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# Comparative Analysis and Dynamic Response of ABS Under UV Light Degradation Using Shock Tube

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# COMPARATIVE ANALYSIS AND DYNAMIC RESPONSE OF ABS UNDER UV LIGHT DEGRADATION USING SHOCK TUBE

By
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## DEDICATION:

I would like to thank my parents Mr. and Mrs. David Ashley Lauber for supporting me and believing in me even when I did not believe in myself. To Dr. Stoddard for always being there for me and helping me with everything from school to life. Also, to all my fellow undergraduate researchers for helping with the testing of these samples and keeping this journey fun.

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**ABSTRACT**

GREER LAUBER: Comparative Analysis and Dynamic Response of ABS Under UV Degradation in Shock Tube

The purpose of this study was to examine the dynamic response of acrylonitrile-butadlene-styrene (ABS) when exposed to UV light. Impact-Resistant Easy-to-Form ABS sheets were tested using a Shock Tube. Three samples were tested at no UV light exposure and three were tested after 15 days of being exposed to rapid UV degradation rays. All samples were tested at a shock wave equivalent to 400 psi. The results showed that the UV damaged samples experienced a decrease in strength and energy absorption in comparison to the non-UV damaged samples. The average peak load for the non-UV degraded was 1261.89 Newtons and for the UV degraded it was 1069.87 Newtons. The specific energy absorption for the non-UV samples was 0.148 kJ/kg and for the UV degraded samples it was 0.130 kJ/kg. There was some embrittlement present in the UV damaged samples which led to it not wanting to deflect as much as the non-UV samples. This also meant that it took less energy to deflect the UV samples in comparison to the non-UV degraded ABS samples.

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# INTRODUCTION

## Purpose

The purpose of this study was to examine the dynamic response of acrylonitrile-butadlene-styrene (ABS) when exposed to UV light. Impact-Resistant Easy-to-Form ABS sheets were tested using a Shock Tube. Three samples were tested at no UV light exposure and three were tested after 15 days of being exposed to rapid UV degradation rays.

ABS was chosen due to its ability to be easily machined and 3D printed. ABS offers material benefits such as a low melting point, high tensile strength, impact resistance, good thermal and electrical conductivity, its low cost, and ability to be recycled [1].

The purpose of this type of testing is to better understand how ABS could be potentially used in military applications. The shock tube can be used to experimentally create a bomb explosion. By testing ABS and its ability to withstand shock forces its material properties and applications for military vehicles, armor, or more can be assessed. Also, by preforming testing on ABS samples that have experienced UV degradation, according to ASTM G-154 standard without condensation, their in-use performance can also be more accurately discussed [2].

## Dynamic Testing

Dynamic testing is used to examine a materials physical response from a system. In research this type of testing is done to gain a fuller understanding of a material's dynamic properties. Various types of equipment can be used to examine a specimen's dynamic properties. For this research, high velocity testing was done using a Shock Tube. A shock tube is used to simulate a shock wave

event. Shockwaves carry internal energy that leads to sudden changes in pressure and propagates at or above the sounds speed of the material [3]. Most shock tubes consist of a driver and driven section of compressed fluid separated by a diaphragm or high-speed valve. When diaphragm burst or high-speed valve actuation occurs a planar shockwave is propagated towards the sample. Before the shock wave can reach the sample two separate sections of the wave are created. These sections are known as the driven gas, which is in front of the shock wave, and the driver gas, which is behind the shock wave. The driven gas remains undisturbed while the driver gas has high pressure disturbance and internal energy that propagates at $U_+$. When the shock front propagates and impacts the sample a reflected shockwave is formed and propagates at speed $U_-$ [4]. Two different sections are once again created, but the driver section is still the gas in the front of the shock wave and the disturbed is the gas behind. The different properties of these sections created by the shock have physical parameters where $u$ is particle velocity, $p$ is pressure, $c$ is sound velocity, $\rho$ is density, $\tau$ is specific volume, and $e$ is specific internal energy [5]. **Figure 1** below shows a schematic for the incident and reflected shock waves.

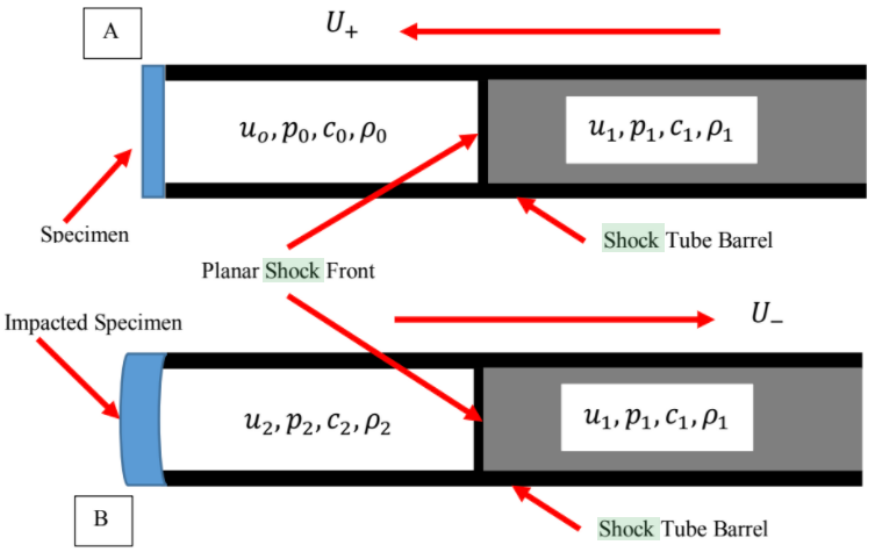


**Figure 1.** Incident and Reflected Shock Wave Schematic [4]

The amount of energy stored in these three sections can be separated into three categories. These categories are "internal energy, translational energy, and the work done by the gas over a time span of $dt$ during the experimental loading conditions with a cross sectional area of $S$, pressure $p(t)$, particle velocity $u(t)$, and $\gamma$ is the adiabatic exponent of the gas" [4,5]. The following equations were used to find the work done by the gas, the internal energy, and the translational energy [4].

**Eq. 1** $$dE_{work\ done} = p(t) \cdot S \cdot |u(t)|dt$$

**Eq. 2** $$dE_{internal\ energy} = \frac{p(t) \cdot S \cdot |u(t)|}{\gamma - 1} dt$$

**Eq. 3** $$dE_{translational\ energy} = \frac{1}{2}\rho(t) \cdot S \cdot |u(t)|^3 dt$$

By integrating the previous equations, the equations to find the incident energy and remaining energy can be found. The subscript 1 denotes incident and subscript 2 denotes reflected [4].

