Low Velocity Impact Tower Feasibility, Setup, and Impact Testing of Carbon Fiber Reinforced Epoxy Thermoset and PEEK Thermoplastic Matrix Composites

A Senior Project

presented to

the Faculty of the Materials Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

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June, 2013

Approval Page

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Date Submitted: June 7, 2013

CAL POLY STATE UNIVERSITY

Materials Engineering Department

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Abstract

A low velocity impact tower was donated to Cal Poly's Materials Engineering Department along with four fiber reinforced polymer matrix composites. The tower was set up in building 192 in the Mechanical Testing Laboratory. Improvements were made to the tower including adding velocity detection capabilities, making loose hardware inclusive, adding an extra tower arm for better consistency, adding a double jawed clamp for faster testing, and rerouting the tower's compressed air system to improve performance. A standard operating procedure was drafted, tested, and redrafted for impact testing composite panels. The four composite panels consisted of two quasi-isotropic 16 ply AS-1 carbon fiber reinforced polyetherether ketone (PEEK) matrix thermoplastic panels in a (45/90/-45/0)2s stacking sequence and two quasi-isotropic 16 ply TR50S carbon fiber reinforced TC27501 epoxy resin thermoset panels in a (45/90/-45/0)2s stacking sequence. The thermoset and thermoplastic panels were cut into twelve 152.4mm x101.6mm samples each and underwent impact testing on the tower per ASTM D7136 standards. 6.7 J/mm is the specified ratio of impact energy to specimen thickness for D7136 testing, and when coupled with the (thermoset) samples' average thickness of about 2.47 mm equated to a 314.9 mm impactor drop height and lower. After impact samples were non-destructively inspected and displayed near a 0.8mm dent-depth with an 11.15mm maximum damage diameter. Damage types included a depression, splitting, cracking, fiber breakage, and delamination. The thermosets' damage measurements and types were compared to the thermoplastic samples' damages and found to be less damaged topically but more damaged internally.

Keywords: Materials Engineering, Carbon Fiber, Impact Testing, Delamination, ASTM D7136, Low Velocity Impact Testing, Impact Properties, Advanced Composites, Fiber Reinforced Polymer Matrix Composites, Impact Tower, Carbon Fiber Composites, Thermoset, Thermoplastic, Epoxy, PEEK

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Introduction

Problem Statement

The Materials Engineering department at California Polytechnic State University, San Luis Obispo currently does not have the capability to conduct impact testing on polymer matrix composite materials. There are two main goals of this project. The first is to obtain, assemble, make operable, and improve a low velocity impact tower donated from Tencate Advanced Composites (Morgan Hill, CA). Success means the machine will be able to perform impact tests according to ASTM Specification D7136 and still be operable in years to come. Additional goals to this first goal include developing a Standard Operating Procedure (SOP) for future person's use, improving the interface of the machine, and optimizing the software to provide useful information about tower functions. The second primary goal of this project is to conduct low velocity drop testing on provided fiber reinforced polymer matrix composites. The newly established tower will be used, and the results will be analyzed and recorded.

Background

Composite materials, often shortened to composites, are materials made from two or more constituent materials with significantly different physical or chemical properties. When combined, these materials produce a material with characteristics different from the individual components, while the individual components remain separate and distinct within the finished structure[1]. Some commonly known examples include reinforced concrete, plywood, and cement. Composites can also be a material manufactured from a fiber embedded in a polymeric matrix material (Figure 1).

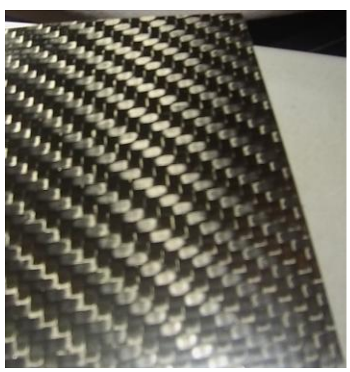

Figure 1. An AS-4 carbon fiber reinforced polyetherether ketone matrix composite.

These materials, when their constituent materials and component geometry work together to optimize performance, are often referred to as "advanced composites."[2] Advanced composites are comprised of thin sheets called *lamina*. These lamina are then adhered to each other to form a thicker *laminate*. Lamina can be orientated a variety of ways within a laminate to bolster and alter the laminate's directional mechanical properties. In this fashion a manufacturer can choose to make an advanced composite extra

strong in one or several specific loading directions by aligning the fibers in those loading directions. The orientation of the laminae within the laminate is referred to as the *stacking sequence*.

Advanced composites have high strength-to-weight ratios that are often used in high-tech industries such as aviation, aerospace, and motor sports. Figure 2 gives a density and mechanical property comparison of some commonly used structural materials along with composite materials for comparison. The relatively high cost of advanced composites compared to other materials is hardly a deterrent to high tech industries that are willing to pay for the best materials to produce high performance components. Other properties that make advanced composites ideal for the aviation industry include environmental and corrosion resistance, improved vibration and damping properties, low and controllable thermal expansion, high fatigue resistance, and the fibers within the composite can be oriented with the direction of principal stresses to increase structural efficiency[2].

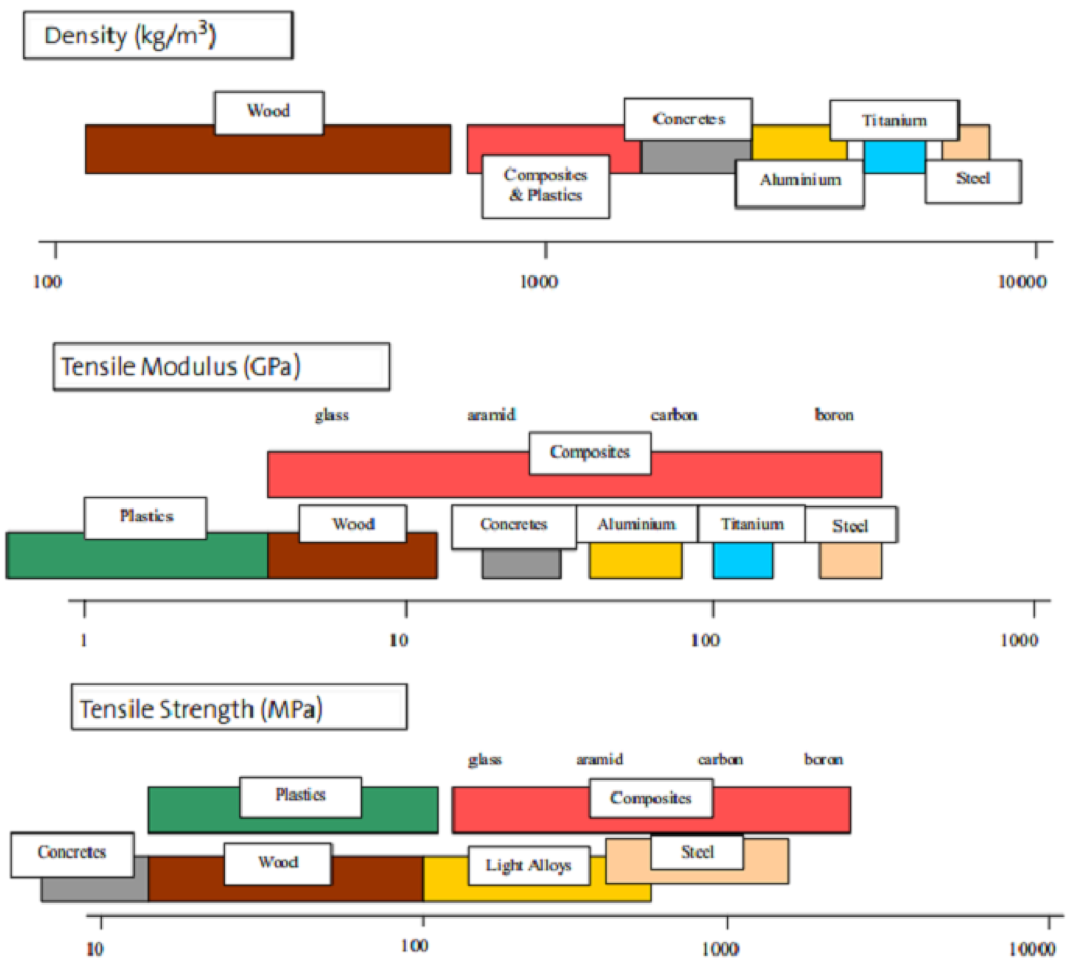

Figure 2. Advanced composite materials are among the lightest and strongest materials that there are, giving them high strength-to-weight ratios among their competitors.[2]

There are two categories of polymer matrices that are typically used with advanced composites: thermoplastics and thermosets. Thermoplastics consist of polymeric chains that are not chemically bonded between each other, but instead are held together by weak secondary bonds or intermolecular forces such as van der Waals forces or hydrogen bonds. Thermosets, on the other hand, have polymeric chains that are crosslinked together through chemical bonds, forming a rigid network structure. Both are used in the aforementioned industries, although thermosets are more commonly used because of their easier manufacturability. Of special importance to this project is the fact that thermoplastics tend to have superior damage tolerance compared to thermosets, including impact damage resistance.

Since advanced composite's advent into industry, it has been discovered that when such materials sustain an out of plane impact, even at low velocity, their compressive strength can be significantly reduced (Figure 3). This significant reduction in compressive strength is associated with the separation of the lamina within the laminate, otherwise known as *delamination,* although other damages are often also present. An oft-thought of example of such a situation that could occur is when a maintenance worker accidentally drops a ~2 kilogram hammer from chest-height onto the advanced composite wing of an aircraft. That panel may now have a dent, broken fibers, a cracked matrix, and most importantly, delamination. The panel will now likely have severely reduced compressive strength, possibly a major problem for the aircraft.

