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DESIGN AND MANUFACTURE OF A COST EFFECTIVE INSTRUMENTED DROP-WEIGHT IMPACT TESTER FOR DAMAGE ASSESSMENT OF COMPOSITES

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Abstract

The Resin Infusion between Double Flexible Tooling (RIDFT) is a promising molding technique for the manufacture of composite materials. The Florida Advanced Center for Composite Technologies (FACCT) develops optimal combinations of lightweight materials with high structural resistance. The purpose of this research is to develop a cost effective impact tester to successfully test composite materials and determine their behavior when subjected to low-velocity impact loads. The impact tester was built under a budget of $3,000 and can be used to test different composites for their impact resistance. The final result is an impact tester equipped with a force transducer and photogates to acquire both the velocity before impact and the force during the impact.

THE FLORIDA STATE UNIVERSITY

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By:

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To

My parents, Javier and Cecilia

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ABSTRACT

The Resin Infusion between Double Flexible Tooling (RIDFT) is a promising molding technique for the manufacture of composite materials. The Florida Advanced Center for Composite Technologies (FACCT) develops optimal combinations of lightweight materials with high structural resistance. The purpose of this research is to develop a cost effective impact tester to successfully test composite materials and determine their behavior when subjected to low-velocity impact loads.

The impact tester was built under a budget of $3,000 and can be used to test different composites for their impact resistance. The final result is an impact tester equipped with a force transducer and photogates to acquire both the velocity before impact and the force during the impact.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Composite materials are increasingly being used in safety critical components. The main purpose of this work is to integrate the known principles of impact testing to the specific composites created through resin infusion between double flexible tooling (RIDFT). The main purpose of the RIDFT process is to improve the already existing resin infusion on flexible tooling (RIFT) and resin transfer molding (RTM) processes. The RIDFT process is faster and cheaper. It also has technical advantages when compared to RTM and RIFT. The RIDFT allows for a better resin flow and more fiber volume, which makes the composite stronger [1]. With the new production process, new unknown variables arise and impact resistance is one of the main concerns when dealing with composite materials. In order to introduce RIDFT as a competitive manufacturing process it is very important to understand the limitations of the final product.

The RIDFT is divided into six steps. Just like RTM the first step is to place the fiber into the machine but not directly over the mold but over the flexible tooling cover with the second flexible tooling and sealed in step 2 creating a closed bag. Then resin is distributed in step 3. Then vacuum is applied to the chamber in step 4 and forming the part is step 5. Finally when the resin is cured the next step is to take the piece out of the machine.

The RIDFT process allow for greater fiber volume fraction since it does not use dry sheets of resin [2]. This means better resistance to impact. This research will explore the impact limitations of the RIDFT composites more deeply.

1.2 Problem Statement

The main need that is addressed in this research is to develop capability for impact damage assessment of RIDFT composition. Several impact tests are used to understand the behavior of the composite materials. In this specific case it is necessary to do a simple low-velocity impact testing (LVIT) since the main concern is to have a starting point to further research and analysis of the RIDFT composites. The improvement of the structural integrity of the RIDFT produced composite materials will provide further knowledge to the future manufacturing of massive production of composite parts.

So far in the development of composites the impact testing plays a major roll in understanding the damage propagation inside composites. The different combination of fibers and resins result in different tolerance levels. This concern arises with the RIDFT composites since the distribution of resin is different than in RIFT and FRTM processes. It is important to understand the resistance levels of impact tolerance in order to compare them with other composites. Taking into account one of the most impressive characteristics of RIDFT composites is resin infusion when the fibers are in a flat surface, which represents a better distribution of resin and fibers throughout the final product suggesting greater strength of the overall product.

In the current lab there is not an instrument that would allow us to perform the necessary tests to study the RIDFT composites under LVIT. It is necessary to develop capability for impact damage assessment of RIDFT composition.

1.3 Objectives

The first task of this research is to design and manufacture the equipment to test composites at low velocity impact, to design an instrument that would efficiently conduct low velocity impact testing of the RIDFT composites. This instrument must provide information to really understand the impact resistance of the composites. The following parameters need to be taken in consideration for the proper design:

- Repeatability: to the instrument must be able to reproduce the same strike several times.

- Space: The instrument must fit in the lab, which means a maximum height of 8ft.
- Materials: The instrument must have a base that resists harsh strikes at low velocities.
- Cost: The completion of the instrument should cost below $3000 dollars.

The construction of the instrument must be done taking in consideration the given guidelines and time limitation.

The second task is to test materials and acquire as much information as possible emphasizing on the limit resistance of the composites to estimate the breaking points of the samples.

The third goal is to show the analysis of the laminates after the impact testing, giving new information about the RIDFT composites for future research. Proper testing guidelines need to be established in order to acquire information that can be used to compare the RIDFT products to other compositions.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Composite materials can be defined as a macroscopic combination of two or more distinct materials, having a recognizable interface between them [2]. The composites can be found in nature as wood, bones, exoskeletons, etc. but also can be man-made. A simple example of a man made composite is a barrel bound with brass rings to strengthen resistance against internal pressure [3]. Man's struggle to find more and better combination of materials has led to great advancements. The further employment of composites rapidly helps develop several common combinations like concrete and polymers, which are of great use in today's industry. For the case of aerospace industry the constant need to make strong, lightweight composites initiated the creation of advance composite materials.

Advanced composite materials made of fiber-resin combinations allowed industry certain freedoms that metals and wood could not. Composites can be cheaper, lighter and more adaptable to the designer's needs. The benefits of advanced composite materials are attained by the precise combination of fibers, resins, and design needs. Composite materials have several mechanical and structural advantages since they can combine properties from several different resins and fibers at the same time [2]. Some theoretical tools may help the designer to achieve specific goals. In the case of high-performance fibrous composites the advantages are: light-weight, torsion stiffness, corrosion resistance, and impact and damage tolerance, among many others [2]. The significantly high strength-to-weight ratios allow composite materials to be extremely useful for the creation of lightweight, safe critical structures.

2.2 Manufacturing of Composite Materials

Composites can be can be manufactured by several techniques including hand lay-up, and liquid composite molding processes. However, the available production processes have limited the utilization of composite materials in the mass production sector. Many of the current processes do not readily lend themselves to mass production due to long cycle times and high emissions of harmful volatile organic compounds (VOCs). Nevertheless, liquid composite molding techniques are technologically promising. Examples include Resin Transfer Molding (RTM), Flexible Resin Transfer Molding (FRTM), Seaman Composites Resin Infusion Molding Process (SCRIMP), and Resin Infusion between Double Flexible Tooling (RIDFT). These closed molding techniques also have the advantage of reducing emissions of VOCs by 90 percent [3].

Cost is a primary consideration in the development of composite production processes. The marine industry manufacturers continue to rely on the validated and cheaper open molding techniques of hand lay-up. The development of the RIDFT process further advances resin infusion technology reducing the higher costs of closed mold techniques.

2.2.1 Liquid Composite Molding Processes

2.2.1.1 Resin Transfer Molding (RTM)

Traditionally, RTM has been the method of choice for the manufacturing of composite parts. RTM offers many advantages over other processes for the manufacturing of fiber-reinforced thermosetting polymer composites. These advantages include improved component thickness tolerances, better surface finish, and reduced emissions of volatiles. However, tooling costs can be prohibitively huge for parts of more than a few meters in dimension, particularly for one-off or small production runs [4]. Figure 2-1 shows a schematic of the RTM process.

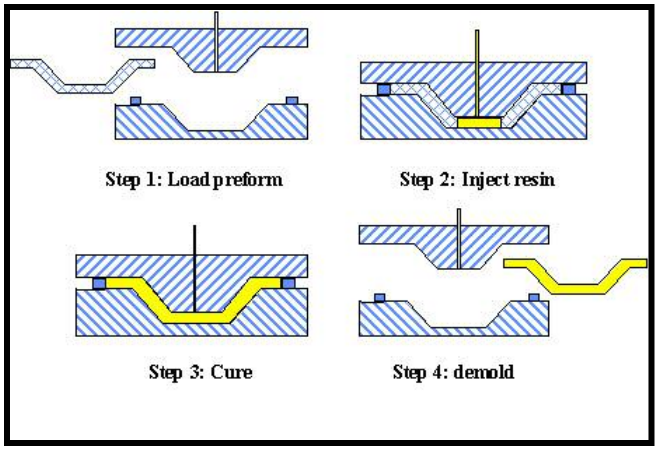


Figure 2.2.1.1.1 Schematic of the RTM Process.

RTM is extensively used in the automotive industry. The advantages are the capability of manufacturing large, complex structures with low-tonnage pressure and relative simplicity of the process [5]. The main disadvantage is the inability for fast manufacturing; large parts require the positioning of fiber layers by hand and special care in the reinforced sections, which consume more time. Such complex or large parts may have cycle times of 24 hours [5].

2.2.1.2 Vacuum Bag Molding (VBM) and Seaman Composites Resin Infusion Molding Process (SCRIMP)

The VBM technique is a closed mold technique and a cost-effective alternative to the open mold processes. SCRIMP is a more common version of the VBM. In this process, a network, which consists of grooves or channels, is used to distribute the resin and reduce the flow resistance and filling time. The resin fills the grooves or channels first by vacuum pressure; then the resin infuse into the fiber perform. In VBM, a one-sided rigid mold and a bag are used to form a mold cavity [6].

The VBM process can be divided into five steps.

1. First, in pre-molding, the mold surface is cleaned, and then a mold release agent and a gel coat are sprayed on the surface.
2. Next, during reinforcement loading, dry fiber mats are mounted into the mold and covered by a flexible bag. The cavity is sealed by vacuum tapes or other techniques, and channel networks or grooves form.

3. In the third step, the cavity of the mold is vacuumed and resin infuses into the fiber mats by the vacuum force.
4. After the cavity is filled with resin, resin begins curing and solidifying into the composite part. This is called the resin-curing step.
5. Finally, the cured composite is taken out of the mold, and the next cycle begins [6].

