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Evaluating Impact Attenuator Performance for a Formula SAE Vehicle

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ABSTRACT

Formula SAE® is one of several student design competitions organized by SAE International. In the Formula SAE events undergraduate and graduate students are required to conceive, design, fabricate and compete with a small, formula-style, race car. Formula SAE safety rules dictate a 7 m/s (or approximately 15.65 mph) frontal crash test for nose mounted impact attenuators. These rules are outlined in section B3.21 of the Formula SAE rule book. Development and testing methods of these energy absorbing devices have varied widely among teams. This paper uses real world crash sled results to research methods for predicting the performance of aluminum honeycomb impact attenuators that will comply with the Formula SAE standards. However, the resulting models used to predict attenuator performance may also have a variety of useful applications outside of Formula SAE. In this paper, various energy absorbers were mounted to a free rolling trolley sitting on top of a crash sled. The sled was launched so that the trolley with the attached attenuator was allowed to strike a rigid barrier. This resulted in a sudden deceleration measured by accelerometers attached to the trolley. The resulting deceleration from each impact attenuator was then correlated to predicted pulses from theoretical calculations. The lessons learned from extensive testing will be discussed including comparisons between size, shapes, and material properties of energy absorption devices. Additionally, a final theory will be presented describing the ideal way to predict impact attenuator performance. Ultimately it will be shown that, given a known geometry, material properties, and safety factor, the behavior of an impact attenuator can be predicted accurately enough that testing will only be needed as verification. This study will ultimately benefit all Formula SAE® teams, as it will help speed up development time and cut costs, while providing a

proven method for creating attenuators that will perform to SAE standards.

INTRODUCTION

OBJECTIVE

The Formula SAE® rules require the use of an impact attenuator mounted to the front bulkhead of the vehicle. An example of an impact attenuator is shown in [Figure 1](#).



Figure 1. Front Impact Attenuator Affixed to the Front of a Formula SAE vehicle

The objective of this paper is to validate the design of an aluminum honeycomb impact attenuator while developing the ability to predict its performance analytically. Findings will

be supported through mathematical explanations and various testing. Following a detailed description of the theory, test procedure and results, suggestions will be provided concerning the proper manner to conduct impact tests so that results are both accurate and consistent.

This paper will ultimately serve as a potential guideline for future Formula SAE® teams who wish to undertake their own testing. It also may answer questions regarding general crash safety center procedures, should any teams wish to utilize the services of crash safety facilities.

BACKGROUND

Section B3.21 in the 2009 Formula SAE® rules states that the impact attenuator should be capable of decelerating a 300 kg (661 lb) vehicle from 7.0 m/s (23.0 ft/s) such that an average deceleration of 20 g's and peak of 40 g's should not be exceeded [1]. Development and testing methods of these energy absorbing devices have varied widely, ranging from drop tests to manned barrier tests. Some of the validation test methods employed by Formula SAE teams have been decidedly unsafe. Crash centers are ideal for collecting reliable data with maximum regard to safety. The deceleration sled in Kettering University's Crash Safety Center was used for this paper to research methods for predicting the performance of various impact attenuators designed to comply with the Formula SAE® standards. The intent is to define a reliable, common way to design an attenuator that will meet Formula SAE® standards.

METHODOLOGY

ATTENUATOR THEORY

Impact attenuators are designed to reduce the peak deceleration that occupants might experience in the event of a frontal crash. A properly designed attenuator should lower the peak acceleration by managing the time variable, or more specifically, by elongating the time it takes to come to a rest so that the occupant can take advantage of “ride down”. Ride down is the effect of the vehicle structure dissipating energy through crush. Ride down is only effective if occupants are restrained properly, meaning they must be fixed to the vehicle.

How impact attenuators manage deceleration is referred to as the “crash pulse” or simply “pulse”. The shape of the pulse shows how an object decelerates over time. The basic advantage of designing an attenuator using aluminum honeycomb is that it provides a relatively constant rate of deceleration as the honeycomb crushes and dissipates energy.

As shown in [Figure 2](#), the force required to crush an aluminum honeycomb attenuator ramps up very quickly before becoming nearly constant and oscillating around an average crush force. The peak occurs just left of the dashed

blue line. Typically, the honeycomb is pre-crushed by a small amount (6 mm or so) to eliminate the initial peak during subsequent compression events. Therefore, these attenuators can be effectively modeled as constant deceleration devices, meaning they are also constant force absorbers because force is simply a scalar of acceleration.

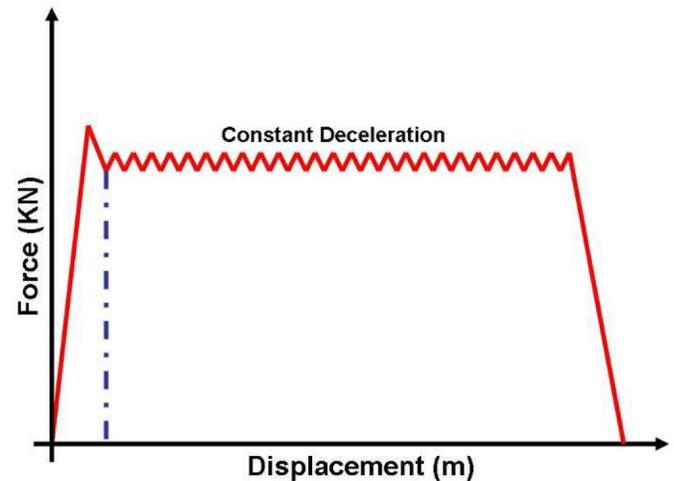


Figure 2. Typical Crush Characteristics of an Aluminum Honeycomb Impact Attenuator

The crush strength (P_{CR}) for the honeycomb is found by taking the average crush strength (F_{CR}) and dividing by the cross-sectional area (A_{CS}) of the test specimen. Basic variables are standard so that mass is symbolized as m , force as f , gravity as g , and weight as W . Since the crush strength is essentially constant, the deceleration resulting from crushing a section of honeycomb with a uniform cross-sectional area is essentially constant and can be found from:

$$F = (m)(a) = (P_{CR})(A_{CS}) \quad (1)$$

$$a_{avg} = \frac{(P_{CR})(A_{CS})}{m} = \frac{(P_{CR})(A_{CS})g}{W} \quad (2)$$

The equation shows that the average deceleration rate can be controlled by properly selecting the honeycomb materials crush strength and cross-sectional area.

