Expandable Foam Impact Attenuation For Small Parafoil Payload Packages

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Executive Summary

Small, unmanned airplanes sometimes carry payloads to be released during flight. These payloads typically have a type of parachute to slow their descent, but often a cushioning system is still necessary to avoid damaging the payload contents. Currently, these payloads are cushioned with a type of cardboard honeycomb mainly because they are cheap and reliable. However, the cardboard honeycomb takes up a lot of room and the unmanned airplanes only have a limited amount of space to carry a payload. One solution to this problem may to be to use foam that expands after the payload has been released from the airplane. The purpose of this experiment is to test the material properties of an expanding foam and assess whether the material is suitable for cushioning a payload released from an unmanned airplane. Specifically, the experiment will look at how well the expanding foam cushions and how much volume it takes up in the unmanned airplane compared to cardboard honeycomb. These material properties will be tested using a constructed drop-test rig and payload to simulate a payload falling from the airplane and hitting the ground. The tests will primary be carried out in the Building 33 hangar and in TELAC, the advanced composites lab. The entire experiment, data analysis, and experiment report will require thirteen weeks to carry out and cost $553.90. This experiment will serve as the foundation for designing an inexpensive and reliable payload cushioning system.

1.0 Introduction

1.1 Background and Motivation

Unmanned Aerial Vehicles (UAVs) are remotely piloted or self-piloted aircraft that can carry cameras, sensors, communications equipment or other payloads, and have been used in a reconnaissance and intelligence-gathering role since the 1950s. Delivery of small payloads is one of many concepts currently under development to enhance the functionality of UAVs. Small parafoils, deployed when payloads are released from UAVs, are a promising delivery method for such payloads and typically slow a deployed payload's vertical descent rate to approximately 15 feet per second. A shock absorption mechanism is then often necessary to attenuate the impact shock at touchdown.

1.2 Overview of Previous Work

Current inexpensive and reliable low-impact attenuators such as paper honeycomb and crushable foam occupy a significant fraction of the volumetric capacity of UAV payload compartments. Other existing impact attenuators such as deployable airbags and "pull-up" mechanisms occupy less pre-deployment UAV payload volume. However, they greatly compromise cost and/or reliability. A new impact attenuation concept that reduces pre-deployment UAV payload volume without significantly increasing cost or reducing reliability is desirable. An expanding foam impact attenuation (EFIA) device may serve this purpose.

1.3 Short Overview of Project

The purpose of this project is to quantitatively compare the advantages and compromises of an expanding foam impact attenuator to a honeycomb impact attenuator for the purpose of deploying small packages from UAVs. Specifically this project will quantify pre-deployment volume, crush efficiency, reliability, and cost through static and dynamic testing.

2.0 Hypothesis, Objectives, and Success Criteria

2.1 Hypothesis

The primary hypothesis is that an expanding foam impact attenuation device (EFIA) will occupy at least 75% less pre-deployment value than paper honeycomb with a crush thickness efficiency loss of no more than 30%. A secondary hypothesis is that other tradeoffs will not exceed an increase in cost of 50% and a decrease in reliability of no more than 10%.

2.2 Objectives

Assess the ability of an EFIA to protect a payload with a 50g impact shock resistance from a 15 ft/s vertical descent rate. This assessment will be conducted by comparing the pre-deployment volume, crush efficiency, cost and reliability of the EFIA against paper honeycomb.

2.3 Success Criteria

Evaluate the aforementioned metrics for an EFIA and for paper honeycomb to an accuracy such that the hypotheses can be assessed.

3.0 Experiment Overview

To accomplish the experiment objective, an expanding foam impact attenuator (EFIA) material will be tested using industrial packing and insulating materials. Paper honeycomb impact attenuators will serve as the baseline for comparing the EFIA's performance. A typical UAV payload may contain electronic equipment that is able to withstand 50 times is own weight (50Gs) and occupies about 1 cubic foot. A drop-test rig approximately 6 feet in height will be built to simulate a parafoil-payload package vertical descent rate of 15 feet per second. The EFIA and the honeycomb impact attenuator will be compared on the following metrics: displacement crush efficiency, deployment reliability, pre-deployment volume, and cost.

The displacement crush efficiency[*] is defined as the ratio of the crush displacement of the impact material to its cushion thickness before impact,

$$\eta_t = \frac{x_{crush}}{\tau_{cushion}}. \qquad \text{(Eq. 1)}$$

This metric is important because payload volume must be reduced to compensate for the extra attenuation material necessary to achieve the required cushion thickness before impact. The displacement crush efficiency will be determined experimentally by dropping payloads of constant mass and constant base area protected by excess cushion thickness, and then measuring crush displacement. The result will be presented as a percent difference between the EFIA crush efficiency and honeycomb crush efficiency.

Pre-deployment volume is defined as the volume of the impact attenuation material occupied inside the UAV payload compartment necessary to effectively cushion the payload from impact. Pre-deployment volume for EFIA and honeycomb will include safety margins to reduce the effect of variations in material properties for each impact attenuation material. The result will be presented as a percent difference between pre-deployment volume for an EFIA and honeycomb impact attenuator.

Deployment reliability is defined as the probability that an impact attenuator will successfully deploy with the desired cushion thickness. Honeycomb does not require any deployment, and so reliability is taken to be 1. An expanding foam impact attenuator will be deployed 30 times. Cushion thickness and time to expand will be measured each trial and compared to the expected cushion thickness and time to expand, resulting in a percent reliability. The result will be presented as a percent change in reliability between an EFIA and honeycomb.

Cost for each impact attenuation device will be defined as the sum of the off-the-shelf pricing for each of the materials necessary to protect the given payload from a shock greater than 50Gs.

[*] Definition taken from unpublished work by Chris Anderson entitled, “Impact Shock Attenuation for Parafoil Payloads”

4.0 Literature Review

Although there does not appear to be previous research investigating the use of an expanding foam material to attenuate the impact of objects deployed from aerial vehicles, there is a great body of literature laying the foundation for such a research experiment. This literature includes various experiments employing standard shock impact testing methodologies, and one resource discussing the use of honeycomb material to attenuate the impact of small payloads deployed from UAVs.

The paper entitled “Design and Testing of the HOPE-X HSFD-II Landing System” written by Gardiner[1] discusses the design, analysis and preliminary testing of the airbag impact attenuation system for the re-entry of the unmanned space vehicle. The paper describes the technical design of the parachute and airbag subsystems, including materials, construction, and deployment techniques. Irvin in-house simulation tools are used to analyze parachute performance, and simulate airbag performance during impact. Airbag drop testing is then performed to validate the simulations. Drop tests include both vertical and horizontal impact velocity components controlled using a rail system. Test output data includes 3-axis acceleration, airbag pressure, rotational rate, vent release monitoring, and high-speed video, and all data is recorded digitally at 1000Hz bandwidth. Gardiner found that drop tests verified computer simulations, and computer simulations were then used to evaluate multiple airbag configurations.

The design and testing of the HOPE-X landing system is primarily focused on simulation verification. Although this aspect of the paper is not useful in designing our impact attenuation experiment, the HOPE-X landing system drop test experiment design provides a baseline with which to design a drop-test rig. Our impact attenuation experiment will be constrained to studying the effect of a vertical impact, and so we are not interested in rotational rates. However, a railing system to control the drop, a 1-axis accelerometer, and a high-speed camera will be incorporated into our experiment. Also, the 1000Hz bandwidth requirement provides a useful guideline for the selection of a data acquisition module.

Another paper entitled, "Parachute Retraction Soft-Landing Systems Using Pneumatic Muscle Actuators" written by Brown and Haggard[2] discusses the analysis and testing of flexible composite technology actuators. The actuators contract in the moments before impact to significantly slow the descent of a payload under a parachute. Brown and Haggard derive a theoretical model for the tension in an ideal actuator as a function of contraction, and use static testing to determine the validity of their model. Static testing also provides a measure of the efficiency for the real actuators. Dynamic drop-tests are then conducted to demonstrate the payload velocity reduction due to retraction. The drop-test setup involves placing a load cell between the payload and retraction actuator, and deriving peak force, peak acceleration, and change in velocity from the force vs. time data.

While the actual parachute retraction system is not relevant to our project, this work echoes the drop-test methodology laid out in the design and testing of the HOPE-X landing system. Although we intend to use an accelerometer rather than a load cell to record behavior during impact, this paper verifies that initial impact velocity of the payload can be successfully extracted from the impact data. Additionally this paper distinguishes between static and dynamic testing. Although we are not deriving a theoretical model for material behavior during impact, we are assuming that every attenuation material possesses an ideal crush efficiency of 100%. We then determine an actual attenuation efficiency using static testing and verify performance through dynamic testing as this paper describes.

