EFFECTS OF UV LIGHT AND MOISTURE ABSORPTION ON THE IMPACT RESISTANCE OF THREE DIFFERENT CARBON FIBER-REINFORCED COMPOSITES

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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DEDICATION

To my parents, my friends, and well wishers

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ABSTRACT

Carbon fiber is extensively used in aircraft components and structures, where its superior strength-to-weight ratio far exceeds that of any metal. Thirty percent of all carbon fiber is used in the aerospace industry. The purpose of this research was to determine the influence of material properties on the impact response of a laminate, whereby specimens were fabricated and cured under a vacuum and high temperature using three types of pre-impregnated (prepreg), carbon fibers, namely unidirectional fiber, plain weave woven fiber, and non-crimp fiber. Each carbon fiber panel, usually known for its low-impact properties, with respective type of prepregs, of 16 plies underwent impact testing using a low-velocity impactor and visual damage inspection by C-scan in order to measure the damage area and depth, before and after impact testing. These panels were treated with UV exposure and moisture conditioning for 20 days each. Water contact angles were taken into consideration to determine the hydrophobicity and hydrophillicity of the respective prepreg material. Experimental results and damage analysis show that UV exposure and moisture conditioning showcased the variation in impact response and behavior, such as load-carrying capacity, absorbed energy, and impact energy of the carbon fiber panels. This study illustrates that non-crimp carbon fiber laminates were far more superior relative to load capacity than woven and unidirectional laminates, with the NCF-AS laminate exhibiting the highest load capacity of 17,244 lb/in (pre-UV) with only 0.89% decrease after UV exposure. This same laminate also had a 1.54% decrease in sustaining impact and 31.4% increase in wettability of the panel. Moreover, the study shows how symmetric and asymmetric stacking sequences affect the impact behavior of non-crimp fiber laminates. These results may be useful for expanding the capacity of carbon fiber, lowering costs, and growing new markets, thus turning carbon fiber into a viable commercial product.

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LIST OF ABBREVIATIONS

AS	Asymmetric
CF	Carbon Fiber
CFRP	Carbon Fiber-Reinforced Polymer
FRP	Fiber-Reinforced Polymer
GFRP	Glass Fiber-Reinforced Polymer
Gpa	Giga Pascal
J	Joule
NCF	Non-Crimp Fiber
NDI	Nondestructive Inspection
PW	Plain Weave
RFI	Resin Film Infusion
RTM	Resin Transfer Mold
S	Symmetric
UD	Unidirectional
UDPT	Unidirectional Prepreg Tape
UV	Ultraviolet
wt%	Weight Percentage

LIST OF SYMBOLS

^{o}C	Degrees Celsius
^{o}F	Degrees Fahrenheit
in	inch
J	Joule(s)
$\cup m$	Micrometer
%	Percent
lb	Pound
®	Registered
™	Trademark

CHAPTER 1

INTRODUCTION

1.1. Background and Motivation

Reinforced composites are widely utilized in diverse manufacturing industries and have been very popular in aviation, automobile, and military applications. Composites are made from constituent materials that have their own distinctive properties; when combined to form a new material system, they have outstanding properties compared to their parent materials. Since composites have significant mechanical, thermal, and chemical properties, they can be customized to meet the needs for an explicit application requiring either high-strength use, such as aerospace parts, or light-weight applications, such as competition sporting goods [1]. Carbon fiber (CF), also known as graphite fiber or carbon graphite, initially industrialized in 1960, is a material comprised of fibers about 5–10 μm in diameter composed mostly of carbon atoms. When united with a plastic resin, CF forms a carbon fiber-reinforced polymer (often mentioned as simply carbon fiber). It has remarkable properties, such as long fatigue life, corrosion resistance, and a high strength-to-density ratio. Frequently used composite materials are carbon fiber-reinforced polymer and fiber glass-reinforced polymer. However, they are comparatively expensive when compared to similar fibers, such as glass fibers or plastic fibers [2]

One of the main drawbacks of composite laminates is that there exists minimum reinforcement in the thickness direction, and they tend to fail as the result of delamination within the panel, such as fiber breaking, matrix cracking and these cracks in the laminate can be at micro and nanoscale size, so it is very difficult to detect thus resulting in the composite's loss of strength and stiffness. Another disadvantage in composite laminates is that they demonstrate brittle failure modes because the intermolecular forces between the carbon fiber layout patterns are relatively feeble van der Waals forces. The environmental factors are introduced into the polymeric composites during the time that the composites are in service and result in breakage of the carbon-hydrogen chemical bonds, formation of oxide species and larger molecules, and internal and external stresses. This development accelerates the aging process, produces fatigue cracks, and reduces the overall mechanical properties and lifetime of the aircraft composites. Making a thin layer of carbon fibers significantly enhances the fire resistance of polymers or thermoset composites because a compact stratum of carbon fibers efficiently reflects heat. Carbon fiber reinforced composites are a non-homogeneous type of material and the machining process plays a significant role in determining the strength of the composite. Therefore a composite laminate consists of compound layers of continuous fibers, with the fiber orientation present depending upon the structural applications of the manufactured composite laminate. Composites are used in applications that are prone to the impact of foreign objects. Hence, to abet in predicting and preventing failures, composites are studied in detail relative to their behavior under extreme structural conditions. A controlled impact test can diminish damage so that it does not spread widely from the initiation phase. A considerable variation in impact parameters can determine information about possible crack initiation zones and propagation. Materials may be tested after construction using several nondestructive inspection (NDI) methods, including ultrasonic's, thermography, shearography and X-ray radiography, which help a great deal in examining the external surfaces in detail [0,4].

Low-velocity impact is considered to be potentially uncertain mainly because the resulting damage may be concealed. Composites used for primary structural applications in aircrafts and in wind turbines are subject to bird strikes, hail damage, lightning strikes, etc. A low-velocity impact would diminish the structural integrity of the panels. The response of a structure to such an impact depends on its geometry, material, and velocity of both the impactor and a representative element of the structure [5]. The overall outcome of the impact can depend on all of these parameters.

The reason for this study lies in the importance of comprehending the response of structural composites to impact. This understanding comprises both the impact phenomenon itself and the influence of material properties on the impact response. This study shows the need for instrumented testing order to elevate our understanding of the impact event, particularly the response of the impacted material.

1.2. Goal

The primary focus of this thesis was to gain a better comprehension of elementary low-velocity impact phenomena, using three types of carbon fiber and examining their behaviors after undergoing UV radiation and moisture conditioning. What drew attention to this research was the test method development, as well as material and damage classification. Since the field of impact on composite structures is still relatively new, no usual established diagnostic methods or test procedures are available. In this study, composite plates composed of different combinations of carbon fiber and hybrid/carbon fiber impact-side facesheets were subjected to low-velocity impacts at energies of approximately 6.7 joule (J) [6,7]. It helps to construct a comparison, both analytically and quantitatively, among impact energies of diverse types of carbon fibers as well as the impact responses between the baseline and the conditioned panels. Moreover, study was also performed on the effect of stacking sequence of the non-crimp fibers under low velocity impact loading. While all parameters for this fabrication and experiment were kept invariable, the type of carbon fiber used was assorted. This type of investigation would identify and discriminate among the behavior of dissimilar types of carbon fiber under the impact of a low-velocity load and would help in predicting and preventing failures under extreme structural conditions. Figures 1 and 2 show the various types of composites used in aircraft.

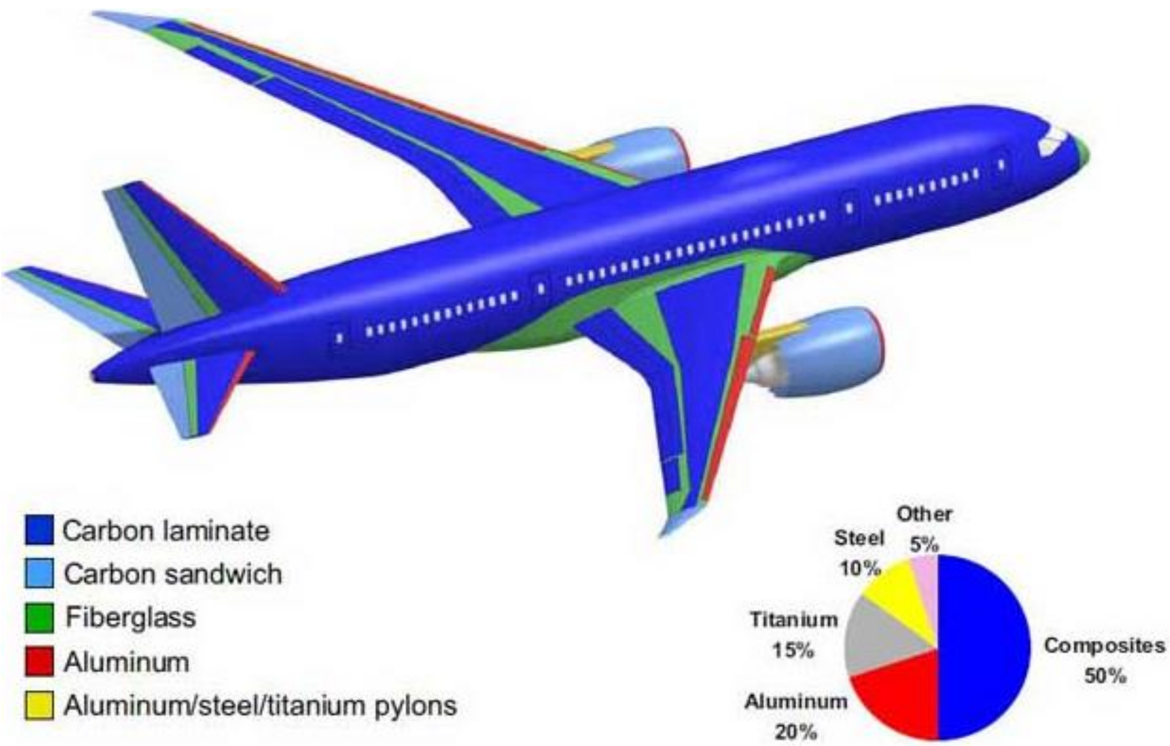


Figure 1: Usage of Composites in B-787 [9]

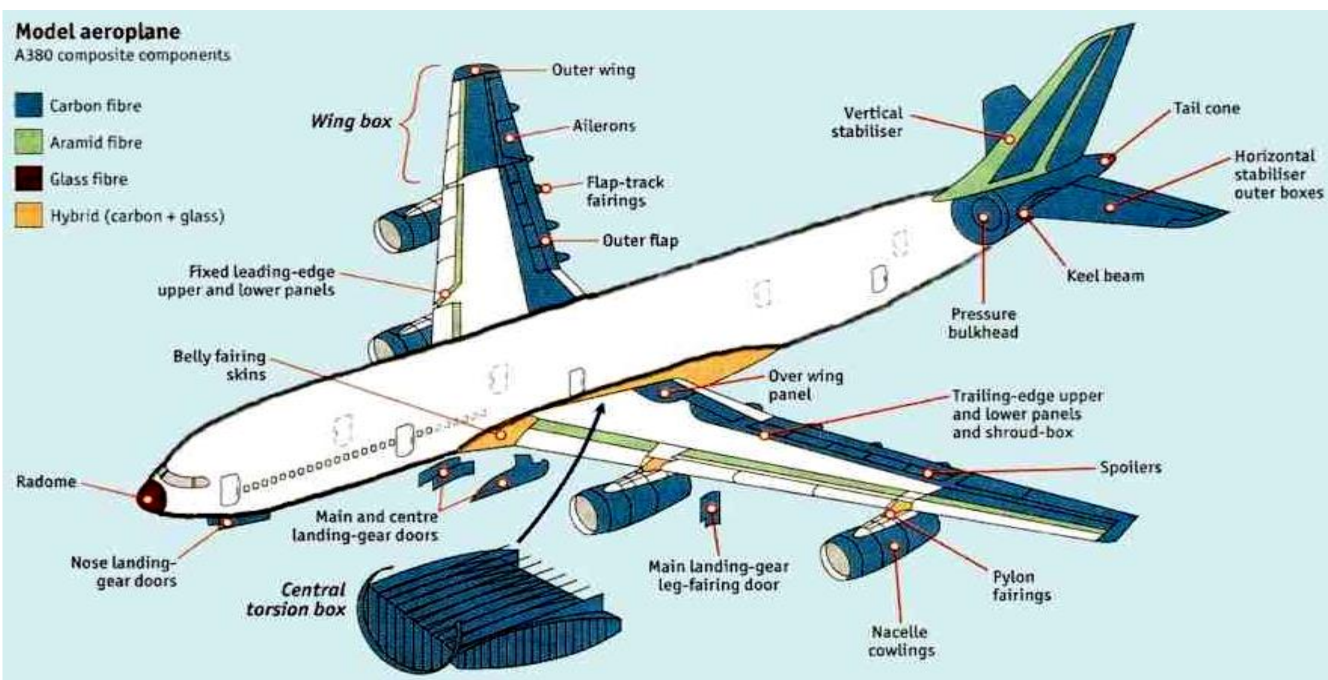


Figure 2: Composite Components Used in A-380 [9]

CHAPTER 2

LITERATURE REVIEW

2.1. Composites

A composite material is a blend of two or more constituent materials of significantly dissimilar material properties that together form a material superior to the parenting materials. A composite material is intended for better mechanical, thermal, or electrical properties and can be customized for suitable applications. Composites can be manufactured to be lighter, stronger, and more robust than the individual parent materials.

Few frequently used composites are concrete, where loose-fitting stones are assorted in cement, and plywood, in which wood is accumulated (glued) at different orientations (fiber directions) to make the entire material stronger. Another process, and currently the most discussed and researched, is fiber-reinforced polymers (FRPs). An FRP can be prepared using carbon fiber-reinforced polymer (CFRP) or glass fiber-reinforced polymer (GFRP). There are reasons and advantages for using FRPs. The vital benefit of using an FRP is that the composite material can be easily adapted to meet the respective application requirements while retaining the preferred mechanical, thermal, or electrical properties [8].

Carbon fiber is a new breed of high-strength material. Recent trends and forecasts of carbon fiber usage have remarkably multiplied. Next-generation lightweight materials, such as carbon-fiber composites, could reduce passenger car weight by 50 percent and improve fuel efficiency by about 35 percent without compromising performance or safety. In recent decades, carbon fibers have found extensive applications in commercial aircraft (up to 50% of the structure as composites), along with recreational (about 50% penetration in golf clubs and fishing poles) and industrial markets, because the price of carbon fiber has decreased and technologies have advanced. The market for carbon fiber has experienced good growth in recent years, except for 2009 due to recession in various parts of the world and economic turmoil. The growth rate for the last 23 years was about 10%. Figure 3 shows the trend between price and consumption of carbon fiber in various applications.

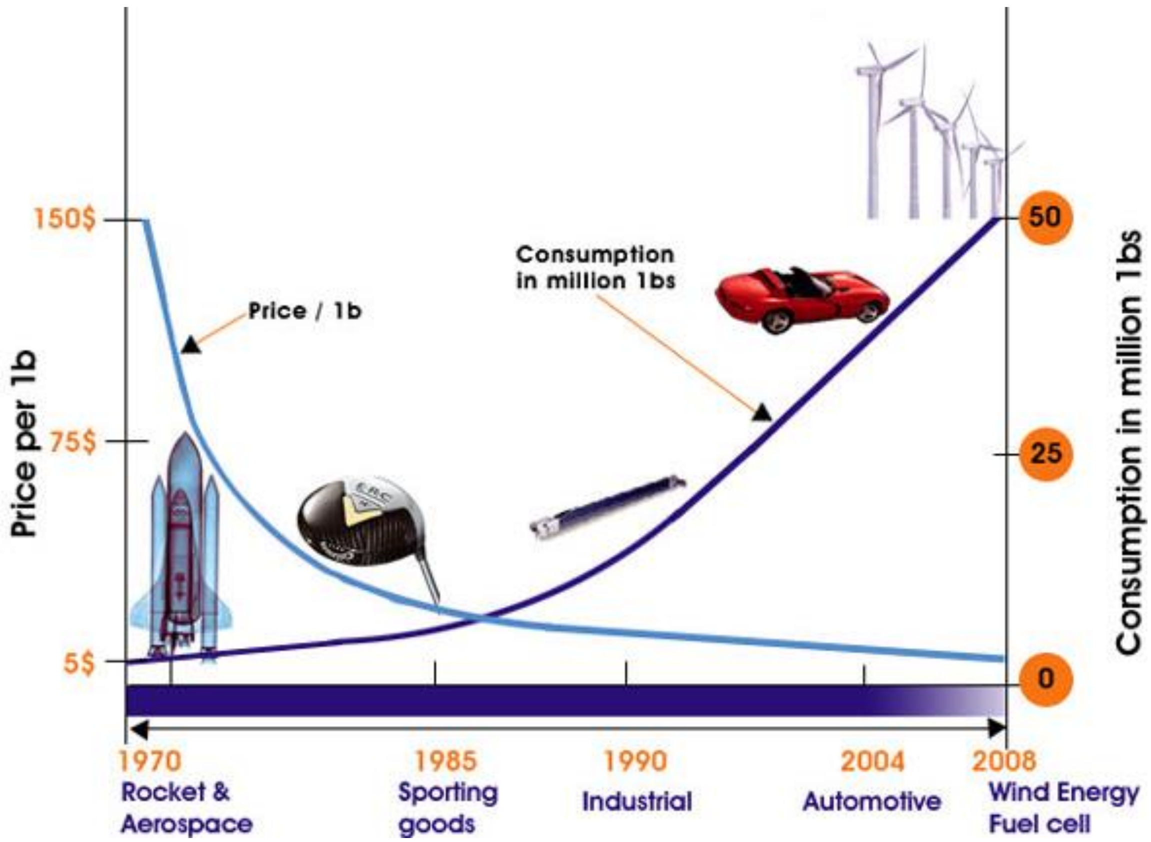


Figure 3: Trends and Forecast of Carbon Fiber in Recent Years

In any case of creating composites, two chief components involved: fiber and matrix. The matrix, or the epoxy, for polymers is classified into two types: thermosets and thermoplastics, each having their own pros and cons, but more importantly, they can be used and regulated for a particular application, or they can be a preference for use with a fiber to engineer the necessary composite. Figure 4 shows an illustration of a carbon fiber composite specimen.

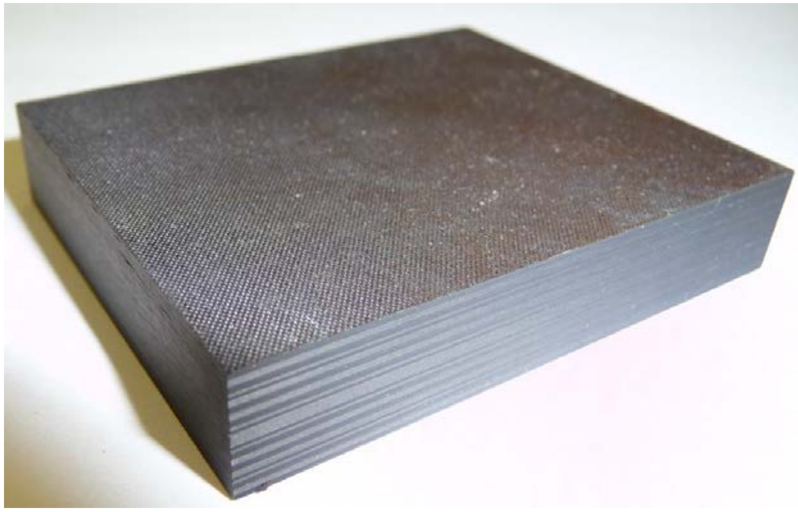


Figure 4: Composite Laminate Specimen [9]

2.1.1. Fiber

The strengthening ingredient material in a composite is the fiber, which mainly carries the load through the composite laminate. The fiber maintains the rigidity of the composite while impeding crack or damage propagation. Carbon fibers are fundamentally very thin strands of carbon, even thinner than human hair, which can be twisted collectively, like yarn. The yarns can be woven together, like cloth. To make carbon fiber take on a permanent shape, it can be laid over a mold and then caked with a stiff resin or plastic. Supplanting steel components with carbon fiber would reduce the weight of most automobiles and aircrafts by 60 percent.

A few advantages and disadvantages of carbon fibers used in industry are as follows:

Advantages

- Very lightweight.
- Five times as strong as steel, and lighter and stronger than glass.
- Two times as stiff as glass fiber, with high modulus and high strength (ultimate high modulus = 2.2 Gpa, ultimate high strength = 2.7 Gpa).
- Durable and safe.

Disadvantages

- Cost, the main stumbling block that carbon fiber must overcome in order to provide a feasible energy solution.
- Waste disposal.
- Difficulty to recycle.
- Time consuming to manufacture

A unidirectional (UD) fiber is one in which the bulk of fibers run in one direction only. A small quantity of fiber or other material may run in other directions with the main intent being to hold the prime fibers in position. Unidirectional fibers typically have their crucial fibers in the 0° direction (a warp UD) but can also have them at 90° to the roll length (a weft UD). UD fibers are straight and non-crimped [10]. For mechanical properties, unidirectional Fiber can only be enhanced on by prepreg unidirectional tape, where there is no inferior material at all holding the unidirectional fibers in place. In these prepreg products only the resin system binds the fibers in place [11]. A unidirectional prepreg is shown in Figure 5.

Figure 5: Unidirectional Prepreg [9]

Plain weave carbon fiber is generally used for insubstantial aerodynamic parts. It wets out quickly and handles easily. A plain weave is defined as a 1X1 weave, meaning the weave is built on a pattern of one fiber over, one fiber under, etc. There is practically no distinction in the strength of the fabric based on its weave. Preference of weave depends on the aesthetics, curve, and weight of the fiber considered necessary for the application. For each fiber bending over or under another, its strength can be compromised to some degree. A plain weave, or 1X1 weave, is the tightest weave. Because the weave is rigid, it is the most likely not to fray at the ends [12]. An example of a plain weave composite is shown in Figure 6.

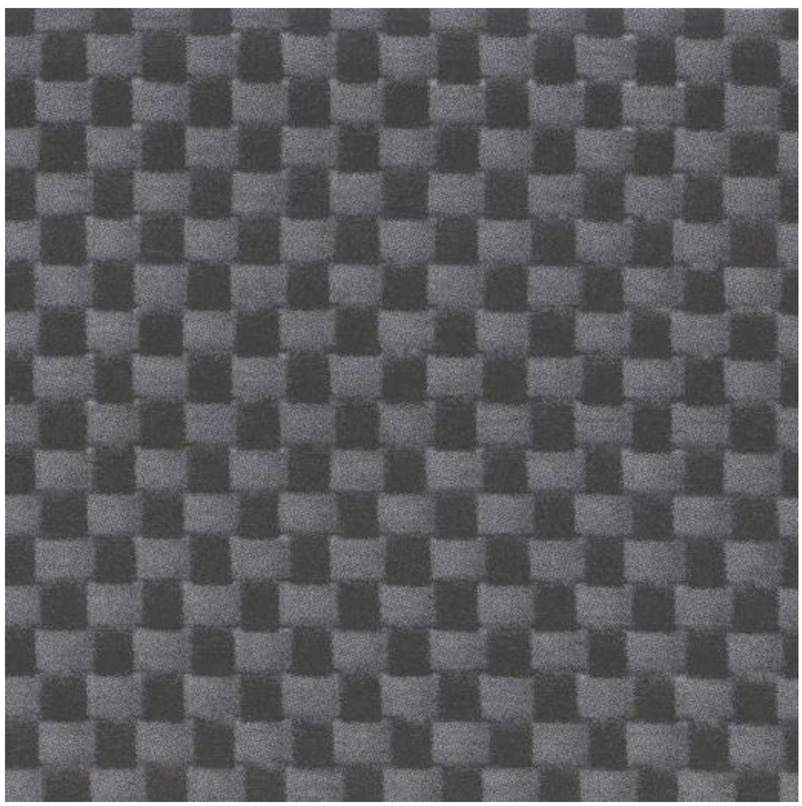


Figure 6: Plain Weave Composite (1X1) [9]

2.1.2. Matrix

Interfaces are amid the most significant and least talked about components of a composite material [14]. The matrix plays a significant task in a composite for the following reasons:

- Holds the reinforcement in the preferred orientation.
- Serves as the intermediary for transmission of load within the fiber.
- Shields fibers from risky environmental effects like moisture and corrosion.