By applying the well-known constant rate of acceleration formulas, other relationships can be determined. For instance, the nominal time for the vehicle to be brought to a stop can be found from:

$$v = v_0 + (-a_{CR})(t_{CR}) \quad (3)$$

$$t_{CR} = \frac{v_0}{a_{avg}} = \frac{(W)(v_0)}{(P_{CR})(A_{CS})(g)} \quad (4)$$

$$a_{avg} = \frac{v_0}{t_{CR}} \quad (5)$$

The resulting equations show that a longer duration (higher t_{CR}) pulse will reduce the average rate of deceleration. As shown in a different manner, the crush strength and cross-sectional area are the primary variables for controlling the pulse duration.

Equation 7 is another constant acceleration formula that may be used to determine the length of material that must be crushed to absorb the impact energy. Note that v_i stands for initial velocity, v_f for final velocity, and S_{CR} denotes the difference in attenuator length after it has been impacted.

$$v_f^2 = v_i^2 + 2(-a_{CR})(S_{CR}) \quad (6)$$

$$S_{CR} = \frac{v_i^2}{2(a_{CR})} = \frac{(W)(v_i^2)}{2(g)(P_{CR})(A_{CR})} \quad (7)$$

An alternative approach to determining the crush stroke is to apply conservation of energy, which can be expressed as:

$$E_{Incoming} = E_{Crush} + E_{Rebound} \quad (8)$$

$$\frac{1}{2}(m)(v_i)^2 = (P_{CR})(A_{CS})(S_{CR}) + \frac{1}{2}(m)(v_f)^2 \quad (9)$$

Performing an energy balance can predict the amount of energy in the system before impact, the energy absorbed by the attenuator, and any energy left over after impact. The energy absorbed by the attenuator should always be less than the energy before impact because of losses due to heat and friction. Additionally, aluminum honeycomb is not an "ideal" attenuator, so not all of the energy will be absorbed. The energy not dissipated will cause the trolley to bounce off the barrier. Therefore, Equation 9 says that the kinetic energy of the trolley moving down the rails and into the barrier is equal to the energy dissipated by the attenuator plus the kinetic energy left over when the trolley rebounds. The velocity is known to be zero immediately after the impact. The velocity was positive as the trolley was heading toward the barrier,

decelerated to zero, and then began moving backward in the negative direction. The quantity v_f is the peak velocity after impact when the attenuator has rebounded off of the barrier.

COMPRESSION TESTING

The attenuator testing conducted for this paper utilized aluminum honeycomb from Plascore rated at a crush strength average of 1689 kPa (245 psi) $\pm 10\%$. It is important to verify these ratings to quantify the relative variation during the crash testing between attenuators. If crash test results contain any anomalies, prior verification of the material's average crush strength will make it easier to rule out possible inconsistencies in the material.

The compression tests conducted followed the ASTM D 7336 entitled "Standard Test Method for Static Energy Absorption Properties of Honeycomb Sandwich Core Materials" [2]. In summary, it consists of crushing samples of honeycomb between two flat faces at a constant change in displacement. The resulting force to crush the sample is measured by a load cell, in this case in pound-force. Additionally, ASTM D 7336 described the proper sized area of the crushed face and depth of the sample as a function of the honeycomb cell size [2]. A 6000lb (approximately 27 KN) load cell was used to collect the data for these tests.

When the aluminum honeycomb is cut there are partial cells left behind which may alter the crush properties. Therefore, the largest square cross-sectional area that would not exceed the capacity of the load cell was selected because a larger area lessens the effect of the edges. Additionally, sectional area was also influenced by the amount of force it will take to crush. A size of 103.225 square centimeters (4 in \times 4 in) was chosen so at an average crush pressure of 1689 kPa the sample should hold approximately 17.4 KN before crushing. It was imperative that the expected load required to crush the attenuator was large enough to accurately read without exceeding the load cell limit of 27 KN. A $\pm 15\%$ margin of error was used because it was uncertain whether or not the sample would truly crush at 1689 kPa. If the samples were within the specified manufacturer tolerances they should fall somewhere between 14.8-20 KN ($\pm 15\%$).

Plascore noted in their brochures that the material properties of their aluminum honeycomb material are consistent until about 70% of the length of the sample is used up. Following this logic, the samples utilized for these tests were 10 in (25.4 cm) long so they could have been crushed up to 7 in (17.78 cm). After this point, the sample will start to experience "stack-up" which is the point when the material becomes overly compressed. When stack up occurs the material has no more room to buckle, forcing the resistance to increase. Once stack up occurs, the material will be outside of the acceptable range for which it is designed. Therefore, the samples should