**Eq. 4** $$E_{incident} = \int S \cdot |u_1(t)| \left[\frac{\gamma \cdot p_1(t)}{\gamma - 1} + \frac{1}{2}\rho_1(t) \cdot |u_1(t)|^2\right] dt$$

**Eq. 5** $$E_{incident} = \int S \cdot |u_2(t)| \left[\frac{\gamma \cdot p_2(t)}{\gamma - 1} + \frac{1}{2}\rho_2(t) \cdot |u_1(t)|^2\right] dt$$

The cross-sectional area of the shock tube is measured and known, and the pressure profile was captured using transducers. The velocities of the gas particles, density, and sound speed were found using **Equations 6-9.** In **Equation 9** the A value represents "a reversible process of the initial state of the gas during an adiabatic process" [4].

**Eq. 6** $$\rho\tau = 1$$

**Eq. 7** $$e = \frac{1}{\gamma - 1} p\tau$$

**Eq. 8** $$\rho c^2 = \gamma p$$

**Eq. 9** $$p = A\rho^{\gamma}$$

The initial pressure jump due to the shock wave can be obtained using conservation of mass, momentum, energy, and particle velocity relative to the planar shock front $v$. From **Equation 19** and the conservation of mass and momentum the following equations can be found [4].

**Eq. 10** $$(\tau_1 + \tau_0)(p_1 - p_0) = v_0^2 - v_1^2$$

**Eq. 11** $$\frac{(p_0 - p_1)}{(\tau_0 - \tau_1)} = \rho_0 v_0 = \rho_1 v_1$$

**Eq. 12** $$\frac{(p_1 - p_0)}{(\rho_1 - \rho_0)} = v_0 v_1$$

The Hugoniot relationship can be derived from the conservation of energy and **Equation 10** [4].

**Eq. 13** $$H(\tau_1, p) = e_1 - e_0 + \frac{1}{2}(\tau_1 - \tau_0)(p_1 - p_0) = 0$$

Since the specific energy and specific volume are unable to be measuring during the testing the Hugoniot relationship can be changed with the parameters obtained during the experiment [4]. **Equation 14** shows the derived equation.

**Eq. 14** $$\frac{p}{p} = \frac{\tau_0 - \mu^2 \tau_1}{\tau_1 - \mu^2 \tau_0}$$

By combining **Equations 8,11, and 14** a relationship where $\mu^2 = (\gamma - 1)/(\gamma + 1)$ where M is equal to the Mach number [4].

**Eq. 15** $$\frac{p}{p} = (1 + \mu^2)M_0^2 - \mu^2 \qquad OR \qquad \frac{p}{p} = (1 + \mu^2)M_1^2 - \mu^2$$

A relationship between the adiabatic exponent of gas, velocity of the shock fronts particle velocities, and sound speed can be found by combining **Equations 8, 12,** and the conservation of energy yield. From the following equations the particle velocity, sound speed, and density of each section during shock loading can be found [4].

**Eq. 16** $$(1 + \mu^2)(U_+ - u_0)^2 - (u_1 - u_0)(U_+ - u_0) = (1 - \mu^2)c_0^2$$

**Eq. 17** $$(1 + \mu^2)(U_+ - u_1)^2 - (u_0 - u_1)(U_+ - u_1) = (1 - \mu^2)c_1^2$$

Using high-speed camera images, the deformation energy of the samples can be obtained. The samples deflection and pressure profile from the reflected wave can be obtained. These two characteristics are what cause the samples to deform. By combining the deflection and pressure profile load-displacement data can be found and used to find the deformation energy of the samples [4]. In this experiment the panels were treated as if their deflection is the displacement through the entire width of the sample [5]. Through a curve fitting method, the front surface deflection can be found. Also, from the curve fit equation the displacement along any point of the front surface can be found. The deformation energy can be found from integrating the press-deflection curve at every point within the loading area [4].

**Eq. 18** $$E_{deformation} = \oint_{S_{shock\,tube}} (\int p_2(t) dl_{deformation}) ds$$

**Background Research**

The plastic materials chosen can be 3D printed and offer other benefits such as ease of machineability and manufacturability. ABS offers material benefits such as a low melting point, high tensile strength, impact resistance, good thermal and electrical conductivity, its low cost, and ability to be recycled [1]. While these materials appear to have promising physical capabilities with regards to its strengths when tested in a controlled environment their ability to perform once exposed to weathering effects, like UV rays, is what is being examined.

In an article by P. Davis, it was reported that when ABS pipes were exposed to UV degradation there was an influence on their fracture failure under static loading conditions. These pipes were noted as experiencing brittle behavior after undergoing UV degradation and that much of the degradation was confined to the specimen's surface [6]. In a study conducted by J.B. Adeniyi

where unstabilized ABS that underwent thermal and UV degradation was studied by i.r. spectroscopy found that once the ABS experienced degradation that its properties become essentially the same as those of polybutadiene. They found that during the thermal degradation polymer hydroperoxides were introduced arising from destruction of the PB-unsaturation. These hydroperoxides acted as a catalyst during the UV portion of the experiment. The ABS samples became insoluble which was believed to be due to the formation of cross-linked structures which occurs mostly in the PB segment [7].

A study by L.C. Mendes looked at HDPE samples both with and without additives after 2520 hours of exposure to UV rays. From the experiment it was found that the HDPE non-stabilized samples had a large drop in their impact resistance capabilities after the 2520-hour time period. As well as a drop in the materials ductility capabilities. It was reported that there was a progressive increase in the samples Young's modulus and a reduction in the molecular weight. It was believed that the crystallinity was the main reason for the change in material properties. The stabilized HDPE samples properties remained consistent with their unexposed levels. This suggested that by having the additives it prevented the sampling from experiencing the effects of the UV rays as much as the unstabilized HDPE samples [8]. In another study conducted by Rongzhi Li, degradation tests based on UV, oxidation, water, and heat weathering were done on wood flake reinforced HDPE. From the experiment it was concluded that UV exposure increased the environmental stress cracks in HDPE, but in the controlled dry conditions the UV impacts were lesser [9].

### Hypothesis

The main purpose of this study was to examine the dynamic response of ABS after having experienced 15 days of UV degradation. Impact-Resistant Easy-to-Form ABS sheets were tested using a shock tube. Three specimens for each material were tested at no UV degradation and at 15 days under UV rays using a QUV Accelerated Weathering Tester. In this experiment it is expected that with the UV degradation there will be a decrease in the ABS sample's ability to withstand the 400-psi burst shock wave. It is also expected that the non-UV degraded ABS samples will be able to withstand and absorb the maximum amount of energy from the shock waves in comparison to the UV degraded samples.

## MATERIALS AND METHODS

### Materials

Impact-Resistant Easy-to-Form ABS sheets were used in this experiment. Three non-UV degraded samples of each were tested as well as three samples that had experienced 15 days with of UV degradation. The samples were degraded in a QUV Accelerated Weathering Tester. Both materials offer benefits such as their ability to be 3D printed, ease of manufacturing, and ease of machineability.

