ONE-SHOT SHOCK

-for that once-in-a-

It's a device you hope will never be needed, but an emergency shock absorber is a vital part of any safety system designed to protect people and equipment. Where impact loads are infrequent or improbable, "throw-away" absorbers offer cost and size savings over reusable types.

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SHOCK protection usually involves dissipating impact energy while maintaining a tolerable level of deceleration. The energy dissipation typically requires converting kinetic energy into the deformation of some type of energy absorbing system.

In general, an energy absorber must meet two basic requirements:

- Object deceleration must be controlled over the entire stopping distance.
- Energy must be completely absorbed.

There are two principal types of energy absorbers. The recoverable type, such as a spring or rubber bumper, converts kinetic energy into stored potential energy. This type of absorber has some amount of springback that must be controlled.

Nonrecoverable energy ab-

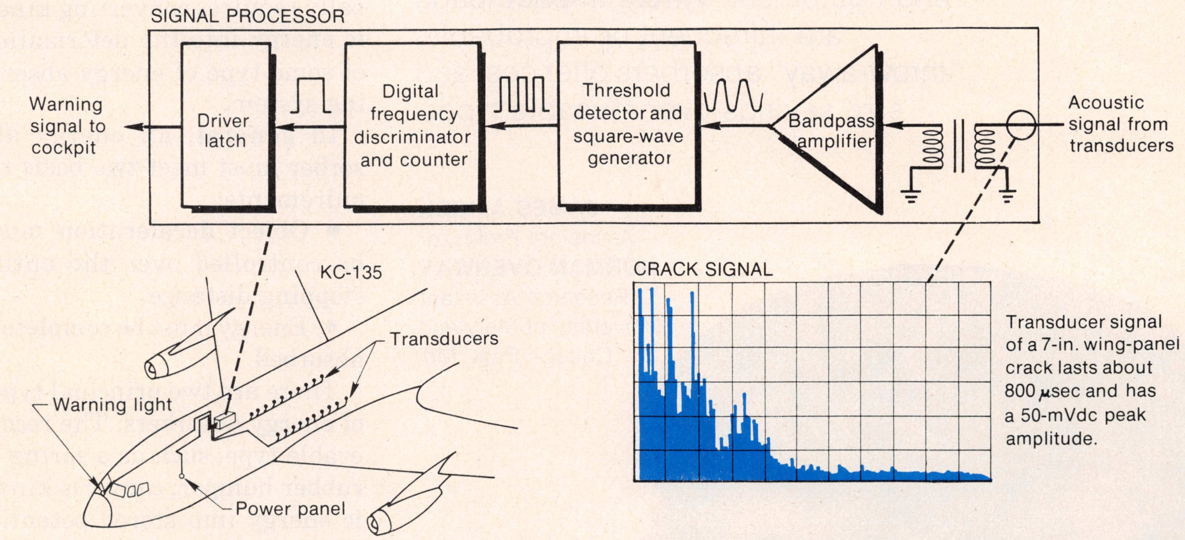
Cracks Make Noise

Cracking metal produces acoustic energy over a wide band of frequencies. This energy, resulting from breaking molecular bonds, extends into the lower MHz range and is easily detected with acoustic monitoring equipment.

Many large structures such as bridges, pressure vessels, fuel tanks, and airplanes have permanently mounted acoustic monitoring equipment that automatically activates an alarm if structural cracks are detected. For example, the Air Force KC-135 tanker-transport has a system for detecting cracks in the lower inboard wing panels in flight. These skin panels are made of strong but brittle aluminum, which may crack under some flight stresses.

Piezoelectric transducers attached to the panels detect acoustic activity, and coaxial cables connect the transducers to a signal processor module that discriminates between crack and noncrack signals. The signal processor triggers a warning light on the instrument panel in the cockpit and produces a permanent record in the event of panel cracking.

Warning of Wing Cracks



Transducer signal of a 7-in. wing-panel crack lasts about 800 μsec and has a 50-mVdc peak amplitude.

welding. These conditions shorten electrode life. However, the use of the acoustic feedback controller is expected to produce more consistent welds and improve tool life dramatically.