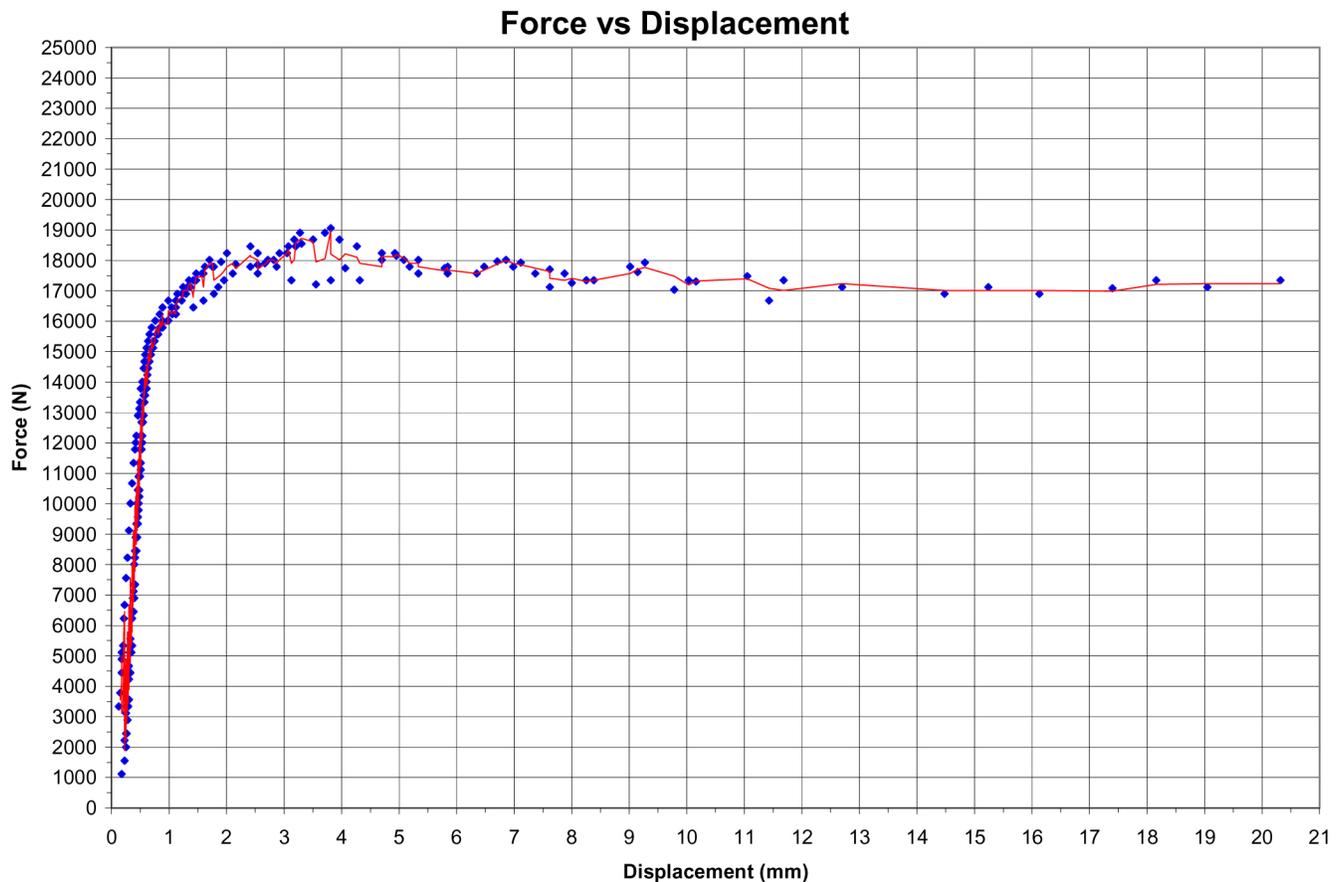


Figure 3. Compression Test Data: Average Load versus Displacement

not be crushed far enough to risk stack-up, or the results of the compression test will not be accurate.

Figure 3 depicts the average load versus displacement of four samples. The samples continue to bear the load to a given point before crushing at a nearly constant and uniform rate. During the compression testing it was observed that none of the samples began to fail until about 17.8 kN, after which, each sample began to crush very consistently. The aluminum folded over in tiny little buckles on the pre-crushed end causing the load to fluctuate between 16.9 and 18.2 kN. Like an accordion, as each small buckle gave way, the load cell reading would abruptly drop and then begin to climb again until the next buckle appeared. As can be seen in Figure 3, after reaching an initial peak, the load that was required to continually compress the honeycomb became relatively constant.

All the compression tests yielded results within the manufacturer tolerance of $\pm 10\%$ of 1689 kPa, as shown in Table 1 where P_{CR} denotes the average crush force required to crush the samples. All the samples held a little more than 17.4 kN, especially Test Sample #2 which held 9.4% more than expected. Test sample #3 held the least, at just 2.4% higher than expected. From this data it can be concluded that

Plascore's rating of 1689 kPa with an error of $\pm 10\%$ is accurate. Note that the material tolerance should be considered when designing an impact absorber so that all attenuators of the same design, using the same material, will pass Formula SAE® rules if tested.

Table 1. Compression Test Results

Test	P_{CR} , expected (kPa)	P_{CR} , measured (kPa)	Difference %
1	1689	1788	5.9
2	1689	1849	9.4
3	1689	1730	2.4
4	1689	1831	8.4
Measured Average:		1800	6.1

To summarize the compression results, the average crushing force or the force required to *continue* crushing the attenuator, is close to the rated 1689 kPa. However, the average of the compression tests was slightly higher at 1800 kPa. Therefore, 1800 kPa will be used instead of Plascore's recommended 1689 kPa for the calculations throughout the rest of this paper. Also note that this test is a static test, because the honeycomb was slowly loaded to the point of failure. This usually results in lower average crush force

values then dynamic tests where the attenuator is smashed into a barrier at speed. However, the average crush force varies with the speed of the attenuator at impact. For this reason the static average crush force is usually a more constant variable to work with.

IMPACT TEST APPARATUS

In typical use, the Kettering Crash Safety Center declaration sled generates a crash pulse by using compressed air to propel the crash sled (or “bed plate”) along the sled track and into the decelerator. For testing Formula SAE® impact attenuators, a trolley was added which rolls independently on a pair of rails on top of the deceleration sled. The trolley served as a fixture for holding the impact attenuator. Ballast was added to the trolley to bring its weight to 300 kg (661 lb). During a test, the crash sled and trolley were accelerated to 7 m/s (23.0 ft/s). The crash sled is stopped by the decelerator. At this point, the trolley continues to move (at 7 m/s) independent from the sled until it contacts the impact structure. The test rig is shown in [Figure 4](#).