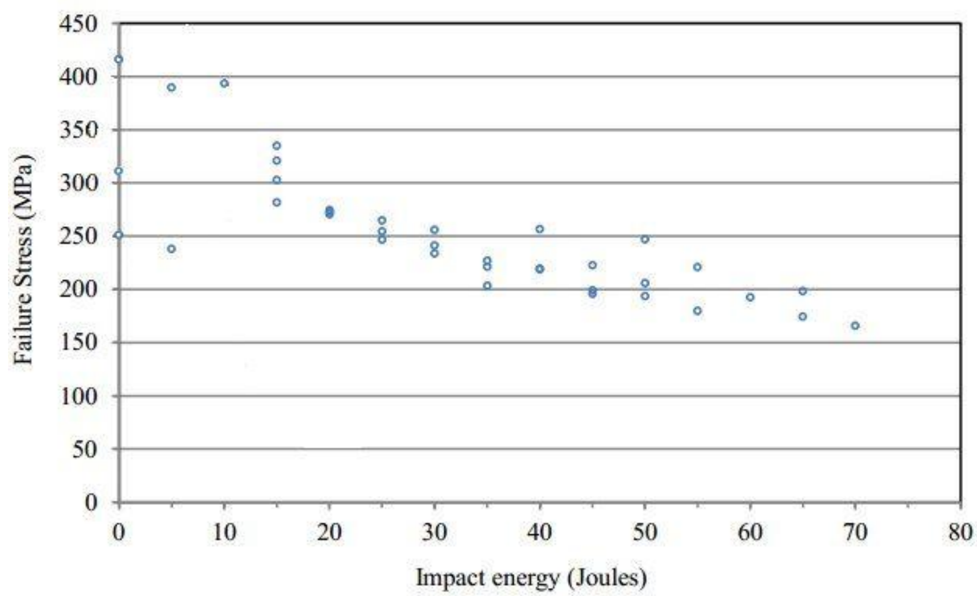

Figure 3. As the impact energy of the out of plane object increases, the compressive properties of the advanced composite are reduced, mainly due to delamination. These results are from 40 ply unidirectional T300 carbon fiber in an epoxy matrix with a fiber volume fraction of 58% and a symmetric stacking sequence of [45º/0º/-45º/90º]5S.[3]

Low Velocity Impact Testing

The early stages of research efforts to characterize impact behavior of advanced composites were inconsistent due to lack of a standardized test for long fiber composites[3]. A recent set of standardized tests (American Society for Testing and Materials (ASTM) D7136 and D7137)[4] to assess the impact tolerance of fiber reinforced polymer matrix composites has remedied the problem and allowed companies to compare and refine their products. ASTM D7136 is the official standard for conducting a low velocity impact test on a fiber reinforced polymer matrix composite, and details the methodology of striking an advanced composite sample with a known energy, and then analyzing the damage. ASTM D7137 is the standard for testing the altered compressive strength of the composite after the D7136 test has been conducted. To run the D7136 test the tester needs several key pieces of machinery and equipment. The foremost piece of equipment needed is a low velocity impact drop tower, such as the one donated for the project shown in Figure 4, with its diagram representation in Figure 5. Other necessary parts include an added impactor weight (Figure 6), a striker tip (Figure 7), a sample clamping mechanism, and assorted hand-held measuring tools[4]. Optional equipment includes velocity detectors and force indicators if the tester desires additional information for analysis purposes. Velocity detectors were included with the donated drop tower.

Figure 4. This is the low velocity impact tower donated to Cal Poly, and the subject of this project. The impactor is lifted to the desired height and then dropped onto the sample. The guides/stabilizers keep the impactor straight and a velocity detector can optionally be attached to provide velocity rates of the impactor immediately before impact.

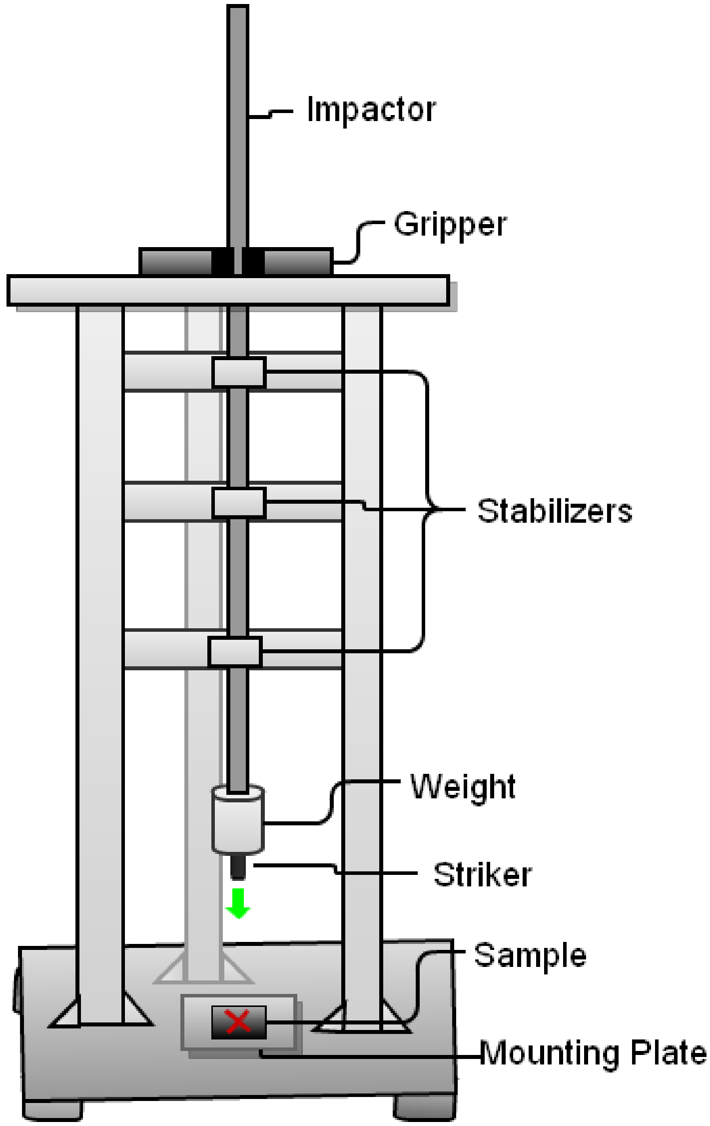

Figure 5. Diagram of a low velocity impact tower and its most important components, including the components in the figure to the left.

Figure 4. Added weight for the impactor. The striker is screwed into one side while the impactor is screwed into the other.

Figure 5. A TUP striker, with a smooth, blunt, semi-hemispherical tip,16 mm in diameter.

Realistic Constraints

Unfortunately manufacturing and economic limitations constrain this project. There is not enough time to manufacture a device that will automatically prevent the impactor from hitting twice on the tower, and there are several other improvements to the tower that simply cannot be made in time. The economic constraint applies to the analysis portion of low velocity impact testing. There is not enough financial support to justify adding either an ultrasonic scanner for B and C-scanning or adding a modal testing machine for modal analysis. At present, the Cal Poly MatE department will outsource these analysis techniques to a third party company to have them done on the tested samples. Although the new impact tower will be able to create delamination, Cal Poly also does not have the equipment and tooling necessary to conduct a D7137 Compression After Impact (CAI) test to test for a decrease in compressive properties. This would be perhaps the most important form of analysis after an impact test. Not having all the equipment limits the MatE department's ability to effectively and completely analyze composite samples on its own after the samples undergo an impact test. This leaves the tester with only the options of using Non Destructive Analysis and outsourcing analysis techniques to other Cal Poly departments or third parties. After following D7136 standards to run the test properly on the tower, the composite will have likely received a dent such as the one pictured in Figure 8. Other possible outcomes from running the impact test include no damage to the composite, barely visible impact damage (BVID), where the damage may be internal, or full punctures, where the striker goes all the way through the composite. BVID may be analyzed using ultrasonic B-Scanning and C-Scanning (Figure 9)[3] to detect delamination and other internal damage(s)[4].

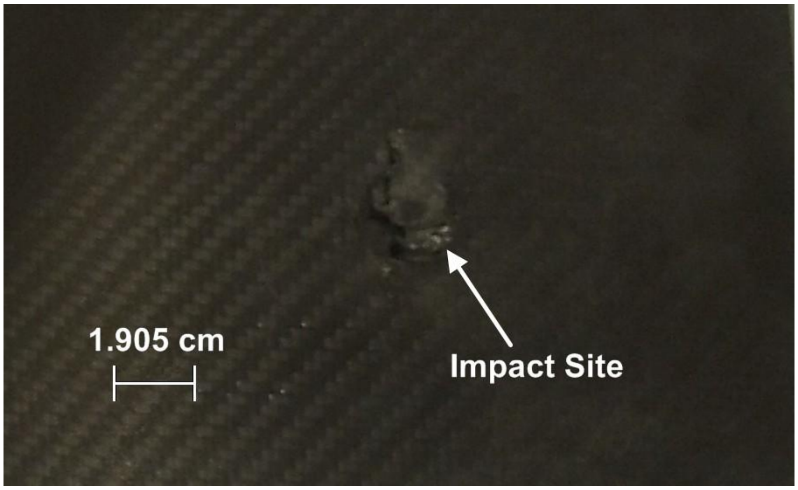

Figure 6. This carbon fiber advanced composite has undergone a low velocity impact test, sustaining visible damage as a result. The damage incurred from the test can now undergo Non-Destructive Analysis (NDA) using calipers, micrometers, depth gauges, modal scanning, and ultrasonic scanning.

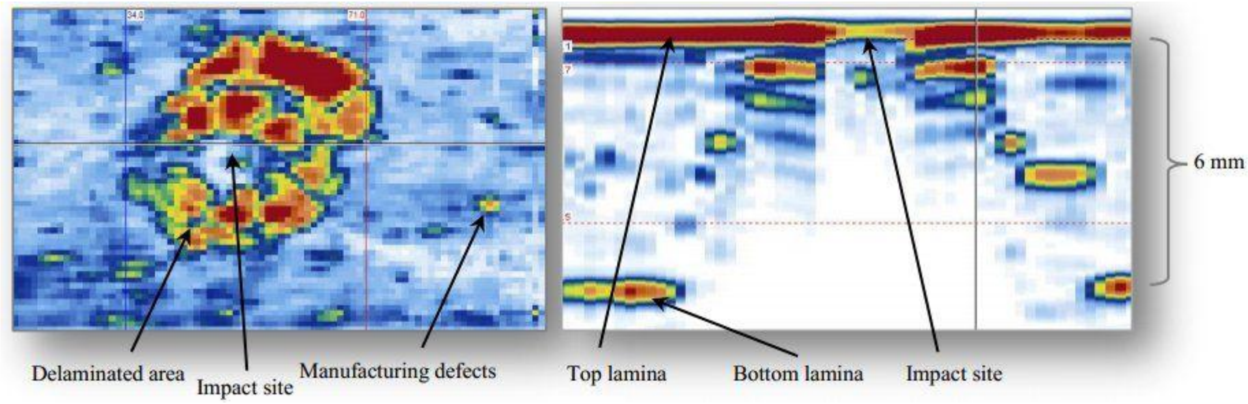

Figure 7 Ultrasonic C-scan (left) and B-scan (right) taken after a 40 Joule impact test. C-scans are taken from the top and B-scans are taken from the cross-section. The B-scan additionally reveals cone-shaped damage propagation from the impact site.[3]

As stated in the Problem Statement, the Materials Engineering department at Cal Poly at the start of this project did not have the capability to conduct ASTM D7136 impact testing on fiber reinforced polymer matrix composite materials. By the end of this project the department will both have this capability and will have utilized it.