Chris Anderson at Draper Labs has also provided a very relevant paper entitled, "Impact Shock Attenuation for Parafoil Payloads".[*] Anderson's work is the only available resource studying impact attenuation materials for use on small payloads deployed from unmanned aerial vehicles. He derives quantitative relationships among impact shock parameters showing two very important facts. Required cushion thickness is proportional the square of payload's initial velocity, while material properties determine the deceleration of the payload. He also defines a metric called material crush thickness efficiency to describe the amount of initial cushion thickness required to

[*] Unpublished Work, given to team February 2003.

achieve a certain crush displacement. These quantitative relationships are then used to choose a honeycomb impact attenuator with the proper dynamic crush stress to shield a given payload from an impact shock greater than 30 Gs. Anderson then verifies results by measuring payload deceleration during drop testing.

This 16.62x project builds directly on Anderson's work, which provides a strong quantitative basis for comparing attenuation properties of expanding foam with honeycomb. Anderson's theory coupled with standard drop-test methodologies provide the basis for exploring a novel impact attenuation system for payloads deployed from UAVs.

5.0 Technical Approach of Experiment

A flowchart describing the experiment technical approach is presented in Figure 1. The experiment is divided into two segments and reflects the separation between the primary and secondary hypothesis. Choosing an expanding foam and honeycomb material is the first step towards assessing both hypotheses. Material properties of the expanding foam and honeycomb play a role in determining payload volume, base area, and mass.

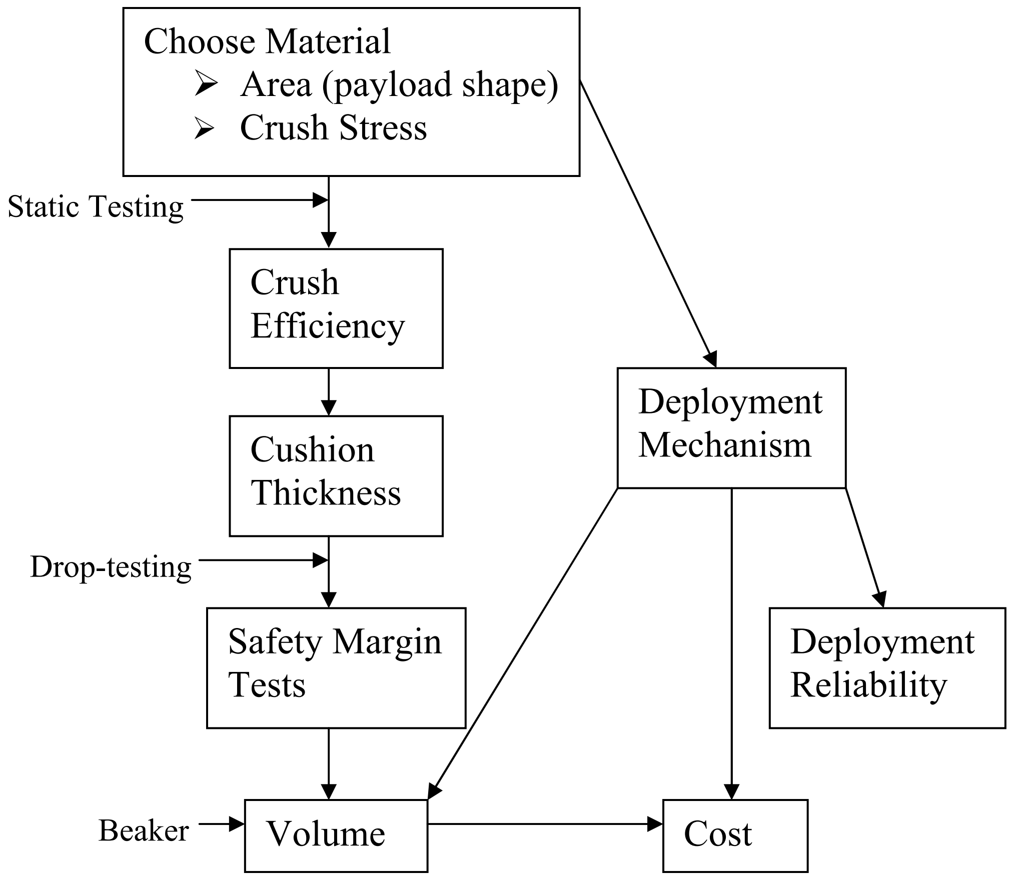

Figure 1: Flowchart of Technical Approach

Once attenuation materials and payload properties are determined, the crush efficiencies for both attenuation materials are characterized through quasi-static testing using a force-press. Quasi-static crush efficiency, given by Equation 1, is determined by loading the attenuation materials with increasing force, and monitoring material displacement. The force vs. displacement curve, it is expected to look like:

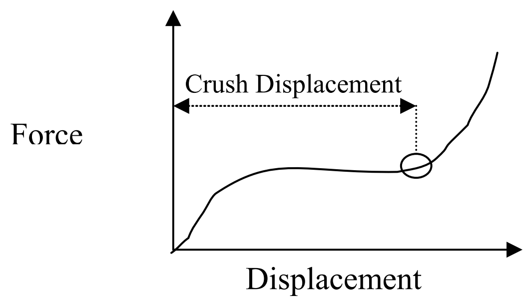

Figure 2: Crush Displacement Curve

The crush displacement is defined as the displacement from zero force to the measured displacement where the force-displacement curve transitions from a plateau to steep slope. Crush displacement efficiency is then determined by taking the ratio of crush displacement to initial cushion thickness.

Cushion thickness to protect the payload from an impact shock no greater than 50G is then given by Equation 2*,

$$\tau_{cushion} = \frac{v^{\wedge 2}}{2gG\eta_t}. \quad \text{(Eq. 2)}$$

Where, initial velocity is 15 feet/second, g is 32 feet/second, G is the deceleration requirement of 50, and η_t is the crush efficiency for the attenuation material being tested.

Drop tests will then be performed to verify that the crush efficiency determined through quasi-static testing matches the crush efficiency exhibited under dynamic conditions. Dynamic testing of the crush efficiency will ensure that the expanding foam and honeycomb materials do not exhibit velocity-dependant attenuation characteristics. For example, a spring's resistance is not dependant on the velocity of the mass attached

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* Equation from unpublished work by Chris Anderson entitled, "Impact Shock Attenuation for Parafoil Payloads"

to its end. However, a dashpot's resistance is dependant on the mass velocity, and so we would say it exhibits velocity-dependant attenuation characteristics.

Dynamic crush efficiency will be determined by dropping the payload-attenuation material system from a certain height using less cushioning material than is calculated to be necessary to achieve a deceleration during impact of 50G. This ensures that the attenuation material will have completely crushed during impact. Maximum crush displacement will be measured using a high-speed camera.

Once crush efficiency is verified, drop-tests will be conducted using the cushion thickness found from Equation 2. This is the marginal cushion thickness necessary to protect a payload from an impact shock greater than 50Gs. However, drop-tests will probably reveal a distribution of shocks felt by the payload centered on 50Gs. From this distribution, a new cushion thickness will be chosen that will protect the payload within two standard deviations from 50Gs. This new cushion thickness will contribute to the final volume occupied by each attenuation material.

The assessment of the secondary hypothesis is contingent on designing a deployment mechanism for the expanding foam impact attenuator. The volume occupied by the deployment mechanism components will be incorporated into the total volume occupied by an EFIA system. Deployment reliability will be determined by triggering the deployment mechanism a statistically significant number of times, and finding the percent of successful deployments to total deployments. Successful deployments of an EFIA are counted as the number of deployments in which the expanding foam expands to within 5% of its expected thickness within two minutes. This value will be compared to a honeycomb deployment reliability of 100%, since honeycomb does not require a deployment mechanism.

Cost for each impact attenuation device will be defined as the sum of the off-the-shelf pricing for each of the components necessary to protect the given payload from a shock greater than 50Gs.

If a deployment mechanism is not designed, the secondary hypothesis cannot be tested. However, a set of requirements outlining the design of a deployment mechanism to meet the secondary hypothesis can be formed based on the results of testing the primary hypothesis.

6.0 Description of Apparatus

The apparatus for conducting this experiment include a drop-test rig, force press, beaker, accelerometer, and a digital timer with photogates.

The drop-test rig will primarily be constructed out of Unistrut metal secured to the Strongwall in the hanger of Building 33. The drop-test rig will consist of two railings held vertical with Unistrut frames. A Unistrut cantilever will extend out from the Strongwall above the railings and hold a pulley. The payload will attach to the two railings through linear bearings. Rope wire will be attached near the top of each face of the payload box and will run through a pulley to a winch located a few feet away from the drop-test rig.

If friction is neglected, a payload must be dropped from a height of approximately 3 feet in order to reach an impact velocity of 15 feet per second. The height of the proposed drop-test rig is 6 feet to account for friction due to the drop-test rails.

An Instron force press available in the advanced composites lab TELAC will be used to measure quasi-static crush efficiency. A beaker will be used to carry out water displacement volume measurements, an accelerometer will be attached to the payload to measure acceleration during impact, and a digital timer with photogates will be attached to the drop-test rig to verify impact velocity.

7.0 Description of Test Articles

The test articles for this experiment include the payload, expanding foam material, honeycomb material, and the expanding foam impact attenuation deployment mechanism.

