Spring 2013

Manufacturing and characterization of polyurethane based sandwich composites

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MANUFACTURING AND CHARACTERIZATION OF POLYURETHANE BASED SANDWICH COMPOSITES

by

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A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

2013

Approved by

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ABSTRACT

Composite sandwich structures have been extensively employed in aerospace structures, ship building, infrastructure, etc. due to their light weight and high strength to weight ratio. The understanding of their behavior under impact and environmental conditions is extremely important for the design and manufacturing of these engineering structures since these problems are directly related to structural integrity and safety requirements. Vacuum assisted resin transfer molding (VARTM) is one of the commonly used low cost composite manufacturing processes. Polyurethane (PU) resin system has been observed to have better mechanical properties and higher impact strength when compared to conventional resin systems such as polyester and vinyl ester. This study has two parts, part one investigates the damage behavior of composite sandwich structures manufactured using the VARTM process with polyurethane resin and two different foam cores, rigid PU 6 lb density and Webcore (TYCOR-W) respectively, under transverse impacts at low velocities. Part two explores how moisture permeation can deteriorate composite sandwich material structures. This part describes an investigation of the mechanical degradation of the composite sandwich structure exposed to moisture.

ACKNOWLEDGMENTS

I extend my deepest appreciation to Dr. K. Chandrashekhara for all the support, guidance and expertise as my advisor during the pursuit of my M.S. and for the help with the preparation of this thesis. I would also like to thank the committee members Dr. Okafar and Dr. Du for their valuable time.

In addition, I am thankful to my fellow graduate students for their advice and assistance in the preparation of thesis, especially Mohaned Mohamed. Without his help, this paper would not have been possible.

I also wish to thank Bayer Material Science for providing the materials necessary to complete this paper.

Furthermore, I want to gratefully acknowledge the Department of Mechanical and Aerospace Engineering for providing financial assistance in the form of a Graduate Teaching Assistantship.

Last, but certainly not least, I would like to thank my family and my friends for their continued support through my pursuit of a master's degree, both in my personal and academic life.

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1. INTRODUCTION

Composites are being considered as an alternative to conventional materials such as aluminum and steel due to their high specific strength, high specific modulus, and corrosion and wear resistance, low thermal conductivity and improved fatigue life. Due to these improved properties, composites have numerous applications in the aerospace, automotive, infrastructure, sports and medical industries [1]. The constituent materials in the composite are fibers and the matrix. Fiber reinforcements are the major load carrying components whereas polymer matrix is used for the load transfer as well as barrier against adverse environments between the fibers. With an increasing use of composites, to achieve their optimum performance, a thorough understanding of material and damage behavior of these composites is necessary [2-4].

Sandwich composite structures, consisting of two thin, fiber-reinforced composite face sheets bonded to a foam core, are widely used in aerospace, marine and many other engineering applications [5-6]. The function of the face sheets is to carry bending and in-plane forces, while the role of the core is to carry transverse shear loads and to help prevent face-sheet buckling. The combination of a thick lightweight core and thin, stiff face sheets results in exceptionally lightweight structures. However, these sandwich composite structures do have disadvantages. One of the main drawbacks of the high-performance structures is the delamination between the faceplate and the core. Another main disadvantage is that their load carrying ability can be significantly reduced by the presence of moisture in the polymer foam core. Even though the composite face sheets lower the rate of moisture diffusion into the core, they do not prevent moisture diffusion

from occurring [7]. Moisture diffusion is extremely slow, thin parts may reach moisture equilibrium while thick parts will never become fully soaked within their service life. Moisture absorption in polymer composites can affect the mechanical properties of a part by degrading the fiber matrix interface, micro-cracking the matrix, changing the stress state, and altering the glass transition temperature [8-9]. In order to ensure reliability of the structure and to determine the time that the mechanism can be in a real life environment before moisture absorption damages structural integrity, the appropriate physical tests are conducted that will analyze the effects of the moisture absorption in the structure.

The Vacuum Assisted Resin Transfer Molding (VARTM) process was utilized in the manufacturing of the composite specimens. VARTM process is one of the most widely used composite manufacturing processes developed in recent years for several engineering applications due to advantages over conventional RTM by eliminating the costs associated with matched-metal mold making, volatile emission, and high injection pressures [10]. In this process the polymer resin is infused through the fiber reinforcements using vacuum pressure. Figure 1.1 shows the VARTM arrangement.

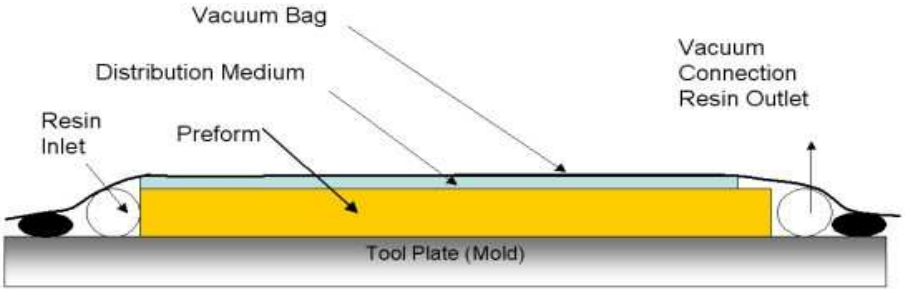

Figure 1.1 VARTM Schematic

1.2 POLYURETHANE

Although the reaction between isocyanate and hydroxyl compounds was originally identified in the 19th Century, the foundations of the polyurethanes industry were laid in the late 1930s with the discovery, by Otto Bayer, of the chemistry of the polyaddition reaction between diisocyanate and diols to form polyurethane. The first commercial applications of polyurethane polymers, formidable elastomers, coatings and adhesives, were developed between 1945 and 1947, followed by flexible foams in 1953 and rigid foams in 1957. Since that time they have been finding use in an ever-increasing number of applications and polyurethanes are now found playing a vital role in many industries. Polyether polyols offered technical and commercial advantages such as low cost, ease of handling, and better hydrolytic stability over polyester polyols and quickly replaced them in the manufacture of polyurethane goods. PU is any polymer consisting of a chain of organic units joined by urethane links. PU polymers are formed by chemical reaction between a monomer containing isocyanate functional groups and another monomer containing alcohol groups in the presence of a catalyst or heat. Figure 1.2 shows the chemical structure of polyurethane.

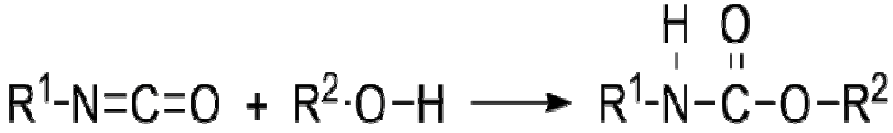

Figure 1.2 Chemical Makeup of Polyurethane

Polyurethane (PU) resin systems are an important and very versatile class of polymer materials with desirable properties, such as high abrasion resistance and impact properties, excellent shock absorption, flexibility and elasticity [11-15] when compared

to conventionally used resin systems such as vinyl ester, polyester and vinyl alcohol. The success of PU is due to its ability to be produced in various forms from flexible to rigid structures. In addition, PU can be processed at low pressures and temperatures in low-cost molds. PU composites are finding an increase in commercial applications due to the increasing demand for lightweight, durable and cost effective compounds [16-17].

1.2.1 Advantages of PU Composites. Composites manufactured from PU resins have superior tensile strength, impact resistance, and abrasion resistance compared with composites based on unsaturated polyester and vinyl ester resins. PU composites are also said to be attractive for their processing advantages. The curing times are much faster than for polyester. They contain no styrene and therefore do not generate large amounts of volatile organic compounds. The superior toughness of PU composites pays off in post manufacturing operations such as drilling, machining, and assembling. Little or no micro-cracking is observed compared with traditional thermoset composites [18].

1.2.2 Limitations of PU Composites. There are two major challenges when using PU resin in vacuum infusion processes: One is maintaining a relatively constant and low viscosity for a long period of time. The second challenge is moisture sensitivity, as the isocyanate portion of the reacting components tends to react with water to produce carbon dioxide, which causes foaming [19].

In this current endeavor, glass fiber reinforced sandwich composites were fabricated using woven E-glass fibers compatible with PU resins (obtained from Ownes Corning) for each face sheet with thermoset polyurethane PU 840871 resin system (obtained from Bayer Material Science) and rigid polyurethane and low density matted foams were used for the core. This paper consists of two parts. In the first part of this

paper, the performance evaluation of the sandwich composites was conducted using low velocity impact tests at three different energy levels (30J, 40J and 50J) and the results were compared. The second part discusses the degradation of mechanical properties in sandwich composites exposed to moisture determined by low velocity impact and flexural tests.

2. BACKGROUND

2.1 COMPOSITE MATERIALS

Composite materials consist of at least two substances including reinforcement fibers and the matrix. The reinforcing material is stiffer and stronger providing the strength for the composite material. The continuous or matrix is the binder or resin and holds the fibers together [20]. The resin researched is a polymer matrix, a liquid resin converted into a hard and brittle solid through chemical cross-linking. Polymer composites can be separated into two categories: thermoplastics and thermosets. Thermoplastics can be softened and hardened through cyclic heating and cooling respectively. Thermosets, however, cannot change shape non-destructively after the application of heat or chemicals. The polyurethane resin system discussed in this paper is a thermoplastic polymer matrix. There are many types of reinforcement fibers currently available. Some commonly used fibers include: glass, aramid, and carbon. The reinforcement fibers are generally available in the form of a tow or a band. A woven form of the reinforcement is also used in certain cases, depending on the application of the composite [21].

The authors of the textbook *Analysis and Performance of Fiber Composites Third Edition,* Ararwal, Broutman, and Chandrashekara subdivided composite materials into two basic types: fiber-reinforced or fibrous composites and particle-reinforced composites or particulate composites and then subdivided those classifications further. Particulate composites are commonly made of small particles, such as in the case of particleboard, and can have an orientation that is either random or preferred. Fibrous

composites can be multilayer (angle-ply) or single-layer meaning that the composites have the same properties and orientation. Single layer composites can be reinforced with discontinuous fibers (fibers cut into small pieces) or continuous fibers (fibers with few or no breaks). Properties of composites composed of continuous fibers are higher than those with discontinuous fibers as a result of fewer breaks in the fibers.

Orientation of discontinuous fiber-reinforced composites can be either random or controlled to give strength in desired directions. Continuous-fiber reinforced composites can be either unidirectional, all the fibers are orientated in one direction, or bidirectional, two directions such as in woven fabrics. Composite materials used in the aerospace industry are mostly multiphase materials made from reinforcing fibers, usually carbon or glass, pre-impregnated (pre-preg) with polymer material or resin system that are combined and cured to create a stronger substance [20].

Multilayered composites are constructed out of numerous layers of plies called lamina stacked on top of each other. Within a ply, the fibers can be unidirectional, bidirectional or in other forms less commonly used. Material properties in bidirectional lamina maintain higher strength along the directions of the fibers, whereas perpendicular to the fiber, the matrix properties dominate, thus, the strength is less in the perpendicular direction.

Most composite structures are not loaded in a single direction, so the laminate structure must be stacked with the lamina's fibers orientated at different angles in order to support the loading. The unique load cases for each component determine the layup, number of layers required, and the fiber orientation of the laminates. Composite

laminates are preferred over more traditional materials such as aluminum because of the high strength to weight ratios and the high temperature tolerance [20].

3. MATERIALS AND METHODS

3.1 POLYURETHANE RESIN SYSTEM

Polyurethane (PU) resin systems are an important and very versatile class of polymer materials. The PU resin system was selected to be used in the VARTM process as they have higher performance characteristics as seen in Table 3.1 and are less difficult to work with during fabrication when compared to conventional resin systems such as polyester and vinyl ester. PU resin systems are generally characterized as aromatic and aliphatic. Aliphatic PU has lower mechanical properties than the aromatic resin system due to its chemical structure. The properties of the materials used in this study can be found in Table 3.2.

Table 3.1 Impact Properties of Polyurethane and Other Conventional Resins

Property	Vinyl Ester	Unsaturated Polyester	Polyurethane
Maximum Load (N)	3260	3047	4088
Energy to Max Load ((N-M))	18.2	11.4	24.8
Total Energy (N-M)	29.3	27.7	38.4

Source: Processing and Characterization of Pultruded Polyurethane Composites by Michael Connolly, John King, Trent Shidaker and Aaron Duncan (Huntsman)[14]

Table 3.2 Approximate Material Properties for Fibers and Resin

Property	Glass fibers: WR18/3010	PU 840871 Resin system
E (GPa)	20.6	2.65
ρ (g/cm^3)	2.56	2.23
Fiber diameter (μm)	16	--

3.2 FOAM CORES

For part one, two different foam cores were used in the manufacture of the sandwich composite parts. Both foams had a thickness of 2 inches. One foam core was a rigid polyurethane based foam and the other was a soft fiber reinforced foam. The soft foam, TYCOR-W, was reinforced by a glass fiber mat that had perpendicular to the plane channels. Once the resin was infused into the part, these channels lined with the mat allowed for the creation of thin support lines normal to the facesheets.

3.3 FABRICATION OF SANDWICH COMPOSITES

The VARTM process was used in the fabrication of the sandwich composite samples. For part one, two 9 inch x 6 inch sandwich composite parts with 4-ply faceplates were manufactured with each of the 2 inch foam cores. The reinforcement material used in creating these composite samples is woven E-glass fiber compatible with PU resins. Woven fiber composites (WFC) offer potentially improved performance over unidirectional tape composites because the woven fiber structure provides obstruction to matrix splitting and delamination growth [9]. The mold was cleaned and heated for two hours at 100 □C to remove any moisture. After the mold cooled, sealant tape and resin dam

tape were set on the mold and three coats of release agent were applied to the mold within the boundaries of the resin dam tape. Meanwhile the containers for the resin, peel ply, distribution medium, foam core and fabric were heated to about 80 □C for two hours to remove any moisture. After the material was heated, the peel ply, distribution medium, foam core and fabric were laid up onto the mold. The PU 840871 resin consists of two components, component A and B, which were measured out in different containers to achieve a ratio of 92 to 100 parts, respectively. One inlet and two outlets (vacuum pressure tube) are set up and two vacuum bags were placed over the part, inlet and outlets. During this setup, the two containers of resin were degassed for 4-5 hours. Just before infusion, component A was poured into the component B container and was then mixed until the resin was homogeneous. The vacuum was turned on and the inlet was clamped to ensure no air could escape from the vacuum bag. The pressure in both vacuum bags was held at 29 inches of Hg. The inlet tube was positioned in the resin container and the clamp was removed to begin infusion. The flow was controlled by use of a C-clamp. Infusion takes about 15-20 minutes and once full saturation of the part was reached, the inlet and vacuum tubes were clamped. The impregnated part was left for about 15-18 hours to cure and for the post cure, the part was removed from the mold and placed in the oven for one hour at 70˚C and then four hours at 80 □ C.

3.4 IMPACT TEST

A Dynatup Instron Model 9250 Impact Testing machine with impulse control and data system was used to perform the low velocity impact tests. At the beginning of a test, the impactor is secured with a hook at the desired height. When the release mechanism is activated, the impactor unhooks and falls down. The drop height can be varied by the

control system adjusting the position of the impactor before the test start. A 0.5 inch hemispherical hardened steel tup is connected to the impactor of the drop tower which impacts the specimens with a mass of 6.5 kg. For the low velocity impact tests, specimens were clamped during the test runs in a fixture concentric with the axis of drop tower passing through the tup. The low velocity impact test fixture is made of steel with a 1.75 inch x 1.75 inch opening to ensure that the test specimens are clamped along all four edges. For part one, the sandwich composites for each foam core were cut into 3 inch by 3 inch samples. The impact tests were conducted at three different energy levels of 30 J, 40J, and 50J and (3) specimens of each core were tested at each energy level.

4. PART I : LOW VELOCITY IMPACT RESPONSE AND CHARACTERIZATION OF FOAM CORE SANDWICH STRUCTURES

4.1 PU RIGID 2 INCH FOAM SANDWICH COMPOSITES IMPACT RESULTS AND ANALYSIS

Section 4.1 investigates the impact behavior of the 2 inch PU rigid foam core sandwich composites. To determine the behavior of the sandwich composite under impact loading at each energy level, three (3) different relationships are discussed: Load vs Time, Load vs Deflection, and Energy vs Time.

Figure 4.1 shows the load carrying ability of the specimens over time at an energy level of 30 J. The tup did not penetrate the facesheet and the damage was minor. The maximum load produced within these samples was about 5,400 N. There was little difference in the behavior of the three samples.

Figure 4.2 represents the load produced on the specimens over time at an energy level of 40 J. The maximum load produced within these samples was about 5,100 N. After impact, the tup did not penetrate the facesheets of samples 2 and 3, but caused a greater amount of damage than at the 30 J energy level. However, there was penetration of the facing into the core of sample 1. The weight lost much of its energy to the faceplate so the load was reduced significantly. The unloaded region represents the load carried by the foam. Energy was absorbed at a constant rate until there was insufficient energy to continue through the core and the remaining energy was absorbed by the foam bringing the load to zero.

In Figure 4.3, the correlation between the load on the sample and time at 50 J of energy. The behaviors of all the samples were very similar. The impact weight penetrated each sample's facing, but did not have enough energy to impact the bottom faceplate. As the tup impacts the core, it was able to penetrate about 0.75 inches into the foam, however, the weight was unable to retain enough energy through the unloading region to strike the bottom facing and the remaining energy was absorbed by the foam.

