Mechanical Energy Absorbers and Aluminum Honeycomb

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In this paper general equations for a replaceable element energy absorber are presented. For long stroke application (1 m or more) a metal cutting energy absorber is preferred. For shorter stroke applications crushing of aluminum honeycomb material is suggested. To evaluate the usefulness of aluminum honeycomb, as an energy absorber, a drop test apparatus was designed and built. Results suggest two effects, a geometry ("size") effect and an impact velocity effect, cause the dynamic crush strength of the honeycomb to be different than static crush strength values. Experimentally the net effect causes less then 20 percent difference between static and dynamic crush strengths at extrapolated impact velocities of 50–100 m/s (164–328 ft/s).

Introduction

Shock protection involves the dissipation of kinetic energy while maintaining a tolerable level of deceleration. This protection may be required to prevent failure of mechanical or electrical components or for human operators in moving vehicles.

For applications where impact is expected to occur infrequently a replaceable element energy absorber (the equivalent of an electrical fuse) may be considered. The remainder of this paper will deal only with replaceable element energy absorbers.

Replaceable Element Energy Absorbers

To better formulate the requirements of a replaceable element energy absorber material consider the drop test shown schematically in Fig. 1. For this example a weight, w, initially at rest, drops from a height, h, onto the energy absorber. The velocity at impact is:

$$V_0 = \sqrt{2gh} \tag{1}$$

and during the interval after impact the equation of motion for the weight (w) is given below.

$$F = \frac{w}{g}(g - \ddot{x}) \tag{2}$$

In addition, the work done on the mass (by the absorber) must equal the change in potential energy of the mass between the start of the process and the finish.

$$\Delta \mathrm{PE} = w(h + l_s) \tag{3}$$

$$\mathrm{Work} = \int_0^{l_s} F\, dx \tag{4}$$

Note that F is the stopping force applied to the mass by the absorber.

For the ideal absorber an optimal choice for F is to have it constant over the stroke length (l_s). This choice will result in a minimum stroke length. Assuming F is constant, equations (3) and (4) can be combined and l_s solved for.

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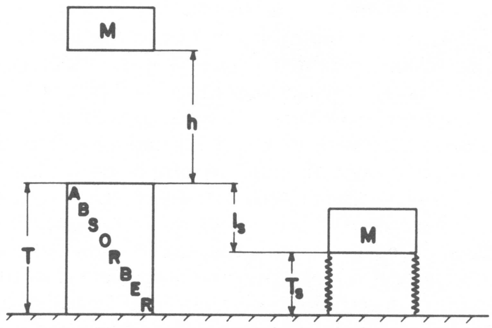

Fig. 1 Schematic of drop test

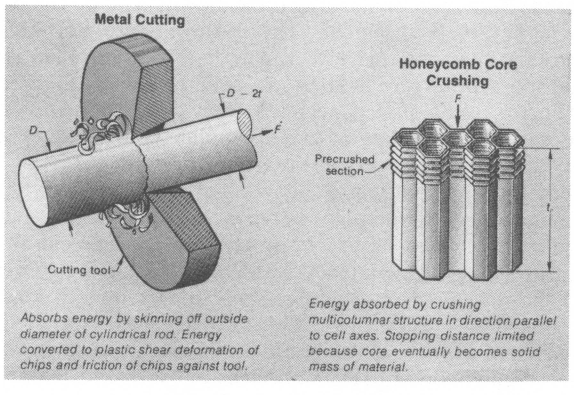

Fig. 2 Two processes for expendable element energy absorbers (from [1])

$$l_s\,(\text{constant force}) = \frac{h}{\dfrac{F}{w} - 1} \tag{5}$$

Kirk and Overway [1] have surveyed potential materials and processes which could provide a constant retarding force (F) independent of velocity and displacement. The authors concluded that the two most favorable processes are metal cutting and crushing of aluminum honeycomb core material. These are shown schematically in Fig. 2. The authors further