Inspecting with Sound

Acoustic monitoring is also used in nonproduction applications. For example, electronic-device makers use acoustic emission to detect loose particles in integrated circuits, transistors, relays, switches, and other electronic components. Particles with masses of less than 0.1/μg and less than 0.001-in. in diameter can be found. The impact of loose particles in the components under test creates high-frequency sound that is detected by a transducer in contact with the component.

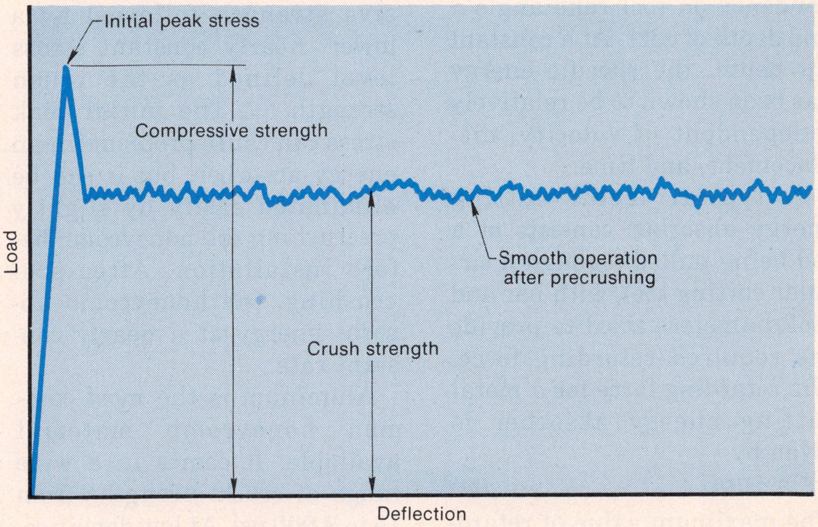
Acoustic emission is used to inspect for corrosion in the Air Force F-111 jet fighter. In this case, acoustic emission monitoring locates interior corrosion in the edges of the stabilizer assemblies by detecting the faint sounds of corrosion. When aluminum corrodes, condensed water vapor combines with the metal to form aluminum oxides and also releases hydrogen gas. The acoustic monitoring equipment detects the sound of hydrogen bubbles as they form, grow, and rupture.

Most applications of acoustic emission inspection involve crack detection. One of the fastest growing application areas is in requalification testing of pressure vessels and piping. The petrochemical industry is the largest user of acoustic emission for requalification through overpressure testing, and over 200 large structures have been tested in the last few years. Also, acoustic emission is used regularly to test reinforced rubber hoses that discharge oil from tankers.

Advanced acoustic emission inspection systems not only detect a crack, but also pinpoint its exact location. Transducers are placed at strategic locations on the structure to be tested. Whenever a defect begins to develop or grow, its emissions are detected by the transducers. A computer processes the transducer signals and displays the location of the emission source. Systems like this are usually used on large structures such as nuclear-reactor pressure vessels, petrochemical tanks, aerospace fuel tanks, bridges, subways, and airplanes. The advanced warning of structural defects these systems give not only increases safety, but also minimizes maintenance costs; minor defects detected early are easier to repair than larger defects found later.

ABSORBERS
lifetime failure

Smoothing Honeycomb Core Crushing



In compression, honeycomb core material exhibits an initial peak stress, caused by the compressive strength, followed by a lower nearly constant stress level. The initial peak stress can be removed easily by slightly precrushing the honeycomb before installation.

sorbers, on the other hand, convert kinetic energy into heat, eliminating springback. These types must be replaced after each use. For occasional mechanical shock, nonrecoverable shock absorbers are considerably less expensive than recoverable ones.

The most useful category of nonrecoverable shock absorbers dissipates kinetic energy through plastic deformation of material. These devices are relatively inexpensive, highly reliable, and applicable to a wide range of problems.

Basics

To design an energy absorber, stopping distance l_s and required retarding force F must be determined first. These quantities are defined by the following parameters:

- Allowable deceleration.
- Weight of object to be stopped.
- Impact velocity of the object; or, for a free falling object, height of the fall.

Required retarding force can be determined by setting the energy to be absorbed equal to the work performed on the absorber. The energy to be absorbed from an object moving in a horizontal path is given by the familiar equation for kinetic energy

$$E = WV^2/2g$$

If the object is moving in a downward vertical path, energy to be absorbed is

$$E = W(l_s + V^2/2g)$$

For a free falling object having zero initial velocity,

$$E = W(h + l_s)$$

The work performed on an absorber equals the area under the curve of retarding force vs stopping distance. For a constant force energy absorber, the equation for work is: Work $= Fl_s = E$.