Low Velocity Impact Testing Capability Setup

For the first quarter into the project, the impact tower was not actually present at Cal Poly, but located at Tencate, in Morgan Hill, California. In early December the tower was moved on campus to Building 192 Room 211 (the Mechanical Testing Laboratory) where it would be permanently stationed. Bubble level gauges were used to make sure the tower was level on the floor, a necessary requirement for the system to work properly.

Air Pressure Setup

To operate the impact tower air pressure is required. The Zaytran GPL-40 gripper on the top of the tower uses the air pressure to grab onto the impactor and prevent it from falling onto the sample unintentionally, and as such, obtaining air pressure for the tower became a top priority when the tower arrived. Originally the facilities department at Cal Poly was contacted to obtain an estimate of the costs associated with routing an air line into the room, but after finding the costs to be too steep and the time frame to be too long, it was decided that compressed nitrogen gas would be used to operate the gripper. For compressed nitrogen gas tanks to be installed within the room, tank holders were bought to hold the tanks against a table nearby the tower. The tank holders prevent the tanks from falling over and thereby possibly rupturing in the event of an earthquake. A regulator was installed along with the tank to control the output air pressure. After connecting the tank to the tower, it was found that the gripper needs at least 50 psi to properly grab the impactor without slipping.

Velocity Detection and Software Setup

The second section of setting up the tower was establishing the velocity detectors and their associated software. The velocity detectors are Vernier Photogates, and they use a LabPro to interface with the computer (Figure 10). The software that runs the LabPro and the velocity detectors is LoggerPro.

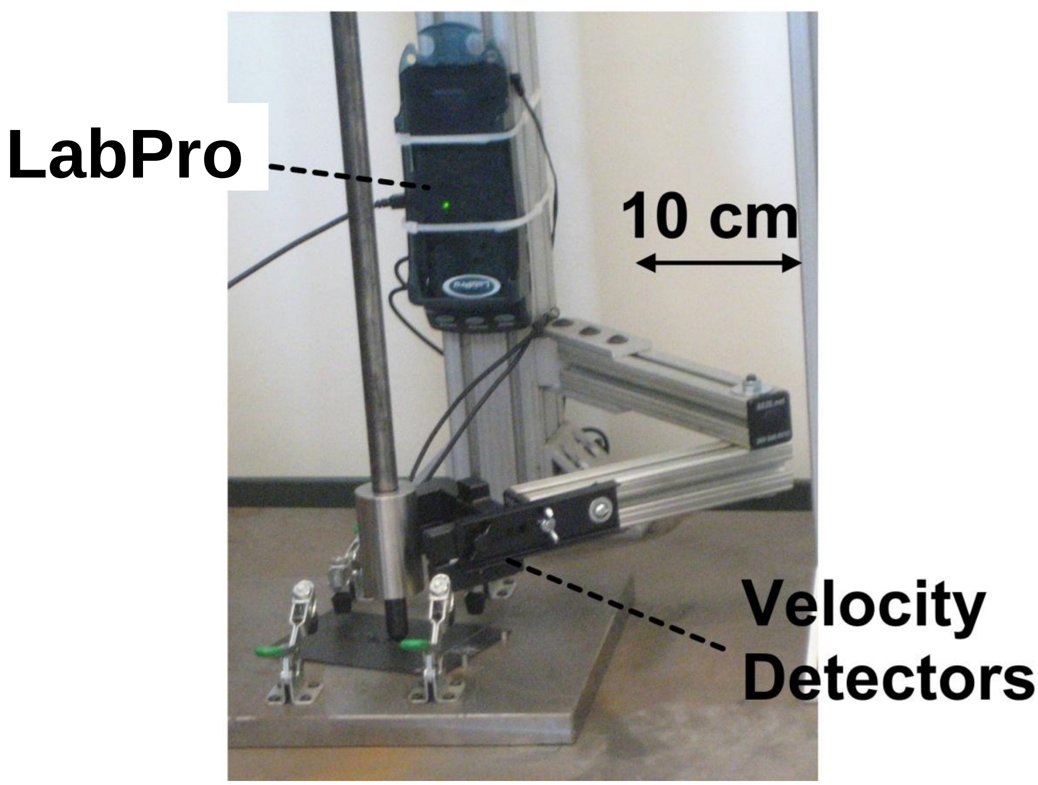

Figure 8. The impact tower and its Vernier photogate velocity detectors plugged into the LabPro.

Photogates contain an emitter and a detector. The emitter projects a laser and the detector receives it. When the laser is blocked by an obstruction the velocity detector cannot "see" the laser and registers "blocked" to the software. When there is no obstruction and the light is allowed to pass into the detector the velocity detector registers "unblocked" to the software. To calculate velocity, two photogates a known distance apart must be connected to the software, and then an equation can be used to find the velocity of objects passing through both photogates. Mounting tape was used to adhere the two velocity detectors together, with the distance between them equal to 2.5 centimeters. By knowing that (distance)=(velocity)(time), and rearranging that equation to (velocity)=(distance)/(time), the only missing variable to find velocity was time.

After extensive trial and error, it was found that the LoggerPro software contained a command that could retrieve the time between the first photogate being blocked to the second photogate being blocked. The command is BlockedtoBlocked("Time", "GateState 2", "GateState 1"). This brings the equation to find velocity within the software to

velocity= 0.025m/BlockedtoBlocked("Time", "GateState 2", "GateState 1") (1)

The velocity detectors were calibrated by dropping objects from a known height through them and checking the measured values against the calculated values. To compensate for the distance between the bottom photogate and the sample, and to additionally compensate for the fact that the velocity detectors were technically calculating the velocity when the impactor was halfway through them, it was found that adding 0.1 m/s to the above equation gave the most accurate readout of velocity. This brought the final equation to:

velocity= 0.025m/BlockedtoBlocked("Time", "GateState 2", "GateState 1")+0.1m/s (2)

Later a new and improved program was developed that could not only calculate velocity, but also impact energy, impact energy per sample thickness, and recommended drop height for the ASTM D7136 standard 6.7 J/mm test.

System Improvements

When the tower first arrived at Cal Poly it was "bare-bones" and in need of improvements. Original interface improvements included taking off superfluous hardware, adding the additional photogate so velocity could be detected, and replacing duct tape in favor of longer lasting bolts and fasteners. Another improvement included adding an additional arm to hold the velocity detectors as close as possible to the sample, while still keeping them in the same place throughout multiple tests. This additional arm uses a wing-nut and bolt combination to allow the arm move out of the way while switching between samples. A hose clamp, idea courtesy of Ross Gregoriev, was added to the impactor rod in order to "save" the position of the impactor for multiple tests conducted from the same height.

It is vital to tower functioning that the gripper on top of the tower close as quickly as possible from the time the switch is flipped to its closure. Quick closing allows the gripper to grab onto the impactor before it bounces off of the sample and hits the sample a second time. Bounces can take less than a quarter of a second during testing, so the gripper must operate as quickly as possible. Streamlining the air setup that operates the gripper would help performance, so alterations were made to the tower to minimize the complexity of the air system. One such modification was disengaging and circumventing the pressure gauge and pressure dial on the tower control panel, which was acceptable because they were redundant with the pressure dial and pressure gauge on the regulator attached to the nitrogen tank. The air hose was also rerouted to circumvent an extension hose. Both improvements helped the gripper close faster and thereby likely decreased 2nd hits during testing.

Some final changes made to the tower included repositioning the air hose to make it more visible to users, affixing a bubble level gauge to the base of the tower in case the tower ever moves, and bundling all of the various hoses, wires, and hardware behind the tower to keep everything in same place and pre-plugged-in. Currently only two wires and the air hose need to be connected by a new user to fully operate the tower.

Standard Operating Procedure

Because the impact tower is a new addition to the MatE department, nobody else knows how to properly operate the tower and software. With this in mind, a Standard Operating Procedure (SOP) was drafted to help new users with the tower. Contents within the SOP include sections on safety, software setup, air pressure setup, sample setup, running a test, troubleshooting, and an additional notes section. Version 1 of the SOP was tested on Joe Vanherweg and Colin Glaves. After feedback, version 2 of the SOP was drafted and then tested on most of the Materials Engineering 3rd year students. Alterations were made and version 3 of the SOP was drafted and is currently the one being used with the tower. Plastic sleeves and a plastic cover were bought for the SOP to increase its longevity. The SOP is hung on a bolt in a clearly-visible position on tower. The full SOP (besides cover page) is in Appendix 1 at the end of this report, in its unedited form.

Experimental Procedure

Damage resistance of composites during ASTM D7136 low velocity impact testing is highly dependent on the geometry of the samples, the technical specifications of the equipment, and even on the clamping support conditions of the samples. Panels significantly larger than the test specimen tend to divert a greater amount of impact energy into elastic deformation, and faulty equipment can give poor results. The tower's specifications, as well as the sample's specifications, were checked against the ASTM standards prior to testing.

Tower Specifications

Following ASTM D7136 required the tower to meet certain specifications, almost all of which were met in the course of this project. The impactor/striker/weight combination must weigh 5.5 kilograms ± 0.25 kilograms. The tower's impactor/striker/weight combination is 5.26 kilograms, within regulation. The striker must have a smooth, blunt, semi-hemispherical tip, HRC 60 to 62, and diameter or 16 mm. Such a tip historically creates more damage in advanced composites when compared to sharper tips. The tower's striker meets the smooth, blunt, semi-hemispherical tip requirement and is 16 mm in diameter, meeting the diameter requirement. Due to time constraints the HRC of the striker could not be measured, and was assumed to be 60 to 62 HRC.

ASTM recommends two double-pronged flags each with a photo-diode emitter and detector to detect velocity. These are the same as the Vernier photogates used on the tower. ASTM *requires* that the detectors be 3 to 6 mm above specimen surface. The velocity detectors on the tower measure velocity a little above 8 mm from the sample surface, slightly above the maximum 6 mm. This fact is compensated for in the 0.1 m/s added to the equation used to detecting velocity in the software.

There is a diagram on the ASTM D7136 standard that outlines the clamping mechanism used to hold samples in place during testing. The tower's mounting unit matches the diagram (Figure 11) and has been positioned so that the striker will hit the sample directly in the center of the sample.

