Shock and Vibration Characteristics of a Bio-Inspired Structure Under Blast Loading

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Abstract
This paper will report the findings of a blast load study on a bio-inspired structure. Tests were performed at the Energetic Materials Research and Testing Center (EMRTC) in conjunction with New Mexico Institute of Mining and Technology’s (NMT) Mechanical Engineering Department to characterize an engineered porous structure under shock loading. The structure was subjected to impulsive loads of varying magnitudes produced by the detonation of one-pound hemispheres of C-4. Variables considered in this experiment included the geometry of the structure and the magnitude of the air blast due to varying standoff distances. Experimental data including acceleration, reflected pressure, and structural deflection were collected in the field using accelerometers, pressure gauges, and digital high-speed cameras.

Introduction
- Air Blasts
When an explosive is detonated in air we can consider the characteristics of an ideal blast wave. “Regardless of the source of the initial finite pressure disturbance, the properties of air as a compressible gas will cause the front of this disturbance to become steeper as it passes through the air ("shocks up") until it exhibits nearly discontinuous increases in pressure, density, and temperature. The resulting shock front moves supersonically, faster than sound speed in the air ahead of it. The air particles are also accelerated by the passage of the shock front, producing a net particle velocity in the direction of travel of the front.” [1] Furthermore, when thinking of this pressure disturbance, we must first make a few assumptions about the explosive and air. First, “Assume the explosion occurs in a still, homogenous atmosphere and that the source is spherically symmetric so that the characteristics of the blast wave are functions only of distance from the center of the source R and time t. Let us further assume that an ideal pressure transducer, which offers no resistance to flow behind the shock front and follows perfectly all variations in pressure, records the time history of absolute pressure at some given fixed distance R.” [1] The record of such a gauge would look much like Figure 1.

![Figure 1: Ideal Blast Wave](image)

Where the parameters of Figure 1 are:
\[ P_0 = \text{Ambient Pressure} \]
\[ P_s + P_0 = \text{Peak Pressure} \]
\[ P_o - P_r = \text{Peak Partial Vacuum Pressure} \]
\[ t_a = \text{Arrival Time} \]
\[ t_a + T^+ = \text{Time when Pressure is between Positive Phase and Negative Phase at } P_o \]
\[ t_a + T^+ + T^- = \text{Time at which Pressure returns to } P_o \]

And where the positive impulse of the blast wave is defined by:

\[ \int_{t_a}^{t_a + T^+} [p(t) - p_o] \, dt \quad (1)[1] \]

The most significant parameters for use in data reduction of air blasts include peak incident overpressure, peak reflected pressure, arrival time, positive phase duration, distance from charge, incident impulse, and reflected impulse. Vast amounts of data have been collected over the years on air blast parameters from TNT spherical air burst and hemispherical surface bursts and are reported in Reference [2]. Figure 2, shows eight different parameters plotted on a single graph that represents data acquired from multiple tests of one-pound TNT hemispherical ground bursts at many different distances.

![Figure 2: Air Blast Parameters vs. Distance for a One Pound Mass TNT Hemispherical Ground Burst [2]](image)

Where the parameters of Figure 2 are:
- \( P_r \) = Reflected Pressure (psi)
- \( P_{so} \) = Incident Peak Overpressure (psi)
- \( I_r \) = Reflected Impulse (psi-msec)
- \( I_s \) = Incident Impulse (psi-msec)
- \( T_o \) = Positive Phase Duration (msec)
- \( U \) = Shock Front Velocity (ft/msec)
- \( t_a \) = Arrival Time (msec)

Explosives detonated on or near the ground can also influence blast waves. A charge detonated on the ground will consist only of the ground reflected wave (Figure 3). These blast waves from large energy sources detonated above, but near, the ground can be considerably modified by certain ground effects such as the reflection off the ground where the fusion of the incident and reflected shock fronts form a third shock front known...
as a Mach stem, which Figure 4 shows in detail. A few other significant variables that come into play are: 1) charge geometry, charge size, and charge confinement, 2) atmospheric conditions, and 3) the effects of after burn due to the oxygen balance of an explosive [3]. All these variables are explained in great detail in References [1], [2], [4], and [5].