During the period when the object and absorber are in contact, the object is acted upon by constant retarding force F. Therefore, equating the kinetic energy of the object with the work performed on the absorber results in the following design equations for stopping distance:

$$l_s = V^2/2a \quad \text{Horizontal path} \qquad (1a)$$

$$l_s = \frac{V^2}{2(a-g)} \quad \text{Vertical path} \qquad (1b)$$

$$l_s = \frac{hg}{a-g} \quad \text{Free fall} \qquad (1c)$$

The analysis assumes a constant retarding force; that is, F is independent of absorber velocity and displacement. This assumption is made because a constant force absorber minimizes stopping distance, minimizes retarding force, and eliminates potentially harmful changes in acceleration.

Types

Ideally, retarding force should be independent of velocity and be a function only of geometry and the material properties of the absorber. In practical terms, five methods come as close as possible to meeting these requirements.

Metal cutting is a simple and inexpensive method of absorbing energy. In this process, chip formation dissipates energy by gross plastic shear deformation of the chips and friction of the chips sliding along the cutting tool. The shear and frictional energies of metal cutting are characterized by a parameter known as specific energy U.

◀ *Metal cutting and honeycomb core crushing are the most predictable methods of absorbing shock mechanically. Retarding force is independent of impact velocity, so devices using these processes are easily sized to fit a wide range of requirements.*

Specific energy is the energy expended or work done in removing a unit volume of material.

For metal cutting operations, specific energy is nearly constant, having only a weak dependency on tool rake angle α and depth of cut t. At a constant cut depth, the specific energy has been shown to be relatively independent of velocity, displacement, and time.

A typical metal cutting energy absorber consists of a rod being pulled through a circular cutting tool, with bar and tool diameters sized to provide the required retarding force. The retarding force for a metal cutting energy absorber is given by

$$F = \pi UDt \qquad (2)$$

The maximum value of retarding force is limited by the yield strength in the reduced diameter portion of the bar; therefore

$$F < (\pi/4)\,(D - 2t)^2\sigma_y \qquad (3)$$

If the bar is to be pushed through the cutting tool, its buckling stability must be checked by the traditional column formula for the applicable end conditions.

Honeycomb core crushing dissipates energy by plastic deformation of the multicolumnar structure in a direction parallel to the cell axes. In compression, honeycomb material exhibits an initial peak stress level produced by the compressive strength followed by a lower, nearly constant stress level defined as the crush strength f_{cr}. The initial peak stress can cause problems in an energy absorber, but it can be eliminated easily by slightly precrushing the honeycomb before installation. After precrushing, the honeycomb absorbs energy at a nearly constant rate.

Aluminum is the most common honeycomb material available. It comes in a wide range of crush strengths from 15 to 9,000 psi. At low densities, crush strength varies nearly linearly with density; however, at high densities, the relationship becomes increasingly nonlinear. A typical tolerance on crush strength is ±15% and must be considered in the design by applying an appropriate safety factor.

Tests also indicate that at moderate impact velocities (about 60 fps), crush strength is 20% to 30% higher than the static value. To compensate for this effect, the design deceleration should be reduced by 30% as a first approximation.

Retarding force produced by a honeycomb energy absorber is

$$F = f_{cr}A \qquad (4)$$

A limiting factor in the use of honeycombs is the percentage of length available for crushing before the core becomes a solid mass of material. Designated as the stroke efficiency β, this factor varies with density and can be approximated by

$$\beta = 0.825 - 0.0125\,\gamma \qquad (5)$$

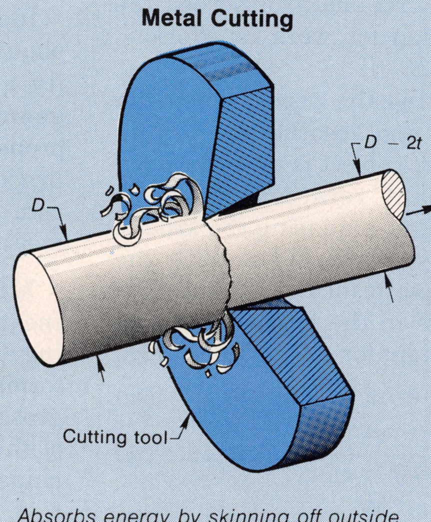
Typically, β varies from 0.75 to less than 0.50.