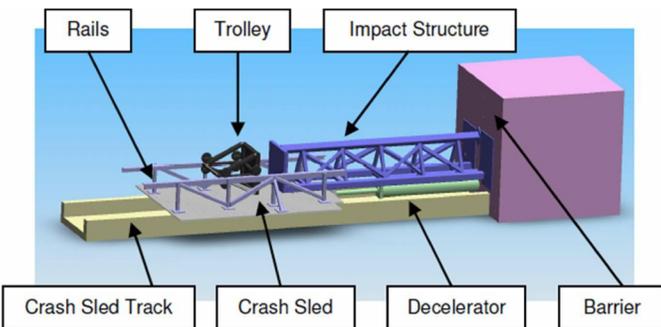


Figure 4. Impact Attenuator Test Apparatus

The impact structure is a rigid, non-deformable structure that the trolley will crash into. The attenuator will be taped to the front of the trolley so it will be caught in the middle and crushed. The impact structure is bolted directly to the barrier, a massive block of cement at the end of the sled. The impact structure only requires a switch secured by tape, which will trigger the data acquisition box the moment the attenuator first touches the barrier. This event will be recorded as time equals zero seconds in the data file.

The trolley rides on top of the sled on another set of rails, and is captured by wheels on both the top and bottom of the rail, as well as a retaining bar along the back to prevent it from sliding off. The trolley is positioned against this retaining bar before each test and is allowed to roll freely into the barrier. The attenuator is taped securely to the flat, non-deformable face of the trolley.

The trolley is the only component of this test that needs to be instrumented. During testing, two Endevco 7290A-100 accelerometers were positioned in the middle of the trolley

behind the face plate. It is important to make sure the accelerometers are as close to the centerline as possible, because the trolley, much like the main sled, could “shimmy” slightly about the centerline as it travels down the rails. Even a small side-to-side movement may introduce unwanted noise in the data if the accelerometers are positioned closer to one side of the trolley. Two accelerometers were used as a check to ensure they were both reading correctly.

The crash sled is brought to a rest by the tunable piston that is normally used to generate the pulse. For Formula SAE® tests it is important to note that deceleration piston has no bearing on the test. It merely stops the main sled, while the trolley begins to move down its own set of rails until it is brought to rest by the attenuator on the front of the sled. The accelerometers mounted on the trolley record the numbers of g's with respect to time. From this data, a graph is generated of acceleration with respect to time which will describe how the tested attenuator behaves in the event of an impact.

DATA FILTERING & ANALYSIS

The Kettering Crash Safety Center uses EVALuation® software to filter and process the information from the accelerometers. EVALuation® is a Kayser-Threde edition of Berlin-based IAT's software. Data is collected from a Kayser-Threde data acquisition system and the accelerometers are filtered per SAE standard J211 [3]. EVALuation constructs a graph of acceleration versus time in g's and milliseconds, respectively.

The analysis of these graphs is very important, as both the peak and average deceleration can be determined from this data. As discussed earlier, the Formula SAE® criteria stipulate that the maximum deceleration cannot exceed a peak of 40g's and an average of 20g's. Therefore, the best performing attenuator will display a combination of the lowest number of peak gs as well as the lowest number of average gs.

[Figure 5](#) is an example of what data from an impact attenuator test might look like. This is included only as an example, so that important points can be clarified. The acceleration of the trolley is shown in red, velocity in blue, and displacement in green, which will be the standard output for actual data shown later. Please note that this data could look inverted to some people, as different facilities report data differently. Since the trolley was decelerating, data collected for this paper was reported as negative gs. Some crash centers will flip the graph to appear positive, despite the fact that the sled is actually decreasing speed as the impact occurs.

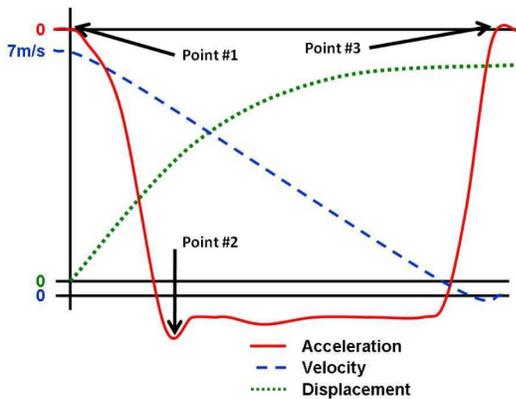


Figure 5. Typical Graph of Acceleration, Velocity and Displacement

Point #1 in [Figure 5](#) is roughly where the attenuator on the face of the trolley just starts to impact the face of the barrier. It will show a small deceleration before the velocity (blue line) is affected. The deceleration will increase quickly such that Point #2 will be the peak number of gs. The velocity will then decrease until Point #3. At this time, the acceleration plot will cross zero and the velocity should also briefly become zero. This is where the trolley has come to a complete stop, and will begin to rebound. The more energy the attenuator dissipates, the less rebound. The rebound is apparent after Point #3, where the velocity becomes negative (it is traveling in the opposite direction), and the acceleration becomes positive.

EVALuation generates a file of data points that can be imported into a spreadsheet. Point #1 and Point #3 ([Figure 5](#)) are the boundaries of the acceleration curve so the data inside these points should be summed and divided by the amount of data points. This will result in a close approximation of the average acceleration over the course of the entire pulse.

Ideally, all the energy would be absorbed by the perfect attenuator causing the trolley to come to a complete stop without rebounding. The ideal attenuator would rapidly decelerate as load is applied to the attenuator until plastic deformation occurs causing it to crush in a constant, uniform pattern. This will appear on the acceleration curve as a nearly flat top. When the kinetic energy is used up and the object being brought to a rest slows down, the acceleration will rapidly drop back to zero. Aluminum honeycomb material can mimic that of an “ideal” attenuator quite well, as long as it is pre-crushed. Pre-crushing a sample is when the leading face of an impact attenuator experiences enough pressure to cause a small amount of deformation.