2.2.1.3 Resin Infusion between Double Flexible Tooling (RIDFT).

RIDFT was developed to solve problems associated with other liquid composite molding techniques. These improvements include achievable fiber volume, part thickness consistency, manufacturing cycle time and process complexity. Figure 2.2 shows a schematic of the RIDFT process.

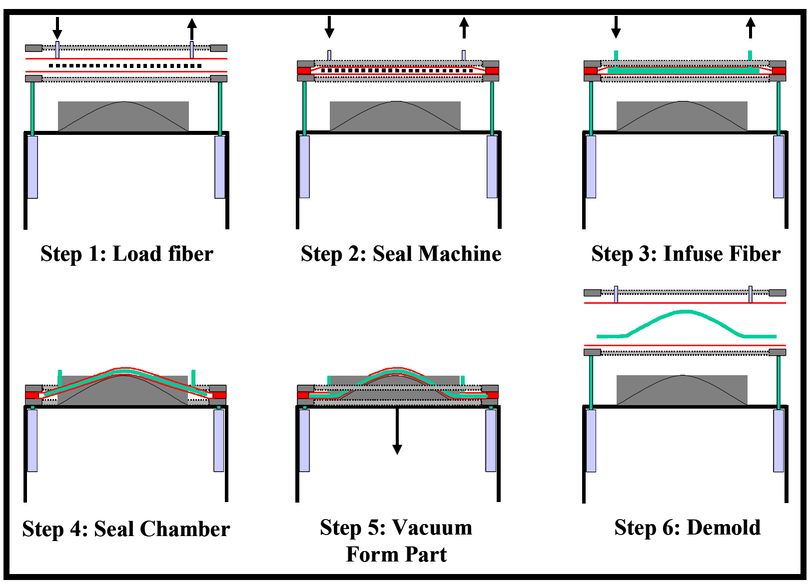


Figure 2.2.1.3.1 Schematic of the RIDFT Process.

As shown in Figure 2-2, dry reinforcement is placed between two membranes. After securing the membranes, resin is infused under a vacuum. The next stage is vacuum forming, during which the membranes are drawn over a male mold (final product shape) by applying a vacuum. The use of a one-sided mold provides huge cost benefits when compared with the RTM process.

2.3 Behavior of Composites

2.3.1 Fibers

Polymer composites are made out of two basic components: fibers and resin. The fibers provide the basic characteristics of a composite material. Best of all they provide the load-carrying characteristics: strength and stiffness, which are most important. When referring to fibers, usually it means a group of filaments since by itself; a filament does not possess adequate strength characteristics. Filaments are only used to test the strength and categorize the different fibers. Fibers are stacked in groups making strands called bundles. Proper selection of type, orientation, and amount is very important, since the selection influences the following characteristics: specific gravity, the tensile strength, compressive, and fatigue strength. The type of fiber also influences electrical and thermal properties of the composite as well as the cost.

The behavior of composites can be understood by identifying the several types of fibers used in the construction of composites. When a load is applied to a composite, the load is distributed to the fiber reinforcement through the matrix (resin), which acts as the lead transfer mechanism. As the fibers break, the composite continues to carry the distributed load until the load overcomes all the fibers. Inside a composite, the arrangement of fibers may be set up continuous or discontinuous. [7] Composites sometimes have reinforcements larger than their cross-sectional dimensions. Such a composite is considered to be discontinuous fiber or short fiber composite if its properties vary with fiber length [8]. There is also the case in which no matter how long the fiber length is, it would not affect the properties of the composite in this case it is called continuous fiber reinforced. Most continuous fiber composites contain fibers that have the same length as the composite. The most common fiber is fiberglass because of its low cost and great availability. Carbon fibers are widely used because of their strength properties. Aramid fibers are basically thermoplastic polymers and considered as high-performance fibers. Boron fibers are employed because they where the first high-performance fibers to be used. Boron fibers were the main material in the fabrication of F-14 and F-15. Glass fibers, carbon fibers, aramid fibers, and boron fibers are extensively used today because they all present different characteristics.[9]

2.3.2 Matrices

Polymer matrices are, according to Reinhart, "The essentially homogenous resin or polymer material which the fiber system of a composite is imbedded."[9] The matrix may be made of polymers, metals, and ceramics. The basic job of the matrix is to bond all the fibers together. Matrices basically transfer stresses between the fibers, provide barriers against the environment, and protect the fibers from abrasion [10].

The overall behavior of the composites seems greatly influenced by the matrix due to its role as the load transfer mechanism. They also generally have lower strength and stiffness than the reinforcing materials. Fibers can resist far more stresses. The selection of matrices is important because they determine the interlaminar shear strength and the in-plane shear strength. Interlaminar shear applies to bending and in-plane shear for torsional loads. The matrix also provides the lateral support against the possibility of fiber buckling under compression. Matrix materials are usually some type of polymer, and these composites are often called reinforced plastics. Other types of matrices, such as metal or ceramic, but polymers are by far the most common. The two most common plastic matrices are epoxy resins and polyester resins

2.3.3 Composites

Composites as a joint body of fibers and matrix properties are best in the direction of the fibers. The matrix properties dominate because load must be transferred by the matrix fiber diameter. Since most structures are not loaded in a single direction, even though one direction may dominate, it is necessary to orient fibers in multiple directions. This is accomplished by stacking multiple plies together. Such a stack is called a laminate. Composites properties can be predicted by using the rule of mixtures. This rule can be applied to mechanical, thermal, and electrical properties. The rule has two forms: one for the properties parallel to the fiber and other for the transversal properties. The properties in the longitudinal direction act as the properties of a several springs in parallel, meanwhile in transversal characteristics act like springs in series. The concept of load sharing between the matrix and the reinforcing constituent (fiber) is central to an understanding of the mechanical behavior of a composite. An external load (force) applied to a composite is partly borne by the matrix and partly by the reinforcement. [11] Also of importance is the response of the composite to a load applied transverse to the fiber direction. The stiffness and strength of the composite are expected to be much lower in this case, since the (weak) matrix is not shielded from carrying stress to the same degree as for axial loading.

$$E_c = E_f + E_m(1\text{-}v_f) \quad (2.1)$$

E is tensile modulus, f is fiber, m is matrix, and c is composite.

The rule of mixtures shows that the composite longitudinal modulus is intermediate between the fiber and matrix modulli. The relationship between these values would provide the average between the properties of both the matrix and the fibers giving an estimate of the composite properties. It is important to understand the numeric relationship between the two when testing the overall performance of the composite material.

2.3.4 Failure of Composites

Composite material may suffer different types of damage due to different forces. The failure modes are divided into three mayor types: fiber failure, matrix failure, and delaminating. The fiber failure is the result of the interaction of the laminate with an external force [12]. This causes single fibers to break, and decrease the total fiber density within the laminate. This is the initiation of the damage process inside the laminate. Fiber failure is controlled by two factors: (i) the statistical fiber strength and (ii) the stress distribution along the fiber direction [12]. Fiber failure and matrix failure can happen either simultaneously or one followed by the other. The propagation of damage may be either fiber-matrix or ply-to-ply so it is possible to divide them in two groups [13]: intralaminar and interlaminar cracking. The intralaminar cracking is basically the damage created by the in-plane stresses that may be perpendicular to the fiber arrangement. The cracks resulting from this kind of interaction are called transverse cracks. The interlaminar cracking is closely related to intralaminar cracking and cannot be separated into a different group. Thus the result of intralaminar cracking causes interlaminar stresses that would lead to a cracking and given sufficient energy, may lead to propagation of the failure and finally, a complete tear of the laminate. The internal interaction of the laminates can be divided in a series of tensions and compressions that would lead to delamination.

The most common type of damage is delamination. Delamination involves the initiation and propagation of cracks running the interlaminar region between two adjacent laminae in the composite. Delamination damage often cannot be detected visually and is very likely to happen in thick laminates or in composites with lower interlaminar shear strengths [14]. The fiber failure can lead to total fracture after delamination and matrix cracking allowing deep or full penetration. Penetration occurs when the impact object strikes the composite and the composite structure does not have enough time to react globally to the loading conditions. Penetration damage after impact cause flexural failure on the rear surface and multiple delaminations throughout the structure [15].

2.4 Impact Behavior

2.4.1 Impact Behavior of Composites

Composite materials have the ability to increase their strength depending on the stacking sequence used in design, yielding a very high stiffness and strength in the loading directions [2]. However, the combination with carbon and glass fibers represents a cost advantage and a gain in energy absorption. Nevertheless, laminated composite materials and sandwich structures have a low stiffness and strength through the thickness direction when compared with the in-plane properties, since no fibers may be present through the thickness, due to their stacking sequence [16]. The strength of a composite is a primary function of the fibers. The ability of the matrix to both support the fibers and provide out-of-plane strength is, in many load situations, equally important. The aim of the construction of a composite material is to provide a system with a balanced set of properties. All the laminate properties, with the exception of those relying on interlaminar strength and stiffness, are almost directly proportional to the basic strength of the fiber [16].

Composites are structured differently so each one has a different way of behaving, but the basic lamina, resin, and fiber lay out can be studied as a whole. Fiber reinforced polymer composites are generally heterogeneous on a macroscopic scale and since the lamina that constitutes the fiber reinforced composite is anisotropic, it does not show a clear crack-like defect but rather a much more complex spreading of damage [17]. Composite material samples may show matrix transverse intralaminar cracks and axial splitting, interlaminar delamination, fibers-matrix de–bonding and pullout, fibers micro buckling and kinking [18]. Sometimes, the behavior of composites may need to be improved for a certain tasks. For example in the case of carbon fibers created for high performance machines, like fighter jets, there is a need to endure high temperatures as well as damage. In order to develop these materials the resulting composite is more brittle. As such, the need to develop a material able to support both impact and high temperatures becomes imperative. Carbon fiber composites are being used in airframes, and have brought about the need for better damage tolerance. As such some parameters where identified by the Federal Aviation Administration in order to understand the behavior of the composites during impact [19, 20]. Some relate to the structure of the sample (materials, thickness, lay-up sequence, etc.) and some relate to the impacting object (shape, velocity, energy).