7.1 Payload

The payload will be cubic in shape and occupy about a cubic foot. A conceptual sketch of the payload/attenuation material system is shown in Figure 3.

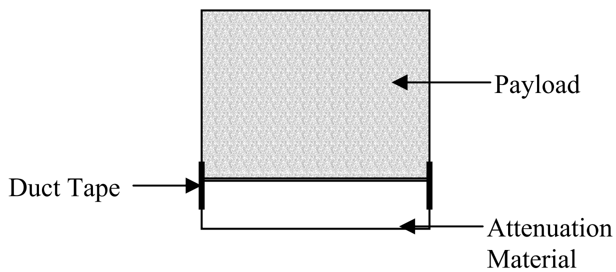


Figure 3: Payload/ Attenuation Material System

The payload base area must be sized so that the readily available expanding foam products of similar dimensions can be easily interfaced with the payload base. Since honeycomb material can be sized to any dimension and is not a limiting factor, the payload base will 15 inches by 18 inches, the same dimensions as smallest expanding foam bag. However, the expanding foam and honeycomb materials possess different critical crush stresses. In order for the payload to achieve the desired deceleration, the mass of the payload is a function of base area, deceleration limit, and critical crush stress as shown in Equation 3,

$$A\sigma_{crush} = mG \, . \qquad \text{(Eq. 3)}$$

Because the critical crush stress is a material property and will vary depending on whether we are testing honeycomb or expanding foam, and both the base area and deceleration limit are fixed, the mass of the payload must vary slightly depending on which attenuation material is being tested. The critical crush stresses of the impact attenuation materials being tested range from 9-11 pounds per square inch, yielding a payload mass of approximately 45 pounds.

Duct tape will serves as the means of attaching attenuator materials to the base of the payload box since it will not contribute to experiment uncertainty by creating another impact interface.

7.2 Expanding Foam Material

The expanding foam product under primary consideration for evaluation is the Instapak Quick Foam Packaging manufactured by Sealed Air Corporation[3] shown in Figure 4. This particular packaging is desirable because it is self-contained. Two small chemical compartments are located inside a sealed plastic bag, and the plastic bag is slowly heated to the optimal temperature for foam expansion using a heating device supplied by the company. Then a person or mechanism applies pressure to the two chemical compartments, breaking a barrier, and causing the chemicals to mix. The chemical reaction results in expanding foam filling the plastic bag. The time to expansion is approximately 20 seconds, which is an advantage over other expanding foam products that take as long as an hour to fully expand.

7.3 Honeycomb Material

The honeycomb attenuation material tested by Chris Anderson[*] was Hexacomb product HEX700 manufactured by Pactiv[4] shown in Figure 5, and will be used again in this experiment.

8.0 Description of Measurements

8.1 Crush Efficiency

Quasi-static and dynamic crush efficiencies are measured using the same parameter of attenuation material cushion thickness, the same dependent variable of material crush displacement, and the same independent variables material and trial number. Test matrices for measuring static and dynamic crush efficiencies are shown in Tables 1 and 2 respectively.

[*] Unpublished work by Chris Anderson entitled, “Impact Shock Attenuation for Parafoil Payloads”

Table 1: Test Matrix for Quasi-Static Crush Efficiency

	Material : Honeycomb						*Material: Expanding Foam*				
Trial #	**Crush Displacement Trials 1-5**					**Trial #**	**Crush Displacement Trials 1-5**				
1						1					
2						2					
…						…					
5						5					

Table 2: Test Matrix for Dynamic Crush Efficiency

	Material : Honeycomb						*Material: Expanding Foam*				
Trial #	**Crush Displacement Trials 1-5**					**Trial #**	**Crush Displacement Trials 1-5**				
1						1					
2						2					
…						…					
5						5					

8.2 Safety Margin

While conducting drop-tests to determine an appropriate safety margin for cushion thickness, the parameters include a fixed height to achieve the desired impact velocity, and the marginal cushion thickness calculated in Equation 2. The independent variables are material and trial number, and the dependent variable to be measured is maximum acceleration during impact. The test matrix for safety margin calculations is shown in Table 3.

Table 3: Test Matrix for Safety Margin Calculations

Material: Honeycomb		*Material: Expanding Foam*	
Trial #	**Max. Acceleration**	**Trial #**	**Max. Acceleration**
1		1	
2		2	
…		…	
N		N	

8.3 Volume

In measuring volume, the only parameter is the new cushion thickness identified for each material by the safety margin tests. The independent variable is material, and the dependent variable is the volume of water displaced by the attenuation material. The test matrix for volume measurements is shown in Table 4.

Table 4: Test Matrix for Volume Measurements

Material	**Volume**
Honeycomb	
Expanding Foam	

8.4 Deployment Reliability

Deployment reliability will only be quantified for the expanding foam impact attenuator. The independent variable is the trial number, and the dependent variable is a Boolean true or false statement for the successful deployment of a cushion thickness within 5% of the expected value in under two minutes. The test matrix for deployment reliability is shown in Table 5.

Table 5: Test Matrix for EFIA Deployment Reliability

Trial #	**Successful Deployment (True/False)**
1	
2	
…	
N	

8.5 Cost

The test matrix for cost only has one independent variable, material. The dependent variable is the off-the-shelf cost of the attenuation mechanism. The test matrix for cost is shown in Table 6.

Table 6: Test Matrix for Cost

Material	**Cost**
Honeycomb	
Expanding Foam	

9.0 Discussion of Errors

The errors of concern in this experiment include instrument errors for measuring acceleration, volume displacement, crush displacement, cushion thickness, and impact velocity. Errors in these measurements lead to indirect errors in crush efficiency. Also, the questions regarding appropriate sampling rates result in additional error considerations for acceleration, crush displacement, and impact velocity.

Acceleration will be measured using a 100G tri-axial vibration accelerometer from Crossbow, and provides sensitivity to within 2%. This error is acceptable. The standard data-sampling rate during impact attenuation drop-tests is approximately

1000Hz[1,5], and is considered negligible in our experiment since data acquisition will be conducted using a PC with a sampling rate of 33 kHz per accelerometer input.

A beaker for measuring volume displacement with a capacity of 3000 milliliters and graduation of 50 milliliters would yield approximately a 5% error in measuring the volume of an unexpanded foam bag. This is reasonable since we are interested in quantifying a change in volume of approximately 75%.

The scale used in the high-speed camera photographs limit the error in crush displacement. Assuming we are using a standard ruler as scale, error is on the order of millimeters, which is acceptable. Additional error due to sampling error is considered negligible since the camera records 8000 frames per second, which is approximately eight times higher than the standard sampling rate for drop-tests.

Cushion thickness will likely be measured with a standard ruler or caliber, which has a maximum error on the order of millimeters.

Error in crush displacement is a function of the non-correlated, independent errors in crush displacement and cushion thickness and is expected to be well within acceptable limits. Error in impact velocity is due to error in the digital time and photogate used to measure the impact velocity as well as error in maintaining a constant drop height for all trials. These errors are also expected to be within acceptable limits. A more detailed analysis of impact velocity and other errors are found in Section 11.1.

10.0 Experiment Design

10.1 Design and Construction of Drop-Test Rig

Detailed drawings for the drop-test rig are included in Appendix A, and a detailed parts list of construction materials and instrumentation are listed in Appendix B. A three-view dimensioned sketch of the test-rig is included on the next page in Figure 7 to supplement the discussion on design and construction of the drop-test rig.

The drop-test rig consists of two frames spaced six feet apart to hold the two six foot long railings. The frames will each be constructed from two long Unistrut lengths, and two short Unistrut lengths cut to size in the Aero/Astro Department Machine Shop. The two long beams are 24.6 inches in length, and the two short beams are 17 inches in length. The railings are attached to the inside of the frames at the midpoint of the short lengths using shaft supports, and the payload is attached to the railing through a sliding linear bearing. An isometric view of this system is shown in Figure 6.

