mm, specimen thickness in mm, binary threshold of the test (recommend 70-95), and whether an export of the crack length video is desired. These inputs are shown in Figure 2.

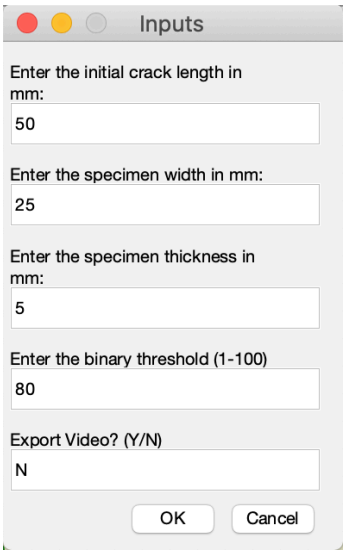


Figure 2 - Program input requirements

The images for one side of the sample should be in order in a single folder along with the data Excel file.

2.1.3 Image Examples

The images should be as clear as possible and the sides of the samples should contain no bubbles or unintended markings. A single black line should be placed on the sample to indicate where the start of the crack is (the end of the Teflon insert). The camera should be setup so that the full sample is shown within the frame, without the hinges in the picture. If desired, a small black marking can be made on the edge of the sample to indicate where to stop the test. An example of a good image frame setup is shown below in Figure 3. It should be noted that for the program to function correctly, the sample must be white with a black background and greyscale images should be used.

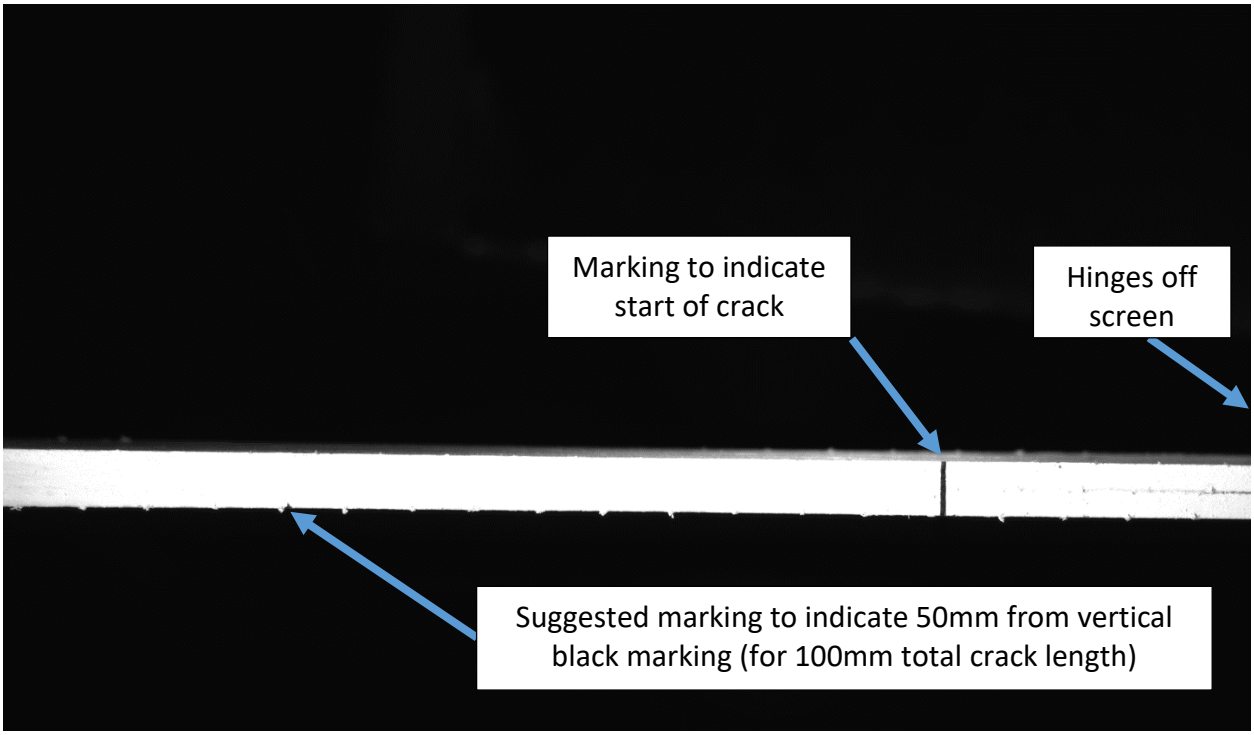


Figure 3 - Sample frame example

As for any testing requiring image acquisition, proper camera setup and lighting is essential to produce good results. For the image above, a FLIR Grasshopper3 camera was used (1920x1200 resolution, 12 megapixels) with a lens length of 45mm. Cameras are placed 0.9m on both side of the sample so crack propagation is obtained from both sides. A schematic of this setup is shown in Figure 4.