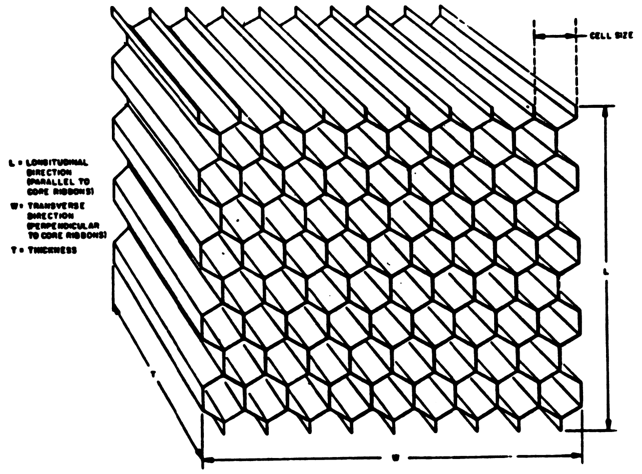

Fig. 3 Reference dimensions for honeycomb (from [10])

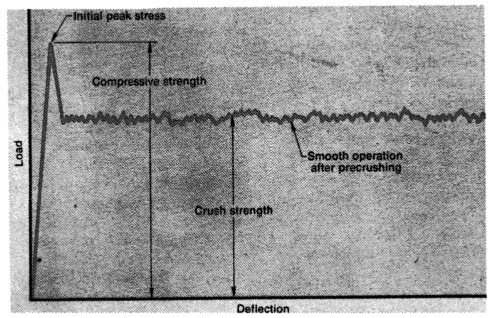

Fig. 4 Aluminum honeycomb core crushing behavior (from [1])

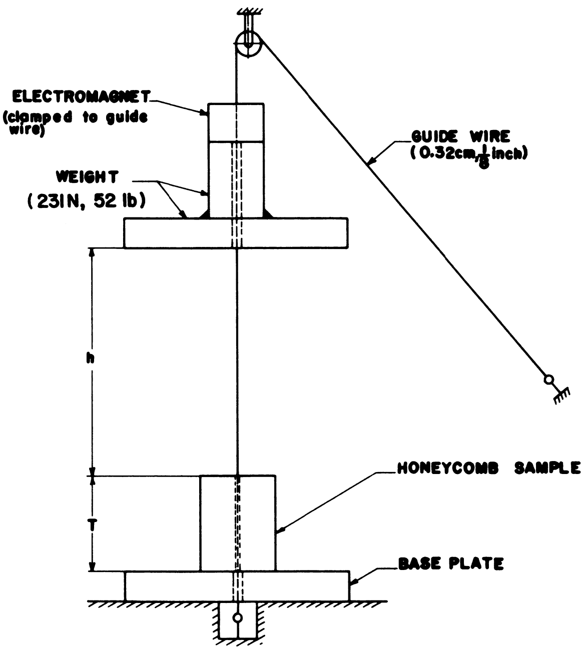

Fig. 5 Drop test apparatus

suggest that for long stroke applications (l_s greater than about 1 m) metal cutting would be preferred.

Metal cutting for energy absorption has been discussed by Shaw [2], Pleck et al. [3] and Kirk and Gay [4]. Kirk [5] has also reported on a metal cutting apparatus which has successfully been used to stop subway cars at the end of line runs.

Crushing of aluminum honeycomb was briefly discussed in a survey article by Coppa [6] on "New Ways to Soften Shock". Although there was not much space to provide details the results presented suggest that the crushing force (i. e. stopping force) increases very little ($\approx$ 2 percent) as impact velocity increases from very slow (near 0) to 30 m/s (100 ft/s). Other researchers such as Conn [7] and Lewallen and Ripperger [8] have used air guns to propel projectiles into an aluminum honeycomb material; however, their work does not appear to have been widely published in the open literature. Their data, in general, suggest that the crushing force does not depend on impact velocity over the range very slow to greater than 30 m/s. In tests by both Conn and Lewallen and Ripperger the honeycomb cross section was the same for all tests. Additional work by Ripperger and Reifel [9] has indicated that the honeycomb retarding force may depend on the size of the honeycomb specimen. The authors were not able to precisely quantify this effect, but they suggest that larger retarding forces are associated with larger crush area to perimeter ratios of the specimen. This conclusion, however, was based upon testing of two dissimilar types of honeycomb having different test geometries (round and square).