ABS offers material benefits such as a low melting point, high tensile strength, impact resistance, good thermal and electrical conductivity, its low cost, and ability to be recycled [1]. ABS is a thermoplastic polymer that is typically used for injection molding. Some of its desirable physical properties include its chemical resistance, its performance in high and low temperatures, strength, stiffness, and it is easy to glue and paint. Some downsides of ABS include how it degrades when exposed to sunlight, its solvent resistance, and hazards it releases into the environment when it is

burned. ABS is commonly used in LEGO bricks, small kitchen appliances, keyboard keycaps, automotive components, protective headgear, and more [10].

**Methods**

The ABS samples were obtained from McMaster-Carr, a private supplier of tooling and materials. The ABS was ordered as a 4 in wide x 4 ft long x 0.25 in thick sheets. These sheets were machined down to a 4 in long x 8 in wide x 0.25 in thick sample using the bandsaw machine in the Machine Shop at the University of Mississippi.

To gain a better understanding of ABS and its material properties 3 samples were placed in the QUV Accelerated Weathering Tester for 15 days with 340nm fluorescent lamps with an irradiance of 0.68 $W/m^2$ for 360 hours [2]. QUV Accelerated Weathering Tester. **Figure 2** shows the QUV Accelerated Weathering Tester which was used to preform accelerated UV damage to the ABS samples for 15 days. **Figure 3** shows the ABS samples loaded into the QUV Accelerated Weather Tester. **Figure 4** shows how the ABS samples were loaded into the QUV Accelerated Weathering Tester. **Figure 5** shows one of the ABS samples after being UV degraded for 15 days.


**Figure 2.** QUV Accelerated Weathering Tester


**Figure 3.** ABS Samples Loaded in QUV Accelerated Weathering Tester

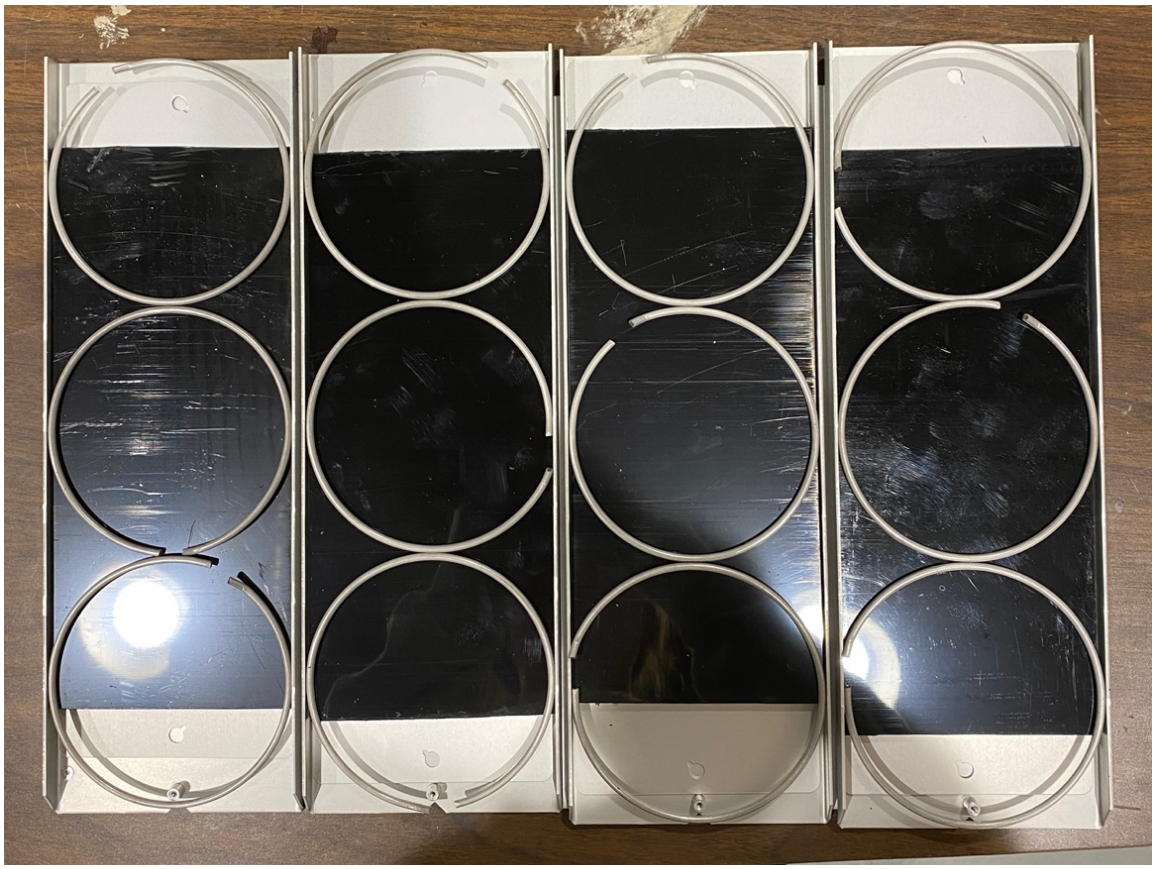

**Figure 4.** ABS Samples Loading Mechanism

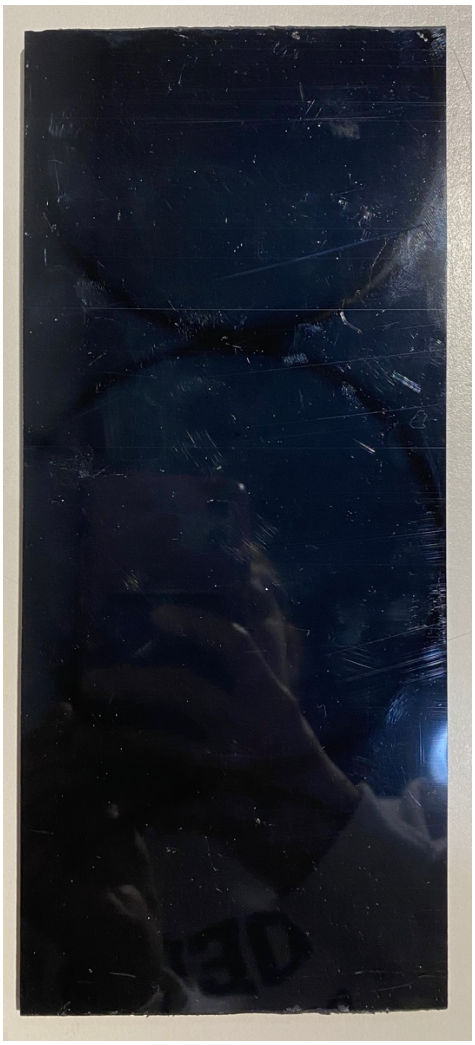

**Figure 5.** ABS Sample after being UV degraded for 15 days

## EXPERIMENTAL SETUP

### Shock Tube

For testing a shock tube made up of a pressure and driver volume section and three high speed valves and an actuating system was used. This setup was used to test the 4 in long x 8 in wide x 0.25 in thick ABS samples in shock loading applications. The shock tube's driver section volume was around 2040 cm^3 of nitrogen gas at 400 psi. **Figure 6** shows the shock tube used for testing. This shock tube was manufactured by Srishti Engineering Innovations PVT. LTD., 2020 [4].