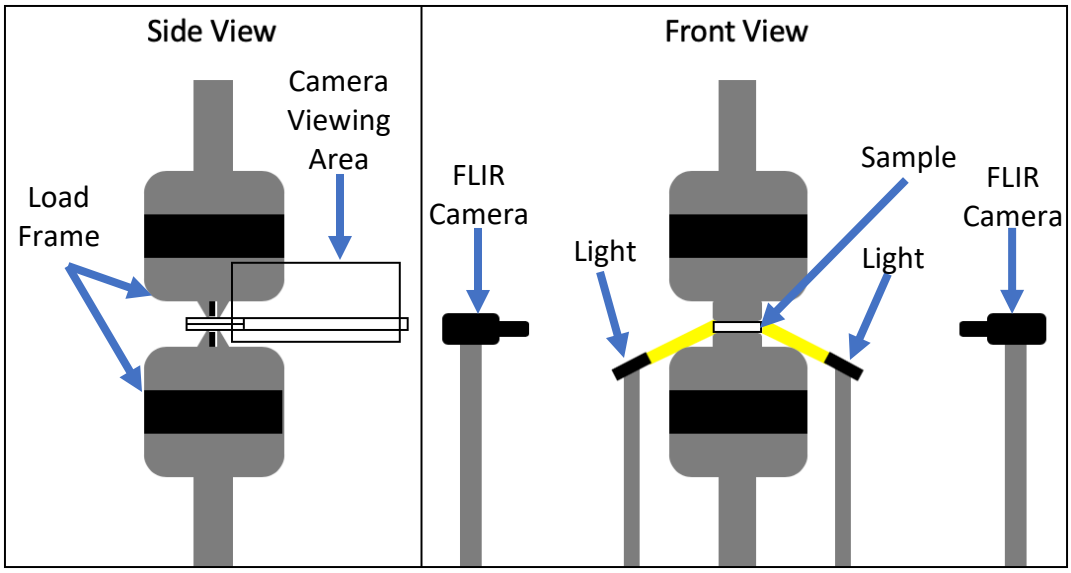


Figure 4 - Example camera setup for optimal imaging of sample

It is possible for the sample to be angled when loaded into the grips if the hinges are not applied perfectly. As the sample is loaded, the tilt is quickly corrected due to the forces acting on the specimen, however this tilt will cause the program to fail. For this reason, a rotation feature was

added into the code to correct for any possible tilt occurring after gripping. After finding the edges of the sample, the program uses a least squares line of both sides of the sample to determine the angle and correct for the tilt. Additionally, the program crops each image to the testing area to reduce computational time. To accomplish this, the start of the crack is located in the first image (from the initial black line) and the final edge of the crack is located in the final image. These two points are then used to crop the image to the required testing area.

Once the images are rotated and cropped, the program locates the crack tip in each image. To do this, the top and bottom edges of the sample are first located, then the program searches column by column along the length of the sample for 'dark' pixels. The shade of pixel that determines the crack tip is set using the binary threshold; one of the required user inputs. Once the crack tip is located within each image, the program can use the load, displacement, and crack length to determine the fracture toughness.

As discussed in the introduction, the ASTM standard indicates three methods to calculate the fracture toughness (MBT, CC, MCC). Each method requires a slightly different compliance plot to obtain the equivalent crack length, which takes into account the rotation that occurs at the crack front. For each method, a compliance plot is created, and a LS line is used to determine the equivalent crack length required for accurate calculation of fracture toughness. Once this value is obtained for each of the methods, the program calculates the fracture toughness using the equations given in ASTM D5528.

2.2 Testing Cases

This next section will explore three separate cases that one may encounter when running a DCB test. The first will focus on a perfect sample, one which is parallel to the ground when loaded into the machine and crack propagation occurs evenly without jumping. The second case will focus on a sample that is tilted when loaded into the machine, and the correction and results. The final case will focus on a sample where the crack jumps more than 2mm, which would typically be cause to remove the sample from the batch.

2.2.1 'Perfect' sample

Figure 5 shows the initial image for a 'perfect' test. The sample has no noticeable rotation, the testing area is well lit, and there is good contrast between the sample and the background.