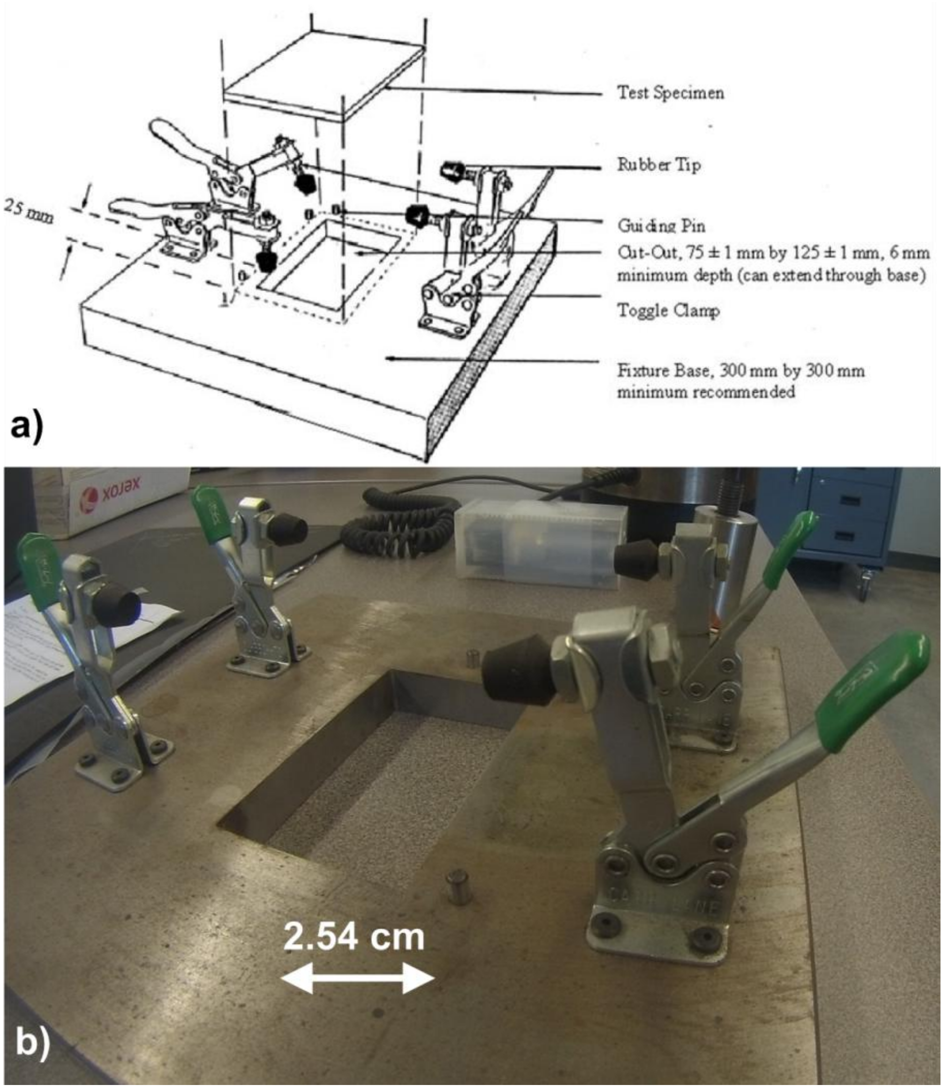

Figure 9.(a)ASTM D7136 specification diagram of the clamping mechanism. (b)The actual clamping mechanism used with the impact tower.

Samples

The samples included quasi-isotropic 16 ply AS-1 carbon fiber reinforced polyetherether ketone (PEEK) matrix thermoplastic in a (45/90/-45/0)2s stacking sequence as well as quasi-isotropic 16 ply TR50S carbon fiber reinforced TC27501 epoxy resin thermoset in a (45/90/-45/0)2s stacking sequence. A thermoset and a thermoplastic. Two panels of each type were received from Tencate. Using a tile saw, the panels were cut into a total of 24 samples, 12 thermoplastic and 12 thermoset samples. To comply with ASTM D7136 standards and so that they would fit on the mounting plate, the samples were 100 x 150 mm (4 x 6 inches) each. For the testing, the samples were wiped of dust and surface particulates before testing. No visible flaws were located in any of the numbered samples, except for some samples that had to be cut a shorter length than the rest. Those shorter samples received letter designations instead of the usual number designations. The lengths and widths were measured with calipers, and the thicknesses were measured by taking micrometer readings of 4 thicknesses around the impact sight and averaging them together. Table I lists the generalized dimensions of the samples.

Table I. *Dimensions of the Thermoset and Thermoplastic Samples*

Thermosets	Average Length (mm)	Average Width (mm)	Average Thickness (mm)
1 to 12	148.98	101.93	2.47
Thermoplastics			
1 to 8	149.01	102.05	2.19
A	146.05	101.37	2.28
B	142.24	102.03	2.27
C	143.97	101.51	2.11
D	145.52	101.04	2.05

Running the Tests

For step by step directions on *how* to run a test using the project's impact tower, refer to the SOP located in Appendix 1. Prior to running tests, and as per ASTM D7136 procedure, it was noted that the moisture level in the air was "*unknown".* Many tests were run near the ASTM D7136 standard of 6.7 J/mm to obtain more robust conclusions within that impact range, simply because that is the typical ASTM and industry standard. Other samples were tested at lower impact energies to attempt to quantify at what impact energies per thickness specific damage types began to appear. Damage types include dent/depression, cracking/splitting, fiber failure, and delamination. Dent depths were recorded immediately after impact because dents in advanced composites have been known to "relax", becoming shallower, over time.

Results and Analysis

Because much of this project was dedicated to the tower's operation, the precision of the velocity detectors was calculated using the standard deviation of the tower's velocity readings, all conducted at the same height (Table II). The velocity detectors were found to be well within precision tolerances.

Table II. *Precision Measurements and Statistics of the Velocity Detectors*

Sample	Chosen Impact Energy (J/mm)	Measured Impact Energy (J/mm)	Measured Velocity (m/s)
1	6.7	6.215	2.416
2	6.7	6.496	2.465
3	6.7	6.635	2.481
7	6.7	6.581	2.481
Drop Height=	About 12.5 inches		Standard Deviation of Measured Velocity=**0.03077**

After a test has been conducted, there are several analysis techniques that can be applied to the sample to qualitatively and quantitatively measure damage. One technique used was measuring the shape and size of the dent by finding the eight points on the dent shown in Figure 12, along with finding the dent depth with a depth gauge. Dent depth is measured from the deepest part of the dent to the surface plane. The other technique used is to identify the specific damage types on the sample.

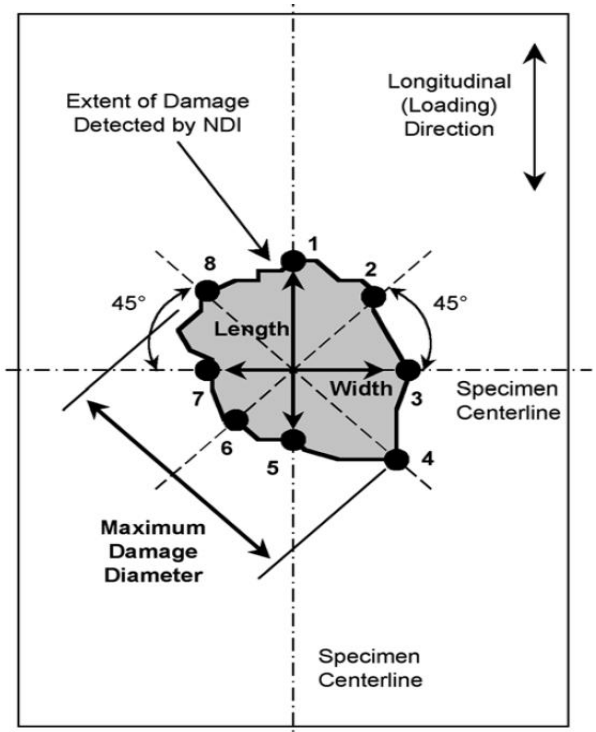

Figure 10. There are eight points that need to be noted when measuring dent size, plus the maximum diameter.

Quantitative

To compare samples in a quantitative fashion, several equations must be utilized. The equations can be found in the ASTM D7136 standard. To use these equations the experimenter must keep in mind that there are both predicted values and measured values, distinct from each other. For example, although an experimenter may intend to impact a sample with exactly 6.70 J/mm, the impact tower is not electronically controlled, so it may strike with a value closer to 6.61 J/mm.

Generally, for the first tests an experimenter will run, he or she will have a specific impact energy per sample thickness, C_e (J/mm), that he or she would like to try first. To do this, the impactor drop height, *H* (mm), needs to be calculated. *H* can be calculated for a specific C_e if the impactor/striker/weight mass, as well as the sample thickness, *h* (mm), is known. The variables C_e and *h* are used to predict the impact energy, *E* (J), that the sample will be hit with. The equation $E=hC_e$ predicts *E*, and by knowing the impactor mass, *m* (kg), the impactor height *H* can be calculated with H=E/(mg). The variable g is the acceleration of gravity. The simplification of these two equations yields the equation

$$H=hC_e/(mg) \quad (3)$$

Now the experimenter has predicted the impactor drop height *H* to use for a test to obtain the desired C_e. For the tower used in this project, the impactor had a mass of 5.26 kg. Many of the samples were tested at C_e=6.7 J/mm impact energy per sample thickness, which led to the equation:

$$H=h(6.7J/mm)/[(5.26\ kg)(9.81\ m/s^2)] \quad (4)$$

This equation was converted to predict impactor height *H* in inches because the tape-measurer used during testing was standard, but not metric, which led to the equation

H (inches) = (5.111946907)h(mm) (5)

Because the thermoset samples all had about the same thickness and all the thermoplastic samples had about the same thickness, H=~12.63 inches for the thermoset samples and H=~11.20 inches for the thermoplastic samples at 6.7J/mm. All samples were tested at or below 6.7 J/mm.

