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OPTIMIZING ALUMINUM HONEYCOMB AREA FOR RACE CAR CRASH SAFETY

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ABSTRACT

Aluminum honeycomb impact attenuators are frontal crash mitigation structures on automobiles, such as racing vehicles in the Formula Society of Automotive Engineers (FSAE) competition. Understanding their mechanical properties, such as the forces it can withstand and the energy it can absorb, will allow FSAE teams to make more informed sizing decisions. Honeycomb samples of varying areas were compression tested. The total energy absorbed, the average force, and the peak force by each sample were plotted against their area. A proportional fit was found to be statistically significant for all parameters. As the area of honeycomb doubled, each parameter also doubled. In conjunction with FSAE requirements, these fits were used to determine that the minimum area for the honeycomb is 0.02293 ± 0.00023 m^2, which is marginally bigger than the standard FSAE aluminum honeycomb impact attenuator area 0.02000 m^2.

Keywords: impact attenuator, aluminum honeycomb, quasi-static test, energy absorption, fsae

1. INTRODUCTION

In 2022, there were almost 6 million car crashes in the US, yet only 2.4 million injured people and 43,000 fatalities [1]. A large part of modern vehicle safety is due to the introduction of crumple zones in the late 1950s. Crumple zones are the simplest feature of passive safety design, absorbing the kinetic energy released in a crash to protect passengers [2]. Crumple zones are particularly important in race cars as they have more severe impacts than street cars due to the nature of their use. Race cars are not exclusive to professional drivers and teams as college students are able to build their own vehicles to bring to various race competitions.

One such example is Formula SAE (FSAE), an engineering competition where university students design, build, and race a single-seater car according to a strict set of rules and regulations put out for each competition year. Each FSAE vehicle requires an impact attenuator mounted onto the front of the car, creating a crumple zone. As it is safety critical for the driver, the competition has strict rules regarding the impact attenuator, including its sizing, the forces through it, and its energy absorption. Impact attenuator testing for MIT Motorsports' Model Year 24 (MY24) car has concluded that the most desirable design is one with the smallest possible area while still meeting the requirements for forces and energy absorption. As development and testing of impact attenuators is time consuming and expensive, knowing what the expected test data of a suggested design before physically testing is insightful during the design process.

Figure 1. Left shows the frame of MIT Motorsports' MY24 car with the impact attenuator mounted on the front, partially covered with black tape. Right shows MY24 driven at the 2024 FSAE Electric competition.

Understanding the relationship between the size of aluminum honeycomb and its mechanical properties will allow for more informed design decisions for the car as well as more efficient testing. Honeycomb samples of different areas will be quasi-static tested using Instron machines. The force-displacement curves given by the Instron provided insight into the total energy absorbed by the honeycomb as well as the peak and average forces through it. From these equations, a prediction was made to find the smallest area of honeycomb that can still meet the functional requirements.

2. BACKGROUND

Finding the mechanical properties of a material is a simple structures problem. However, it must be put into the context of FSAE to understand the optimal sizing decision. Thus, a closer look at prior research in FSAE impact attenuators, the FSAE rules and requirements, and the behavior of aluminum honeycomb must be taken before diving into the experiment.

2.1 PRIOR RESEARCH

Many studies have been conducted on the design, analysis, optimization, and testing of impact attenuators. However, these studies primarily focus on using alternative material in place of the honeycomb, such as aluminum cans [3, 4]. There is also a lack of studies that physically tested their different proposed designs of honeycomb impact attenuators; instead, their method of testing their designs was finite element analysis and crash simulations [5-14]. These models are insightful but ultimately unhelpful without correlation to physical data. Thus, physical testing is the most certain way to verify the functional requirements and understand the material properties of the honeycomb. Prior to the 2024 FSAE Electric Competition, MIT Motorsports tested seven different honeycomb designs and concluded with the hypothesis that a larger area correlates with high forces and energy absorbed.