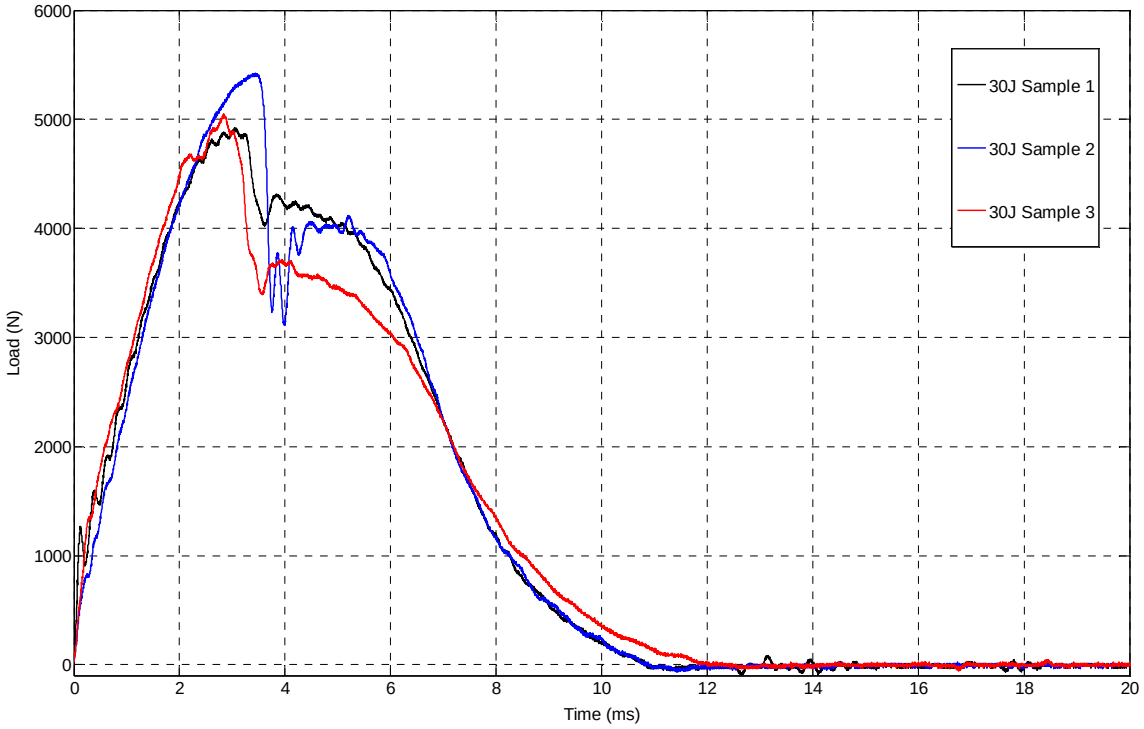

Figure 4.1 Load vs Time 30 J Impact of PU Rigid Sandwich Composite

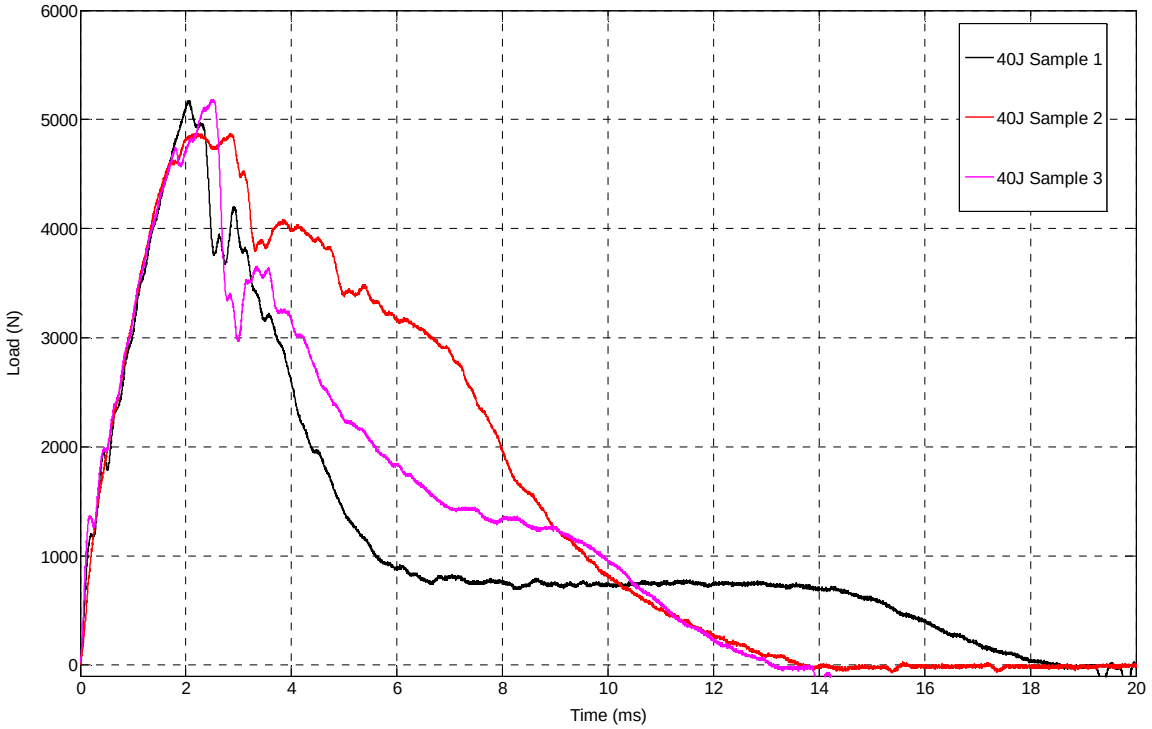

Figure 4.2 Load vs Time 40 J Impact of PU Rigid Sandwich Composite

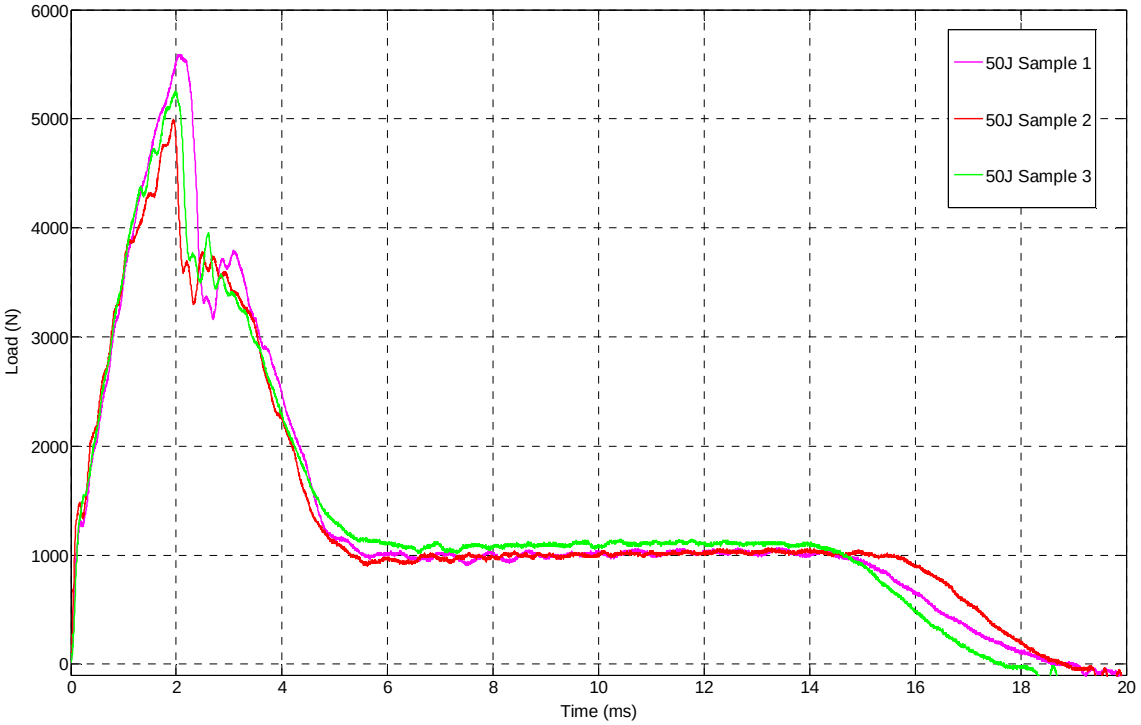

Figure 4.3 Load vs Time 50 J Impact of PU Rigid Sandwich Composite

Figure 4.4 illustrates the relationship between the load and deflection of the specimens at 30 J. The variation between the samples' deflection is minimal with all of the samples falling within a range of just 0.3 of a millimeter or 0.0118 of an inch. After the initial impact, there was a large deflection in the facesheet and as the impact weight recoiled and impacted the samples again, the specimens saw another, although smaller, increase in the deflection. At that point, the energy had diminished enough to where the weight could not produce enough load to further damage the specimens. Since there was no penetration of the facings, the remaining energy was absorbed by the weight until the load on the samples decreased to zero.

Figure 4.5 demonstrates the relationship between the load and the deflection of the samples at 40 J. The deflections of these samples were larger than those of the 30 J samples since a higher energy level would naturally produce a larger load resulting in a larger deflection. The maximum deflection within these samples was 17 mm (0.67 in) and the minimum deflection was about 11 mm (0.433 in). The large deflection in sample 1 was due to the complete penetration of the faceplate into the foam. In sample 2, there was no penetration so the facesheet absorbed much of the load from the impact weight until there was not enough energy to continue producing a load powerful enough to further damage the faceplate resulting in the unused energy being transferred back to the weight reducing the load to zero. The impact weight partially penetrated the facesheet of sample 3. This partial penetration allowed for a larger deflection than in sample 2, but less than that of sample 1. Since the faceplate was partially intact, there was energy transferred back to the impactor similar to sample 2.

Figure 4.6 shows how the load relates to the deflection of the samples at 50 J. The tup penetrated each sample's facesheet resulting in large deflections. The maximum deflection was about 24 mm (0.945 in) and the minimum was about 22 mm (0.866 in). These three samples at 50 J demonstrated a similar behavior to that of sample 1 at 40 J, but had a larger deflection due to the higher energy level. Since the foam absorbed energy at a constant rate, the load remained the same once the tup entered the core, but the deflection continued to increase until the energy within the impactor was insufficient to penetrate deeper into the foam.

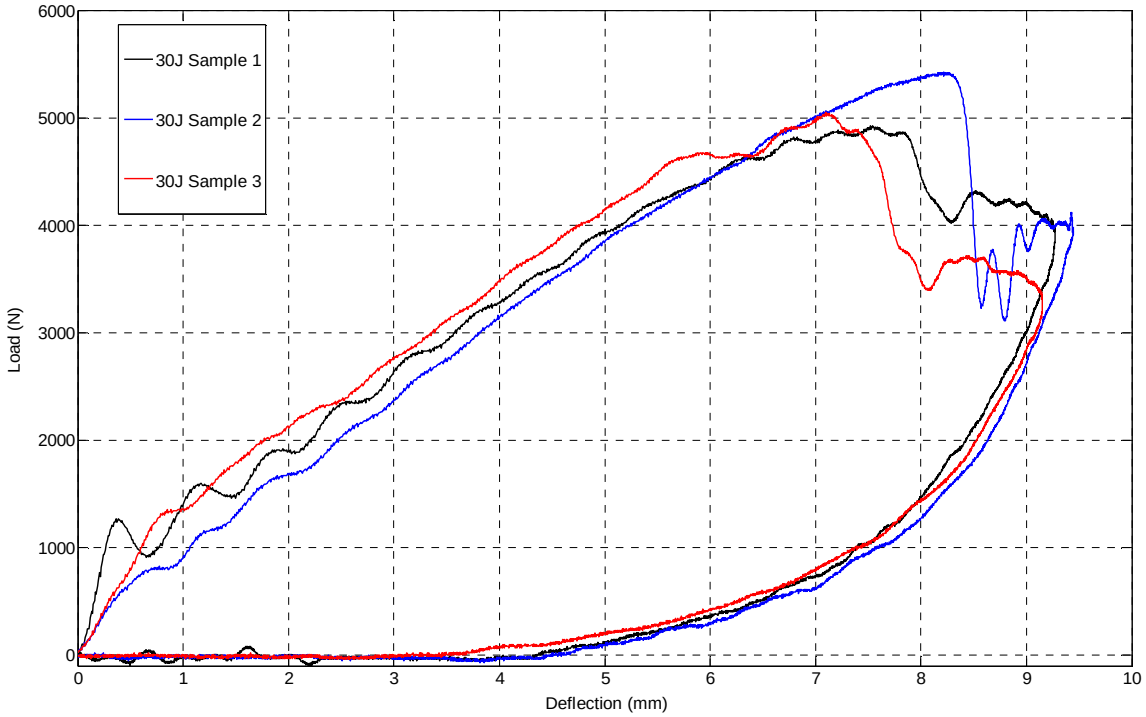

Figure 4.4 Load vs Deflection 30 J Impact of PU Rigid Sandwich Composite

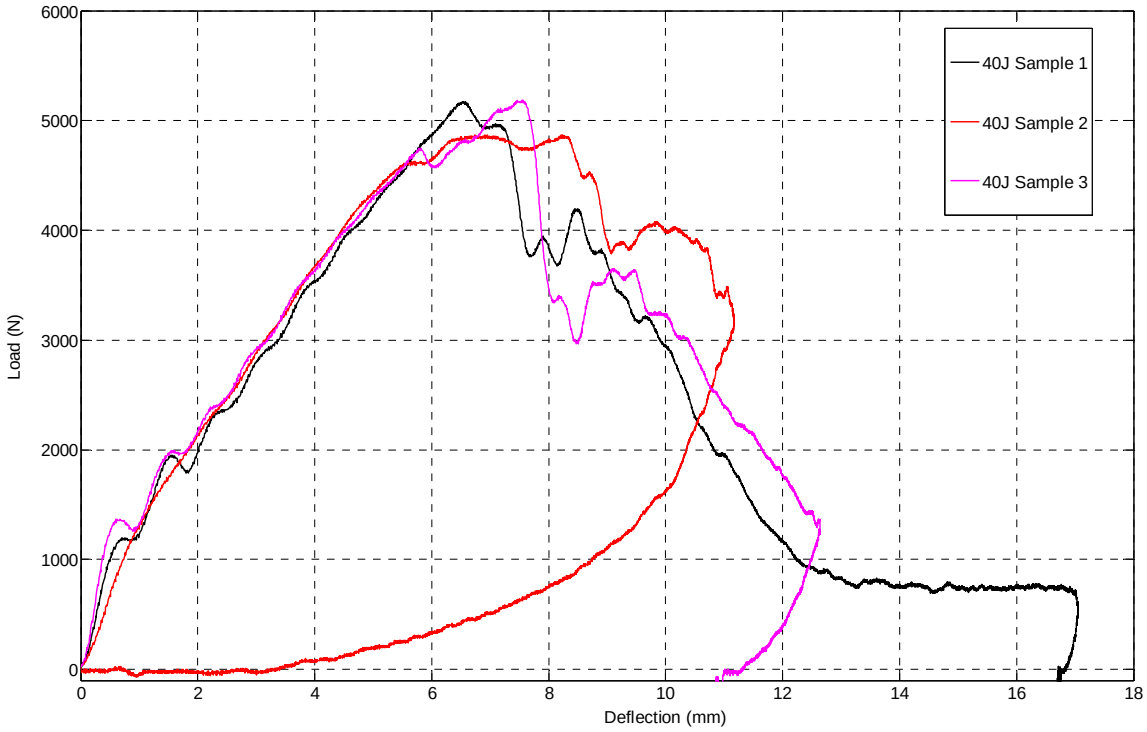

Figure 4.5 Load vs Deflection 40 J Impact of PU Rigid Sandwich Composite

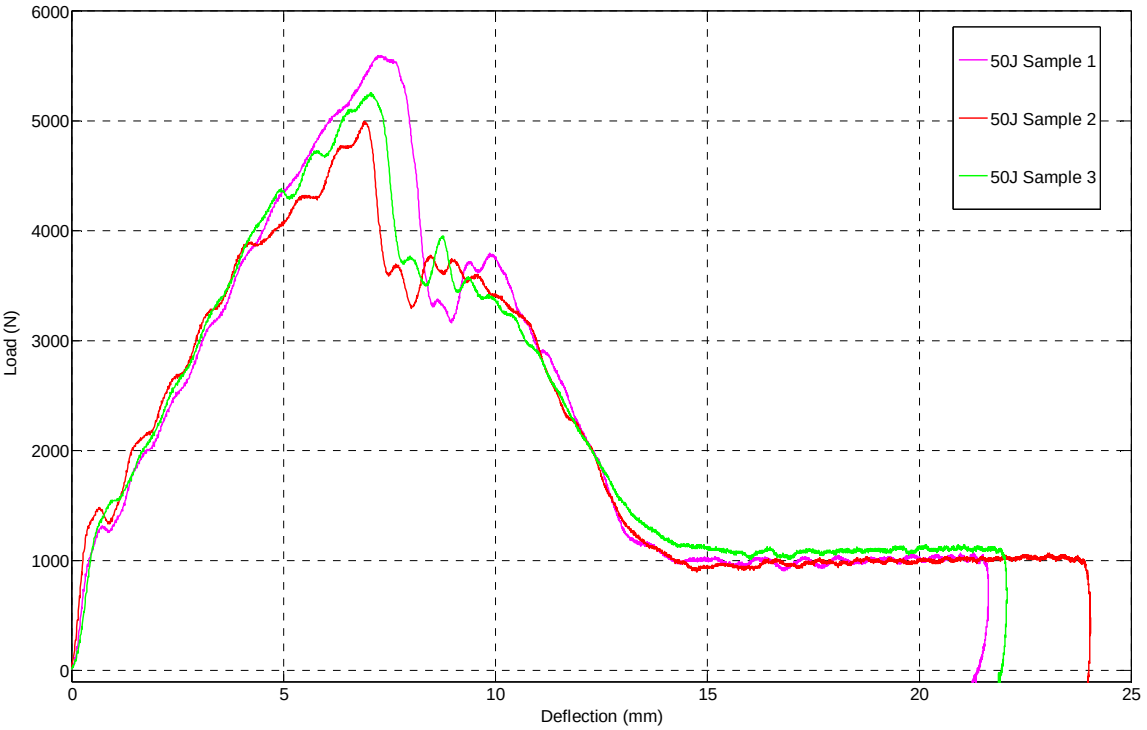

Figure 4.6 Load vs Deflection 50 J Impact of PU Rigid Sandwich Composite

Figure 4.7 displays the energy absorbed by the specimens over time at an energy level of 30 J. The energy absorbed by all three of these samples was about 25 J. There was no penetration of the facesheets so the samples were not able to absorb all the energy and the remaining energy was transferred back to the weight.

Figure 4.8 shows the energy absorption within the samples over time. Since the tup penetrated the facesheet of sample 1, the entire 40 Joules of energy was absorbed by the sample. The tup did not penetrate the facesheet of sample 2 so it was only able to absorb about 33 Joules from the impact weight. Due to the partial penetration in sample 3, most of the energy, about 39 J, was absorbed by the sample.

Figure 4.9 represents the energy absorption within the samples at 50 J. Since the energy level was too great for the faceplates to handle, the energy was dispersed through the foam core.

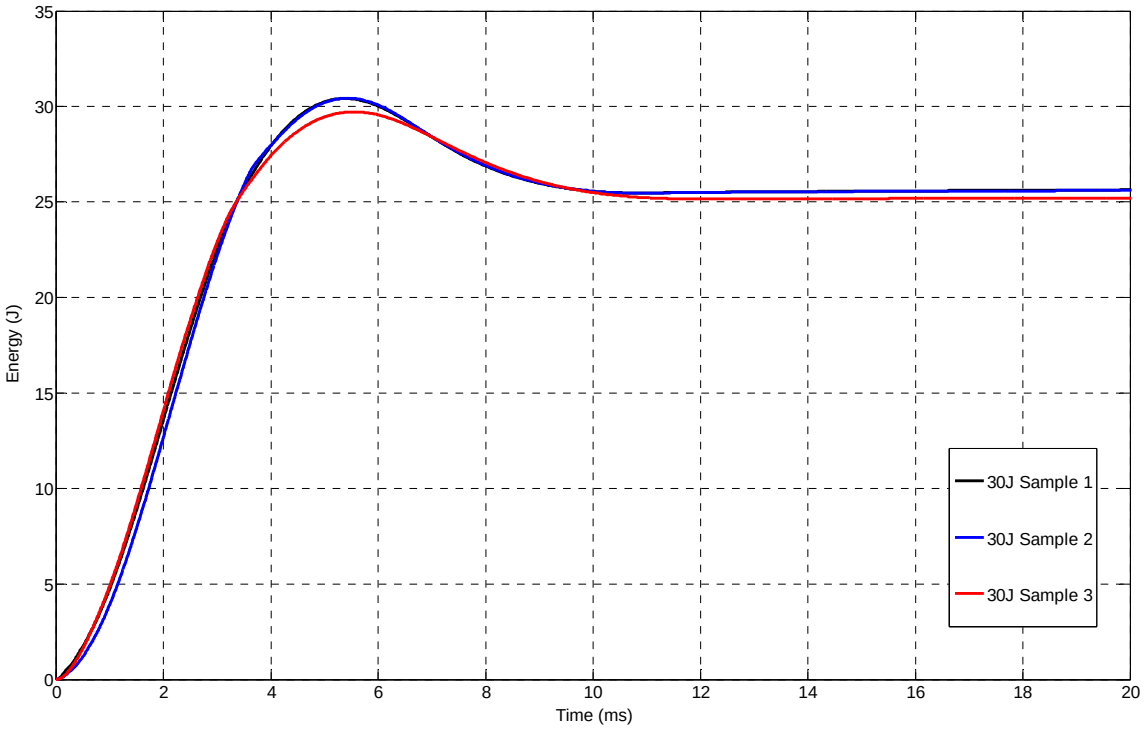

Figure 4.7 Energy vs Time 30 J Impact of PU Rigid Sandwich Composite

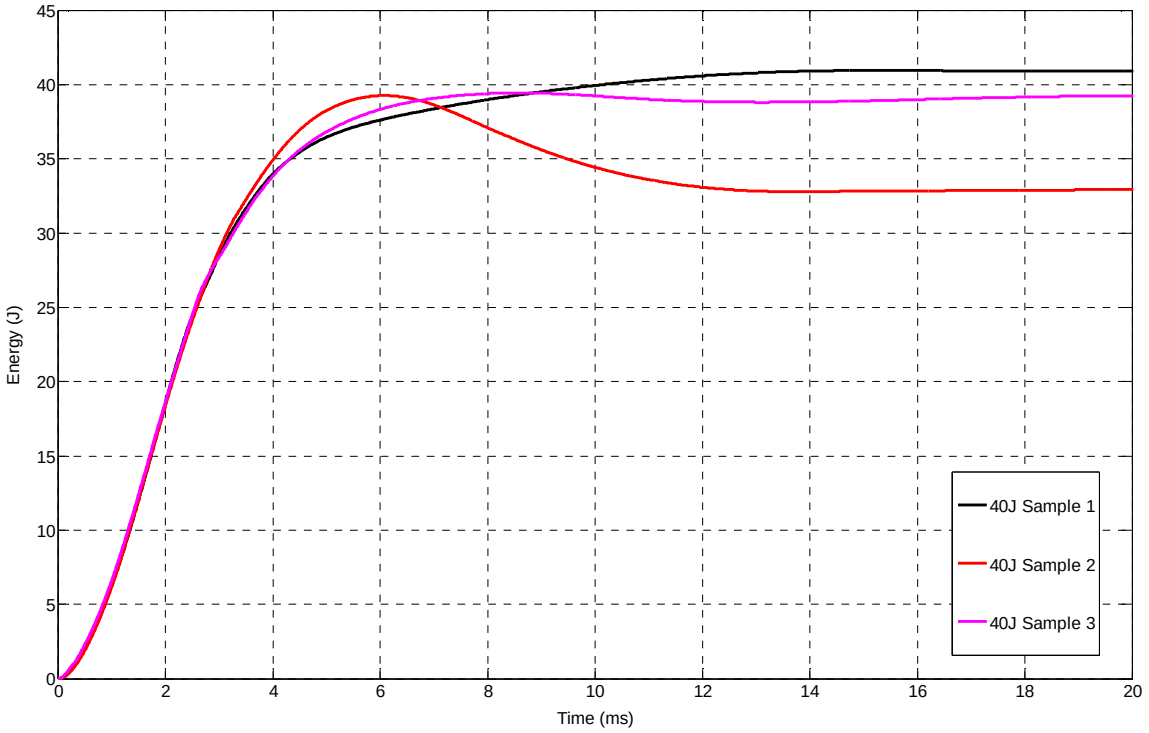

Figure 4.8 Energy vs Time 40 J Impact of PU Rigid Sandwich Composite

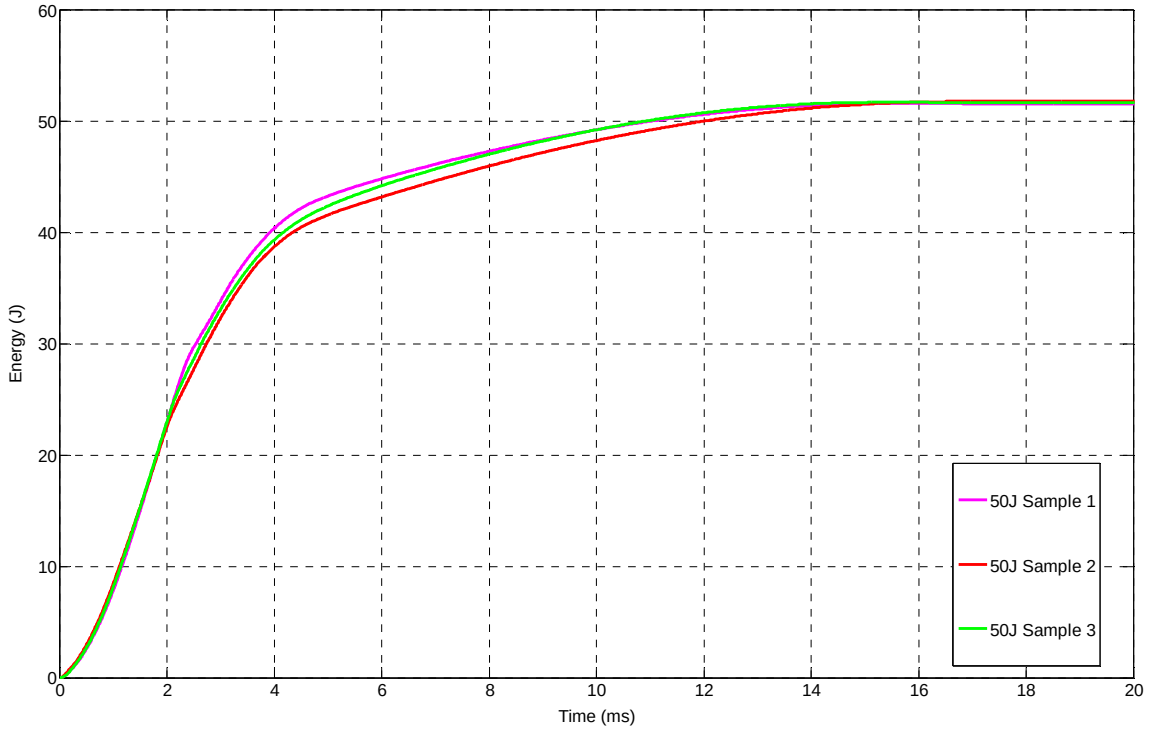

Figure 4.9 Energy vs Time 50 J Impact of PU Rigid Sandwich Composite

4.2 WEBCORE (TYCOR-W) 2 INCH FOAM SANDWICH COMPOSITE IMPACT RESULTS AND ANALYSIS

Section 4.2 investigates the impact behavior of the 2 inch Webcore foam core sandwich composites. To determine the behavior of the sandwich composite under impact loading at all three energy levels, three (3) different relationships are discussed: Load vs Time, Load vs Deflection, and Energy vs Time at 30J, 40J and 50J.