2.4.2 Impact Damage in Composites

The sensitivity of composite materials to out-of-plane loading is of major importance and is being studied with different theoretical and experimental approaches [15]. To predict damage progress in composite materials several numerical and analytical methods have been created, but there is not a general approach to the initiation and propagation of damage during impact [17]. Some empirical evidence relates the initial kinetic energy of the impactor to the damaged area. Generally the area increases with the impact energy but the relationship between the amount of energy and the initiation of damage is not clear yet. Research conducted by Schoeppner [21] shows the existence of a Delamination Threshold Load proving that the initiation of damage will be predictable using the load-time histories. This is a useful tool for the future design and analysis. There are also other parameters that have been taken in consideration when analyzing the impact and post-impact effects. For instance, for a given fiber type, the penetration energy is influenced by the total fiber volume and tup diameter and less influenced by the type of resin or fiber architecture and stacking sequence [22]. Then there is a way to relate the indentation depth with the impact energy so that for in-plane isotropic composites giving again another tool to the comparison and development of composites [23]. In low velocity impact tests the delamination threshold is shown in the force in time graph, which is usually represented by a bell shape and shows impact peak value.

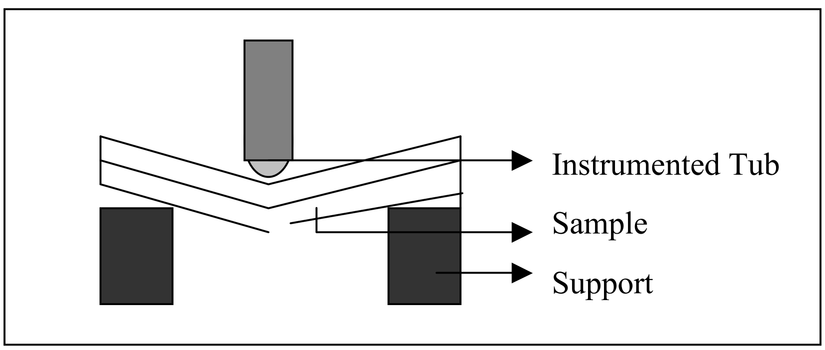


Figure 2.2.4.1 Impact Composite

Most low velocity impacts results in some vibratory load and responses from the composite specimen, the impactor tub and the specimen supporter [24]. The impact creates a chain effect when it touches the sample with enough strength. First the outer layer will bend until the fibers compression and tension goes beyond breaking point causing the fibers that start breaking and the resin to crack. Then the composite is said to fail when it stops performing satisfactorily [17]. Sometimes failure of the composite does not necessarily mean total breaking of a sample. In some cases failure can be just a small deformation that will limit its ability to perform satisfactorily.

2.4.3 Low-velocity Impact Testing

Soldiers in the field rely on their helmets that are subjected to a lot of small punishments daily. A helmet dropped from the truck may not suffer any visual or critical damage, but a small crack may result that can eventually compromise the helmet's structure. The low velocity impact testing might be one of the most practical studies of composite materials since it predicts the composite's behavior. The interest in low velocity impact testing arises when taking into consideration situations like the helmet example. Other examples are dropped tools, runway debris, hails storms and other situations that would slowly deteriorate the structural integrity of the composite material without actually affecting the macroscopic integrity of the composite.

The utilization of composite materials calls for an effort to understand the behavior of laminates in different impact scenarios. There are several types of impact tests which include the Izod impact test, the reverse impact test, and the Charpy impact test. The Izod impact test is a test for shock loading in which a notched specimen bar is held from one end and broken by striking, and the energy absorbtion is measured. The reverse impact test consists of striking a sheet from one side by a pendulum or a falling object and then the reverse side is inspected for damage. The Charpy impact test is a test for shock loading in which a centrally notched sample bar is held at both ends and broken by striking the back face in the same plane as the notch [2].

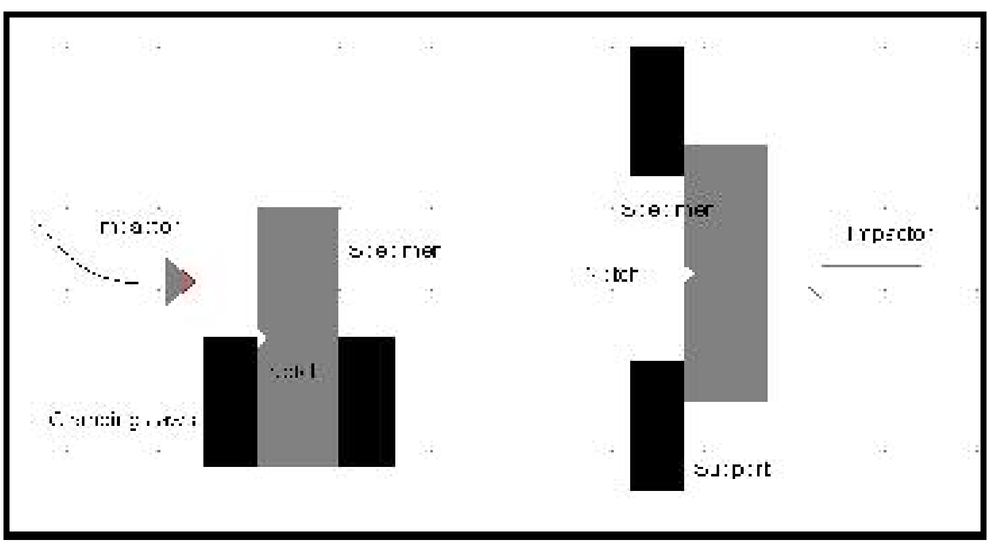


Figure 2.4.3.1 (a) Izod Test (b) Charpy test

The Izod and Charpy tests are the most well know pendulum impact tests because of their simplicity. In both tests the initial and final potential energy of the pendulum are measure and the lost energy of the pendulum is attributed to fracturing the specimen. The Izod test is not adequate for testing composites since it was designed for testing metals originally. The Izod test does not take in consideration the kinetic energy of the test piece after impact. Additionally, the radius of the notch tip prescribed at 250 microns in the standard is too blunt to give conservative data. Sometimes this test will give very misleading information when dealing with composites [11]. The Charpy test can be better when instrumented with a force transducer in the striker. However, the Charpy test is prone to dynamic effects.

During a slow velocity test, the sample has enough time to deform and force equilibrium in the structure. As the test rate increases, the typical response of composites is flexural waves. This leads to violent oscillations in the measurements of the load and may also lead to complex crack growth behavior where the stress waves interact with the growing crack leading to acceleration, deceleration and sometimes stick-slip crack growth where the cracks in short bursts followed by a period of crack arrest [11].

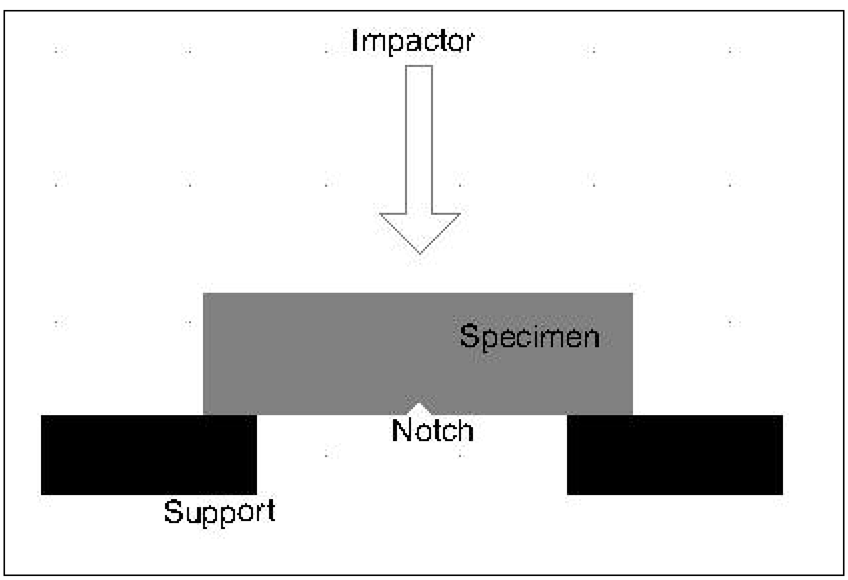


Figure 2.4.3.2 Falling weight drop test

The falling weight drop test (FWDT) is more suitable for composites. This is the most popular test for composites and has the advantage that realistic geometries can be tested. The specimen is supported horizontally either clamped [10] or just simply supported [11]. The energy absorbed can be taken from the initial potential energy of the striker, taking into consideration any rebound or the kinetic energy of the striker after impact. Displacement gauges are often used to measure the velocity of the striker just before impact. Sometimes the impactor is instrumented to allow force-time records of the impact event to be captured. An advantage of this test is the ability to create several shapes for the striker that can simulate realistic impacts. One disadvantage of this test is when penetration occurs, energy is lost in friction [11].

CHAPTER 3

METHODOLOGY – EQUIPMENT CONSTRUCTION

3.1 Reasoning

In order to study the impact behavior of RIDFTed composite laminates, it was imperative to obtain a cost effective drop-weight impact tester at the Florida Advanced Center for Composite Technologies (FACCT). FACCT stuff determined that it was cost effective to build the FACCT impact tester to the ASTM D5428-98a standard. A major constraint was the height of the facility. The maximum height was 8 feet. This height was sufficient to create a low-velocity impact tower. The initial concept was a simple free fall weight drop. This way the calculations are simplified by using the potential energy of the striker:

$$\Delta \mathrm{E} = mgh \qquad \textbf{(3.1)}$$

Where E is the potential energy, m is the mass, g is the acceleration due to gravity, and h is the drop height. The initial concept utilized the weight and height as parameters for energy calculations. However, a concern for repeatability arose and a guide system was required. In order to properly guide whatever striker (impactor) was selected to be used, some friction would be involved, as such, calculations were changed to utilize the kinetic energy of the striker in the determination of impact energy (Equation 3.2).

$$KE = \frac{mv^2}{2} \qquad \textbf{(3.2)}$$

Where, KE is Kinetic energy, and v is the velocity of the impactor.