Because the recently calculated impactor drop height *H* can only *attempt* to hit the sample with the desired energy, the *actual measured* impact energy needs to be calculated after a test is run. The only data that the tower can collect is velocity, *v* (m/s), but with a measured velocity measured C_e and *E* values can be calculated. The equation to find impact energy *E* from velocity *v* and impactor mass *m*:

$E= mv^2/2$ (6)

Which, because we already know the value of m=5.26 kg simplifies to $(2.63kg)v^2=E$. This equation is altered to calculate C_e by first substituting E for hC_e to get $(2.63kg)v^2=hC_e$ and therefore $C_e=(2.63kg)v^2/h$. Because we know the sample thickness *h* and now have a measured velocity *v* we now know the energy that the samples was struck with per sample thickness, which now allows for comparison across samples with different thicknesses. During the course of this project it was recognized that the bulk of these values could be calculated directly in the software's readout, so the above equations were compiled to obtain the following readouts in the software (Table III).

Table III. *Equations Utilized by the Software to Obtain Values*

Sample Thickness (mm)- h	Impactor Drop height (inches) @ 6.7 J/mm- H	Velocity (m/s) –v	Impact Energy (J)- E	Impact Energy per thickness- (J/mm) - Ce
User entered data	5.1119(h)	0.025/BlockedtoBlocked(“Time”, “GateState 2”, “GateState 1”)+0.1	$2.63v^2$	E/h

Table IV shows the complete readout of all of the acquired qualitative information obtained for each test and sample, including the maximum dent diameter and dent depth of each sample. A graphical summation of the dent damage of the samples is presented in Figure 13.

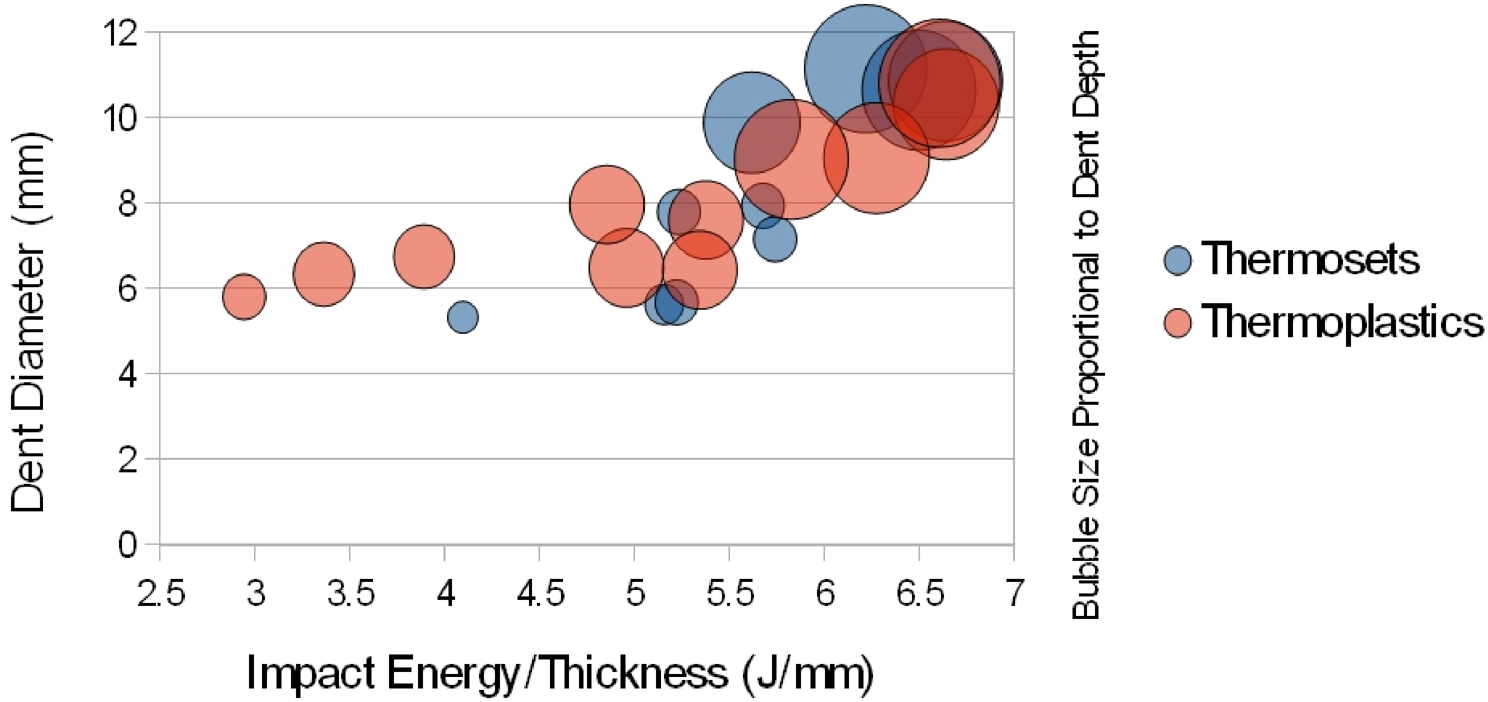

Figure 11.The colored circles represent all of the valid tests conducted during the experiment. Upon observation there appears to be no statistically significant difference between the thermoset and thermoplastic samples in terms of dent size per impact energy per thickness.

Table IV. *Numerical Data Obtained During Testing*

Thermoset	Drop Height-H (mm)	Measured Impact Energy- E (J)	Measured Impact Energy per Thickness- C_e (J/mm)	Measured Velocity- v (m/s)	Maximum Dent Diameter (mm)	Dent depth (mm)
1	314.9	15.35	6.22	2.42	11.15	0.8
2	319.9	15.98	6.50	2.47	10.65	0.7
3	319.9	16.19	6.64	2.48	10.86	0.7
4	254.0	12.87	5.23	2.21	7.8	0.1
5	254.0	12.73	5.15	2.2	5.63	0.08
6	254.0	12.89	5.22	2.21	5.68	0.1
8	279.4	13.93	5.62	2.3	9.89	0.5
9	279.4	14.07	5.67	2.31	7.94	0.1
11	279.4	14.06	5.74	2.31	7.16	0.1
12	203.2	10.15	4.09	1.96	5.33	0.05
Thermoplastic						
2	294.1	15.05	6.64	2.39	10.32	0.6
3	279.4	14.34	6.27	2.34	9.06	0.6
4	266.7	13.68	6.61	2.28	10.81	0.8
5	241.3	12.32	5.82	2.16	9.03	0.7
6	228.6	11.76	5.37	2.11	7.61	0.3
7	228.6	11.27	4.96	2.07	6.49	0.3
8	203.2	10.31	4.85	1.98	7.97	0.3
A	177.8	8.87	3.89	1.84	6.75	0.2
B	152,4	7.63	3.36	1.71	6.34	0.2
C	127.0	6.16	2.94	1.53	5.81	0.1
D	215.9	10.92	5.34	2.04	6.44	0.3

Qualitative

As mentioned above, the other methodology used to analyze tested samples was to visually inspect them for specific damage types. Damage types include dent/depression, cracking/ splitting, fiber failure, and delamination, which are all shown in both sample types in Figure 14. Because delamination is the most important damage type, an enlarged image is shown of it is shown in Figure 15. The *thermoset* samples 1, 2, 3 and 8 displayed delamination, dent/depression, cracking/splitting, and fiber failure. Samples 4, 5, 6, 9, and 11 displayed delamination, dent/depression, and cracking/splitting, but not fiber failure. Sample 12 only displayed dent/depression and cracking/splitting. *Thermoplastic* samples 2, 3, 4, 5, 6, 7, 8, B, and D displayed delamination, dent/depression, cracking/splitting, and fiber failure were present. Sample A displayed dent/depression and cracking/splitting. Sample C displayed only a dent/depression.

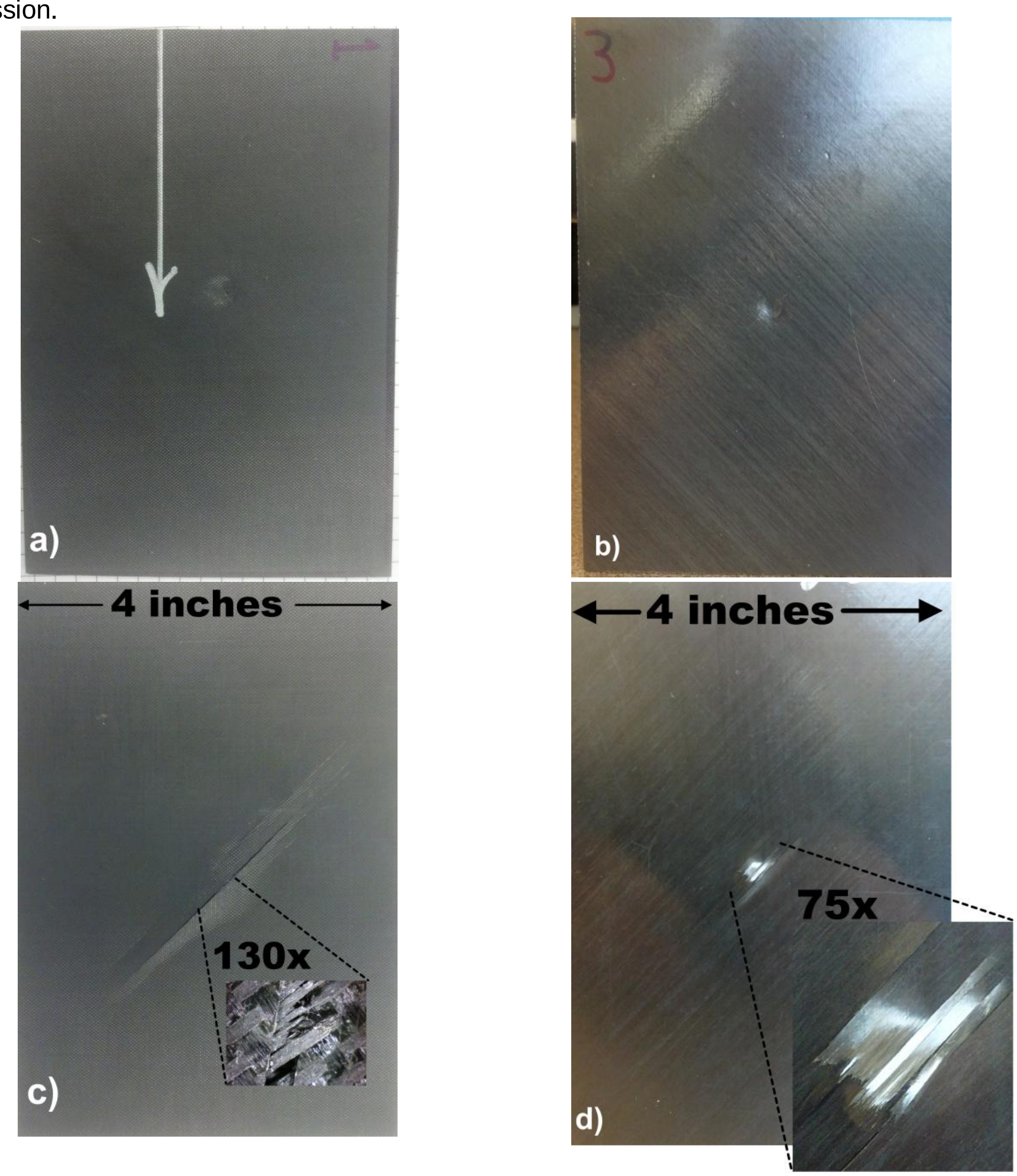

Figure 12. (a) Damage on front of thermoset sample. (b)Damage on front of thermoplastic sample. (c) Damage on back of thermoset sample. (d) Damage on back of thermoplastic sample. Zoomed in views are provided to more easily see the fiber breakage and the cracking that occurred.

