MASTERS THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF **MASTER OF ENGINEERING**

TITLE: Development and Characterization of a Composite Cylindrical Column with an Aluminum Foam Core

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1. Introduction

Energy absorption in automotive structures is very important when one considers the effect of collisions on safety. A literature review reveals a strong emphasis within the field of mechanical engineering on the design and development of energy-absorbing devices. With the increase in speeds and reduction in weight, there is an ever increasing need for better energy absorption within the structure. Energy absorption can be accomplished in a number of ways, one of which is the using structural elements that transform kinetic energy into plastic strain energy. The ideal structural energy absorber is one that dissipates a large amount of energy while transmitting the minimal force possible into the main structure.

For practical reasons, the structures that have been considered are tubular ones and many have a core of lightweight material. Of all cross sectional shapes considered, the circular ones are the most ubiquitous owing to the ease of manufacturing, analysis and their added ability to absorb energy under axial loading.

Aluminum foam is a cellular material with an open cell structure and aluminum ligaments. They are used heavily in shock absorption, particularly in cases of protecting occupants from explosions in the undercarriage of vehicles [1]. Aluminum foams-filled tubes have been discussed in the literature, especially in the context of high specific energy absorption which is a measure of absorbed energy per unit weight [2]. In addition, previous works[3–11] investigated the crashworthiness when aluminum foam-filled single tubes or thin-walled structures are used.

The aim of this project is to conduct an experimental study into the crushing behavior and the energy absorption characteristics of aluminum and carbon fiber tubes with a Duocel® aluminum foam core. The core is coupled to the tube using epoxy injected into a section of a Duocel® aluminum foam.

Chapter 2 describes the makeup and construction of this material. Chapter 3 describes the testing methodology. Chapter 4 presents results and discussions while Chapter 5 gives the conclusion and future work.

2. Experimental Setup

The energy absorption is quantified using a cylindrical test specimen which is loaded in compression on a servo-hydraulic universal testing machine. The test specimen, shown in Figure 2-1 has a length L = 60 mm, an outside radius R_1 = 12.7 mm and an inside radius R_2 = 11.8 mm. The value of R_2 is nominal, as there are slight variations between the different materials. Two different materials are used for the outside tube; an aluminum alloy and a carbon fiber. The details of both material are given in subsequent parts of this paper. The core, constructed from aluminum foam, fills the inside the tube with or without an epoxy layer that couples the two. The thickness of that layer is ∂ =1mm.

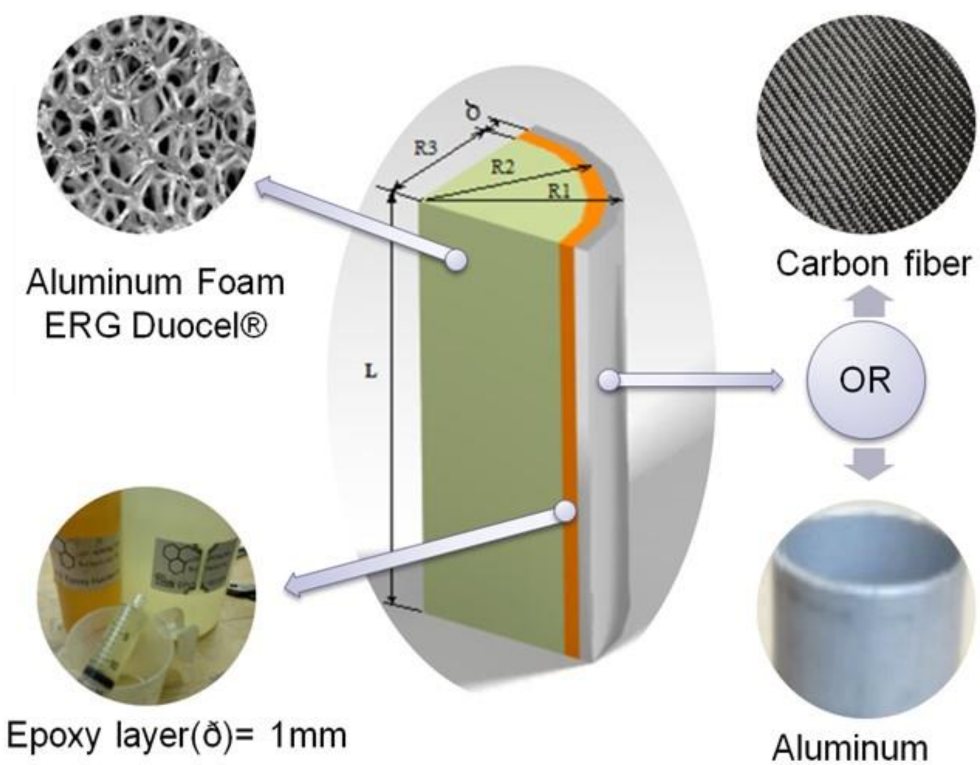


Figure 1 - Construction and dimensions of a test sample

Material Selection

Two materials were chosen for the tubular structure. The first is a high strength carbon fiber tube sourced from McMaster-Carr (part number 5287T21). The tube has an outside diameter of 25.4 mm (1 in), an inside diameter of 23.8 mm (0.928 in), resulting in a wall thickness of 0.787 mm (0.031 in). The manufacturer specification of this material shows a tensile strength in the range of 830-1200 MPa (120-175 Ksi), a compressive strength in the range of 520-900 MPa (75-128 Ksi) and a nominal density in the range of 1380-1850 Kg/m^3 (0.05-0.067 $lbs./in^3$).

The second material chosen for the tube is a high strength 2024 aluminum, heated to a T3 specification which implies that the alloy was heat treated, cold worked and naturally aged. The aluminum was sourced from McMaster-Carr (part number 1968T171) and has an outside diameter of 25.4 mm (1 in), an inside diameter of 23.6 mm (0.930 in) resulting in a wall thickness of 0.889 mm (0.035 in). The manufacturer specification shows a yield strength of 290 MPa (42 Ksi), a tensile strength of 428-483 MPa (62-70 Ksi) and a nominal density of 2796 Kg/m^3 (0.101 $lbs./in^3$).