2.2 RULES AND FUNCTIONAL REQUIREMENTS

FSAE teams are allowed the choice between standard and custom impact attenuators. Teams that use a custom design must prove their design meets the functional requirements by testing a sample of their design. The functional requirements state the impact attenuator must a) decelerate the vehicle at a rate not exceeding an average force of 20 g and a peak force of 40 g and b) absorb at least 7350 J of energy [15]. The force requirements can be converted into Newtons using the second law of motion (1), which relates acceleration, mass, and force. The functional requirements assume a total mass of 300 kg, so the requirements are successfully converted and summarized in Table 1. FSAE rules dictate a minimum geometry of the impact attenuator: a length of and width of at least 200 mm, and a height of 100 mm [15]. For the purposes of this paper, the area of the honeycomb will refer to height times width as shown in Figure 2.

$$F = ma \tag{1}$$

Table 1. FSAE force requirements converted into Newtons for a 300 kg mass.

Requirements	Calculation to Newtons
Average force: ≥ 20 g	$F = 60{,}000\ N$
Peak force: ≥ 40 g	$F = 120{,}000\ N$

2.3 ALUMINUM HONEYCOMB PROPERTIES

Known for its lightweight properties, high strength-to-weight ratio and energy-absorbing ability, aluminum honeycomb is used to reduce weight in interior body panels, spoilers, floors, chassis components, wings and diffusers [16]. For FSAE specifically, it is typically used for impact attenuators due to its energy absorption capability. Shown in Figure 2, the honeycomb in this experiment is made of 5052 aluminum alloy, has a 3/8" cell size, and has a density of 5.4 pounds per cubic foot (0.848 kN/m^3).

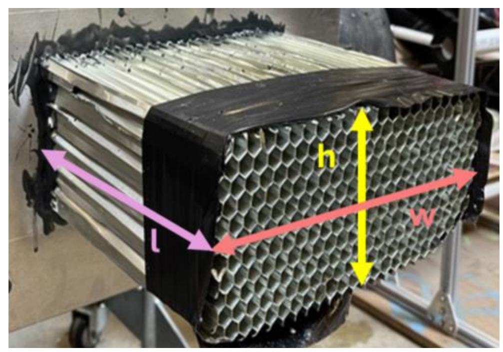

Figure 2. Photo of MIT Motorsport's 2024 Impact Attenuator, with dimensions annotated.

The mechanical properties of the honeycomb are determined by its manufacturing process. The geometry of its shape means that the hexagon uses the least amount of material to hold the most weight. Due to the six-sided nature of the cells, they can fit perfectly with each other and be packed closely together. The cell size and thickness of the aluminum foil typically determines its density, which influences the area of application for the honeycomb. For two samples with the same area, the honeycomb with the smaller cell size will be heavier but absorb more energy than the sample with a larger cell size.

When put under the Instron, the honeycomb undergoes out of plane compression loading. The cells first elastically buckle and then, past the yield limit, plastically collapse as shown in Figure 3. This uniform plastic collapse process happens along the thickness of the honeycomb block. During this time, the kinetic energy of the vehicle will be converted uniformly to the deformation energy of the honeycomb block [8].

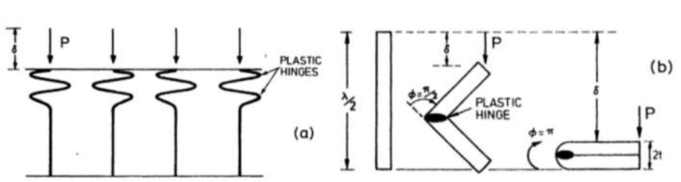

Figure 3. Plastic deformation of honeycomb (a) in general and (b) in one wall [17].

3. EXPERIMENTAL DESIGN

This section will cover the preparation of the honeycomb samples as well as the test apparatus.

3.1 HONEYCOMB SAMPLES

To test the performance of the honeycomb material in relation to size, the height was held constant at about 100 mm and the width varied between groups of samples. As exact dimensions are tough to cut on a bandsaw, each height and width was not the same on each sample. The area was gotten from multiplying length and width to get an understanding of the performance of a general honeycomb size under axial loading. Table 2 shows the nominal lengths that were cut as well as the number of samples for each. A wide range of widths were chosen to guarantee an accurate representation of the honeycomb in all parameters as its area varies. Though the goal was to reach at least three samples in each category, as well as more categories between 132 mm and 200 mm, there were material limitations that resulted in the final number and sizes of samples.