Rod and wire drawing expends energy by reducing the rod or wire diameter and by friction of the rod sliding against a die. A typical rod drawing energy absorber consists of a round rod or wire drawn through a circular die, with rod and die diameters sized to produce the required retarding force. With these devices, the absorber should be designed to apply a pulling force on the rod to avoid buckling.

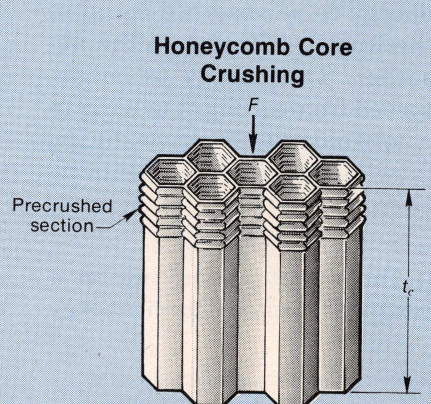
The retarding force for a rod

Quick Guide to One-Shot Shock Absorbers

Constant-force energy absorbers stop an object in the shortest possible distance and at the smoothest rate. The five methods shown here come as close as possible to providing this ideal operation.



Absorbs energy by skinning off outside diameter of cylindrical rod. Energy converted to plastic shear deformation of chips and friction of chips against tool.



Energy absorbed by crushing multicolumnar structure in direction parallel to cell axes. Stopping distance limited because core eventually becomes solid mass of material.

Specific Energy of Rod Materials

Material	Specific Energy, U (in.-lb/in.^{3})
6061-T6 Aluminum	100,000
Brass	250,000
Copper	400,000
Steel	
150 BHN	300,000
200 BHN	350,000
250 BHN	380,000
300 BHN	400,000
350 BHN	460,000
400 BHN	570,000

drawing energy absorber is a function of geometry, yield stress, and coefficient of friction and is given by

$$F = \left[\frac{\pi D_f{}^2\sigma_y}{4}\right]\left[\frac{1+B}{B}\right] \times \left[1 - \left(\frac{D_f}{D}\right)^{2B}\right]$$

where $B = \mu/\tan\phi$.

It has not been established that retarding force is independent of velocity for this process because both σ_y and μ can change with velocity. However, as velocity increases, higher strain rates and higher temperatures produce compensating effects which tend to maintain constant σ_y. Thus, rod drawing is potentially useful as an energy absorber. The upper limit on retarding force for drawing is determined by the yield strength in the reduced diameter portion of the bar; therefore

$$F < \pi D_f{}^2\sigma_y/4$$

Strip bending dissipates energy by plastic deformation of flat metal strips. A typical strip bending energy absorber might consist of two back-to-back flat metal strips retained at one end and supported by a casing. The strips are subjected to a reverse 180° bend and pulled through the casing in a continuous bending operation.

The retarding force for a strip bending energy absorber is a function of casing geometry, strip geometry, and yield stress. Retarding force is approximated by

$$F = \frac{\sigma_y b t_k{}^2}{2r}$$

In general, it has not been established that retarding force is independent of velocity for this process, and additional study is necessary to determine the relationship. Based on geometry, the upper limit on F is

$$F < 2\sigma_y b t_k$$

Tube buckling dissipates energy by forming and collapsing pleats and stretching the circumference of a tube. A typical buckling tube energy absorber consists of a collapsing tube guided internally by a mandrel. Tests have shown that uniform pleats are formed over a wide range of thickness-to-diameter ratios when a mandrel is employed. Without a mandrel, collapsing action is usually complex and unpredictable.