Finally, it should also be pointed out that the typical dynamic crush test involves a free moving mass impacting the aluminum honeycomb. Photographic or accelerometer measurements of the impacting mass (Cohn and Ripperger, et al.) shows that the crush force stays approximately constant as the mass decelerates. This would suggest that it is reasonable to look at the initial and final dimensions of the honeycomb in order to evaluate energy absorber behavior.

Honeycomb Parameters

Honeycomb material refers to a geometric arrangement of thin sheets (e. g. aluminum) bonded together to form cells of uniform shapes, usually hexagonal. The cores are made by either assembling corrugated ribbons or by strip bonding flat ribbons and then expanding the core cells to the proper shape. Reference areas for honeycomb cores are shown in Fig. 3.

The parameters which are controlled by the manufacturer of the honeycomb, and which determine the mechanical behavior, are foil material, foil thickness, and cell size (across flats). The two honeycomb manufacturers follow the format of reference [10] in describing honeycomb behavior in their technical literature [11, 12].

If a hexagonal core honeycomb is slowly compressed (at

Nomenclature

A = honeycomb crush area, cm^2
f_{cr} = static crush strength, Pa
f_{crd} = dynamic crush strength, Pa
F = retarding force, N
g = acceleration of gravity, m/s^2
h = drop height, m
l_s = crush (or stroke) length, m
$\bar{l}_s$ = average crush length, m
L = honeycomb longitudinal direction, cm
P = honeycomb perimeter, cm
P.E. = potential energy, Nm
T = honeycomb thickness, cm
$\bar{T}_s$ = average crushed honeycomb thickness, cm
V_0 = impact velocity, m/s
w = impact weight, N
W = honeycomb transverse direction, cm (perpendicular to core ribbons)
$\ddot{x}$ = impact weight acceleration, m/s^2

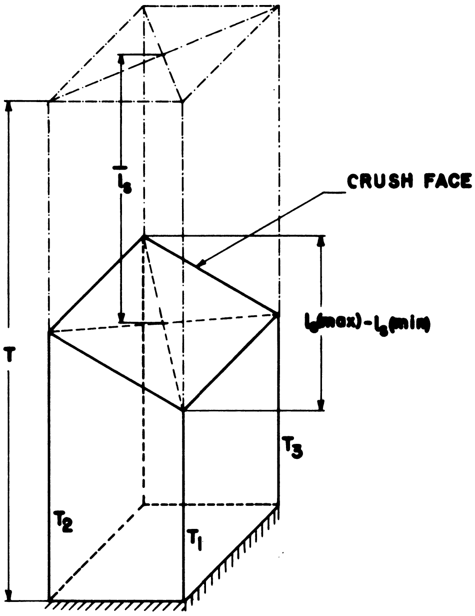

Fig. 6 Honeycomb dimensions after the drop test

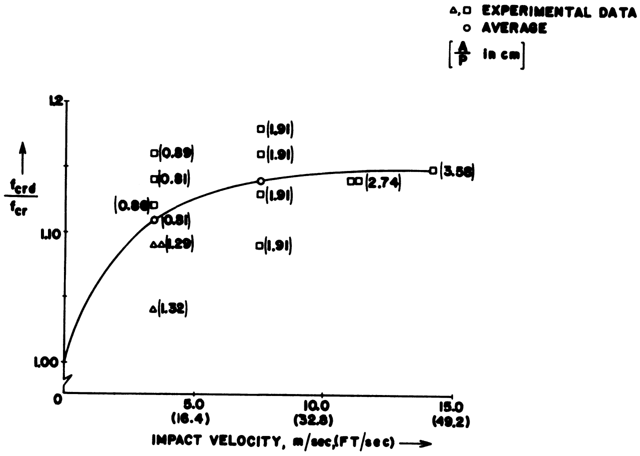

Fig. 7 Dynamic crush strength versus impact velocity; type I honeycomb, $f_{cr} = 1.02$ mPa (148 psi)