At a maximum height of 8 feet, the attainable velocity range was 0 – 6.9 $m.s^{-1}$. The following calculations demonstrate the limitations of the experimentation. At the conceptualization stage, it was determined that it was necessary for the equipment to produce impact energy up to 500 Joules.

$$\text{Work} = 1/2\, Mv_1^2 \qquad \textbf{(3.3)}$$

$$v_1 = [(2/M)(\text{Work})]^{1/2} \quad \textbf{(3.4)}$$

Using M (mass) and converting v_1, the mass center velocity, to initial impact point velocity p_1:

$$p_1 = (d/r)[(2/M)(\text{Work})]^{1/2} \ \textbf{(3.5)}$$

From the coefficient of restitution formula:

$$p_2 - s_2 = c(s_1 - p_1) \quad \textbf{(3.6)}$$

$$p_2 = cs_1 + s_2 - cp_1 \quad \textbf{(3.7)}$$

Now knowing p_1 and p_2, we can find $v_1 - v_2$ by multiplying by the ratio of the mass center radius (r) to the impact point distance from the axis (d) and plugging in the derived values of p_1 and p_2:

$$v_1 - v_2 = (r/d)\ [p_1 - p_2] \quad \textbf{(3.8)}$$

$$v_1 - v_2 = (r/d)\ [(d/r)[(2/M)(\text{Work})]^{1/2} - cs_1 - s_2 + c((d/r)[(2/M)(\text{Work})]^{1/2})] \quad \textbf{(3.9)}$$

$$\text{Imp. Impulse} = M\,(v_1 - v_2) \qquad \textbf{(3.10)}$$

$$\text{Imp. Impulse} = M(r/d)[(d/r)[(2/M)(\text{Work})]^{1/2} - cs_1 - s_2 + c((d/r)[(2/M)(\text{Work})]^{1/2})] \ \textbf{(3.11)}$$

Simplifying:

$$\text{Impact Impulse} = M\{(1 + c)[(2/M)(\text{Work})]^{1/2} - (r/d)(cs_1 + s_2)\} \quad \textbf{(3.12)}$$

Impact impulse is measured in momentum units ($kg.m.s^{-1}$). Dividing impact impulse by the time it operates will yield $kg.m.s\text{-}^{2}$, which by Newton's Second Law must be a force, measured in Newtons of force (1 Newton = 0.225 lb). The time to divide by is time of impact.

Impact Force = Impact Impulse/dwell time

$$\textbf{Impact Force} = (\boldsymbol{M} / \boldsymbol{t})^*\{(1 + \boldsymbol{c})^*[(2/\boldsymbol{M})^*(\text{Work})]^{1/2} - (\boldsymbol{r/d})^*(\boldsymbol{cs}_1 + \boldsymbol{s}_2)\} \quad \textbf{(3.12)}$$

3.1.1 Calculations

The ASTM has two standards applicable in this case were the *Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Falling Dart (Tup or Falling Mass) D5628-96* [25] and *Standard Test Method for Impact Resistance of Flat Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact) D5428-98a* [26]. Both methods refer to the impact testing method and suggest certain geometries that were taken in consideration in the design of the striker. The ASTM D5628-96 [25] deals more with impact testing at lower heights and gave a guideline of the parameters taken in consideration. The ASTM D5428-98a was the backbone of the design since the geometries of the strikers and bases were made to the given measurements. The height is going to be subjected to space availability, which range between 0-2.4 meters (0-8 ft).

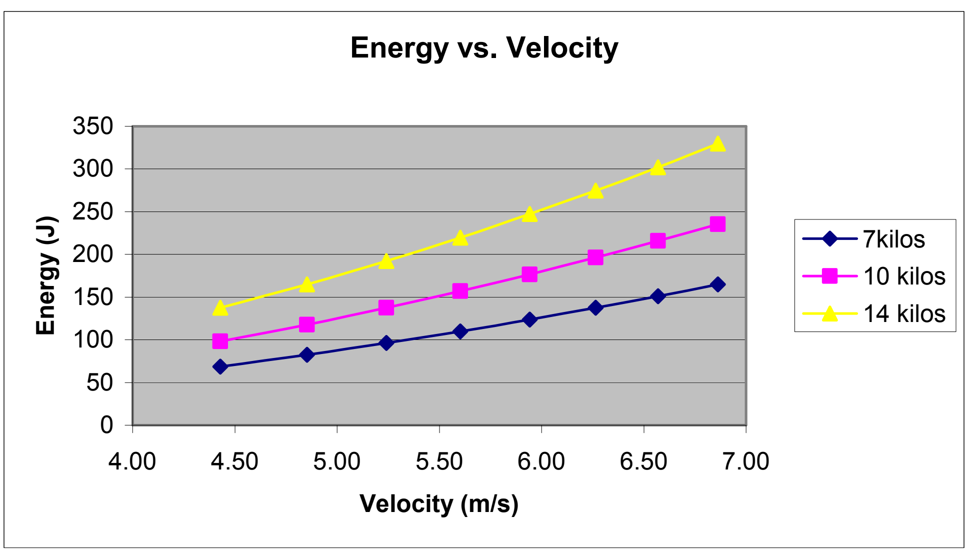
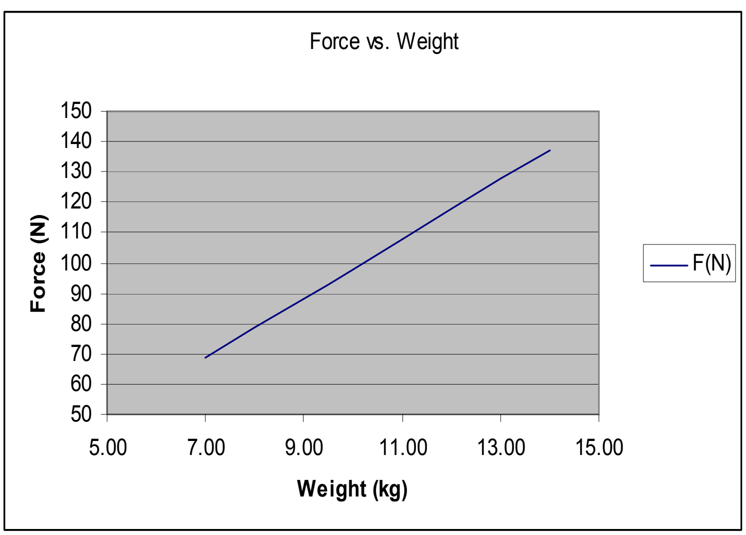


Figure 3.1.1: Energy vs. Velocity graph.

Table 3.1: Calculated parameters

Weight (kg)	Height (m)	Velocity ($m.s^{-1}$)	Kinetic Energy (J) Using 7kg	Kinetic Energy (J) Using 10kg	Kinetic Energy (J) Using 14kg
7.00	1.00	4.43	68.67	98.10	137.34
8.00	1.20	4.85	82.40	117.72	164.81
9.00	1.40	5.24	96.14	137.34	192.28
10.00	1.60	5.60	109.87	156.96	219.74
11.00	1.80	5.94	123.61	176.58	247.21
12.00	2.00	6.26	137.34	196.20	274.68
13.00	2.20	6.57	151.07	215.82	302.15
14.00	2.40	6.86	164.81	235.44	329.62

Figure 3.1.1 shows a set of calculations based on the possible velocities given by the height limitations. The different lines show the theoretical values of a load between 7 and 14 kilos (approx 16 to 30 lb), taking into consideration the minimum amount of energy that are acquired from the free fall. The values given in Table 3.1 give a range of penetration energy before impact. These would increase depending on the total penetration distance of the impactor.



Weight (kg)	Force (N)
7.00	68.67
8.00	78.48
9.00	88.29
10.00	98.1
11.00	107.91
12.00	117.72
13.00	127.53
14.00	137.34

Figure 3.1.2: Force vs. Weight Graph.

The force striking the composite sample was between these ranges. So after calculations of impact time, the actual values for the impact force would be up to 53,000N assuming that the penetration distance is minimal (1mm) in a very hard material and a velocity of 2.4m/s before impact.

3.2 Materials

The simplest guide concept resulted in a pair of vertical guide rods made out of steel with a horizontal aluminum plate with linear bearings that would guide the plate and reduce the friction. The material used in the guide rods was RC60 steel with linear bearings in a flanged mount. The guide mechanism solved the accuracy problem. However, there was also the need to empirically capture the velocity of the falling weights.