Where the parameters of Figure 4 are:

- $H$ = Height of Burst
- $R$ = Slant Distance
- $l$ = Incident Shock Wave
- $\alpha$ = Angle of the Incident Shock Wave with Respect to the Horizontal
- $P_T$ = Path of Triple Point
- $M$ = Mach Wave (Mach Stem), Mach Front
- $H_T$ = Height of Triple Point
- $R_G$ = Ground Distance to Object

-TNT Equivalency

Traditionally, all explosives have their power output compared to that of TNT, because of TNT’s long history in military applications and the tremendous body of knowledge relating to its “ideal” explosive properties. This comparison is referred to as “TNT equivalency”. TNT equivalency is one of the prime tools utilized to judge the work output of a non-ideal explosive [6]. TNT equivalency is simply defined as the mass of TNT needed to replicate an effect produced by a given explosive, divided by the mass of the explosive tested. An example being, two pounds of explosive “X” was needed to do the work of one pound of TNT, so the TNT equivalency of explosive “X” would be 1 lb / 2 lb = 50% [7]. TNT equivalency is based on explosive energy in various ways. The preferred method of calculation is to use either the hydrodynamic or the thermodynamic work function, as shown in Reference [8]. TNT weight equivalence is defined as:

$$wt(\text{TNT equiv}) = wt(\text{HE}) \times \left(\frac{E_{\text{EXP}}(\text{HE})}{E_{\text{EXP}}(\text{TNT})}\right)$$

(2)[8]
Where,

- \( wt\ (HE) \) = Weight of Questioned Explosive
- \( E_{\text{EXP}}(HE) \) = Explosive Energy of Questioned Explosive
- \( E_{\text{EXP}}(\text{TNT}) \) = Explosive Energy of TNT

**NOTE:** Some values for \( E_{\text{EXP}}(HE) / E_{\text{EXP}}(\text{TNT}) \) can be found in References 2 and 9.

Other methods for estimating TNT equivalence are based either on correlation, empirical tests, or chemical composition. Some empirical tests include Air Blast, Trauzl, Ballistic Mortar, Sand Crush, and Plate Dent [1, 6]. The values used in the calculations in this report were based off C-4 air blast pressure data that was compared to TNT air blast pressure data at the same distances. These comparisons give a first order approximation of the non-ideal explosives TNT equivalencies, which will be discussed in detail in the results section of this report. One more simplified version of TNT equivalence is reported in Reference [8] as being:

\[
\text{TNT equivalent} = \frac{D^2}{D_{\text{TNT}}^2}
\]

(3) [8]

Where,

- \( D \) = Detonation Velocity (km/s) of the Explosive in Question
- \( D_{\text{TNT}} \) = Detonation Velocity (km/s) of TNT @ 1.64 g/cm\(^3\) = 6.95 km/s

For C4 this calculation would produce values equal to:

\[
\text{C-4 (TNT equivalency)} = \frac{8.193^2}{6.95^2} = 1.39
\]

**Sample Construction**

The main objective of this testing was to compare the properties of different shapes of Poron® foam with and without water introduced into the foam’s pores during explosive loading. We were hoping to find that a foam sample with a domed shape and filled with water would perform better under an explosive load. We theorized at the beginning of this project that the flat fluid filled samples would have the least amount of deflection during the testing, but that the fluid filled domed shaped sample would take the highest explosive load before failure.

Before the explosive testing could be completed the samples had to be constructed. Four different samples of the same black polymer based Poron® foam were constructed. The four samples constructed were:

1) dry and flat with the faces coated with Lexel,
2) filled with water, flat, and coated with Lexel,
3) dry and dome shaped with the faces coated with Lexel,
4) filled with water, dome shaped, and coated with Lexel.

The foam used in the samples was a \( \frac{1}{2} \) in thick and 8 in square black Poron® Quick Recovery Polyurethane Foam (Figure 5).

![Figure 5: Sheet of \( \frac{1}{2} \) in Poron® Quick Recovery Polyurethane Foam](image)

This foam displays a 4-8 psi compression at 25% deflection. It has a density of 15 lb/ft\(^3\), a minimum tensile strength of 40 psi at 0.2 in/min strain rate, and a useful temperature range of -40°F to 250°F.

Lexel is a type of caulk/glue that was spreadable, adhesive, and stretchy enough after setting (~25% stretch) to be used in this experiment. Lexel also bonds to plastics and will even bond if the material is wet, which was useful for our application (Figure 6). Another added bonus is that Lexel dries clear so that the foam sealed in the Lexel can be observed. One downside to the Lexel is that it takes 30 minutes to become tack free, cures firm in 2-4 days, and it only fully cures after 1-2 weeks.