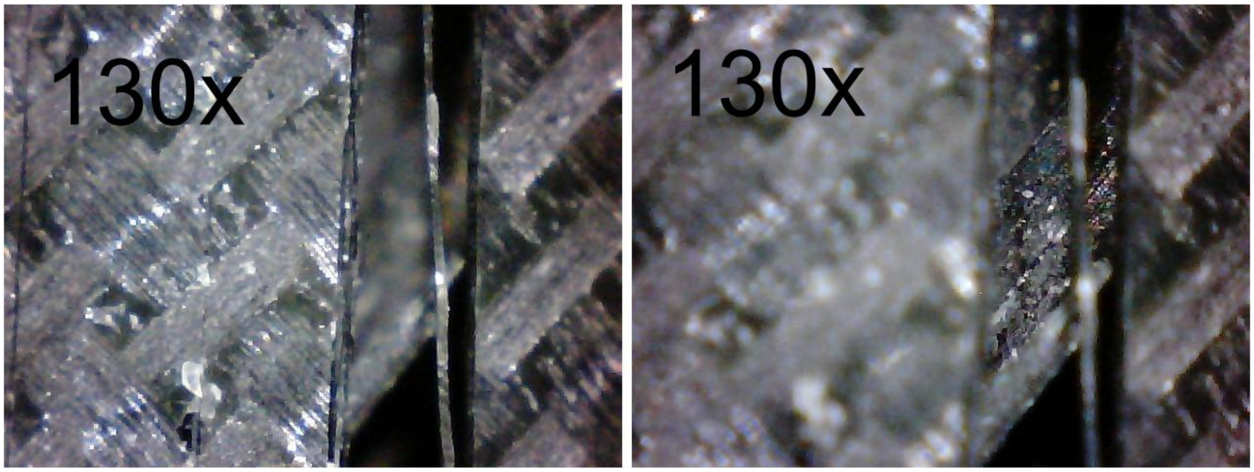

Figure 13. The left image is a zoomed view of the crack on the back a thermoset sample, focused on the surface. The right side image is of the exact same area, but with the focus on the ply below the surface. This is to clearly show that delamination occurred within the sample.

Ultrasonic Scanning

Appendix 2 contains several ultrasonic C-scans of the samples, obtained from Tencate during analysis. The scans of the thermosets show far more extensive delamination than the scans of the thermoplastics (hit with similar energies). Damaged area for the thermosets, measured from the dotted lines surrounding the damage, was found to be up to around 11 times greater than the thermoplastics. These results are in line with the convention that thermoplastics have better impact resistance than thermosets. They also draw attention to the fact that BVID (barely visible impact damage) is extremely difficult to detect from the surface, but can be extensive internally within an advanced composite.

Discussion

When comparing the dent sizes per impact energy over thickness, it was found that, despite common convention, thermosets seem to have a better impact resistance than thermoplastics. Delamination is still the damage type that is the most responsible reduction in compressive strength though, and that is where the usefulness of C-scanning comes into play. Appendix 2 shows a much different scene than what the dent measurements alone could reveal. The delamination *could not be seen* from the surface, but it is highly visible from the scans.

Conclusions

The first goal of this project was to set up the capability to run low velocity impact testing on fiber-reinforced polymer matrix composites. With the impact tower operational, the new standard operating procedure in plain sight, and the new functional software up and running, this first goal was successfully

met. However, complete success of this first goal will be determined by how far into the future or through how many uses the tower remains operational, and to a lesser degree its components. No quantitative measure was established to determine how far into the future or how many uses signify complete success, but the tower was set up with not only operation and ease of interface in mind, but also with duration. Backups of the SOP were created and stored digitally on the computer, moving parts have been minimized, most cords and hoses have been permanently plugged in and tucked away from disturbance, no part of the tower besides the base will be hit by the impactor, and the troubleshooting section of the SOP covers a myriad of foreseen possible problems.

The second goal of the project was to test, analyze, and compare carbon fiber reinforced thermoplastic and thermoset samples. When analyzing surface damages and impact energies, tentative impact energy starting points for each damage type were extracted. For thermosets, 5.31 J/mm impact energy and greater caused denting, cracking, fiber failure, and delamination, 5.15 J/mm and greater caused denting, cracking, and probable delamination, and 4.09 J/mm and greater caused denting and cracking. For the thermoplastics, 3.36 J/mm impact energy and greater caused denting, cracking, fiber failure, and delamination, and 2.94 J/mm and greater caused denting. Scans revealed that all samples, especially the thermosets, were actually delaminated to a much greater extent than the surface inspection indicated.

Acknowledgments

I would like to thank the people that made this project possible. My advisor, Professor Blair London, helped me to stay organized and complete assignments in a timely manner, while still managing to call his contacts left and right to help me advance. My sponsor at Tencate Advanced Composites, Barry Meyers, was an invaluable resource for information when I needed it, and gave purpose and direction for the project. Additionally, I would like to thank Ross Gregoriev for his insightful recommendations and help, and Joe Vanherweg and Colin Glaves for helping me test my SOP. Thank you all for making my senior project a worthwhile success!

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Appendix 1

Standard Operating Procedure

Table of Contents

I. Safety

- Wear safety glasses, closed toed shoes, and long pants when operating the tower

- If inexperienced using nitrogen tanks and regulators, contact lab professor for assistance
- Try to minimize the amount of time body parts are under the impactor during testing
- Make sure no cords or wiring will ever be in the way of an impactor during testing
- Note that changes to velocity detector orientation may void velocity measurements made by the software

II. Software Setup

- Turn on computer (you may need to move it next to the tower) and open the program called "LoggerPro"
- Plug LabPro power cord into an electrical outlet (a sound cue indicates power)
- ***<u>After</u>*** LoggerPro has already been opened, plug in USB cable from LabPro into the USB port on the ***<u>back</u>*** of the computer (a green light indicates the connection)

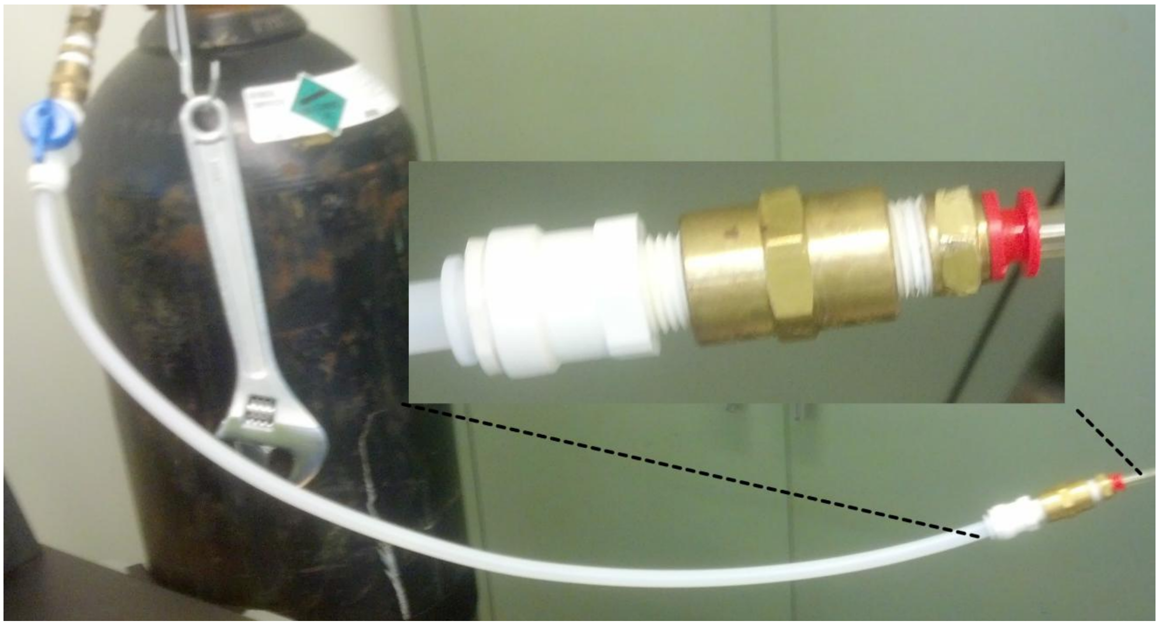
- On LoggerPro, click File/Open
    - My Computer/C/Program Files/Vernier Software/ Logger Pro 3/ Experiments/Low Velocity Impact Testing/ Velocity Detection.cmbl

- Make sure the program is reading "blocked" and "unblocked" states of the velocity detectors *under the top toolbar*. It should **not** say "device not found." If it does say "device not found" then close the program, unplug the detector, reopen the program, and plug the velocity detector into the **<u>back</u>** USB port, in **that order**.
- If the file is not found or cords are messed up, see troubleshooting

III. Air Pressure Setup

If inexperienced using nitrogen tanks and regulators contact lab professor for assistance

1. Connect tower air hose to nitrogen tank air hose



2. Turn PVC valve attached to regulator so that it is parallel with hose

3. Turn main nitrogen tank valve counterclockwise (about a quarter of a turn) to turn on gas

4. Using the regulator knob, adjust the outer regulator pressure gauge to 50 psi. Turn clockwise to increases outer pressure, and counterclockwise to decreases outer pressure.

(a) Flip the tower's switch on and off (with the impactor resting at the bottom) to make sure the outer regulator dial always comes to rest at 50 psi.