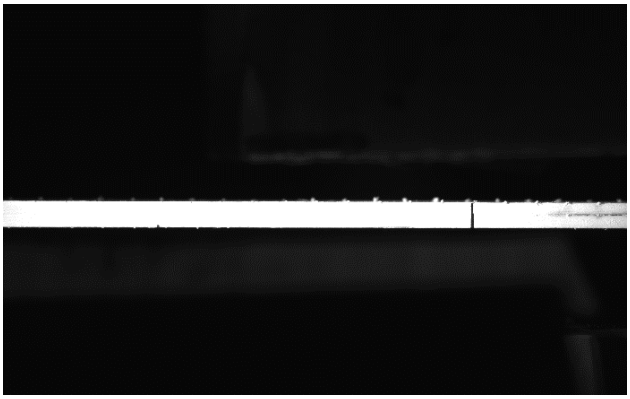


Figure 5 - 'Perfect' DCB sample before crack propagation

Figure 6 shows the result after the cropping procedure has taken place. The first and last images in the sequence are shown as examples. The sample is automatically flipped along the vertical, as analysis occurs from right to left. The cropped images show that only the full testing area of the sample remains after the operation, cutting down the computational time to analyze the crack length. The original images had a resolution of 1200 x 1920 pixels, while the final images a resolution of 645 x 1045 pixels; the required area to analyze is reduced by about 70 %. Additionally, the noise in the background of the initial image was reduced through a contrast operation, leading to more accurate tracking of the crack front.



Figure 6 – First image (a) and last image (b) of test. Cropping box determined by program.

2.2.2 Angled sample

As discussed above, sometimes the sample can be angled when gripped in a load frame if the hinges are not adhered properly. This typically resolves itself within the first 10-15 seconds of testing as the even load on each side of the sample causes it to straighten out. If the sample is angled at the start of the test it still creates an issue for the program, thus a rotation correction was implemented into the code. Figure 7 shows an example of this case where the sample is slightly angled within the image (note that the hinges are off screen to the right of the image).

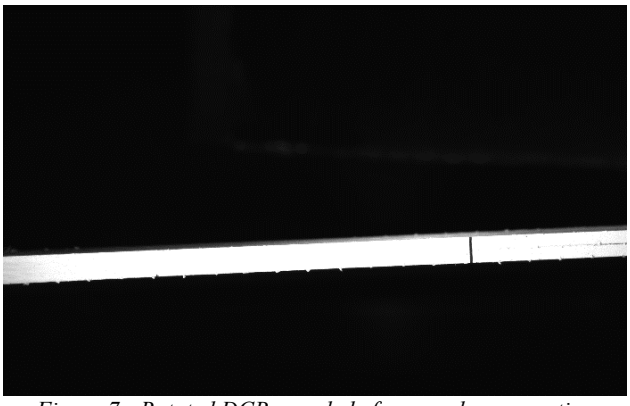


Figure 7 - Rotated DCB sample before crack propagation

Figure 8 shows the results after the rotation and cropping procedure has been completed. Again, the image has been flipped along the vertical to allow for proper analysis. Additionally, there is now no noticeable rotation in either final image. This allows for more accurate analysis of the crack length.

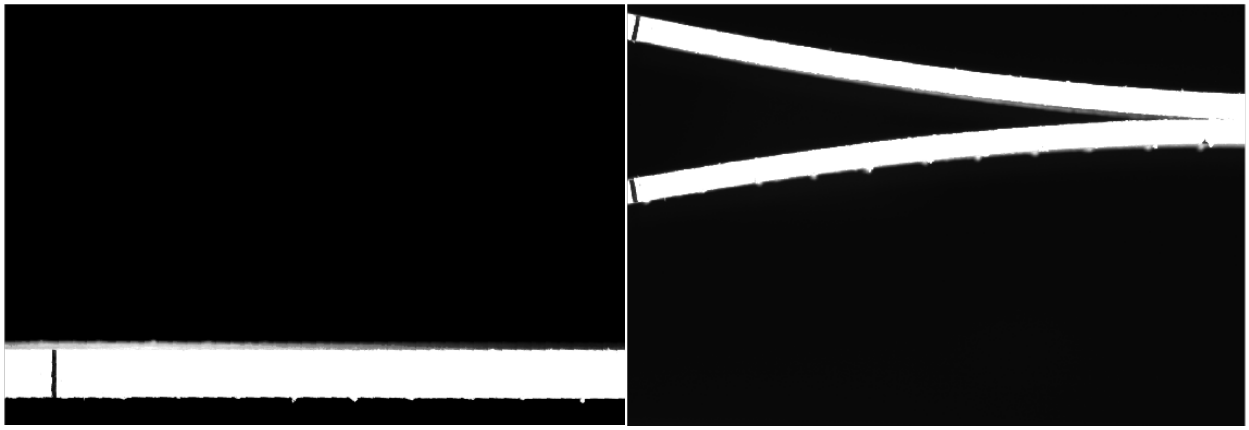


Figure 8 - First image (a) and last image (b) of angled sample test. Cropping box determined by program.