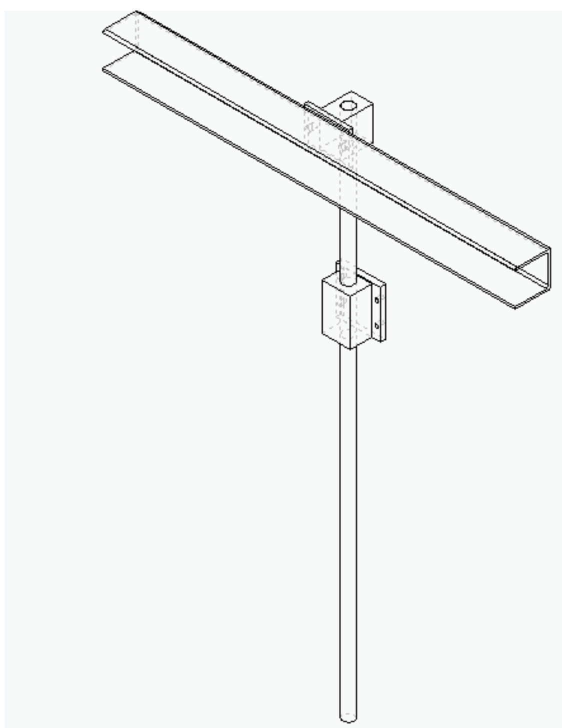


Figure 6: Isometric View of Unistrut, Railing, and Shaft Support

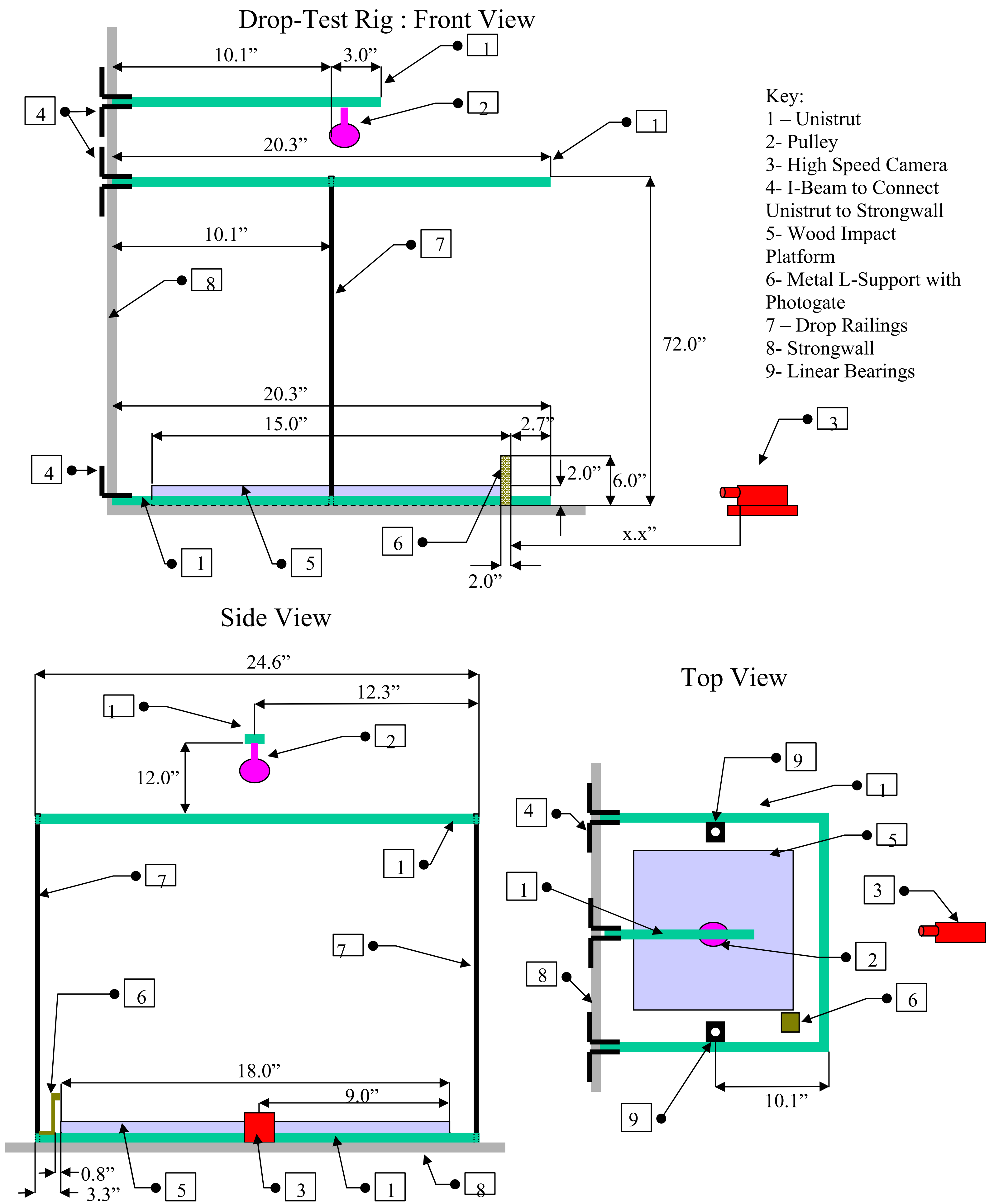


Figure 7: Three-View Drawing of Drop-Test Rig

Two holes with 0.11 inch diameter must be drilled 1.5 inches apart and centered on each short Unistrut length to bolt the shaft support to the frame. The each Unistrut frame will be assembled using two right-angled Unistrut brackets attached to the outside of the frame. A 13.1 inch cantilever Unistrut is used to mount the pulley, will be placed 12 inches above the top frame, resulting in a drop-test rig height of about 7 feet. The frame and cantilever Unistruts are attached to the Strongwall in the hangar of Building 33 by an I-beam connectors specifically designed to interface with the Strongwall.

A two inch tall wooden platform with a base area of 15 inches by 18 inches is placed inside the bottom frame and rests on the floor. This serves as a hard surface for the payload to impact. A 6 inch tall metal L-shape holding a photogate to measure impact velocity will be clamped to the bottom frame 2.7 inch from the frame edge as shown in the dimensional sketch. The distance from the bottom of the photogate to the floor is variable and must be calculated for the cushion thickness used during the drop-test. This distance if found by adding the platform height, blinder width, and cushion thickness. The high speed camera will be placed 2 inch above the floor and face a side of the frame where the L-shape does not interfere with a picture of the attenuation material during impact, as shown in the dimensional sketch. A ruler will be placed next to the platform, facing the high-speed camera to measure attenuator crush displacement during impact.

10.2 Design and Construction of Payload Box

Detailed drawings for the payload box are included in Appendix A, and a detailed parts list of construction materials and instrumentation are listed in Appendix B. Figure 8 shows an isometric view of the payload design to supplement the discussion on the design and construction of the payload box.

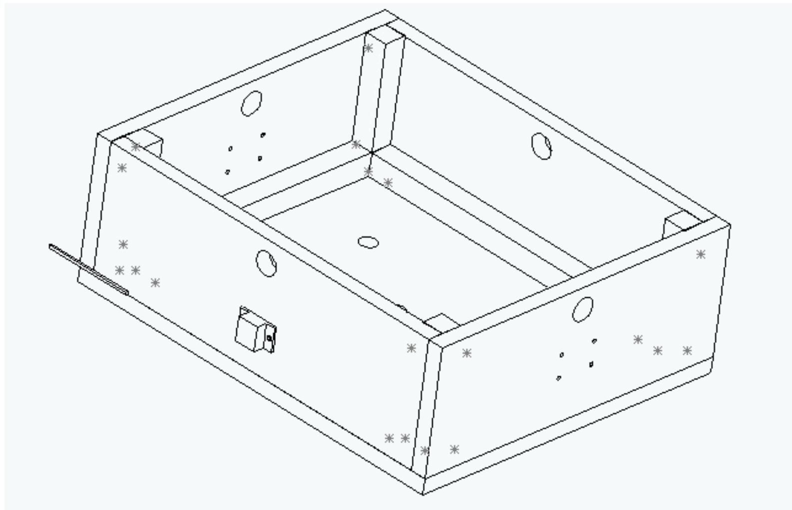


Figure 8: Isometric View of Payload Box

The payload box is constructed of 0.7 inch thick plywood cut to the dimensions specified in Appendix A and screwed together to form a box with a base of 15 inches by 18 inches. Box structural reinforcements are sawed to the appropriate dimensions specified in Appendix A and screwed in along each inner edge as shown.

The box must be modified in order to interface with the drop-test rig and to accommodate appropriate instrumentation. Four holes must be drilled on two faces to attach the box to the railing ball bearings. Two holes must be drilled to attach the accelerometer to a face not fastened to ball bearings. The accelerometer should be screwed onto the box with connecting wires pointing up such that the wires will not interfere with the frame during drop testing. Five holes must be drilled into the payload box base to insert bolts that will secure the weights inside the box. Finally, a hole near the top of each payload box face will provide a place to tie the rope wire. This rope wire will run through the pulley in the drop-test rig to a winch and quick release mechanism used to raise and drop the weighted payload box. The diameters and locations of all holes are specified in Appendix A.

The blinder that interrupts the photogate to measure impact velocity must be milled in the Aero/Astro Machine Shop to be 4 inches long, 0.120 inches +/- 0.005

wide, and 0.1 inch thick. This blinder will be attached to the bottom of the front payload face as shown in Appendix A.

10.3 Measurement Systems

Four measurement systems are necessary to evaluate the primary hypothesis: an Instron force press, high speed camera, accelerometer, and digital timer with photogates.

Instron Force Press

The Instron force press, located in the advanced composites lab TELAC, is a self-contained system and does not require any additional hardware interfaces in order to measure a material's crush displacement under varying force. The force-displacement data is recorded on a computer using Instron software and can be imported into an Excel file to plot the force-displacement curve.

High Speed Camera System

The high speed camera is connected by a cable to a designated computer that records the image data. The data can then be analyzed using the high speed camera software package. Specifically, the software is capable of measuring distance in the picture frames using a cursor controlled by the user.