- Ignore the pressure gauge and pressure dial on the tower, as they have been purposely disconnected.
- Listen for air leaks (especially where the tower’s air hose connects to the tank’s air hose) and tighten connections accordingly

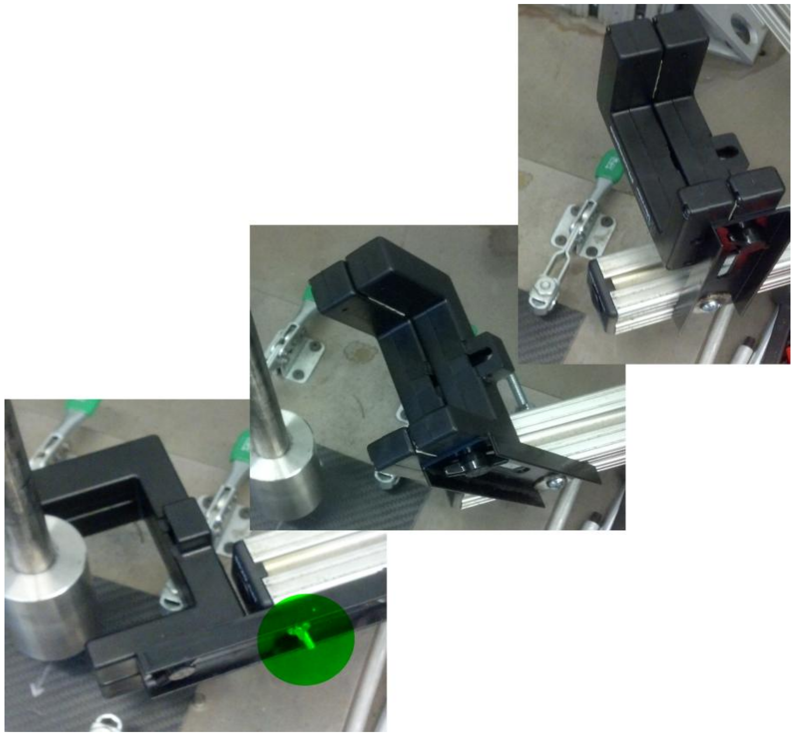
IV. Test Setup

Samples must be 4 inches by 6 inches to fit on the mounting plate, and the impactor must hit the center of the sample/cavity. The impactor is **5.26 kg**. When the sample thickness **h** (mm) is entered into the first column (second row) of the program, the software will tell you the impactor drop height **H** (mm or inches) **if** you are testing at C_e=6.70 J/mm (1500 lb-in/in). If testing at $C_e \neq$ 6.70 J/mm (1500 lb-in/in) then impactor drop height **H** will be different than the readouts.

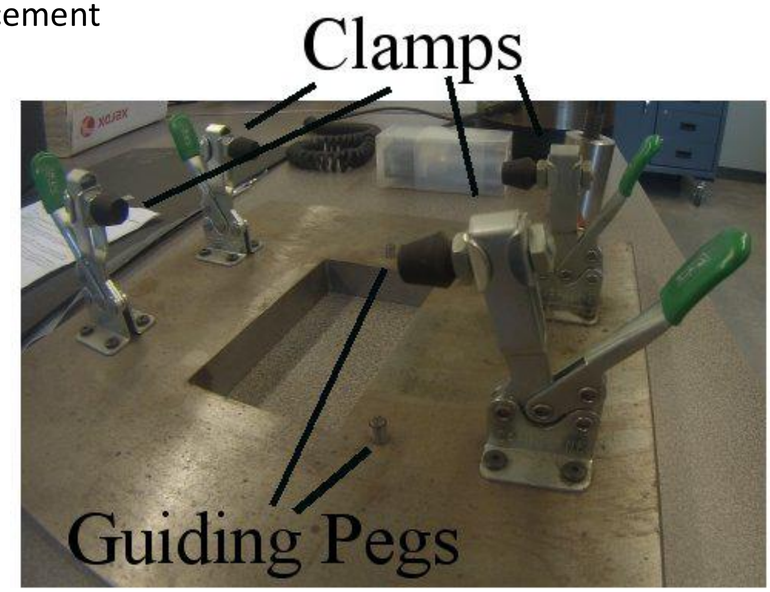
1. With switch starting in the down position, move impactor to desired height (*from sample surface to the tip of the striker)* and then flip switch up to lock impactor in place

   (a) At this point you may consider attaching the double-jawed clamp to the impactor cylinder in order to "remember" your position. This is useful for multiple tests at the same height

2. To place/replace the sample, you **might** need to move the velocity detector out of the way. To do this unscrew the wingnut and remove the bolt



3. Clamp sample down using clamps on the mounting plate, using the guiding pegs for placement



4. Put the velocity detector back down (**if** moved out of the way) and put the bolt and wingnut back in place.

V. Running a Test

Read whole section before running a test.

1. Hit Play on the Logger Pro software.
2. Before flipping the switch down to release the impactor, know that **you will need to quickly flip the switch back up right before the first impact to prevent a second impact that would *void* your results.**
   (a) Flip the Switch down to release the impactor, remembering to flip the switch back up to prevent the second hit

3. Hit Stop on the LoggerPro Software

- The software is set up to measure *but not log* data, so it must be written down
- Relevant data will show up on the **second row** each time, replacing the data from previous tests. Sample thickness **h** (and subsequently the two **H**'s) will not be replaced, as they are user-entered data and likely need to be changed between tests.
- Readings on lower rows are typically the irrelevant results of second hits
- To run additional tests, firmly grasp the impactor, flip the switch down, lower the impactor to its resting position and then follow *IV. Sample Setup* onward
- If the impactor striker tip hits the metal base of the tower during testing discontinue testing and see troubleshooting

VI. Troubleshooting

- This SOP is extremely worn out or only available digitally
  - Contact the lab's professor (Dr. Blair London), he may have a backup
  - Look on the desktop of the computer for a backup
  - Print and bind the new SOP for future users
- LoggerPro is not installed onto the computer
  - Contact the lab's professor for assistance, there should be the installation cd near the tower. Administrative rights may be needed
- The nitrogen tank is out of gas
  - Contact professor of lab to replace it, or do it yourself if able
- The gripper mechanism on top of the tower is not sufficiently gripping the impactor
  - Check the air hose connection(s) for leaks, and consider tightening the connection(s) further with a wrench
  - The tank may be empty
  - Consider moving the pressure up to 55 psi
- The pressure gauge and dial on the tower are not working
  - This is by design in order to have a quick reaction time for the gripper.
    - Look at the regulator pressure gauge for pressure information
- The impactor goes through the sample and hits the steel base
  - This is **bad**, discontinue testing as this may damage the impactor striker tip.
  - Contact lab's professor for assistance on how to proceed so that it **doesn't do that**
- I badly hurt myself using the tower
  - Go to the doctor
- I need to hit my sample harder than the tower can operate at.
  - Tough cookies, use a harder hitting tower (aero lab)
- I cannot seem to time the switch flipping to prevent the second hit
  - Consider flipping the switch quicker and earlier
  - Make sure the air hose connection circumvents the extension hose, and looks like the connection in *III. Air Pressure Setup*
- Velocity Detector is not working
  - Make sure it is connected to the LabPro *in correct fashion* and not directly to the computer

    - The top velocity detector should be connected to LabPro slot **DIG/Sonic 1**
    - The bottom velocity detector should be connected to LabPro slot **DIG/Sonic 2**
  - Make sure the slide gates on the velocity detectors are in the opened position
  - You may need to slide the green tab on the LabPro over to find its USB outlet
  - Try disconnecting the LabPro from the computer, exiting and restarting LoggerPro, and reconnecting LabPro to the bottom USB port on the back the computer

- File not found
  - The Lab's Professor (Dr. Blair London) may have a copy, also check the desktop on the computer
    - Save the file to My Computer/C/Program Files/Vernier Software/ Logger Pro 3/ Experiments/Low Velocity Impact Testing/ Velocity Detection.cmbl
  - Otherwise you have to set up the file manually
  - With LoggerPro open and the LabPro connected, there should be a Distance, Velocity, and Acceleration Graph. If not, then follow the last direction under "Velocity Detector is not working" under *VI. Troubleshooting*
    - On the top toolbar, click Data/Delete Column/Velocity 1
    - On the top toolbar, click Data/Delete Column/Velocity 2
    - On the top toolbar, click Data/Delete Column/Distance 1
    - On the top toolbar, click Data/Delete Column/Distance 2
    - On the top toolbar, click Data/Delete Column/Acceleration 1
    - On the top toolbar, click Data/Delete Column/Acceleration 2
    - Also delete the three now blank graphs
    - On the top toolbar, click Data/New Manual Column
      - Name: Sample Thickness
      - Short Name: h
      - Units: mm
      - Lock Column: Unchecked
      - Data Type: numeric

- Generate Values: unchecked
  - Click Done

- On the top toolbar, click Data/New Calculated Column
  - Name: Impactor Drop Height for 6.70 J/mm
  - Short Name: H
  - Units: mm
  - Data Set: Latest
  - Checked: Add to All Similar Data Sets
  - Equation: 5.111946907*(“Sample Thickness”)*2.54*10
    - Checked: Display During Live Readouts
    - Click Done

- On the top toolbar, click Data/New Calculated Column
  - Name: Impactor Drop Height for 1500 lb-in/in
  - Short Name: H
  - Units: inches
  - Data Set: Latest
  - Checked: Add to All Similar Data Sets
  - Equation: 5.111946907*(“Sample Thickness”)
    - Checked: Display During Live Readouts
    - Click Done

- On the top toolbar, click Data/New Calculated Column
  - Name: Measured Velocity
  - Short Name: V
  - Units: m/s
  - Data Set: Latest
  - Checked: Add to All Similar Data Sets
  - Equation: 0.025/BlockedtoBlocked(“Time”, “GateState 2”, “GateState 1”)+0.1
    - Checked: Display During Live Readouts
    - Click Done

- On the top toolbar, click Data/New Calculated Column
    - Name: Measured Impact Energy
    - Short Name: E
    - Units: J
    - Data Set: Latest
    - Checked: Add to All Similar Data Sets
    - Equation: 2.63*("Measured Velocity")^2
        - Checked: Display During Live Readouts
        - Click Done
- On the top toolbar, click Data/New Calculated Column
    - Name: Measured Impact Energy per Sample Thickness
    - Short Name: C_e
    - Units: J/mm
    - Data Set: Latest
    - Checked: Add to All Similar Data Sets
    - Equation: ("Measured Impact Energy")/("Sample Thickness")
        - Checked: Display During Live Readouts
        - Click Done