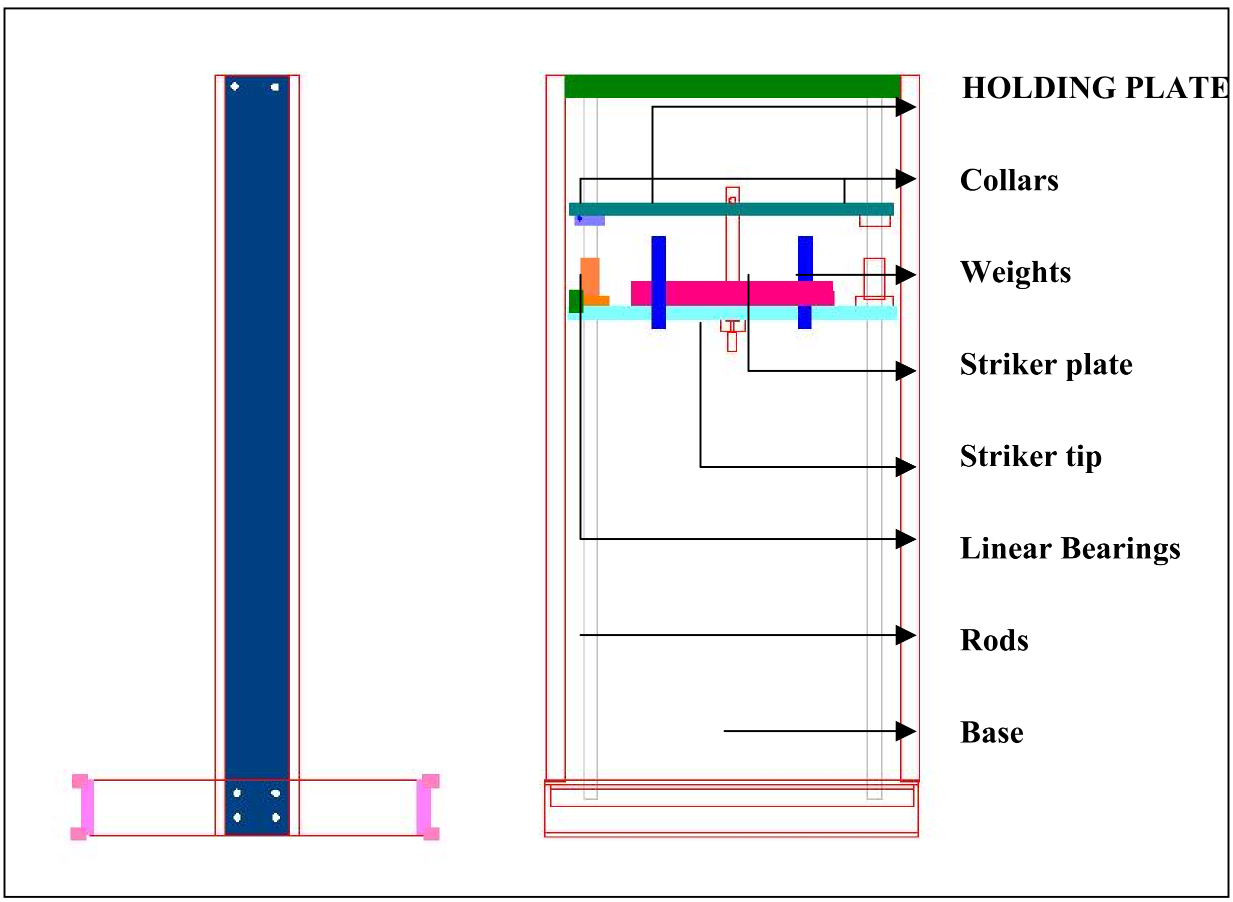


Figure 3.2.1: Preliminary design. Side and front view.

Cost played an important role in determining the best method for acquiring data from the falling striker. Hence, photogates became the primary option. Photogates work by counting the times the red LED is obstructed and sending a digital signal that are transformed into valuable information. Using three photogates connected in a daisy chain, the precise velocity, distance, and acceleration of the falling striker are determined. These in turn was used to determine the force and energy of the impact. One photogate located at the beginning of the drop will give the initial starting values. The photogate situated in the middle of the drop would give the information required to complete graph of acceleration and velocity in time. The final photogate gave the last values of velocity and acceleration. In order to acquire several data points with each sensor, the fence principle will be used. This consists of several measurements with the same sensor by modifying the striker piece. Several weights may be used at differing heights (up to six feet). Data were acquired by means of a data logger (Pro Logger 3) processed using Microsoft Excel.

Figure 3.2.1 was the preliminary design, and assessed the different materials that were to be used. The main blue structure is aluminum, minimizing the weight of the structure and ensuring stiffness. The steel frame creates a stabilizing heavy base that will resist use. The clear blue rods are the guides for the striker and function to hold the photogates. The yellow area is where the sample is going to be situated, but since there are different geometries to be used, a hole was created to allow for the use of different bases.

Table 3.2: Table of geometries [25].

Geometry	Striker Diameter mm (in.)	Support Plate Inside Diameter mm (in.)
GA	15.86 ± 0.01 (0.625 ± 0.004)	76.0 ± 3.0 (3.00 ± 0.12)
GB	15.86 ± 0.01 (0.625 ± 0.004)	15.86 ± 0.01 (0.625 ± 0.004)
GD	12.70 ± 0.01 (0.500 ± 0.004)	15.86 ± 0.01 (0.625 ± 0.004)

The geometries used (Table 3.2) will yield sufficient proof of the bending, fracture and fatigue of the laminate. The geometries that are not going to be used (GC, GE) can be left for further investigations on penetration. The bases are going to be constructed as instructions show [25]. All the geometries specified in the ASTM standard D5420-98a will be constructed, but will not be used in this research. The test will basically cover the ranking of the material according to the amount of energy needed to crack or break flat, rigid plastic specimens under the impact of the striker with different loads of weight.

3.3 Design

The goal in terms of instrument design, to be able to analyze the same energy strike several times to fully understand the impact behavior of the RIDFTed components. Figure 3.3.2 (Bottom view of 3.2.3) shows the aluminum U-channels that were used in main structure to hold the main frame. The top green piece will also be made out of aluminum and the squared base is steel. The concept is relatively simple and allows the striker to be set up at any height along the rods by untying the collard that holds the horizontal supporter.

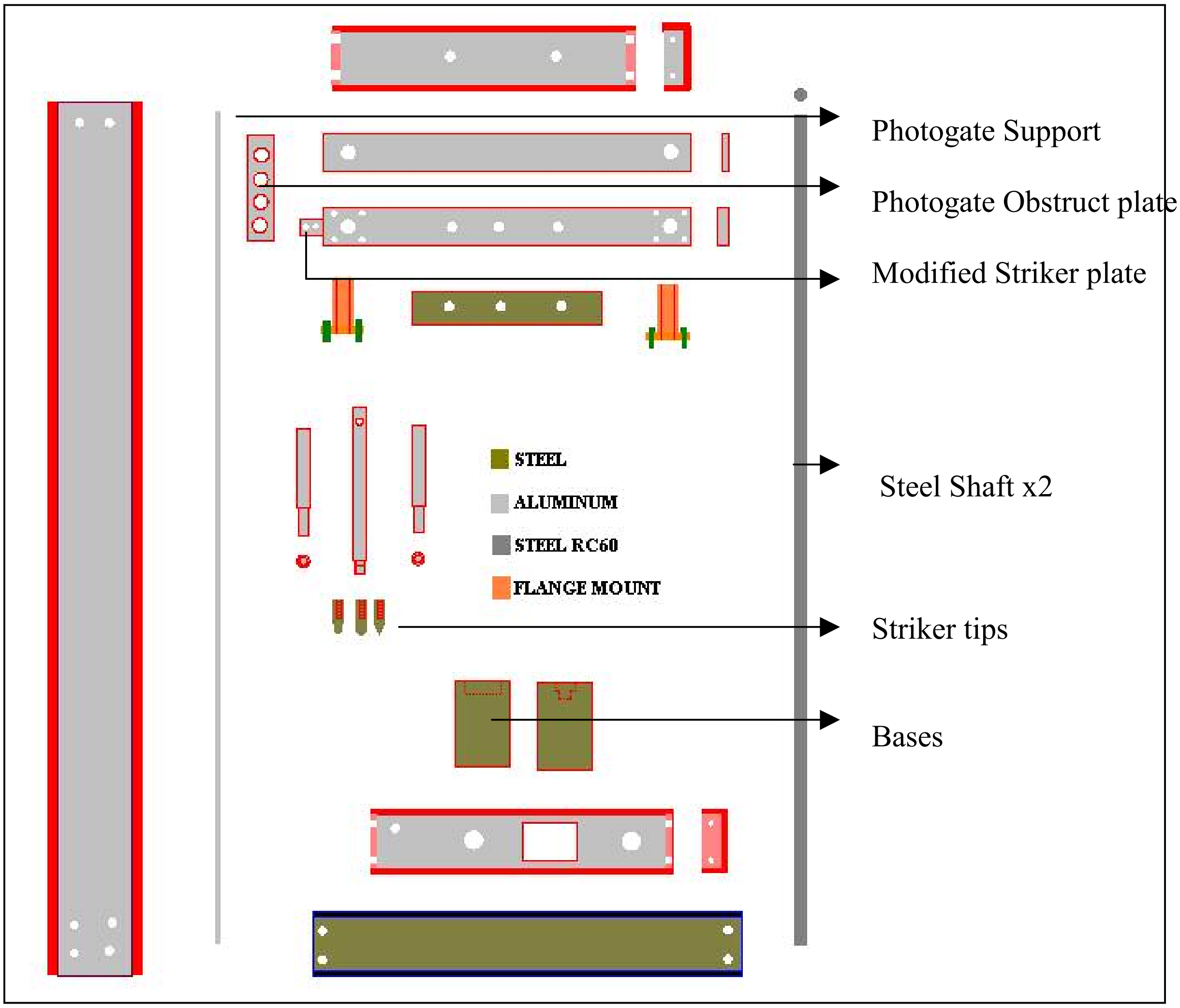


Figure 3.2 1 Exploded pieces final design.

The striker is the primary piece because it holds the weights and the linear bearings in the flange mounts. The most important component of the design is the total parallelism of the rods since the aluminum plate will keep the distance between them equal. In case the shafts are not completely parallel, then the striker will slow and eventually stop.