Table 2. Widths and areas of samples that were tested during this experiment.

Nominal widths (mm)	Nominal areas (mm^2)	Number of samples
44	4400	3
88	8800	3
132	13200	1
200	20000	2
210	21000	1
220	22000	2
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3.2 INSTRON TESTING

Though the use case of the honeycomb is a fast impact, FSAE assesses quasi-static testing to be as effective as dynamic testing rigs in evaluating the honeycomb's mechanical properties. As it is more cost-effective and accessible, the samples for this experiment were quasi-static compression tested using Instron machines. Quasi-static testing is a structural experimental test that is commonly used to maintain the crushing response and energy absorption mechanisms of thin-walled multi-cell structures, like aluminum honeycomb [18]. The term "quasi-static" implies testing is conducted at a sufficiently slow rate such that dynamics effects, like strain rate and loading rate, are insignificant, relying on force and displacement to give insights on the mechanical behavior of the tested material.

Two different Instron machines were used for this project as shown in Figure 3. One was the 68TM-50 model, rated for up to 50 kN; the other was the 5984 model, rated for up to 150 kN. Testing was initially done on the smaller Instron for the first few batches of samples. However, the larger Instron was used to test larger samples as knowledge from previous tests on MY24's impact attenuator showed the peak and average force through the honeycomb would exceed the smaller Instron's rating. For each Instron, the test set up was identical.

Figure 4. Physical test setup on a) the 50 kN Instron and b) the 150 kN Instron.

As for test procedure, the sample was placed on a fixed platform. A compression plate was mounted to the upper leg of the Instron, which would slowly compress the sample. The compression plate was unable to cover the area of the larger sample, but this was rectified by using a steel plate to ensure forces were distributed equally across the area. As the compression plate was driven downward by the Instron as in Figure 5, the sample was put under axial loading and the Instron generated a force-displacement curve. This data was used to verify the sample's performance against the functional requirements.

Average and peak forces can easily be found from the data. Due to the quasi-static nature of the test, the energy absorbed by the sample at one point in time is calculated using (2), where W is work, F is force, and d is displacement. The sample's total energy absorption is the summation of all the moments of energy absorbed across the entire displacement.

$$W = Fd \tag{2}$$

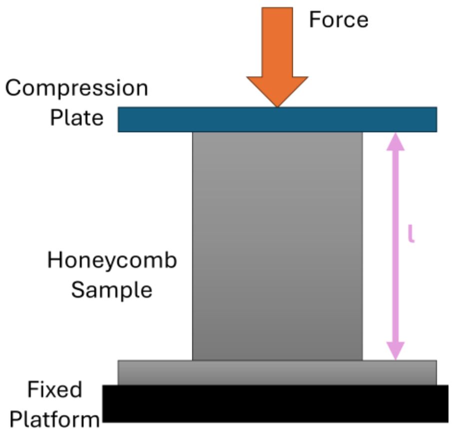

Figure 5. Instron testing of aluminum honeycomb to measure its mechanical properties.

4. RESULTS AND DISCUSSION

This section will cover the interpretation of raw data, the relationship between the honeycomb's mechanical properties and its area, and the minimum honeycomb area for an FSAE impact attenuator.

4.1 FITTING MECHANICAL PROPERTIES

From the raw data, force-displacement graphs were generated for each sample. Figure 6 depicts an example of a force-displacement graph indicating where the observed parameters appear. The area under that curve represents the total energy absorbed by the sample. The peak force on the sample is at the initial peak; the average force on the sample generally follows along where the raw data stabilizes. To ensure comparison between samples was equivalent, the data collection was stopped after a displacement of 150 mm on all samples.