![Figure 6: Lexel](image)
8in square, ½in thick polyurethane rings, with a 6 ¼ in hole in the middle (Figure 7) were manufactured by the machine shop in Workman Hall on campus.

![Figure 7: Polyurethane Ring](image_url)

These rings were used as a mounting and reinforcement for the different samples during testing. The foam left exposed in the open space of the ring was the portion of the sample that underwent the testing. The flat dry sample was the easiest to manufacture (Figure 8).

![Figure 8: Flat Sample](image_url)

The 8 in square foam piece was placed on a table and the top face was then coated with a thin layer of Lexel. The Lexel became tack-free in 30 minutes and cured firm in 2 days. After waiting the 2 days a thin sheet of plastic was put on the table and coated with chalk to ensure that the Lexel from the top side of the foam would not bond with the plastic sheet. The sample was then turned over with the Lexel coated side on the chalk covered plastic sheet. The bottom side of the foam was then coated with Lexel and the polyurethane ring was then placed on top of freshly coated Lexel side. This was done so that there would not have to be the separate step of gluing the ring to the sample after the Lexel dried 2 days later, saving time in the process. With 2 days cure time the samples were ready to test.

A ¼ in thick, 10in square piece of steel was then laid in the water with a same sized piece of plastic sheet on top. The foam was then placed on top of the plastic sheet. An approximately 100 lb steel cylinder (Figure 10) was then placed on the foam.
This cylinder was rolled back and forth over the foam sample to remove the air from the sample and fill it with water. After the foam was rolled over approximately 20 times with the cylinder it was removed and weighed to compare its wet weight to its dry weight. Each sample gained about 2 ½ times its original weight after being filled.

The foam was porous enough that water could be put inside it but the pores were also small enough to keep the water from flowing out at a high rate after the water was inside the foam and the foam was removed from the pan.

The sample was then placed on a sheet of plastic and patted dry around the top and edges with paper towels. The samples never fully dried on the outside, but they dried enough for the Lexel to bond to and seal the sample. Lexel was then spread on the top and sides of the sample. A thicker bead of Lexel was used along the edges of the samples to ensure that the sides were sealed. The samples were then left for 3 days while the Lexel cured. It was decided that the wet samples should cure a day longer than the dry samples due to the possible lengthening effect of the present water on the Lexels cure time.

The samples Lexel seals were then examined. Samples that appeared to need added sealing were touched up after the initial 3 day cure time and allowed to cure for an additional 2 days. The sealed samples were then turned over and the plastic sheet was cut off leaving as much of the Lexel side seals intact as possible. The last side of the samples was then sealed with Lexel (Figure 11) and the polyurethane ring was placed on top.

This was once again done to combine the last stage of sealing the sample and gluing the ring to the sample into the same step to save time. With 3 days of cure time the samples were ready to test.

The curved dry samples were first sealed flat like the flat dry samples. Creating and holding a dome shape in the samples without ripping or separating the Lexel seal from the foam was now the problem to overcome.

It was decided that the dry samples should be experimented on first to ensure that the wet samples kept their water until the dome creating technique was perfected. A plastic salad mixer with an approximate 7 in diameter hemispherical top was purchased. This top was the best sized dome shape that was found for this application (Figure 12).

There was an aluminum ring covered in tape and chalk with a 6 ½ in inside diameter that was made by the on campus machine shop that also played a role in this fabrication (Figure 13).
A 7in gear with a 3in inside diameter hole (Figure 14) was also used.

The aluminum ring, 2 of the plastic mounting rings, the gear, the salad mixer top, 4 clamps, tape, chalk, a hair dryer (Figure 15), and Loctite Power Grab Adhesive (Figure 16) all played a part in the fabrication of the domed samples.

The dome shaped salad mixer lid was placed on the table and covered with chalk dust to ensure that the sample did not stick to the lid. This prevented the Lexel from delaminating from the foam. The aluminum ring and the gear were used to prevent the brittle plastic rings from breaking due to bending during clamping. Clamping was needed to ensure that the sample stay in shape while the adhesive cured. The aluminum ring was covered with a tape and chalk dust to prevent sticking to the Lexel during clamping. The aluminum ring was then placed on the dome shaped lid. The first plastic mounting ring was used to mount the foam to its bottom side with the Loctite Power Grab.