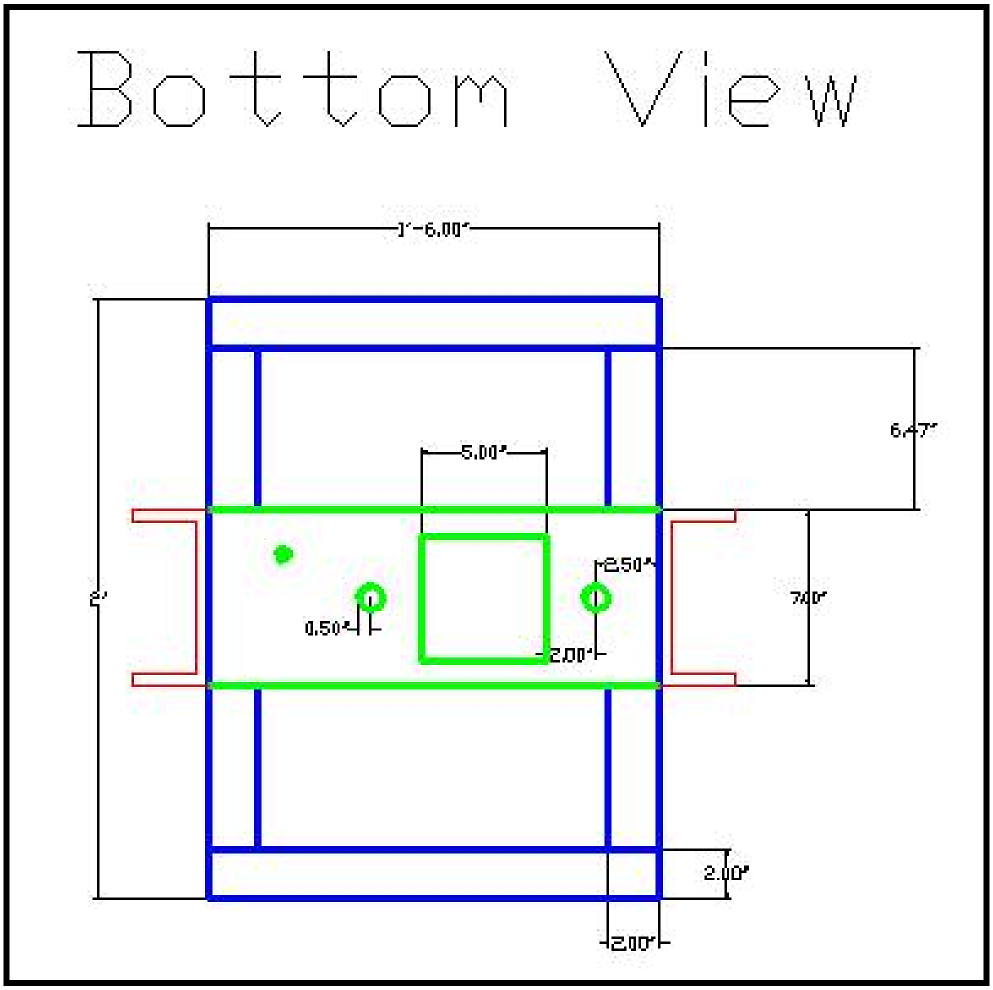


Figure 3.2 2 Bottom view of the base.

The base frame must be very heavy and stiff because the strike of the weight load cannot affect the integrity of the structure. The blue pieces are all steel that will be bolted down. The main frame will be constructed with U-Channels of aluminum and steel. The channels are going to be modified in the ends by placing a plate with two holes so that they can be bolted together. The bases are made out of steel even though the ASTM standard D5420-98a says it should be aluminum. Each of the bases will weight 15 lbs.

The Figure 3.2 1 shows the design of the pieces and how they are arranged. This design, as well as the bottom view, show that the holes are slightly moved to the right since an aluminum tube will be used to hold down the photogates. Also in this schematic the aluminum piece with several holes will be attached to the striker plate creating more data acquisition point when passing through the photogate.

The main change in the Figure 3.2 3 to the design from Figure 3.2.1 is that the striker plate is modified and the aluminum tube is contemplated. The instrument is no longer symmetric but should not be a problem if the rods are properly assembled and tied down. The bases are probably not gong to be solid cubes but rather cylindrical so when fitted in the square hole sufficient space would allow it to be mounted by hand.

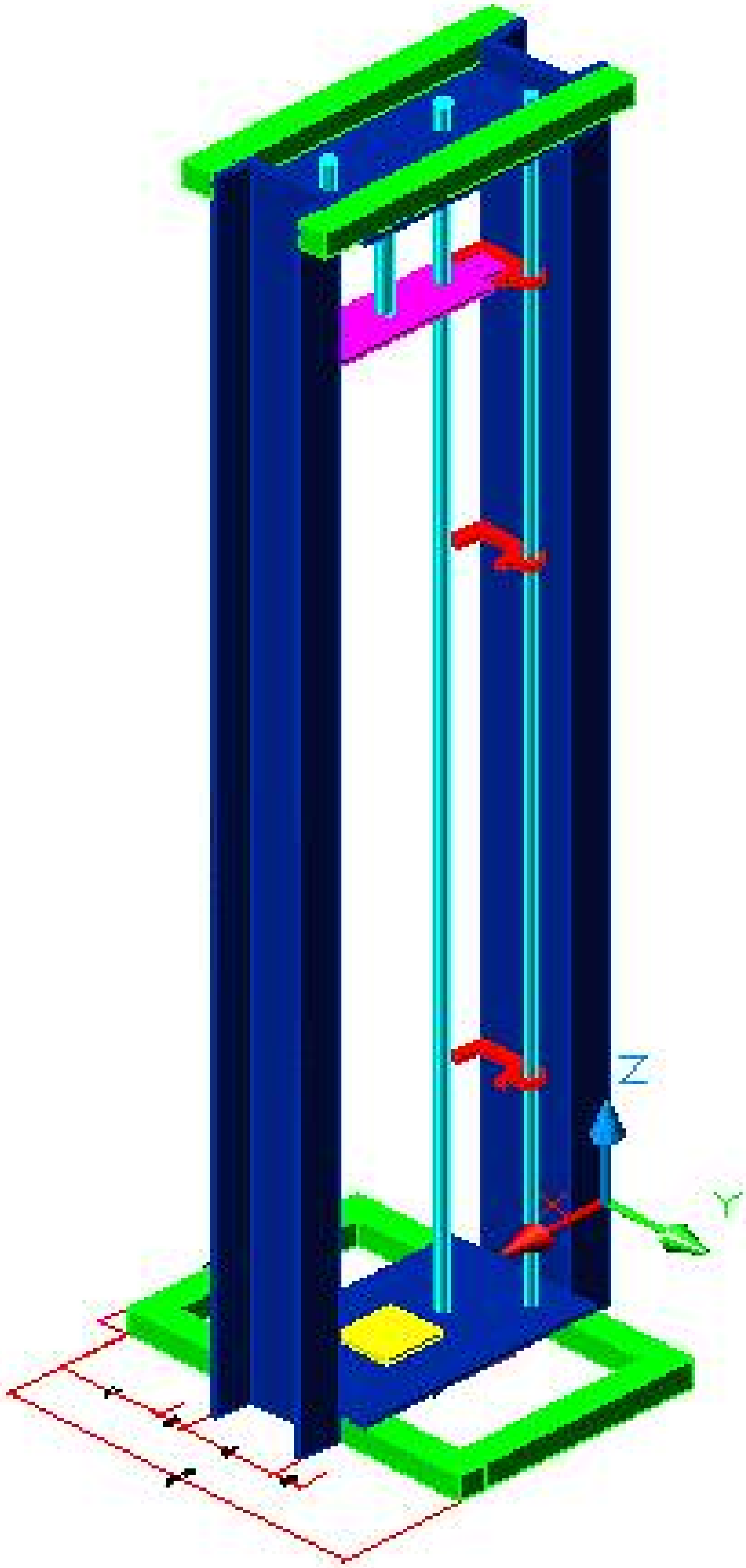


Figure 3.2 3 3D isometric view

3.4 Construction

The construction of the instrument was simple since the parts were meticulously cut and drilled. The first step was to build the base and make it square so that it does not tumble and then secure the structure and weld it so that it will remain flat. Then the second step was to bolt and screw the large aluminum U-channels in the sides and then screw the top pieces to secure the whole structure. The next step is to put together the striker plate. It consisted of the basic aluminum plate with the long screw that will hold the weights and the main 10” screw that will have the striker tip and the two 8” screws that hold the weights. The two-flange mounts screwed to and the aluminum plate for the photogate obstruction. Then the rods were placed through the first holes after the base and the main frame was screwed together. Then the holding plate, the collars, and striker plate placed in. The then the rods were placed through the second hole and tied. Then the aluminum support tube for the sensors was positioned close enough so that the striker properly obstructs the sensors.

3.5 Instrumentation

Two types of sensors were used in the analysis of the falling impactor. For velocity and distance purposes the photo sensors in daisy chain in order to properly measure the velocity at several points of the fall. The latest addition to the instrument was the force transducer.

The force transducer used was a quartz-based sensor that maintains a steady voltage and increases as pressure is applied. The sensor connected to a signal conditioner that maintains the voltage range steady and helped calibrate the signal. The signal then goes to a switchboard that translated the signal to a digital signal that the data acquisition board in the computer could read. The software used to acquire the information is LabView 7.0.

CHAPTER 4

TESTING

4.1 Introduction

In order to ascertain the reliability of the impact tester, it was necessary to test the equipment under service conditions. The main objectives of the testing performed with the equipment are the determination of:

- Equipment ability to record both velocity and impact force accurately.
- Repeatability, both of the actual impact on the sample target, and comparison of results at the same conditions.
- Sensitivity – how changes in test setup affect results acquired.

Two main tests were performed in order to simulate real testing conditions and determine the equipment limitations.

4.2 Impact Testing

Fiberglass is one of the most common reinforcement materials utilized today in the composites industry. Glass Fiber Reinforced Composite (GFRC) laminates were used to determine the impact tester behavior. Several laminates were tested under differing service conditions, by varying the loading heights and weights. This resulted in variations in both the impact velocity and impact force. Photogates were used to give both the velocity profile and the maximum velocity before impact. The minimum loading weight was 15 lbs. Weights could be increased in 5 lb increments as required. The use of a PCB force transducer in the impact tester allows the recording of impact force to be made as a function of time for the duration of the impact event. The impact velocities recorded ranged from 2 to 4m/s. Table 4.1 shows a matrix of the used height, weight and calculated energy.