The material chosen for the core is the Duocel® open cell aluminum foam manufactured by ERG Aerospace. The foam is made of 6101-T6 aluminum alloy with a 10% nominal density, meaning that 90% of a particular volume is open voids which are filled with air. The manufacturer specification lists the tensile strength at 1.24 MPa (180 psi) and compressive strength at 2.53 MPa (367 psi). The foam is listed by a pore per inch (PPI) designation which is a measure of the pore size. The particular foam used in this research had a linear pore density of 20 PPI.

The epoxy used was sourced from Composite Envisions LLC and is a 4:1 two part epoxy resin Type 635 (Model number 538). There are no published technical specification other than a set time of 1-2 hours and a drying time of 3-4 hours.

Method of Construction

This section is concerned with the methodology developed primarily to bond the aluminum foam core to the inner surface of the outside tube. The finished specimen are shown in Figure 2.

Figure 2 - Finished carbon fiber composite specimen on left and aluminum specimen on right.

<u>Step 1: Preparing the tubes</u>

The first step is to cut the tubes and finish the ends on a lathe as to ensure flat and parallel surfaces. The tubes need not be cut to finished length since the process of cutting to exact length can be done in the final stage. In this study, the tubes were cut to approximately 150 mm sections, which can ultimately produce two 60 mm specimens, accounting for manufacturing allowances and other length requirements related to process of adding the epoxy. This will be described in step 3.

Step 2: Preparing the aluminum foam cores

The aluminum foam is a notoriously difficult material to machine and shape. The difficulties stem from the soft nature of the aluminum ligaments which easily deform under cutting forces experienced in traditional cutting operations. To mitigate against these difficulties, the aluminum foam was first cut using a high speed band saw into 25X25X127 mm samples shown in Figure 3.

Figure 3 – Aluminum foam cut into 25X25X127 mm samples

The 25X25 mm square sections are then turned on a lathe at slow cutting speed (80 rpm) and feed (feed is the speed of the cutting tool) to circular sections of diameters 23.6mm for aluminum and 23.8 mm for carbon fiber. Figure 4 shows the circular cross-sectioned specimen. Note the presence of the short square section at the end. This is an artifact of the manufacturing process, as the square specimen were held using a 4 jaw chuck on one end and held on center at the other end. The square section is cut prior to step 3.

Figure 4 – Aluminum foam turned into circular cross-sectioned cylinders

<u>Step 3: Assembly and preparation for epoxy</u>

The circular cross-sectioned aluminum foam cylinders are inserted into the tubes from step 1. It is important to note that the aluminum foam was cut to ensure slight interference fit with the tube. It is difficult to measure the aluminum foam diameters and give a tolerance range given the surface irregularities, but it was left to the machinist to ensure that the aluminum foam fits snugly, namely that it requires medium thumb pressure to insert the aluminum foam core into the tube. The author apologizes for the imprecision of the terminology used to describe the fit.

The aluminum foam cores are cut to such a length as to leave 10 mm of open side on either side after insertion. That space will allow rubber stoppers to be introduced on both ends. The purpose of the rubber stoppers is to prevent the epoxy that will be introduced in the next section from seeping out. The sub-assembly of core, tube and stoppers is shown in Figure 5, with the space denoted by (a) and the stoppers denoted by (b).

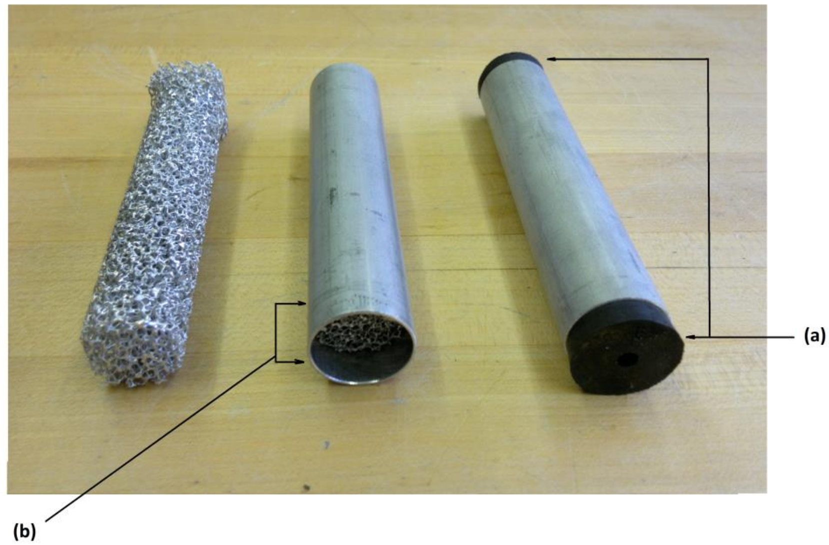


Figure 5 – Sub-assembly of core, tube and stopper with free space denoted by (a) and stoppers by (b)

Step 4: Introduction of epoxy

A 9 mL amount of the epoxy described earlier is injected into the tube. That amount is designed to ensure a 1 mm thick layer on the inside of the tube. The tube is then placed on a turning lathe immediately after the epoxy is introduced to the capped cylinder. That cylinder is rotated at 500 rpm and under a 120 ^{o}F provided by a heat lamp, as shown in Figure 6. The relatively high rotation speed ensures that the epoxy is spread evenly on the inside surface of the tube. The tube is spun for a period of four hours, which is ample enough time for the epoxy to set.

Step 5: Finishing to desired length

The specimen are then cut to desired length and turned on the lathe so that to ensure that the top and bottom surface are flat and perpendicular to the length. Care is taken to ensure that the samples are 60 mm long and that the foam and epoxy are both present at top and bottom surfaces.