The gear and second plastic ring were not placed on top of the first plastic ring during the first trial fabrication. This resulted in the ring breaking in half during the clamping process. Once this was observed it was decided that a rigid ring was also needed for the top, in addition to the aluminum ring on the bottom, of the sample during clamping to ensure that the rings did not bend to failure. The second plastic ring was incorporated to make sure there was enough room between the foam and the gear to create a dome shape.

Once this assembly was laid together like a sandwich one person pushed down on the sample to create the dome shape from the salad mixer top below. The other person then clamped the aluminum ring and gear on opposite edges of the sample. This ensured that the adhesive would set before the sample moved.

While allowed to sit on top of the salad mixer, the foam was heated with a hair dryer to soften the material enough to get even more of the desired dome shape. Once the sample was heated it was allowed to sit on the mixer top clamped over night and cool to room temperature (Figure 17).
This allowed the foam to stretch enough and cool enough from the heating to keep its shape. The next day the sample was unclamped and set aside (Figure 18) to make room for more sample fabrication.

Before the fabrication of this sample, a \(\frac{1}{4}\) in sample of dry foam was experimented on by heating while in the dome shape to see if it would keep its form after it was unloaded and allowed to cool. It kept its shape for approximately 3 weeks, so it seemed that heating to shape was a good tactic.

The curved wet samples were first sealed flat like the flat wet samples. They were also formed into shape the same way the dry dome shaped samples were formed. There was, however, a problem encountered during this forming. When the sealed wet samples were pushed onto the dome and clamped between the gear and the aluminum ring some of the water inside of the samples was pushed out at a slow drip-like rate through small gaps in the Lexel that were overlooked when the samples were first sealed. The samples that lost water had to be submerged in water for 2 days to regain their water weight and then carefully gone over with Lexel to seal up any noticeable gaps in the original Lexel seal. The samples then had to cure for another 2-3 days. Once all of this was done the samples were once again ready to shape into form. Once formed, the dome shaped wet samples posed another problem. They would only keep their dome shape for a short amount of time; approximately \(\frac{1}{2}\) hour (Figure 19).

It was theorized that this was due to the added water weight of the foam and a possible softening effect that the water may have on the foam. If the sample lost its shape it would have to be formed again and let to sit over night. This had to be done the night before testing to ensure that the sample would hold its shape, and the sample was taken out of the forming setup as close to testing as possible. To manufacture all 4 samples took about 2 weeks due to cure time of the Lexel and adhesive, and the time required to get the desired dome shape out of the samples.

**Sample Water Absorption**

The data sheet for the polyurethane foam that was used stated that the sheets of foam had a density of 15 lb/ft\(^3\) ~ 240.28 kg/m\(^3\). Each sample was \(\frac{1}{2}\) in thick and 8 in by 8 in square ~ 0.000524 m\(^3\). This should have given the dry samples a mass of \(\sim 126\) g. Water has a density of 1000 kg/m\(^3\). The sample material was previously determined to be 80% porous by Pablo Garibay and Holly Chamberlin. Therefore the wet samples, if fully saturated with water, should have had a mass of approximately 545 g. The mass of the samples with and without the introduction of water are listed in Table 1:

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Mass (g) Dry</th>
<th>Mass (g) Saturated With Water</th>
<th>% Void Volume Filled for 80% Porosity</th>
<th>% Void Volume Filled with Air For 80% Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dry</td>
<td>131</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2 Dry</td>
<td>139</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3 Wet</td>
<td>136</td>
<td>346</td>
<td>52.5</td>
<td>47.5</td>
</tr>
<tr>
<td>4 Wet</td>
<td>128</td>
<td>352</td>
<td>53.9</td>
<td>46.1</td>
</tr>
</tbody>
</table>

Table 1: Volume of Pores Filled in Sample Foam

If the pores were mostly saturated with water I would assume that the foam had an approximate porosity of 50%. This discrepancy was due to using cold instead of hot water during the fluid filling process. The warmer water would have opened the pores more and allowed more water to fill the voids. The cold water actually closed off the pores more and allowed less water into the samples.
EMRTC Test Description

- Instrumentation

Pressure and impulse data was collected on all 6 tests by means of PCB™ piezoelectric transducers and a corresponding PCB™ 855 gauge power amplifier. The amplifier used managed the reflected pressure measurements for each experiment. Reflected pressure gauges were mounted in the stand, at locations shown in Figure 20.