speeds less than 5 cm/min), along the cell axis direction, the behavior shown in Fig. 4 is observed. The crush strength (f_{cr}) is obtained by dividing the crush force (F) by the crush area ($A = L \times W$) and $f_{cr} = F/A$. Depending on the aluminum honeycomb parameters crush strengths vary from 68 kPa (10 psi) to 68 MPa (10,000 psi). During crushing the honeycomb cells collapse in a uniform manner and the crush strength remains constant over approximately 70 percent of the original core thickness. The initial peak stress is removed in energy absorber applications by slightly precrushing the honeycomb.

Description of Drop Test

The drop test apparatus shown in Fig. 5 was used to evaluate the dynamic crush strength of (f_{crd}) samples of aluminum honeycomb core material.

The guided drop apparatus was composed of an electromagnet, the drop weight, and the honeycomb sample. Prior to testing, the guide wire was passed through the weight and the honeycomb. With the arrangement on the floor the electromagnet was energized and the assembly was pulled into position with the guide wire taut. When all small oscillations of the weight damped out, the test was conducted. After the drop the guide wire was disconnected and the honeycomb sample removed. A summary of the types of honeycomb which were tested and of the range of test conditions is shown in Table 1.

After the drop test was completed the height of the honeycomb at each of the four corners was measured ($T_1 \ldots . T_4$) as shown in Fig. 6. The average height was computed ($\bar{T}_s$) from the four corner measurements, and from this number the average value of crush length ($\bar{l}_s = T - \bar{T}_s$) was obtained. To be systematic (although arbitrary) it was decided to throw out the data from those samples that had excessive tilt on the crush surface. This was accomplished by determining $l_{s(\max)} - l_{s(\min.)}$ for each specimen. This difference was then divided by $\bar{l}_s$ for the specimen and this tilt ratio (a measure of percentage of tilt) was compared for all the tests which were run. In general the worst percent tilts occur for large drop heights and it was decided (after looking over all the experimental data) to keep only the data having a tilt ratio of 20 percent or less. It should be pointed out that at all impact velocities less than the maximum tilt ratios were approximately 10 percent or less (they averaged 5 percent) and tilt distortion was not a problem.

Table 1 Aluminum honeycomb drop test

Type I	: 5052 aluminum 0.48 cm(3/16 in.) cell size 0.025 mm(0.001 in.) foil thickness f_{cr} = 1.02 mPa (148 psi)
Type II	: 5052 aluminum 0.64 cm(1/4 in.) cell size 0.025 mm(0.001 in.) foil thickness f_{cr} = 938 kPa (138 psi)
Maximum drop height	: 10.7 m(35 ft)
Maximum impact velocity	: 14.5 m/s(48 ft/s)
Drop weight	: 231 N(52 lbs)
Maximum sample thickness	: 33.0 cm(13.0 in.)

Results and Discussion

Before conducting a drop test the outside dimensions of the honeycomb sample were carefully measured. After the drop test an average value of crush length, $\bar{l}_s$ (Fig. 6), was obtained. If it is assumed that the retarding force (equation (5)) remains approximately constant during crushing then the following equation may be assumed to hold for the honeycomb sample,

$$F = f_{\rm crd} A \qquad (6)$$

where $f_{\rm crd}$ is termed the dynamic crush strength. If equation (6) is substituted into equation (5), $f_{\rm crd}$ may be found as:

$$f_{\rm crd} = \frac{w(h + \bar{l}_s)}{\bar{l}_s A} \qquad (7)$$

A value of $f_{\rm crd}$ was computed for each drop test and the results are plotted in Figs. 7 and 8.