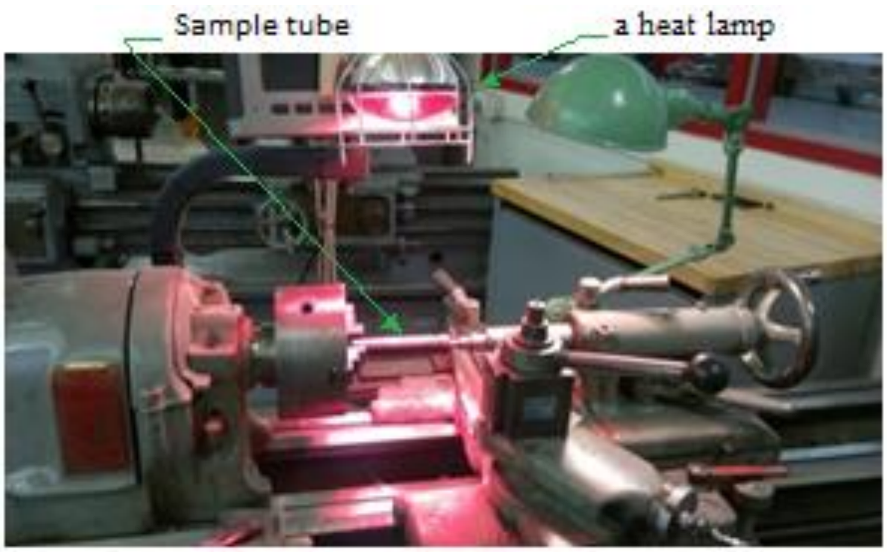


Figure 6 – Tube with foam core and epoxy on a lathe at 500 rpm and under heat lamp

Aluminum Foam Specimen

Compression specimen of aluminum foam were made in anticipation of the need to draw quantitative comparisons. The quantitative comparison in question relates to the increased plastic deformation energy owing to the presence of the aluminum foam core. Namely, if the plastic deformation energy of the tube alone is x, that of the tube and core is y, and that of the aluminum foam core alone is z, how does z relate to y-x? In other words, if z is equal to y-x, then the core contributed as a parallel element, which is not the intended purpose. For one to draw a positive recommendation for adding a core, z will have to be less than y-x, meaning that the core is adding value beyond its mere energy absorption capacity.

The aluminum foam samples must be constructed and loaded in such a way as to reflect its loading condition inside the tube. The aluminum foam core, inside the tube, undergoes uniaxial change in length but is unable to expand laterally due to the presence of the tube. To mimic this condition, two samples are made by tightly wrapping carbon fiber weave on the outside using adhesive tape. The carbon fiber weave offers little or no restrictions to the vertical deformation but substantially restricts any lateral deformation. Such embodiment confines the aluminum foam in the same initial cylindrical shape. The process is illustrated in Figure 7, where part (a) shows the carbon fiber 0-90 weave, part (b) shows the strip with adhesive backing, part (c) shows it being wrapped and part (d) shows the finished samples.

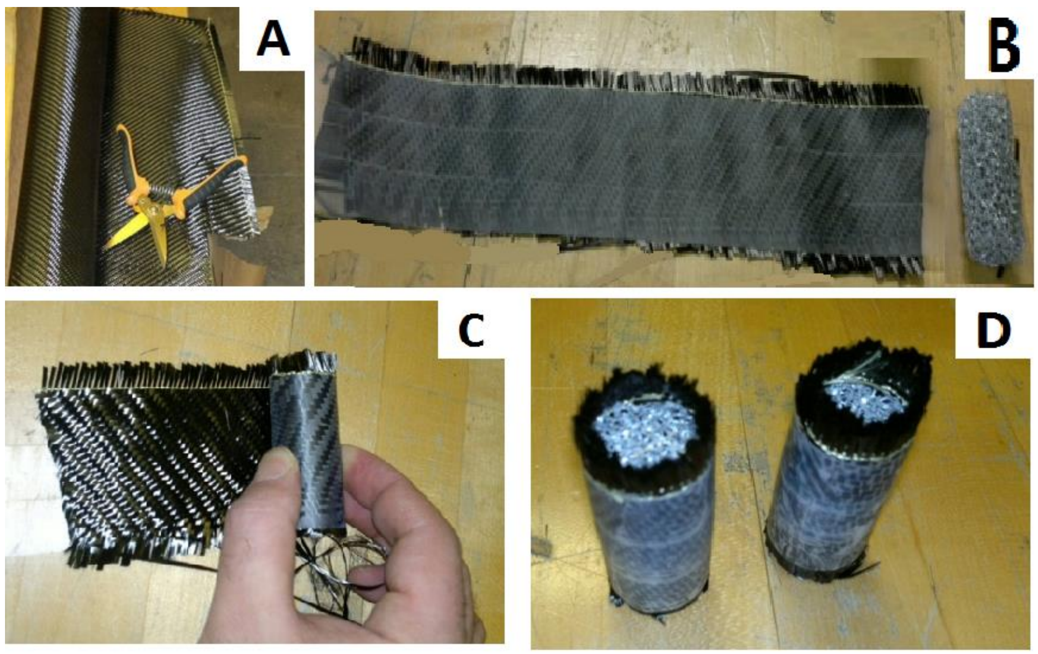


Figure 7 – Process for making the aluminum foam only compression samples

Test Samples

Two samples were made for each test type: aluminum tube; aluminum tube with core; aluminum tube with core and epoxy; carbon fiber tube; carbon fiber tube with core; and, carbon fiber tube with core and epoxy. Also, two samples of aluminum foam only were made. All samples were made to the same size and were weighed in order to normalize the plastic deformation energy against the weight. The characteristics of all samples are given in Table 1.

Table 1 – Type and weight of test samples

Number of samples	Type of Material	Weight(g) per sample	Frame of tubes
Sample 1	Aluminum tube only	10.2	
Sample 2		10.1	
Sample 1	Aluminum tube with aluminum foam	14.5	
Sample 2		14.5	
Sample 1	Aluminum tube with aluminum foam and epoxy	21.0	
Sample2		22.1	
Sample 1	Carbon fiber tube only	5.2	
Sample 2		5.2	
Sample 1	Carbon fiber tube with aluminum foam	11.2	
Sample2		11.1	
Sample 1	Carbon fiber tube with aluminum foam and epoxy	16.8	
Sample 2		16.3	

3. Experimental Procedure

The test setup involve low speed compression of a test specimen as shown in Figure 8. The crushing speed is 10 mm per minutes and the total crushing distance is 20 mm, which is a third of the total length of the samples (60 mm). The force was measured using a load cell located under the bottom platen. The displacement was measured using the crosshead displacement by an LVDT built into the actuator.

Figure 8 – Servo-hydraulic universal testing machine (left) and sample being crushed in uniaxial direction (right)

The data was acquired using a LabView based data-acquisition, shown in Figure 9. The data collected include the time (sec), displacement (mm) and load (N).