The choice of matrix according to the application requirements can vary among ceramic, metal, and polymer. The most commonly used matrix these days is a polymer resin, such as Epon™ 828. Matrixes can be classified into thermosets and thermoplastics.

Thermosetting resin is a petrochemical that exists in a supple solid or tacky state and then changes irreversibly into an infusible, insoluble polymer network by curing, which encourages polymer chain cross-linking. Curing can be induced using heat or appropriate radiation, or both. A cured thermosetting resin is called a thermoset, such as epoxy, phenolics, bismaleimide, and fluoropolymers. Thermoplastic resin is a polymer that transforms into a liquid when heated, and freezes to a glassy condition when left to cool adequately. Thermoplastics are flexible and supple over the glass transition temperature and can go through melting/freezing cycles continually [13]. Thermoplastics are known to be superior for their impact resistance. But in contrast to thermosets, manufacture of a thermoplastic material is far more intricate with sophisticated methodologies. Thermosets are generally stronger than thermoplastics due to polymer cross-linking, and they have a higher tolerance for heat [14]. Hence, comparing two polymer type matrices, thermoset resins demonstrate elevated strength and stumpy shrinkage during curing. They are known for their toughness and resistance to chemical and environmental harm. Depending on the formulation, epoxy resins are used as casting resins, potting agents, resin binders, or laminating resins in fiberglass or composite production. One such resin used for easy fabrication is Epon™ 828, an adaptable resin system.

2.2. Pre-Impregnated Fiber

Prepreg is an idiom for “pre-impregnated” composite fibers, where a matrix substance such as epoxy, already exists as the current medium. The fibers frequently take the form of a weave, and the matrix is used to join them together and to other components during manufacture. The matrix is cured to allow easy handling. This is called B-Stage material and requires cold storage to prevent complete curing, since heat quickens complete polymerization. Therefore, composite structures built of prepregs will mostly necessitate an oven or autoclave to cure. A prepreg allows the fibers to be saturated on a flat workable surface and then later formed into an outline using the hot injection process. The prepreg also allows a bulk amount of fiber to be impregnated and then stored in a cooled area for an extended period of time to cure later. However, this process can be time consuming, in comparison to the hot injection method.

The first, and most important, benefit of using prepregs is their ease of use. To fabricate a flat panel out of carbon fiber and epoxy resin, the epoxy resin and hardener are used to form the epoxy. Most epoxy hardeners are considered unsafe, and dealing with resins in a liquid state can be messy. Secondly, with an epoxy prepreg, only one quantity needs to be ordered. Thirdly, prepregs come with sheet-like films on both sides of the fabric to shield it during transit and preparation. Then the prepreg is cut to the preferred shape, the film is peeled off, and the prepreg is laid into the mold or tool. Both heat and pressure are then applied for a precise amount of time. Some of the most general types of prepregs take an hour to cure, at approximately 250 degrees F, but different systems are available for both lower and higher cure temperatures and times. In view of the fact that the epoxy is in a B-stage, it must be refrigerated or frozen prior to use. In addition, the overall shelf life can be low and Pre-impregnated fibers also reduce the possibility of defects during the manufacturing of composite panels. This is why I preferred using prepregs in my study. Figure 7 shows examples of an epoxy-filled carbon fiber prepreg roll.

Figure 7: Carbon Fiber Prepreg [9]

2.3. Non-Crimp Fibers

Pre-impregnated tapes are still the main alternative for designing load-bearing structures. Nevertheless, due to their elevated material costs, sensitivity to out-of-plane loads, and heterogeneous structure, the use of composites fabricated from pre-impregnated tapes has been restricted. Non-crimp fabric-based composites address both of these concerns, without any considerable decrease in in-plane performance [15]. Because of their outstanding through the thickness performance, NCF are a very good choice for primary structural applications in aerospace, marine and automotive applications. Non-crimp fibers (NCFs) are bundles that are kept collectively by a thin polyester knitting yarn instead of weaving the bundles together as described for the woven composites. Multiaxial layers, which are configured to each customer's unique structural requirements at angles of 0, 90, +45, and –45 degrees, are then held together in place by a stitch matrix, as shown in Figure 8.

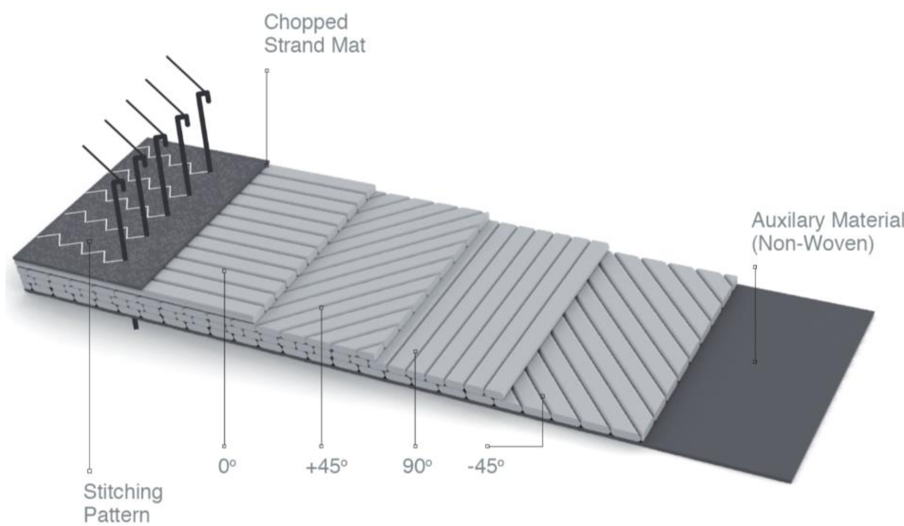


Figure 8: Schematic Diagram of NCF Composite [16]

Moreover, non-crimp fabric offers the following advantages in specific applications:

- Increasing stiffness at low density.
- Better mechanical properties due to a higher fiber volume fraction with respect to traditional fabrics (lower resin consumption), and a higher impact strength.
- Fibers in stitch-bonded fabrics are straight and directly aligned with the load path, therefore more fatigue resistant.
- Improved interlaminar strength and lower resin consumption since the surface finish has fewer interstices, meaning less resin usage.
- Improved interlayer wet out.
- Shorter process cycles because the extensive choices of fiber orientation helps to avoid the manufacture of traditional fabrics that need to be offset in layup; therefore, fewer

layers need to be included in the laminate sequence, which reduces application times in the final composites structure.

- Easily adjustable drape ability of the fabric is because of its variable stitch construction.

NCF bundles are kept together collectively like knitting yarn, which hypothetically should produce a bundle of fibers without out-of plane waviness in the fiber bundles. This built-up technique creates dry fibers that are effortlessly shaped into intricate shapes before it is consolidated into the ultimate composite. Carbon fiber non-crimp fibers are especially used because they offer superior stiffness at low density. This is key reason for why this research has focused attention on NCF prepregs [16].

The first NCF fabrication of a +45° ply knitted mutually with a –45° ply to form a double-bias fabric occurred in 1983. It is known that one layer in the NCF composite corresponds to approximately four prepreg layers. Parameters for the prepreg fabrication are the following: fiber used in the tows, inter-tow gap, stitch tension, stitch type, stitch density, and stitch material. Figure 9 shows the material structure of NCF composites.

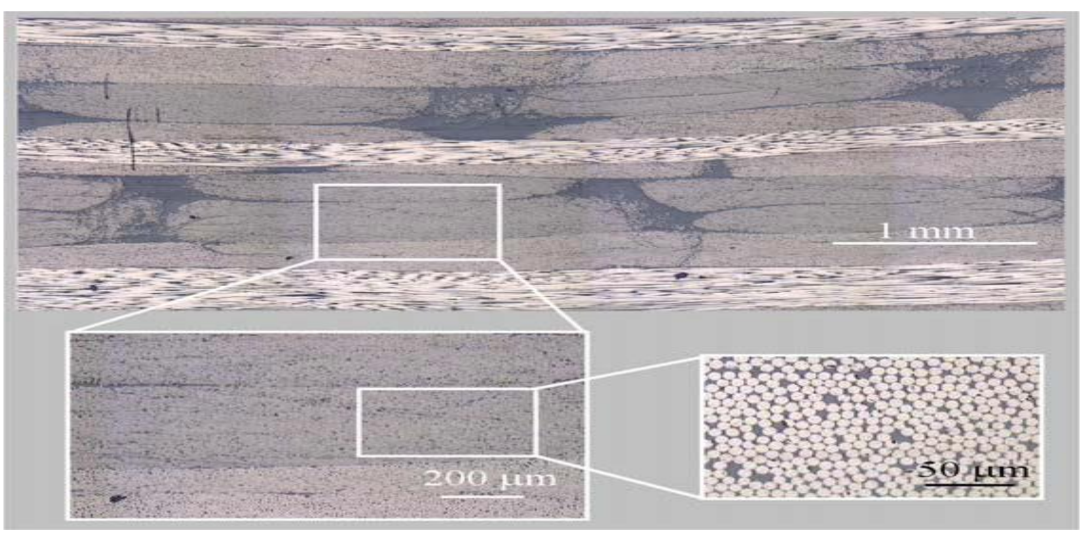


Figure 9: Hierarchical Structure of NCF Composites [16]

When exploring the mechanical properties of an NCF composite, it has been reported that they reveal higher out-of plane fracture toughness and damage tolerance when evaluated with unidirectional prepreg tape (UDPT) laminates. Usually NCF composites are considered to have lesser tensile strength in comparison to corresponding UDPT composites. Conversely, the strength degradation shows a significant discrepancy due to disparity in volume fraction of fibers, damage, and misalignment stimulated in the fibers by the knitting process. However, it has been found that the flexural strength of NCF composites is 15% less compared to the equivalent UDPT composites, which might signify that NCF composites have mediocre flexural properties compared to UDPT composites. Moreover, inconsistency also showed that among interlaminar shear strength and compressive strength of NCF composites due to failure modes, delamination occurred between different oriented plies and brittle failure along the tension side [16].

The literature review regarding NCF composites revealed that NCF laminates have been fabricated using three diverse manufacturing techniques. Prepregging the fabrics followed by auto-clave curing by resin film infusion (RFI) and resin transfer mold (RTM) showed that prepregged NCF composites and prepreg tape-based composites with an identical layup had analogous behavior under impact. It was also established that NCF composites fabricated by RFI and RTM showed increased impact resistance with a lower level of damage for a known impact energy [16].

However an analytical study should be carried out on a comparison of impact resistance between NCF carbon composites, unidirectional and plain weave. One of the main shortcomings of fiber-reinforced plastics compared to metallic structures is intricacy, because many dissimilar unidirectional layers must be processed manually in a mold. One solution to avoid this is by using non-crimp fibers. Laminates prepared with NCFs show superior compressive strength than woven fabric composites due to less waviness. NCF composites have elevated fiber volume fractions and thus higher strength, in view of the fact that they do not have resin pockets, which is in contrast to woven fabrics. Adams. D. studied the mechanical properties and failure mechanisms of a glass fabric/epoxy composite and used unstitched plain weave and biaxial non-crimp fabrics for evaluation. They reported that the compressive strength of non-crimp laminate samples was about 15% superior to the woven fabric composites because of the waviness in the woven fabric composites. For woven fabric composites, the failure mechanism mode was delamination followed by microbuckling and global buckling, while the non-crimp fabric composites appeared to fall short via kinking followed by fiber buckling [17].

2.4. Impact Test

In simple terms, an impact is defined as an elevated force or shock applied over a short time phase when two or more bodies collide. Such a force or acceleration generally has a superior effect over a lower force applied over proportionally longer time duration. The effect depends critically on the relative velocities of the bodies to one another.

Currently three impact tests are used to test specimen material, i.e., Charpy, Izod, and drop weight. The Charpy and Izod impact tests are pendulum category tests, whereby an impactor swings to strike the specimen and the response of the specimen is mapped out in terms of the energy absorbed. This type of test can determine the toughness of the material. The drop test is a falling weight test, which predominately judges the impact energy to failure of the specimen. It helps in obtaining knowledge of the damage resistance properties of a laminated composite plate which is useful for product development and material selection. Moreover, it helps to compare quantitatively the relative values of the damage resistance parameters for composite materials with different constituents. The damage response parameters can include dent depth, damage dimensions, and through-thickness locations.

2.4.1. Charpy Impact Test

The Charpy impact test, also known as the Charpy V-notch test, is a quality, high strain-rate test that follows ASTM standard testing (E23), which establishes the amount of energy absorbed by a material during fracture. This absorbed energy is an evaluation of a given material's notch toughness and acts as a medium to comprehend temperature-dependent ductile-brittle transition.

The standard Charpy test specimen is comprised of a bar of metal or other material such as composites, ceramics, or polymers, with a 55 x 10 x 10 mm notch machined across one of the larger measurements. The V-notch should be 2 mm deep, and have a 45° angle and 0.25 mm radius alongside the base. The U-notch and keyhole notch should be 5 mm deep with a 1 mm radius at the base of the notch. The Charpy impact test involves striking a suitable sample with a hammer on a pendulum arm while the sample is held firmly at each end. The hammer strikes opposite the notch. The energy absorbed by the specimen is accomplished by precisely measuring the decrease in motion of the pendulum arm [17].

2.4.2. Izod Impact Test

Izod impact testing is another ASTM standard scheme (D256) of determining the impact resistance of materials. This test is like the Charpy impact test but uses a dissimilar array of the specimen under testing. The notched Izod impact test is a single-point test that determines a materials resistance to impact from a swinging pendulum. It is defined as the kinetic energy essential to initiate fracture and sustain the fracture until the specimen is broken. Izod specimens are notched to avoid deformation of the specimen upon impact.

The standard ASTM specimen is 64 x 12.7 x 3.2 mm (2½ x ½ x 1/8 in). The most communal specimen thickness is 3.2 mm (0.125 inch), but the ideal thickness is 6.4 mm (0.25 inch) because it is not expected to bend or crush. The depth under the notch of the specimen is 10.2 mm (0.4 inch). The specimen is fastened into the pendulum impact test fixture with the notched side facing the striking edge of the pendulum. The pendulum is unconstrained and permitted to strike through the specimen.

2.4.3. Drop Test

Drop testing is executed for numerous reasons: to devise impact-tolerant manufactured goods; to reproduce the damage that might occur during manufacturing, shipping, and installation; and, to expedite life testing. In this test, a weight is dropped in the vertical direction using rails or guides to impact the test specimen. This load dropping on the specimen is a dynamic load, meaning it is isolated after a few milliseconds. Drop weight impact testing imitates real-life conditions. For that reason, in this investigation, the drop-weight testing method was ideal for performing low-velocity impact testing.

2.5. Test Standards

2.5.1. ASTM for Drop-Weight Impact

ASTM D7136/D7136M is the preferred test standard used for evaluating the damage tolerance of a fiber-reinforced polymer matrix composite to a drop-weight impact. The scope of this investigation was to establish the damage resistance of a composite panel with multidirectional layers and a polymer matrix, and was restricted to continuous fiber reinforcement only. This type of test is used for screening materials for damage resistance or to impose damage onto a specimen. The importance of this test is to achieve knowledge of the damage resistance properties of a laminated composite panel. The information obtained helps in product expansion and selection of material. With this test, the damage resistance boundaries can be quantitatively evaluated for different variants in a carbon-epoxy composite material. The composite plate should be flat and rectangular in shape, and would be subjected to an out-of-plane impact force intensified at the center of the panel. The impact on the panel is made with a drop-weight device having a hemispherical impactor. The potential energy of the impact, which is the resultant of the product of mass and drop height of the impactor, is converted into kinetic energy at the time of impact as based on the principle, “law of conservation of energy”. The drop-weight impact test tower is equipped with contact force and velocity measurement devices. The damage resistance properties of the test panel are governed by many factors, such as specimen geometry, layup, impactor geometry, impactor mass, impact force, impact energy, and boundary conditions. Figure 10 shows the impactor equipment mechanism.

Figure 10: Drop-Weight Impactor Equipment Mechanism [9]

2.5.2. ASTM for Ultraviolet Conditioning

Following specimen machining, and prior to conditioning, it is important to execute a baseline non-destructive examination of the specimen to distinguish flaws or defects that may exist prior to impact testing. A range of NDI techniques are available for detecting both surface and interior flaws in composites. Visual inspection and liquid penetrant methods can be used for identifying surface defects, while more sophisticated techniques are required for detecting internal flaws such as cracks, splits, and delaminations. The amplified use of fiber-reinforced polyester composites in an outdoor environment has led to uncertanity concerning the environmental resilience of these materials, particularly when exposed to ultraviolet (UV) light. Under natural sunlight, environmental effects can change the configuration of a material; this effect is often referred to as weathering. UV light, moisture, and air are three critical factors for in material degradation. In this thesis, the effects of UV radiation on mechanical properties of carbon/epoxy composites were explored in great detail. Since UV is a surface mechanism, it is constrained to the degradation of the mechanical properties of resin and does not involve fiber degradation. The focus here targeted resin properties and the rate of resin depletion. Test samples impregnated with epoxy resin were treated in a UV chamber through accelerated tests.

ASTM D4329 and ASTM D4587 are the preferred standards used to expose test samples to unstable conditions of the most destructive components of weathering namely, ultraviolet radiation. Here, a UV test chamber uses fluorescent lamps to provide a radiation spectrum that is centered in the ultraviolet wavelengths. In general, flat plates or disks are used for accelerated weathering studies. Depending upon the performance, such an evaluation may involve measurements of haze, yellowness index, color change, or physical properties such as impact strength [18,19].

2.5.3. ASTM for Moisture

The recommended pre-test condition is effective moisture equilibrium at a specific relative humidity, as established by ASTM D5229/D5229M. The phrase "moisture," as used in this test method, includes not only the vapor of a liquid and its condensate, but the liquid itself in large quantities, as in the case of immersion. Kumosa and Kumosa stated that customized polyester-based composites have demonstrated the worst moisture absorption performance. Epoxy-based materials had sufficient rates of absorption; however, these materials did not accomplish equilibrium and slowly kept taking on more moisture [20].

However, in this conditioning test, the porosity or void fraction, which is a measure of voids in a material, becomes apparent. This is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0% and 100%. The composites were bare in a damp environment with a relative humidity of 56% at 53°C, and different exposure times for sample conditioning, performance under environmental exposure, and decision on material selection were determined.

2.6. Impact of Prepreg Panels

Lin, H.J has stated that low-velocity impact was generally quasi-static in nature except for localized damage [21]. Sjoblom et al. stated that the energy loss during impact is a more direct evaluation of the damage formed during impact than the impact energy [1]. Both the impact and rebound velocities should therefore be calculated accurately. The epoxy panels showed two very dissimilar failure accounts: delamination and back-face damage, which resulted in both matrix cracking and fiber failure. Future work should focus on the expansion of a consistent test for impact resistance. Efforts should be made to develop smaller, laboratory-size impact specimens for preliminary material characterization. Also, more research must be prepared in the area of analysis of failure performance after the primary elastic response of plates subjected to resolute transverse loads, both analytically and experimentally. More work is also required in the area of damage inspection and characterization. A through-thickness C-scan is insufficient, since it gives no depth information.

Berketis also concluded that low-velocity impacts, at levels of premeditated energy, caused compressive strength reduction. Environmental exposure causes a marked decrease in the residual compressive strength, even if no impact damage is present. Impact damage introduced after water immersion caused a larger drop in strength, compared to damage from the impact introduced before water immersion at the same energy levels. The harshness of damage caused by the impact increases with span of time and temperature. This is an outcome of the fact that material immersed in water degrades, the resulting deprivation being a function of time and temperature [0]. Therefore, the study in this thesis focused on using consistent low-velocity impact energy of 6.7 J on all fabricated laboratory specimens and implementing a head-to-head comparison between baseline and conditioned specimens for material characterization, which also aids in failure analysis between different carbon fiber-reinforced composites. Figures 11 and 12 show different modes of failure at which damage takes place and damage propagation on an impacted area.

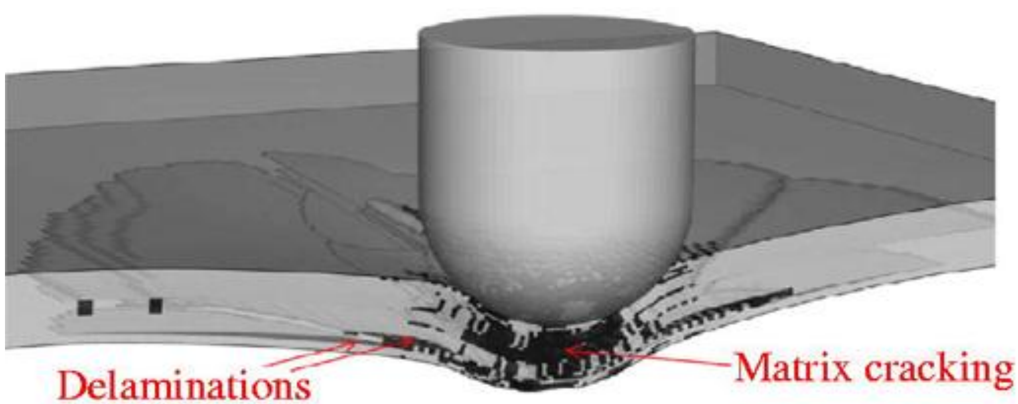


Figure 11: Failure Modes Imparted by Impactor [23].