- Hide the Time, State 1, and State 2 columns
- Save the file @ My Computer/C/Program Files/Vernier Software/ Logger Pro 3/ Experiments/Low Velocity Impact Testing/ Velocity Detection.cmbl
- Under its properties change the file to **read-only**

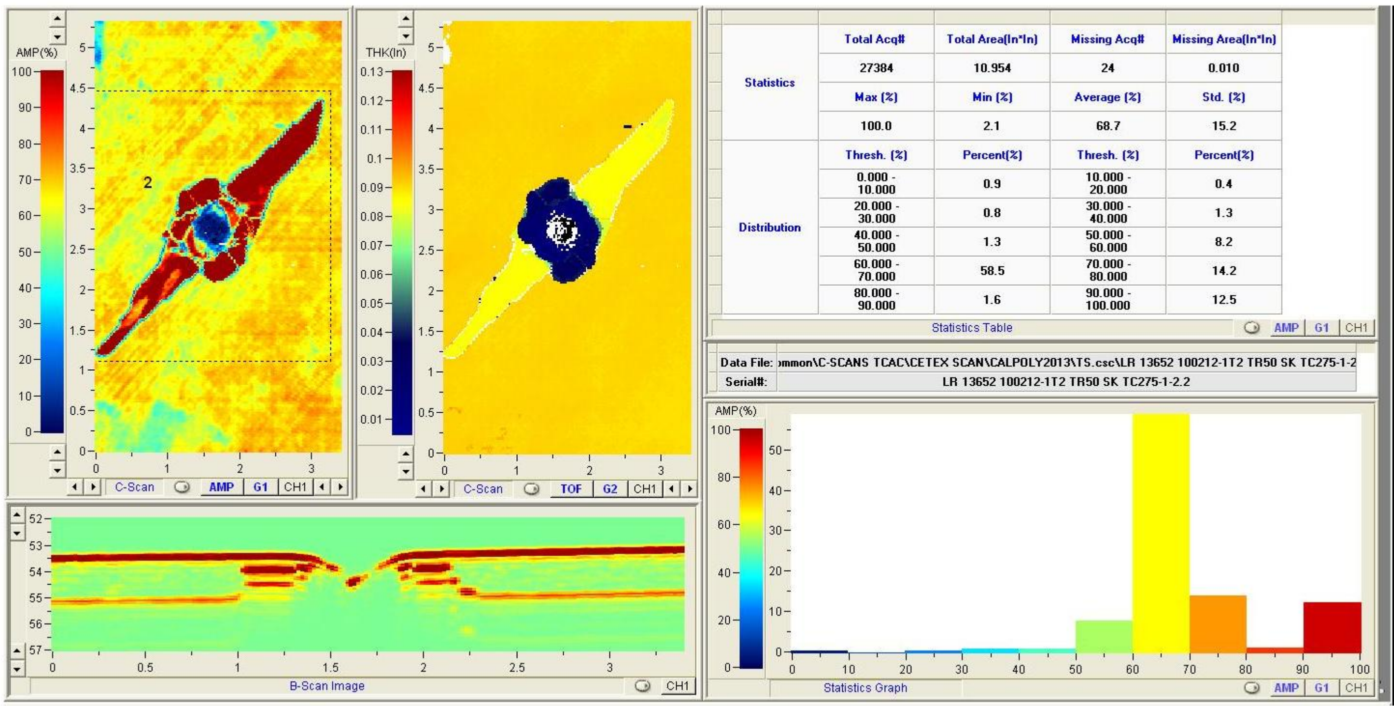
VII. Additional Notes:

- The total mass of the impactor is 5.26 kg
- Use **ASTM D7136** to run test
- Hardness of the striker is ____________

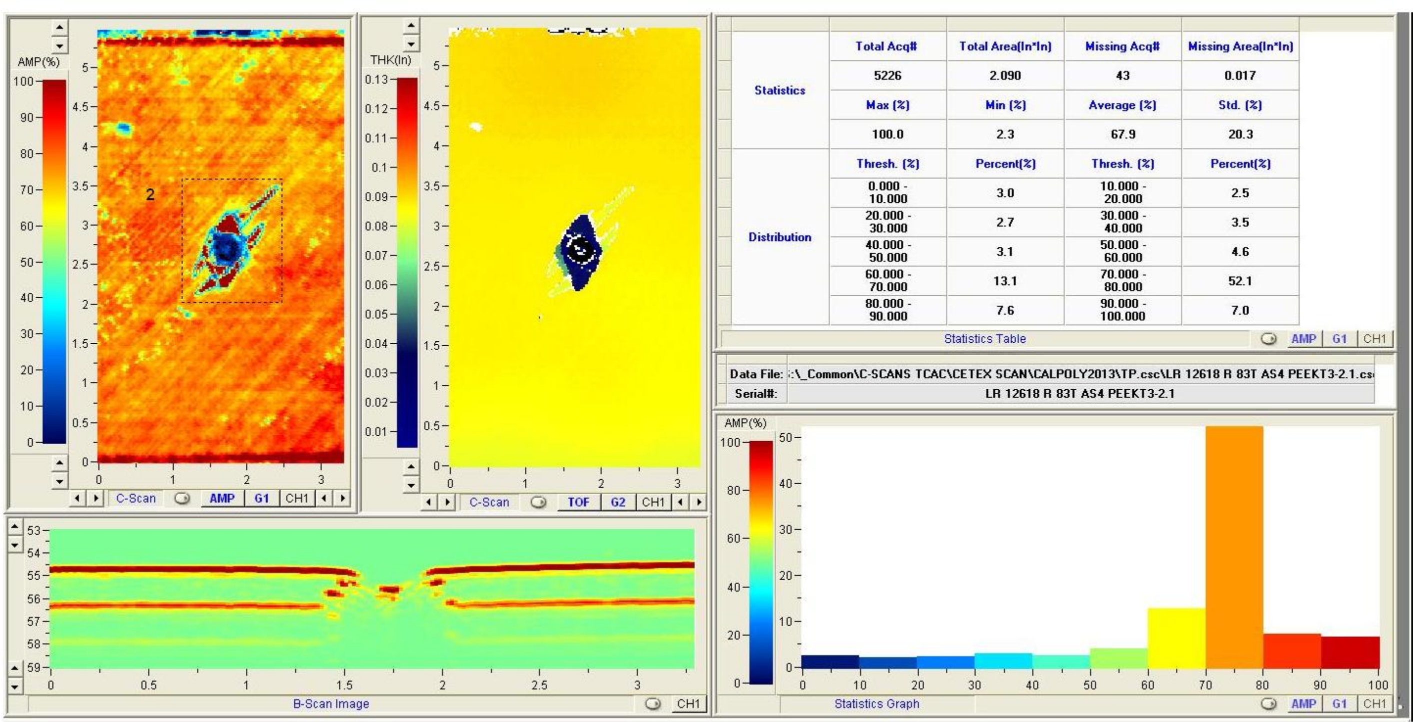
Appendix 2

Ultrasonic C-Scans

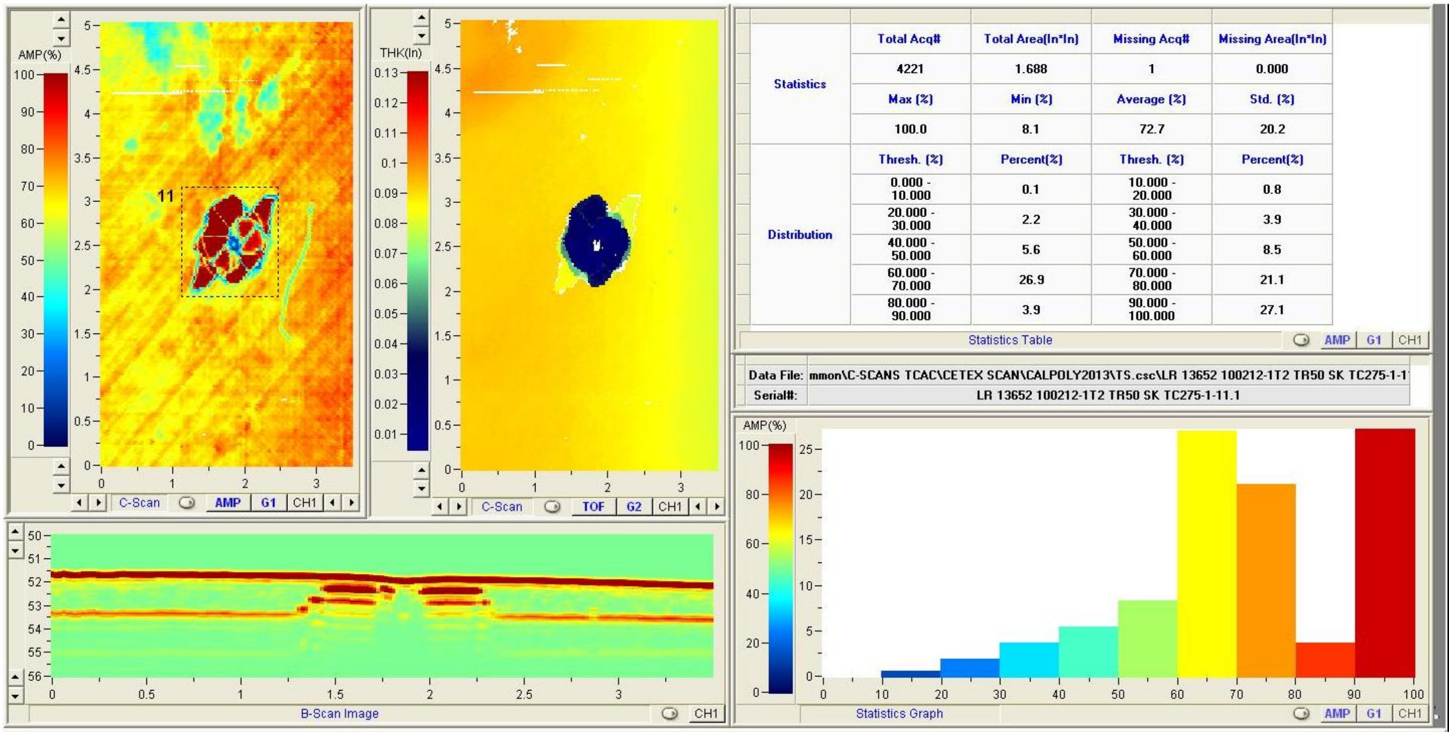
Thermoset Sample with 6.5 J/mm impact



Thermoplastic Sample with 6.64 J/mm impact



Thermoset Sample with 5.74 J/mm impact



Thermoplastic Sample with 5.37 J/mm impact