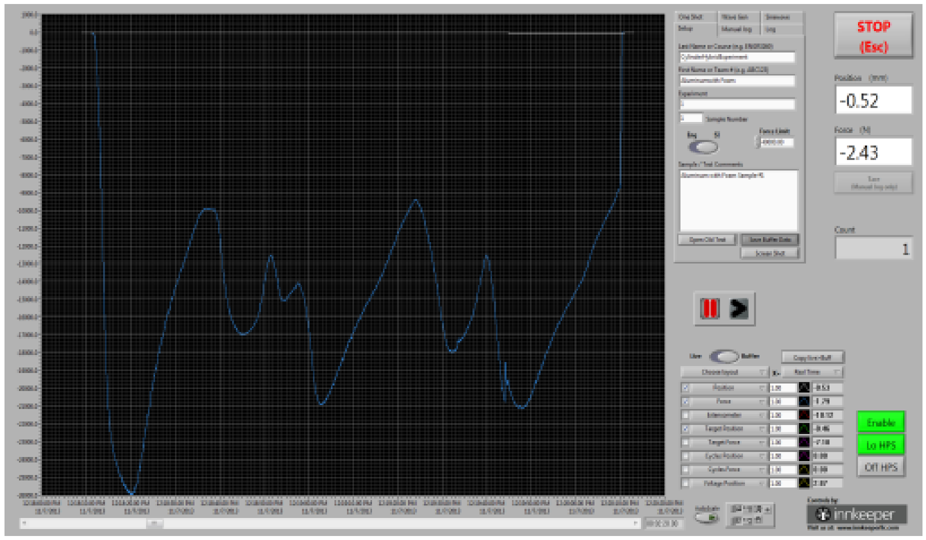


Figure 9 – Data acquisition program

The energy W absorbed by the crushing of the tube is calculated by integrating the force-displacement curve using the formula

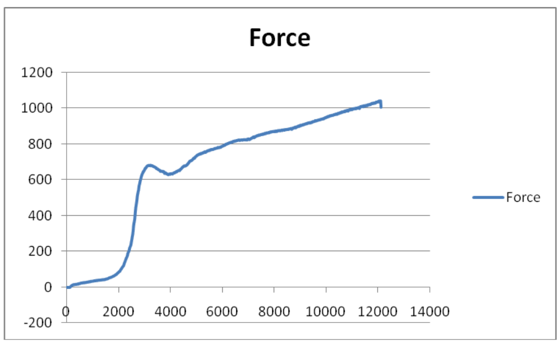
$$W = \int_0^X F dx = \sum_0^N F_i \Delta x \qquad 1$$

where F is the force in N, X is the displacement in mm, N is the number of data samples, Δx is the displacement intervals between samples in mm.

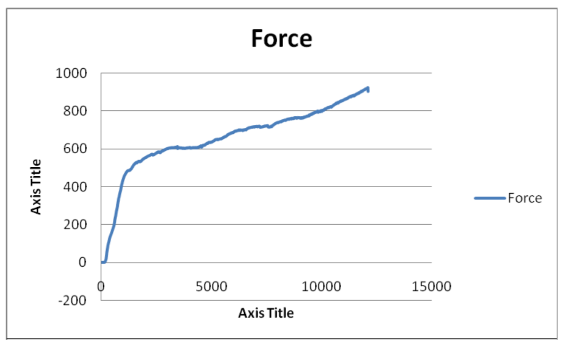
4. Results and Discussions

Aluminum foam-only samples:

The two aluminum foam-only samples were tested under the same testing methodology used for all specimen. The purpose is to quantify the energy absorption for the core material for comparison purposes. The load displacement curves for the two samples are shown in Figure 10. The area under the curve shows the two samples to have absorbed 13.3 and 13.1 Joules (J). The maximum force is measured at 1024 and 921 Newtons (N). It is important to note that metallic cellular material such as aluminum foam exhibits an increase in force with displacement due to a process of densification whereby the open cells collapse and result in increased metal-to-metal contact.



The max force for sample (1)= 1024 N



The max force for sample (2)= 921 N

Figure 10 – Load-displacement curves for the aluminum foam-only samples

Carbon fiber-only samples:

The carbon fiber-only samples exhibited a characteristic load-displacement curve for this type of material. The load increases rapidly as a result of elastic deformation and then reaches a peak with the onset of physical damage. The maximum force for the two samples is 9250 N and 10250 N, respectively. The load then drops to a near constant level as the carbon fiber undergoes a repeating process of physical damage. The energy absorbed by the compressive crushing of the samples is found to be 147.2 J and 147.0 J, respectively. The load-displacement curves for the carbon fiber-only samples are shown in Figure 11.

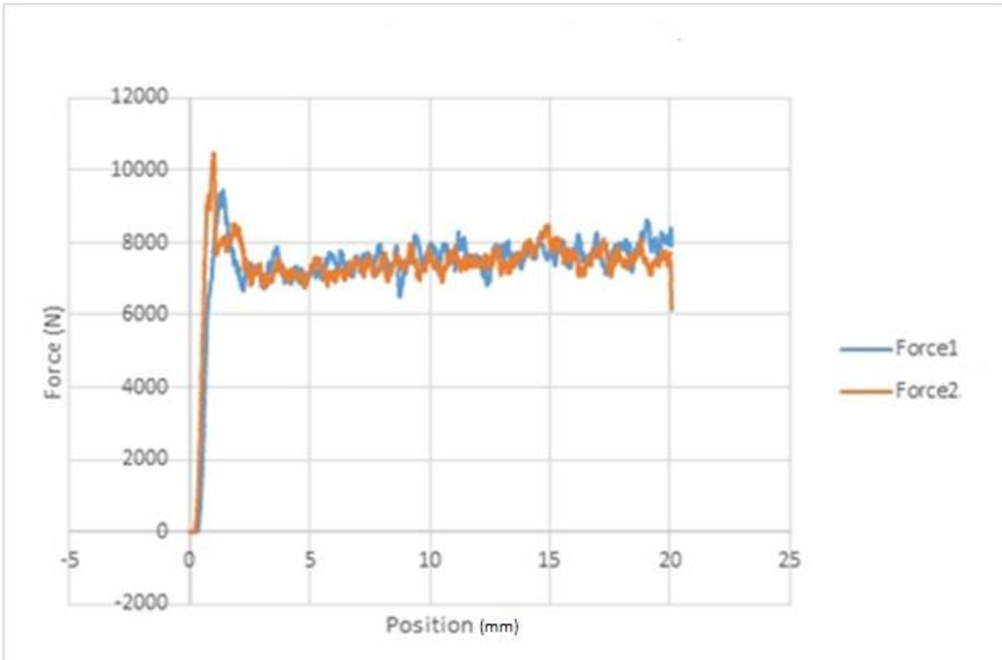


Figure 11 - Load-displacement curves for the carbon fiber-only samples

Carbon fiber samples with aluminum foam cores and no epoxy

The addition of an aluminum foam core to the carbon fiber tube resulted in a marked increase force as well as absorbed energy over carbon fiber-only samples. The load-displacement curves, shown in Figure 12, reveals a maximum load as high as 15500 N. Application of Equation 1 shows the energy absorbed by the crushing of the two samples to be 204 J and 201 J, respectively.