**Figure 6.** Variable Pressure Shock Tube

**Figure 7** shows a diagram of the shock tube including the closed tank experimental mode used in this experiment [4].

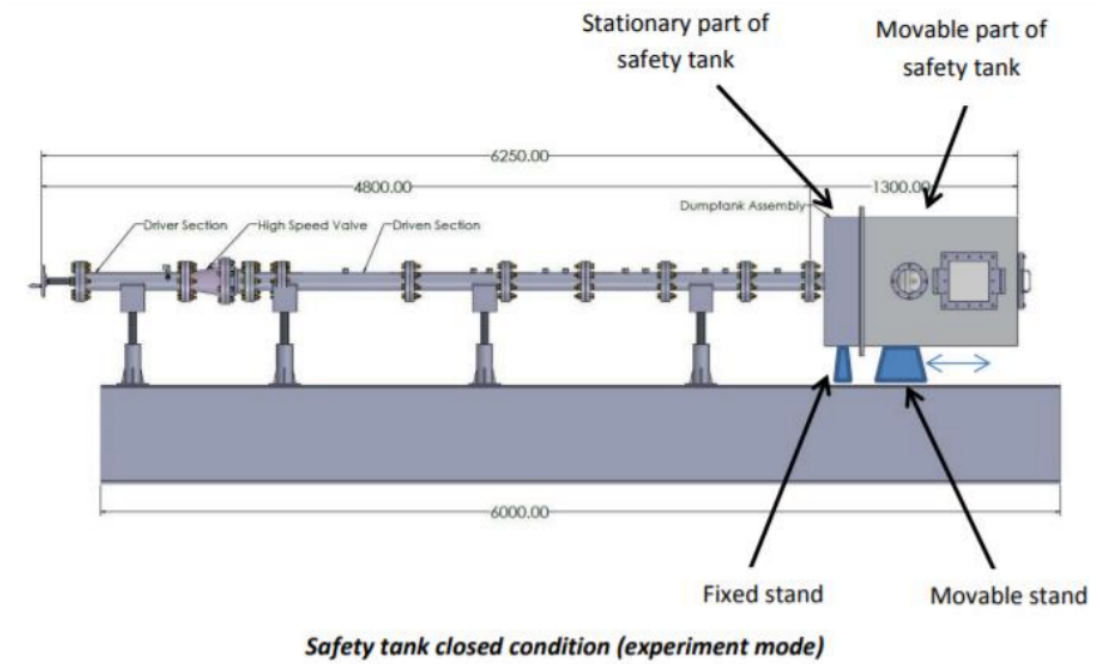


**Figure 7.** Diagram of Shock Tube in Closed Condition Experimental Mode

**Data Acquisition**

To record the data during testing two Kulite HKS-HP-375-5000SG pressure transducers were used to record the incident and reflected shock pressure waves. These pressure transducers had a maximum capacity of 34 MPa. The transducers were 125 mm apart from each other with the transducer closest to the sample being only 6 mm from its front face. The closest pressure transducer was able to capture the pressure reflected from the samples surface. **Figure 8 (a & b)** shows the location of the two pressure transducers in the shock tube [4].

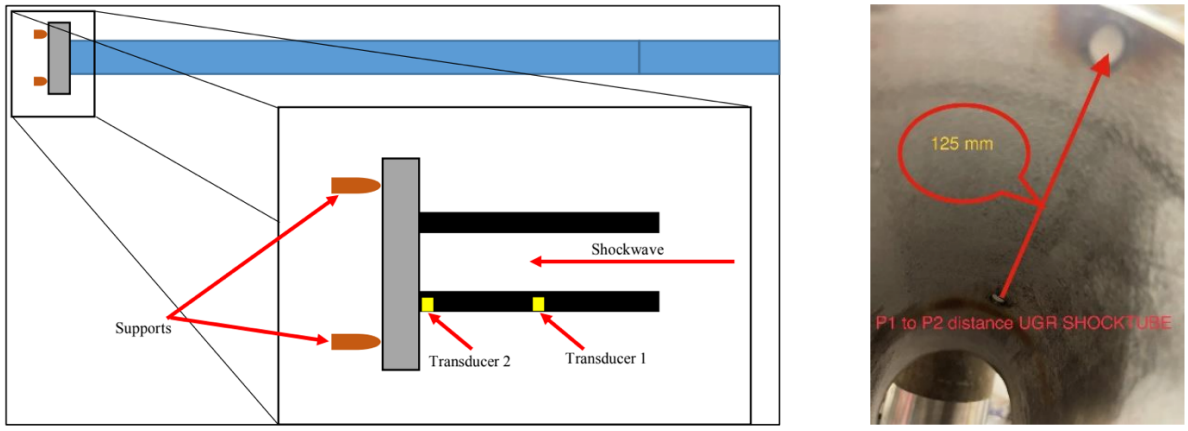


**Figure 8. (a)** Diagram of Transducer Locations **(b)** Shock Tube Transducer Location

The two pressure transducers were connected to a Kulite KSC-2 signal conditioning and amplification system with maintained the signal noise at $\pm$ 5 mv. To ensure increase the signal output at a high enough level for synchronizing the high-speed camera and the data acquisition from the reflected wave pressure the signal pregain was set to 64x and postgain was set to 4x. The transducer excitation and maximum output voltages were set to 5 volts with a 10 kHz filter. The rectangular plate ABS samples were set in a steel specimen holder located inside the safety tank. The holding fixture was designed to allow the specimen to equally overhang the top and bottom to provide sufficient resistance. The fixture had a span of 152.4 mm was used to gather reliable

results that were consistent with other studies [4,5,13]. The fixture was placed so that the ABS samples front surface was touching snuggly the edge of the shock tube barrel without bending the sample. **Figure 9** shows the fixture set up used to hold the samples in the shock tube [4].