Figure 4.10 displays the load in the specimen over time. Sample 1 was able to carry a load of about 5,700N and the other two were able to handle about 5,500 N. Sample 1 was impacted on a support channel and did not have much damage on the facesheet, but there was buckling and breaking in the supports through the foam. The load in this sample linearly decreased because load was distributed through the support channels by the faceplate. The faceplates of sample 2 and 3 were more robust than the faceplate of sample 1 and even though the load exerted on samples 2 and 3 was slightly smaller, the faceplates were able to absorb more of the load and endured a larger amount of damage than sample 1.

In Figure 4.11, the relationship between the load the sample can withstand over time at 40 J. The largest load handled by the three specimens was about 6,300 N and the smallest was about 5,200 N. Sample 1 was able to handle a higher load than the other two samples because the weight impacted the intersection of two support lines allowing the specimen to withstand a larger load. As the tup penetrated through the faceplate into the foam of sample 3, it created a region of unloading representing the load carried by the foam. The load remained almost constant in the unloaded region due to the foam's ability to absorb energy at a constant rate. The weight did not have enough energy to reach the second facesheet so the remaining energy was absorbed by the foam.

Figure 4.12 displays the load exerted on the samples over time at an energy level of 50 J. There was not much discrepancy between the maximum and minimum loads in the specimens. The minimum was about 6,000 N and the maximum was 6,200 N. Sample 1 was struck on a support line and much of the load was transferred through the channels causing them to buckle and break. The faceplate began to fail at 5,000 N, but continued to carry load until 6,000 N. Since the facesheet was not penetrated, the load was dissipated through the support channels and steadily decreased to zero. The facesheet of sample 2 was penetrated completely, and showed a similar behavior to sample 1 where the faceplate began to fail before the maximum load was reached. Sample 3 endured similar damage, but did not show the same facesheet failure as sample 1 and 2. The faceplate began to fail at the maximum load. The tup penetrated the foam core in samples 2 and 3 leading to the unloaded regions.

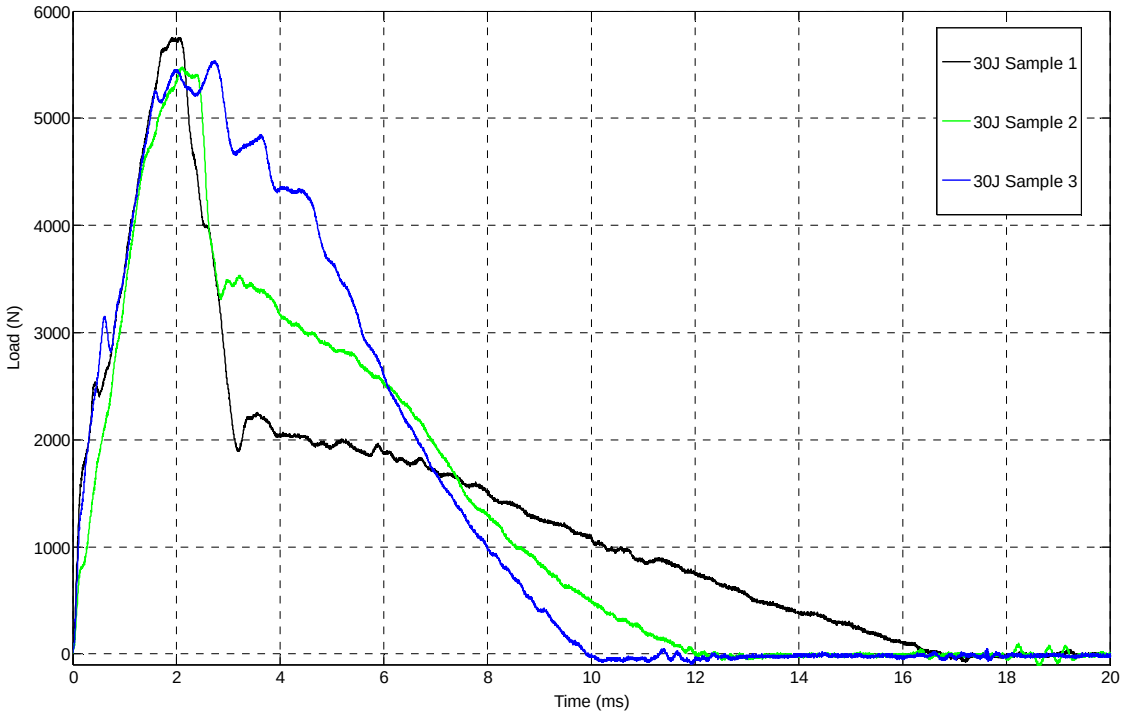

Figure 4.10 Load vs Time 30 J Impact of Webcore Sandwich Composite

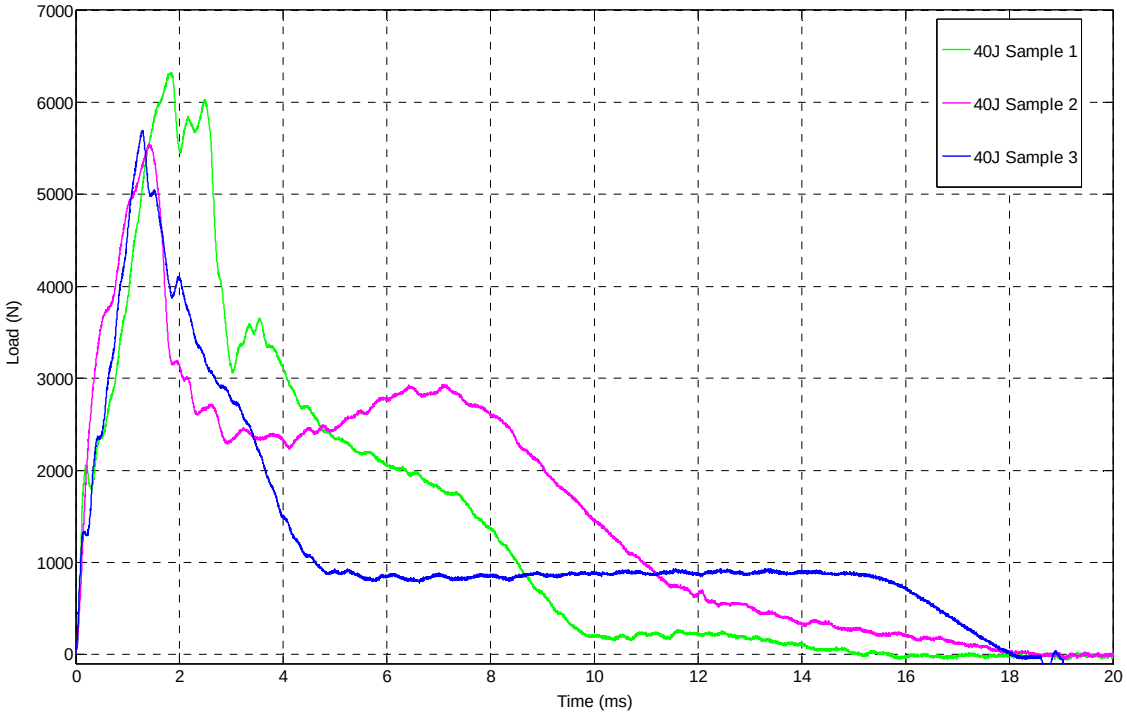

Figure 4.11 Load vs Time 40 J Impact of Webcore Sandwich Composite

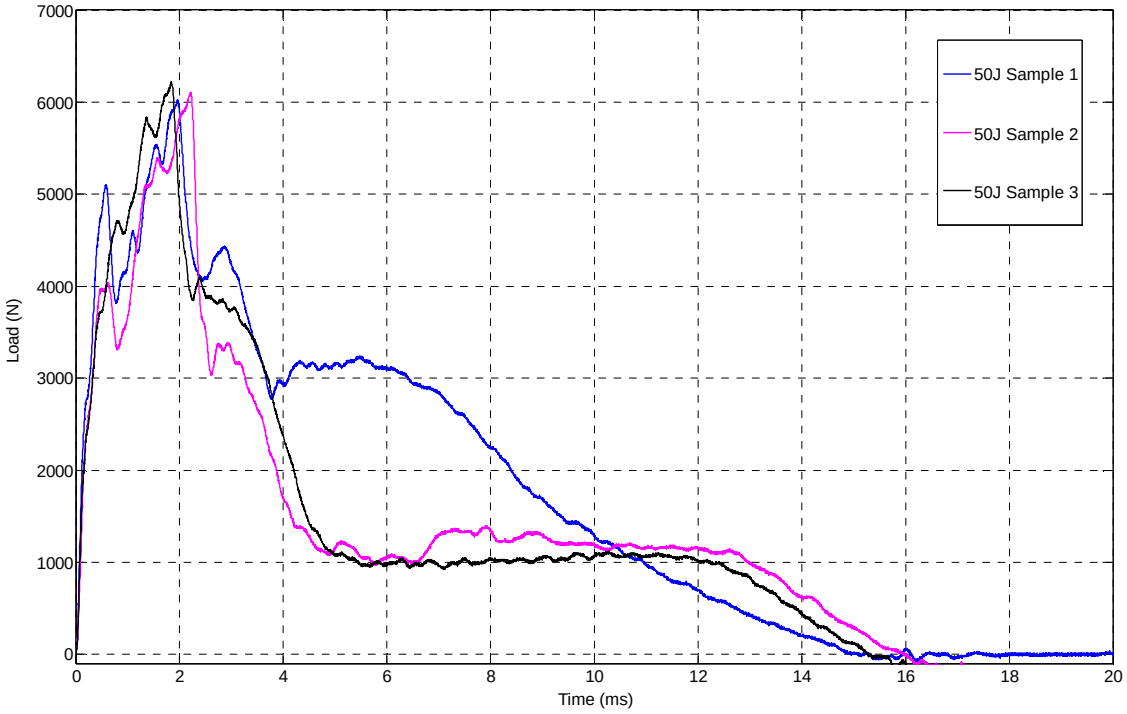

Figure 4.12 Load vs Time 50 J Impact of Webcore Sandwich Composite

Figure 4.13 shows the relationship between the load on the sample and induced deflection. There was a significant difference between the lowest and highest deflection. Since there was little damage done to the facesheet of sample 1, the facesheet acted as a distribution medium and load was dispersed through the supports causing them to buckle resulting in a large deflection. Sample 2 saw similar results as sample 1, but the facesheet was able to carry more of the load before it was distributed to the supports. Sample 3 had the most damage in the facesheet so there was little or no load sent through the supports so the deflection was less.

Figure 4.14 displays the deflection with respect to the load on the sample at 40 J. Although sample 1 was able to handle the largest load, it endured the smallest deflection of about 11 mm (0.433 in) due to the location the weight struck the specimen. The tup struck directly on the intersection of two support lines which allowed the sample to effectively resist deformation causing the specimen to have a lower deflection. The faceplate of sample 2 was partially pentrated after initial impact resulting in a larger deflection. The impact weight completely penetrated the facesheet of sample 3 after initial impact causing the largest deflection.

The relationship between the load on the specimen and the amount of deflection within it is shown in Figure 4.15. There was a significant difference in deflection between the first sample and the other two. Sample 1 had a deflection of 12.5 mm (0.492 in) while samples 2 and 3 saw a deflection of around 17 mm (0.67 in) and 19 (0.748 in) mm respectively. These large deflections were the result of the penetration of the facesheet whereas the facesheet of sample 1 remained unbroken. Once the tup impacted the foam core, the load remained almost constant, but the foam was still being displaced

until the impactor did not have the energy needed to continue and the foam absorbed the remaining energy. Since sample 1 was not penetrated, it saw a smaller deflection and energy was transferred back to the impact weight.

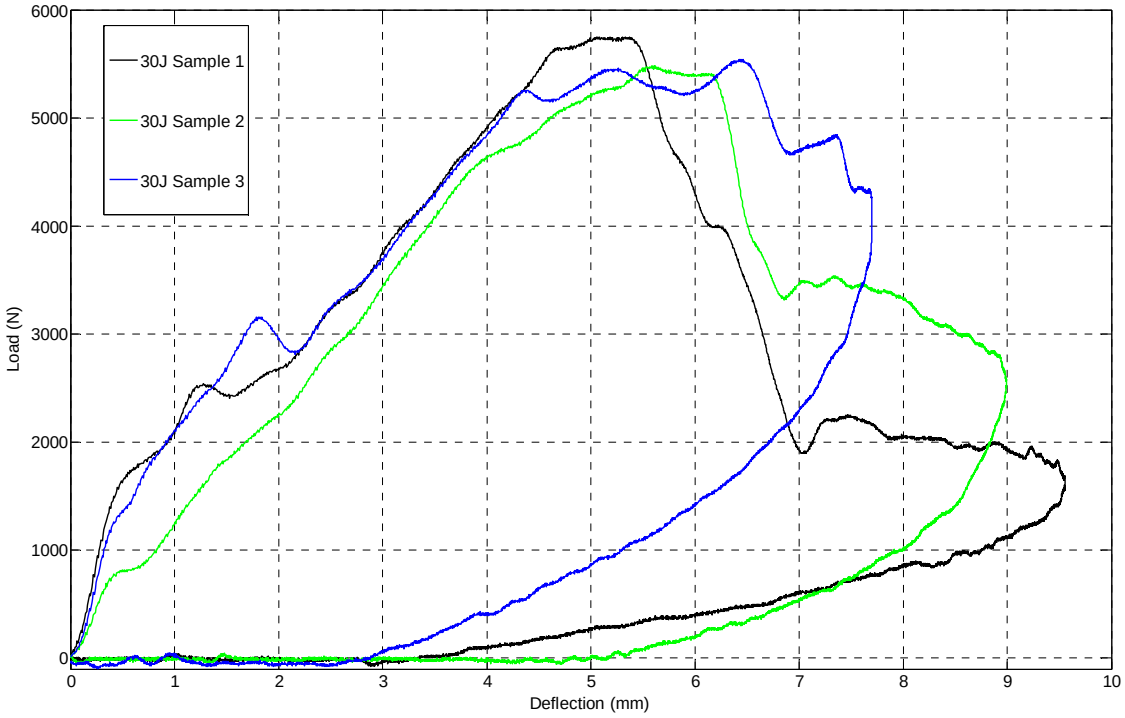

Figure 4.13 Load vs Deflection 30 J Impact of Webcore Sandwich Composite

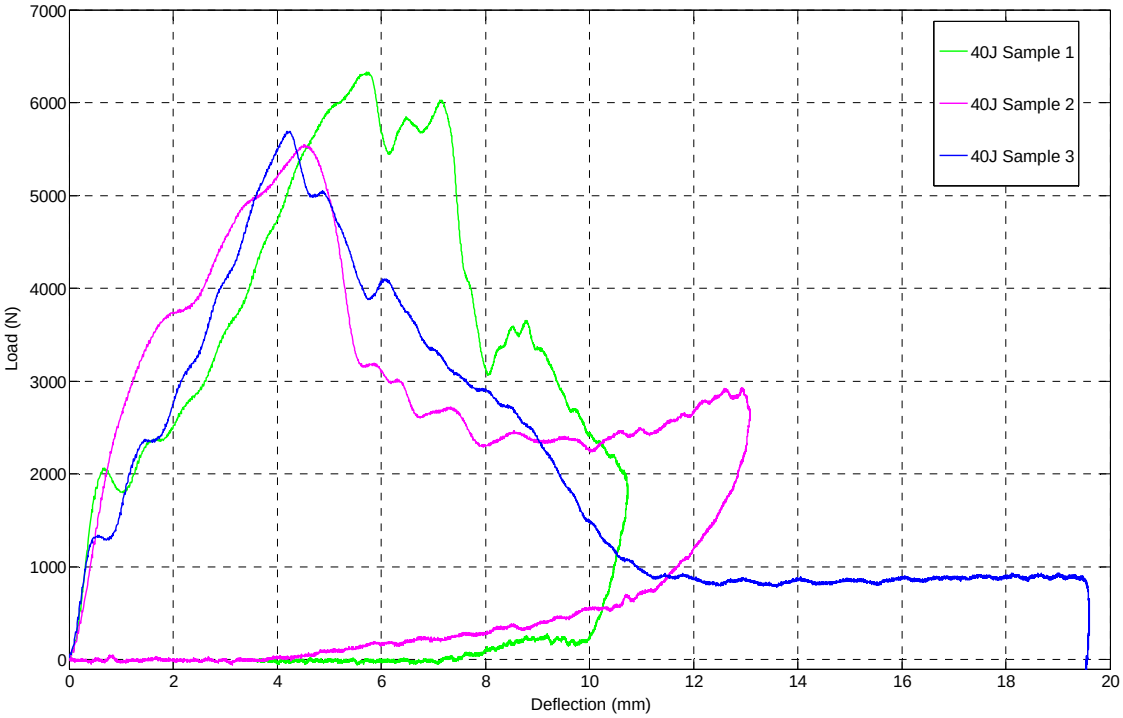

Figure 4.14 Load vs Deflection 40 J Impact of Webcore Sandwich Composite

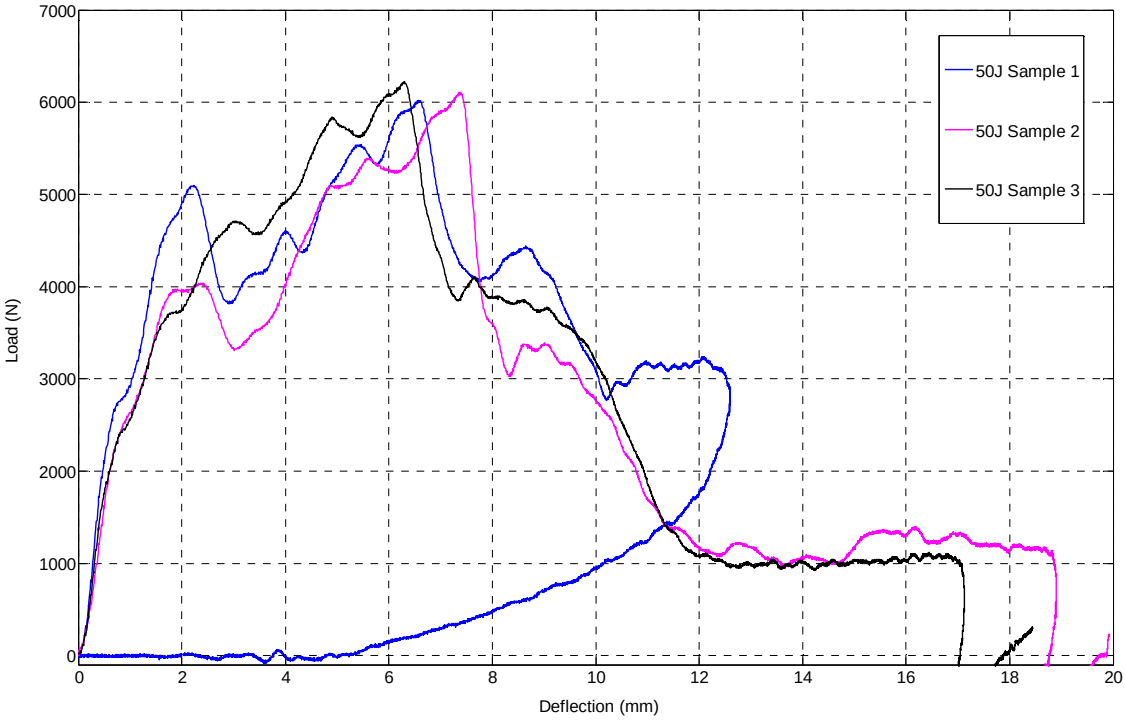

Figure 4.15 Load vs Deflection 50 J Impact of Webcore Sandwich Composite

Figure 4.16 displays the energy absorbed over time. Sample 1 and 2 absorbed about 26 J while sample 3 absorbed about 22 J. Sample 3 absorbed less energy since the facesheet absorbed most of the energy at initial impact and little energy was dispersed through the supports so that remaining energy was able to return to the weight. In samples 1 and 2, the facesheet did not absorb as much energy as sample 3, but acted more as a distribution medium that sent the energy to the supports resulting in higher energy absorption.