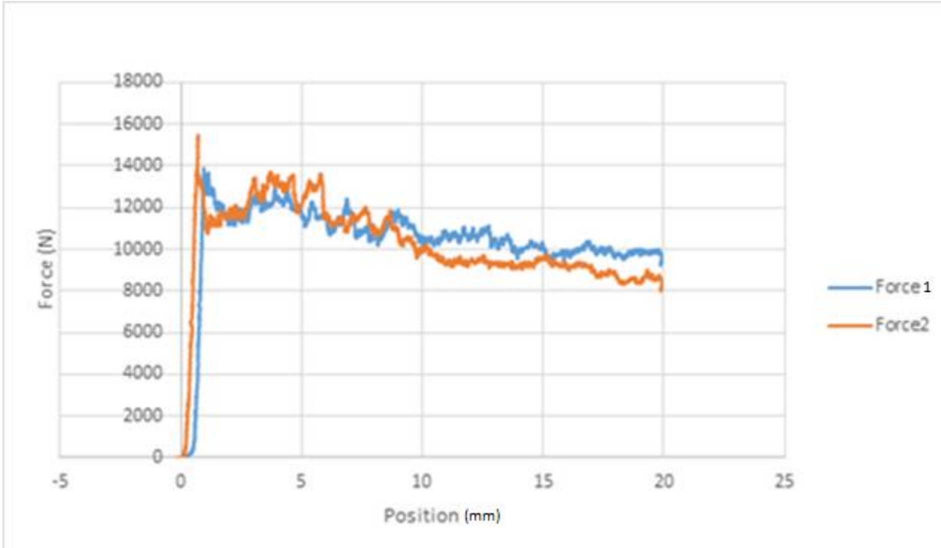


Figure 12 - Load-displacement curves for the carbon fiber with aluminum foam cores samples – No epoxy.

Carbon fiber samples with aluminum foam cores and epoxy

The addition of the 1 mm layer of epoxy to the interior of the tube is intended to provide shear coupling between the carbon fiber and the aluminum foam. It also adds a relatively significant amount of structure to the column by virtue of its strength, regardless of the adjacent material. This added strength is manifested in a maximum force of 22000N and 25000N and absorbed energy of 315 J for both samples. The load-displacement curves for these samples are shown in Figure 13. Note that the tow that is observed has been compensated for in the calculations.

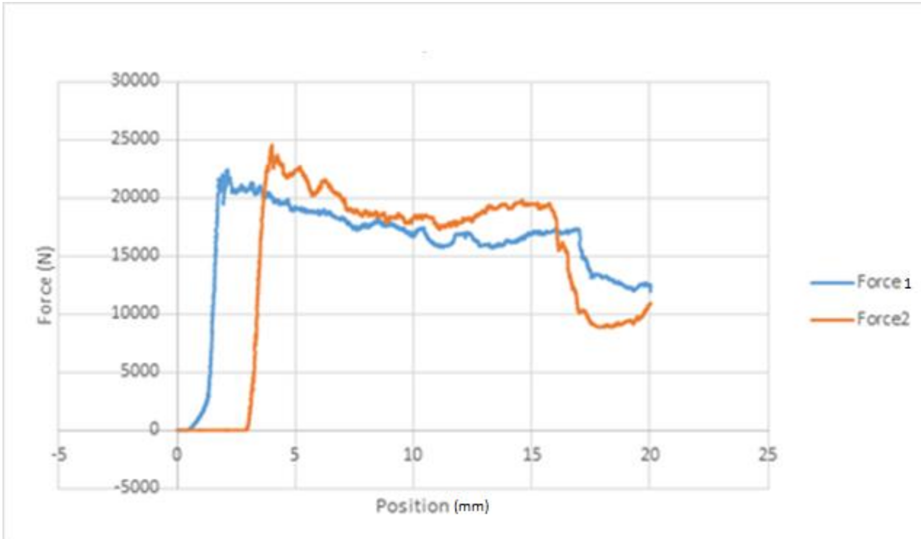


Figure 13 - Load-displacement curves for the carbon fiber with aluminum foam cores samples with epoxy

Aluminum tube-only samples:

The aluminum tube exhibits the well-known folding phenomenon which sees the outer surface fold in sequential layers as shown later in Table 2. That failure mode manifests in an oscillatory load-displacement curve is seen in Figure 14. The maximum load before the onset of folding deformation was 25000 N and the energy absorbed throughout the cycle was 299 J.

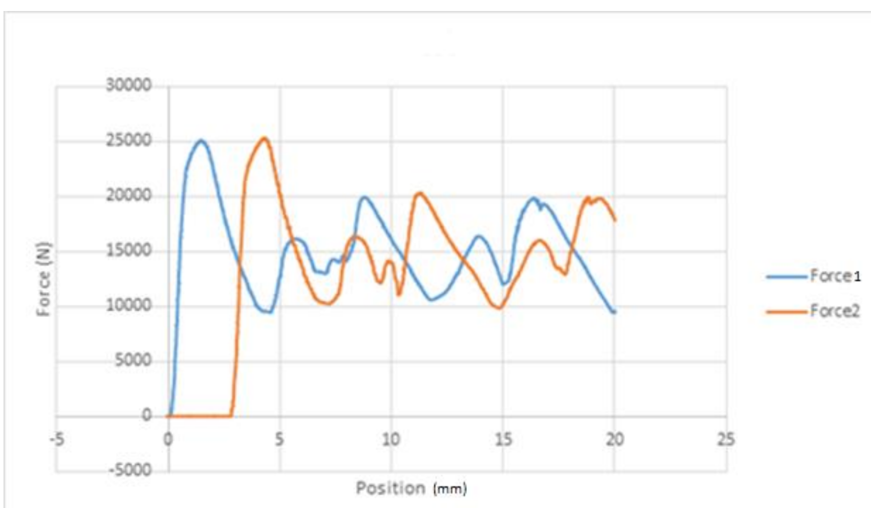


Figure 14 - Load-displacement curves for the aluminum tube samples.