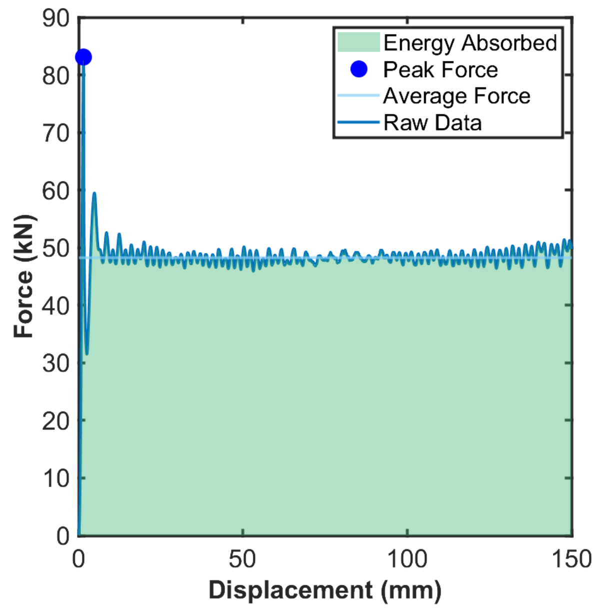

Figure 6. Graph of the force-displacement data for a 220 mm long sample. The parameters being observed in this experiment of peak force, average force, and energy absorbed are annotated over the raw data how their numbers are derived. For this sample, the peak force is 83.102 kN, the average force is 48.223 kN, and the total energy absorbed is 7229 J.

The average force, the peak force, and total energy absorbed by each honeycomb were plotted against the sample area. Figure 7 shows these parameters are proportional to the area. As area doubles, each parameter also increases by a magnitude of 2. This agrees with the initial hypothesis that simply increasing the area of honeycomb also increases the other parameters. Though the confidence intervals of the average force and total energy absorbed fits are quite tight, such that they are not visible on the plots, the confidence interval of the peak force fit grows as the area increases. This indicates more variability in the peak force for honeycombs of larger areas. In Figure 7b, the group of larger samples that range in area between 0.0205 m^2 and 0.0227 m^2 demonstrate this variability with peak forces between 59,126 N and 83,102 N.

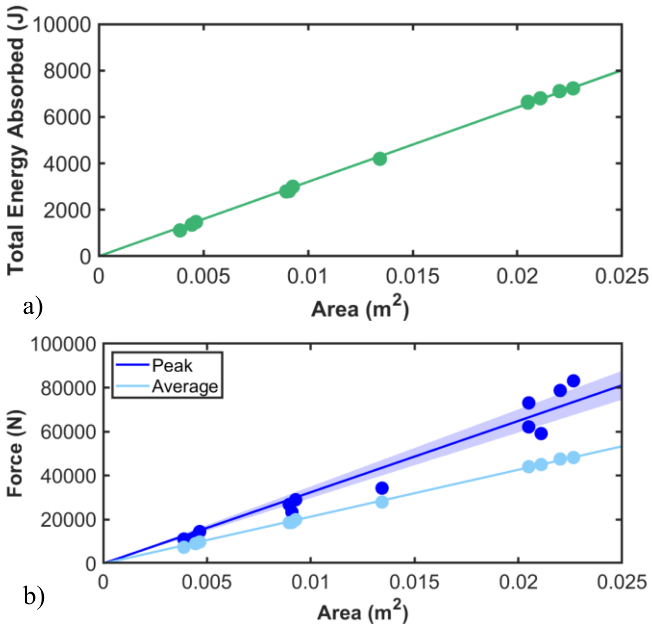

Figure 7. Graphs of the observed parameters vs area for each sample, showing total energy absorbed in a) and the peak and average forces in b). In all cases, a proportional fit was found to be statistically significant. In a), the slope for total energy absorbed is $(3.205 \pm 0.032) \times 10^5$ J/m^2; in b) the slope for peak force is $(3.24 \pm 0.26) \times 10^6$ N/m^2, and the slope for average force is $(2.134 \pm 0.021) \times 10^6$ N/m^2.

4.2 SIZING THE IMPACT ATTENUATOR

To choose the smallest size for the honeycomb, the FSAE functional requirements are plotted as planes in 3D space in Figure 8. To reiterate, the average and peak forces must be below 60,000 N and 120,000 N, respectively; the total energy absorbed must be over 7350 J. The red highlighted space represents the space that fits all these requirements, which is where the honeycomb should be designed around. From experimental data, a line can be plotted in the configuration space as honeycomb area varies.