![Figure 20: Placement of Reflected Pressure Gauges on Stand.](image)

Accelerometers were attached to the back of the samples (Figure 21).

![Figure 21: Attached Accelerometer](image)

Phantom high speed cameras (Figure 22) on either side of the test set up were also used to measure the displacement of the samples and to have data to compare to the accelerometer data.

![Figure 22: Phantom High Speed Cameras on Either Side of the Test Stand](image)

This was done to determine the validity and approximate error of the accelerometer data. 1 in lines were drawn onto toothpicks glued next to the accelerometers (Figure 23). This mark was made as a reference point to determine the displacement of the samples during testing from the phantom high speed cameras.

![Figure 23: Toothpick Mark](image)

The wet samples were placed in the south opening of the test stand and the dry samples were placed in the north opening of the stand to keep track of sample data (Figure 24).
Figure 24: North and South of Test Stand

6 tests were conducted. The flat dry and flat wet samples were hit with a blast wave from a 1 lb hemispherical charge of C-4 set at 45, 35, and 25 ft (each distance was a separate test). The accelerometer separated from the dry sample during the 35 ft test (Figure 25).

Figure 25: Separated Accelerometer Flat 35 ft Test

It stayed attached, according to the displacement plot, long enough to record the initial acceleration and displacement. It was reattached and stayed attached during the 25 ft test.

The dome shaped dry and wet samples were also hit with a blast from a 1 lb hemispherical charge of C-4, but the distances changed to 45, 25, and 15 ft to push the limits of the accelerometers delaminating from the samples. The accelerometer slightly delaminated from the wet dome shaped sample during the 25 ft test. This may have led to some error in the data. Both accelerometers separated from the samples during the 15 ft test (Figure 26) showing a need for better adhesion to the samples in the future if close blast tests are to be performed.

Figure 26: Separated Accelerometers Domed 15 ft Test

EMRTC Data Reduction

EMRTC's raw data was reduced using DPlot software. The pressure traces were used to determine the peak pressures and were integrated to find the positive phase peak impulses. The acceleration traces were used to determine the peak accelerations in the positive direction (blast direction), and they were double integrated to generate the maximum positive displacements. The maximum positive displacements were also collected from the Phantom 7 software and are reported in table 2. Figure 27 shows an example of the EMRTC data plot for reflected pressure.
Results

Table 2 is a list of the face reflected pressures and displacement of the 4 different samples during the explosive testing.

<table>
<thead>
<tr>
<th>Test</th>
<th>Displacement (in)</th>
<th>Displacement (in)</th>
<th>Displacement (in)</th>
<th>Displacement (in)</th>
<th>Reflected pressure (psi)</th>
<th>Reflected pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acc. 1 Wet (South)</td>
<td>Acc. 2 Dry (North)</td>
<td>Phantom 1 Wet (South)</td>
<td>Phantom 2 Dry (North)</td>
<td>PR 1</td>
<td>PR 2</td>
</tr>
<tr>
<td>Test 1</td>
<td>0.131</td>
<td>0.14</td>
<td>0.144</td>
<td>0.148</td>
<td>2.97</td>
<td>2.85</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.203</td>
<td>0.234</td>
<td>0.219</td>
<td>0.242</td>
<td>4.63</td>
<td>4.77</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.304</td>
<td>0.353</td>
<td>0.342</td>
<td>0.352</td>
<td>7.2</td>
<td>6.85</td>
</tr>
<tr>
<td>Test 4</td>
<td>0.138</td>
<td>0.146</td>
<td>0.131</td>
<td>0.147</td>
<td>2.99</td>
<td>2.82</td>
</tr>
<tr>
<td>Test 5</td>
<td>0.306</td>
<td>0.321</td>
<td>0.325</td>
<td>0.313</td>
<td>6.67</td>
<td>7.43</td>
</tr>
<tr>
<td>Test 6</td>
<td>1.28</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Clipped</td>
<td>Clipped</td>
</tr>
</tbody>
</table>

Table 2: Displacement and Reflected Pressure Experimental Results (Plotted in Appendix A)

The reflected pressure difference from the top and the bottom of the stand was negligible for all of the 6 tests and can be explained as the error in the pressure sensors themselves.