The sole purpose of pre-crushing honeycomb is to take away the initial peak in the resistance. [Figure 6](#), is an example of the difference of an ideal pre-crushed specimen as opposed to an ideal attenuator that may not have been pre-crushed. In

certain dynamic events some attenuators will experience an early spike in deceleration as the attenuator is loaded to the point of initial failure. Less force is required to continue to crush the impact attenuator after the initial material failure so the rate of deceleration will decrease and become consistent until the energy is depleted enough that it can no longer deform the attenuator.

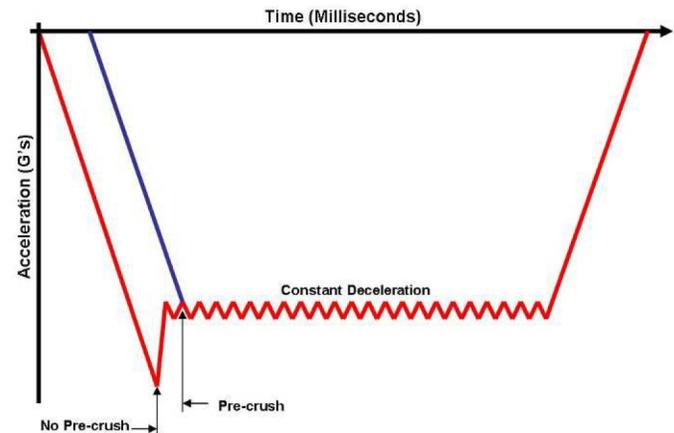


Figure 6. Pre-Crushing Effects on Attenuators

The pre-crushing method mitigates and sometimes eliminates initial spike because it shifts the materials elastic modulus. If a component is plastically deformed and then the pressure is released, the next time it is loaded the whole stress-strain curve will shift to the right. This means plastic deformation the second time around will pick up where pre-crushing ended.

When pre-crushing attenuators it is important to load the face of an impact attenuator evenly until it the end fails just enough to create a few small, even buckles. A deformation of 5 mm should be more than enough to significantly lower the peak deceleration that the attenuator will exhibit during an impact.

MAIN TEST RESULTS

Four impact attenuators were tested utilizing the deceleration sled trolley. All were rectangular cubes, used the same aluminum honeycomb and were rated at the same average crush force. [Table 2](#) outlines the size of each attenuator for each test. The minimum requirements for Formula SAE are a height, width, and length of 10 cm, 20 cm, and 20 cm respectively.

Table 2. Attenuator Dimensions

Test	Type	hght	wdth	lngth	area	vol.
----	----	(cm)	(cm)	(cm)	(cm ²)	(cm ³)
#01	cube	15.56	22.86	25.4	355.6	9033.4
#02	cube	14.61	20.32	25.4	296.8	7538.1
#03	cube	14.29	20.32	25.4	290.3	7374.2
#04	cube	14.29	16.83	25.4	240.4	6106.7

Equations 1,2,3,4,5,6,7,8,9 were used to predict the crush characteristics of each attenuator. The predicted values versus the actual results are shown in [Table 3](#).

Table 3. Predicted Total Crush vs. Actual Crush & % Difference

Test	Speed (TEMA)	Pred.	Actual	Diff.
----	V(m/s)	S (cm)	S (cm)	%
#01	7.06	11.65	9.95	14.6
#02	6.80	12.98	13.00	-0.2
#03	6.83	13.37	13.23	1.1
#04	6.79	15.98	15.84	0.9

[Table 3](#) shows the method used to predict an attenuator's performance during the design phase appears to work, though there is a small difference between actual and predicted crush. This suggested some of the energy was being used up in another manner besides crush. One way energy lost is through heat which is apparent after a test when the attenuator is often a bit warm. However, the quantity of energy lost to heat is probably not significant enough to be within the scope of this paper.

Energy lost to rebound was also taken into consideration. The quantity of energy left over after the impact determines the rebound velocity. This left over energy is an indicator of how effectively the attenuator absorbed the energy of the impact. Essentially, the greater the rebound speed, the less effective the attenuator must have been at dissipating the kinetic energy of the trolley.

The accelerometers on the trolley are typically accurate enough for most tests, but some error may be introduced during the data filtration process, especially when measuring relatively small accelerations. The acceleration and velocity of the trolley as it approaches the barrier is recorded as positive. Therefore, the velocity should have become negative after impact as the sled reverses direction. The filtered data did not report post-impact velocity as negative but the data did show .5 gs of acceleration indicating that the trolley did bounce off of the face of the barrier ([Figure 7](#)). It became clear that the data needed to be investigated after the test video confirmed that the trolley did reverse direction after impact.

To determine the true rebound velocity, a program called TEMA (TrackEye Motion Analysis) by Image Systems AB headquartered in Linkoping, Sweden, was used. TEMA is motion analysis software which uses triangulation to locate the position of points within a high speed video. So to use this program effectively, it was important that the distance between pertinent objects were accurately measured. [Figure 8](#) shows the velocity integrated from the accelerometers are considerably different from the TEMA derived acceleration during the rebound portion of the event. However, the slope of the velocity is the same during the impact (not shown in [Figure 8](#)) which indicates that the actual pulse recorded by the trolley accelerometers should be accurate. As mentioned earlier, the accelerometers may have trouble measuring an event as small as one g, which could be one reason for the discrepancy in rebound velocity. In short, the crash pulse is valid, but the rebound velocity is not. Therefore, data collected from TEMA will be utilized when discussing rebound speed.

The results of the TEMA simulation and the recorded acceleration are shown in [Table 4](#). [Table 4](#) shows acceleration recorded during each of the four attenuator tests.

Table 4. TEMA Derived Incoming Trolley Speed & Predicted Deceleration vs. Actual Deceleration

Test	Speed	Pred.	Actual	
----	(m/s)	Avg. (g)	Avg. (g)	Peak (g)
#01	7.06	20.43	17.62	25.0
#02	6.80	17.05	14.85	19.5
#03	6.82	16.68	14.34	18.5
#04	6.80	13.81	12.41	16.0

[Table 4](#) indicates that the attenuators would have passed Formula SAE® standards, as the peak gs are well under 30, and no average deceleration exceeds 18 gs. The fourth test performed best at about 16 peak gs and under 13 average gs. This is physical evidence that the smallest possible cross-sectional area on an attenuator will yield the best results from an occupant safety standpoint. In accordance, a longer attenuator will have more material to dissipate energy, lowering the peak deceleration. However, the minimum cross-sectional area is limited by the crush stroke, which should be designed to remain safely inside of 70% of the total length.