Table 4.1: Velocity measurements and resulting energy from impact event

Weight (lbs)	Height ft (m)	Max Velocity m/s	Energy J
15 lbs	1 ft [0.3m]	2.41 m/s	20 J
20 lbs	1 ft [0.3m]	2.43 m/s	27 J
25 lbs	1 ft [0.3m]	2.40 m/s	34 J
15 lbs	2 ft [0.6m]	3.45 m/s	40 J
20 lbs	2 ft [0.6m]	3.51 m/s	54 J
15 lbs	3 ft [0.9m]	4.2 m/s	62 J
25 lbs	2 ft [0.6m]	3.47 m/s	67 J
20 lbs	3 ft [0.9m]	4.3 m/s	81 J
25 lbs	3 ft [0.9m]	4.32 m/s	102 J

4.2.1 Impact Behavior

In order to determine the impact behavior of target materials, the impact tester was intended to measure both the velocity before impact, and the impact force during the event. Logger Pro was used to measure the velocity profile, and LabView 7.0 Express was used to acquire the impact force in time. The velocity is determined by the compilation of different velocity points as the weight falls; due to the methodology some points fall away from the actual profile but these outliers (Figure 4.1) are easily found and discarded. Outliers may also be present after the impact velocity is recorded. These are attributed to noise of the test system resulting from bouncing of the target. GFRC tend to be more pliable than carbon fiber composites, thus creating a greater possibility for bouncing.

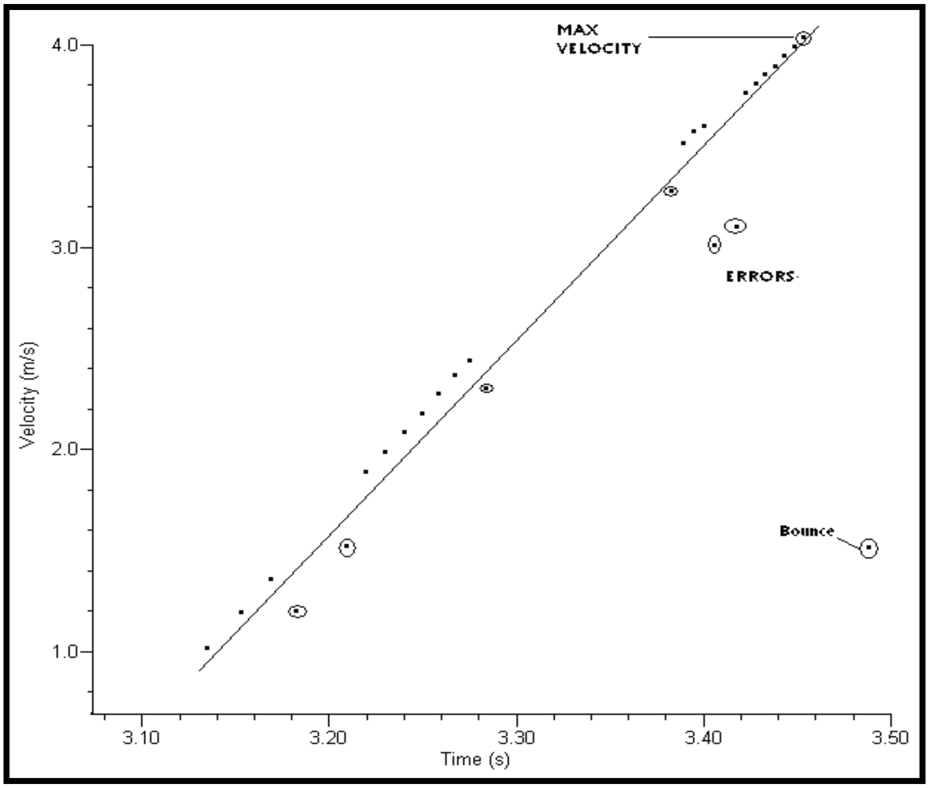


Figure 4.1: Velocity Profile using Logger Pro

The velocity profile (Figure 4.1) gives information on the velocity/time response of the system. Maximum velocity recorded is assumed to be the impact velocity. The bounce information indicates the impact event is over. It was observed that brittle materials result in deeper penetration of the impactor, resulting in a smaller impact force to failure. However, tougher/stronger materials yield less penetration, and a greater chance of bounce. The acquisition of impact force necessitated the use of LabVIew. Figure 4-2 shows the software ideal output for an impact test.

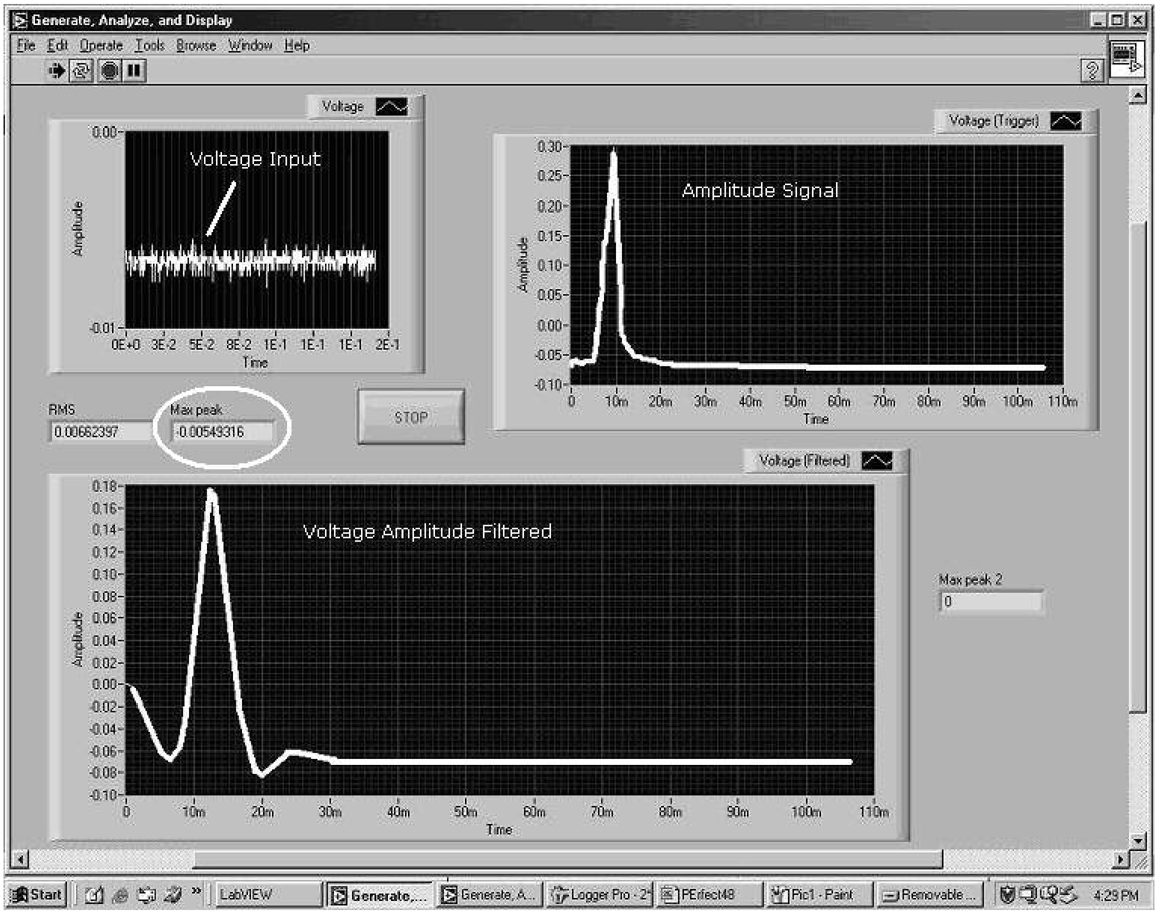


Figure 4. 1 LabView window for impact analysis

It can be observed from Figure 4.2 that the voltage input is a negative number close to zero. The reason for this initial voltage input at setup is because the signal trigger starts at zero voltage so it will show the increments in voltage amplitude. This maximum peak value shown in Figure 4.2 should be added to the value at the peak of the graph to acquire the true maximum value also known as the energy threshold [18]. Sometimes the max peak value would not make much difference because it is a very small value. The values acquired from the impact would include 20 points before the trigger in order to understand the material behavior during impact.

The results from the experimentation performed at three different heights with three different weights are shown in Figure 4.3.

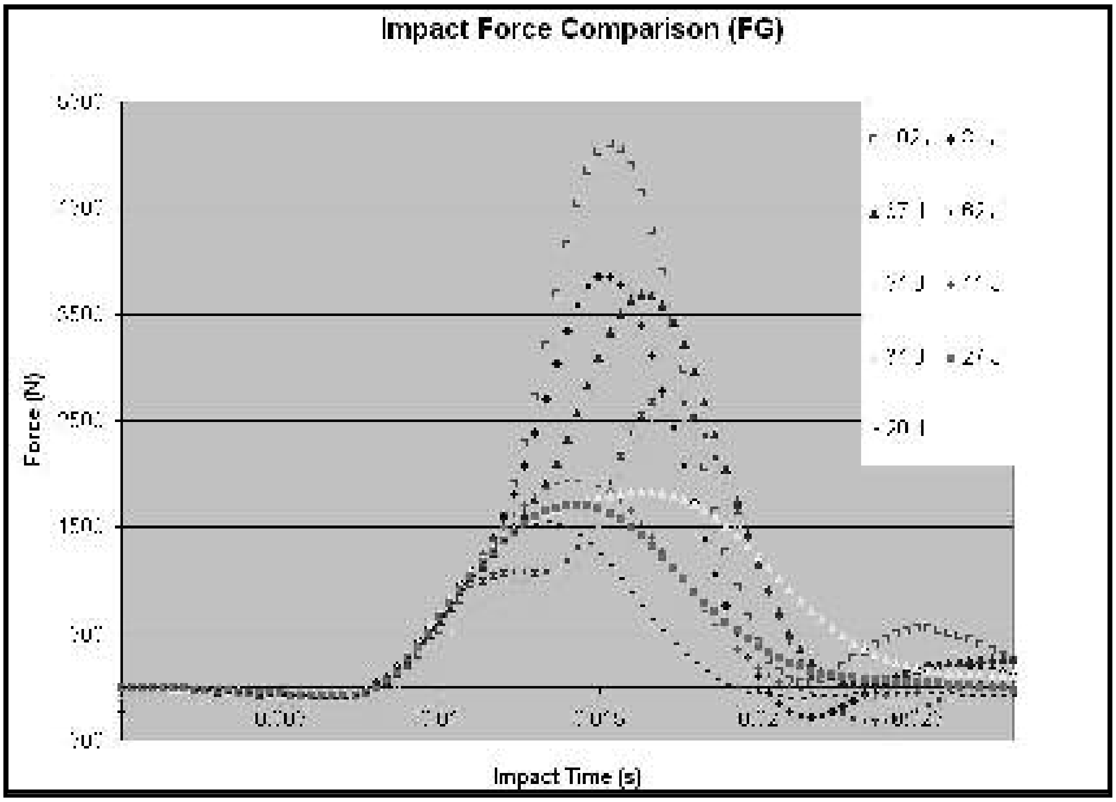


Figure 4.2.1 Impact Force Comparison (resulting kinetic energy obtained using different weights as shown in Table 4.1)

It should be noted that the resulting curves in Figure 4.3 were produced using differing impact conditions of mass and height (Table 4.1). The force applied is transformed into impact energy. Notice the two-stepped curve at 54 J showed a different material behavior since the sample bent and then allowed further penetration creating a second cycle of tension and compression interaction. The testing samples were not clamped and as a result, some further bouncing produced uneven increments in the impact force. Notice in the 67 joules was almost as high as the 81 Joules, because the sample at 67 joules did not bounce after impact creating a greater impact force value.