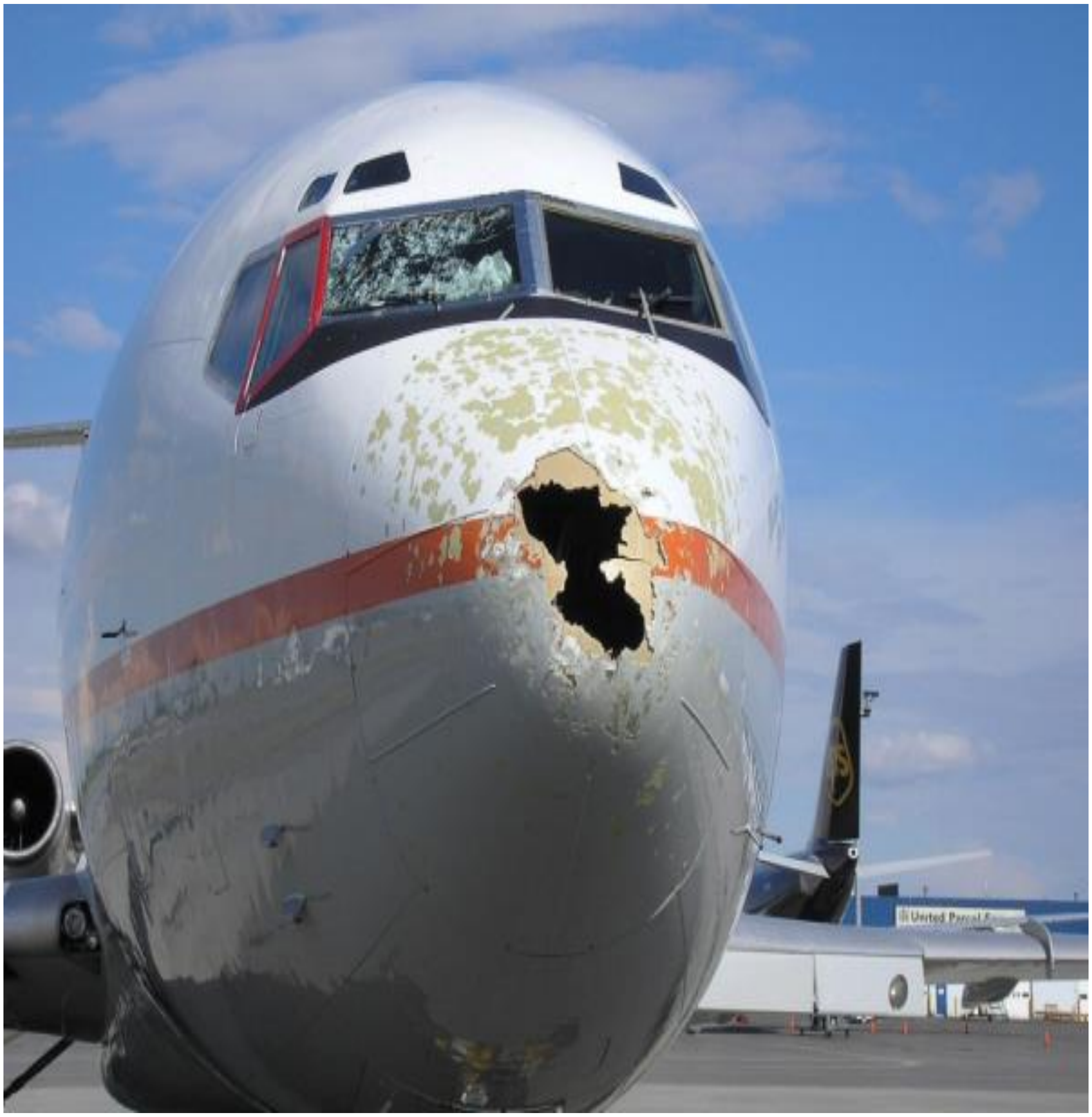


Figure 12: Damage on Nose of Aircraft Due to Bird Strike [9]

CHAPTER 3

EXPERIMENT

3.1. Materials

A unidirectional tape laminate (Cytec 5320-1), like that shown in Figure 13, was manufactured with the appropriate number of unidirectional plies to accomplish a total cured thickness nearest 0.254 mm (0.010 in) with a stacking sequence of [45/0/–45/90]NS. This laminate was fabricated with a ply count of 16 according to ASTM D5687/D5687M. The laminated plate layup was well-defined such that the 0° fiber orientation was allied with the lengthwise (long) dimension. Figure 13 shows unidirectional tape laminates.

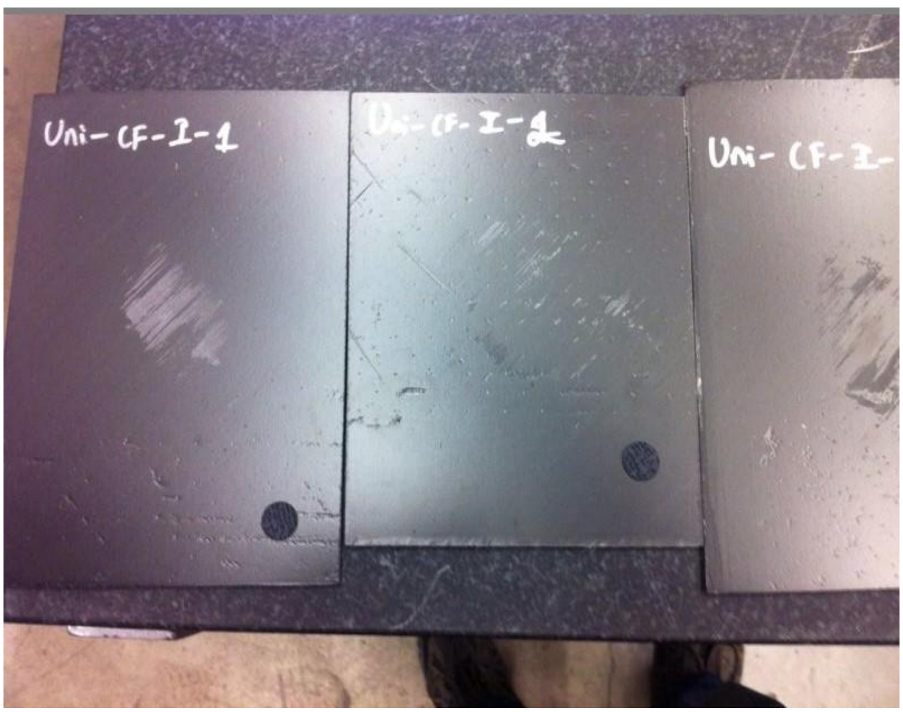


Figure 13: Unidirectional Carbon Fiber Laminates

Woven fabric laminate (Cytec 5320-1), like that shown in Figure 14, was constructed with the appropriate number of fabric plies to accomplish a total cured thickness nearest 0.254 mm (0.010 in) with a stacking sequence of [(+45/–45)/ (0/90)] NS, and the ply count was 16, according to ASTM D5687/D5687M. The designations (+45/-45) and (0/90) represent a single layer of woven fabric with the warp and weft fibers oriented at the specified angles. Figure 14 shows fabricated woven CF laminates.

Figure 14: Woven Carbon Fiber Laminates

Laminates fabricated using other layups or fiber orientations, or both, were evaluated for drop-weight impact damage resistance using this test method. Damage characteristics and failure strengths of the composite laminates were examined, and composites were fabricated using a polyester matrix with three different carbon fibers: non-crimp fiber, woven fiber, and unidirectional fiber. It was concluded that impact energy absorption of laminates varies with the fiber structure. Non-crimp fiber was the most appropriate selection for composite laminates because of its property of increasing resistance to impact. Therefore, non-crimp carbon fiber laminates, as shown in Figure 15 and 16, were constructed with the appropriate number of fabric plies to accomplish a total cured thickness nearest 0.254 mm (0.010 in) with a stacking sequence of [(+45/–45)/(0/90)]NS, and the ply count was 16, according to ASTM D5687/D5687M.

Figures 15 and 16 show fabricated asymmetric and symmetric non-crimp carbon fiber laminates, respectively.

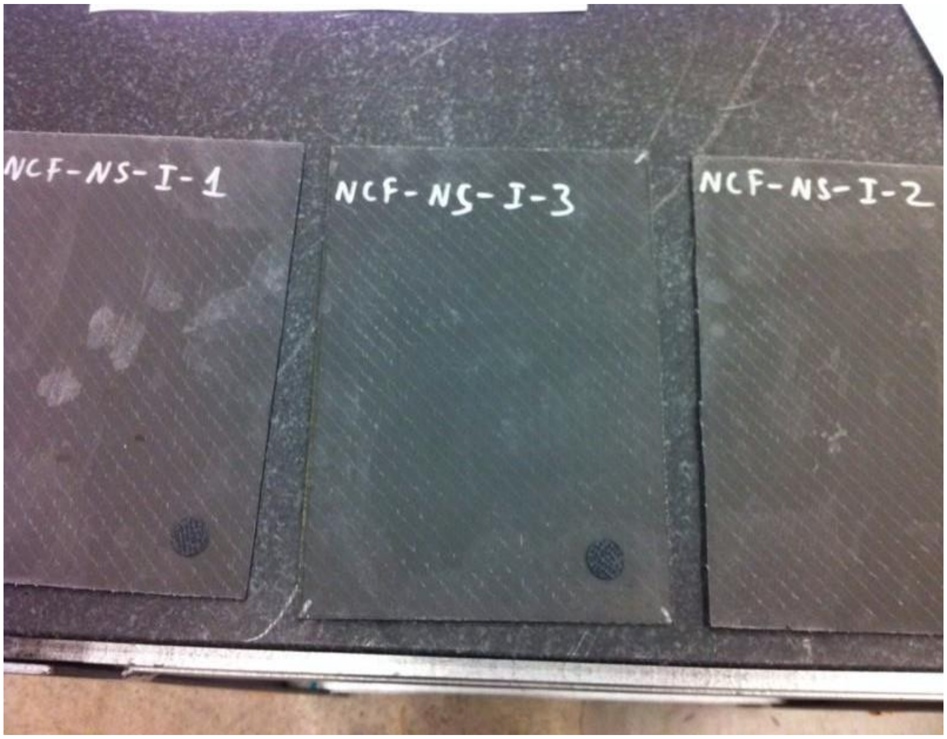


Figure 15: Non-Crimp Carbon Fiber Laminates (Asymmetric)

Figure 16: Non-Crimp Carbon Fiber Laminates (Symmetric)

3.2. Methods

Prior to layup, each mold or layup surface must be sterile by using non-contaminating cleaners, such as acetone or alcohol. Mold preparation is done outside the layup room. After cleaning, each mold was applied with non-contaminating release agents in agreement with the supplier's instructions. The cutting and layup area was ensured to be free of contaminants. Upon their removal from storage, the prepreg materials were allowed to warm to room temperature inside the preserved moisture-proof bag for at least 3.5 hours or until noticeable moisture was not seen from outside of the bag. Lint-free cotton gloves were essential for personal protection. Talc-free latex or nitrile gloves were satisfactory alternatives. No cutting of prepreg materials was allowed on the tool [24].

Debulking was performed in order to accomplish suitable compaction. Moreover, the bagging procedure was equally crucial for manufacturing the specimen with regard to the use of peel plies, bleeder materials, breather materials, and bagging materials. The following bagging procedure was used:

- Apply one layer of non-porous release fabric over the prepreg layup.
- Apply one layer of breather on top of the non-porous release film. If the breather is not contaminated with resin or other alien materials, then it may be re-used.
- Set up the nylon bagging film over the laminate or form-fit a silicone rubber bag and stick it down along the edge to the tool with vacuum bag sealant.
- Mount the vacuum connector through the bag, and use multiple vacuum connectors so that no point on the part is more than 60 inches from a vacuum supply.
- Apply a vacuum of at least 25 inches Hg for a minimum of 15 minutes at a rate that does not cause the prepreg to reallocate.

The laminate may be excited to 100°F maximum and held for 10–15 minutes during vacuum application, but no more than six debulks at 100°F was done on any layup. The final debulk was for 30 minutes minimum [25]. Figure 17 shows a typical laminate layup.

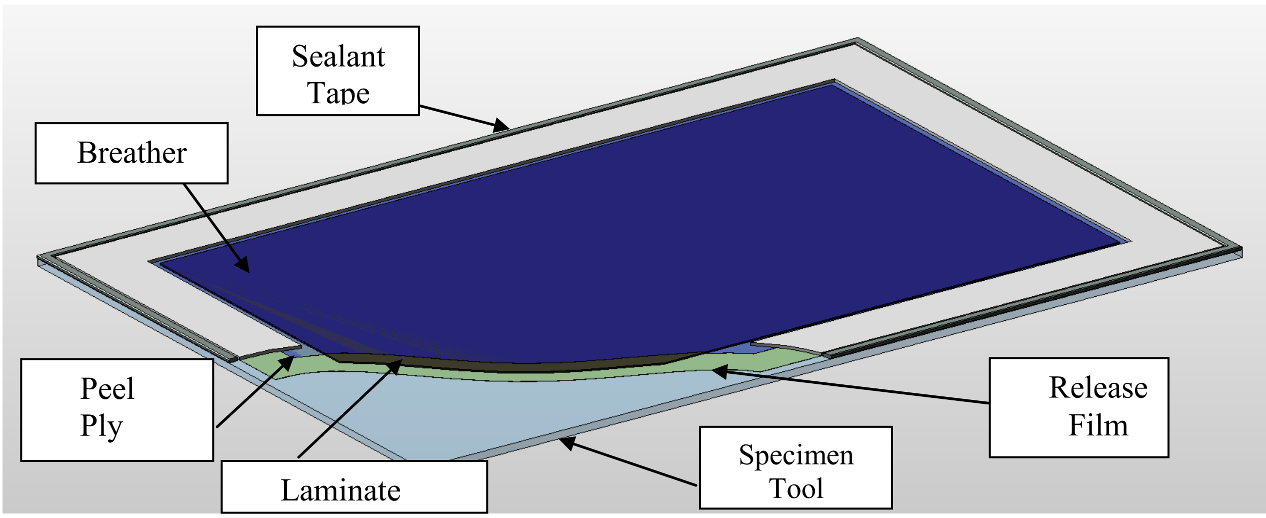


Figure 17: Laminate Layup (Vacuum Bag and Port Not Shown for Clarity)

3.2.1. Sizing and Fabrication

Having control over fiber alignment is critical. Inconsistent fiber alignment will affect the measured properties and also increase the coefficient of variation. Specimens were from a homogeneous cross-section over the entire surface and did not have a thickness taper greater than 0.08 mm (0.003 in) in any direction across the length and width of the specimen. The coefficient of variation for thickness measurements should be less than 2%. Specimen groundwork was very important for this specimen. Precautions were taken when cutting specimens from large panels to avoid notches, undercuts, rough and uneven surfaces, or any delaminations due to unsuitable machining methods. Figure 18 shows the 150 mm x 100 mm (6 in x 4 in) drop-weight test specimen according to ASTM standards.

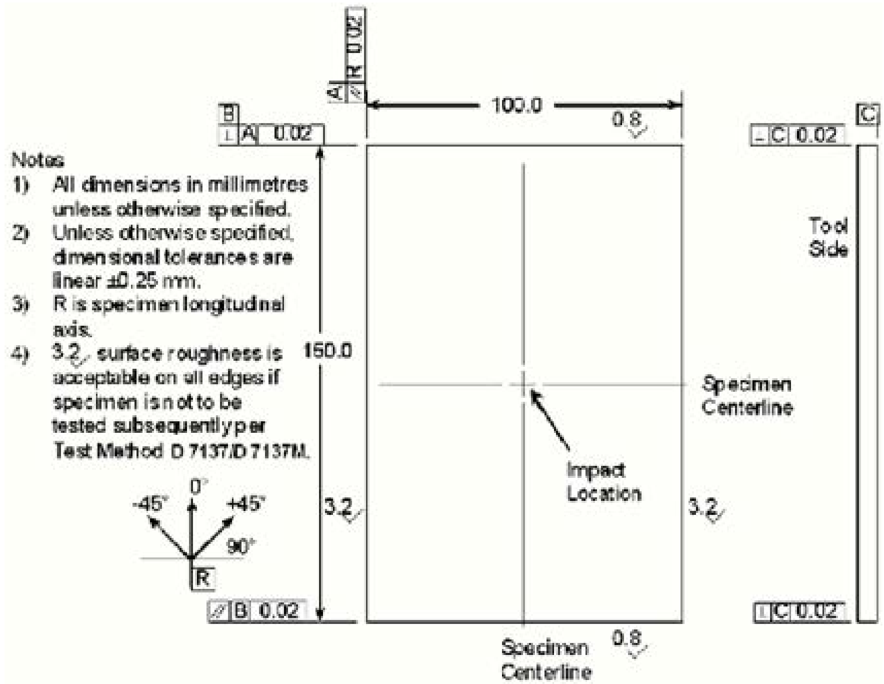


Figure 18: Drop Weight Impact Test Specimen [2,7]

3.2.2 Laminate Curing

A Grieve® industrial oven (Figure 19) was used to cure the composite layups under a vacuum. This oven, capable of creating a heated environment up to 400°F, has air outlets to maintain the bagged composite tool under a vacuum at constant pressure. All prepreg materials were cured according to strictly controlled time, temperature, and vacuum necessities.

Figure 19: Industrial Oven Showing Program Setup and Controls [1]

The following procedure was used for laminate curing of the NCF:

- Apply the full vacuum.
- Apply pressure at 45 psi.
- Vent at 22 psi.
- Start heating at 5°F/minute.
- Increase the temperature to 275°F, and hold for 2.0 hours.
- Remove the specimen at or below 140°F.

CYCOM® 5320-1 is a hard-edged epoxy resin prepreg system intended for out-of-autoclave manufacturing of primary structural applications. Because of its lower temperature curing potential, it is also appropriate for prototyping where low-cost tooling or vacuum-bag-only curing is required. This system handles standard prepreg, yet use vacuum bag-curing to fabricate autoclaved quality parts with very low porosity. It offers mechanical properties equivalent to other 350°F (177°C) autoclave-cured toughened epoxy prepreg systems after a 350°F (177°C) freestanding post-cure [26]. Suggested processing parameters are shown in Table 1.

TABLE 1

CURE CYCLES FOR WOVEN AND UNIDIRECTIONAL CARBON FIBER LAMINATE [24]

Parameter	**Cure Cycle A**	**Cure Cycle B**
Ramp Rate	1–3°F/minute (0.6–1.7°C/minute)	1–5°F/minute (0.6–2.8°C/minute)
Cure Temperature	200 ± 10°F (93 ± 6°C)	250 ± 10°F (121 ± 6°C)
Cure Time	12 hours	3 hours
Free-Standing Post-Cure	2 hours at 350°F (177°C)	2 hours at 350°F (177°C)

The post-curing procedure is as follows:

- Prior to removing the vacuum bag from the cured part, examine the bag for evidence of ballooning, charring, rupture, resin contact, tearing, or other conditions that would stipulate bag failure during the cure cycle.
- Take out the vacuum bag.
- When removing the cured laminate from the tool surface, do not use sharp objects or tools that could damage the surface of the part or the mold.
- Do not bend the cured laminate or the detail part.
- Do not remove any peel ply at this time.

3.2.3 Impact Testing

Each specimen was tested with the Instron® Dynatup 8250 drop test tower. At the most, the impact device consisted of a rigid base, a drop-weight impactor, a rebound catcher, and a guide mechanism. The rebound catcher is typically an inertially driven latch that trips upon initial impact and then catches the impactor on a stop during its second decent. The rebound catcher must not influence the motion of the impactor until after the impactor has misplaced contact with the specimen after the initial impact. This drop test tower is operational with a drop-weight impactor weighing 7.87 lbs, along with a rebound catcher and a guide mechanism. The diameter of the indenter (impactor/Tup) is 1 in. Using the thickness of the laminate as a reference (ranging from 0.09 in [2.286 mm] for NCF and unidirectional to 0.116 in [2.946 mm] for woven), along with the initial height (ranging from 17.158 in [436 mm] for NCF and unidirectional, and 22.155 in [563 mm] for woven), and also the weight of the impactor, the calculated impacted energy was found for NCF, unidirectional, and woven carbon fiber laminates. Although these analysis could have been conducted for various other impact energy values, such as 25J and 17J, every other above-mentioned experimental factor was kept constant, expect for the variation of carbon fibers utilized and the applied constant impact energy of 6.7 J. Hence, test data can be compared based on this variation. In Figures 20 and 21 show the Instron® Dynatup 8250 drop-test unit and the secured carbon fiber composite test specimen and target, respectively.

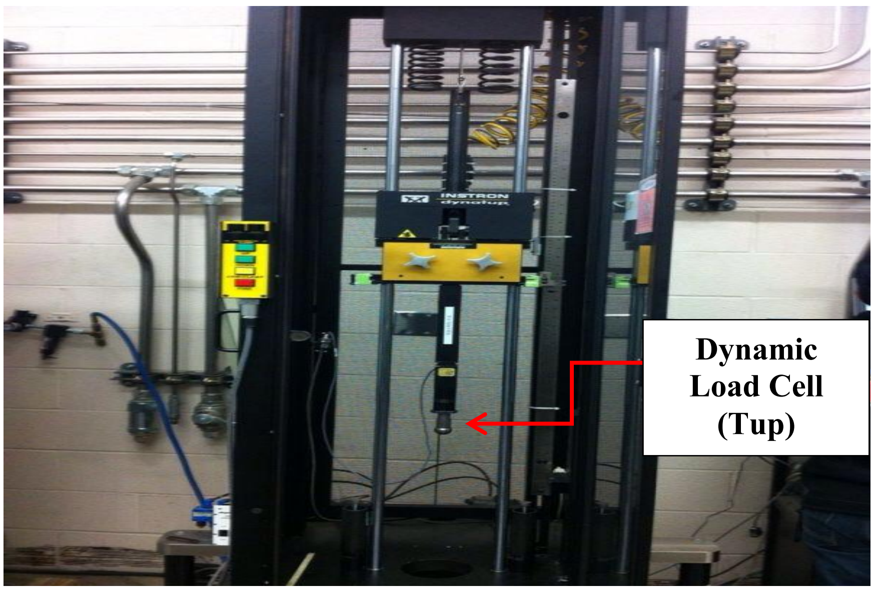


Figure 20: Instron® Dynatup 8250 Drop-Test Unit

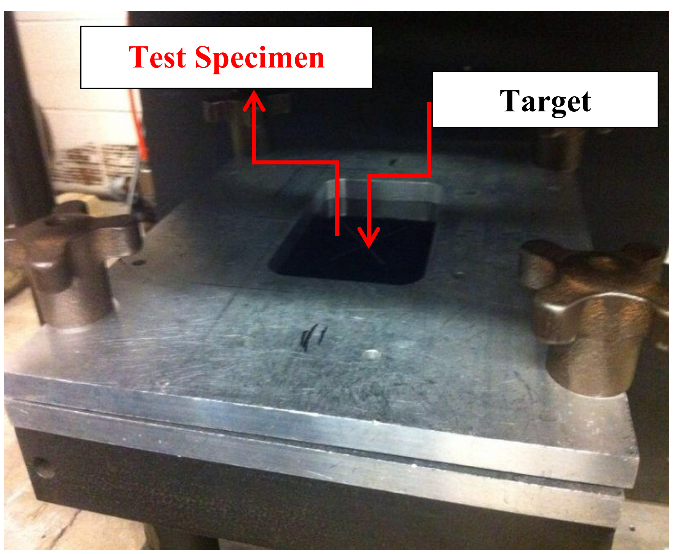


Figure 21: Secured Carbon Fiber Composite Test Specimen and Target

3.2.4 C-Scans

C-scans of each coupon, taken prior to and following the impact test, showed two vital factors:

- Intensity of porosity in the specimen.
- Aftermath of the impact behavior, where the image was used to analyze the damage area, and measure the initial depth of the impacted zone.

Using a depth gauge, the depth of the damage area was documented immediately after impact. A lapse in reading the depth would overthrow or nullify any depth taken later, because due to the elastic manner of the laminate, the surface would level itself temporarily. This depth reading of each coupon represents the displacement or recovery of the specimen after an impact.

3.2.5 Ultraviolet Chamber/Salt Chamber

For studying the pre-conditioning of impact panels, the surface was exposed to environmental degradation. A UV chamber was used to show the damaged area of each of the test sample that had been exposed to UV light. Short wave sunlight was triggered by UVA- 340 lamps in a chamber known as the QUV Accelerated Weathering Tester, manufactured by the Q-Lab. The UV spectrum can generate photo-degradation in a few days or weeks, which is equivalent to numerous months or years of outdoor direct sunlight exposure. Figures 22 and 23 shows the UV chamber and test specimen setups, respectively.

Figures 24 and 25 show two different views of the salt fog chamber, which can be used to imitate environmental conditions other than UV exposure, such as salt fog, humidity, water fog, etc. Test specimens were placed in the salt chamber to expose them to moisture and water fog. The salt and UV chambers were used alternatively for pre-conditioning the laminates for a period of 20 days each.