The first attenuator experienced the highest rebound velocity, and consequently was the least accurately predicted. Additionally, the first attenuator had the greatest cross-sectional area, meaning it required more force to crush. The attenuator will absorb energy at a nearly constant rate until the amount of energy left is no longer enough to overcome the average crush force. At this point it bounces off. The attenuator with the largest cross-sectional area will require

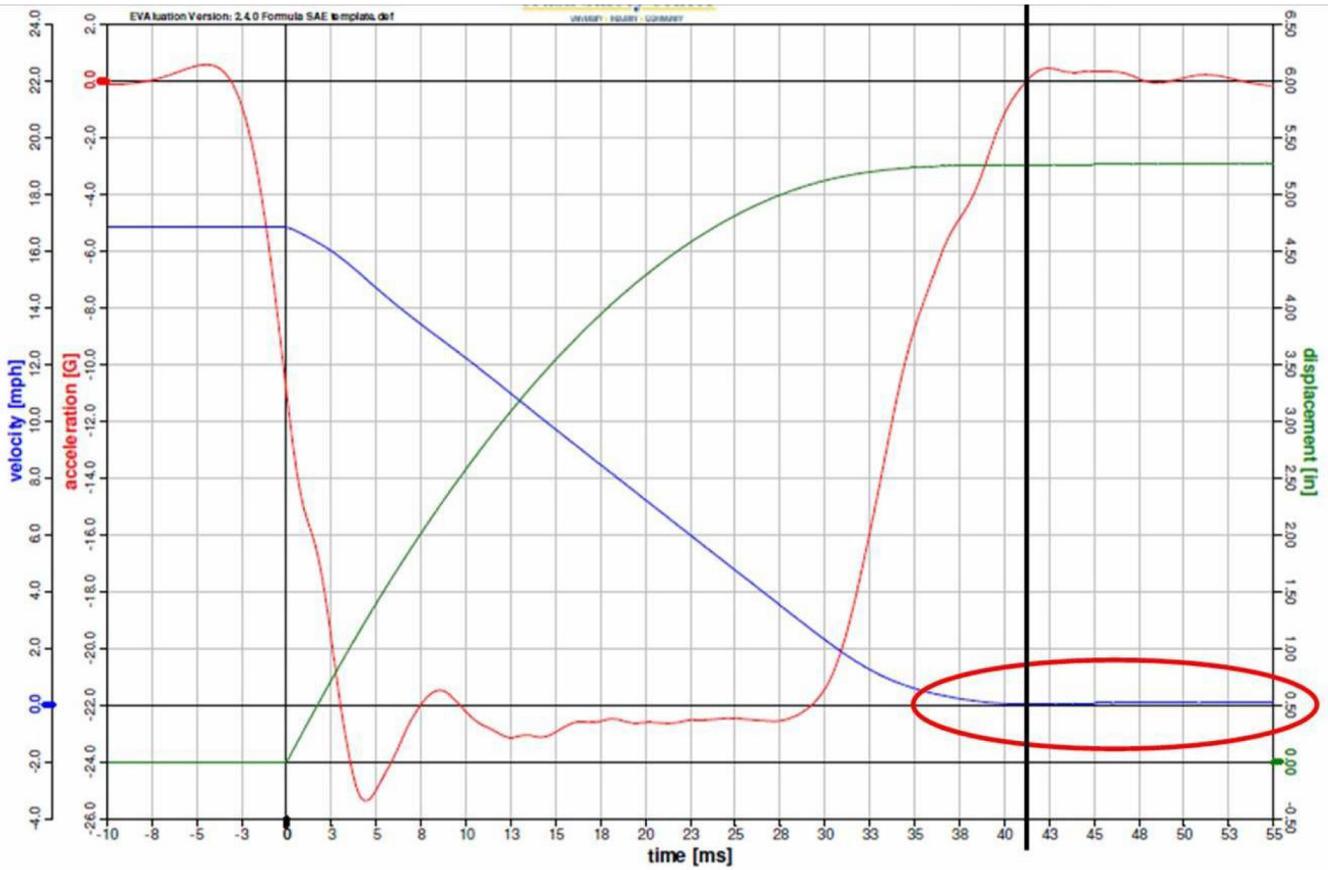


Figure 7. Rebound Phase Accelerometer Error (Circled in Red)

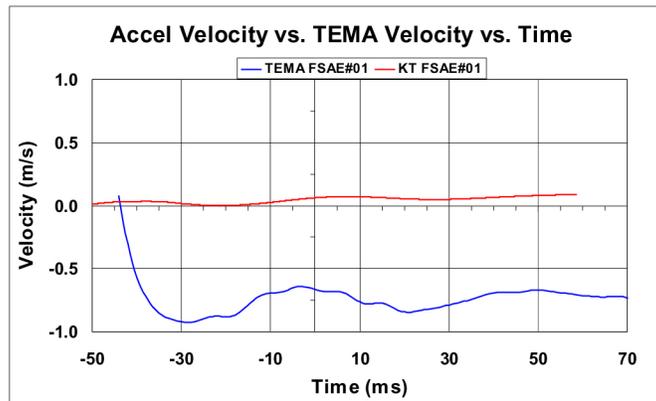


Figure 8. Rebound Portion of Test (TEMA Results Shown In Blue & Accelerometer Integrated Velocity in Red)

the most force to crush meaning the energy left over that it cannot crush, will be greater. Therefore, it makes sense that the first test would experience a greater rebound velocity, while Test 4 exhibited the least amount of g's and the smallest rebound velocity. Table 4 shows the actual peak acceleration for each test, and the first test clearly exhibited the highest peak.