Aluminum tube samples with aluminum foam cores

The load-displacement curves for the aluminum tube samples with aluminum foam cores but with no epoxy are shown in Figure 15. The addition of the aluminum foam cores to the aluminum tubes netted a relatively small gain in absorbed energy along with a small increase in maximum force. The energy absorbed was 310 J as compared to 299 J for the empty aluminum tube. Given that the aluminum foam alone absorbs around 13 J as was shown earlier in this paper, the results indicate that addition of the aluminum foam netted no synergistic gains. The maximum load of 26000 N also indicates that the combination of aluminum tube and aluminum foam behaves as parallel elements with little or no coupling between the two.

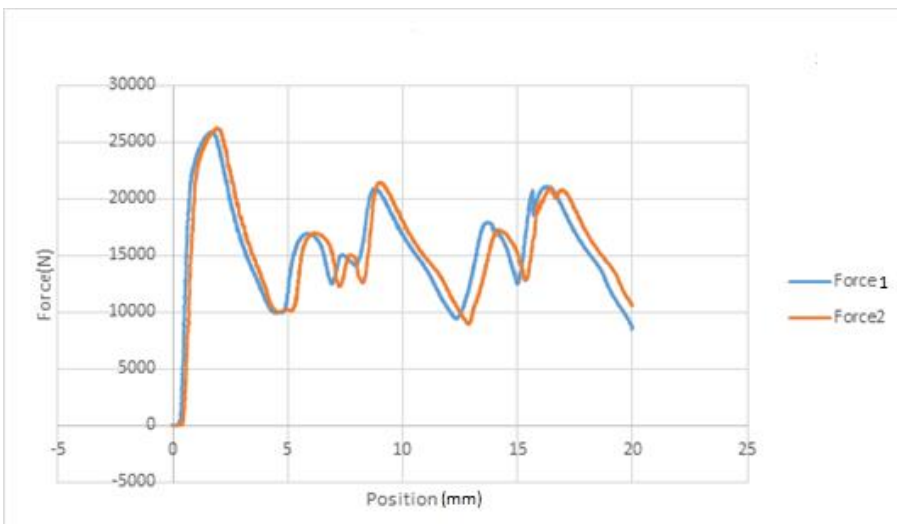


Figure 15 - Load-displacement curves for the aluminum tube with aluminum foam cores samples – No epoxy.

Aluminum tube with aluminum foam and epoxy

The load-displacement curves for the aluminum tube samples with aluminum foam cores but with added epoxy are shown in Figure 16. The epoxy significantly altered the makeup of the sample and the load-displacement characteristics. The maximum force increased drastically to 37000 N and the absorbed energy to 441 J and 410 J, respectively. The failure mode of the material is similar to that of the carbon fiber with aluminum foam and epoxy samples in that the tube breaks into longitudinal sections and forms a petal-like pattern.

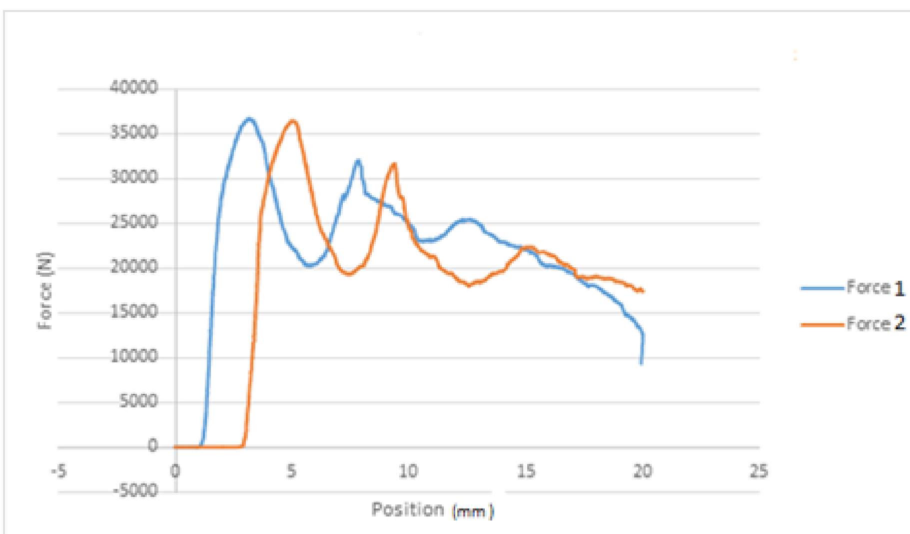


Figure 16 - Load-displacement curves for the aluminum tube with aluminum foam cores samples with epoxy.

Summary of Results

The energies absorbed during crushing of the various carbon fiber samples are summarized in Table 2 and shown in Figure 17.