Figure 4.17 displays the energy absorbed by the samples over time. Sample 1 almost absorbed all the energy from the impactor, but since much of the energy wasn't absorbed by the facesheet, and dispersed to the support lines in the foam, the specimen was able to absorb a greater amount of energy. In sample 2, the facesheet was not damaged enough for the tup to contact the foam so the specimen was only able to absorb about 36 J of energy while the remaining energy was returned to the impactor. The third sample's faceplate was completely penetrated so all the energy was absorbed by the sample's core.

Figure 4.18 shows the amount of energy absorbed by the samples over time. Sample 1 was able to absorb about 42 J where the other two samples absorbed all the energy from the impactor. Samples 2 and 3 were able to absorb all the energy due to the penetration of the faceplates. Sample 1, however, was not penetrated so as the sample exerted a force back on the weight resulting in the transfer of energy back to the weight.

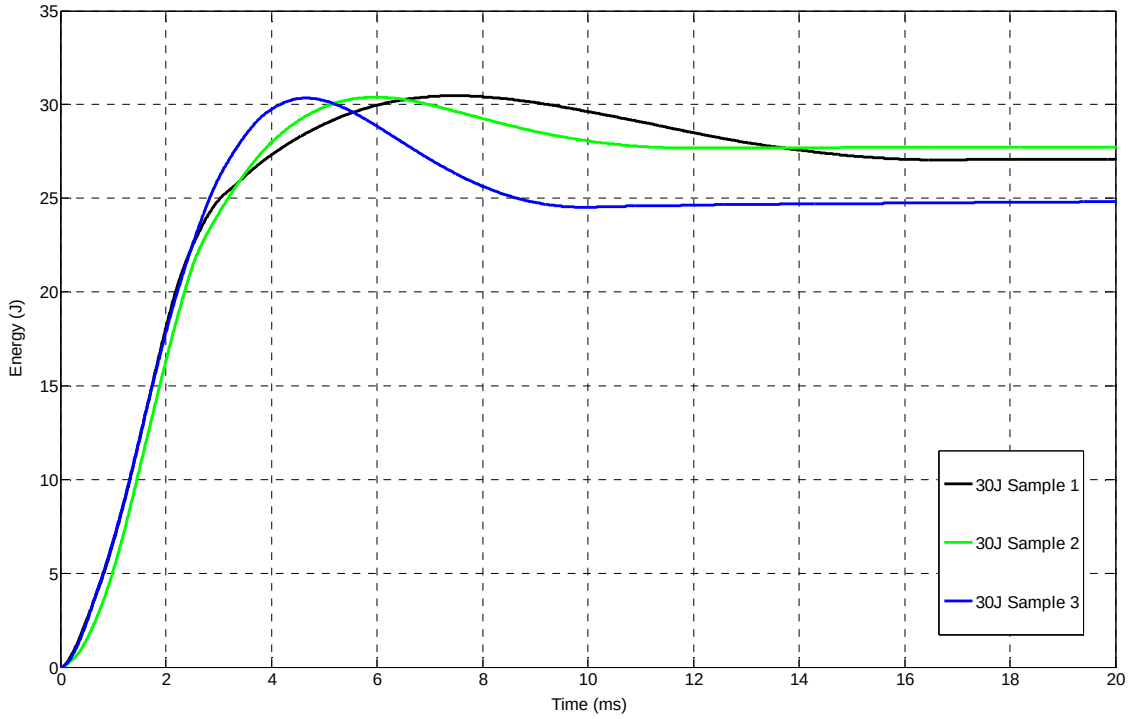

Figure 4.16 Energy vs Time 30 J Impact of Webcore Sandwich Composite

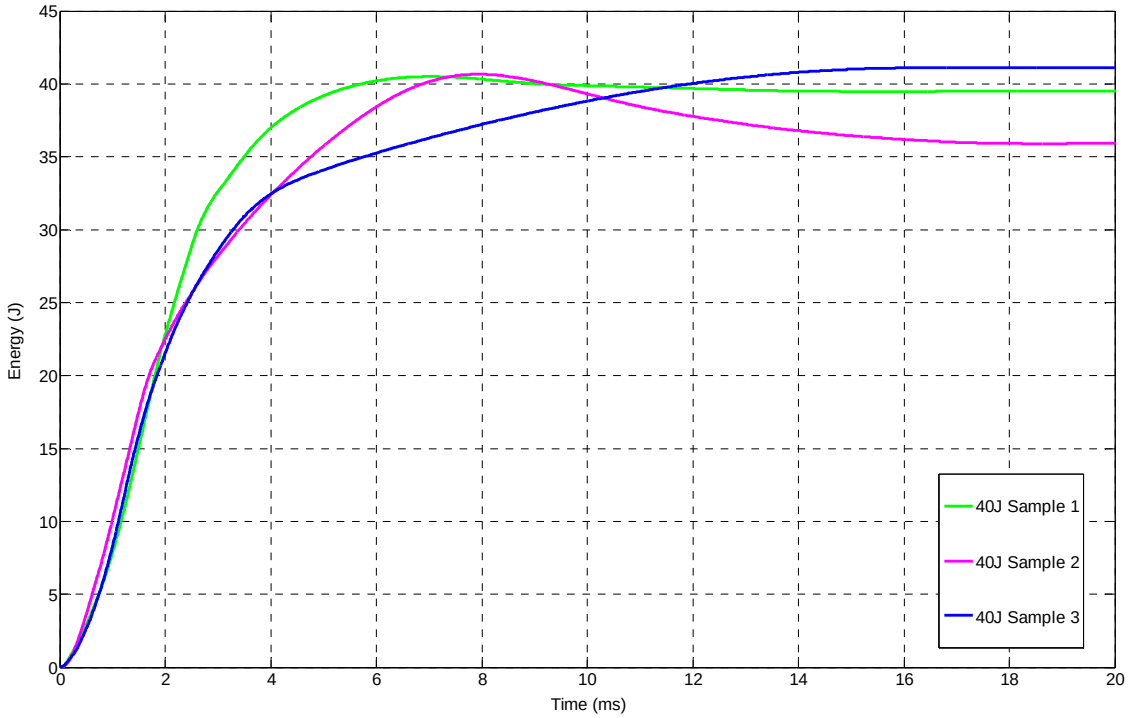

Figure 4.17 Energy vs Time 40 J Impact of Webcore Sandwich Composite

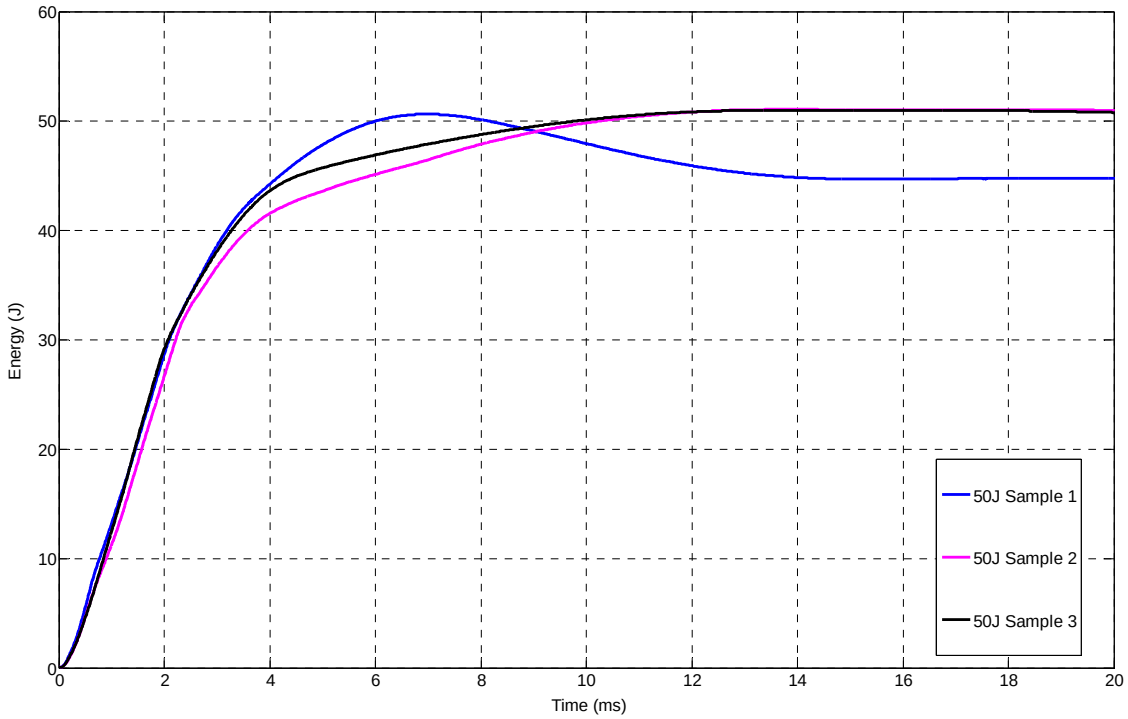

Figure 4.18 Energy vs Time 50 J Impact of Webcore Sandwich Composite

4.3 COMPARISON OF PU RIGID AND WEBCORE (TYCOR-W) SANDWICH COMPOSITES

The average of each of the three (3) samples tested at each energy level for each foam core was determined and is illustrated in Figures 4.19 through 4.27. Table 4.1 quantifies these figures. The Webcore compsite samples were able to withstand higher loads than that of the rigid samples. Even though the Webcore foam core was composed of a softer foam, the extra support produced by the glass fiber reinforcment allowd the Webcore specimens to handle greater loads. The webcore composites were able to carry about 14% more load than the rigid composites at the highest energy level.

According to Table 4.1, the Webcore samples were able to absorb slightly more energy at 30 and 40 Joules. At 50 Joules, the rigid foam sandwich composite absorbed more energy than the Webcore, but at the expense of the complete failure of the facing.The fact that less energy was absorbed by the Webcore specimen shows that it has

the potential to withstand a higher energy level impact without penetration of the faceplate.

The deflection experienced by the rigid samples was more than that of the webcore specimens. For both sandwich composites at 30 and 40 J of energy, the displacements were very similar, only about a 6 % difference between each. However at 50 J, the PU rigid foam composite had a significantly higher displacement, about 28 %, than the Webcore sample as shown in Table 4.1.

After the failure of the faceplate, the impactor caused more damage to the PU rigid foam core than to the Webcore foam core. The support channels gave the Webcore composite a higher resistance to impact and when the impactor pentrated the foam, the channels were able to limit the damage within the core to 26% and the depth of penetration to 0.563 inches. The PU rigid foam, although dense, was not as robust with it only being able to limit the depth of penetration to 0.75 inches, about 25% more than the Webcore, and the damage to the rigid sample was 38%, a 12% increase when compared to the Webcore.

Even though the foam was less dense in the webcore composite, the resin infused support channels added a significant amount of mass causing them to weigh more than the rigid core composite samples. The Webcore specimens also had a more unpredicable impact behavior than the rigid core because of the varying strength depending on where the sample was impacted.

Table 4.1 Average Weight and Low Velocity Impact Results

	E-glass/PU Rigid Foam			E-glass/Webcore Foam		
Impact Level	**30 J**	**40 J**	**50 J**	**30 J**	**40 J**	**50 J**
Contact Force (N)	5133.03	5076.00	5277.70	5588.63	5853.93	6115.23
Energy Absorbed (J)	25.50	37.40	50	26.57	38.49	48.24
Displacement (mm)	9.29	13.62	22.59	8.75	14.47	16.20
Percent Damage (%)	37.5			25.7		
Weight (g)	67.04			72.74		