Retarding force for a buckling tube energy absorber is a function of tube geometry, Young's modulus, and yield strength, and is estimated by

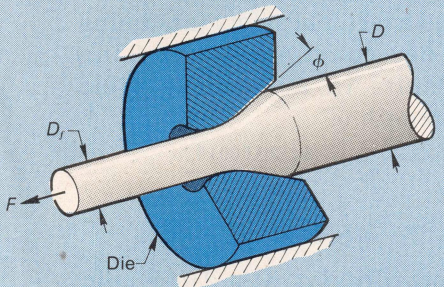
$$F = \frac{\pi\sigma_y t_w}{2}\left[\frac{\pi t_w D_m}{h_p} + h_p\right]$$

where

$$h_p = \pi t_w\left(\frac{E_y}{12\sigma_y}\right)^{1/2}$$

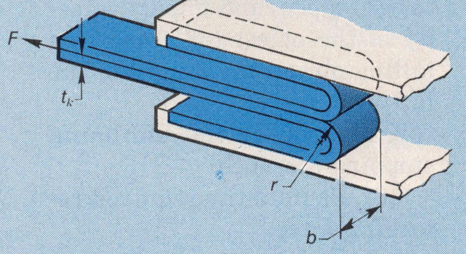
The amount of energy absorbed by buckling tube is a product of retarding force and the decrease in tube length. As with honeycomb core, the length available for crushing before bottoming (stroke efficiency) is an important consideration in the design. Stroke efficiency, which varies inversely with tube thickness, cannot be readily calculated from tube

Rod and Wire Drawing



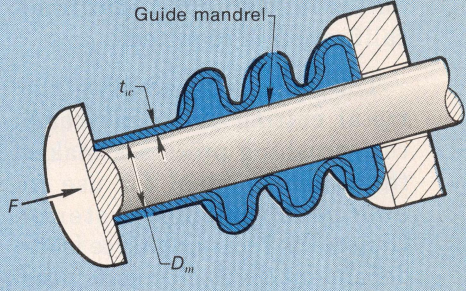
Absorbs energy by reducing rod or wire diameter. Energy converted to plastic deformation of rod and friction of rod against die.

Strip Bending

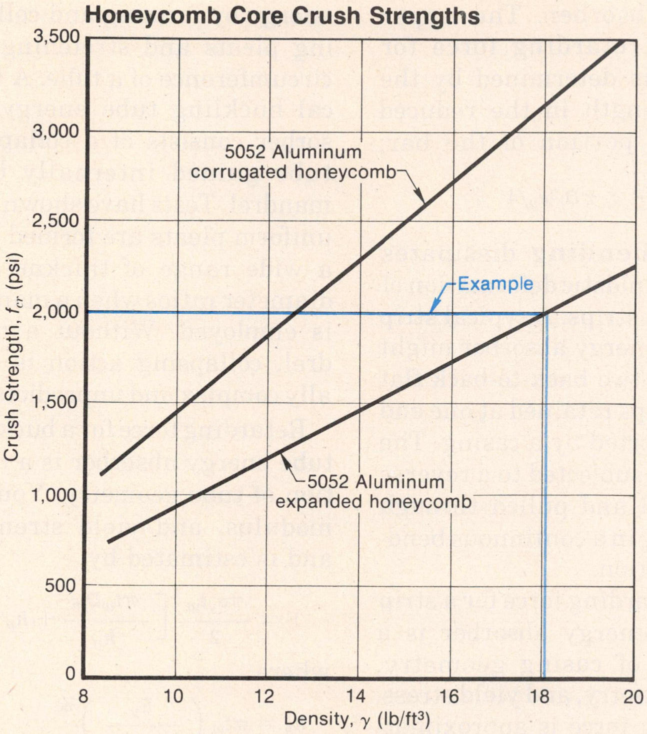


Energy absorbed by bending metal strips 180°. Retarding force may not be independent of object velocity.

Tube Buckling



Energy absorbed by forming and collapsing pleats and by stretching tube circumference. Mandrel aids uniform formation of pleats, providing predictable energy dissipation.



The crush strength of honeycomb core material varies nearly linearly with density. However, at higher densities, the relationship becomes increasingly nonlinear, sometimes varying by as much as ±15%.

geometry. However, it is limited by

$$\beta < 1 - 2t_w/h_p$$

Retarding force for this process depends on both displacement and velocity. The force increases to a maximum and then decreases gradually to a minimum with each buckling cycle. Low velocity tests (approximately 7.5 fps) produce results which differ significantly from static tests, suggesting these two equations can be used for initial sizing but that final calibration is required.