Figure 22: UV Chamber Setup

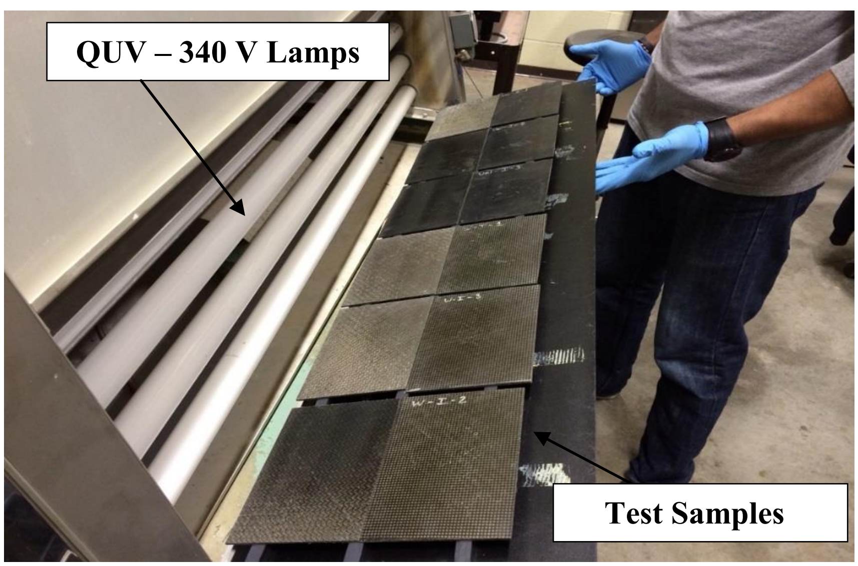


Figure 23: Test Samples Setup for Exposure in UV Chamber

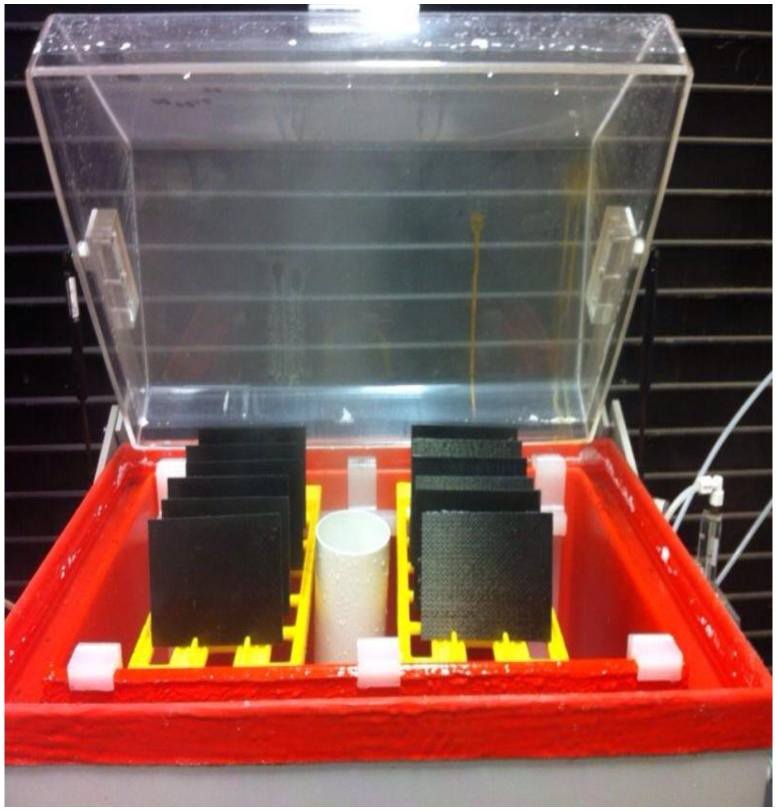


Figure 24: Test Samples Setup for Humidity Exposure in Moisture Chamber

Figure 25: Test Samples Undergoing Humidity Exposure in Moisture Chamber

3.2.6 Optical Water Contact Angle Goniometer

The contact angle of a water droplet on the surface of material provides insight on the surface veracity of the material. With the angle known for different types of surfaces, it is possible to approximate a comparison between different characteristics, such as porosity, for various samples. A contact angle larger than 90 degrees corresponds to the surface being hydrophobic, which means the surface is non-porous. A lower contact angle means the surface is hydrophilic; hence, the surface is porous.

Figure 26 displays the optical goniometer and computer, which were used to gather readings of the water contact angles on the surface of each test specimen. With the help of a camera, and the sessile drop method, the software generated a profile of the water droplet, which is on the surface of the test panel, and using applicable (built-in) software, the contact angles were calculated and displayed. The data gathered for each test specimen were evaluated with each other and are shown in Table 2.

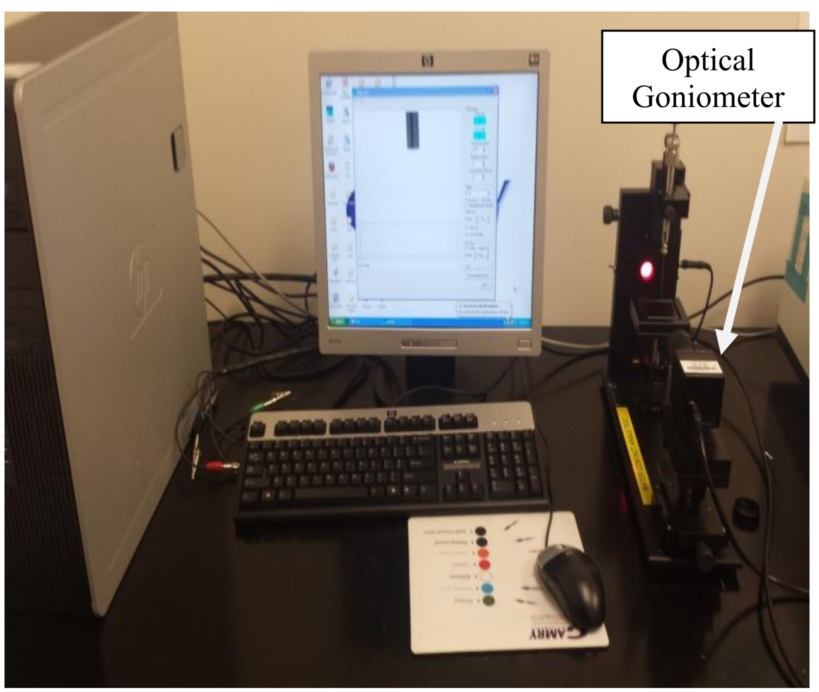


Figure 26: Optical Goniometer Setup

TABLE 2

NUMBER OF SPECIMENS USED FOR STUDY/EXPERIMENT

Set Number	Quantity	**Test Panel**
1	3 3 6	Baseline/Unidirectional CF Laminate Woven CF Laminate NCF CF Laminate
2	12	UV and Moisture Conditioning

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Impact Analysis

Carbon fiber composite panels were manufactured using diverse types of CF prepregs and then subjected to impact testing using a low-velocity drop test tower. ASTM D7136 test measures were imposed during the experimental trials. A significant amount of data obtained substantiated and interpreted the impact resistance behavior of the carbon fiber composite panels. Parameters were set according to the ASTM standards listed in Tables 3 to 6.

TABLE 3

IMPACT PARAMETERS OF UNIDIRECTIONAL LAMINATES

Specimen ID	Thickness (in) (H)	Impact TUP Size	Drop Height (H)/Weight	Maximum Load-1 (lb)	Impact Velocity-1 (in/min)(V)	Impact Energy-1 (in lb)	Total Energy-1 (in lb)	Total Time-1 (ms)	Time to Max Load-1 (ms)
UNI-CF1	0.09	1	17.158/7.87	937.9	7015.44	139.34	111.34	8.1055	1.5747
UNI-UV1	0.09	1	17.158/7.87	953.11	6953.09	136.87	111.22	7.2998	2.0142
UNI-CF2	0.09	1	17.158/7.87	853.13	6991.09	138.37	108.54	8.5327	1.5259
UNI-UV1	0.09	1	17.158/7.87	963.84	6966.83	137.41	118.46	8.2886	1.5259
UNI-CF3	0.09	1	17.158/7.87	919.87	6897.09	134.68	106.63	8.0322	1.5625
UNI-UV3	0.09	1	17.158/7.87	947.03	6945.74	136.58	112.6	7.8369	1.5137

TABLE 4

IMPACT PARAMETERS OF WOVEN LAMINATES

Specimen ID	Thickness (in) (H)	Impact TUP Size	Drop Height (H)/Weight	Maximum Load-1 (lb)	Impact Velocity-1 (in/min)(V)	Impact Energy-1 (in lb)	Total Energy-1 (in lb)	Total Time-1 (ms)	Time to Max Load-1 (ms)
W-CF1	0.116	1	22.155/7.87	1078.59	7835.64	173.82	121.48	6.4331	2.6123
W-CF1 UV	0.116	1	22.155/7.87	1116.04	7781.69	171.44	129.42	6.1401	2.0874
W-CF2	0.116	1	22.155/7.87	1074.98	7781.51	171.43	116.99	6.4819	2.6489
W-CF2 UV	0.116		22.155/7.8	1075.03	7818.24	173.05	127.45	6.2988	2.5879
W-CF3	0.116	1	22.155/7.87	1142.88	7859.14	174.87	119.12	6.0669	2.478
W-CF3 UV	0.116	1	22.155/7.87	1055.23	7842.48	174.13	128.4	6.1768	2.2339

TABLE 5

IMPACT PARAMETERS OF NCF SYMMETRIC LAMINATES

Specimen ID	Thickness (in) (H)	Impact TUP Size	Drop Height (H)/Weight	Maximum Load-1 (lb)	Impact Velocity-1 (in/min)(V)	Impact Energy-1 (in lb)	Total Energy-1 (in lb)	Total Time-1 (ms)	Time to Max Load-1 (ms)
NCF-S1	0.09	1	17.158/7.87	1483.83	6983.78	138.08	52.63	5.5664	2.6977
NCF-S1 UV	0.09	1	17.158/7.87	1455.05	6913.41	135.31	59.58	5.5298	2.5635
NCF-S2	0.09	1	17.158/7.87	1497.24	7041.84	140.39	55.71	5.481	2.478
NCF-S2 UV	0.09	1	17.158/7.87	1453.57	6935.66	136.19	59.76	5.481	2.6245
NCF-S3	0.09	1	17.158/7.87	1130.16	5590.55	88.48	28.77	5.7495	2.9053
NCF-S3 UV	0.09	1	17.158/7.87	1516.38	6967.4	137.43	60.34	5.4321	2.3315

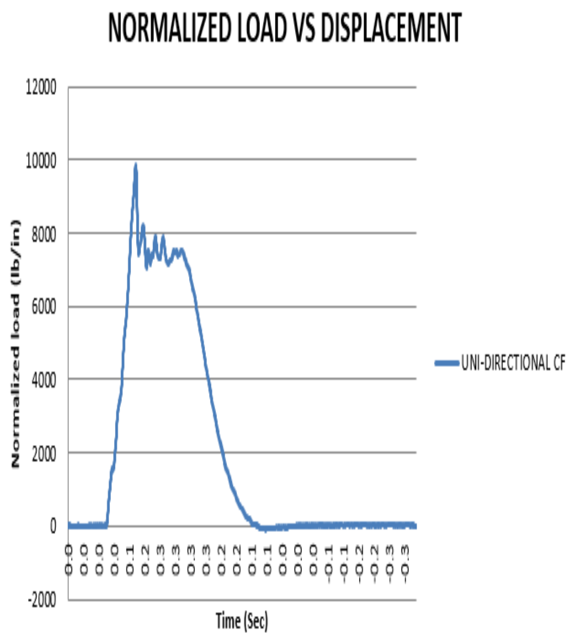
TABLE 6

IMPACT PARAMETERS OF NCF ASYMMETRIC LAMINATES

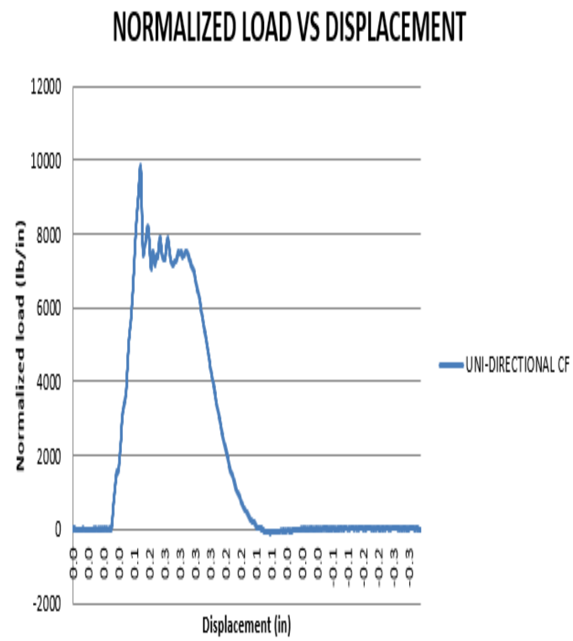
Specimen ID	Thickness (in) (H)	Impact TUP Size	Drop Height (H)/Weight	Maximum Load-1 (lb)	Impact Velocity-1 (in/min)(V)	Impact Energy-1 (in lb)	Total Energy-1 (in lb)	Total Time-1 (ms)	Time to Max Load-1 (ms)
NCF-AS1	0.09	1	17.158/7.87	1600.02	7084.95	142.11	46.5	5.4199	2.6855
NCF-AS1 UV	0.09	1	17.158/7.87	1545.88	6939.11	136.32	49.28	5.3711	2.6489
NCF-AS2	0.09	1	17.158/7.87	1508.13	7062.36	141.21	55.91	5.5664	2.5513
NCF-AS2 UV	0.09	1	17.158/7.87	1538.93	6964.78	137.33	50.07	5.3589	2.6245
NCF-AS3	0.09	1	17.158/7.87	1535.16	6899.3	134.76	44.17	5.4457	2.735
NCF-AS3 UV	0.09	1	17.158/7.87	1574.8	6971.38	137.59	50.46	5.3101	2.6611

When fabricating NCF and unidirectional laminates, thickness, drop weight, drop height, and tup size parameters are invariant, and other variant parameters are instantaneously recorded. Tables 3, 5, and 6 explain the impact parameters of these laminates. This also applies to woven laminates, but they are fabricated using various thickness and other parameters, compared to other manufactured laminates, as shown in Table 4. Thus, data recorded was normalized by thickness for a comparative study. Three panels for each set underwent impact for baseline investigation, followed by another three sets of samples for each set fabricated for post-UV/salt-moisture impact study. The investigation is supported with numerous graphical plots.

Figures 27 to 35 show plots of normalized load versus time and displacement, and normalized impact energy versus time for CF laminates. These plots explain load and impact energy applied on the panels with respect to time in the load direction. The nature of the plots resembles a stress-strain curve and explains stiffness characteristics of the specimen. The zero-degree aligned fiber in unidirectional laminates is highest in the load-bearing element. In CF laminates with woven fortification, damage was restricted and confined by the fabric weave.

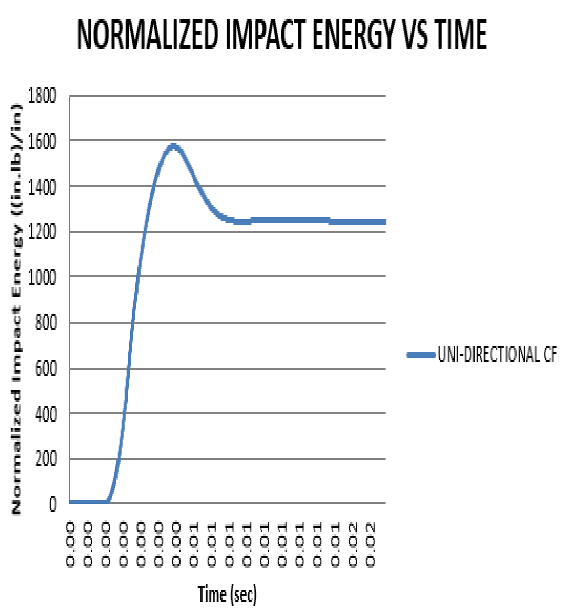


(A)



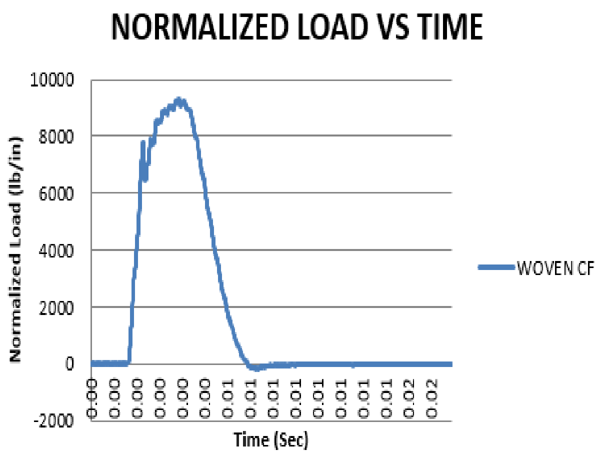
(B)

Figure 27: (A) Unidirectional CF Load (lb/in) vs. Time (sec) Plot and (B) Unidirectional CF Load (lb/in) vs. Displacement (in) Plot



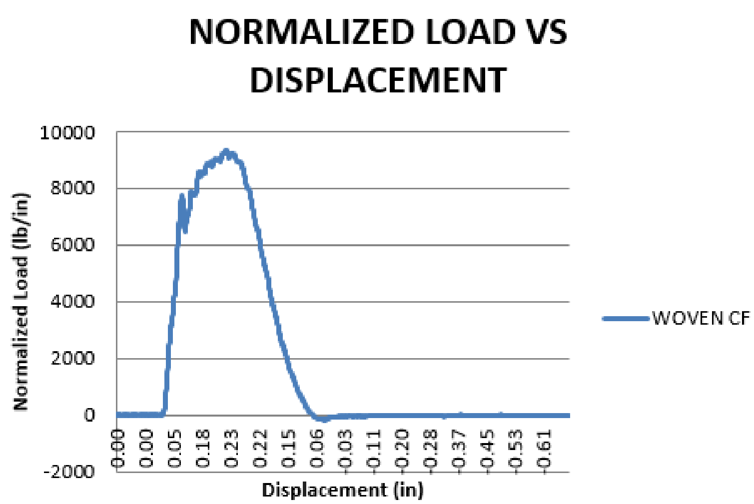
(C)

Figure 28: (C) Unidirectional CF Impact Energy ((in.lb)/in) vs. Time (sec) Plot

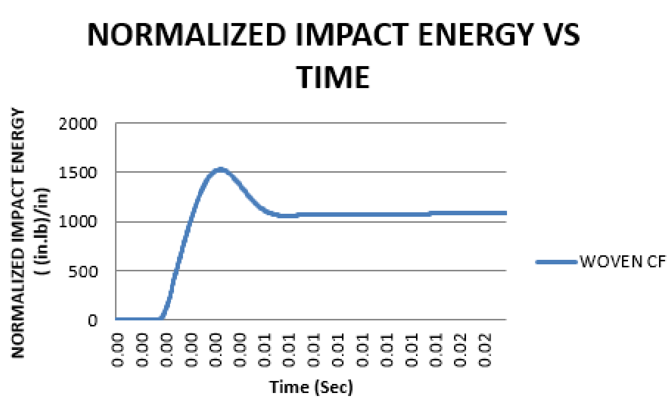


(A)

Figure 29: (A) Woven CF Load (lb/in) vs. Time (sec) Plot



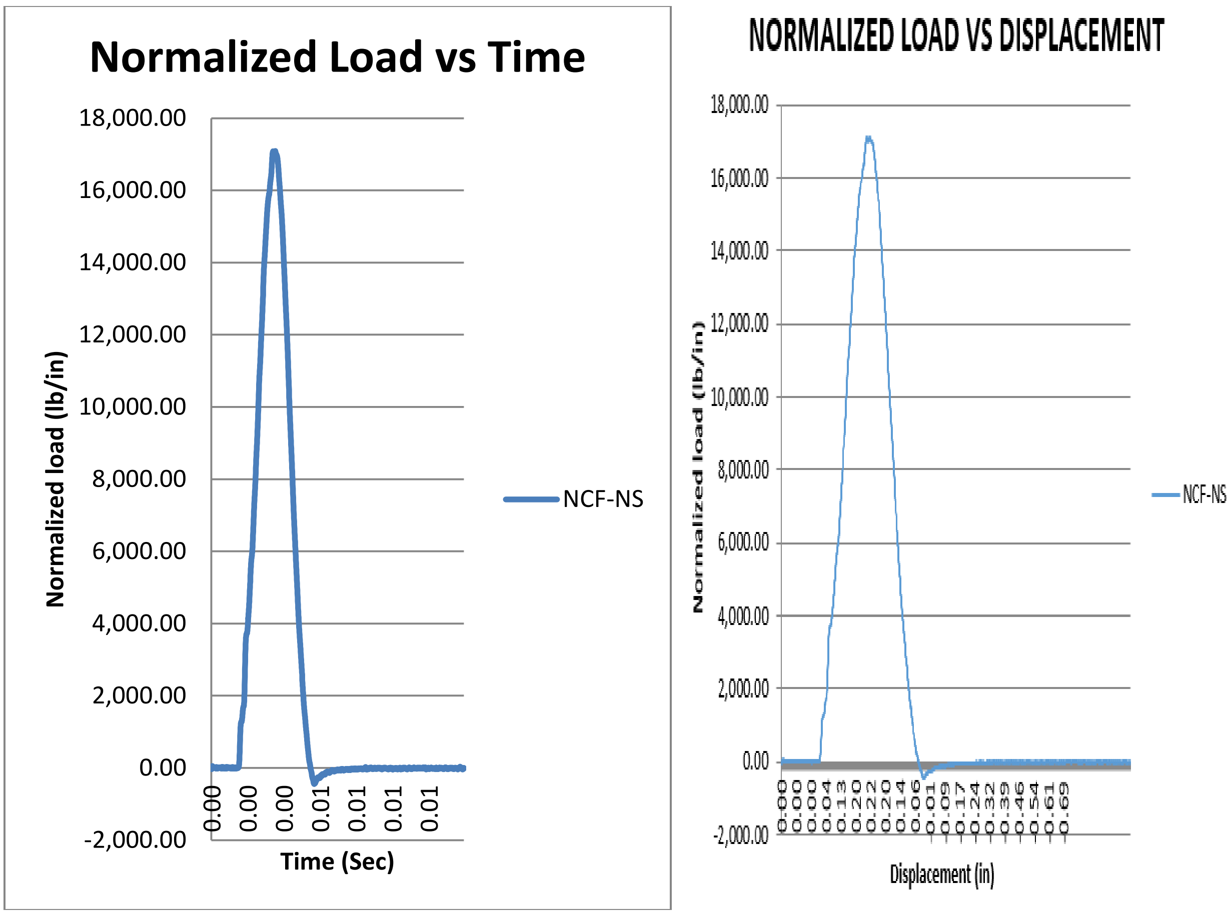
(B)



(C)

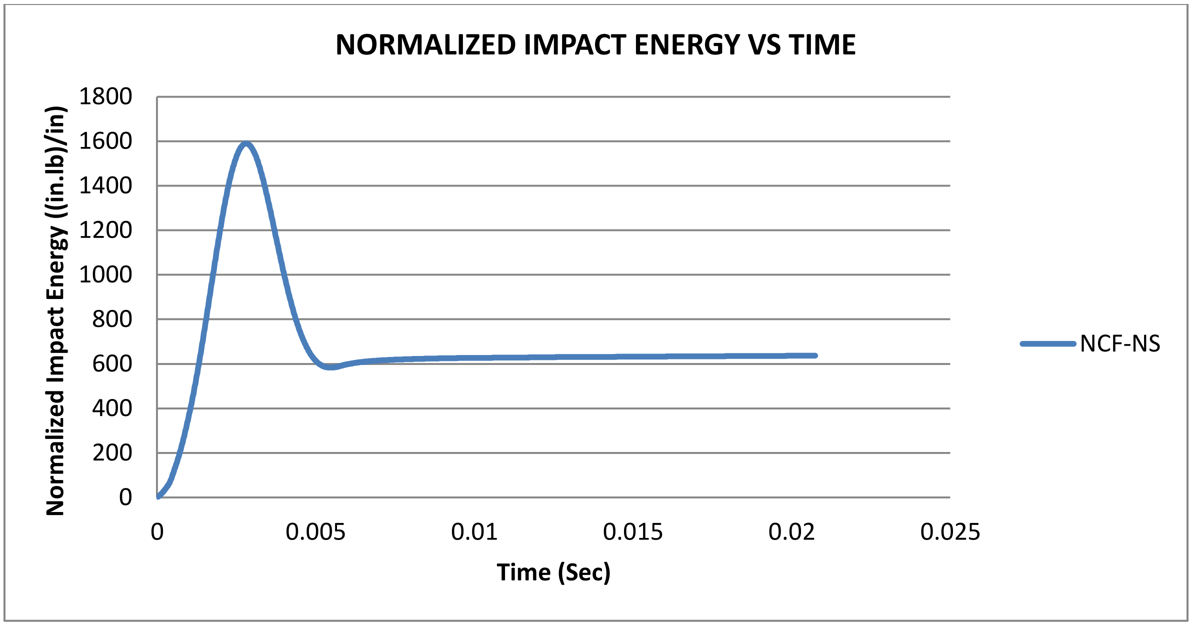
Figure 30: (B) Woven CF Load (lb/in) vs. Displacement (in) Plot and (C) Woven CF Impact Energy (in.lb/in) vs. Time (sec) Plot

Non-crimp fabric composites are very reliant on their internal meso and micro-structures, which are defined by the manufacturing practice of the fabric and composite processing conditions. The plots of NCF symmetric and NCF asymmetric laminates have a similar nature or pattern, and the variations are due to the difference in stacking sequences of NCF carbon fiber prepregs and possibly more UV exposure.