Table 2 – Energy absorption for the various carbon fiber samples

<table>
<tr><th>Sample number</th><th>Type of Material</th><th>Energy absorption (J)</th><th>Photograph of crushed samples</th></tr>
<tr><td>Sample 1</td><td rowspan="2">Carbon fiber tube only</td><td>147</td><td rowspan="2"></td></tr>
<tr><td>Sample 2</td><td>147</td></tr>
<tr><td>Sample 1</td><td rowspan="2">Carbon fiber tube with aluminum foam</td><td>204</td><td rowspan="2"></td></tr>
<tr><td>Sample 2</td><td>203</td></tr>
<tr><td>Sample 1</td><td rowspan="2">Carbon fiber tube with aluminum foam and epoxy</td><td>315</td><td rowspan="2"></td></tr>
<tr><td>Sample 2</td><td>315</td></tr>
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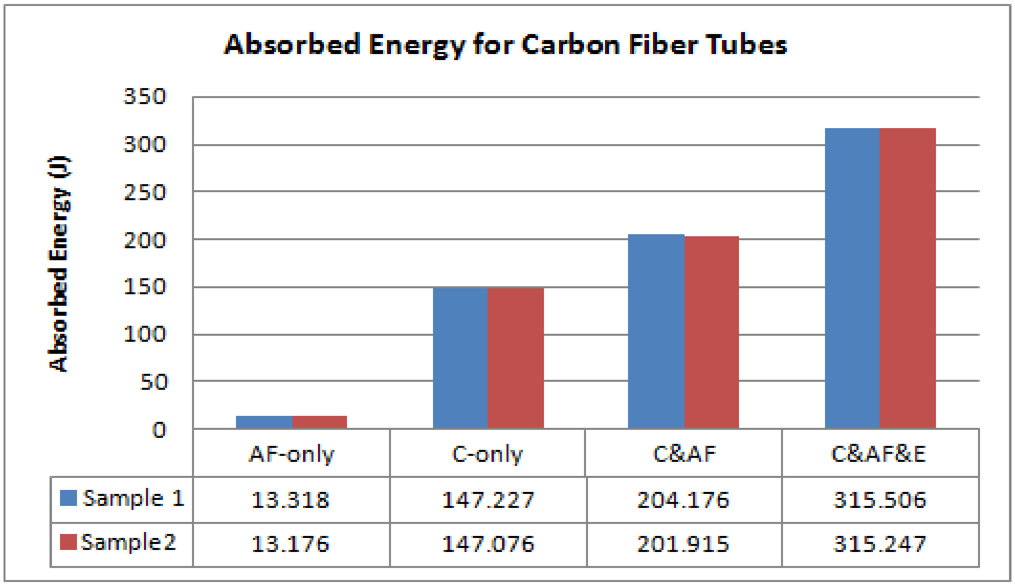

Figure 17 – Graph of absorbed energy for the various carbon fiber samples as well as the aluminum foam. AF denotes aluminum foam, C denotes carbon fiber and E denotes epoxy.

Referring to Table 2 and Figure 17, the energy absorbed by the crabon fiber increased by a 50 J with the addition of the aluminum foam core which is far higher than the 13 J that can be directly attributed to the aluminum foam. This indicates a dramatic change in the failure mode and that can be observed in the photographs in Table 2. In the case of the carbon fiber tube, the material splintering with some fibers oriented towards the interior of the tube and others oriented to the exterior. With the aluminum foam core, the fibers were constrained to fail toward the exterior and that failure mode became even more pronounced with the addition of the epoxy.

Table 3 - Energy absorption for the various aluminum samples

Sample number	**Type of Material**	**Energy absorption (J)**	**Photograph of crushed samples**
Sample 1	Aluminum tube only	299	
Sample 2		300	
Sample 1	Aluminum tube with aluminum foam	310	
Sample 2		311	
Sample 1	Aluminum tube with aluminum foam and epoxy	441	
Sample 2		410	

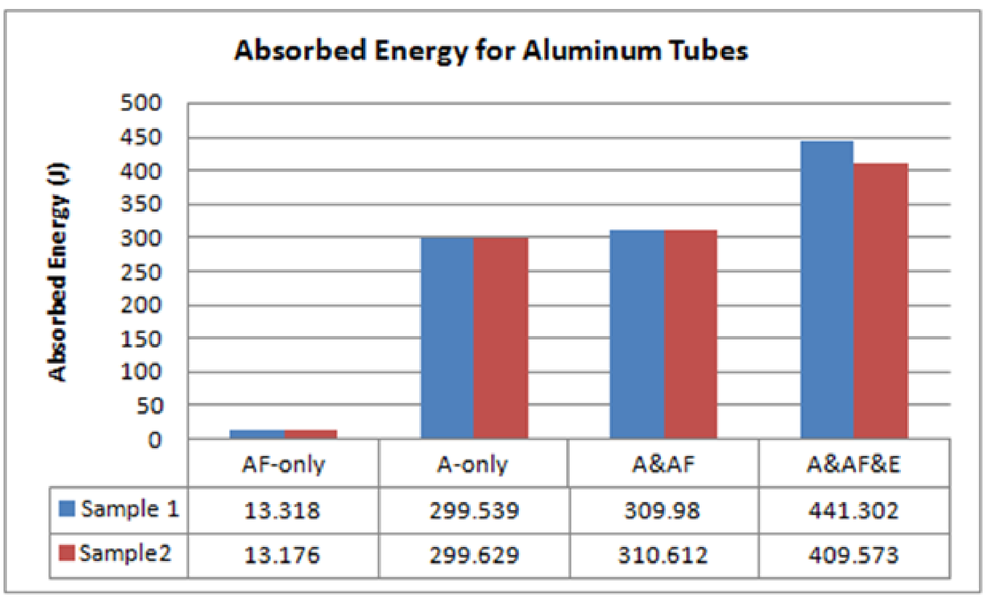

Figure 18 - Graph of absorbed energy for the various aluminum samples as well as the aluminum foam. AF denotes aluminum foam, A denotes aluminum tube and E denotes epoxy.

Referring to Table 3 and Figure 18, the energy absorbed by the aluminum tube increased by 10 J with the addition of the aluminum foam core. Given that the core itself absorbs a comparable amount of energy, one can draw the conclusion that the core did not contribute synergistically to the combined structure. The photographs of the deformed structure in Table 3 shows the similarity in the failure modes for the aluminum tube with and without the core.

The addition of the epoxy caused a significant change in the absorbed energy with an additional 100 J recorded. The bottom picture in Table 3 reveals a drastically altered failure mode where the tube splits longitudinally and forms what looks like the petals of a flower.

The maximum force measured during the crushing cycle is given for each sample in Figure 19. The epoxy added nearly 10000 N of crushing force to both the aluminum and carbon fiber samples, which is problematic in crash situations as the aim is to minimize the force. The addition of the aluminum foam to the carbon fiber caused a 5000 N addition in crushing force, which is representative of the changed failure mode observed in the photographs of Table 2. Given that the aluminum foam alone should add a crushing force in the neighborhood of 1000 N, the five thousand extra Newtons of crushing force represents a movement in the wrong direction and should be noted as an ineffective addition.