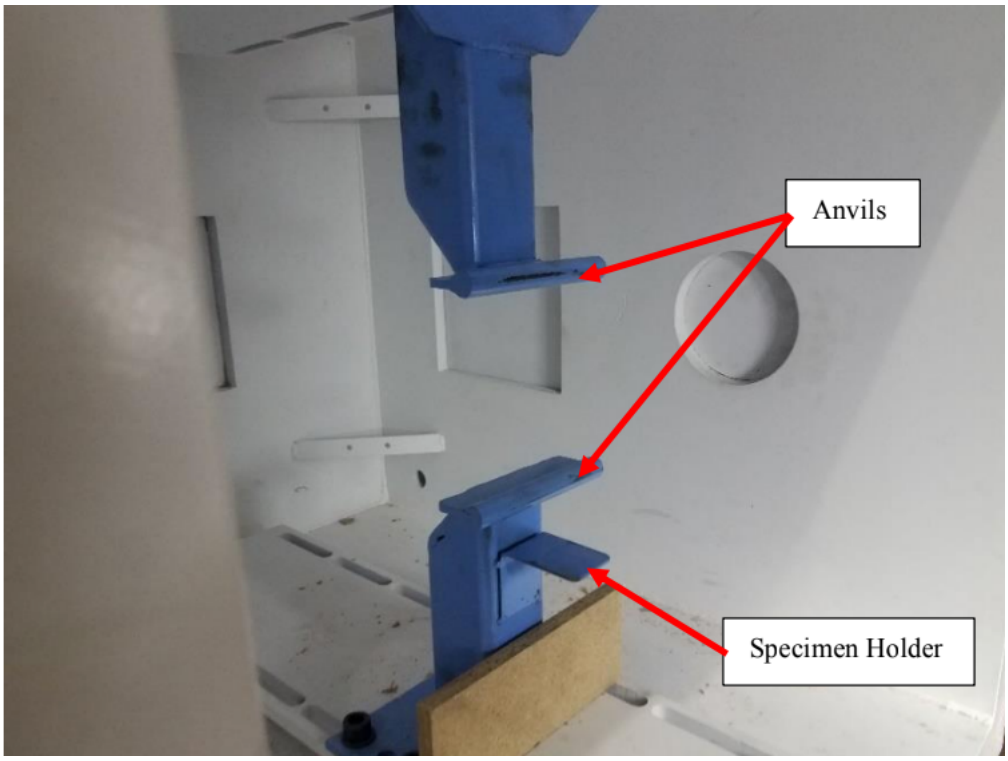


**Figure 9.** Shock Tube Bend Fixture

A Shimadzu HPV-2 high speed camera was used to record and take pictures of the samples deformation at a rate of 16 $\mu$s/frame making it a total capture time of 1.6 ms. The camera resolution was set to 312x260 pixel. By using the high-speed videos with the ProAnalyst software center point deflections could be tracked using the 1D line tracking feature. Digital image correlation was used to get the displacement of the samples during testing. The deformation was recorded for the front and back surface of the samples [4]. **Figure 10** shows the ProAnalyst software using digital image correlation line tracking analysis.

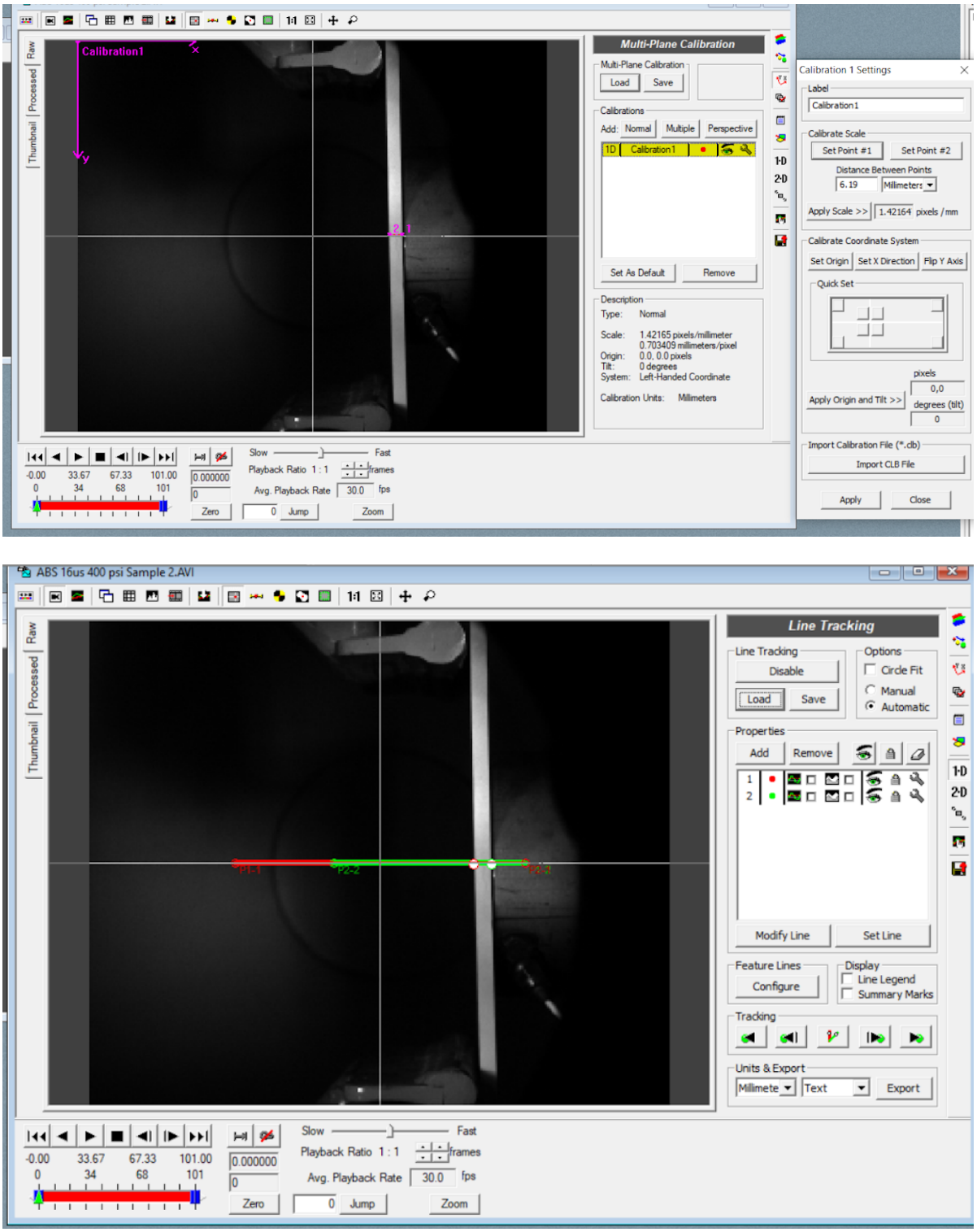


**Figure 10.** ProAnalyst Digital Image Correlation Line Tracking Analysis

**ASTM Standard**

The standard used for testing was the (American Society of Testing and Materials) ASTM G154. For this experiment the condensation portion of this standard was not run. According to the standard the samples were placed in a QUV Accelerated Weathering Tester with 340nm fluorescent lamps with an irradiance of 0.68 $W/m^2$ for 360 hours [2].