Accelerometer System

The accelerometer must be interfaced with a computer through the use of an analog-to-digital-board (A/D board). The accelerometer has five output pins for: a 5-volt supply, ground, x-axis acceleration, y-axis acceleration, and z-axis acceleration. The 5-volt supply pin is connect to a battery, the ground is connected to a ground on the A/D board, and the acceleration measurements are connected to A/D board inputs. The A/D board cable interfaces with a computer, and acceleration measurements are acquired using Labview software. There is a possibility that the accelerometer cannot interface with the same computer used for the high speed camera, and a separate computer for collecting accelerometer measurements will be available.

Digital Timer with Photogates

The digital timer with photogates is a stand-alone system and does not need to be hooked up to a computer for data acquisition. The instrument consists of a digital timer and two photogates. The digital timer can be set to display the instantaneous velocity of an object through each of the two photogates. The user records the instrument measurements manually between trials.

10.4 Buy/Make Decisions

The vast majority of equipment, instruments, and materials necessary for this project are being borrowed from the Aero/Astro Department. However, certain materials must still be constructed or bought. The Detailed Parts List in Appendix B specifies how each part will be acquired and the Specification Sheet in Appendix C lists the part numbers and order codes for materials to be purchased.

Items To Be Bought

While the Aero/Astro Department already has two 4 foot long railings for conducting drop testing, these are not tall enough to ensure the specified impact velocity of 15 feet per second. Thus, two 6 foot long railings will be purchased and delivered over the summer for use in the fall term.

One Instapak Heater and two cartons of 48 Instapak Quickpak Expanding Foam Bags (15 inches by 18 inches in area) must be purchased. However, the honeycomb impact attenuation material does not need to be purchased. The project advisor Christian Anderson is able to supply four 48 inch by 96 inch sheets of 1 inch thick honeycomb. An addition four 48 inch by 96 inch sheets of 0.5 inch honeycomb can be ordered as samples from the manufacturer Pactiv at no cost.

A 3000-milliliter measuring cup with 50-milliliter graduations must be ordered to perform displacement volume measurements of appropriate accuracy on the unexpanded Instapak Expanding Foam Bags. Also one inch by inch by bass wood lengths must be bought to reinforce the payload box design.

Items To Be Made

The payload box must have a base area of 15 inches by 18 inches based on the expanding foam bag area. Rather than modify an existing box with a smaller base by adding a adapter base or work with an existing box of larger base where the entire base would not be cushioned with attenuator material, the decision was made to build a box to the appropriate dimensions out of plywood. An impact platform for the drop-test rig must also be cut with an area of 15 inches by 18 inches. The blinder to interrupt the photogate cannot be bought and must be manufactured in the Aero/Astro Machine Shop. Also, the metal-L to hold the photogate at the appropriate height on the drop-test rig must be made.

10.5 Safety Concerns

The primary safety concern associated with the experiment is the danger of the falling payload box injuring a person. However, using a winch and quick-release mechanism reduces this danger. A winch stationed a few feet away from the drop-test rig ensures that the person conducting the drop test is safely away from the rig while the weighted payload is raised. Also, the quick-release mechanism allows the person to release the payload from a safe distance.

Operational safety measures will ensure that observers will not be injured. The person operating the winch will ask observers to step away from the drop-test rig when the payload is being raised and check that there is no one near the drop-test rig before releasing the payload.

11.0 Data Analysis

11.1 Data Reduction Techniques

11.1.1 Quasi-Static Crush Efficiency

The Instron Force Press produces a force-displacement graph conceptually similar to Figure 2 shown again here for reference. Five trials will be conducted for each impact attenuation material being tested resulting in five force-displacement curves for each material. The initial cushion thickness and crush displacement for each graph is measured, and five quasi-static crush efficiencies are calculated and averaged to produce the final quasi-static crush efficiency for a given material.

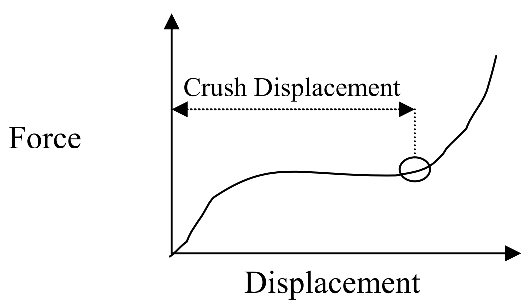


Figure 2: Crush Displacement Curve

The force-displacement graph will not have a sharp corner at the transition from plateau to steep slope clearly marking the maximum crush displacement. Averaging the calculations from five different graphs per material reduces the effect of errors in choosing an approximate maximum crush displacement.

11.1.2 Dynamic Crush Efficiency

Dynamic crush efficiency is calculated using a high-speed camera to measure crush displacement. Conceptual examples of snapshots from the high-speed camera are shown in Figure 9.

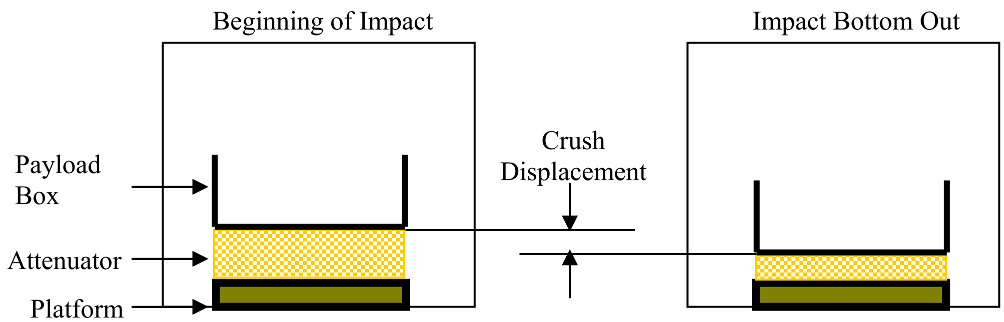


Figure 9: Crush Displacement Measured from the High Speed Camera

Five drop-tests using the high-speed camera are performed for each attenuator material. The initial cushion thickness and bottom out thickness are measured for each trial using the high-speed camera software and subtracted to find the crush displacement. Dynamic crush efficiencies are then calculated for all trials and averaged to yield an average dynamic crush efficiency for a given material.

The quasi-static and dynamic crush efficiencies should not be dramatically different. If there is a significant difference than this may indicate velocity-dependent attenuation characteristics. Whether the differences between the quasi-static and dynamic crush efficiencies are slight or large, the dynamic crush efficiency will be used to calculate theoretical cushion thickness since it will more accurately reflect the performance characteristics of the impact attenuator under the specified requirements.

11.1.3 Safety Margin Tests

Once a theoretical cushion thickness is chosen, the payload is drop-tested with attenuator material of the theoretical cushion thickness. Acceleration during the impact is recorded using Labview and the peak acceleration is extracted from each graph. These peak accelerations form a distribution of maximum acceleration felt by the payload during impact.

The number of drop-tests necessary to guarantee that the peak acceleration distribution is representative of the distribution of the attenuator population must be calculated using a Student-T test. This is because the standard deviation of the population is unknown. A statistical analysis shows that 24 drop-tests are necessary for the attenuator material to be 95% confident that 95% of the actual peak acceleration measurements are within two sample standard deviations above the sample mean.

The peak acceleration distribution mean and the acceleration two standard deviations above the mean can be calculated using a Matlab command. The difference between the two standard deviation acceleration and the mean acceleration is the impact deceleration limit safety margin. The final cushion thickness is calculated using

$$G_{safety} = G_{requirement} - \Delta G, \quad \text{(Eq. 4)}$$

where $G_{requirement}$ is the impact deceleration limit and ΔG is the impact deceleration limit safety margin.

11.1.4 Pre-deployment Volume

The honeycomb attenuator material volume is calculated by multiplying the final cushion thickness by the base area of the payload box. The expanding foam attenuator volume is found by submerging the number of unexpanded foam bags necessary to achieve the final cushion thickness in a graduated beaker to measure water displacement. In the case that the number of unexpanded bags necessary to achieve the final cushion thickness is not an integer, the number of bags necessary will be rounded up to achieve a conservative estimate of expanding foam pre-deployment volume.

11.2 Error Analysis

The purpose of this analysis is to quantify the error in the measurements of crush displacement efficiency and pre-deployment attenuator volume used to assess our primary hypothesis.

11.2.1 Crush Displacement

Crush displacement efficiency is calculated by dividing material crush displacement by initial cushion thickness. Quasi-static measurements of crush displacement are conducted with an Instron force press machine available in the advanced composites lab TELAC, and dynamic measurements of crush displacement are conducted with a high-speed camera and drop test rig.

Quasi-Static Crush Efficiency Error

Crush displacement measurements using an Instron force press are accurate to within 0.01 inches, and cushion thickness is measured using a standard ruler with accuracy conservatively estimated to within one-sixteenth of an inch.