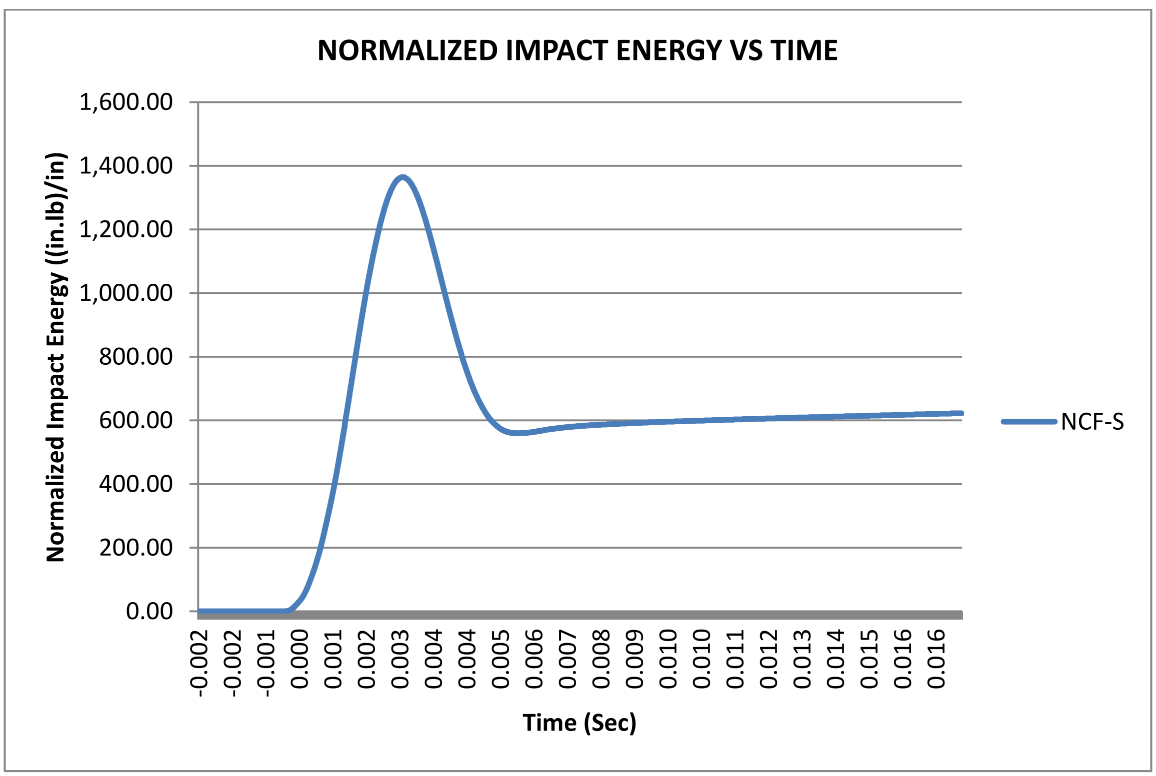
(A) (B)

Figure 31: (A) Nonsymmetric NCF Load (lb/in) vs. Time (sec) Plot and (B) Nonsymmetric NCF Load (lb/in) vs. Displacement (in) Plot



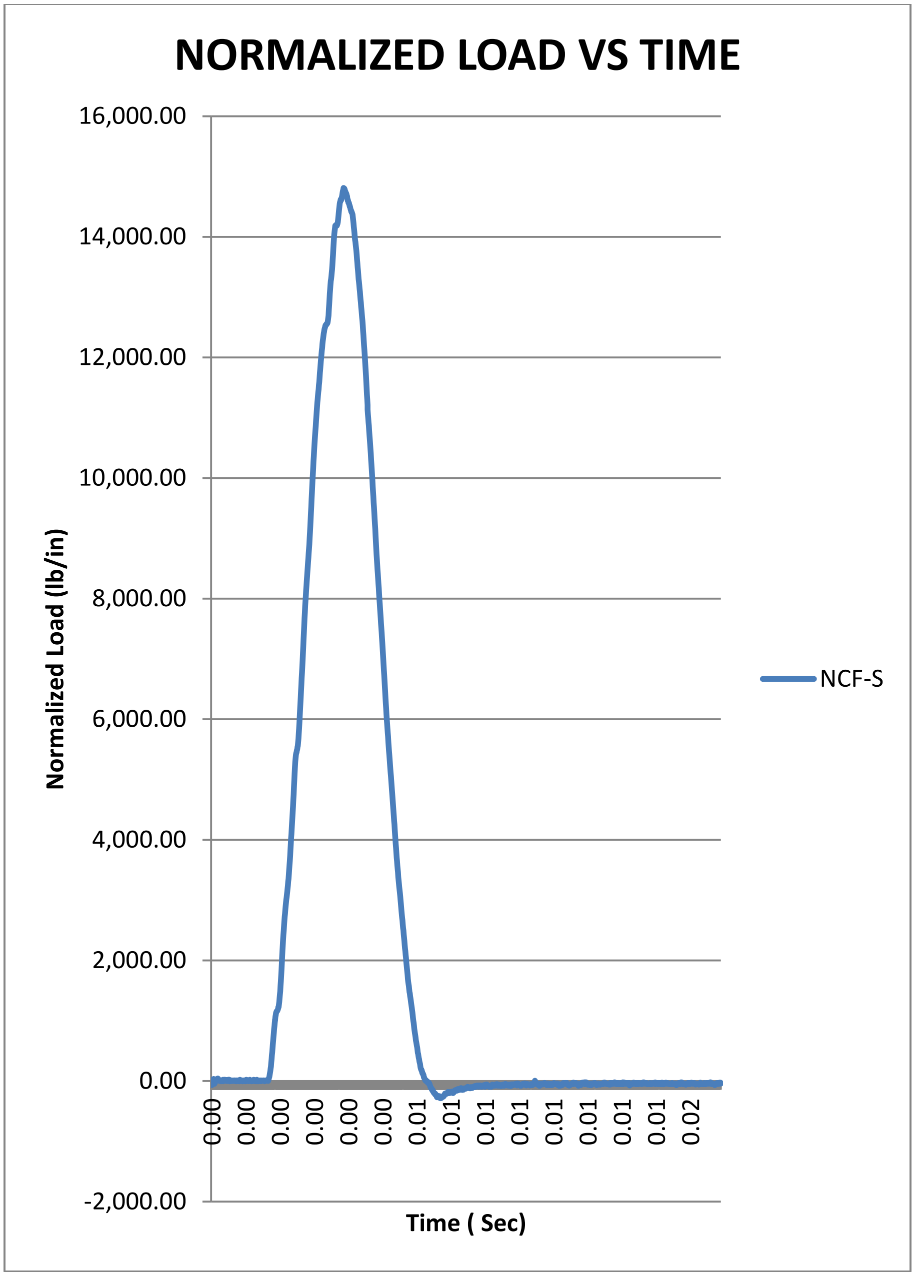
(C)

Figure 32: (C) NCF Non-symmetric Impact Energy (in.lb/in) vs. Time (sec) Plot



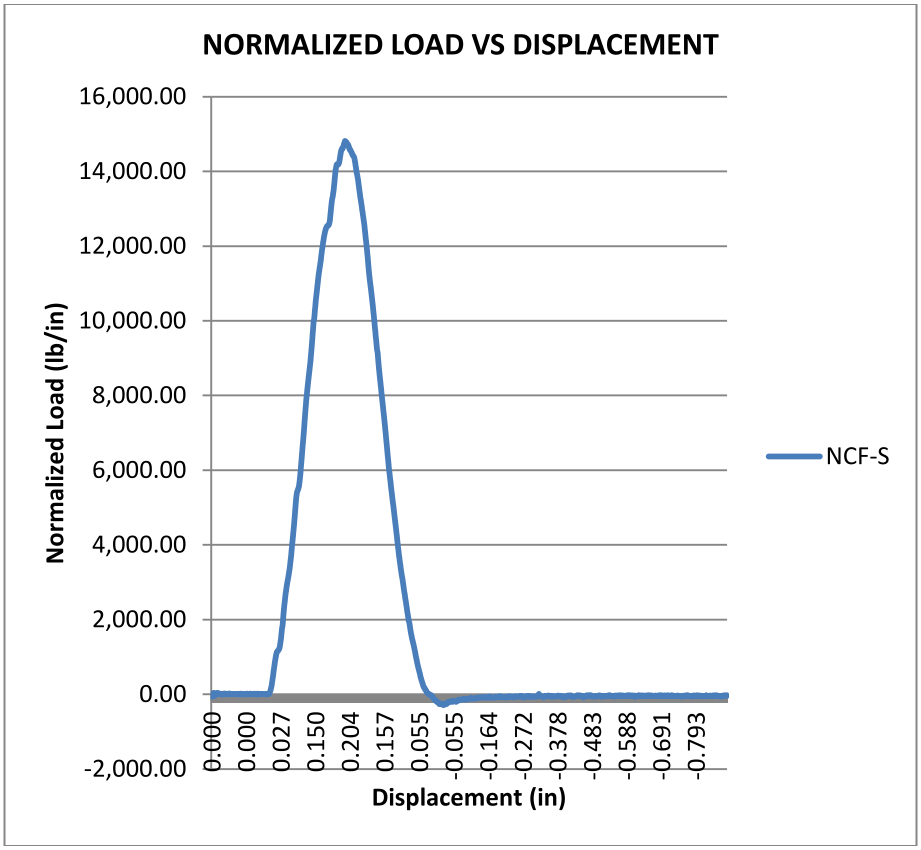
(A)

Figure 33: (A) NCF Symmetric Impact Energy (in.lb/in) vs. Time (sec)



(B)

Figure 34: (B) NCF Symmetric Load (lb/in) vs. Time (sec) Plot



(C)

Figure 35: (C) NCF Symmetric Load (lb/in) vs. Displacement (in) Plot

The absorbed energy, which is exposed as the region above the linear part of the plot from the peak of the energy-time curve, is shown in Figure 36. This type of energy is defined as the energy calculated from the time the load begins to ascend until the first event of 0 loads after the maximum point. This value can be used as an indicator of a material's ductility or toughness and also the impact response of the laminate. The drop seen from the maximum load point shows energy lost as sound energy and other losses by force oscillations due to "impactor ringing" (impactor components not rigidly attached and flexural vibration of the specimen) [27].

In Figure 36, impact energy versus time is shown for four different types of carbon fiber laminates without UV and moisture exposure (baseline). NCF asymmetric laminates showed the highest impact energy of ~1584 in.lb/in with the high absorbed energy of ~974 in.lb/in, and NCF symmetric laminates with the impact energy of approximately of 1555 in.lb/in and absorbed energy of ~844 in.lb/in. They suffered negligible amount of damage. The difference between NCF laminate impact values and absorbed values, as mentioned earlier, is due to the variance in stacking sequences between laminates. This also indicates that NCF has high damage tolerance compared to woven and unidirectional laminates. Woven laminate shown falls next in place after the unidirectional laminate having absorbed energy of 470 in.lb/in with impact energy of approximately 1528 in.lb/in.

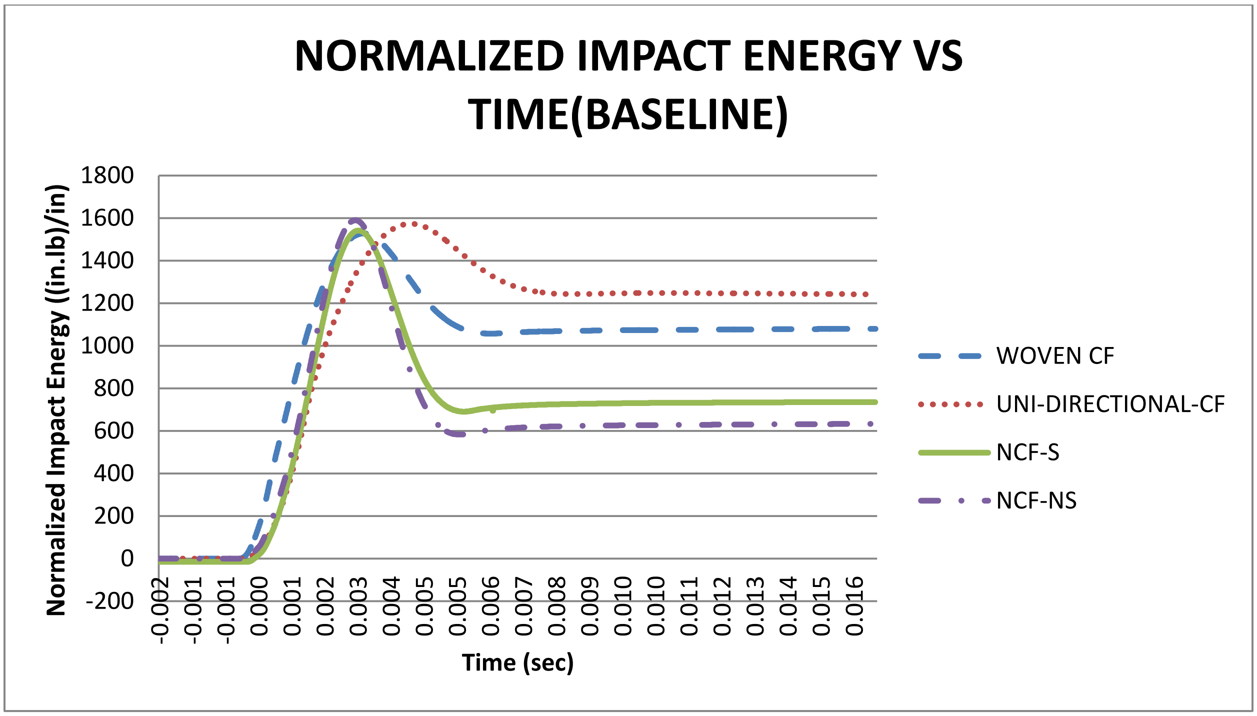


Figure 36: Normalized Impact Energy (in.lb/in) vs. Time (sec) for Four CF Laminates (Baseline)

The plot also justifies that the unidirectional laminate had the lowest absorbed energy, which is shown around 323 in.lb/in, indicating that unidirectional laminate suffered most of the impact (~1573 in.lb/in) and underwent a considerable amount of damage.

In Figure 37, both asymmetric and symmetric NCF laminates have high impact energies with corresponding maximum load points of approximately 17,000 lb/in and 16,000 lb/in compared to Uni-D laminate (~9,500 lb/in) and Woven laminate (~10,130 lb/in).

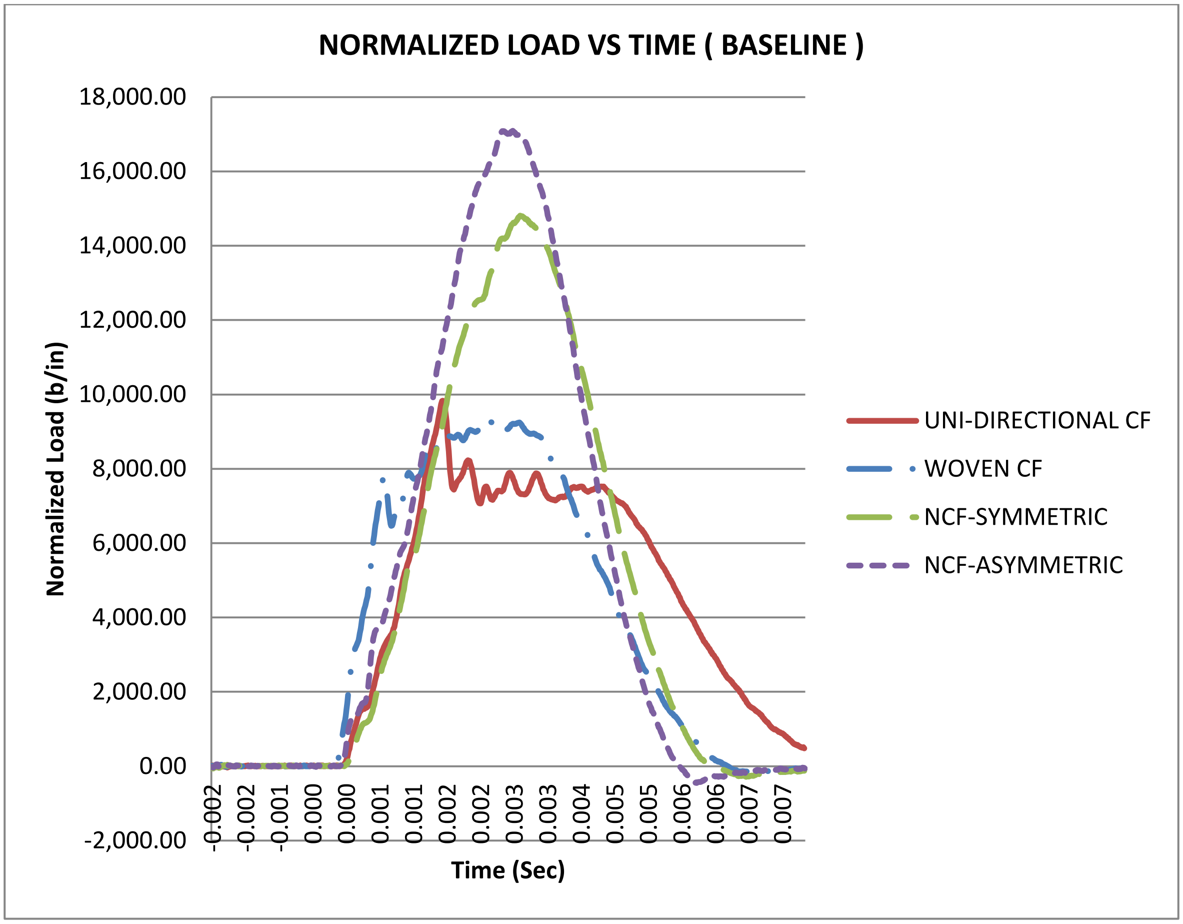


Figure 37: Normalized Load (lb/in) vs. Time (sec) (Baseline)

Figure 37 also shows that NCF laminate has lower tensile strength compared to unidirectional laminates for the following reasons:

- Heterogeneous structure
- Complex geometry
- Reduction in elastic modulus
- Interface de-lamination

- 0 degree bundle waviness
- Out-of-plane stress
- bundle cracks

In Figure 38 it can be verified that the peak load that each test panel has accomplished, to the displacement of the test panel in the load direction. It can be decided that recuperation, in terms of displacement, of the test panel can be calculated. When the load is detached off the test panel, the displacement of the test panels didn't riposte to zero. However, due to the elastic deformities, the impact region had a permanent damage, indentation, and the resistance to penetration reliant on its elasticity. The NCF laminates recuperate at a minimum of 0.22 inches, followed by woven laminates which displace by approximately 0.24 inches. The maximum recuperation is by the unidirectional laminate which is approximately 0.27 inches.

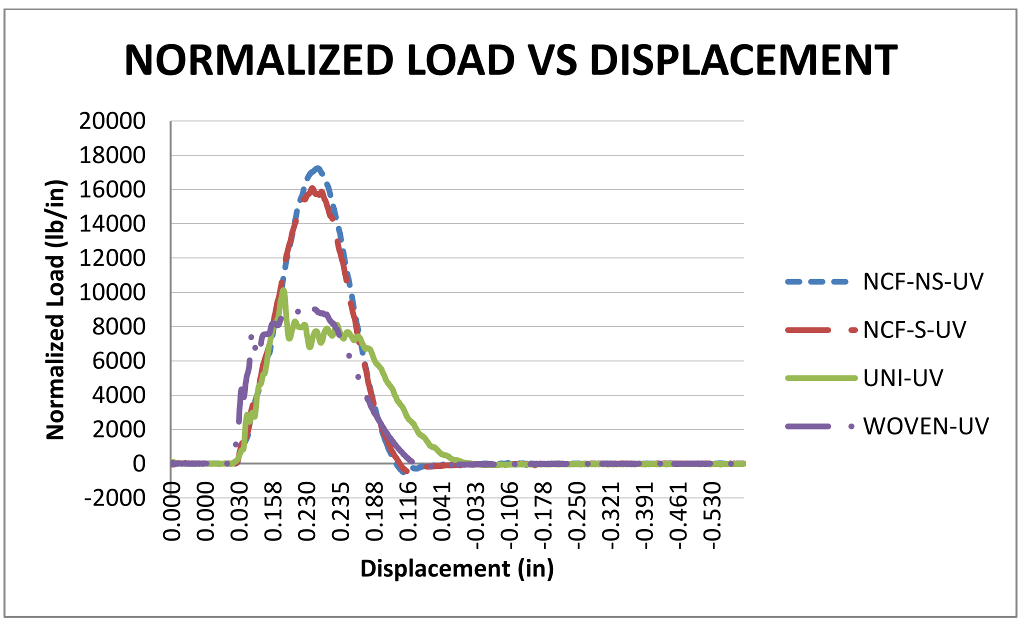


Figure 38: Normalized Load (lb/in) vs. Displacement (in) (Baseline) for Four CF Laminates

The plots in Figure 39 to 41 show load versus time, load versus displacement, and impact energy versus time, respectively, after pre-conditioning (UV and moisture) of the laminate.

Compared to the baseline plots, they follow a similar curve or pattern, thus indicating data consistency.