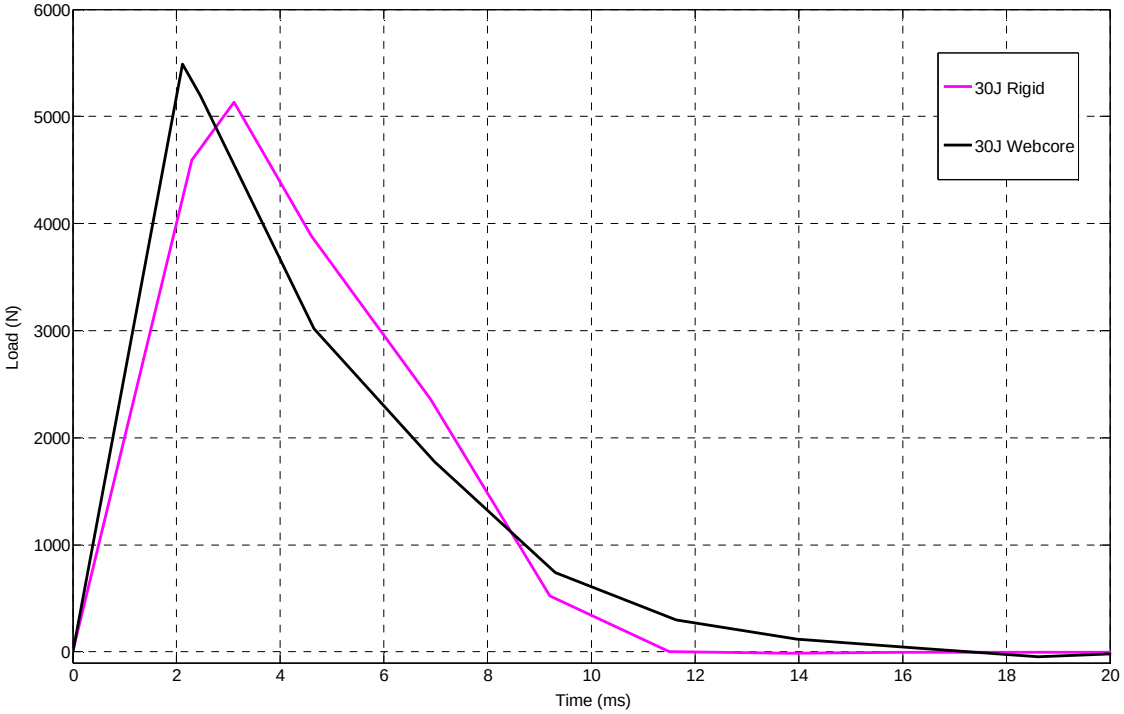

Figure 4.19 Average 30J Load vs Time of Rigid and Webcore Composites

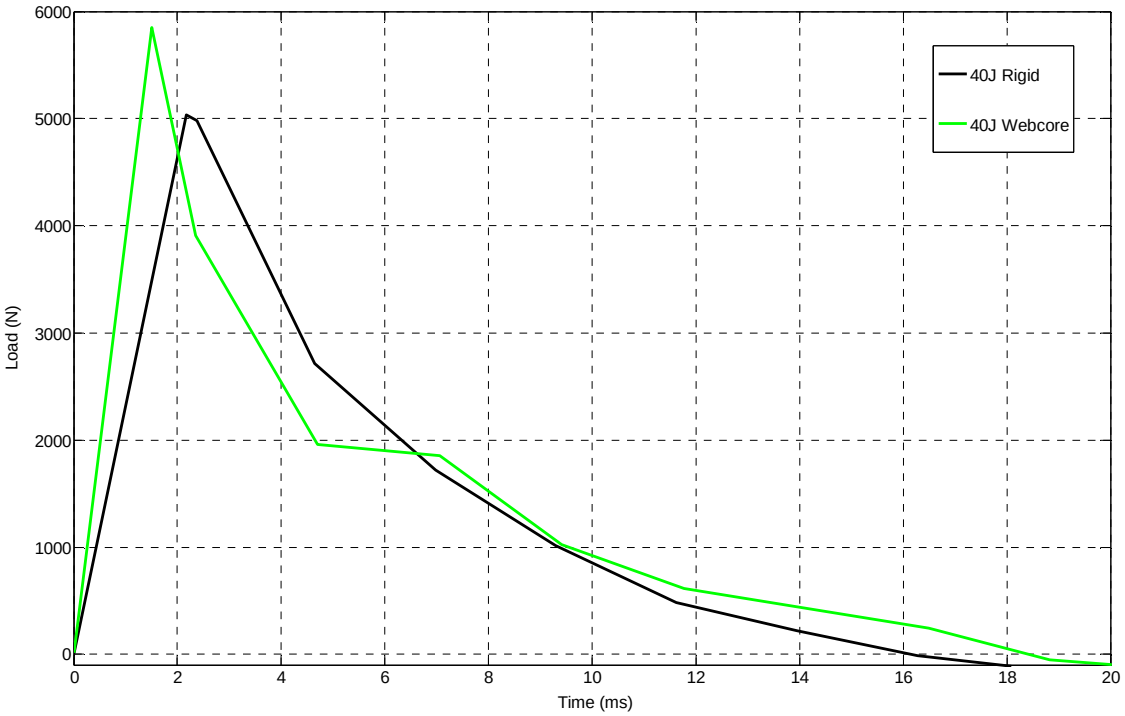

Figure 4.20 Average 40J Load vs Time of Rigid and Webcore Composites

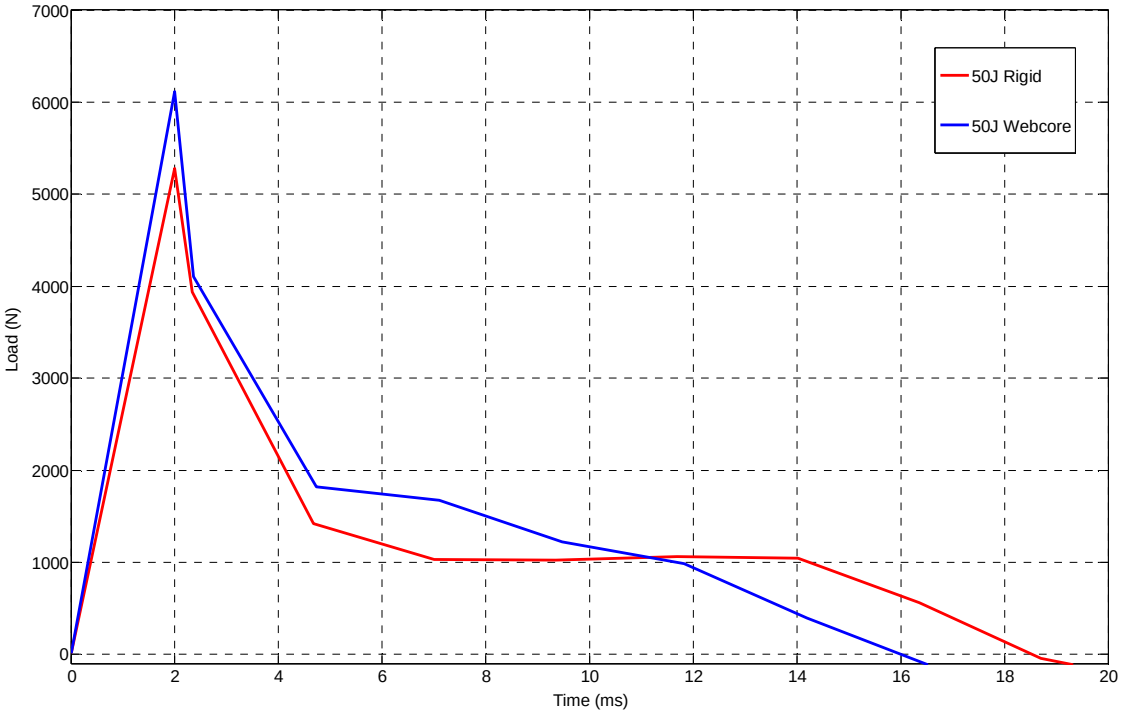

Figure 4.21 Average 50J Load vs Time of Rigid and Webcore Composites

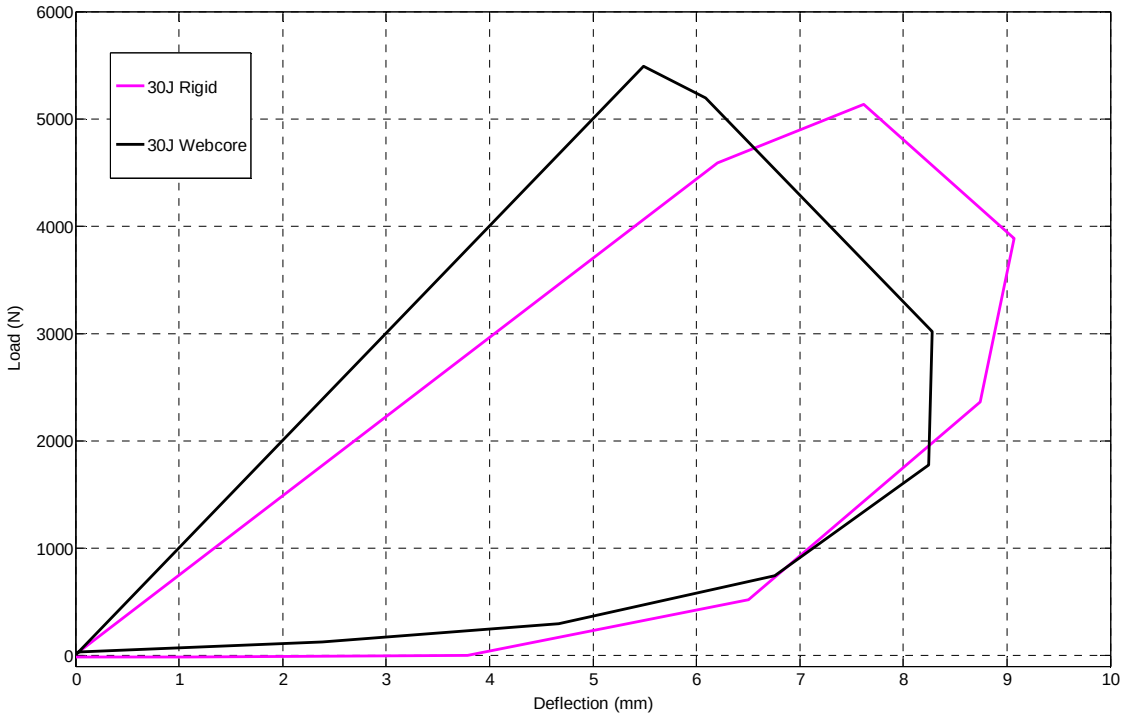

Figure 4.22 Average 30J Load vs Deflection of Rigid and Webcore Composites

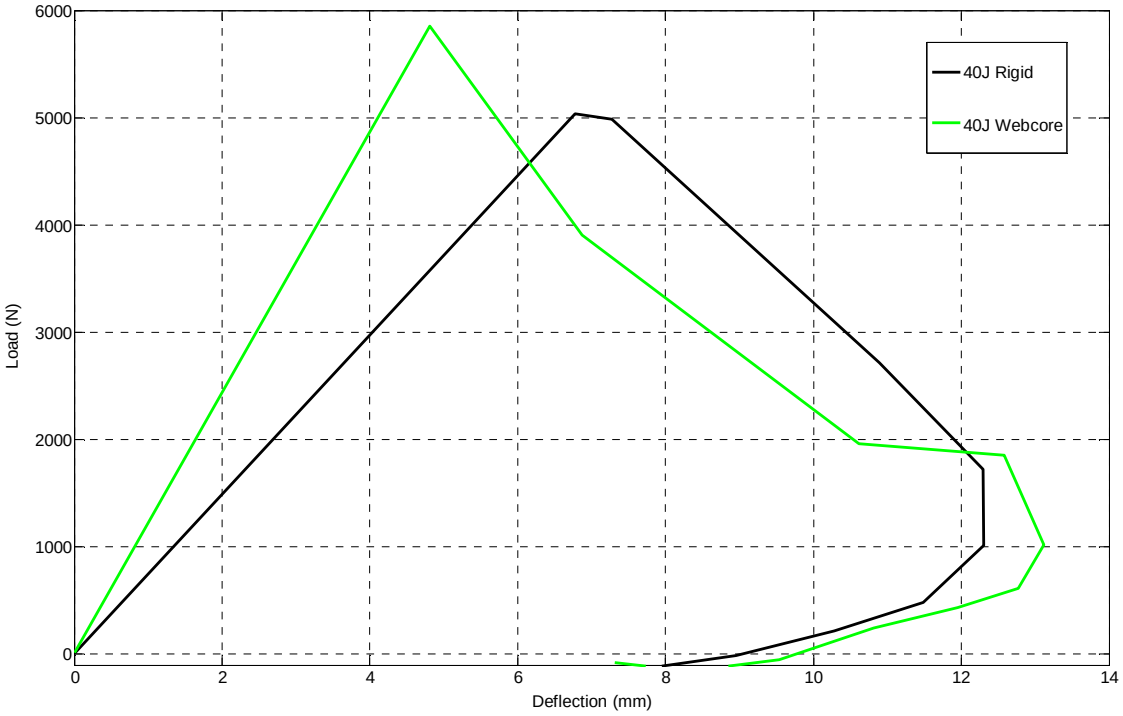

Figure 4.23 Average 40J Load vs Deflection of Rigid and Webcore Composites

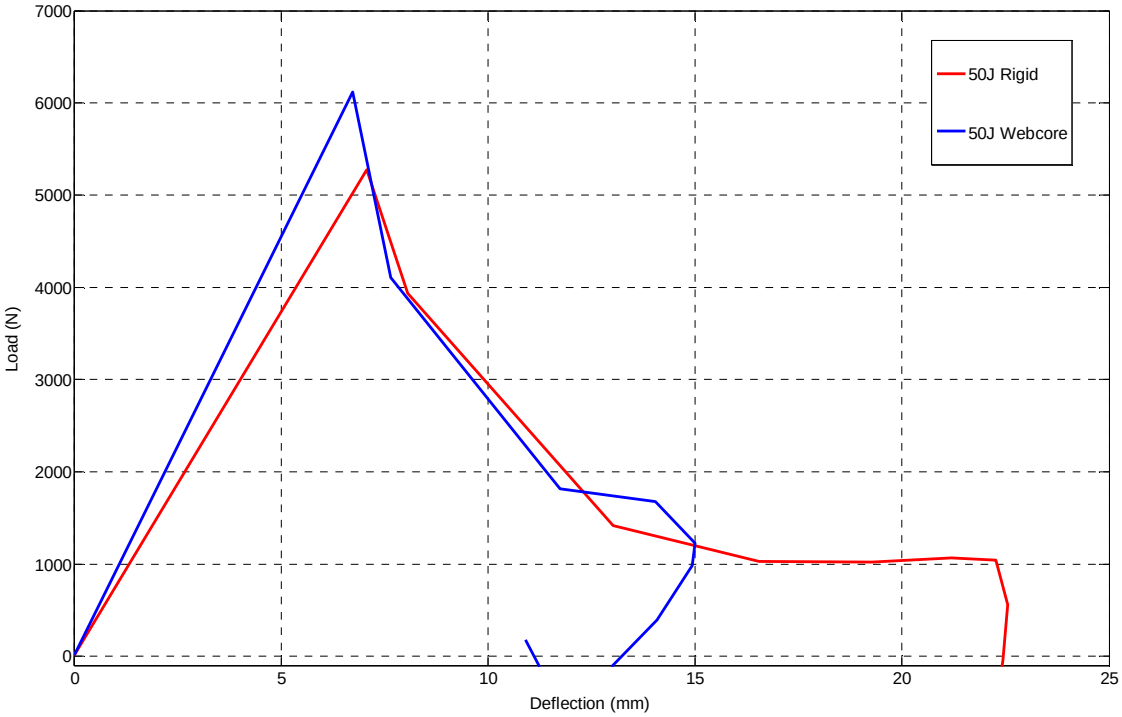

Figure 4.24 Average 50J Load vs Deflection of Rigid and Webcore Composites

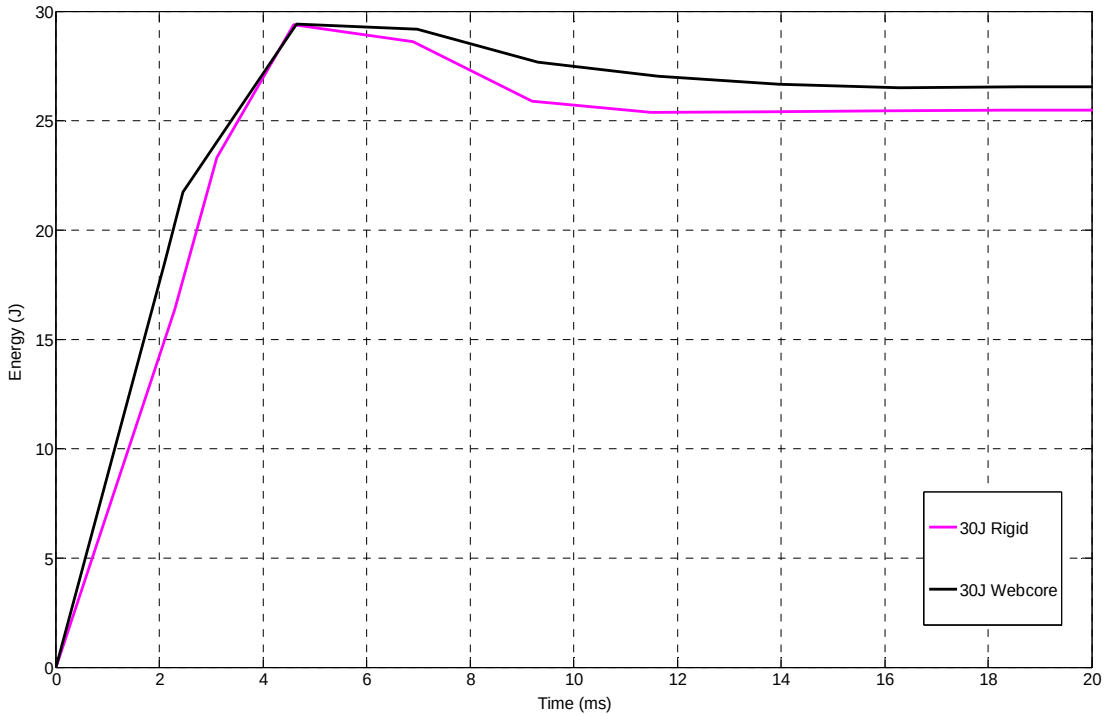

Figure 4.25 Average 30J Energy vs Time of Rigid and Webcore Composites

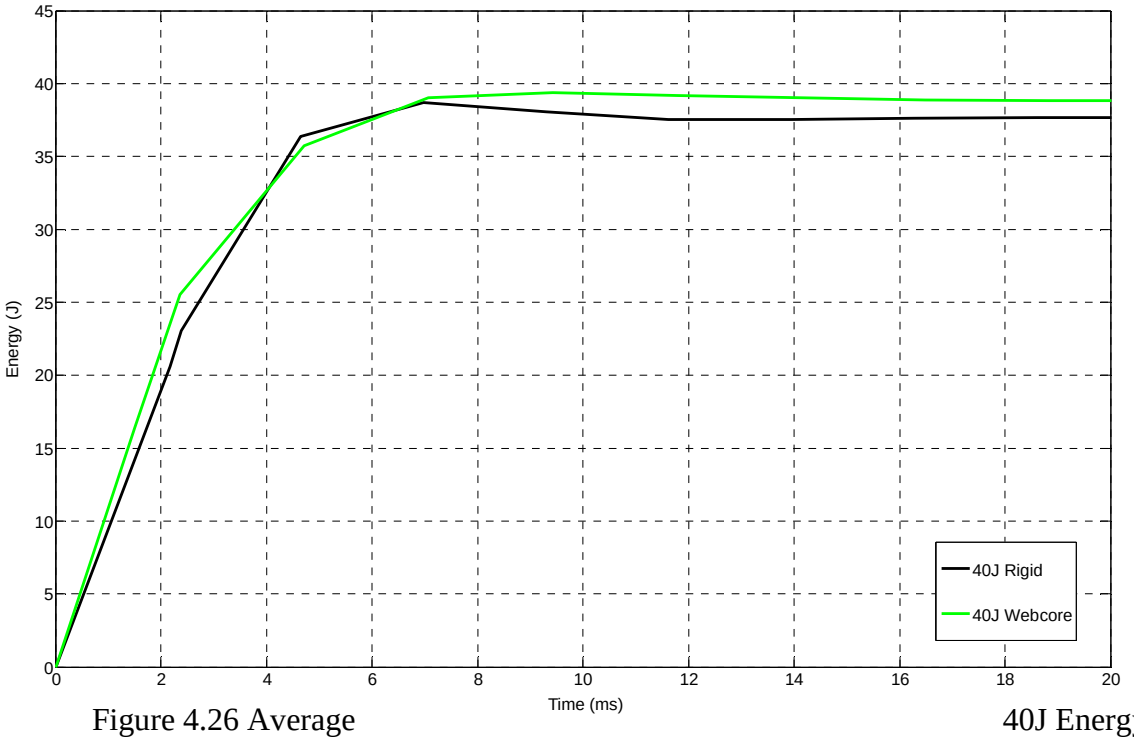

Figure 4.26 Average 40J Energy vs Time of Rigid and Webcore Composites

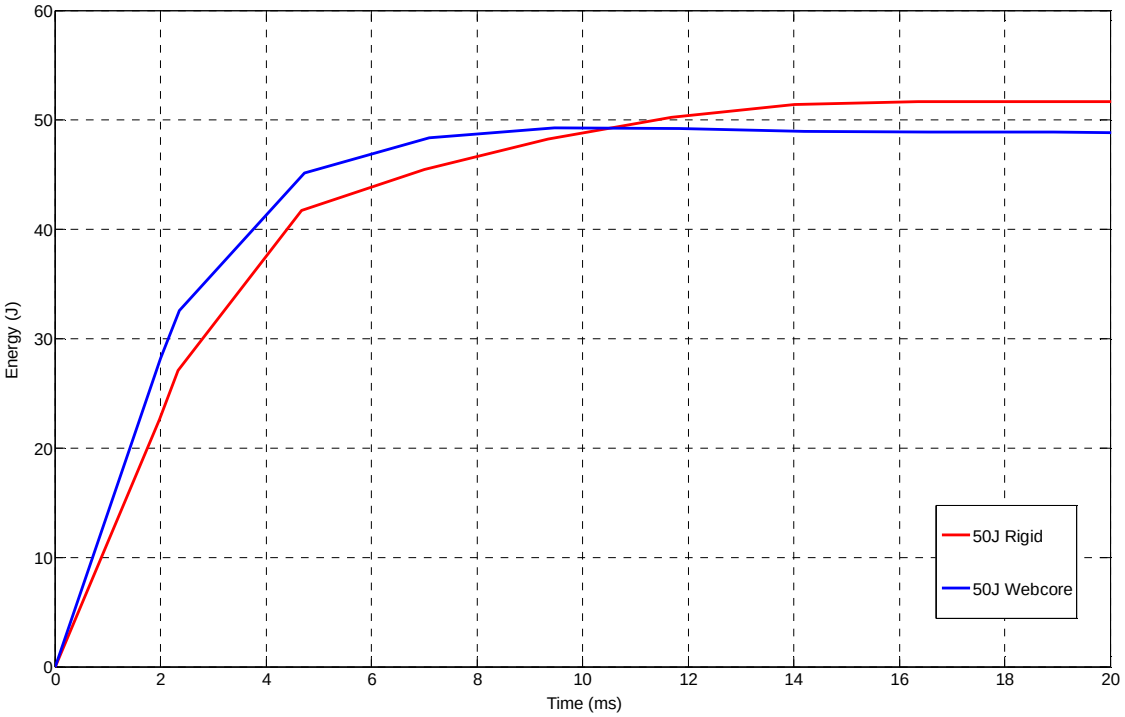

Figure 4.27 Average 50J Energy vs Time of Rigid and Webcore Composites

4.4 PART I CONCLUSIONS

Upon a thorough analysis of the PU rigid and Webcore (TYCOR-W) foam core sandwich composite, Webcore was determined to be the superior choice of core when under impact. The webcore composite was more robust at higher energy levels than the rigid. The PU rigid foam composite saw a significantly larger displacement, about 28% more, at a higher energy level than the Webcore composite. The Webcore foam was able to absorb about 14% more load on average due the support channels. After failure of the faceplate, the Webcore composite had 12% less damage done to the core than the rigid. The only undesirable property of the Webcore was that the PU rigid foam composite weighed about 5 grams less on average.

5. PART II: THE EFFECTS OF MOISTURE EXPOSURE ON THE MECHANICAL PROPERTIES OF FOAM CORE SANDWICH STRUCTURES

5.1 TESTING PROCEDURE

5.1.1 Manufacturing Method. The VARTM process was used in the fabrication of the sandwich composite samples. Four 10 inch x 10 inch sandwich composite samples were manufactured with 3-ply faceplates using a 0.5 inch foam core. Woven E-glass fiber compatible with PU resin systems is the reinforcement material that composes the faceplates of the sandwich composite.

5.1.2 Moisture Exposure. Two dry impact and flexure samples were weighed, tested and used for reference. The remaining impact and flexure samples were immersed in distilled water. After a 15 day period, two impact and flexure samples were removed from the water, weighed and tested. This process was continued for up to 90 days. At the end of each 15 day period, impact and flexure tests were performed on these wet samples to determine the degradation of the mechanical properties as compared to the dry samples.

5.1.3 Impact Test. A Dynatup Instron Model 9250 Impact Testing machine with impulse control and data system was used to perform the low velocity impact tests. The low velocity impact test fixture is made of steel with a 1.75 inch x 1.75 inch opening to ensure that the test specimens are clamped along all four edges. Each 10 inch x 10 inch sample was cut into 3 inch x 3 inch impact samples and three (3) samples were tested after each 15 day period. The tests were conducted at an energy level of 30J for both the dry and wet samples. Section 5.2 investigates the impact behavior of the 0.5 inch PU

rigid foam core sandwich composites after moisture exposure. To determine the behavior of the sandwich composite under impact loading at each energy level, three (3) different relationships are discussed: Load vs Time, Load vs Deflection, and Energy vs Time.

5.1.4 Flexure Test. The flexure experiments were performed on the sandwich composite according to ASTM standard (D7250-12) respectively [22]. The three-point bending test was adopted to characterize the flexural properties of the sandwich composites. In this test, a flat specimen was simply supported at two ends and was loaded by a central load. Three (3) specimens were tested on each run. Table 5.1 gives the specimen dimensions and loading rates of the test.

Table 5.1 Three-point Bending Specimen Data

Specimen Label	Crosshead Speed (in/min)	Geometry	Fixture Type
Sample #	0.04	4" x 1" x 0.5"	3-point

5.2 IMPACT RESULTS AND ANALYSIS OF THE PU RIGID 0.5 INCH FOAM SANDWICH COMPOSITES

Section 5.2 investigates the impact behavior of the 0.5 inch PU rigid foam core sandwich composites. To determine the behavior of the sandwich composites, dry and wet samples, under impact loading at 30 J, three (3) different relationships are discussed: Load vs Time, Load vs Deflection, and Energy vs Time.

5.2.1 Dry Impact Sample Analysis. Figures 5.1 through 5.3 demonstrate the behavior of the dry sample under impact loading. The dry sample was used as a reference for the wet samples to determine the degradation of the properties of the samples due to continuous moisture exposure over time. The sample was able to carry about a maximum load of 4,000 N. The facesheet began to fail immediately after the maximum load was reached, but did not completely fail for about another 4 milliseconds. The facesheet was not penetrated by the impactor resulting in the transfer of energy from the facesheet to the impactor. The maximum deflection within this sample was about 13 mm (0.512 in). Even though the foam core was rigid, the specimen was thin making it more susceptible to enduring a larger deflection. Since the facesheet was not penetrated, most of the energy was absorbed by the facing also resulting in a larger deflection. The energy absorbed by the composite was about 35 J. The maximum was about 37 J so the specimen absorbed much of the energy from the impact weight, but because the facesheet was not penetrated, there was some energy transferred back to the impactor. In Figures 5.4 through 5.18 below, the impact behaviors of the five wet samples under impact loading are demonstrated.