In Figs. 7 and 8 the numbers in parentheses are the area/perimeter (A/P) ratio (in units of cm) for the sample tested. At any specific impact velocity if the symbols are the same (□ and Δ at 3.4 m/s in Fig. 7) the tests were identical and the results are indicative of the amount of data scatter. Thus, at an impact velocity of 3.4 m/s, three tests were identical with an A/P ratio of approximately 0.85 and three other tests were identical with an A/P ratio of approximately 1.30. The smooth curve in each of the figures is drawn through the average $f_{\rm crd}/f_{\rm cr}$ ratio for all data at that particular impact velocity.

Based on Figs. 7 and 8 it would appear that the lowest impact velocity test results suggest that there is some type of

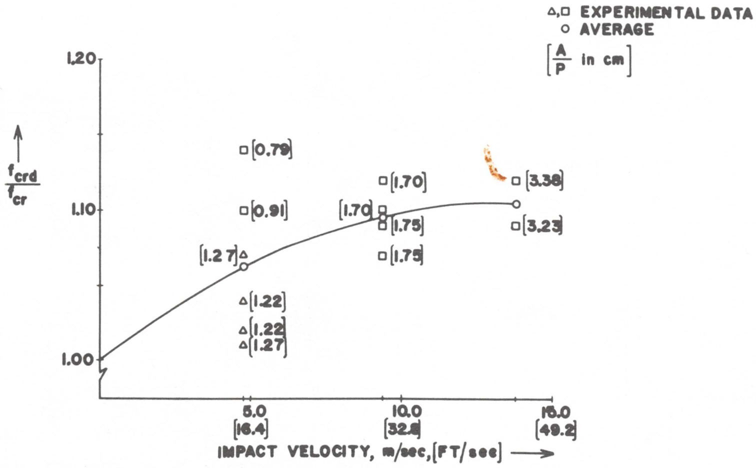

Fig. 8 Dynamic crush strength versus impact velocity; type II honeycomb, f_{cr} = 938kPa (138 psi)

sample geometry effect ("size effect") which causes a variation in f_{crd}. The larger the honeycomb crush area compared to the perimeter (larger A/P ratios) the smaller the value of f_{crd}. It would thus appear that the size effect ratio (A/P) tends to lower f_{crd}. Because of the limited testing at other impact velocities it can not be stated at this time whether the size effect is less important at larger A/P ratios or higher impact velocities. Current work is underway to understand more about the cause of the size effect.

In addition to the size effect the results shown in Figs. 7 and 8 suggest that f_{crd} increases with increasing impact velocity. In both figures the size effect ratios (A/P) are larger at the higher impact velocity tests. Since the size effect ratio appears to lower f_{crd} these results suggest a trend of increasing f_{crd} with impact velocity. A higher f_{crd} at larger impact velocities is consistent with the explanation that the yield strength of the aluminum foil material is greater at higher strain rates (i. e. at higher impact velocities).

The combination of the size effect ratio (A/P) decreasing f_{crd} and the velocity effect increasing f_{crd}, hold overall f_{crd} variations to less than 20 percent at impact velocities up to 15.0 m/s (49 ft/s). Since the average f_{crd}/f_{cr} curve flatttens out considerably at impact velocities above 10 m/s (33 ft/s) it would appear that this aluminum honeycomb material would behave predictably at much higher impact velocities. The material would thus make an excellent energy absorber for a wide range of impact velocities.

Conclusions

A drop test apparatus for evaluating the crush behavior of aluminum honeycomb, at various impact velocities, has been described. Results of drop testing has identified two effects which influence the dynamic crush strength of the aluminum honeycomb.

1 The first effect is termed a size effect and depends on the A/P ratio of a sample. As the A/P ratio increases, f_{crd} decreases.

2 The second effect is termed a velocity effect and depends on impact velocity. As impact velocity increases, f_{crd} increases.

Experimentally, for two different honeycomb samples, the combination of these two effects causes less than a 20 percent increase in dynamic crush strength (f_{crd}) up to an impact velocity of 15.0 m/s (and extrapolated to possibly 50 - 100 m/s).

The results presented in this paper suggest that aluminum honeycomb is an excellent energy absorber for a wide range of impact velocity applications.It would appear that the static crush strength (f_{cr}) is a reasonable predictor of dynamic crush behavior (when used with an appropriate factor of safety).

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