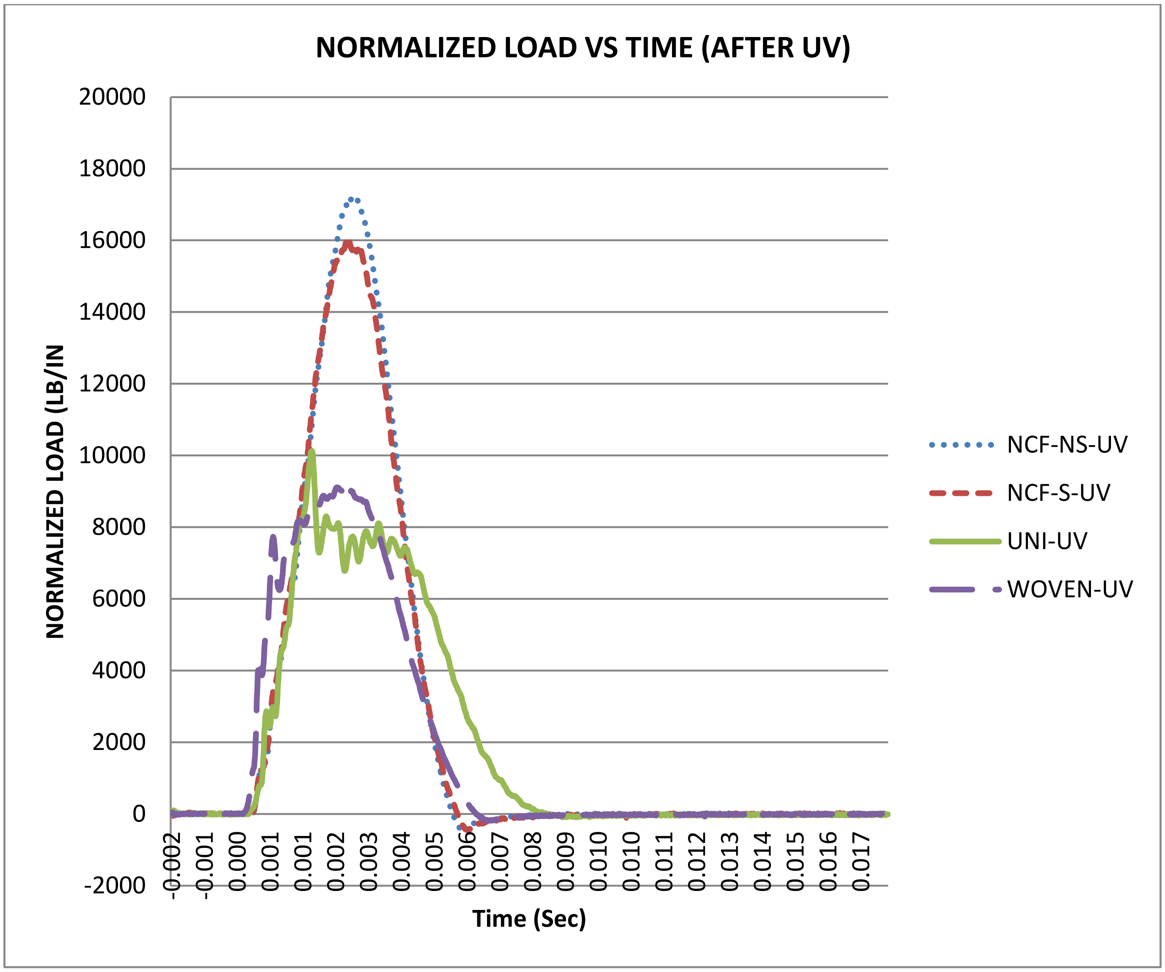


Figure 39: Normalized Load (lb/in) vs. Time (sec) (after UV) for Four CF Laminates

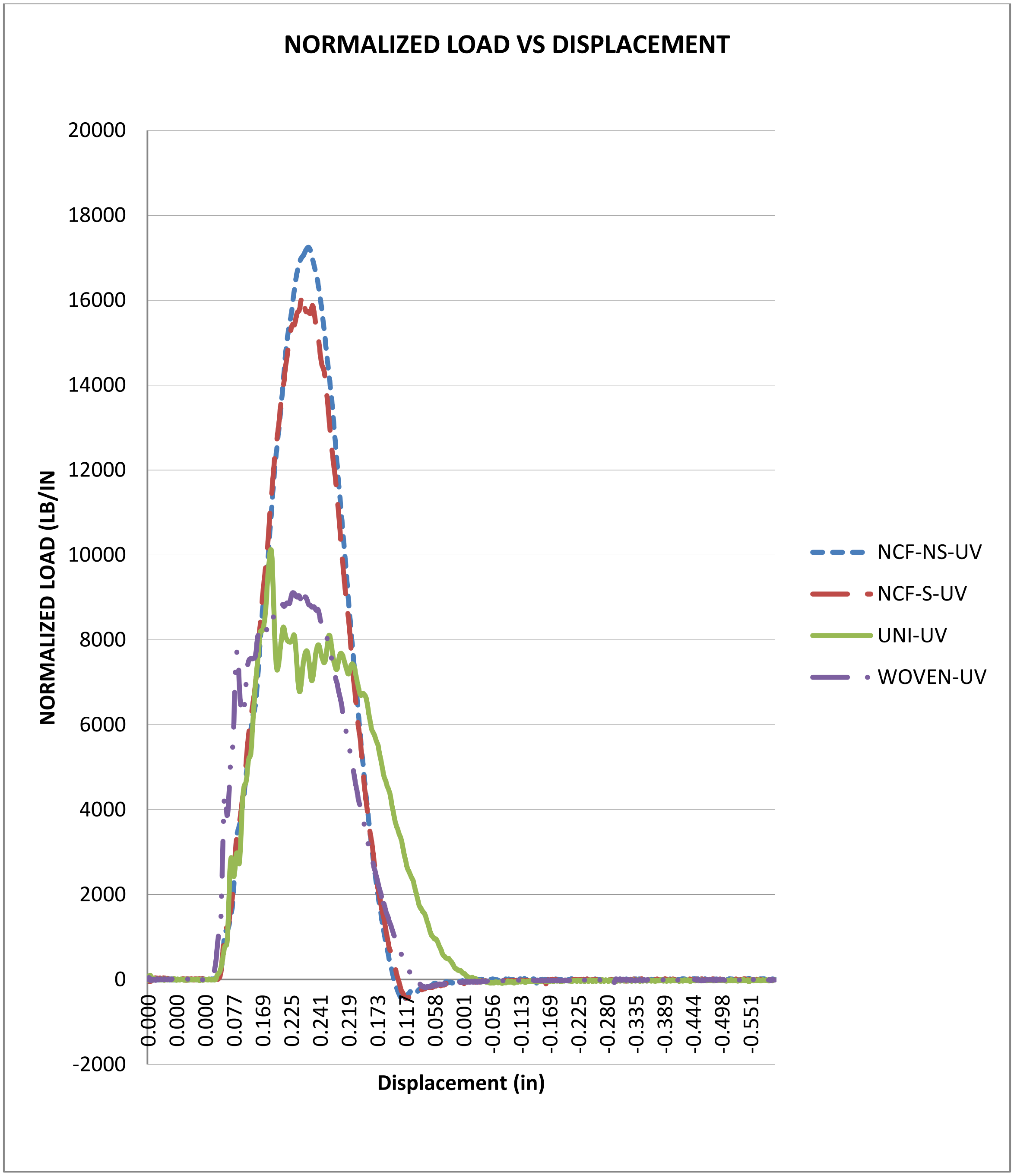


Figure 40: Normalized Load (lb/in) vs. Displacement (in) (after UV) for Four CF Laminates

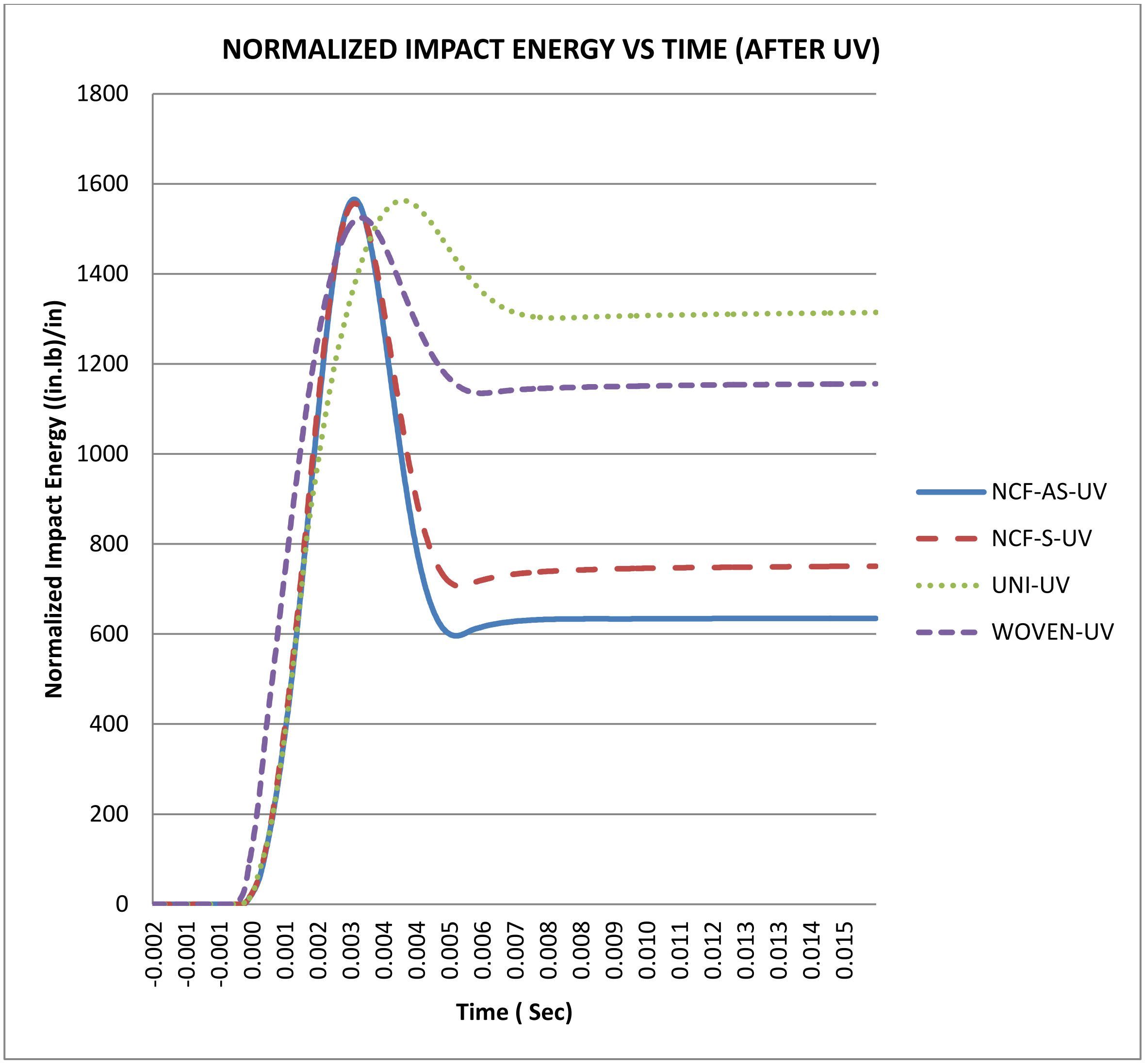


Figure 41: Normalized Impact Energy vs. Time (after UV) for Four CF Laminates

In Figures 42 and 43, and TABLE 7, percentage differences were calculated between impact energies of baseline and post-UV treated samples. As shown, there was a considerable reduction in impact energies after UV and moisture treatment since a degradation environment is a function of time and temperature, which leads to voids between fibers. NCF laminates showed more damage tolerance compared to woven and unidirectional laminates.

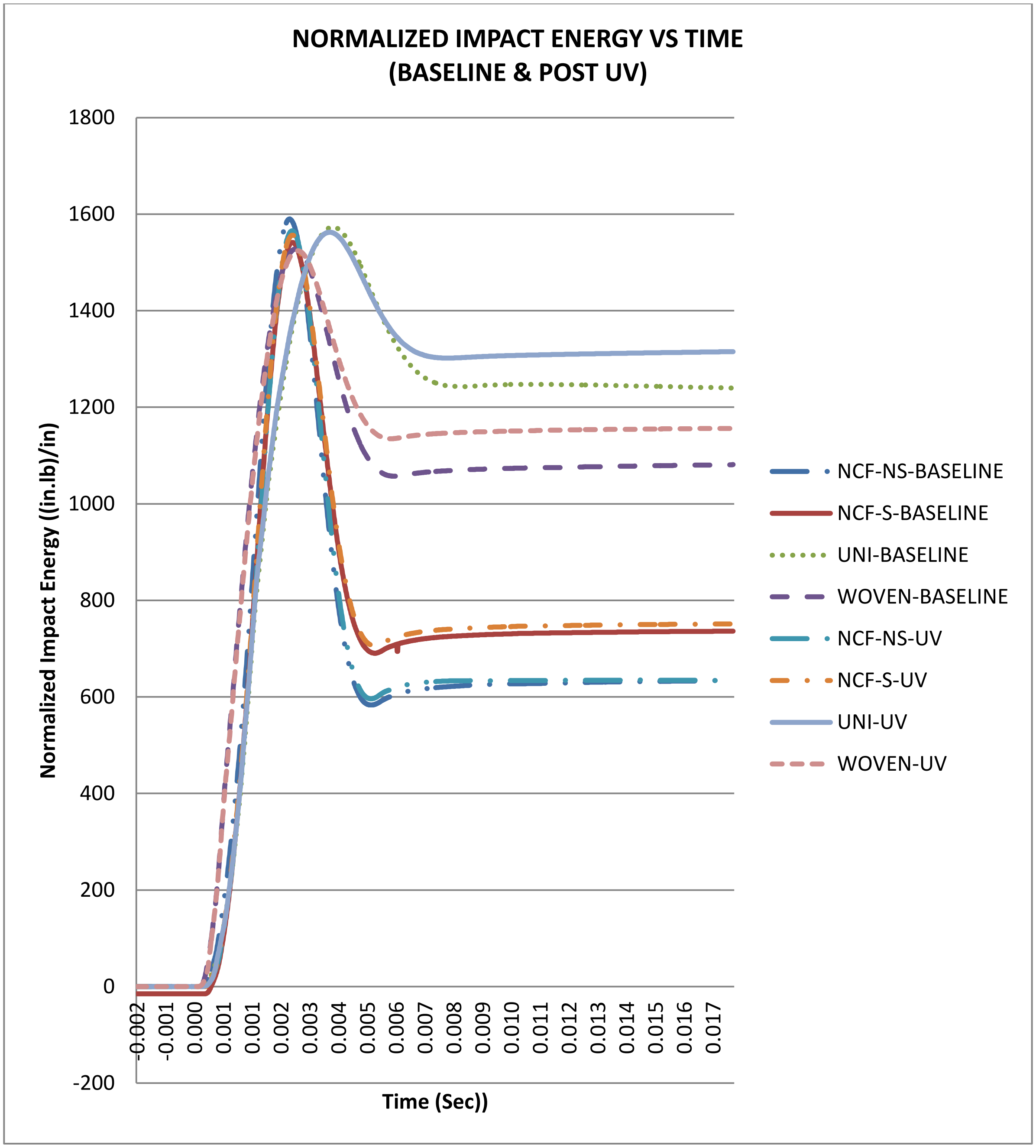


Figure 42: Normalized Impact Energy (in.lb/in) vs. Time (sec) (Baseline and Post-UV)

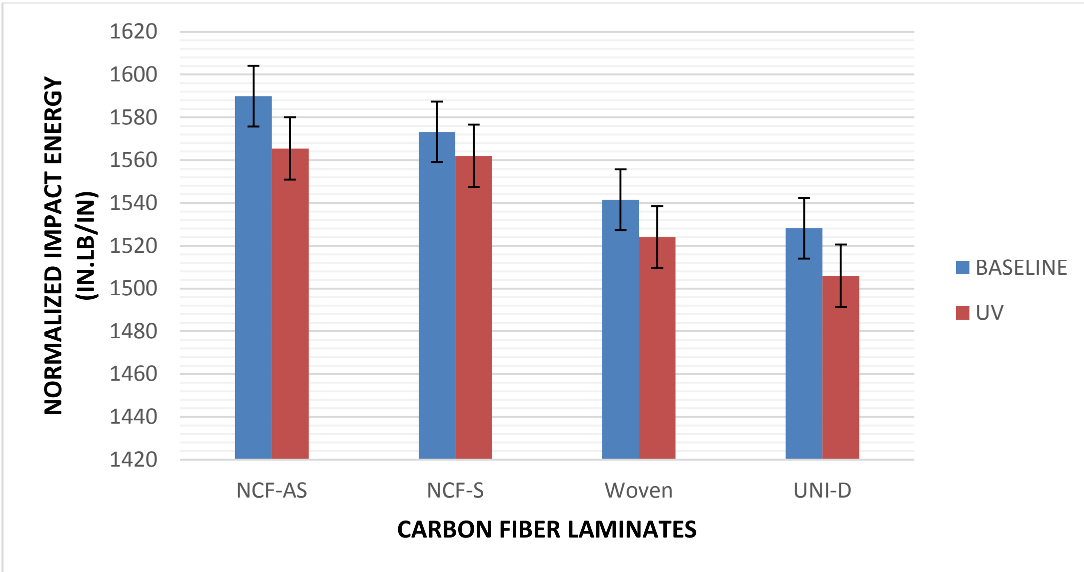


Figure 43: Comparison of Impact Energy (in.lb/in) between Baseline and Post-UV Carbon Fiber Laminates

TABLE 7

PERCENTAGE DIFFERENCE OF IMPACT ENERGY AFTER UV IMPACT

Sample	Impact Energy (in.lb/in) (Baseline)	Impact Energy (in.lb/in) (Post-UV)	% Difference (Baseline–Post-UV)
WOVEN	1541	1524	1.10
UNI CF	1528	1506	1.43
NCF-NS CF	1589	1565	1.51
NCF-S CF	1573	1562	0.69

In Figures 44 and 45, and TABLE 8, the difference percentages were calculated between normalized loads of baseline and post-UV treated samples, indicating that the normalized load carrying capacity of the post-UV specimens decreased marginally compared to baseline specimens. This was due to the environmental degradation of fibers and bundle cracks. NCF laminates showed high load carrying capacity in comparison to unidirectional and woven laminates.

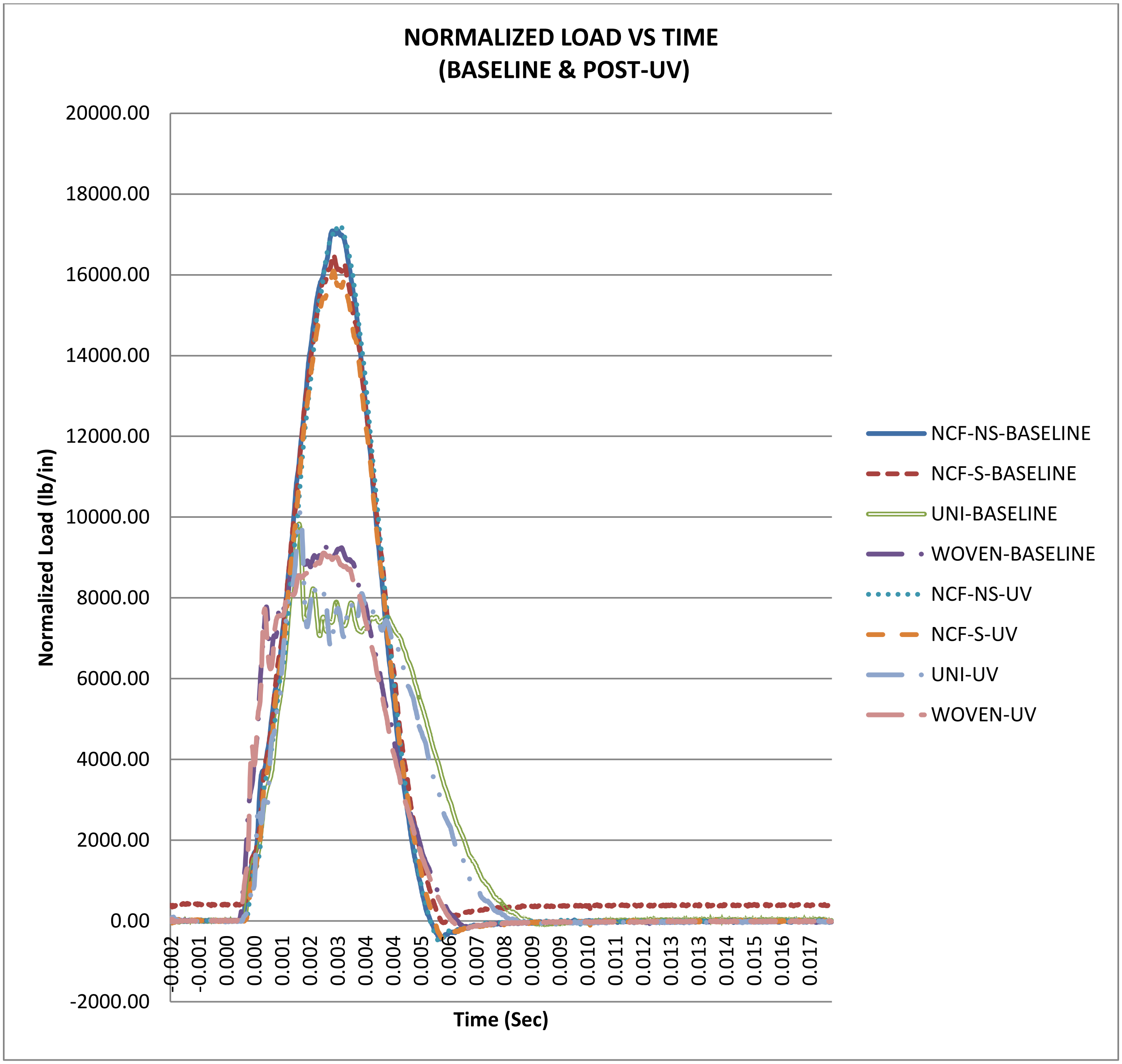


Figure 44: Normalized Load (lb/in) vs. Time (sec) (Baseline and Post-UV)

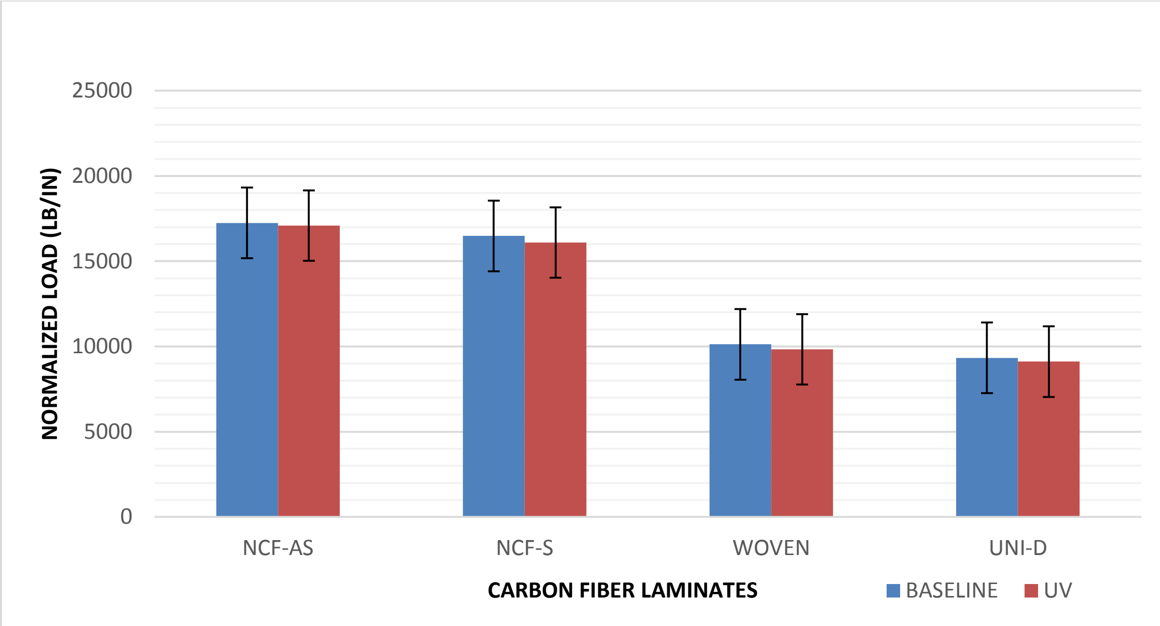


Figure 45: Comparison of Load (lb/in) between Baseline and Post-UV Carbon Fiber Laminates

TABLE 8

PERCENTAGE DIFFERENCE OF NORMALIZED LOAD AFTER UV IMPACT

Sample	Load (lb/in) (Baseline)	Load (lb/in) (Post-UV)	% Difference (Baseline–Post-UV)
WOVEN	10,130	9,833	2.93
UNI CF	9,332	9,113	2.34
NCF-NS CF	17,244	17,090	0.89
NCF-S CF	16,496	16,096	2.42

As shown in Figures 46 and 47, and TABLE 9, NCF laminates after post-UV exposure did not cause to affect them much. Due to their heterogeneous structure and multi-axial fiber placement, the fibers should be closely packed at the impact zone. The unidirectional laminates are the least penetrating panel, followed by woven laminates.