The comparison between the striking energy to the impact force is shown in Table 4.2. The maximum impact force on the fiberglass samples was 5102 N, which resulted in fiber cracking and delamination on the sample but not total penetration. The 6 ply samples demonstrated greater flexibility that absorbed the impact and did not allow total penetration at the stipulated testing conditions.

Table 4. 2 Energy and Impact Force

Energy	Max Impact Force
20 J	1543 N
27 J	1711 N
34 J	1837 N
40 J	1944 N
54 J	2563 N
62 J	2738 N
67 J	3691 N
81 J	3853 N
102 J	5102 N

Figure 4.2.2 Impacted Samples

In summary, the impact tests on the GFRC laminates demonstrated to a satisfactory degree, the efficacy of the instrumented drop-weight impact test equipment built at the Florida Advanced Center for Composites Technology. The force transducer accurately reported the impact force exacted on the laminates. Kinetic energy on impact was easily calculated, giving an indication of the projectile impact energy. Impact energy absorbed by the laminates may be obtained from the area under the force-distance curve.

4.2.2 Material Characterization Tests

The purpose of the tests was to determine the impact behavior of different types of composite laminates. Composites with different reinforcements were tested. A recently developed fiber called Spectra was combined with carbon and compared to a carbon-Kevlar composite. Spectra fiber is mainly used for ballistic protection because of its strong properties. Kevlar is also a strong fiber used for years now in very similar applications.Two orientations of carbon-spectra laminates were used. The fibers combinations are shown in Table 4.3.

Table 4.3: Fiber combinations for tested laminates

CK4545	CK090	CS090	CS4545	CS4545
This was a sample of combined carbon and Kevlar fibers, arranged in a 45° 45°	This was a sample of combined carbon and Kevlar fibers, arranged in a 90°0°	This was a sample of combined carbon and Spectra fibers, arranged in a 90°0°	This was a sample of combined carbon and Spectra fibers, arranged in a 45°45°	This was a sample of combined carbon and Spectra fibers, arranged in a 45°45°

The fabrication of the samples was done specifically for a test to show which combination is stronger over the same circumstances and to determine their impact resistance. In order to acquire the maximum impact force, the material can handle the penetration level is crucial and so only 3 plies where used in the creation of the samples tested. The impact test results are shown in Figure 4.4. The smaller graphs on the left (CS090 and CS4545-1) represent the first tests performed on the carbon/spectra combination, which showed that when subjected to 25 J (kinetic energy), the material would not break.

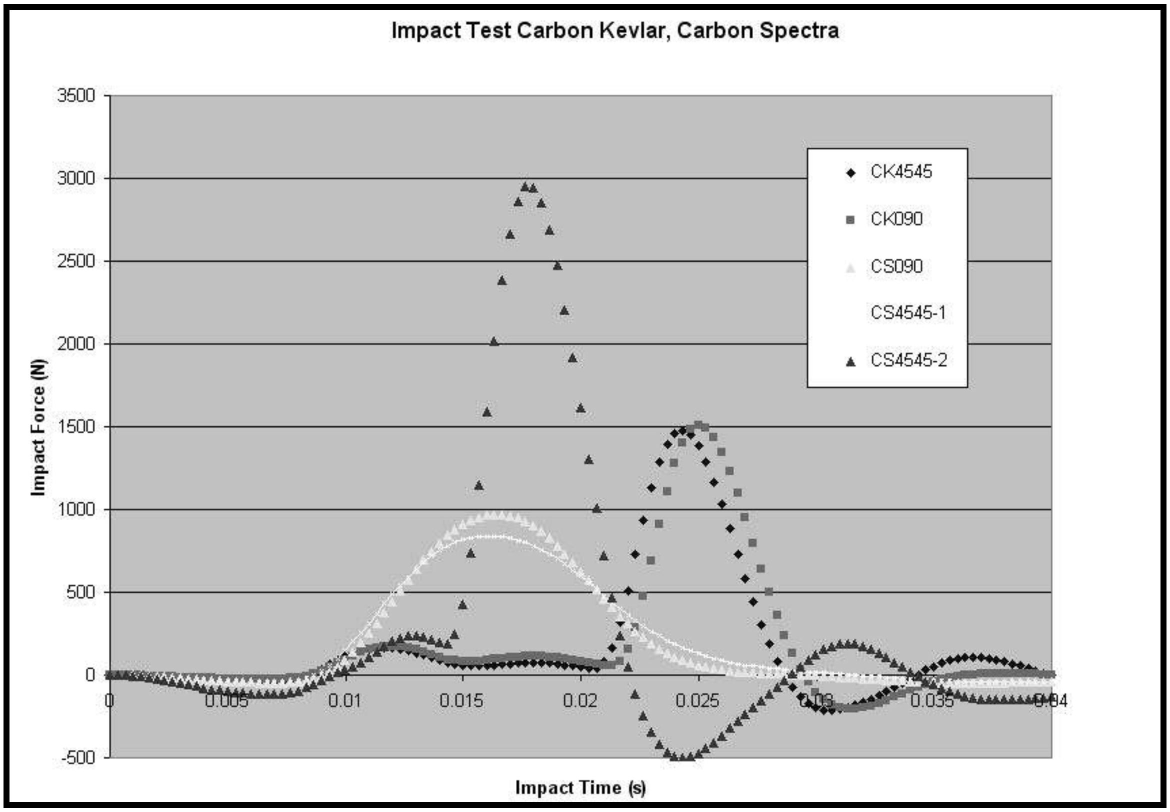


Figure 4.2.2.1 Impact test on Carbon Kevlar and Carbon Spectra

On the other hand, the carbon/Kevlar combination demonstrated to be much weaker and when subjected to the same 25 J the material was completely penetrated. The highest value in the un-penetrated carbon/spectra samples was around 900 N meanwhile the same energy applied to the carbon/Kevlar resulted in 1500 N and total penetration. Then in order to find the maximum value for the carbon/spectra sample, twice the energy was used (50J). The result was notable because the sample was completely penetrated and showed almost twice as much resistance than the carbon/Kevlar. Overall these simple tests were successful in demonstrating how the impact analysis combined with the data acquired with the impact tester can successfully differentiate the material characteristics and performance.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The completion of the low velocity impact tester fulfills all the objectives determined at the beginning of the project. The main purpose of the project was to create reliable impact tester that would accurately strike the same point repeatedly and would gather the information regarding the velocity and the force at impact. The limitations stated were the space, money and materials and the equipment was completed within these parameters.

The complete construction cost of the impact tester totalized to the $3,000 budget. The material cost accounted for almost one half of the cost, and the instrumentation and software represent the remainder of the costs.

5.2 Improvements

The constant strive for a more accurate and precise equipment resulted in several small changes made to the machine. The cable connecting the force transducer to the data-logger broke several times due to whiplash. To resolve this, a special casing was designed and built to protect the force transducer. Furthermore, the holding brackets for the photogates were redesigned. The new fixture now holds the photogates in a more convenient way so the cable of the transducer would not get stuck on the photogate holders.

Furthermore, modifying the photogate obstruct plate increased the resolution of the velocity-time measurements. This also enabled the estimation of the projectile penetration distance traveled within the specimen.

5.3 Testing Recommendations

During testing, the positioning, clamping, and bouncing of the sample may interfere with the results and the instrument performance. It is important to understand this effect before performing a test. Moreover, when impact-testing non-flat samples special care must be observed during sample positioning in order to strike the sample at the right point and still acquire the information needed. For example an experiment was performed on airplane nose cones. The first test showed that the shape of the transducer would interfere with the nose penetration; therefore some support was positioned inside the cone to stop the sensor after penetration. This solution worked and utilizable data was acquired. In the same test, aluminum inserts were placed inside the composites to increase the impact resistance. The results showed a small increment on the material overall performance in that given shape, but the material visible failure was transferred to the edges of the aluminum insert making the material analysis more complex.

Bouncing can be an issue when performing impact testing. Clamping a sample or securing it with some adhesive tape may be useful depending on the test being performed. Caution should be observed, since specimen clamping introduces complexities to the test system. The actual bouncing of the sample results in a strong resonance affecting the transducer sensitivity. The weights on the impact tester can be set on the impactor and in practice; small pieces of rubber have been placed underneath to decrease the metal-to-metal contact.

5.4 Weight Handling Recommendation

After several tests, it was clear that using the tester with large weights could prove difficult to handle. When adding additional 5 lbs weights to the tester, the base can be as heavy as 45 lbs, which can difficult to handle with one hand. So far no problems have been presented, but it is something to be cautious about when doing tests at 5 or 6 ft. A pulley system or pneumatic system to pull the weights up could be implemented in future improvements.

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