It was hypothesized that the wet samples would deflect less and exhibit less acceleration than the dry samples due to the added mass of the water. Table 2 shows that the wet samples deflected less than the dry samples except for the phantom data for test number 5. This discrepancy may have been due to some slight delaminating of the accelerometer on the wet sample during test number 4.

No data was gathered from test number 6 due to the total separation of the accelerometers from the samples during loading. A better adhesive will have to be used in the future to prevent this from happening at ranges less than 15 ft. Although during test number 2, the accelerometer totally delaminated from the dry sample during loading. This was due to inadequate application of the adhesive between the accelerometer holder and the Lexel surrounding the foam sample. This was corrected before test number 3 was conducted with a stronger epoxy.

Table 3 shows that the wet samples exhibited close to half the initial forward and reverse acceleration as the dry samples. This makes sense due to the added mass of water in the wet samples.

<table>
<thead>
<tr>
<th>Test</th>
<th>Distance (ft)</th>
<th>G’s Wet</th>
<th>G’s Dry</th>
<th>Impulse 1 (psi s)</th>
<th>Impulse 2 (psi s)</th>
<th>Avg Impulse (psi s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>117.47</td>
<td>212.3</td>
<td>2.75E-03</td>
<td>2.70E-03</td>
<td>0.002724</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>183.7</td>
<td>296</td>
<td>3.58E-03</td>
<td>3.89E-03</td>
<td>0.003738</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>298.51</td>
<td>442.32</td>
<td>5.23E-03</td>
<td>5.46E-03</td>
<td>0.005345</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>162.43</td>
<td>222.68</td>
<td>2.90E-03</td>
<td>2.74E-03</td>
<td>0.002819</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>380.75</td>
<td>593.64</td>
<td>5.27E-03</td>
<td>5.43E-03</td>
<td>0.0053495</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>850.6</td>
<td>1212.44</td>
<td>9.53E-03</td>
<td>9.74E-03</td>
<td>0.009635</td>
</tr>
</tbody>
</table>

Table 3: Impulsive Loading and Initial G’s of the Samples Experimental Results (Plotted in Appendix B and C)
Table 3 also lists the initial impulses (lb*s) during the tests calculated by integrating the reflected pressure curves from the pressure sensors on the test set up. This data was used to calculate the impulse velocity (s) with the equation:

\[ V = \frac{I}{\rho H} \]  

(4)[10]

\( V \) = Impulse Velocity (s)  
\( \rho \) = Material Density (lb/in\(^3\))  
\( H \) = Sample Thickness.

The impulse velocities are listed in Table 4 below:

<table>
<thead>
<tr>
<th>Test</th>
<th>Impulse Velocity Wet (s)</th>
<th>Impulse Velocity Dry (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.2937</td>
<td>20.2103</td>
</tr>
<tr>
<td>2</td>
<td>11.3811</td>
<td>27.7335</td>
</tr>
<tr>
<td>3</td>
<td>16.2739</td>
<td>39.6564</td>
</tr>
<tr>
<td>4</td>
<td>8.5830</td>
<td>20.9151</td>
</tr>
<tr>
<td>5</td>
<td>16.2876</td>
<td>39.6898</td>
</tr>
<tr>
<td>6</td>
<td>29.3356</td>
<td>71.4854</td>
</tr>
</tbody>
</table>

Table 4: Impulse Velocities

These values were needed in order to calculate a theoretical displacement of the samples to compare to the experimental values.

Next the plastic collapse moment of the samples had to be calculated from the equation.

\[ M_o = \frac{\sigma_o H^2}{4} \]  

(5)[10]

\( M_o \) = Plastic Collapse Moment  
\( \sigma_o \) = Material Yield Stress

The approximate material yield stress at the high impulse loading rates of the dry and wet samples were back calculated from the following equations as 1750 psi for the dry samples and 800 psi for the wet samples.