Given the equation for crush efficiency (Eq.1) and the general rule for combination of errors:

$$dz = \sqrt{(\frac{\delta F}{\delta x_1})^2 dx_1^{\,2} + (\frac{\delta F}{\delta x_2})^2 dx_2^{\,2} + (\frac{\delta F}{\delta x_3})^2 dx_3^{\,2} \ldots} \quad , \qquad \text{(Eq. 5)}$$

where $z = F(x_1, x_2, x_3 \ldots)$ the error in crush efficiency is given by

$$d\eta = \eta * \sqrt{(\frac{d\,x}{x})^2 + (\frac{d\tau}{\tau})^2} \, . \qquad \text{(Eq. 6)}$$

Using the impact velocity specification of 15 ft/s and an impact deceleration limit of 50G, Equation (2) yields an expected crush displacement (x) of 1.29 inches. The expected cushion thickness (τ), based on Anderson's paper*, is 2 inches. This yields an expected crush efficiency of 0.65. Substituting these values and the expected errors into the equation results in an error for quasi-static crush efficiency of 2.1%.

* Unpublished Work, given to team February 2003.

Dynamic Crush Efficiency Error

The crush displacement measured using a high-speed camera incurs two sources of errors. The high-speed camera software possesses the capability of measuring distances between objects in a frame given an initial reference distance; one error is due to the accuracy of the ruler in the picture frames used to calibrate the camera software. The second source of error is due to the camera's frame rate of 8000 frames per second since the impact attenuation material may continue to crush during the interval between frames.

Assuming a standard ruler to calibrate distance measurements in the picture frames, the accuracy in crush displacement ($_{crush1}$) is approximately one-sixteenth of an inch (0.0625 inch or 0.005 feet).

In order to quantify the error due to the camera's frame rate, consider a worst-case situation where the payload decelerates at 50G down to zero velocity and then rebounds with the same acceleration of 50G. The maximum amount of time the attenuation material may continue to crush between camera frames is one half the time between picture frames. The time between pictures frames is given by the reciprocal of 8000 frames per second and yields a maximum of $t_{camera} = 1.25 * 10^{-4}$ seconds between frames. The maximum error due to this frame rate is given by

$$d_{x_{crush2}} = \frac{1}{2} a t^2 \quad , \qquad \text{(Eq.7)}$$

where $t = \frac{1}{2} t_{camera}$ and a = 50G = 1610 ft/sec^2, and yields an error in crush displacement of 3.78 x 10 ^-5 inches, or 3.14 x 10 ^-6 ft. The total error in crush displacement due to these two errors is given by:

$$d_{x_{total}} = \sqrt{(dx_{crush1})^2 + (dx_{crush2})^2} \; , \qquad \text{(Eq.8)}$$

and yields an error of 0.063 inches or 0.0052 inches.

The error in crush efficiency is given by:

$$d\eta = \eta * \sqrt{(\frac{d_{x_{total}}}{x_{total}})^2 + (\frac{d\tau}{\tau})^2} \quad \text{(Eq.9)}$$

As with the quasi-static crush efficiency error calculation, we use the specified requirements for initial velocity and an impact deceleration limit. This yields a crush displacement of 1.29 inches. Assuming a cushion thickness of 2 inches yields an approximate crush efficiency of 0.65. This results in a dynamic crush efficiency error of 3.75%, which is acceptable to measure our hypothesis.

Experimental results for quasi-static and dynamic crush efficiency are expected to be very similar. However, in the case of a disparity, dynamic crush efficiency will be the quantity used to calculate other metrics since it will more closely describe the material performance in the real-world application of parafoil/payload system impact attenuation. As a result, the error in dynamic crush efficiency will be propagated to calculate the error in other metrics rather than the error in quasi-static crush efficiency.

The experiment primary hypothesis states that expanding foam has a crush efficiency of no more than 30% less than honeycomb's crush efficiency. In order to definitively evaluate this metric to an accuracy such that the hypothesis can be assessed, we must show one of two results:

1) To prove the hypothesis true, we must show that the crush efficiency of expanding foam is no more than 26.25% less than the crush efficiency of paper honeycomb.
2) To disprove the hypothesis, we must show that the crush efficiency of expanding foam is more than 33.75% less than the crush efficiency of paper honeycomb.

11.2.2 Pre-deployment Attenuator Volume

Pre-deployment attenuator volume is calculated through a series of steps. First, initial cushion thickness is calculated using experiment specifications for velocity and impact deceleration limit, and the calculated dynamic crush efficiency. Then the payload is drop-tested using the initial cushion thickness to form a distribution of peak accelerations felt by the payload. This distribution will be widened due to random accelerometer error and random error in achieving a constant drop height for all trials. The distribution is shifted due to bias errors in impact velocity measurement, crush efficiency, and initial cushion thickness. A final cushion thickness is calculated from the peak acceleration distribution to ensure the payload can withstand up to two standard deviations from the mean impact shock. This final thickness then results in a pre-deployment volume.

Initial Cushion Thickness Error

The initial cushion thickness is given by the equation:

$$\tau_{initial} = \frac{v^2}{2gG\eta}, \qquad \text{(Eq.10)}$$

where the impact velocity specification (v) is 15 feet per second, the impact deceleration limit (G) is 50. The crush efficiency (η) has an accuracy of +/- 3.75%. Since crush efficiency is the only error, the general rule for combination of errors yields:

$$d\tau_{initial} = \sqrt{\left(\frac{v^2}{2gG\eta^2}\right)^2 d\eta^2}\ , \qquad \text{(Eq.11)}$$

where η is given the approximate value 0.65 as with the crush efficiency error analysis. This yields an initial cushion thickness error of 0.234 inches, or 0.020 feet.

Error Effects on the Distribution of Peak Accelerations

<u>*Random Error*</u>

There are two sources of random error affecting the distribution of peak accelerations. One source is due to the accelerometer instrumentation error. The other error occurs because it is not possible to achieve the exact same drop-height for all trials.

Peak acceleration is measured using a Crossbow Accelerometer series CXL100HF3. According to the product specification sheet, the input range is +/- 100g and the sensitivity is +/- 10 millivolts/g. According the specification footnote, this corresponds to a +/- 2% error in the accelerometer measurement. Operating near and around the impact deceleration limit of 50G, this causes a 1g random measurement error.

The error due to uncertainty in the fixed drop-height results in random error in impact velocity. This in turn results in a variation of the payload's acceleration during impact that is not due to material properties of the attenuation material. Assuming the payload drop-height can be fixed to within one-eight of an inch (by either lining up a mark on the wire to a mark on the winch, or else by lining up a mark on the payload to a mark on the drop-test rig), the error in impact velocity is given by:

$$dv = \sqrt{2g(dh)}\ , \qquad \text{(Eq. 12)}$$

where dh is the error in drop-height = 1/8 inch or 0.0104 feet. This results in an impact velocity error of 0.819 feet per second.

Impact velocity is related to the acceleration felt by the payload during impact by:

$$A = \frac{v^2}{2\eta\tau_{initial}}\ . \qquad \text{(Eq.13)}$$

The velocity impact requirement is 15 feet per second with a random error of 0.819 feet per second as calculated above. The error in crush efficiency (η) and initial cushion thickness ($\tau_{initial}$) are bias errors and are dealt with separately later. Therefore the random error in acceleration felt by the payload is due to an error in drop-height. This error is given by:

$$dA = \sqrt{(\frac{v}{\eta \tau_{initial}})^2 dv^2}\ , \qquad \text{(Eq. 14)}$$

where v is the impact velocity requirement of 15 feet per second, η is estimated to be 0.65, and $\tau_{initial}$ is estimated to be 1.29 inches or 0.11 feet. This results in a variation of 5.34 g in the payload's acceleration during impact not due to material properties of the attenuation material.

Combining the errors due to the accelerometer measurement and variation in drop-height using the general rule for combination of errors yields an equation for the total random error in acceleration not due to material properties:

$$dG_{random} = \sqrt{d_{accelerometer}{}^2 + d_{drop-height}{}^2}\ . \qquad \text{(Eq.15)}$$

This yields a total random error not due to variation in material property of 5.43g. This random error means that if all the peak acceleration measurements fall within +/- 5.43g of the distribution mean, the spread cannot only be attributed to material property variation. However, measurements greater than +/- 5.43g from the distribution mean are not only a result of instrument error and can be attributed to material property variations.

Bias Error due to Initial Cushion Thickness, Crush Efficiency, and Impact Velocity Measurements

The impact acceleration felt by a payload impacting the ground at a given velocity, with an impact attenuation of a certain cushion thickness and crush efficiency is given by

$$A = \frac{v^2}{2\eta\tau_{initial}}. \qquad \text{(Eq. 16)}$$

While the error in the accelerometer measurement yields a lower limit in the spread that can be attributed to material property variations, the errors in initial crush thickness, crush efficiency, and impact velocity measurements will also impact how the peak acceleration distribution is interpreted.