The most important parameter to focus on is the total energy absorbed plane because the line does not go near the average force plane nor the peak force plane. As such, both force equations can be disregarded when making the sizing decision. Thus, the smallest area is at the point where the line crosses the total energy absorbed plane. To pass the FSAE functional requirements, an area should be chosen that definitively passes the total energy absorbed requirement. To account for the uncertainty and find the desired area A_d, the defined energy E will be divided by the associated slope's lower boundary in its confidence interval as seen in (3). The desired area is found to be 0.02316 ± 0.00023 m^2.

$$A_d = E \div (a - a_{unc}) \tag{3}$$

A system of equations can then be used with (3) to find the height and width of a honeycomb that will satisfy both the functional and geometrical requirements for FSAE. (4) comes from the basic understanding that the area is equal to the width times height; (5) and (6) are from the FSAE minimum requirements for width and height. The optimal height is found to be 108 mm, and the optimal width is found to be 215 mm. To confirm this sizing fits the other requirements, the area is plugged into the equations for peak force and average force. For this area, the peak force is found to be 75.6 ± 6.0 kN and the average force is found to be 49.54 ± 0.48 kN, which are both well within the functional requirements.

$$A_d = wh \tag{4}$$
$$h \geq 100mm \tag{5}$$
$$w \geq 200mm \tag{6}$$

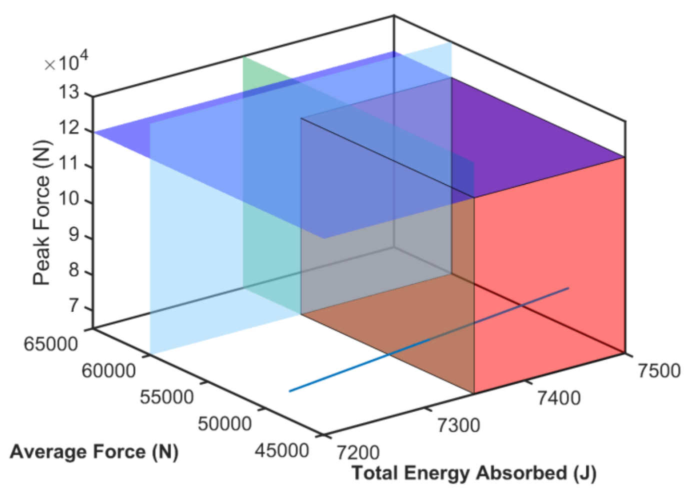

Figure 8. 3D visualization of configuration space within the context of FSAE requirements. The total energy absorbed minimum plane is green; the maximum peak and average force planes are dark blue and light blue respectively. The plotted line is a combination of the equations relating each parameter as a function of area in the configuration space.

CONCLUSIONS

The results proved a proportional relationship between aluminum honeycomb's area and its total energy absorption, peak force, and average force. As the area doubles, these mechanical properties also double. The proportional fits were used to determine a system of equations to find the smallest area that meets the FSAE functional and geometrical requirements of impact attenuators. A 3D visualization of configuration space with the requirements marked up established that the total energy absorption requirement is the most important equation to consider when designing FSAE impact attenuators. Finally, the system of equations showed the smallest area that meets requirements is 0.02316 ± 0.00023 m^2, with the height being 108 mm and the width being 215 mm.

The results of this experiment will be used to decide the honeycomb area for the impact attenuator on MY25 – MIT Motorsports' 2025 car. MY24 showed that multiple rounds of testing are expensive and time intensive; the goal for MY25 is to only conduct one impact attenuator test to save money and materials. The next step will be to test the proposed honeycomb size and see how the predictions match with actual data. For future work in understanding the mechanical properties, more aluminum honeycomb samples should be tested in terms of more categories of lengths as well as more numbers of samples within those categories. This may help in understanding the phenomenon of increasing peak force variability with increasing area.