The non dimensional initial kinetic energy (Table 5) was calculated from the following equation:

\[ \lambda = \frac{\mu V^2 R^2}{M_o H} \]  

(6)[10]

\( \lambda \) = Non-Dimensional Initial Kinetic Energy  
\( \mu \) = Mass Per Unit Area (slugs/in\(^2\))

<table>
<thead>
<tr>
<th>Test</th>
<th>Non Dimensional Initial Kinetic Energy Wet</th>
<th>Non Dimensional Initial Kinetic Energy Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8238</td>
<td>4.0961</td>
</tr>
<tr>
<td>2</td>
<td>3.4345</td>
<td>7.7133</td>
</tr>
<tr>
<td>3</td>
<td>7.0223</td>
<td>15.7711</td>
</tr>
<tr>
<td>4</td>
<td>1.9533</td>
<td>4.3868</td>
</tr>
<tr>
<td>5</td>
<td>7.0341</td>
<td>15.7976</td>
</tr>
<tr>
<td>6</td>
<td>22.8186</td>
<td>51.2472</td>
</tr>
</tbody>
</table>

Table 5: Initial Kinetic Energy
The initial theoretical displacement (Table 6) was then calculated from:

\[ W_f = \frac{H(0.84)\lambda}{12} \]  

(7)[10]

\( W_f \) = Maximum Initial Displacement of the Center Point of the Sample Face

<table>
<thead>
<tr>
<th>Test</th>
<th>Initial Theoretical Displacement Wet (in)</th>
<th>Initial Theoretical Displacement Dry (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0638</td>
<td>0.1433</td>
</tr>
<tr>
<td>2</td>
<td>0.1202</td>
<td>0.2699</td>
</tr>
<tr>
<td>3</td>
<td>0.2457</td>
<td>0.5519</td>
</tr>
<tr>
<td>4</td>
<td>0.0683</td>
<td>0.1535</td>
</tr>
<tr>
<td>5</td>
<td>0.2461</td>
<td>0.5529</td>
</tr>
<tr>
<td>6</td>
<td>0.7986</td>
<td>1.7936</td>
</tr>
</tbody>
</table>

Table 6: Theoretical Maximum Displacement

Tables 5 and 6 assume a yield stresses of 1.4 psi for the samples at the high impulsive velocities in Table 4.

<table>
<thead>
<tr>
<th>Mass/Unit Area (slug/in(^2))</th>
<th>Test 1 Deflection (in)</th>
<th>Test 2 Deflection (in)</th>
<th>Test 3 Deflection (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Dry</td>
<td>1.12E-05</td>
<td>0.14</td>
<td>0.234</td>
</tr>
<tr>
<td>Experimental Wet</td>
<td>2.97E-05</td>
<td>0.131</td>
<td>0.203</td>
</tr>
<tr>
<td>Theoretical Dry</td>
<td>1.12E-05</td>
<td>0.1434</td>
<td>0.27</td>
</tr>
<tr>
<td>Theoretical Wet</td>
<td>2.97E-05</td>
<td>0.0638</td>
<td>0.1202</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass/Unit Area (slug/in(^2))</th>
<th>Test 4 Deflection (in)</th>
<th>Test 5 Deflection (in)</th>
<th>Test 6 Deflection (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Dry</td>
<td>1.12E-05</td>
<td>0.146</td>
<td>0.321</td>
</tr>
<tr>
<td>Experimental Wet</td>
<td>2.97E-05</td>
<td>0.138</td>
<td>0.306</td>
</tr>
<tr>
<td>Theoretical Dry</td>
<td>1.12E-05</td>
<td>0.1535</td>
<td>0.5529</td>
</tr>
<tr>
<td>Theoretical Wet</td>
<td>2.97E-05</td>
<td>0.0684</td>
<td>0.2462</td>
</tr>
</tbody>
</table>

Table 7: Experimental and Theoretical Deflections Compared

The data in Table 7 is plotted out for each test in the next six graphs. It can be seen that using a yield of 1.4 psi for the dry samples gives a close comparative theoretical displacement to the experimental values but not as close for the wet samples. Figures 28-33 plot the theoretical and experimental displacements of the samples vs. the mass of the samples.