2.2.3 Crack-jump sample

In some cases, a crack will propagate through the sample for a period of time, and then the crack will arrest. Once the required energy is reached to continue crack growth, propagation will continue along the sample. Figure 9 is an example of a test with a crack that jumps 4mm in just over one second, which could be cause to discard the results using the traditional ASTM method.

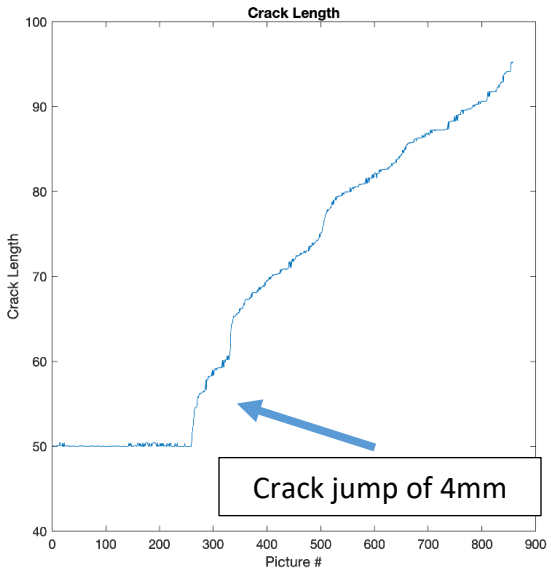


Figure 9 - Crack jump observed during testing

Compliance plots for the test in Figure 9 are shown in Figure 10. The left compliance plot shows a dataset used by the program with over 800 datapoints, whereas the right plot has only 18 datapoints; the number specified by the ASTM D5528 standard. The left plot results in a fracture toughness value of 0.4208 kJ/m^2 and the right plot results in a fracture toughness value of 0.4495 kJ/m^2. Depending on the application, a fracture toughness difference of 6% could make a significant impact on the performance of the system and being able to accurately predict when it will fail.

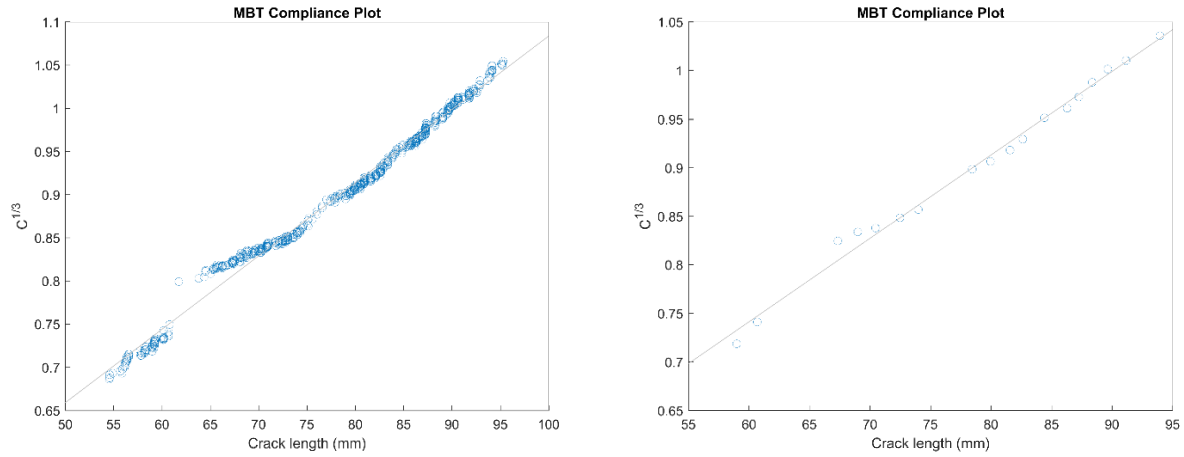


Figure 10 - Compliance plot showing how crack jump can potentially skew data

3. RESULTS

Verification of the code is important to ensure valid data is produced from experiments when using this program. To accomplish this, cracks within images were measured by hand and this data was used to calculate the fracture toughness values. 11 tests were completed and compared to the values output by the program. ImageJ was used to measure 18 data points evenly spaced throughout the tests.