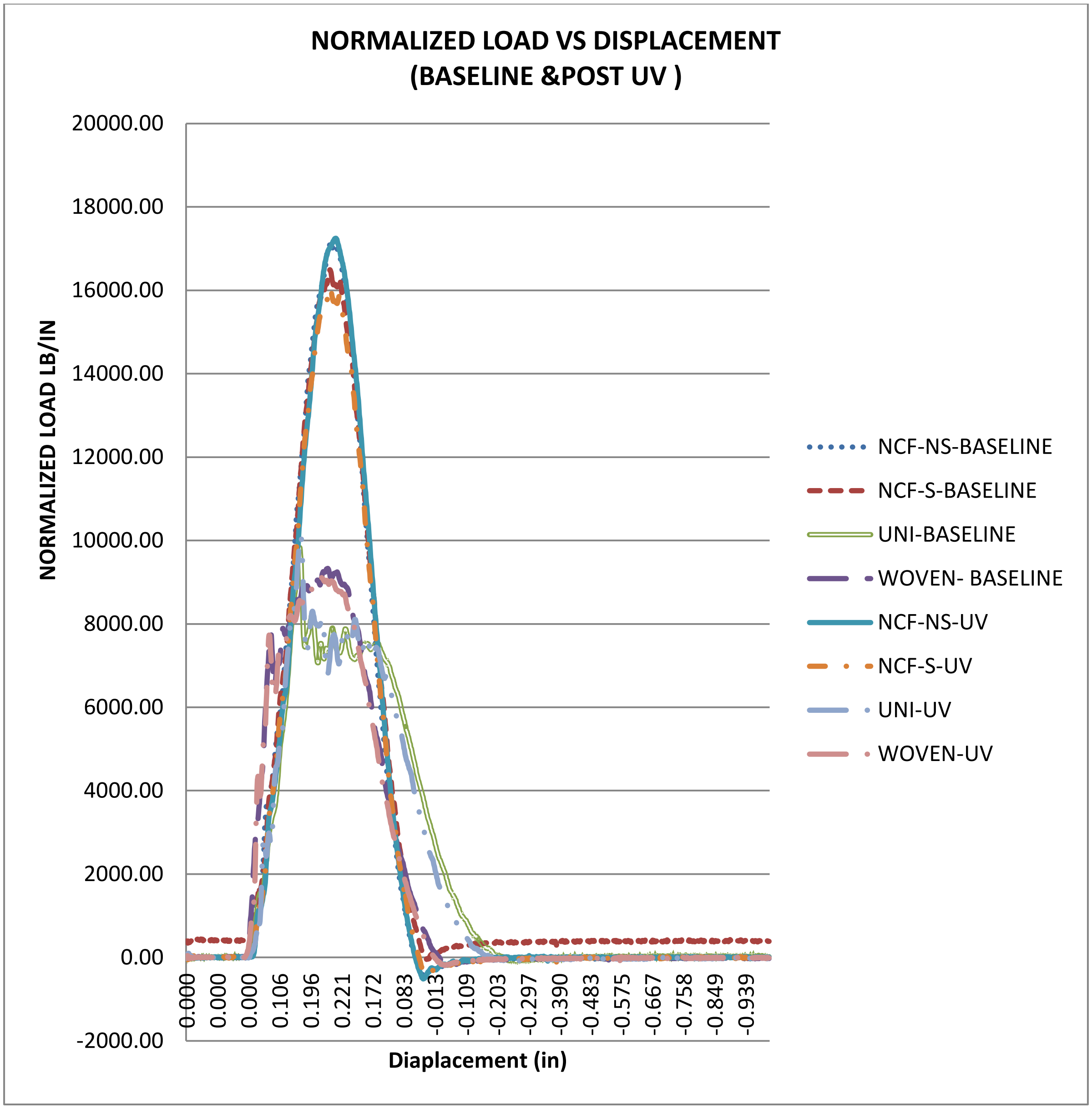


Figure 46: Normalized Load (lb-in) vs. Displacement (in) (Baseline and Post-UV)

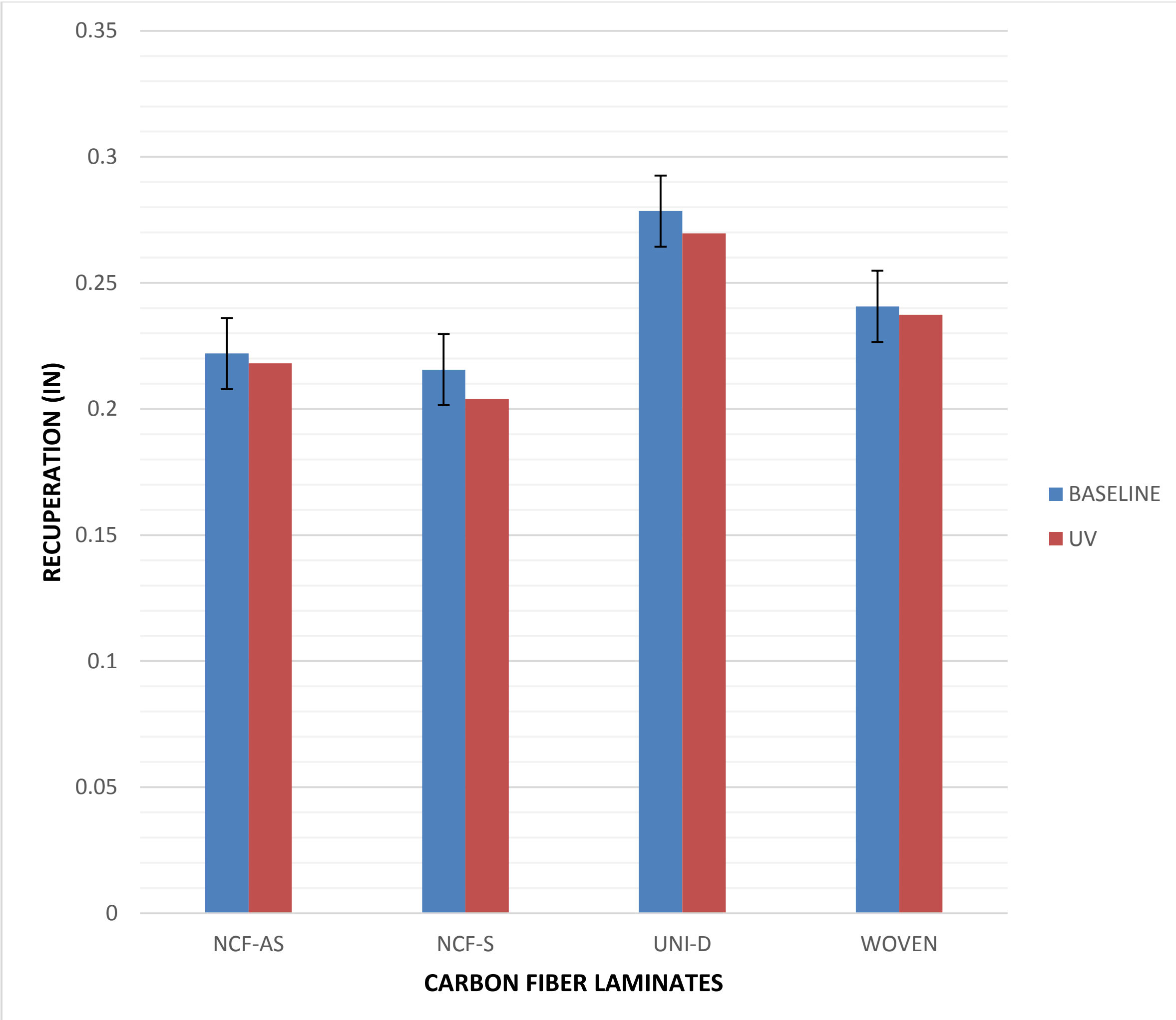


Figure 47: Comparison of Recuperation (in) between Baseline and Post-UV Carbon Fiber Laminates

TABLE 9

PERCENTAGE DIFFERENCE OF RECUPERATION AFTER UV IMPACT

Sample	**Recuperation (in) (Baseline)**	**Recuperation (in) (Post-UV)**	**% Difference (Baseline–Post-UV)**
UNI CF	0.2785	0.2697	3.15
WOVEN CF	0.2407	0.2374	1.37
NCF-NS CF	0.222	0.2181	1.75
NCF-S CF	0.2156	0.2039	5.42

Figure 48 and TABLE 10 show the percentage difference of absorbed energies of CF laminates. After UV impact, a reduction in absorbed energies was seen in comparison to the baseline specimens. The difference in absorbed energies of the NCF laminates was quite insignificant, so further duration of UV exposure on NCF laminates should be considered. The percentage difference of absorbed energies between unidirectional and woven laminates was found to be 20.74% and 17.44%, respectively, which also indicates that unidirectional laminate is the least energy-absorbed panel followed by the woven laminate. A similar observation trend can be seen in parameters such as impact load and recuperation of the panel.

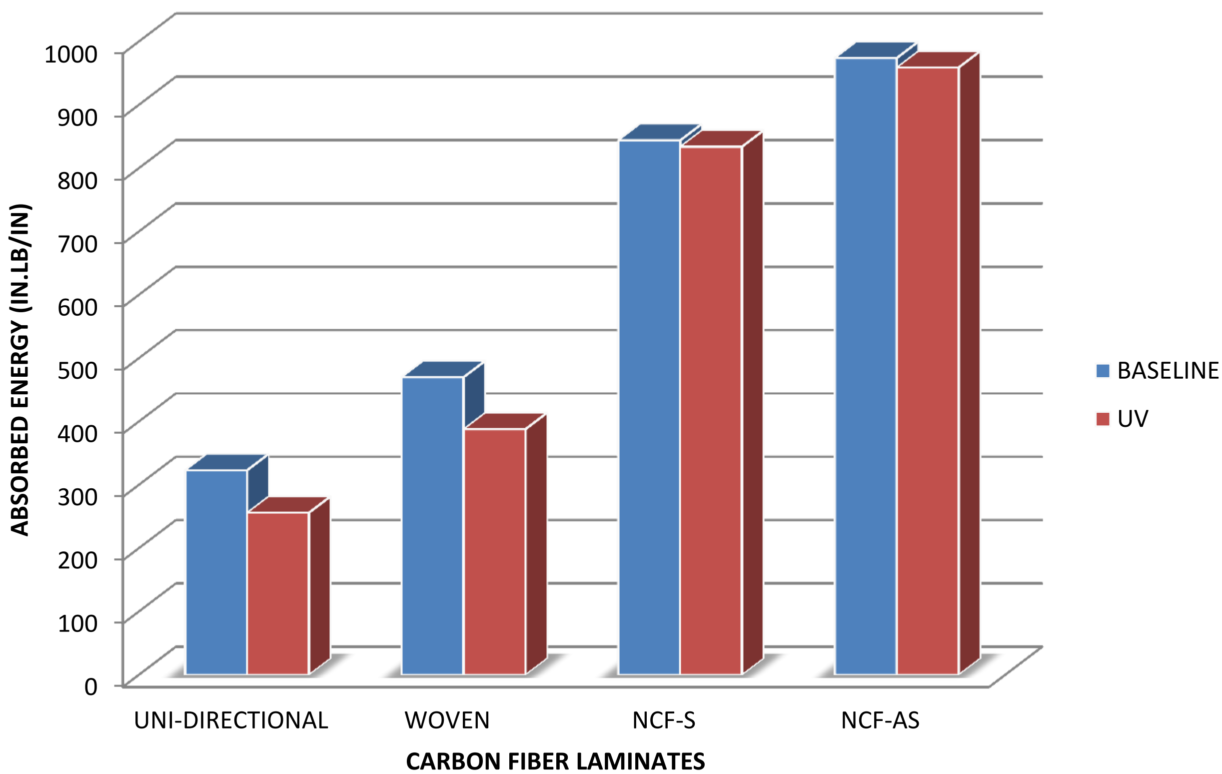


Figure 48: Comparison of Absorbed Energy between Baseline and Post-UV Carbon Fiber Laminates

TABLE 10

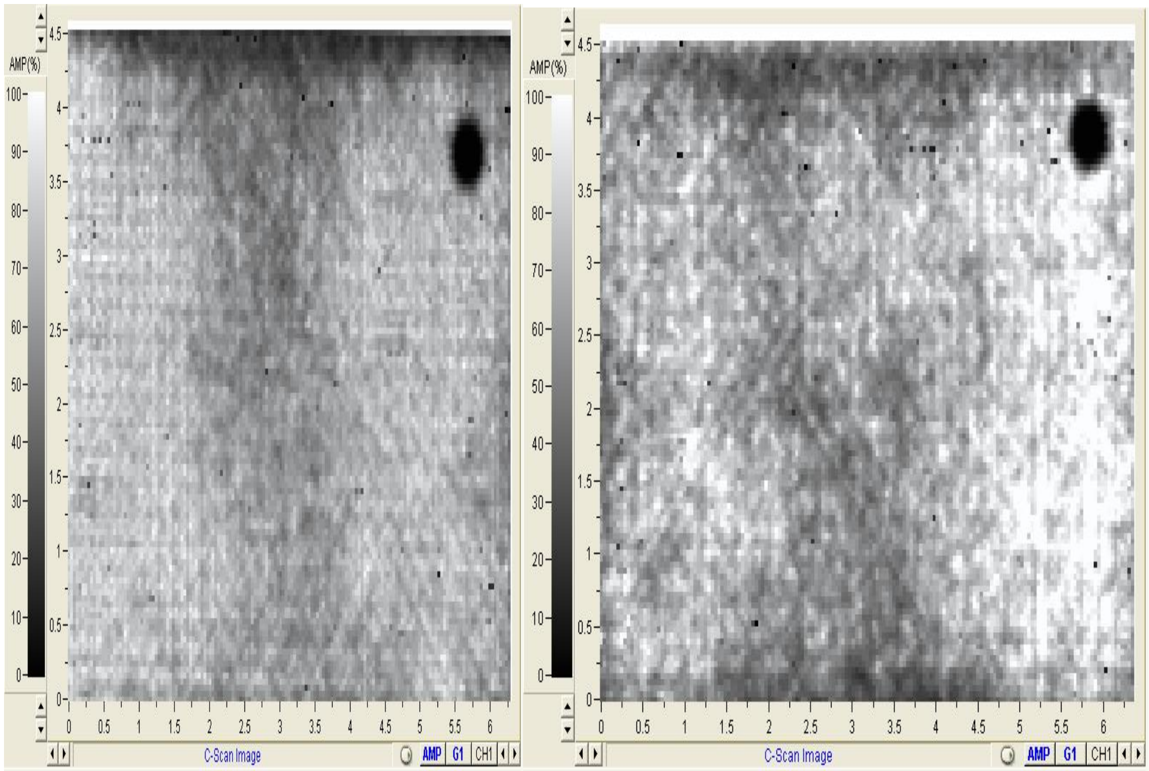
PERCENTAGE DIFFERENCE OF ABSORBED ENERGIES AFTER UV IMPACT

Samples	Baseline	Post-UV	% Difference
Unidirectional	323	256	20.74
Woven	470	388	17.44
NCF-S	844	834	1.18
NCF-AS	974	959	1.54

4.2. Damage Analysis

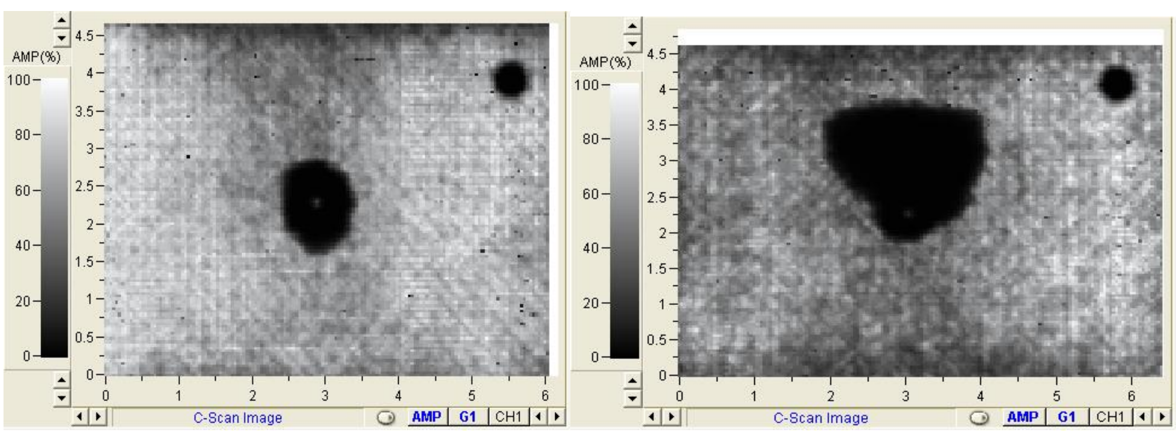
Figures 49 to 52 show the pre-impact and post-impact C-scans of the carbon fiber laminates. The dark black speck at the center of each image is associated with the damaged or impacted zone. The damage areas of the test panels were determined using software.

Tables 11 and 12 tabulate the damaged area, which was obtained from the C-scan imaging, and the dent depth, which was measured using a depth gauge instantaneously after the impact tests. As mentioned earlier, the NCF test panels had the least penetration, followed by the woven laminates. NCF laminates, both symmetric and asymmetric, do not have much variance in terms of damage tolerance. As compared to unidirectional laminates, NCF laminates had more damage tolerance but less significant tensile strength due to misalignment of fibers in the NCF laminates. Woven laminates have fibers that are placed over one another; therefore, there is no reinforcement along the thickness. Damage upon impact is stress concentrated, and the fibers are unable to carry the distributed load, unlike NCF laminates, which can accommodate the distribution of load produced by impact along their multi-axial fibers and reinforcements, thus visually seeing the damage over a large area of the impacted NCF laminate. As shown, the post-UV panels also have similar C-scans and comparable damage view.



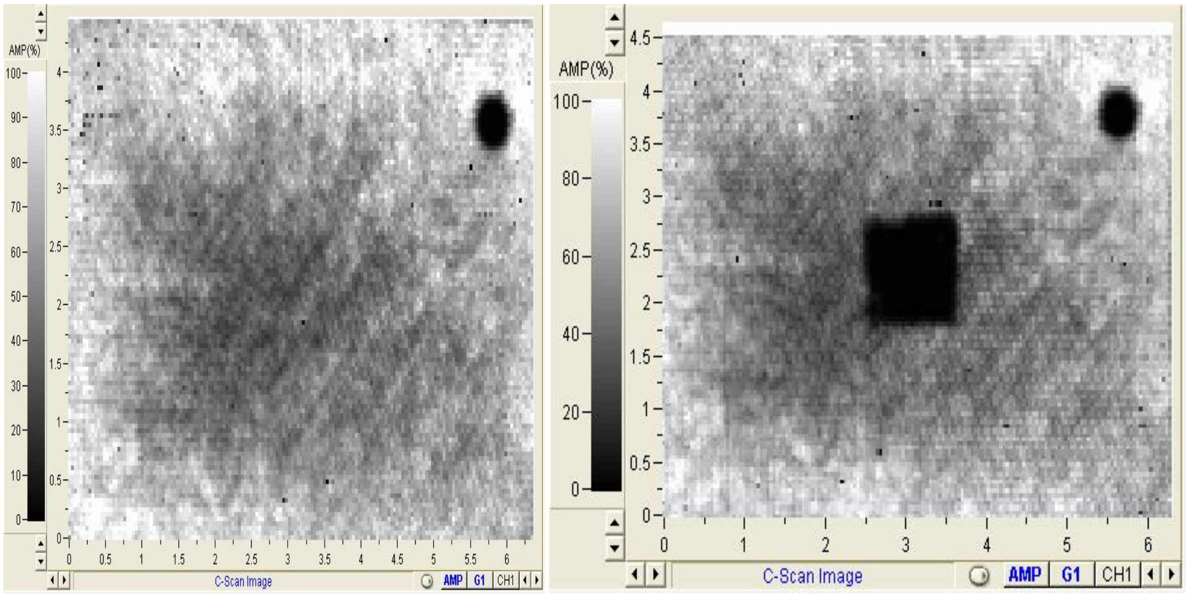
(A) (B)

Figure 49: (A) C-Scan of NCF–Symmetric Laminate and (B) C-Scan of NCF-Asymmetric Laminate



(A) (B)

Figure 50: (A) C-Scan of Post-Impact NCF-As-CF Laminate and (B) C-Scan of Post Impact NCF-S- CF Laminate



(A) (B)

Figure 51: (A) C-Scan of Pre-Impact Woven CF Laminate and (B) C-Scan of Post-Impact Woven CF Laminate

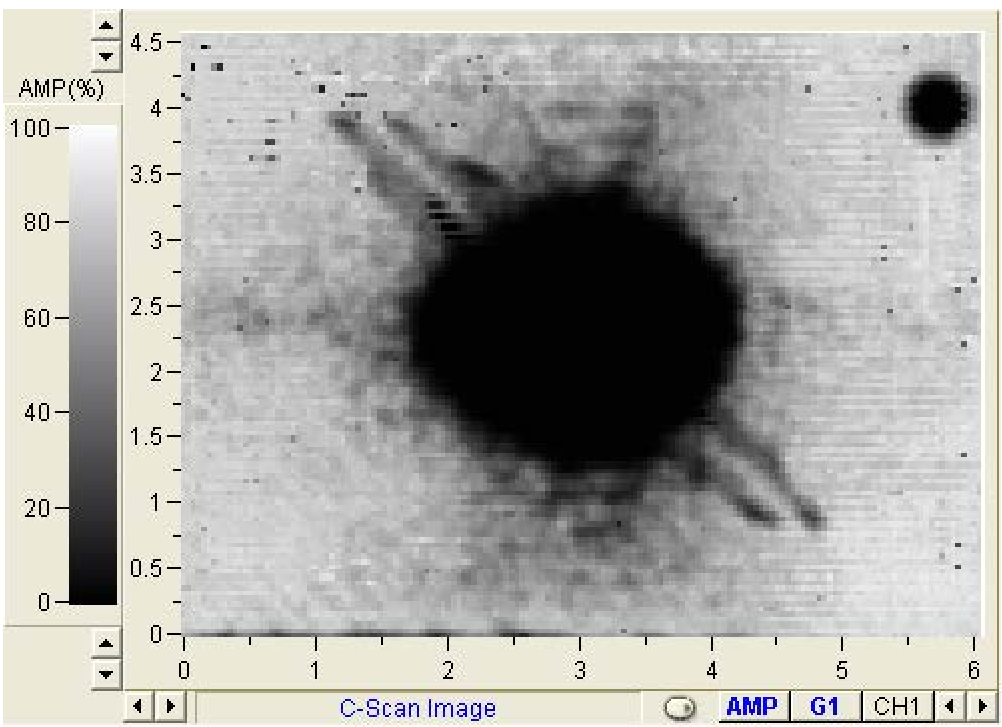


Figure 52: C-Scan of Post-Impact Unidirectional CF Laminate

TABLE 11

DENT DEPTHS SUMMARY (BASELINE)

Type of Laminate	TUP Diameter (in)	Impact-Energy ((in.lb)/in)	Dent Depth (in)
NCF-S-1	1	1500	.0056
NCF-S-2	1	1500	.0055
NCF-S-3	1	1000	.0065
NCF-NS-1	1	1500	.0050
NCF-NS-2	1	1500	.0055
NCF-NS-3	1	1500	.0045
W-CF-I-1	1	1500	.0250
W-CF-I-2	1	1500	.0205
W-CF-I-3	1	1500	.0185
U-CF-1	1	1500	.0525
U-CF-2	1	1500	.0605
U-CF-3	1	1500	.0580

TABLE 12

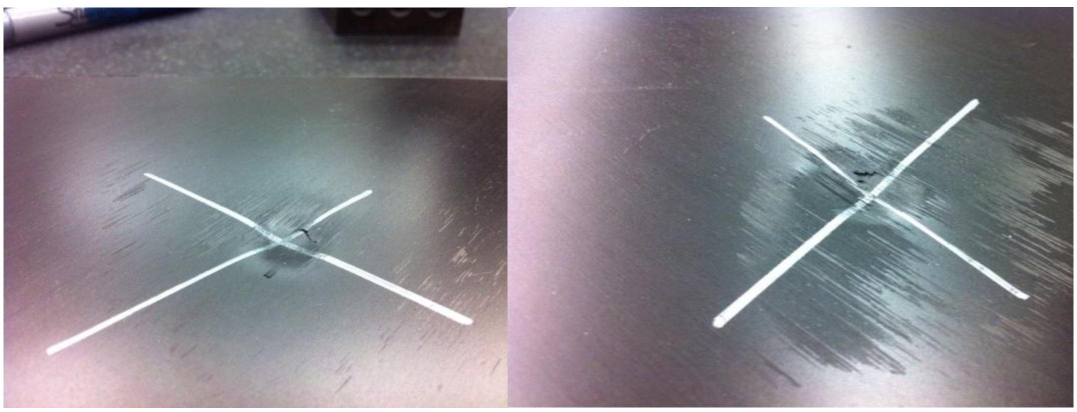
DENT DEPTHS SUMMARY (POST-UV/ SALT CHAMBER)

Type of Laminate	TUP Diameter (in)	Impact-Energy ((in.lb)/in)	Dent Depth (in)
NCF-S-UV-1	1	1500	0.0065
NCF-S-UV-2	1	1500	0.0065
NCF-S-UV-3	1	1000	0.0065
NCF-NS-UV-1	1	1500	.0050
NCF-NS-UV-2	1	1500	.0045
NCF-NS-UV-3	1	1500	.0055
W-CF-I-1	1	1500	.0205
W-CF-I-2	1	1500	.0255
W-CF-I-3	1	1500	.0255
U-CF-1	1	1500	.0480
U-CF-2	1	1500	.0535
U-CF-3	1	1500	.0545

Consequences are affected by the inflexibility of the impact device, friction between the impactor and guides during the drop, impactor geometry, and impactor mass. Errors can result if the test sample and sample support fixture are not centered with respect to the impact device. Variables differences such as impact velocity, and impact energy, wave propagation and vibrations in the specimen, impactor, impact device and support fixture during the impact occurrence can also lead to off target outcomes. It is shown that symmetric and asymmetric NCF laminates have more or less the same intensity of damage recovery in comparison among baseline and post-UV panels, but superior resistance in comparison to woven and unidirectional laminates. It's also quite evident that woven laminates have much better impact opposition against unidirectional laminates. Microscopic variation between baseline and post-UV panels exist relative to dent values because the aftermath of UV exposure leads to possible resin degradation in UV exposed panels and also because of dent relaxation phenomenon .