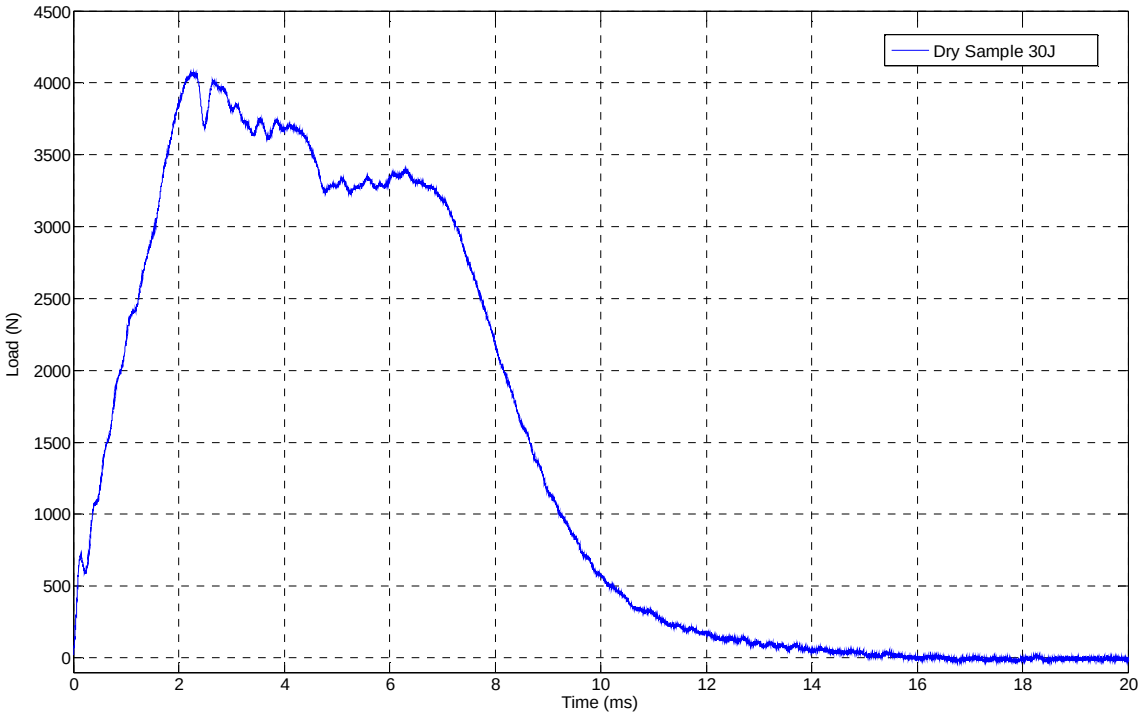

Figure 5.1 Load vs Time of the Dry Impact Sample

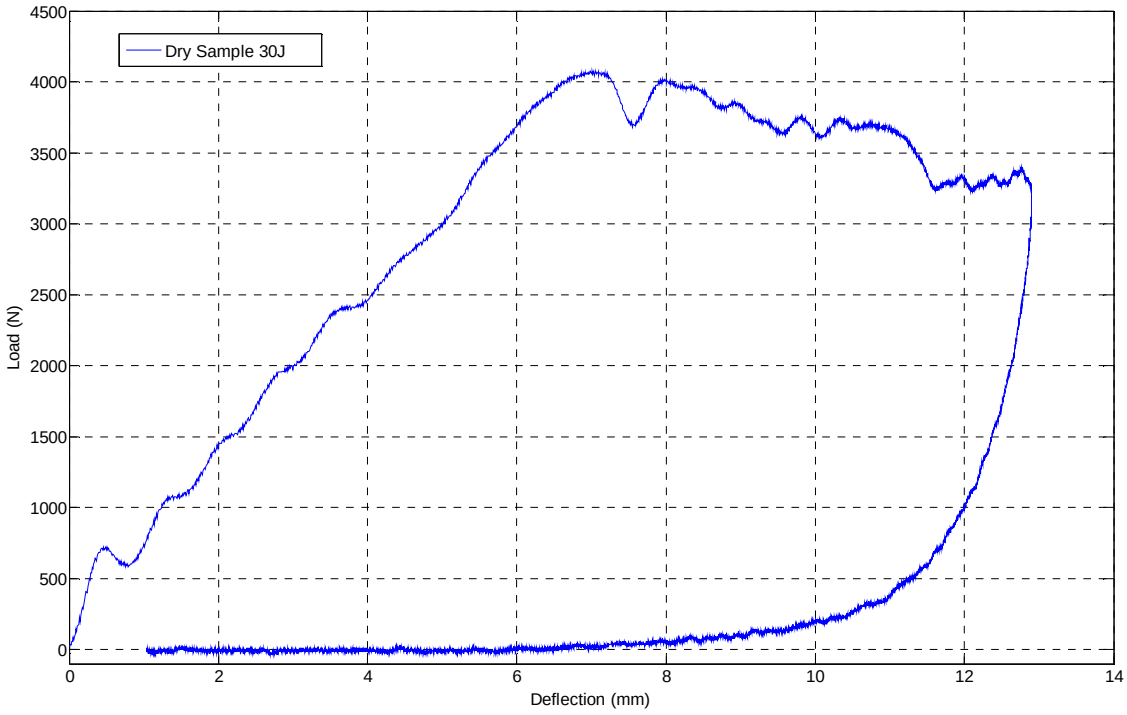

Figure 5.2 Load vs Deflection of the Dry Impact Sample

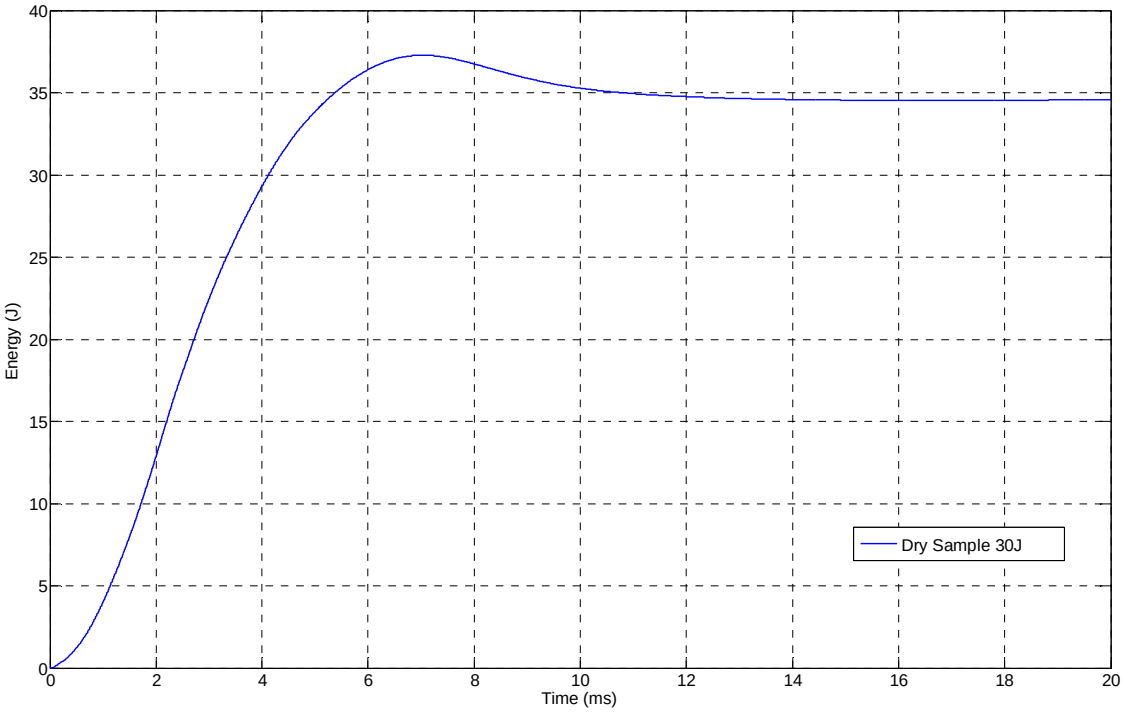

Figure 5.3 Energy vs Time of the Dry Impact Sample

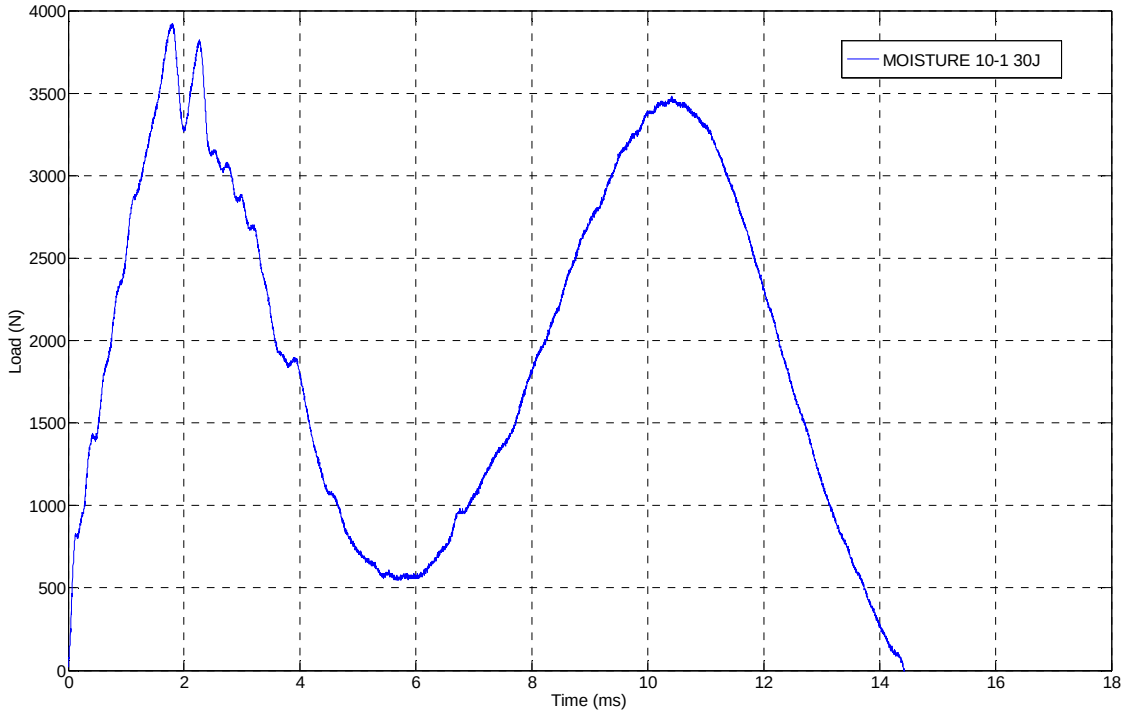

Figure 5.4 Load vs Time of First Impact Run (Wet Sample 1)

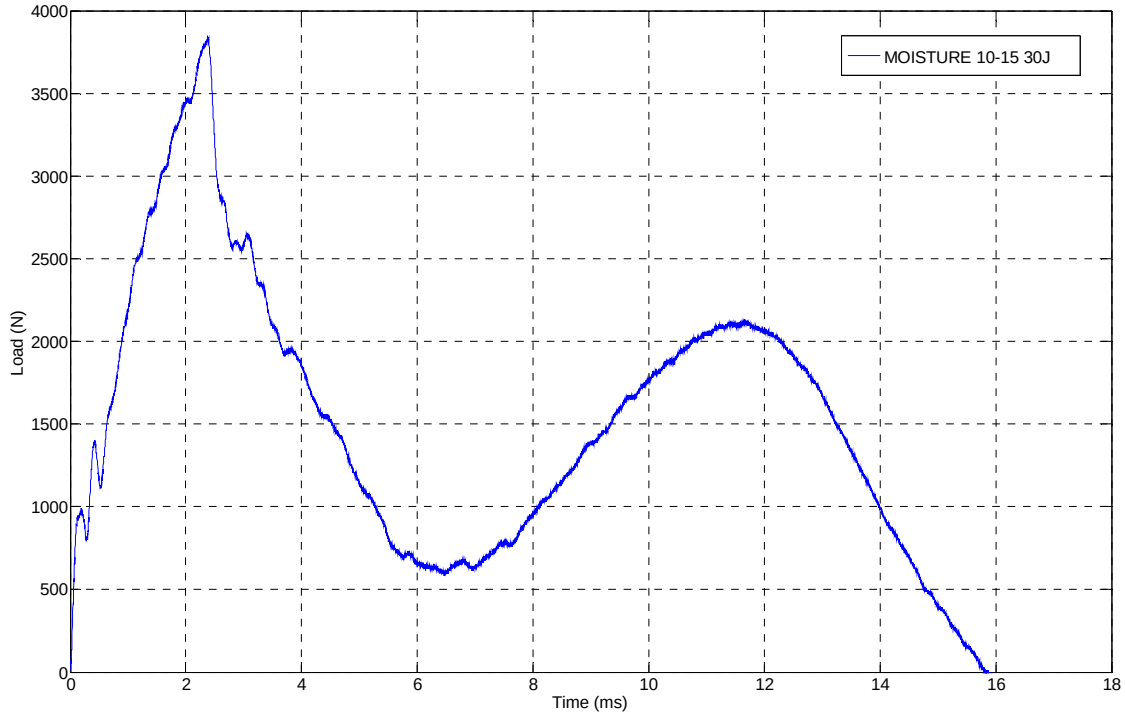

Figure 5.5 Load vs Time of Second Impact Run (Wet Sample 2)

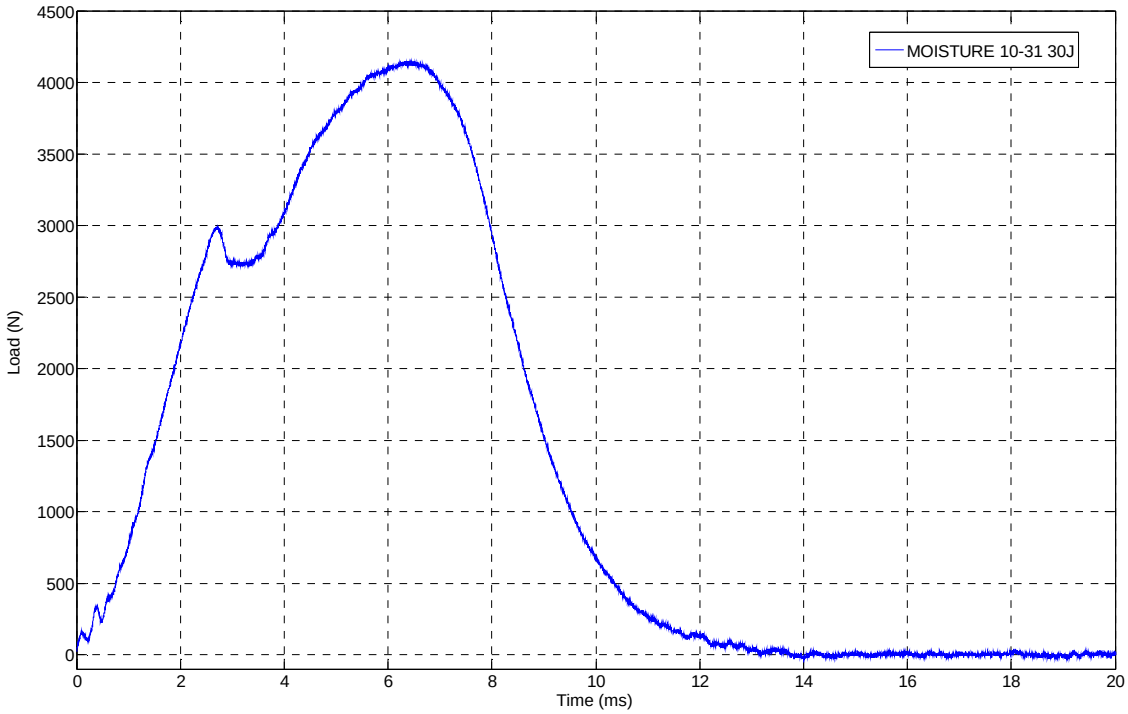

Figure 5.6 Load vs Time of Third Impact Run (Wet Sample 3)

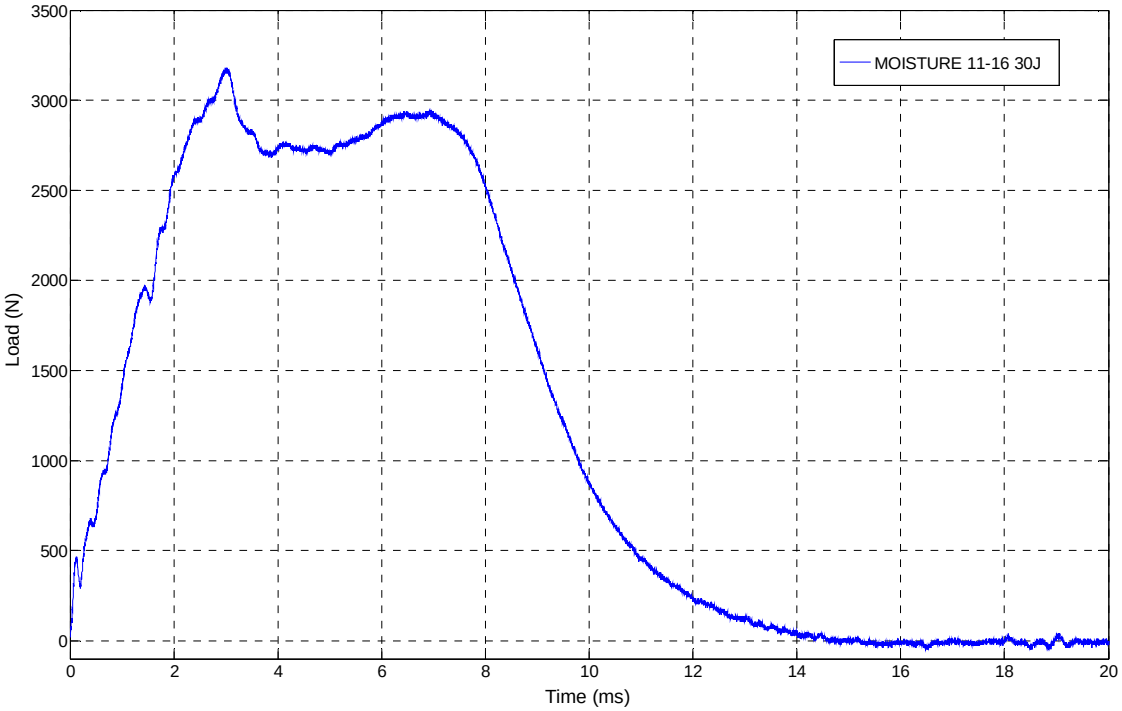

Figure 5.7 Load vs Time of Fourth Impact Run (Wet Sample 4)

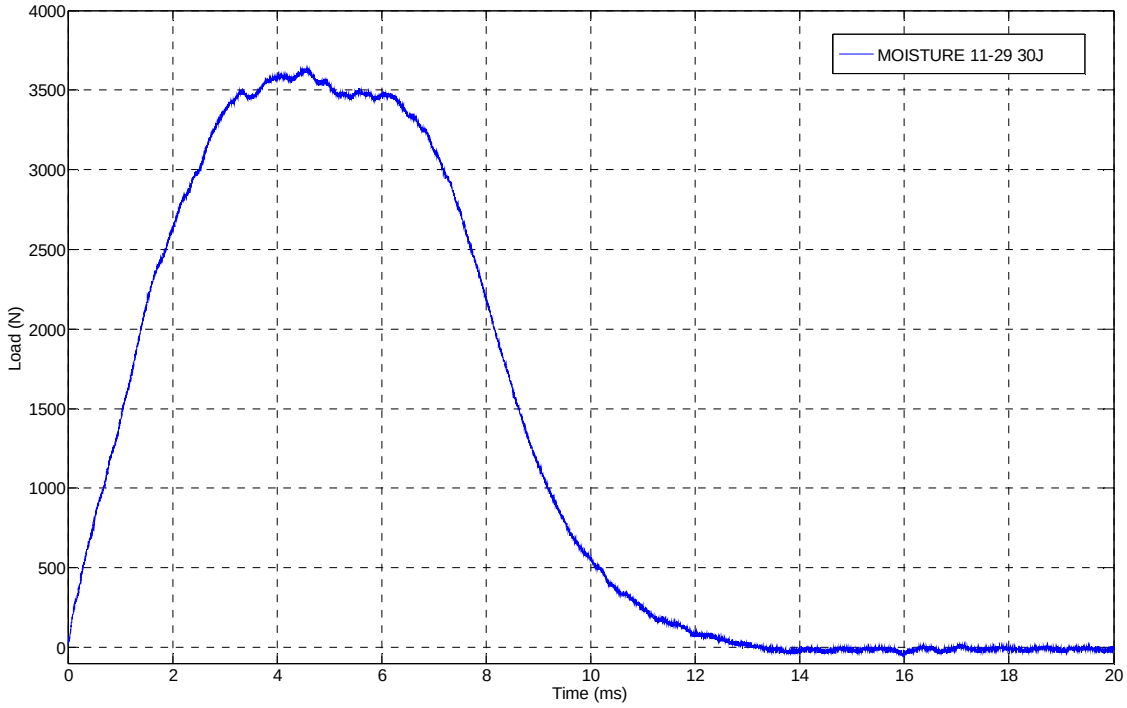

Figure 5.8 Load vs Time of Fifth Impact Run (Wet Sample 5)

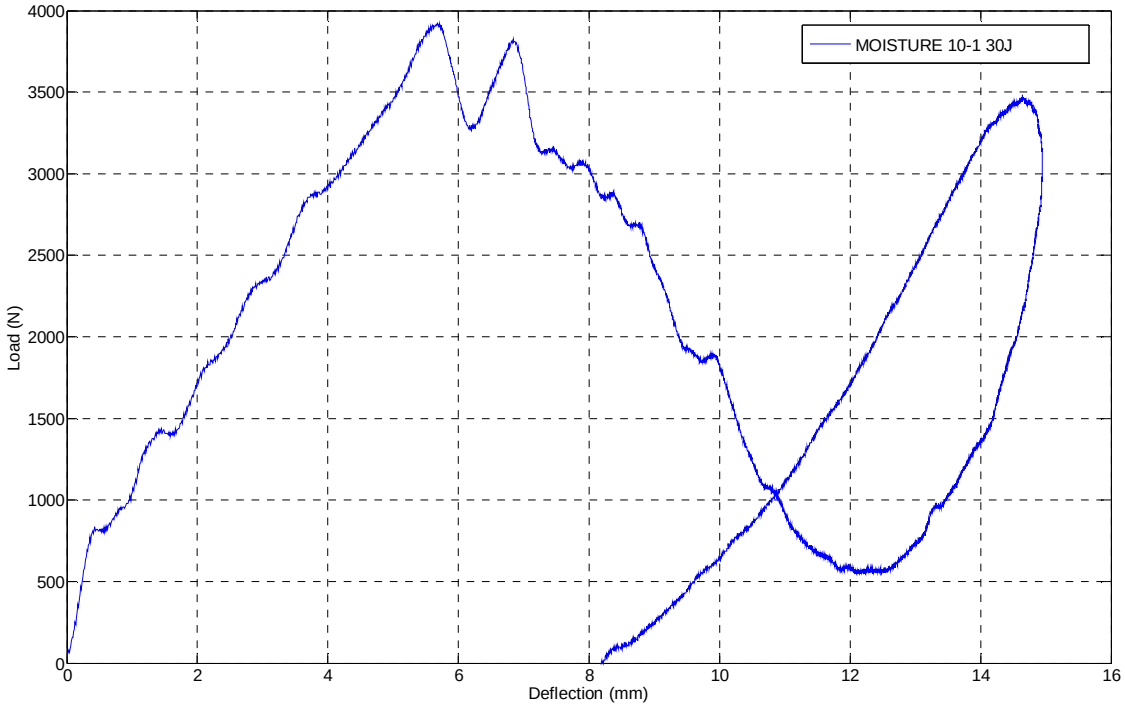

Figure 5.9 Load vs Deflection of the First Impact Run (Wet Sample 1)

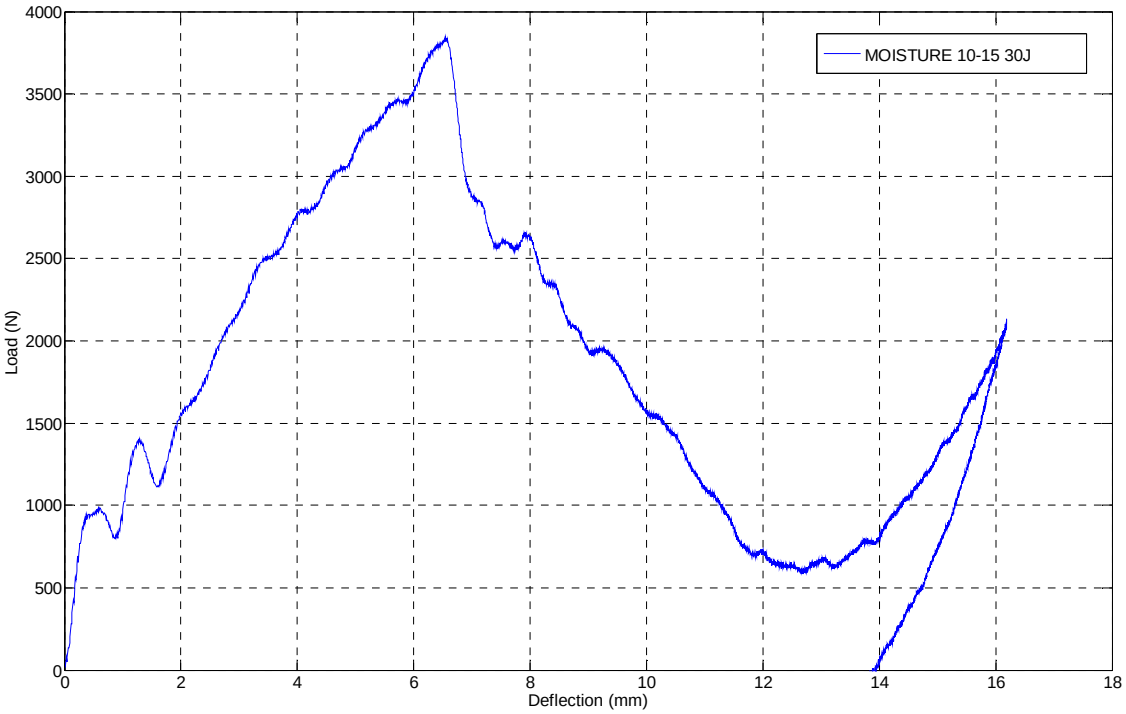

Figure 5.10 Load vs Deflection of the Second Impact Run (Wet Sample 2)