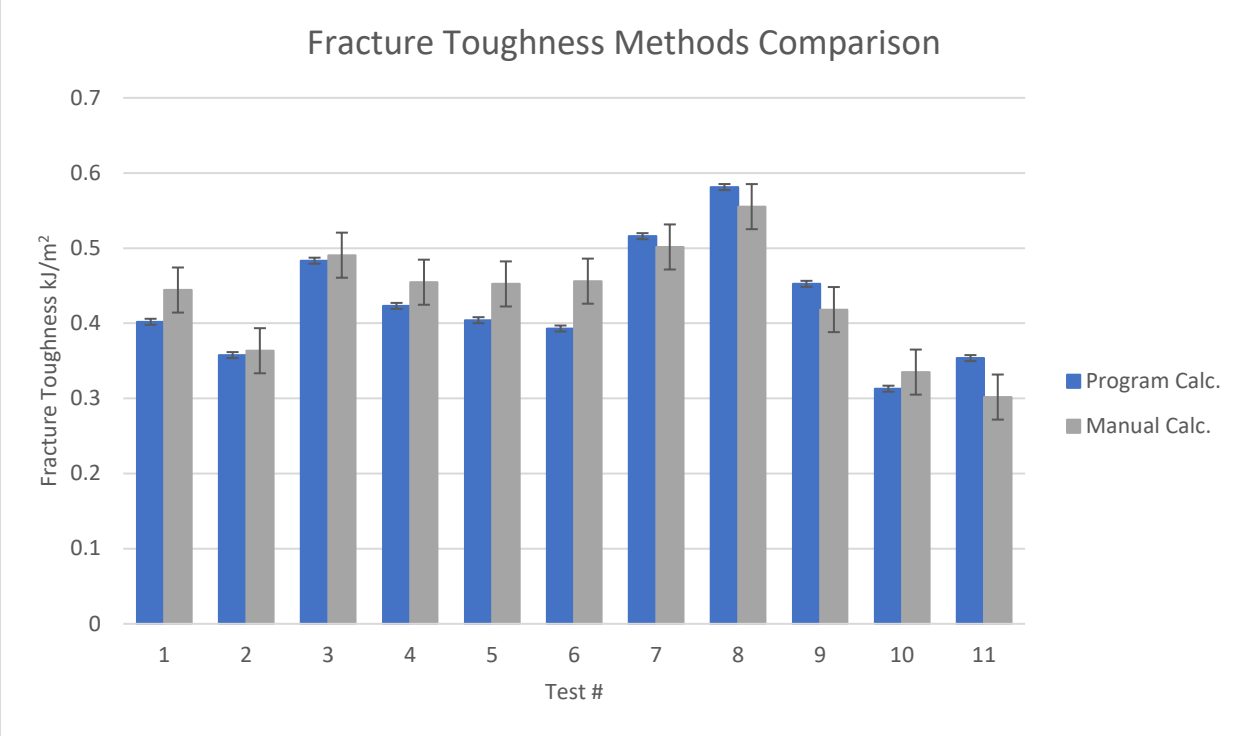


Figure 11 - Comparison of fracture toughness values calculated using the program and by measuring crack length by hand

The error bars on the plot show the 95% confidence interval for the tests. As the program uses close to 1000 datapoints for each calculation, whereas the hand calculation only uses 18, the values calculated by the program are likely more accurate than the ones calculated by hand as any effect

the outliers have on the data are reduced by the number of datapoints. Both the program and manual fracture toughness values are very close in each test, varying by less than 0.05 kJ/m2. This indicates the program is working properly in determining the fracture toughness values through autonomous tracking of the crack tip.

4. CONCLUSIONS

As discussed, the ASTM D5528 method for determining the fracture toughness of an adhesive joint between two fiber reinforced composite pieces using a double cantilever beam (DCB) test can be improved through the autonomous crack tracking program written using MATLAB as it allows for easier analysis of the tests and reduces potential errors from sample fabrication or measurement of crack length during the test. Any error from misplaced markings is eliminated when using the program as only one initial marking is required for the location of the start of the crack. Additionally, the number of data points is dependent on the data sampling rate, so thousands of data points could be used to determine the fracture toughness of an adhesive, rather than only 19 per the ASTM standard, which further eliminates errors and also allows for accurate analysis of samples where the crack jumps.

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