The reaction of a laminated plate sample to out-of plane drop-weight impact is reliant upon many factors, such as laminate thickness, ply thickness, stacking sequence, environment, geometry, impactor mass, striker tip geometry, impact velocity, impact energy, and boundary conditions. As shown in figure 53 to 55, the nature of the impact response is well evaluated. The unidirectional laminate as compared to woven and NCF laminates shows that it has weak impact response and presence of damage modes like dents, depression, and a combination of splits/cracks, fiber breakage, and material puncture. The woven laminates are considerably better, showing dent and depressions with only slight splits or cracks. The NCF laminates indicate a superior impact response, showing bruised surfaces with negligent depressions, splits or fiber breakage. Therefore, NCF laminates have an excellent impact resistance property. The post-UV panels also showed similar damage whereby the dent depth may condense with time or upon exposure to different environmental conditions.

(A)



(B)

Figure 53: (A) and (B) Post-Impact Unidirectional CF Laminates

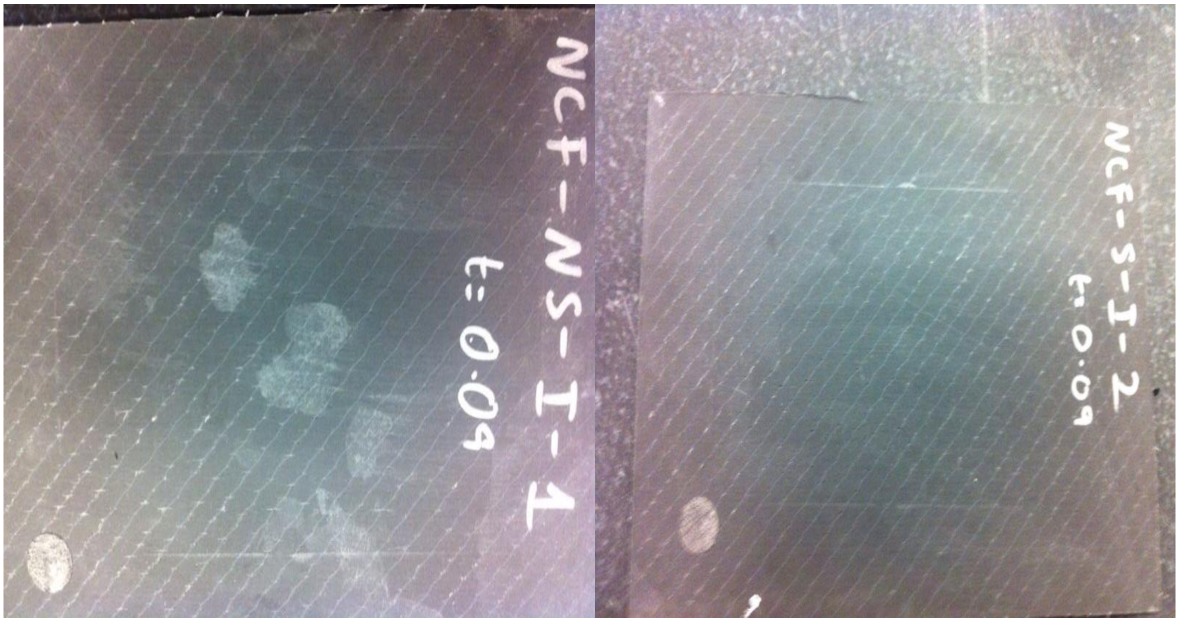


Figure 54: Post-Impact NCF CF Laminate

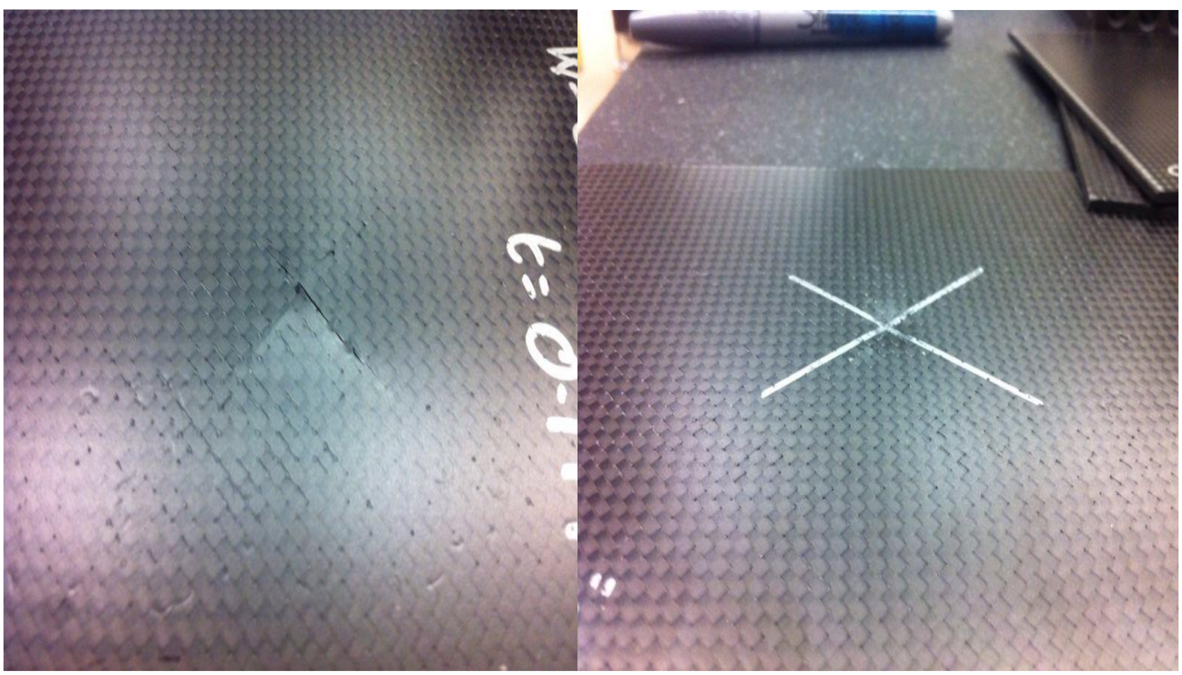


Figure 55: Post-Impact Woven CF Laminate

4.3. Contact Angle Measurement

Contact angles are extremely responsive to contamination; values reproducible to better than a few degrees are usually only acquired under laboratory conditions using distilled liquids and very dirt-free solid surfaces. If the liquid molecules are strongly attracted to the solid molecules, then the liquid drop will completely spread out on the solid surface. On an exterior surface that is rough or contaminated, there will also be contact angle hysteresis. Even in such a smooth surface, a drop will presume contact angle hysteresis. Using the sessile drop method, the same laminate surfaces were put to the test. The woven laminate showed superior hydrophobicity at around 112.16 degrees compared to NCF-non symmetric carbon fiber, which showed 96.10 degrees. The unidirectional and NCF-symmetric carbon fiber showed an almost similar hydrophobic nature measuring 94.51 and 94.22 degrees, respectively. Exposure of the panels to the environment, where degradation occurs as it is a function of time and temperature. Unfortunately it compromises the panels to be recorded or to be measured for water contact angle data because after post moisture conditioning the resin disintegrates and leaves voids between the fibers on the panel. Post-UV, the wettability increases drastically around 31% in NCF panels. But when moisture seeps into these voids, it skews the results, because the contact angle is supposed to decrease, and instead increases, which defies its valid theory. Figures 56 and 57 show the water contact angle trend between different carbon fiber laminates before and after UV treatment.

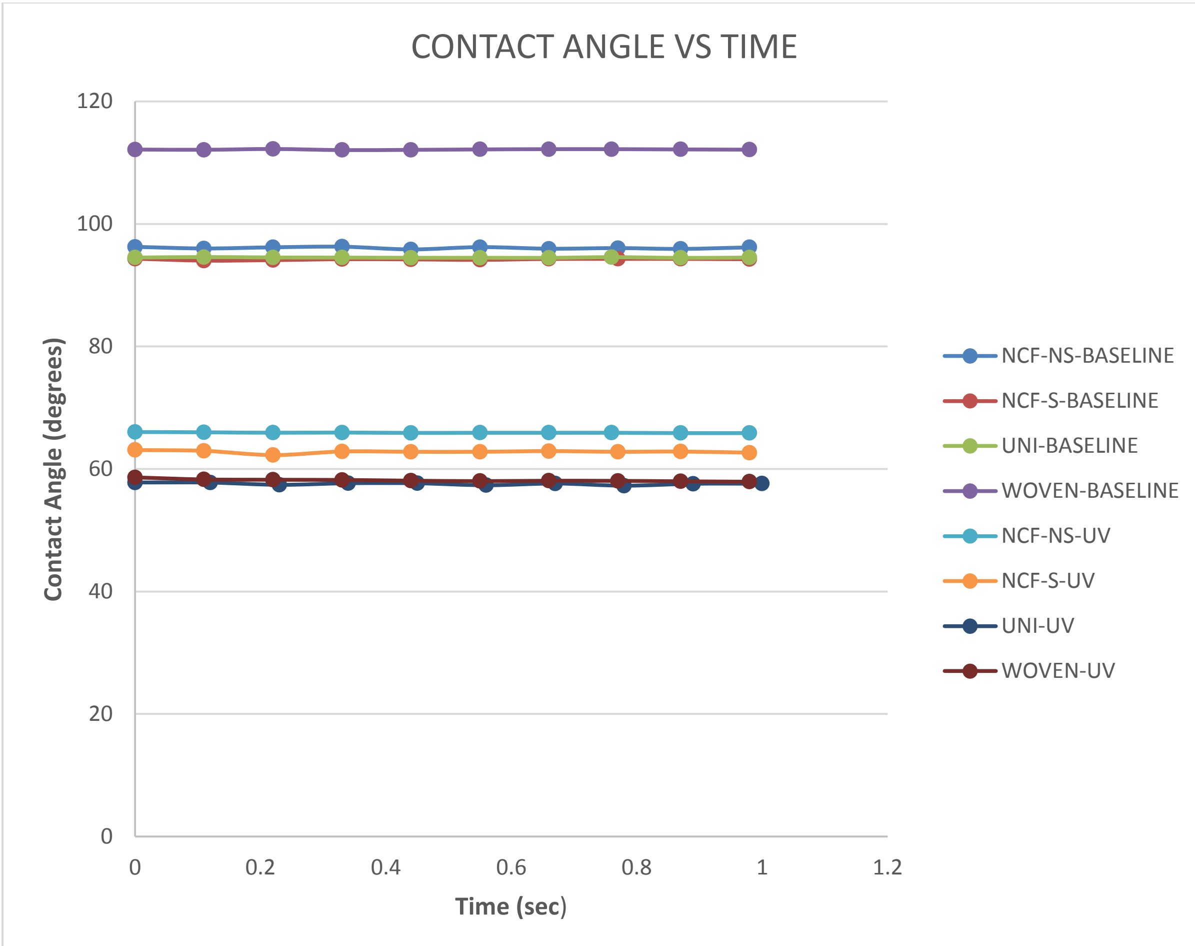


Figure 56: Water Contact Angle (Degrees) vs. Time (Sec) between laminates

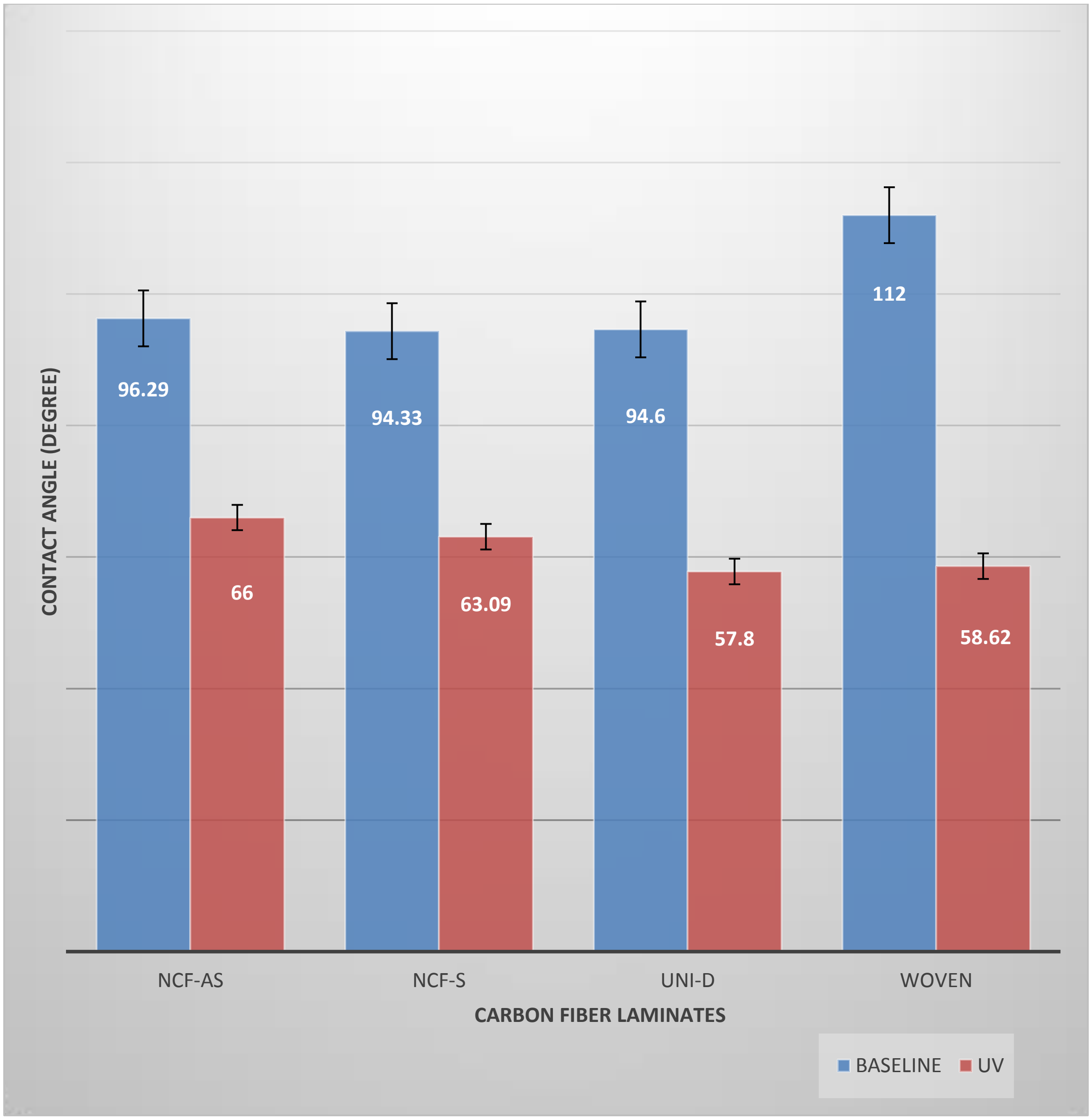


Figure 57: Water Contact Angle (degree) for various Carbon Fiber Laminates

CHAPTER 5

CONCLUSIONS

A total of 24, 150 mm x 100 mm (4 in x 6 in) carbon fiber/epoxy composite panels with woven, non-crimp fiber, and unidirectional fiber types were manufactured. Twelve sets of the panels were tested using ASTM D7136 (impact testing for composites). Experimental data was quantitatively examined to determine an evaluation pattern among the baseline specimens, ultraviolet samples, and moisture samples. The damaged composite samples were put under the c-scanner to have a two-dimensional apparition for the damage study. Then the damaged locale of each composite panel was exposed to UV illumination and moisture exposure for a total of 20 days each, and the water contact angles around the damage area were recorded at four-day intervals.

This damage study showed that the NCF-S and NCF-AS samples were damaged the least in comparison to the other composite panels, undertaking the most load of 17,244 lb/in (pre-UV) with only 0.89% decrease after UV, as well as NCF-S laminate with 1.54% decrease in sustaining impact. The damage among NCF-S and NCF-AS composite samples in comparison to baseline and post-UV-treated panels had no significant difference, since the multi-axial fibers are closely packed and the need for exposure to more UV illumination is required to see if they had any significant changes. The unidirectional composite specimen was damaged the most in terms of damage region. The average water contact angles were quantitatively examined for baseline and post-UV treatment, where 31.4% increase in wettability was found in the NCF-AS panels but after moisture conditioning, the measurement for water contact angles became invalid.

The damage locale of each panel was found to be affected by UV light and moisture, because fluctuating development was observed in the water contact angles readings. Extensive UV exposures in several lead to micro cracks on the surface of the coated specimens in the absence of nanoscale inclusions, while very negligible cracks or degradation appeared on the baseline samples. Test results also showed that UV exposure along with salt fogging reduced the impact loads and energies of samples [34].

Post-UV treatment showed no comparative outcome on the NCF specimens under an impact incident. Post-UV conditioning content decreases the impact load resistance by a minute percentage; also, a reduction in elastic modulus exists. On the other hand, NCF laminates were found to be advanced in terms of impact load and energy in both baseline and post-UV samples. The NCF epoxy test panel showed the highest impact load (0.89% more than post-UV), with the most impact energy as well (1.51% more than post-UV) and insignificant recuperation. In terms of absorbed energy, the NCF composite panel absorbed the most energy (974 (in.lb/in) of a 6.7 J/mm impact), while the unidirectional and woven composite panels comparatively showed less absorbed energy, and a significant difference was observed as compared to their respective post-UV treated composite panels where the UV treated NCF-AS panels had 1.54% decrease .

Constant research is necessary on significant changes in NCF laminates under prolonged UV exposure, in different resin systems, varying process parameters, and influence of material properties on the impact response of composite panels under different impact energies which are required to obtain a complete grasp of the impact behavior of composites. Repeated drop-weight impact tests offer a very good perceptive of the impact damage tolerance of polymer composites and help to grade them on this basis.

CHAPTER 6

FUTURE WORK

Impact investigation of composite materials is very critical in order to monitor them for structural reliability. Impact assessment is a very broad field of study, and therefore, further research is required. More research must be done in the area of analysis of failure conduct after the preliminary elastic response of specimens is subjected to intense transverse loads, both analytically and experimentally. Further work is also needed in the area of damage inspection and characterization.

Compression after the impact examination method covers the compression residual strength properties of multidirectional polymer matrix composite laminated plates, which can be tested using ASTM D7137, "Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates." This test can foresee the damage tolerance of the material, since the damage properties are highly reliant on the size, composition of the material, stiffness, etc. Hence, this test is a supplementary to ASTM D7136, which would also provide residual strength data used for material specifications.

Moreover, there should be a focus on the measure of resin/polymer degradation and dent relaxation. Upon exposure to various environmental factors and UV (photo-induced) degradation, these polymers undergo a change in properties, often called "aging." This can be measured with a Fourier transform infrared micro spectroscopy. Since environmental degradation affects these impacted specimens, valid solutions should therefore exist in order to improve corrosion resistance.

Since environment degradation affects these impact specimens, valid solutions should therefore exist in order to improve corrosion resistance.

In addition, prepreg recycling should be considered, in order to reduce the disposal of hazardous waste, landfill requirements, and the use of toxic products, since prepregs have limited lifecycle, and the disposal of expired prepregs are extremely expensive. When composite materials fail to function, they are usually destroyed or cast off into landfills, due to the lack of recycling know-how and uses of recycled composites and fibers. This has created a disturbing impact on the environment and economy due to lethal resin systems which are used to manufacture composite materials. The removal of this perilous waste is very expensive, so efficient recycling of these materials is needed [33]. Introduction of possible improved process methods, such as utilization of scrap prepregs as reinforcements in plastics and transition of the newly process methods into the commercial sector should be initiated. Also, recycling will thwart any scarcities of these fibers, especially carbon fibers used today.

Familiarity of the constituent content is essential for assessing the quality of a manufactured material and the processes used during its fabrication. The void volume of a composite material may considerably affect some of its mechanical properties. Higher void volumes typically mean lower fatigue resistance, greater vulnerability to moisture infiltration and weathering, and increased dissimilarity or scatter in strength properties. Awareness of a composite material's void volume is as an indication its quality, which can be determined by acid digestion tests on the panels.

Angle-ply or axially biased composite laminates are an essential class of laminates because they associate good properties in the axial and shear directions. The U.S. Army has been fascinated in these laminates for various ballistic applications. It helps in the selection of composite failure criterion for compression performance, design of test coupons for compliance testing, and the selection of laminate architectures for optimum combinations of compressive and shear behavior.

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