## RESULTS AND DISCUSSION

The shock tests were performed using the Shock Tube on three ABS samples that were new and three samples that had experienced advanced UV degradation for 15 days in a QUV Accelerated Weathering Tester. The samples were assessed as simply supported beam specimens. High speed photography using a Shimadzu HPV-2 was used to record failure mechanisms and out-of-plane deformation [4]. Some deformations seen in the ABS beam samples bending deformation and fracturing. **Figure 11** shows the bending deformation failure experienced during testing.

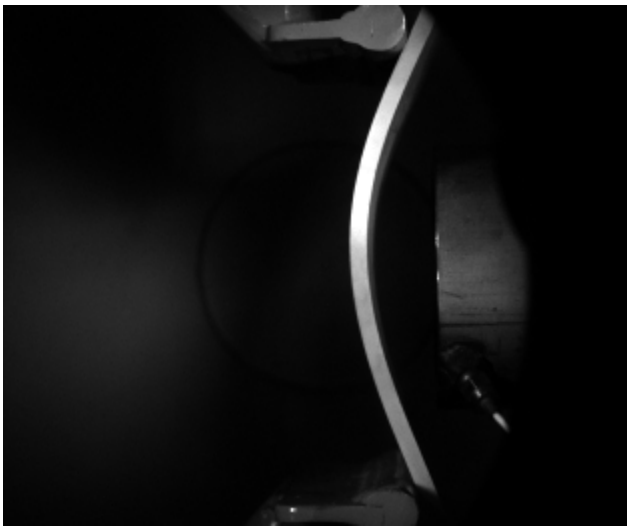

**Figure 11.** ABS Samples During Shock Loading

Overall, the UV damaged samples experienced a decrease in strength and energy absorption in comparison to the non-UV damaged samples. There was some embrittlement present in the UV damaged samples which led to it not deflecting as much as the non-UV samples. This also meant that it took less energy to deflect the UV samples in comparison to the non-UV degraded ABS samples.

**Pressure Profile**

**Figure 12** shows the typical pressure profiles recorded for both non-UV treated ABS and the UV-treated ABS samples. Since the shock tube is a repeatable set up and process there was little variation between results of each test. The reflected pressure waves are what causes a sample to deform. The UV damaged samples displayed a slight drop in performance for how much pressure is rebounding. This correlates to a slightly reduced deformation energy. This analysis is only done for up to 1.6 ms because that is when the camera stopped.

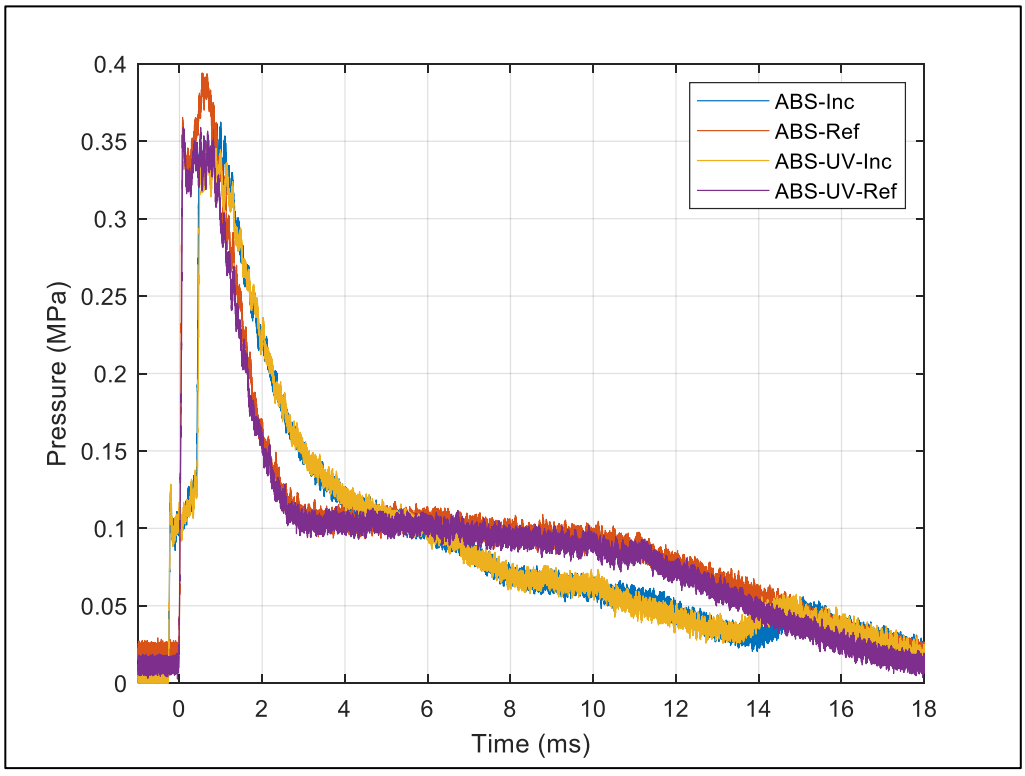

**Figure 12.** UV Treated and Non-UV Treated ABS Samples Pressure Profiles

**Load vs Displacement**

**Figure 13** shows the load vs displacement curve for the non-UV and UV degraded ABS samples. From this figure it can be seen that it takes more force to get the non-UV degraded samples to deflect at the same displacement in comparison to the UV degraded samples.