The pre-crushed end of the impact attenuator was mounted on the face of the trolley so all four of the tests conducted crushed at the rear of the attenuator. This behavior was also apparent during the compression tests when the pre-crushed top buckled and the uncrushed bottom did not. Additionally, all four tests displayed relatively constant crush and constant deceleration. Shown in Figure 9 are the deceleration plots for each of the four impact attenuator tests. Notice that the first

Acceleration vs Time of 4 Attenuators

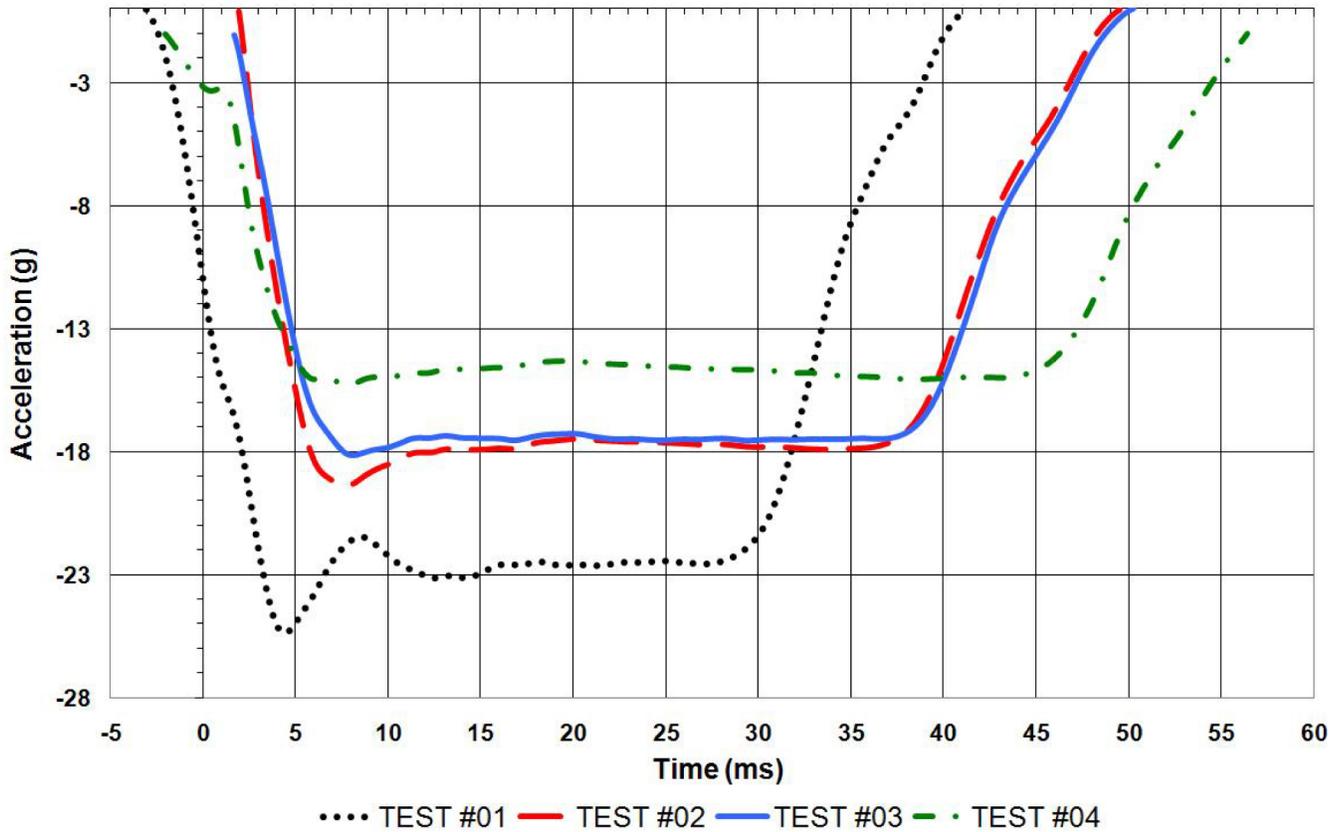


Figure 9. Impact Attenuator Deceleration Results Overlay

test was an outlier in comparison to the other three in that it peaks more than the others.

Impact attenuator performance can be roughly predicted from the energy balance method shown earlier in Equation 9. As shown below, accelerometer values can be plugged into the kinetic energy portion of Equation 9 to determine the amount of energy striking the barrier. This was how the Kinetic energy data from Table 5 was generated. Using the same equation an SAE team can predict the kinetic energy their impact attenuator must dissipate before they test their energy absorption device. The energy absorbed during the crash phase was found using displacement, or volumetric change. The equation for this is $(P_{CR})(A_{CS})(S_{CR})$ which also comes from Equation 9.

$$\frac{1}{2}(m)(v_i)^2 = (P_{CR})(A_{CS})(S_{CR}) + \frac{1}{2}(m)(v_f)^2$$

$$\frac{1}{2}(m)(v_i)^2 = \frac{1}{2}(299.8kg)(7.0563m/s)^2 \approx 7463J = \text{Kinetic Energy} \tag{9}$$

The first test was again the outlier, showing considerable difference between the crash energy and initial energy. This

indicates that there must have been considerably more energy during the rebound phase. As expected, all the other tests show very little difference in total energy absorbed and the incoming kinetic energy, proving that aluminum honeycomb is an effective great impact attenuator material.

Table 5. Effectiveness of Crush Energy Prediction through Volumetric Change

Test	Kinetic (Eq. 5) Energy (J)	Crush (Eq. 5) Energy (J)	Diff. %
#01	7458	6371	14.6
#02	6933	6945	-0.2
#03	6985	6911	1.1
#04	6915	6852	0.9

Besides rebound energy, the reason why all the energy is not accounted for may be attributed to error the calculations. Recall that 1800 kPa was used as the average crush force instead 1689 kPa due to the outcome of the compression tests. Perhaps 1800 kPa is a slight over estimation, which would explain why Test #2 shows that slightly more energy

was dissipated than was initially in the system. Regardless, [Table 5](#) shows that the equations outlined earlier in this paper are very effective for attenuator design, and can be trusted within a reasonable margin.