Once an initial cushion thickness is calculated its error will remain fixed with respect to a theoretical cushion thickness calculated in a world without measurement errors. Therefore, this error is a bias error and will shift a peak acceleration distribution mean to the left or right some fixed amount. Likewise, once crush efficiency is calculated it will possess a constant error resulting in a distribution bias. Error in the measurement of impact velocity can also be considered a bias error if the payload is consistently dropped from a precisely marked height as described above. This is because the measurement in impact velocity is used to precisely mark the drop-height and once the height is set, the velocity measurement error remains constant with respect to the true height necessary to achieve the appropriate impact velocity. The total expected bias error can be quantified using the general rule for combination of errors. While errors in initial cushion thickness and crush efficiency have been calculated, error in impact velocity measurements with a digital time and photogate remains to be quantified.

Velocity Error

The digital timer and photogate measurement system has two sources of error. One error comes from the photogate sampling rate, and the other error occurs because the blind is accelerating through the photogate.

The photogate uses a quartz oscillator of 6 MHz frequency to create a beam of light, and samples the light at 1 MHz +/- 50 Hz to detect a break in the light. As a result the sampling rate is the limiting factor, not the quartz oscillator. The digital timer's accuracy in time is the reciprocal of the sampling time. The uncertainty +/- 50 Hz is negligible, and the resulting uncertainty in time is approximately 1.0 x 10^-6 seconds.

Instantaneous velocity is measured using one photogate, a barrier of a certain width, and a measurement of the time that the barrier blocks the light. Velocity is found from the following equation:

$$V_{impact} = \frac{w_{barrier}}{t_{sample}} \quad , \qquad \text{(Eq. 17)}$$

where $w_{barrier}$ = barrier width and t_{sample} = the reciprocal of the number of samples that are dark.

Using the general rule for combination of errors, the error in velocity is given by:

$$dv_1 = v\sqrt{(\frac{dw_{barrier}}{w_{barrier}})^2 + (\frac{dt_{sample}}{t_{sample}})^2} \ . \qquad \text{(Eq.18)}$$

According the the digital timer and photogate manual, the smallest allowable barrier is 3 millimeters in width or 0.12 inches, and this can be machined on a mill to within 0.005 inches. A barrier of this width results in a t_{sample} of 6.67 x 10^-4 seconds. Substituting these values and the impact velocity requirement of 15 feet per second into the equation for velocity error results in an impact velocity error of 0.625 feet/second.

However, the blind is accelerating through the photogate and this leads to a second error in velocity measurement. The photogate is actually measuring the average velocity of the blind through the gate, and so the error due to acceleration is given by one half the change in velocity through the gate.

The change in velocity is given by

$$\Delta v = \sqrt{2gw_{barrier}}\ , \qquad \text{(Eq.19)}$$

and the error in velocity is given by:

$$dv_2 = \frac{1}{2}\Delta v\ . \qquad \text{(Eq.20)}$$

This results in a velocity error due to acceleration of 0.40 feet per second. The total error in velocity is then given by

$$dv_{total} = \sqrt{dv_1^{\ 2} + dv_2^{\ 2}}\ , \qquad \text{(Eq.21)}$$

which yields a total velocity error of 0.743 feet per second.

Total Bias Error

The bias errors due to initial cushion thickness, crush efficiency, and impact velocity measurements shift the peak acceleration distribution. Each error's contribution to the shift is assumed to be random and independent of the other errors. Therefore these errors can be combined using the general rule for combination of errors:

$$G_{shift} = \sqrt{(\frac{v}{g\eta\tau})^2 dv^2 + (\frac{v^2}{2g\eta^2\tau})^2 d\eta^2 + (\frac{v^2}{2g\eta\tau^2})^2 d\tau^2}\ . \qquad \text{(Eq. 22)}$$

This results in a total bias error of 10.93 Gs, which means our peak acceleration distribution could be shifted up to 10.93 Gs due to measurement errors.

Final Cushion Thickness Error

Final cushion thickness is calculated using the equation:

$$\tau_{final} = \frac{v^2}{2g(G - \Delta G)\eta}, \qquad \text{(Eq.23)}$$

where (v) is the impact velocity requirement of 15 feet/second, and (G) is the impact deceleration limit of 50. Crush efficiency (η) has an error of +/- 3.75%, and (ΔG) is defined as the two standard deviation G variation on the peak acceleration distribution plus a random error of +/- 5.43g not due to variation in attenuator material properties.

Using the general rule for combination of errors, the error in the final cushion thickness as a function of the error in crush efficiency and the error in ΔG is given by

$$d\tau_{final} = \sqrt{\left(\frac{v^2}{2g\eta(\Delta G - G)^2}\right)^2 d\Delta G^2 + \left(\frac{v^2}{2g\eta^2(\Delta G - G)}\right)^2 d\eta^2}\ , \qquad \text{(Eq .24)}$$

where we estimate an approximate value for ΔG to be 15. This yields an error in final cushion thickness of 0.025 ft or 0.30 inches.

Notice the bias errors do not affect the error in the final cushion thickness. This is because the bias errors only serve to shift the mean of the distribution, and do not affect its spread. Thus they do not affect the relative distance of two standard deviations from the distribution mean.

Pre-deployment Volume Error

The pre-deployment volumes are calculated differently for honeycomb and expanding foam. Since honeycomb maintains the same volume in the pre-deployment stage and post-deployment stage, pre-deployment volume is calculated by multiplying the payload base area by the final cushion thickness. An expanding foam impact attenuation material is different in nature. The foam expands to the final cushion thickness after deployment. Therefore, the final cushion thickness dictates how many Instapak Quickpak expanding foam bags are necessary to achieve desired impact attenuation. These bags are then submerged in a beaker and the water displacement volume yields expanding foam pre-deployment volume.

The predeployment volume for the honeycomb impact attenuation material is given by:

$$V_{honeycomb} = A_{base} * \tau_{final} , \qquad \text{(Eq.25)}$$

where the error in the pre-deployment volume of honeycomb is a function of the error in final cushion thickness and base area measurements. Assuming each side of the 15" x 18" payload base is constructed to within 1/16", the error in the base area measure is 0.010 square feet or 0.122 square inches.

The error in the predeployment volume of honeycomb is given by:

$$dV_{honeycomb} = \sqrt{A_{base}{}^2 d\tau_{final}{}^2 + \tau_{final}{}^2 dA_{base}{}^2} , \qquad \text{(Eq.26)}$$

where the base area is 15" x 18" or 1.875 square feet with an error of 0.010 square feet, and the final cushion thickness is approximated to be 2.5" or .208 feet with an error of 0.0483 feet. This yields a volume error of 0.047 cubic feet and results in an 11% error in volume based on the approximate final cushion thickness and payload base.

The error in predeployment volume for the expanding foam material is more difficult to calculate without physical access to the Instapak foam bags. However, the pre-deployment volume will be integer multiples of the unexpanded foam bag volume. It appears that each foam bag expands to approximately 3 or 4 inches in thickness, which would likely make the effect of a 0.5 inch error small.

The experiment primary hypothesis states that expanding foam occupies at least 75% less pre-deployment volume than paper honeycomb. In order to definitively evaluate this metric to an accuracy such that the hypothesis can be assessed, we must show one of two results:

1) To prove the hypothesis true, we must show that the pre-deployment volume of expanding foam is at least 86% less than the pre-deployment volume of paper honeycomb.

2) To disprove the hypothesis, we must show that the pre-deployment volume of expanding foam is at most 64% less than the pre-deployment volume of paper honeycomb.

This analysis was carried out using estimated values for crush efficiency, two standard deviations from the peak acceleration distribution mean, and final cushion thickness. Once the experiment has been conducted, this analysis can be updated with experimental values for these quantities.

11.2.3 Summary of Error Analysis Implications for Proving/Disproving Primary Hypothesis

The first metric in the primary hypothesis states that expanding foam occupies at least 75% less pre-deployment volume than paper honeycomb. In order to definitively evaluate this metric to an accuracy such that the hypothesis can be assessed, we must show one of two results:

1) To prove the hypothesis true, we must show that the pre-deployment volume of expanding foam is at least 86% less than the pre-deployment volume of paper honeycomb.
2) To disprove the hypothesis, we must show that the pre-deployment volume of expanding foam is at most 64% less than the pre-deployment volume of paper honeycomb.

The second metric in the primary hypothesis states that expanding foam has a crush efficiency of no more than 30% less than honeycomb's crush efficiency. In order to definitively evaluate this metric to an accuracy such that the hypothesis can be assessed, we must show one of two results:

1) To prove the hypothesis true, we must show that the crush efficiency of expanding foam is no more than 26.25% less than the crush efficiency of paper honeycomb.

2) To disprove the hypothesis, we must show that the crush efficiency of expanding foam is more than 33.75% less than the crush efficiency of paper honeycomb.

12.0 Project Planning

12.1 Budget

The budget required to carry out this experiment totals $553.90 and is summarized in Table 7.