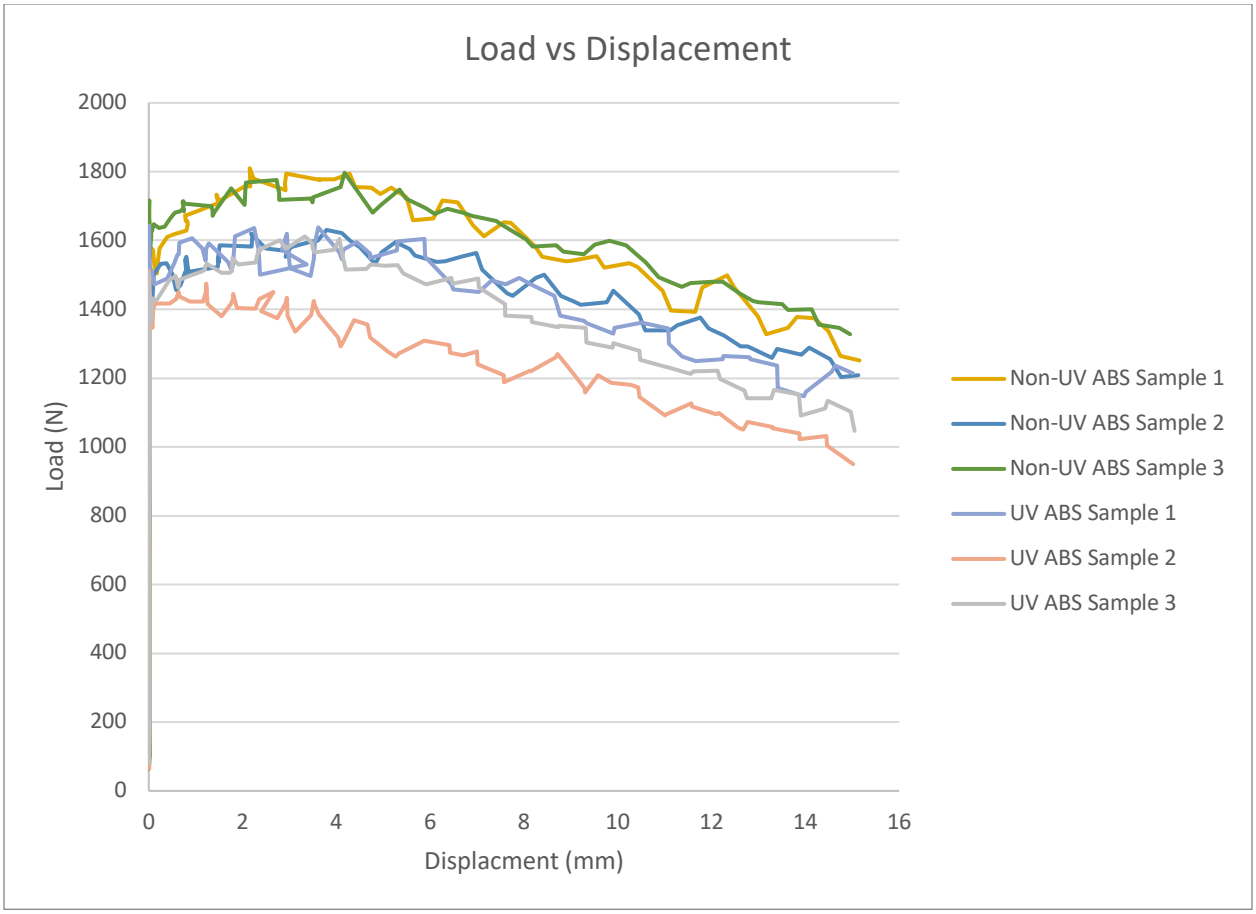


**Figure 13.** Load vs Displacement

**Deformation Energy vs Displacement**

**Figure 14** shows the deformation energy vs displacement curve for the non-UV and UV degraded ABS samples. From this figure it can be concluded that all the UV degraded samples took less energy to deflect at the same amount as the non-UV degraded samples.

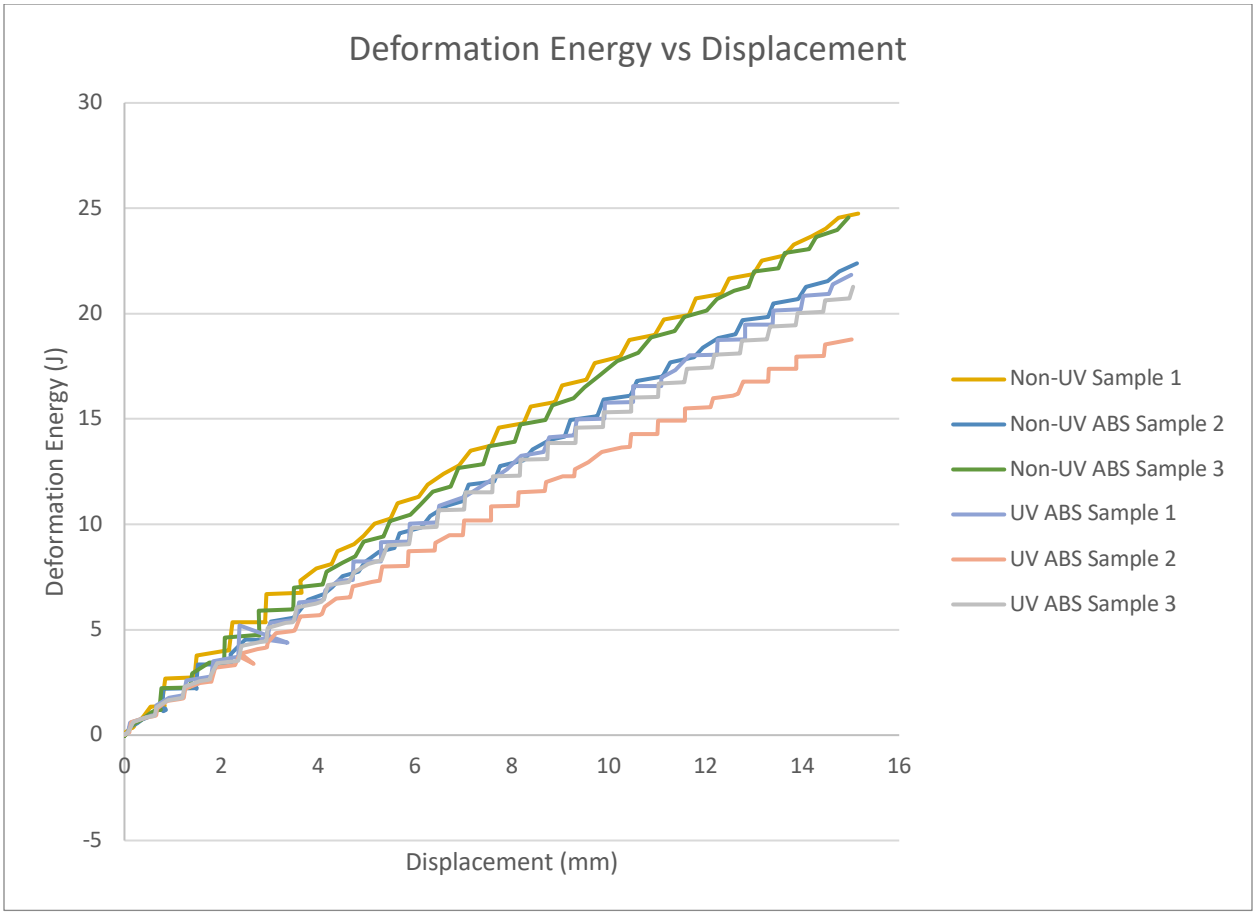


**Figure 14.** Deformation Energy vs Displacement

**Total Deflection**

**Figure 15** shows the total deflection values for the non-UV and UV damaged ABS samples. There was a 15% reduction in the total deformation for the UV damaged samples in comparison to the non-UV damaged samples.