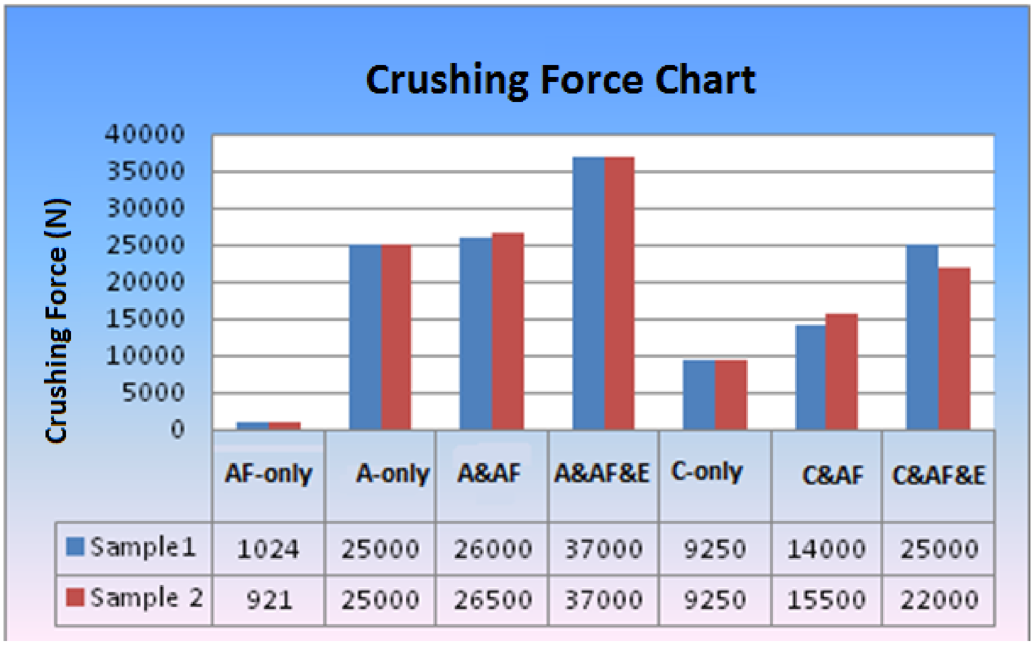

Figure 19 – Maximum crushing force. AF is aluminum foam, A is aluminum, C is carbon fiber and E is epoxy.

Specific Energy Comparison

A true measure of the effectiveness of the aluminum foam and epoxy can only be made when comparing the specific energy, which is the absorbed energy divided by weight in kg. Table 4 shows the specific energy for the carbon fiber tubes.

Table 4 – Specific energy for carbon fiber samples.

The Materials	AF- only	C- only	C& AF	C& AF&E
Weight (kg)	0.005	0.0052	0.011	0.0165
Absorbed Energy(kJ)	0.013247	0.147	0.203	0.315
Absorbed Energy/ Weight:(kJ/kg)	2.6494	28.2	18.45	19.09

The specific energy decreased with the addition of the aluminum foam by 10 kJ/kg and increased slightly with the addition of the epoxy. Such a result is a clear indication that the addition of aluminum foam and/or epoxy leads to a less effective solution.

Table 5 - Specific energy for aluminum samples.

The Materials	AF- only	A- only	A& AF	A& AF&E
Weight (kg)	0.005	0.01	0.0145	0.021
Absorbed Energy(kJ)	0.013247	0.3	0.31	0.4
Absorbed Energy/ Weight:(kJ/kg)	2.6494	30	21.37	19.04

The specific energy for the aluminum samples are shown in Table 3. The aluminum samples fared just as poorly as those of the carbon fiber with the addition of the aluminum foam and/or epoxy with a 10 kJ/kg drop in specific energy. This result is further validation that, from a specific energy point of view, the addition of the aluminum foam with or without epoxy is not effective in this particular embodiment.

The reasons behind the decrease in specific energy for the carbon fiber and aluminum are different. In the case of the aluminum tubes, the aluminum foam contributed little added energy compared to the aluminum tube itself. As a result, its added weight, albeit small, became a liability. In the case of the carbon fiber, the aluminum foam contributed significant added energy but its weight was comparable to that of the carbon fiber.

From these observations, the ideal solution is one where the weight of the carbon fiber is significantly higher than aluminum foam. That can be accomplished either through a lighter aluminum foam (97% porosity versus the 90% porosity of the current material) or through clever manipulation of the geometry. Both options will be the subjects of future studies.

Maximum Force Comparison

Absorbed energy normalized to the maximum force is another measure of effectiveness to the specific energy discussed previously. A higher absorbed energy per maximum force indicates that the material is able to absorb more energy while transmitting less force into the underlying structure. The results for the carbon fiber and aluminum tubes are given in Tables 6 and 7, respectively.

Table 6 – Energy absorption per maximum transmitted force for carbon fiber

The Materials	AF- only	C- only	C& AF	C&AF&E
Max Force (KN)	0.972	9.25	14.750	23.5
Absorbed Energy(KJ)	0.013247	0.147	0.203	0.315
Absorbed Energy/ Max Force (KJ/KN)	0.013628	0.014	0.0137	0.0134

Table 7 - Energy absorption per maximum transmitted force for aluminum

The Materials	AF- only	A- only	A& F	A&AF&E
Max Force (KN)	0.972	25	26	37
Absorbed Energy(KJ)	0.013247	0.299	0.31	0.425
Absorbed Energy/ Max Force (KJ/KN)	0.013628	0.01196	0.01192	0.0114

The absorbed energy per maximum force values are remarkably constant for both aluminum and carbon fiber with the addition of the core as well as core plus epoxy. This indicates a proportional relationship where absorbed energy is doubled and so is the transmitted force. This relationship is what would be observed if one uses two tubes adjacent to each other and indicates a complete lack of synergy and thus ineffectiveness of this type of construction.

5. Conclusions and Future Work

The addition of 90% porosity Duocel© aluminum foam cores to either aluminum or carbon fiber tubes was investigated under slow speed axial crushing. The study also investigated the case where the aluminum foam core was coupled to the inside of the tube using an epoxy layer. The results revealed that the addition of the aluminum foam core led to a reduction in the specific energy in kJ/kg, at least for the size of the tube (25.4 mm outer diameter with thin walls). The addition of the epoxy did not fare any better. Thus, from the standpoint of specific energy, the addition of an aluminum foam core with or without epoxy was counterproductive. Future studies will investigate the effects of lower density foams as well as various geometries.

The investigation also revealed that the absorbed energy normalized to the maximum force transmitted was nearly the same for all three variations (tube, tube with aluminum foam and tube with aluminum foam and epoxy). This reveals a complete lack of synergy and must be investigated further.

This study focused on low speed crushing of this material combination. Future work will involve the dynamic loading of this material to better ascertain its crash performance.

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