Figure 28: Test 1 Theoretical vs. Experimental Displacement
Test 2 Experimental vs. Theoretical Deflection

![Figure 29: Test 2 Theoretical vs. Experimental Displacement](image)

Test 3 Experimental vs. Theoretical Deflection

![Figure 30: Test 3 Theoretical vs. Experimental Displacement](image)

Test 4 Experimental vs. Theoretical Deflection

![Figure 31: Test 4 Theoretical vs. Experimental Displacement](image)

Test 5 Experimental vs. Theoretical Deflection

![Figure 32: Test 5 Theoretical vs. Experimental Displacement](image)
To have the wet samples theoretical deflection come close to the experimental values the wet samples would have to exhibit a yield at approximately 0.85 psi. This would give theoretical displacements of:

Table 8: Theoretical Deflections at 0.85 psi Yield Stress

<table>
<thead>
<tr>
<th>Test</th>
<th>Initial Theoretical Displacement Wet (in)</th>
<th>Initial Theoretical Displacement Dry (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1051</td>
<td>0.2361</td>
</tr>
<tr>
<td>2</td>
<td>0.1979</td>
<td>0.4446</td>
</tr>
<tr>
<td>3</td>
<td>0.4048</td>
<td>0.9091</td>
</tr>
<tr>
<td>4</td>
<td>0.1126</td>
<td>0.2528</td>
</tr>
<tr>
<td>5</td>
<td>0.4054</td>
<td>0.9106</td>
</tr>
<tr>
<td>6</td>
<td>1.3154</td>
<td>2.9542</td>
</tr>
</tbody>
</table>

Conclusion
We expected that the dry samples would have the most amount of deflection due to having less mass than the wet samples and therefore exhibiting more initial acceleration to accommodate the same amount of load as the wet samples. Table 7 shows that the experimental and theoretical data agreed with this assumption except for the camera data from test 5 (Table 2). This error was due to a slight delaminating of the accelerometer from the wet sample during test number 4.

We expected the dome shaped samples to deflect more than the flat samples due to more surface area exposed to the impulsive load. At first glance Table 7 seems to show that the domed samples do deflect more than the flat samples. A couple of things needed to be considered. The impulse data for the dome shaped samples is slightly higher than the same for the flat samples. Also, the dome shaped samples inherently have more surface area than the flat samples [11]. Combining equations (4) through (7) yields:

\[
W_f = \frac{(0.28)\mu R^2}{\rho^2 H^4 \sigma_o}
\]

Equation (8) shows that the impulse and radius have squared influence on the deflection of the sample. Table 9 below shows that the dome shaped samples actually were slightly more efficient in resisting deflection than the flat samples.

Table 9: Efficiency Difference of Dome Shaped Samples from Flat Samples for Deflection
This must be due to the dome shape and the added surface area of the dome shaped samples absorbing or deflecting more energy than the flat samples. This shape factor will have to be studied more in depth in the future to analyze its magnitude of affect on energy absorption.

Previous static indentation testing led to an assumption of a possible softening affect of the water on the foam material itself (Figure 34).

![Figure 34: \(\frac{1}{2}\) in Plate Under Cylinder, Area Difference is 19%](image)

As shown in Figure 34, the stress vs. strain curve from 0 to 0.01 strain shows a lower modulus for the wet sample. This is shown by the smaller slope for the wet sample. Interestingly enough this softening affect seemed to also be observed in these series of blast loading tests.

Acoustic tests done on the same material have not shown a significant difference in transmission loss between \(\frac{1}{4}\) in and \(\frac{1}{2}\) in foam leading to the assumption that the thickness of the sample, within a certain range, does not affect the energy absorption of the material. If this is true for blast loading then equation (8) will have to be modified to match this case, or a new equation must be derived all together. This phenomenon will have to be studied more in depth in the future.

Table 6 assumes that the yield stress of both the wet and dry samples is 1.4 psi. This closely agrees with the deflections experimentally observed for the dry samples (Table 2). The given values of the compressive yield stress [12] for the sample material range from ~4 psi to ~8 psi. The model used to calculate the theoretical displacements in this paper is not valid for visco-elastic materials, but it does yield a close value to the book value for the dry material [12]. For the wet samples to have close to experimentally observed values they would have to exhibit a yield stress of ~0.85 psi according to the model used in this paper (Table 8). Figures 28 through 33 also show that the wet samples exhibited more deflection than the theoretical model yield value of 1.4 psi would imply. The ratio of dry to wet yield strength in the test shown in Figure 34 is ~1.67. The ratio of dry to wet yield strength in this test is ~1.65. This shows that there is an affect of the water on the foam material. This softening affect will also have to be further studied in the future to determine the actual magnitude of it’s affect on the foams material properties.
References