Table 7: Budget

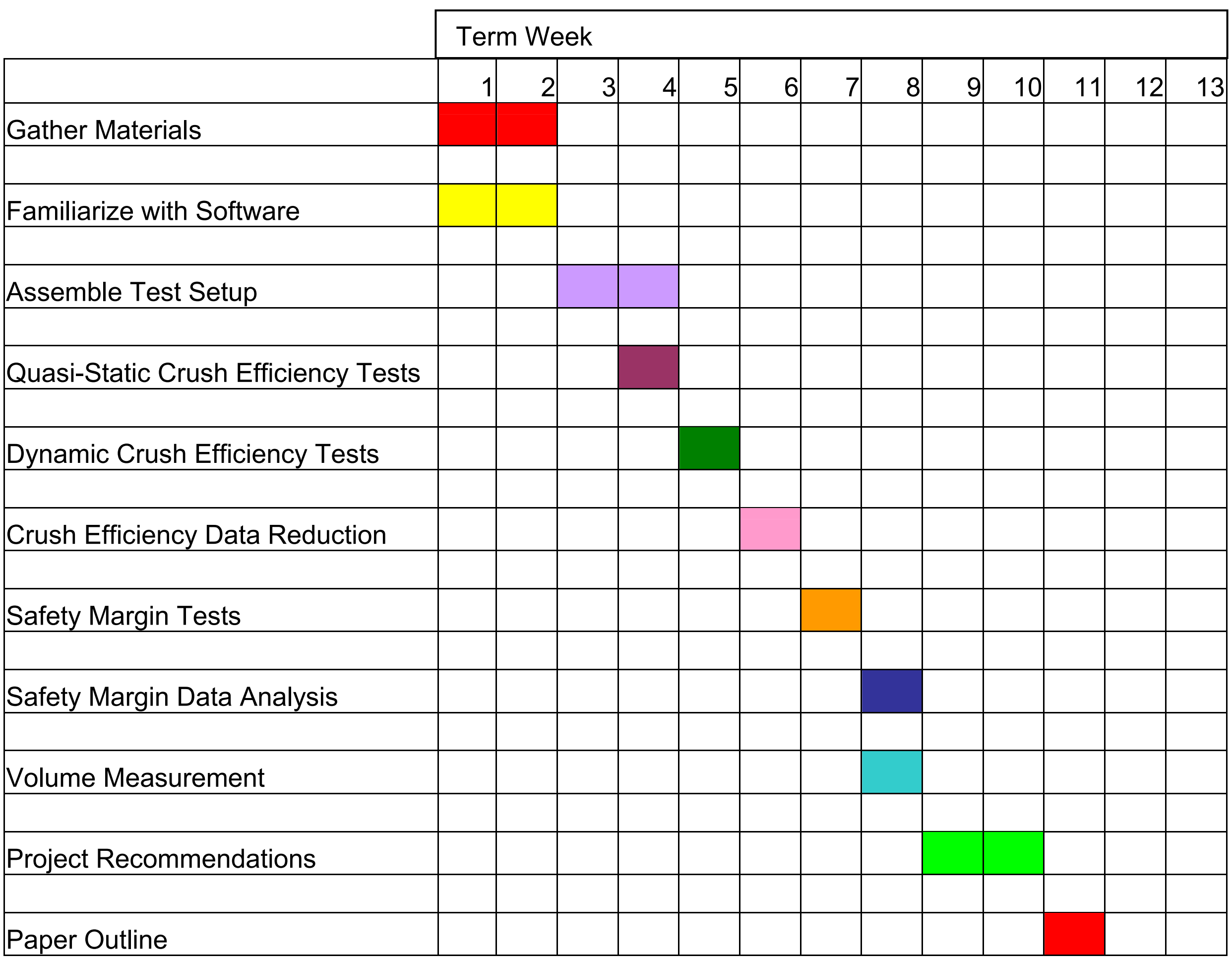
Part, Material, Instrumentation to be Purchased	Quantity	Price ($)
72" long, 1/2" diameter shafts for rails	2	83.94
Instapak Quick Foam Packaging bags	2 cartons of 48 bags	263.00
9" by 12" Instapak Quick Warmer (18 bag capacity)	1	189.00
1" by 1" thick bass wood blocks	5 pieces, 1 ft long each	10.00
3000 ml Beaker with 50 ml increments	1	7.92
Total		553.90

12.2 Detailed Schedule for Fall Term 16.622

The fall term 16.622 schedule mandates that a maximum of ten and a half weeks be devoted to data collection. The project detailed schedule includes goals for all ten and a half weeks with weeks of high workload interspersed with weeks of light workload. This provides a scheduling buffer in case of project delays and will help in balancing the 16.622 workload with other class work. The last few weeks of the fall term are devoted to drafting a Jointly Authored Paper and preparing a Final Oral Presentation.

The 16.622 general project schedule is presented in Table 8. A more detailed schedule follows.

Table 8: Fall Term Project Schedule



Final Oral Presentation													
Final Written Report													

Week 1: September 2-7th

- Gather building materials for the drop-test rig and store near the Building 33 Strongwall.

Week 2: September 8-14th

- Gather building materials, instrumentation, and impact attenuation materials
- Familiarize with Labview and High Speed Camera software
- Report progress at Team Meeting

Week 3: September 15-21st

- Assemble drop-test rig and payload box with instruments
- Continue to familiarize with Labview and High Speed Camera software

Week 4: September 22-28th

- Connect and verify instrumentation with software
- Conduct quasi-static crush efficiency tests in the advanced composites lab TELAC
- Prepare for Oral Progress Report

Week 5: September 29th – October 5th

- Conduct drop-tests to measure dynamic crush efficiency
- Present Oral Progress Report

Week 6: October 6-12th

- Perform data reduction on quasi-static and dynamic crush efficiency tests

Week 7: October 13-19th

- Conduct safety margin tests

Week 8: October 20-26th

- Analyze safety margin data
- Conduct pre-deployment volume measurements

Week 9 & 10 : October 27th – November 13th

- Form project recommendations based on secondary hypothesis

Week 11: November 13-18th

- Prepare outline for Jointly Authored Paper

Week 12: November 18- 25th

- Prepare Final Oral Presentation

Week 13: November 25 – December 9th

- Prepare Final Written Report

12.3 Facilities, Tech Staff Support, and Space Needed

Quasi-static crush efficiency tests will be carried out in the advanced composites lab TELAC and drop-testing to evaluation dynamic crush efficiency and safety margins will be conducted near the Strongwall in the Building 33 hangar. A two foot by two foot by seven foot tall area will be needed near the Strongwall to set up the drop-test rig. An additional five foot by five foot floor space will be necessary to set up instrumentation for data acquisition. The expertise of John Kane will be necessary in familiarizing with the Instron force press in TELAC, and the expertise of Richard Perdichizzi will be helpful in constructing the test rig apparatus and setting up instrumentation.

13.0 Project Summary

The purpose of this experiment is to evaluate the material properties of expanding foam as an impact attenuator for the small payloads deployed from unmanned aerial vehicles. By quantifying nominal pre-deployment volumes and crush efficiencies of expanding foam and honeycomb, this experiment is the first step in assessing the viability of using expanding foam as an inexpensive and reliable low-impact attenuator.

14.0 List of References

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Appendix A: Detailed Drawings of Apparatus

(next four pages)

Appendix B: Detailed Parts List

Borrowed Parts, Tools and Materials	**quantity**
Winch	1
Pulley	1
Quick release	1
Rope wire	30 ft
McMaster shaft supports	4
McMaster Ball Bearings	4
2lb and 5lb Weights	45 lb
21" by 48" by 0.7" plywood	1 board
Saw	1
Drill	1
Hammer	1
0.25" thick aluminum sheet for blinder	1
Metal L to mount photo-gates	1
Duct tape	2 rolls
Industrial adhesive	1
Screws for shaft supports	8
Screws for ball bearings	8
Screws to bolt weights	5
1 1/2" long Wood screws	20
1/2" thick Paper Honeycomb (Hexacomb 700 from Pactiv Corporation)	4 sheets 96" by 48"
1" thick Paper Honeycomb (Hexacomb 700 from Pactiv Corporation)	8 sheets 96" by 48"
Unistrut Metal Framing® components	
Unistrut channelled sections with smooth faces	2 beams >= 25"
	4 beams >= 19"
	1 beams >= 14"
Spring nuts	8
Fittings	4
I-beams	5
Borrowed Instrumentation	
Accelerometer	1
High-Speed camera	1
Photo-gates and digital timer	1 set
Analog to Digital board for accelerometer	1
Computers for data acquisition	2
Ruler	1

Appendix C: Specification Sheet For Purchases

Part, Material, Instrumentation to be Purchased	Quantit y	Purchase Specification	Suppliers
72" long, 1/2" diameter shafts for rails	2	McMaster Carr Catalog Number 6061K93	order from McMaster.com
Instapak Quick Foam Packaging bags	2 cartons of 48 bags	SealedAir Corporation Catalog Number IQH0000-10	Chiswick Trading (Tel. 1 800 225 8708)
9" by 12" Instapak Quick Warmer (18 bag capacity)	1	SealedAir Corporation Catalog Number IQW0000-15	Chiswick Trading
1" by 1" thick bass wood blocks	5 pieces, 1 ft long each	Not Applicable	Pearl Arts and Crafts Stores
3000 ml Beaker with 50 ml increments	1	McMaster Carr Catalog Number 9896T4	order from McMaster.com