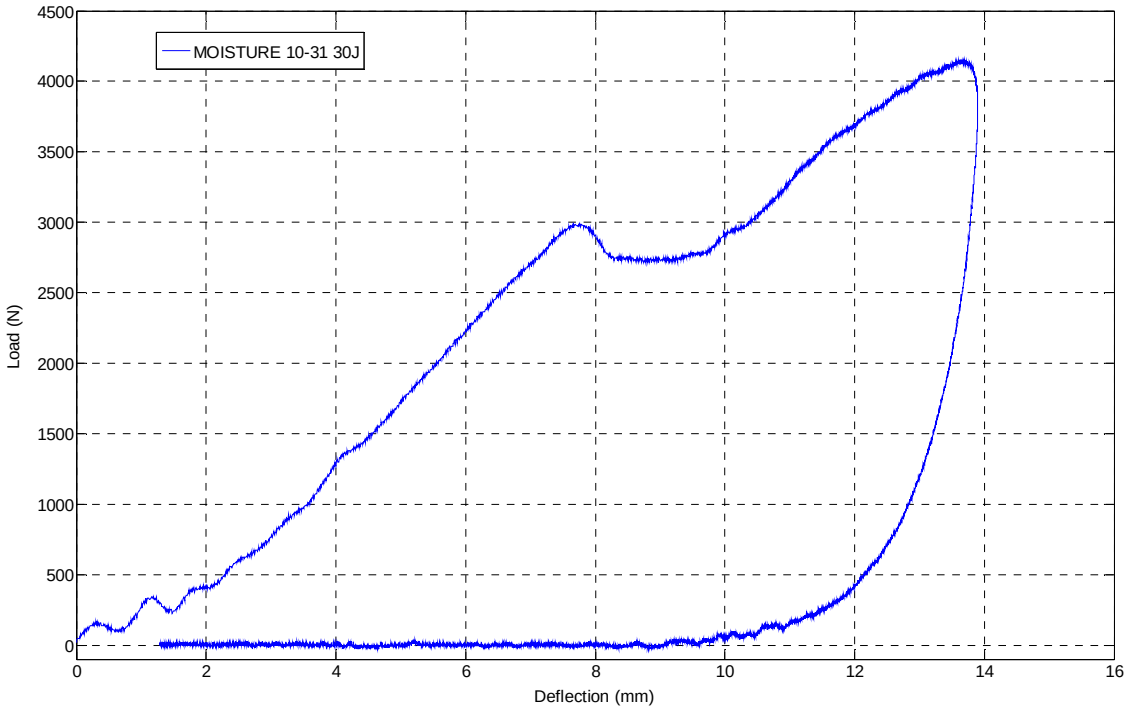

Figure 5.11 Load vs Deflection of Third Impact Run (Wet Sample 3)

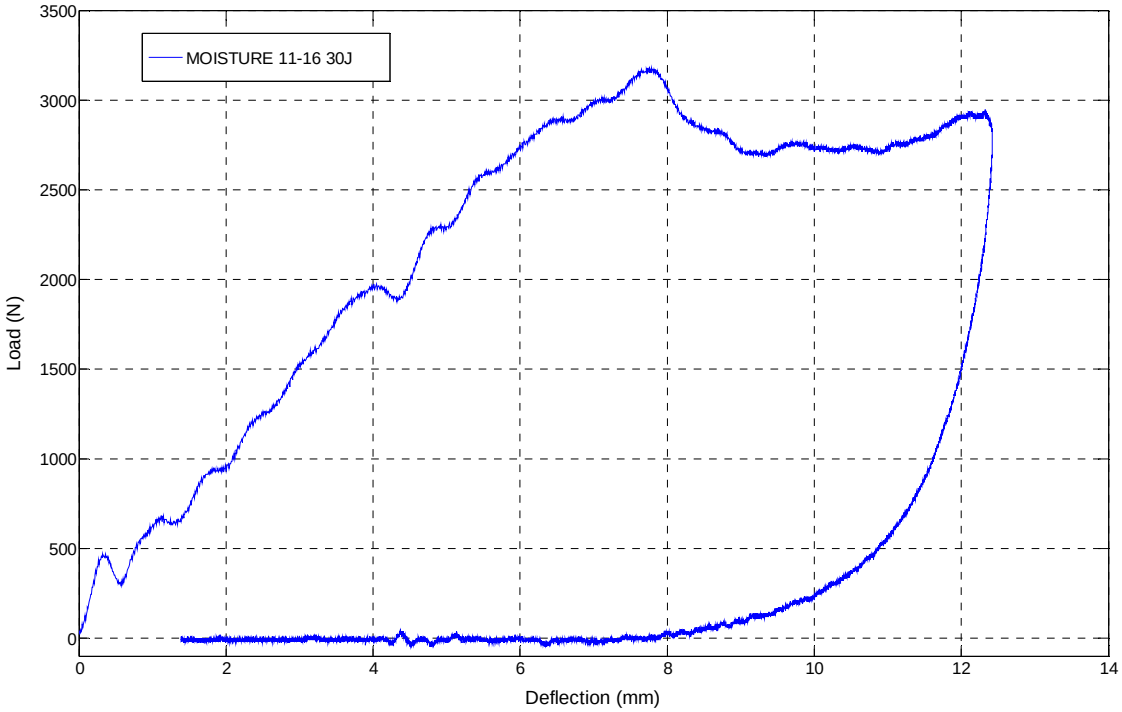

Figure 5.12 Load vs Deflection of the Fourth Impact Run (Wet Sample 4)

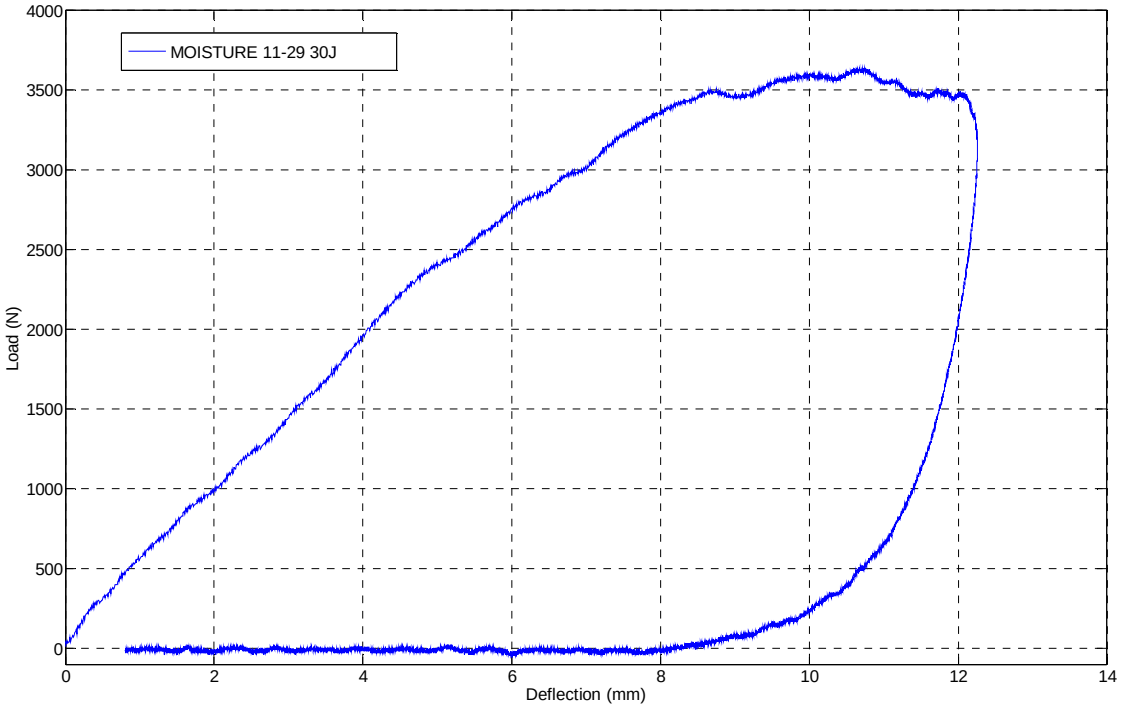

Figure 5.13 Load vs Deflection of the Fifth Impact Run (Wet Sample 5)

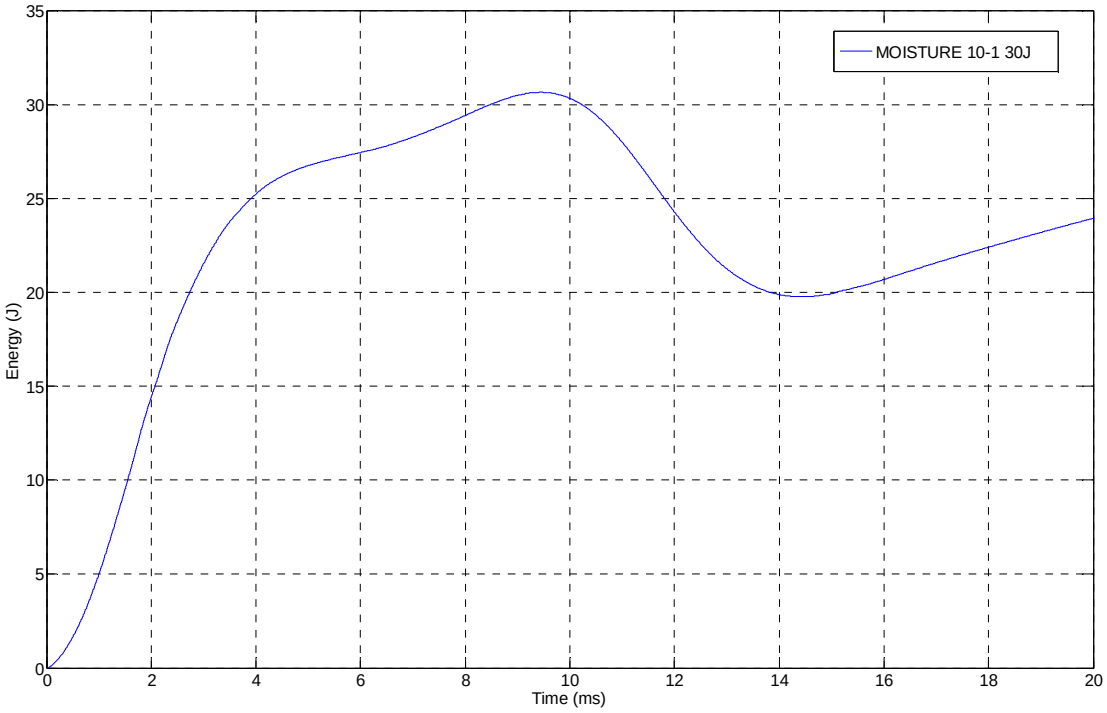

Figure 5.14 Energy vs Time of First Impact Run (Wet Sample 1)

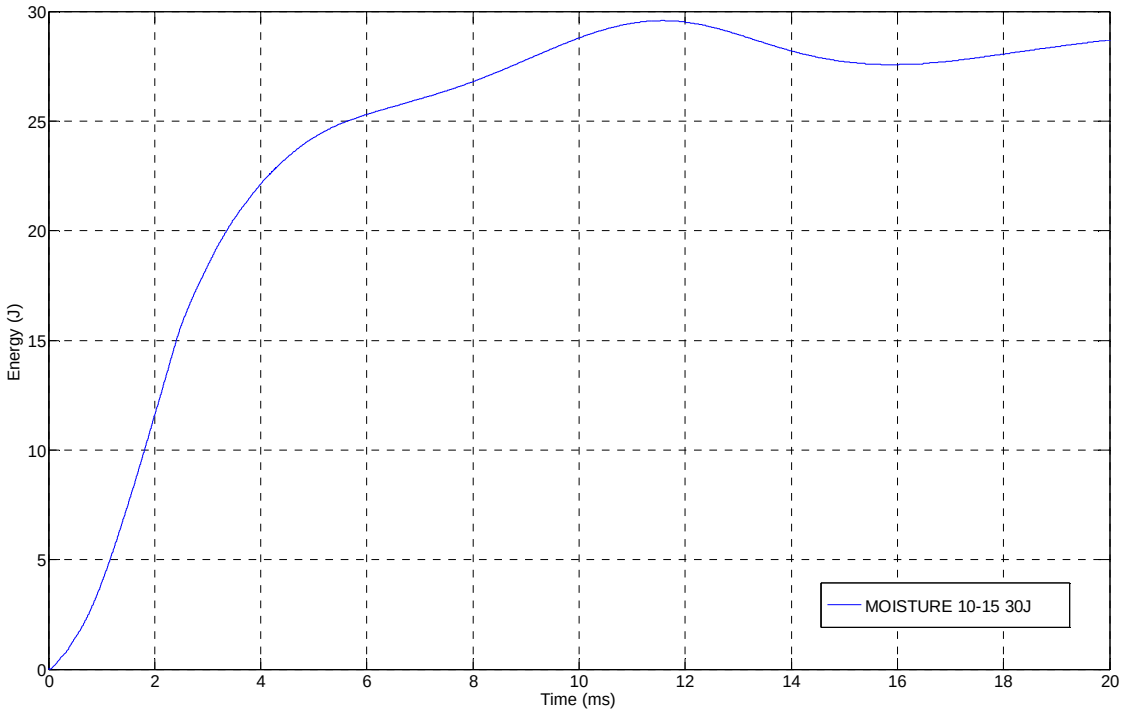

Figure 5.15 Energy vs Time of Second Impact Run (Wet Sample 2)

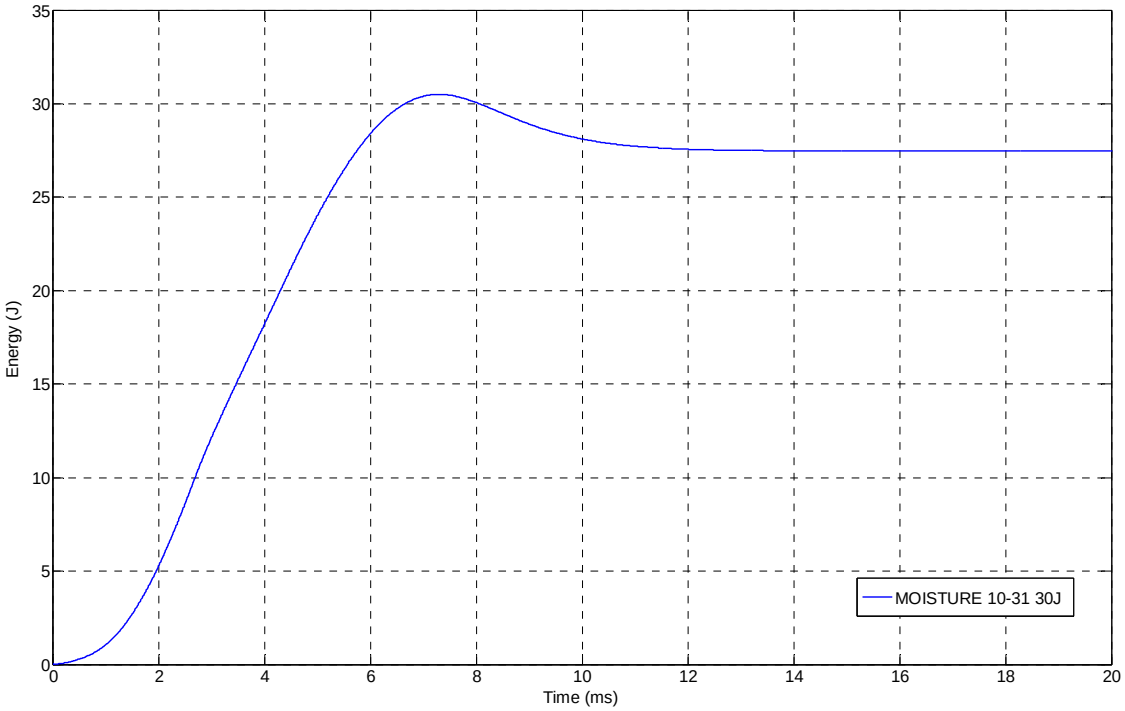

Figure 5.16 Energy vs Time of Third Impact Run (Wet Sample 3)

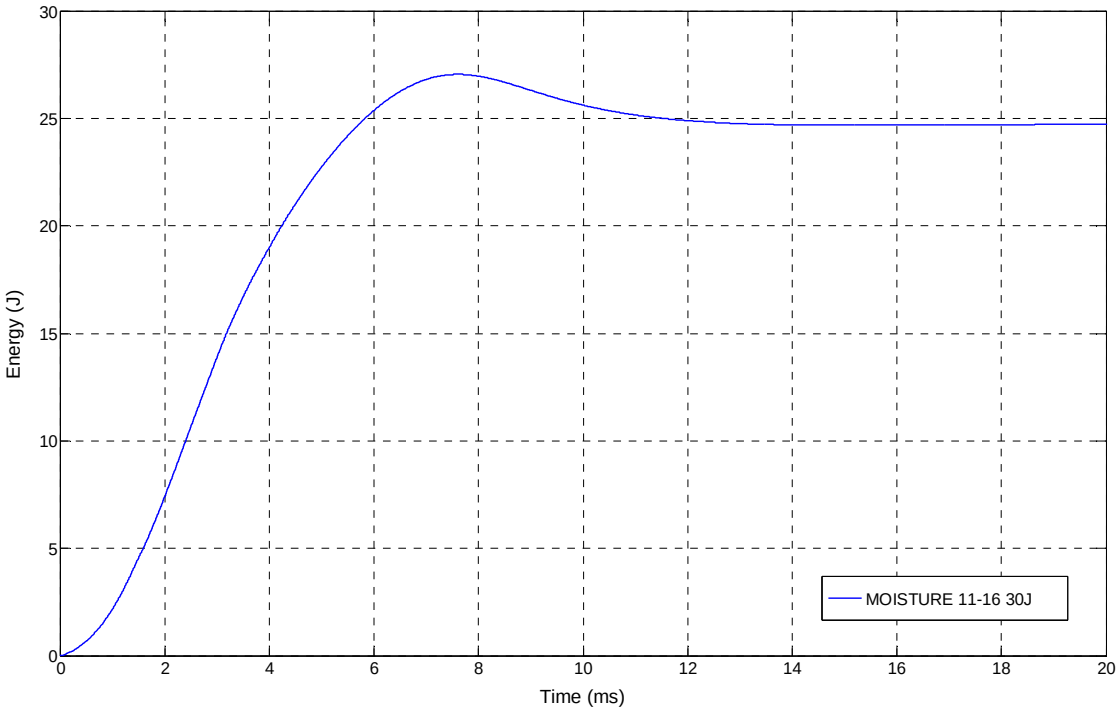

Figure 5.17 Energy vs Time of Fourth Impact Run (Wet Sample 4)

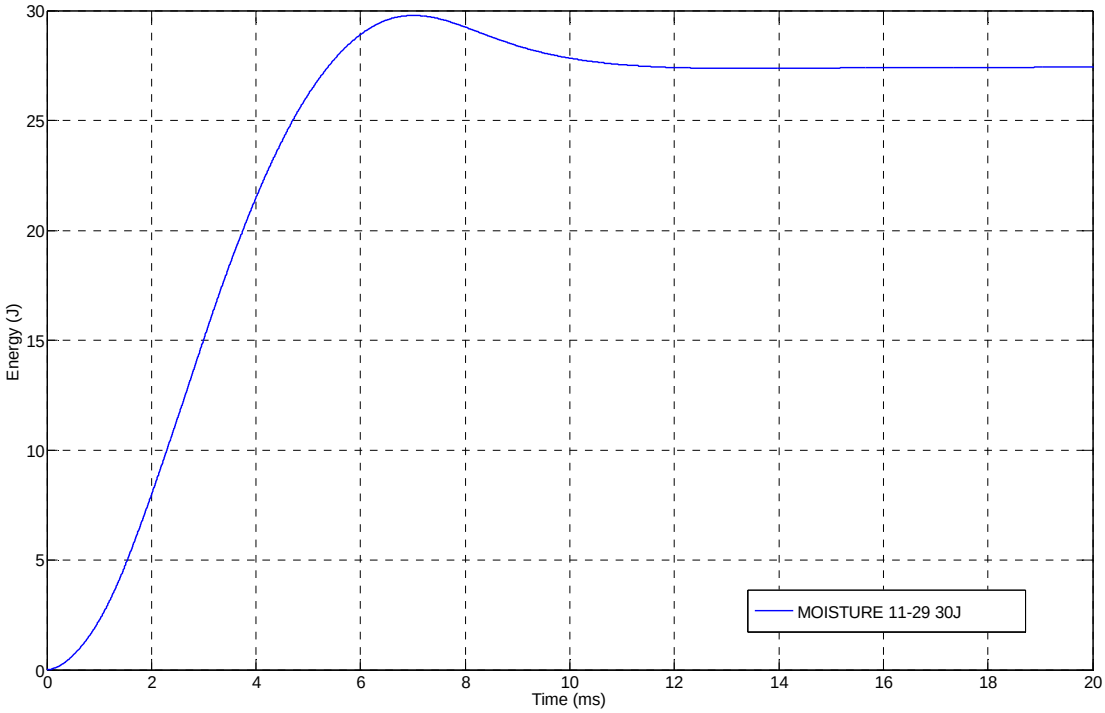

Figure 5.18 Energy vs Time of Fifth Impact Run (Wet Sample 5)

5.2.2 Dry and Moisture Impact Comparison. The degradation within the PU rigid foam core sandwich structures can be clearly seen in Table 5.2. Figures 19 through 21 demonstrate the behaviors of both dry and wet samples under impact loading. Table 5.2 quantifies the properties determined from the impact test. The dry sample was used as the reference to compare the wet samples against to determine this loss of structural integrity. The wet samples 1 and 2 exhibited the expected pattern of degradation behavior as compared to the dry sample. Although wet sample 1 integrity had decreased when compared to the dry sample, it still exhibited better properties than those of wet sample 2, which was immersed for 15 days longer. The load exerted on wet samples 1 and 2 was about 6% less than the load carried by the dry sample. Those two samples also endured a significantly greater displacement and absorbed a lesser amount of energy. Wet sample 3, however, was able to carry a larger load than the dry sample due to the moisture inability to completely saturate the center of the facesheet, where the impactor struck the sample. This would allow the specimen to endure a larger load than the first two wet samples and quite possibly the dry sample, although the maximum load of the dry sample and the wet sample 3 only have about a 1% difference between them. It also had a lower displacement than the previous two wet samples also a side effect of the location where the impact weight made contact being less saturated. The third impact run seems to be where the behavior of the sample begins to show a change in behavior. Wet samples 4 and 5 behaved as expected when compared to the dry sample, but they did see slightly smaller displacements, 4% and 5% respectively. The standard deviation of the impact properties can be found in Table 5.2. The deviations of the impact properties were relatively small showing that most of the values fell within an acceptable range.