A slightly more involved, though potentially more accurate method, would be to plot the force versus displacement of the crashing attenuator and integrate to find the area under the curve, which would be the total amount of energy dissipated in the impact. The results from the integration are nearly identical to the crash energy method from [Table 5](#). The results from the integration method are shown in [Table 6](#).

Table 6. Effectiveness of Crush Energy Prediction through Integration

TEST	Crush (Eq. 5)	Integration	Diff.
----	Energy (J)	Energy (J)	%
#01	7458	6766	9.3
#02	6933	6881	0.8
#03	6985	6888	1.4
#04	6915	6881	0.5

Note that either accelerometers or TEMA will be needed to use the integration method because there must be a significant amount of good data points to integrate. Once the data has been collected, choosing the appropriate data to cut out of the file is also important. This means that only the point of impact to the end of impact should be integrated. Other points are not relevant simply because they have nothing to do with the actual impact.

ADDITIONAL TEST RESULTS

TESTING WITH BULKHEADS

Another factor considered in earlier testing was the effect of the bulkhead on the impact attenuator. During this testing, some attenuators were taped directly to the face of the trolley while others were first fastened to a bulkhead representative of that used on Formula SAE® cars.

After looking over the crushed attenuators and comparing the results of some of these tests, it was found that attaching a bulkhead in between the trolley face and attenuator may introduce unwanted variances in the test procedure. This can result in an inaccurate measurement of the attenuator's energy absorption properties. The bulkhead may change the deceleration curve by deforming in its own manner, sometimes even if there is no evidence of bulkhead deformation after the test. For example, some of the video from the old testing shows attenuators crushing normally when attached directly to the face of the trolley, while those with bulkheads often had the rear of the attenuator crushing abnormally.

Removing the bulkhead from the system essentially isolates the attenuator so that its individual properties may be studied. Therefore, it would be ideal to test attenuators flush against the non-deformable face of the trolley, so that the properties of the attenuator itself can be measured without question. As a general rule, all objects other than the attenuator should be non-deformable in order to ensure the most accurate impact attenuator results.

This is not to say the bulkhead is not important. If improperly designed it may deform too much, causing unwanted intrusion into the foot well area. In contrast, it could be designed so stiff that it is impractically heavy or unsafe. For this reason, the impact attenuator should first be isolated from the system and studied independently to ensure it performs properly. Once an energy absorption device has proven itself worthy, it is up to the individual team to make certain that the bulkhead is adequately designed for the attenuator.

CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

In summary, if the equations and methods outlined in this paper are followed, designing an impact attenuator can be very straightforward. Of the four aluminum attenuators discussed in this paper, #1-#3 would have met Formula SAE criteria. While the predicted crush stroke and energy dissipated varied in accuracy, the results have shown that the performance of can be predicted within a few percent. This observation intentionally excludes attenuator #1, because it was felt that this sample was an anomaly and should be treated as an outlier.

While attenuator #4 shows that the deceleration can be very well managed by a right-sized attenuator, it should be noted that it is smaller than Formula SAE® minimum requirements. If appropriate safety factors are used, it is conceivable that a Formula SAE® team could design an impact attenuator that will pass the safety standards on the first attempt.

The results show that HexWeb® aluminum honeycomb is highly effective and very predictable for constant force / constant acceleration applications. The evidence is found in [Figure 9](#) which depicts relatively flat-topped curves meaning the rate of deceleration, and therefore the amount of force needed to crush the attenuators was very constant over the course of the crash event.

Additionally, the better an attenuator is optimized for a given speed, the less rebound will be experienced at that speed. However, if an attenuator is optimized for 7m/s, for example, it will be more likely to use up the entire useful crush stroke at higher speeds. If the crush stroke exceeds 70% of the total length of the attenuator stack-up may occur. After stack-up

begins the occupant may experience a much higher rate of acceleration. This is noteworthy from an occupant protection standpoint.

RECOMMENDATIONS FOR THE FUTURE

Several lessons were learned during the testing for this paper, especially in regard collecting accurate data. For instance, a strobe light should be wired to the same trigger so that the exact time of impact can be easily determined on the video. While not having a strobe light did not prevent data from being evaluated, it certainly made it more difficult and perhaps a little less accurate. A strobe light would be especially useful for TEMA analysis. Similarly, syncing the video and data would have been much easier if the trigger for the video was linked to the accelerometer trigger.

Data filtering sometimes introduces an error into the system so it is wise to have a reliable speed check. For example, a velocity trap should be used as a reference so that the incoming speed can be verified independently of the sled and trolley accelerometers. It would also be helpful if another velocity trap could record the rebound velocity.

Future testing will most likely make use of different accelerometers. The peak acceleration was well within the 100 g accelerometer limit as shown in EVALUATION® but the unfiltered data had some very high peaks cut off. It appears that this data is simply noise from the somewhere else in the system because the peaks were extremely narrow and only the very top was missing. However, it would be good practice to use an accelerometer with a little large range, though not so big that the data resolution suffers.

Initially, there were no plans to use TEMA to analyze the video. It was assumed that the data collected from the accelerometers would be accurate enough. For a Formula SAE® team concerned with simply passing or failing the impact attenuator requirements, accelerometers would be enough. However, for a paper it was important to strive for optimum accuracy. In the end, TEMA was very helpful as a validity check as well as for calculating more accurate velocities. In order to use TEMA, accurate distances must be measured between individual targets, and the camera and targets. If done properly, TEMA can be a very reliable data validity check.

This is not to say that a Formula SAE® team with good motion analysis software can always rely on cameras rather than accelerometers. There is one problem with using TEMA for these tests, at least when trying to find the displacement. The video for these tests was recorded at 1000 frames per second while the trolley was impacted the barrier at approximately 7 m/s. This equates to the trolley traveling about 7mm per frame. A margin of error of about +/-7

millimeters may be too large for some calculations to be useful.

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