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REFERENCES

[1] United States. Department of Transportation. Bureau of Transportation Statistics, 2019, "National Transportation Statistics (NTS)", https://doi.org/10.21949/1503663 (Accessed 11/5/2024)

[2] "Car Safety - a Brief History," SMMT (blog), 2015, https://www.smmt.co.uk/2015/02/car-safety-brief-history/ (Accessed 11/5/2024)

[3] Prasetya, L.W. et al., 2021, "Crashworthy Examination of a Newly Proposed Impact Attenuator Design: Experimental Testing and Numerical Analysis, Modelling and Simulation in Engineering," https://doi.org/10.1155/2021/5001060 (Accessed 9/22/2024)

[4] Prasetya, L.W et al., 2021, "Design of crashworthy attenuator structures as a part of vehicle safety against impact: Application of waste aluminum can-based material." Theoretical and Applied Mechanics Letters, **11**, 0.1016/j.taml.2021.100235.

[5] Fahland, J. Hoff, C., and Brelin-Fornari, J., 2011, "Evaluating Impact Attenuator Performance for a Formula SAE Vehicle," SAE International Journal of Passenger Cars. Mechanical Systems, **4**(1), pp. 836–847, https://doi.org/doi: 10.4271/2011-01-1106.

[6] Chavan, A. G., "Design and Development of Impact Attenuator for Racecar Safety," https://inpressco.com/wp-content/uploads/2016/10/Paper63281-285.pdf (Accessed 9/22/2024)

[7] Dokhe, C. S. and Shinde, S. V., 2021, "To Design and Analysis of Attenuator Structure for Better Impact Performance of FSAE Car," International Journal of Creative Research Thoughts, **9**(1), https://www.ijcrt.org/papers/IJCRTF020028.pdf

[8] Krzikalla D. et al., 2020, "On Aluminum Honeycomb Impact Attenuator Designs for Formula Student Competitions," Symmetry, **12**, https://doi.org/10.3390/sym12101647.

[9] Oshinibosi, A., "Chassis and Impact Attenuator Design for Formula Student Race Car," https://community.altair.com/community/en?id=community_blog&sys_id=0f75a1b11b02f110c4dfdbd9dc4bcb71, (Accessed 9/20/2024)

[10] Arifin, Z. and Gunawan, S., 2019, "Design and Testing Impact Attenuator of Formula SAE FG17 Garuda UNY Car," Journal of Physics: Conference Series, **1387**(1), https://doi.org/10.1088/1742-6596/1387/1/012091.

[11] Belingardi, G. & Obradovic, J., 2010, "Design of the impact attenuator for a formula student racing car: Numerical simulation of the impact crash test." Journal of the Serbian Society for Computational Mechanics, **4**. pp. 52-65.

[12] Vettorello A. et al., 2020, "Numerical-Experimental Correlation of Dynamic Test of a Honeycomb Impact Attenuator for a Formula SAE Vehicle," Metals, **10**(5), pp. 652. https://doi.org/10.3390/met10050652

[13] Wheatley, G. and Zaeimi, M., "Front Impact Attenuator Design for a Race Car," International Journal of Crashworthiness, **27**(2), pp. 466–475, https://doi.org/10.1080/13588265.2020.1807699.

[14] Kaya, D. and Özyurt, E., "Design and Optimization of Impact Attenuator for a Formula SAE Racing Car," Sigma Journal of Engineering and Natural Sciences, **40(**2), pp. 390–401.

[15] Formula SAE Rules 2025. Formula SAE. (2024, August 8). https://www.fsaeonline.com/cdsweb/gen/DownloadDocument.aspx?DocumentID=349fa543-c65d-467f-ac12-730949d0dc85. (Accessed 9/14/24)

[16] Khabiri N., “Corex Honeycomb Details Aluminium Honeycomb Properties,” https://corex-honeycomb.com/why-is-aluminium-honeycomb-so-strong/ (Accessed 9/22/2024)

[17] Gibson, L.J. and Ashby, M.F. Cellular Solids: Structure and Properties; Cambridge University Press: Cambridge, UK, 1999

[18] Yao R. et al., 2023, “On the Crashworthiness of Thin-Walled Multi-Cell Structures and Materials: State of the Art and Prospects,” Thin-Walled Structures, **189**, https://doi.org/10.1016/j.tws.2023.110734.