Table 5.2 Moisture Impact Test Results

Sample Condition	Test Date	Impact Level (J)	Moisture Absorbed (%)	Contact Force (N)	Energy Absorbed (J)	Displacement (mm)
Dry Sample	10/1/2012	30	0.00	4,074	34.57	12.90
Wet Sample 1	10/1/2012	30	3.03	3,823	25.66	14.85
Wet Sample 2	10/15/2012	30	3.17	3,848	29.21	16.15
Wet Sample 3	10/31/2012	30	4.24	4,150	27.46	13.98
Wet Sample 4	11/16/2012	30	11.09	3,180	24.74	12.40
Wet Sample 5	11/29/2012	30	10.12	3,596	27.45	12.25
Standard Deviation of Wet Samples			3.53	322.14	1.56	1.48

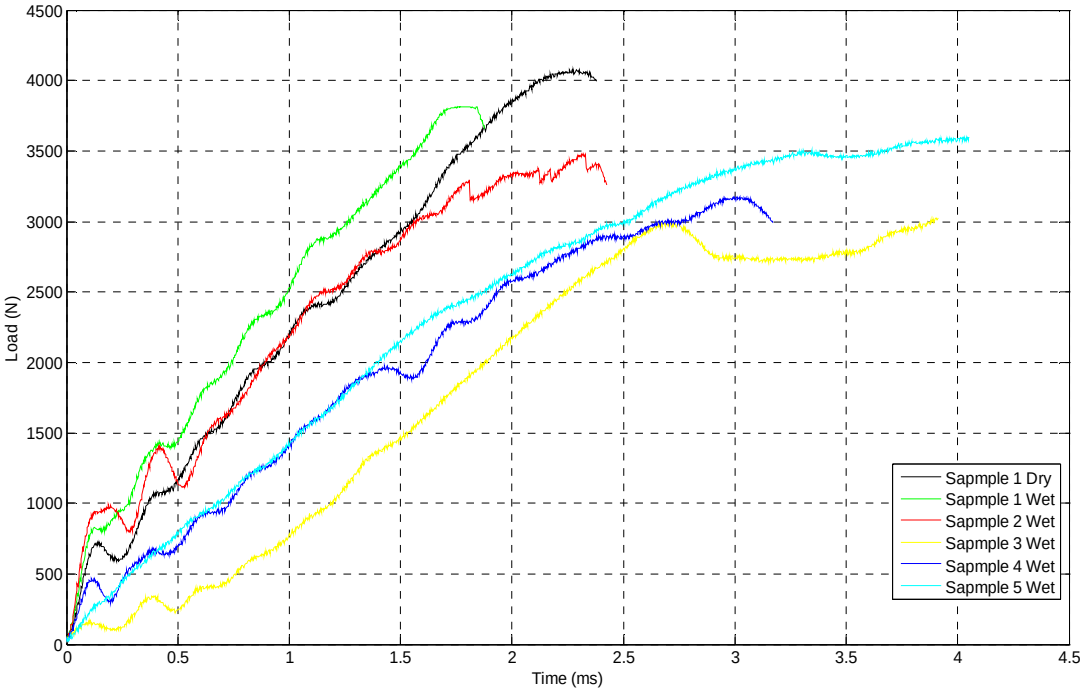

Figure 5.19 Load vs Time of the Dry and Wet Impact Samples

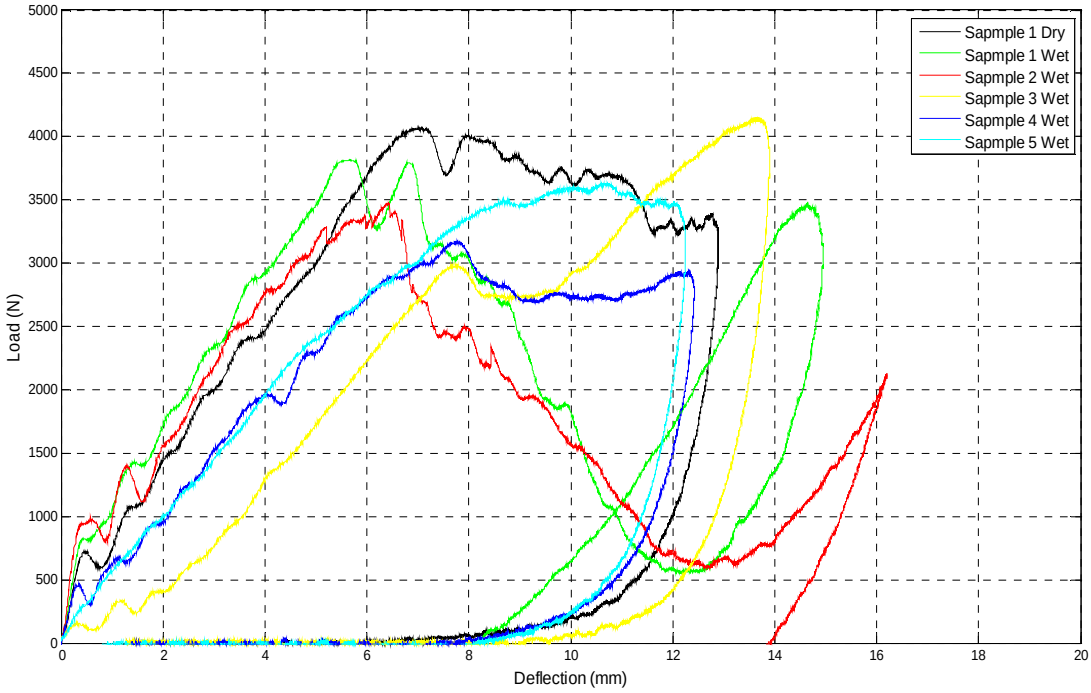

Figure 5.20 Load vs Deflection of the Dry and Wet Impact Samples

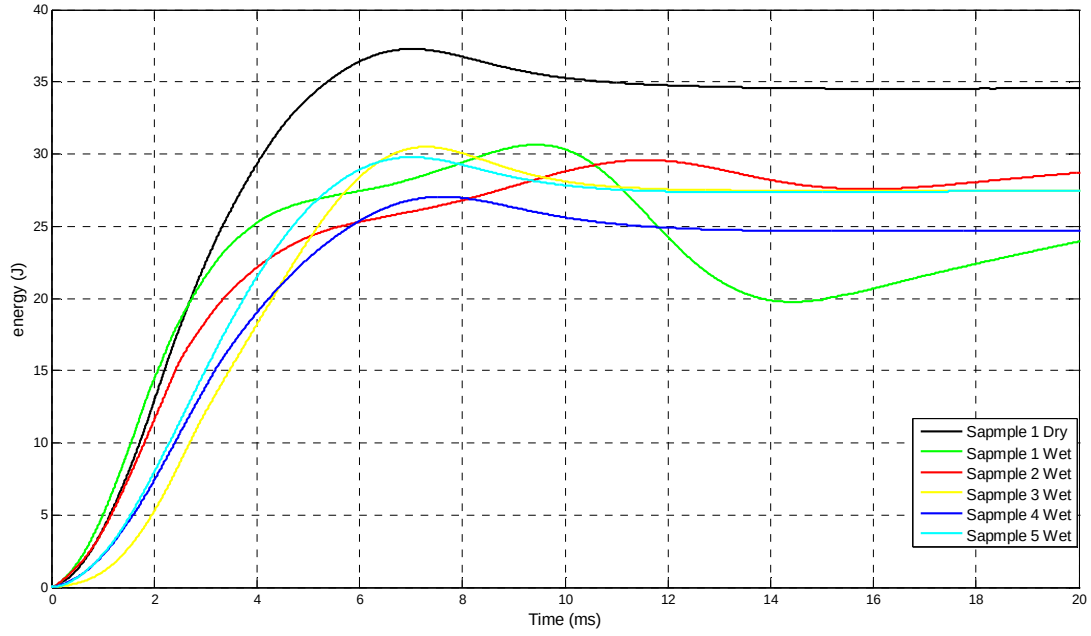

Figure 5.21 Energy vs Time of the Dry and Wet Impact Samples

5.3 FLEXURAL RESULTS AND ANALYSIS OF PU RIGID 0.5 INCH FOAM SANDWICH COMPOSITES

The bending test presents a case where the stress varies across the thickness of the specimen, shown in Figure 5.22, during the three-point bending test. The stress changes from compression at the point where the loading anvil touches the specimen, marked as point “Compression”, to tension on the opposite surface of the specimen, marked as point “Tension”.

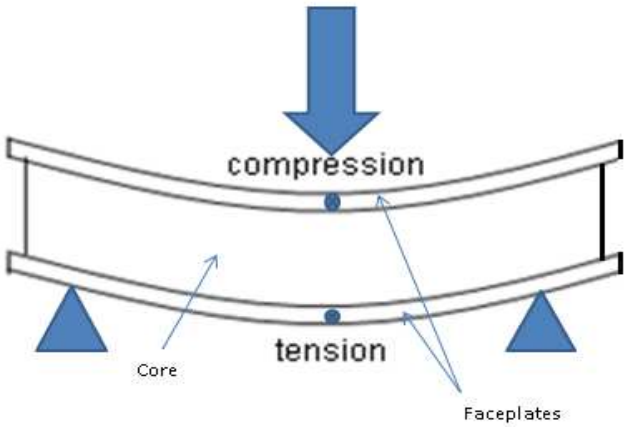

Figure 5.22 Three-point Bending Schematic

In addition, shear stresses act along the length of the specimen. The core or facings can fracture under these three types of stresses depending upon their properties under such stresses. The interface between the facings and the core can also fracture under shear stresses. Hence, crack origination locations and propagation directions will help in determining the types of stresses that cause failure.

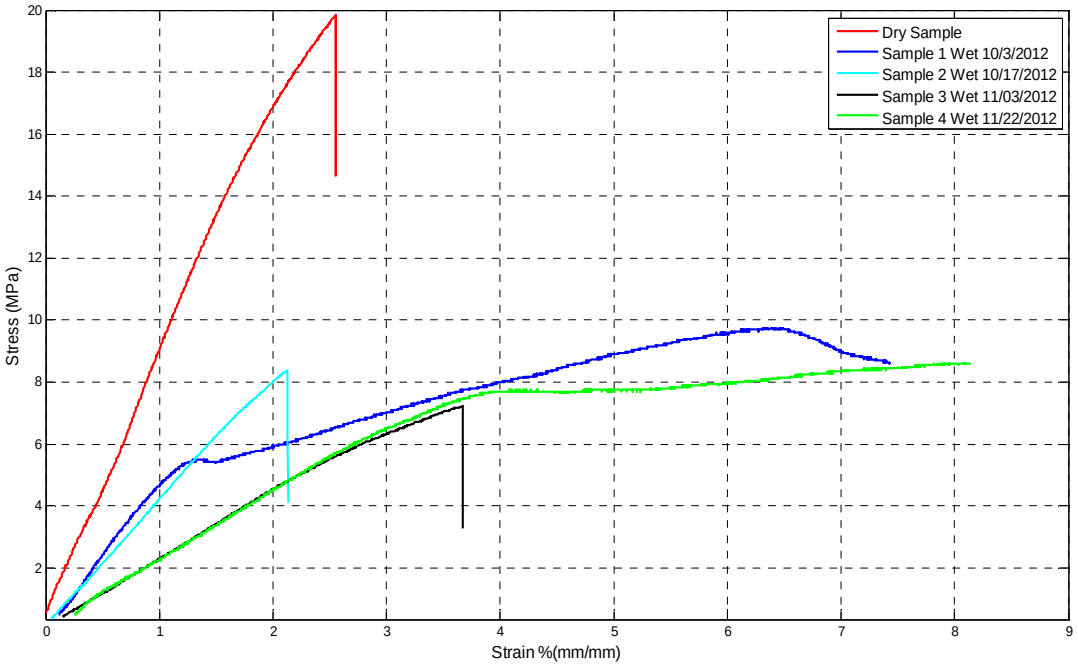

Figure 5.23 Stress-Strain Curves for Flexure Test

The Stress-Strain curves for each run of core sandwich composites for the test are shown in Figure 5.23. Some of the general observations from these curves and the observations of the samples during deformation are listed below, and will be discussed in the following sections.

1. The load decreases sharply after the end of the elastic region due to failure initiation in the sandwich composites.
2. Some of the samples show complete fracture, whereas others show a plateau region after this decrease in the load.
3. The failure initiates on the tensile side of the specimen.

Within the elastic region of the displacement, where no significant damage is induced, the responses of the specimens to the applied loads are quite similar. This is visible in the form of nearly the same slope in the elastic region of the load-displacement

curves for different samples. It is observed that the failure starts in the form of crack initiation on the tensile side of the specimen as the displacement increases. This crack tends to grow towards the compression side of the specimen.

Table 5.3 Moisture Flexure Test Results

Sample Condition	Flexural Strength (MPa)	Flexural Failure Strain (%)	Maximum Load (N)	Displacement (mm)
Dry Sample	20	2.53	382	2.45
Wet Sample 1	9.73	6.30	262	8.38
Wet Sample 2	8.063	2.18	217	3.45
Wet Sample 3	6.061	2.70	220	3.79
Wet Sample 4	6.9	2.80	224	3.86
Standard Deviation of Wet Samples	1.38	1.64	18.21	2.03

There was a significant difference between the maximum strength of the dry sample and the wet samples. After the first 15 day period, wet sample 1 was tested and only had a flexural strength of about 10 MPa. Wet sample 1 was only immersed in the water for 15 days, but the sample had a large decrease of about 50% in strength as shown in Table 5.3. The rate of degradation slowed from wet sample 1 to wet sample 2 from a 50% decrease to a 17% decrease. The strength continues to decrease from sample to sample except from wet sample 3 to wet sample 4. Wet sample 4 had a slightly higher strength, about 12% higher, than the sample 3. This was due to the flexure specimen reaching full saturation. The difference between samples 2 and 3 was obviously greater than the difference between samples 3 and 4 showing that the samples were beginning to

reach moisture equilibrium. The standard deviation of the wet samples, shown in Table 5.3, was determined. The deviations of the samples were small showing that the values of each flexure property tend to be close to the mean of their respective property.

5.4 PART II CONCLUSIONS

Moisture exposure has a significant effect on the performance of sandwich composites. Degradation of the impact and flexure samples increased as the longer the specimens were immersed in the water. When the samples reach the point of complete saturation, the properties do not continue to decrease. The percent difference between flexure samples 1 and 2 is about 17%, but the difference between samples 2 and 3 and samples 3 and 4 were both about 1%. The flexure samples had a dramatic 50% decrease in strength from the dry sample to sample 1. The deviations of the impact and flexure properties were relatively small showing that most of the values fell within an acceptable range.

6. CONCLUSIONS

Key conclusions from Part I and Part II are summarized below:

- The PU rigid foam composite saw a significantly larger displacement, about 28% more, at a higher energy level than the Webcore composite

- The Webcore foam sandwich composite was able to absorb about 14% more load on average due the support channels.

- After failure of the faceplate, the Webcore composite had 12% less damage done to the core than the rigid.

- Degradation of the impact and flexure samples increased the longer the specimens were immersed in the water.

- When the samples reach the point of complete saturation, the properties do not continue to decrease. The percent difference between flexure strength in samples 1 and 2 was about 17% and the difference between the strengths of sample 2 and 3 and samples 3 and 4 were both about 1%.

- The deviations of the impact and flexure properties were relatively small showing that most of the values fell within an acceptable range.

REFERENCES

1. Huntsman Polyurethanes: “Urethanes Offer High Pultrusion Speeds,” Reinforced Plastics, Vol. 50, pp.18, 2006.

2. Wonderly C., Grenestedt J., Fernlund Go¨ran, Ce˘pus Elvis, “Comparison of Mechanical Properties of Glass Fiber/Vinyl Ester and Carbon Fiber/Vinyl Ester Composites. Composite Part B: Eng;36(5),” pp.417–26.2005.

3. Mouritz, A., “Ballistic Impact and Explosive Blast Resistance of Stitched Composites. Composite Part B: Eng;32(5),” pp.431–9.2001.

4. Mouritz, A., “The Damage to Stitched GRP Laminates by Underwater Explosion Shock Loading,” Composite Science Technology; Vol. 55(4): pp.365–74. 1995.

5. Katzman H., Castaneda R., Lee H., “Moisture Diffusion in Composite Sandwich Structures,” The Aerospace Corporation. 2008.

6. Aviles F., Aguilar-Montero M., “Moisture Absorption in Foam-Cored Composite Sandwich Structures,” Centro de Investigacio´ n Cientı´fica de Yucata´ n, A.C., Unidad de Materiales, Calle 43 No. 103, Col. Chuburna´ de Hidalgo, Me´ rida, Yucata´ n 97200, Mexico. 2009

7. Hazizan A., Cantwell W., “The Low Velocity Impact Response of Foam Based Sandwich Structures,” Department of Materials Science and Engineering, University of Liverpool. 2002.

8. Yang J., Yang Q., and Liu Wei, “Moisture Diffusion Behavior of Permeable Fiberreinforced Polymer Composite,” *Front Mech. Eng. China 2010*, Higher Education Press and Springer-Verlag, Heidelberg, pp. 347-352, 2010.

9. Whitcomb J., and Xiaodong T., “Micromechanics of Moisture Diffusion in Composites with Impermeable Fibers,” Journal of Composite Materials Vol. 36, No. 9, pp. 1093-1101, 2002.

10. Ramazan K., Emer E., Mehmet A., “Impact Characterization of Glass/Epoxy Composite Plates: An Experimental and Numerical Study,” Composite Part B Vol. 41, pp.388-395, 2010.

11. John J., Bhattacharya M., Turner R., “Characterization of Polyurethane Foams from Soybean Oil,” Journal of Applied Polymer Science, Vol. 86, pp. 3097–3107. 2002.

12. Desai S., Thakore I., Sarawade B., Devi S., “Effect of Polyols and Diisocyanates on Thermo-mechanical and Morphological Properties of Polyurethanes,” European Polymer Journal, Vol. 36, pp. 711–725. 2000.

13. Husic´ S., Javni I., Petrovic´ Z., “Thermal and mechanical properties of glass reinforced soy-based polyurethane composites,” Composites Science and Technology. Vol. 65, pp. 19–25. 2005.

14. Usama Y., “Development of PU-based RTM and VARTM Technology,” American Composites Manufacturing Association. February 9-11, 2010.

15. Connolly M., King J., Shidaker T., and Duncan, A. (Huntsman), “Processing and Characterization of Pultruded Polyurethane Composites,” 2006

16. Szycher, M., “M. Szycher‘s Handbook of Polyurethanes ,” CRC Press, Boca Raton. 1999.

17. Latere dwan‘isa J., Mohanty, A, Misra M., Drzal L., and Kazemizadeh M., “Novel Soy Oil Based Polyurethane Composites Fabrication and Dynamic Mechanical Properties Evaluation,” Journal of Materials Science, Vol. 39, pp. 1887 – 1890, 2004.

18. Sherman, L., “Polyurethane Composites: New Alternative to Polyester & Vinyl Ester,” Plastics Technology Online, Feature Article http://www.ptonline.com/articles/200603fa2.html. December 2006.

19. Dale M., Acha B., Carlsson L., “Low Velocity Impact and Compression After Impact Characterization of Woven Carbon/Vinylester at Dry and Water Saturated Conditions,” Department of Ocean and Mechanical Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL, USA. 2012

20. Agarwal Bhagwan D., Broutman, L., and Chandrashekhara K.: *Analysis and Performance of Fiber Composites Third Edition*: John Wiley & Sons, Inc. Hoboken, NJ, pp. 2-10 & 407, 2006.

21. Ratwani M., Ph. D, “Composite Materials and Sandwich Structures – A Primer,” R-Tec, 28441 Highridge Road, Suite 530, Rolling Hills Estates, CA, USA.

22. ASTM D7250-12 Standard Practice for Determining Sandwich Beam Flexure and Shear Stiffness, ASTM International, West Conshohocken, PA, USA

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