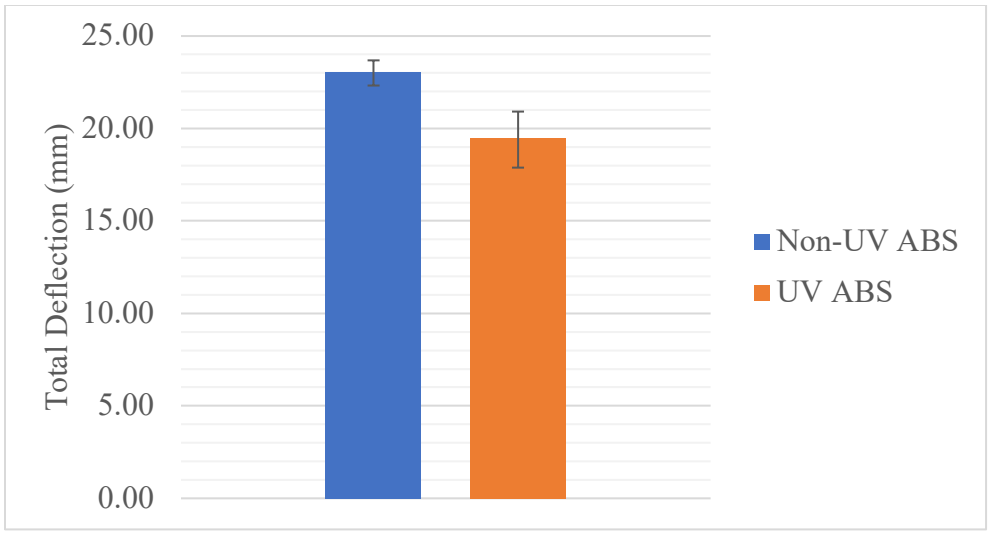


**Figure 15.** Total Deflection

**Specific Energy**

**Figure 16** shows the specific energy values for the non-UV and UV damaged ABS samples. There was a 13% decrease in specific energy for the UV damaged samples in comparison to the non-UV damaged samples.

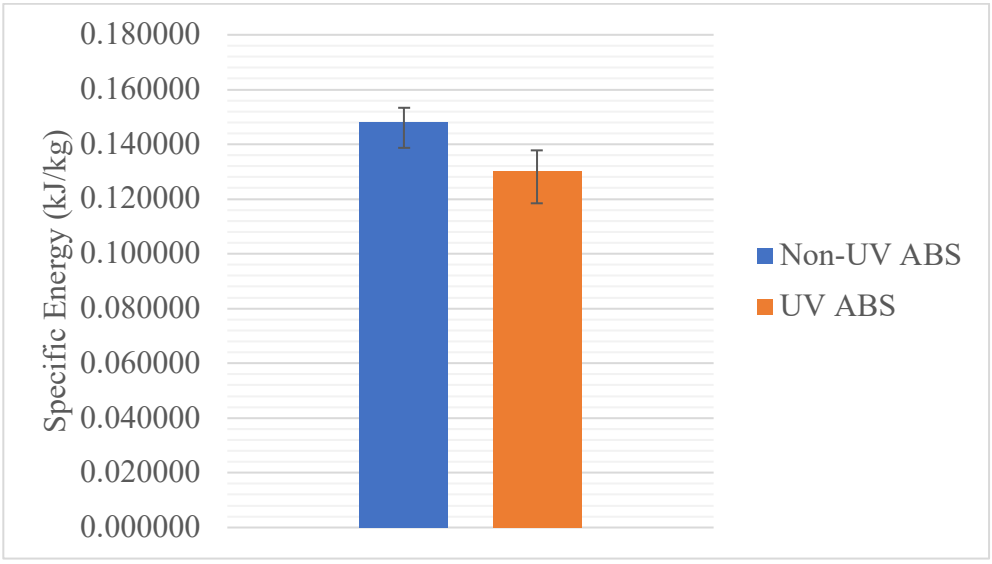


**Figure 16.** Specific Energy

### Acceleration

**Figure 17** shows the acceleration values for the non-UV and UV damaged ABS samples. There was a 12.7% decrease in acceleration for the UV damaged samples in comparison to the non-UV damaged samples which is good regarding force. Besides acceleration the data suggests that the non-UV samples are better for in use. Overall, there was less total deflection, less acceleration, and less specific energy on the UV degraded samples. The whole goal was to quantify how much of a reduction in performance seen between the non-UV and UV degraded samples.

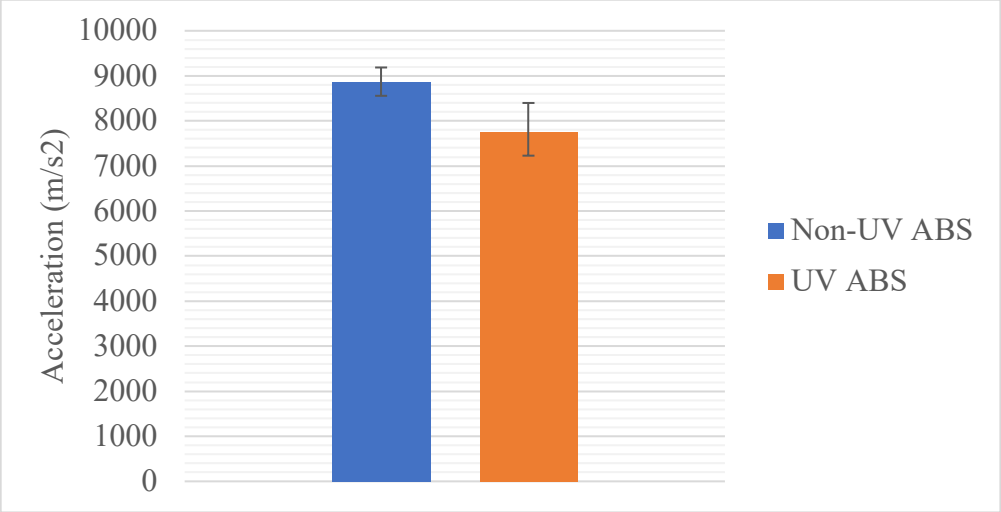


**Figure 17.** Acceleration

## CONCLUSION

Impact-Resistant Easy-to-Form ABS sheets were tested using a Shock Tube. Three samples were tested at no UV light exposure and three were tested after 15 days of being exposed to rapid UV degradation rays. All samples were tested at a shock wave equivalent to 400 psi. The goal was to quantify how much of a reduction of performance was seen between the non-UV and UV degraded samples. The results showed that the UV damaged samples experienced a decrease in strength and

energy absorption in comparison to the non-UV damaged samples. There was some embrittlement present in the UV damaged samples which led to it not wanting to deflect as much as the non-UV samples. This also meant that it took less energy to deflect the UV samples in comparison to the non-UV degraded ABS samples. The average peak load for the non-UV degraded was 1261.89 Newtons and for the UV degraded it was 1069.87 Newtons. The specific energy absorption for the non-UV samples was 0.148 kJ/kg and for the UV degraded samples it was 0.130 kJ/kg. Overall, there was less total deflection, less accelerations, and less specific energy for the UV degraded samples. Besides the acceleration data this experiment suggests that non-UV degraded samples are better for in use.

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