The good predictability of the metal cutting and honeycomb core crushing processes makes them nearly ideal for use in energy absorbing systems. Generally, retarding force is independent of velocity, so devices using these processes are easily sized to fit a wide range of requirements.

The other processes—rod and wire drawing, strip bending, and tube buckling—are less predictable and must include a greater margin of safety or must be calibrated to meet specific requirements. Therefore, the remainder of this discussion will be limited to designing energy absorbers using metal cutting or honeycomb core crushing.

Absorber Design

The basic steps in designing an energy absorber are:

1. Identify the allowable deceleration, weight of the object to be stopped, and impact velocity of the object (or, for a free falling object, the height of the fall).
2. Determine the minimum stopping distance.
3. Calculate the required retarding force.
4. Select a method for absorbing the energy.
5. Choose the material to be used in the energy absorber and its properties.
6. Compute the geometry of the components in the energy absorbing device, applying the appropriate safety factors.

Generally, if the required stopping distance is short, a honeycomb core should be used. Metal-cutting energy absorbers should be used for longer stopping distances.

For example, consider a 5-ton elevator operating in a building 100-ft high. The maximum tolerable deceleration in the event of a free-fall is 12 g. The pit in the basement of the building can be constructed to accommodate any reasonable shape and size energy absorption system. Design a system to meet these requirements.

Terminal velocity $V = (2gh)^{1/2}$ = 80 fps, and the minimum stopping distance from Equation 1c is

$$l_s = \frac{1\,(100)}{12 - 1}$$

$$= 9.1 \text{ ft}$$

The required retarding force is $F = Wa/g$ = 120,000 lb. Because of the relatively long stopping distance the metal cutting process is selected as the method for absorbing energy.

Symmetrical loading is provided by using four bars in a parallel arrangement with one bar on each side of the car. Material selection is made based on yield strength as determined by the limiting retarding force and a safety factor of six. Rearranging Equation 3 to include the number of bars and a factor of safety (assuming a bar cut diameter of 2 in.) results in a required yield strength of

$$\sigma_y > \frac{4\,(120{,}000)\,6}{4\pi\,(2)^2}$$

$$> 57{,}300 \text{ psi}$$

Accordingly, AISI 1045 cold drawn steel is selected having a yield strength of 80,000 psi and Brinell hardness of 195 BHN. From the table, specific energy of this material is approximately 350,000 in.-lb/in.^{3}

Geometry to be determined for the energy absorber is bar diameter and length and cutting tool inside diameter. Using the selected yield strength and maximum retarding force (Equation 3), required bar cut diameter ($D-2t$) is

$$(D-2t) > \left[\frac{4\,(120{,}000)\,6}{4\pi\,(80{,}000)}\right]^{1/2}$$

$$> 1.69 \text{ in.}$$

The next larger standard bar size is 1.75 in. The depth of cut can now be determined by rearranging Equation 2 to produce

$$t = \frac{120{,}000}{4\pi\,(350{,}000)\,(1.75)}$$

$$= 0.0156 \text{ in.}$$

and the tool inside diameter is

$$D_t = D - 2t$$

$$= 1.7188 \text{ in.}$$

The bar and tool diameters of 1.750 in. and 1.7188 in. produce the maximum allowable deceleration. Any variation in bar or tool diameters from manufacturing tolerances must be such that they only decrease deceleration, which increases stopping distance. Tolerance on cold drawn steel bar stock is +0.000, −0.004 in., and the tool ID can be machined to a tolerance of +0.001, −0.000 in . Thus, the minimum value of t is

$$t_{\min} = \frac{(1.750 - 0.004) - (1.7188 + 0.001)}{2}$$

$$= 0.0131 \text{ in.}$$

The maximum stopping distance can now be determined for the worst case tolerance accumulation. In addition, a factor of safety should be applied to the maximum stopping distance. (A value of 1.25 is reasonable)

$$l_{s\max} = hf_s\left[\frac{\pi U D t_{\min} N}{W} - 1\right]^{-1}$$

$$= 13.8 \text{ ft}$$

Thus, four steel bars 1.75-in. in diameter and about 14-ft long safely stop the elevator when cutting tools having an ID of 1.7188 +0.001, −0.000 in. are used. The cutting tools should have a rake angle of 10°, a 10° clearance angle , and be made of a higher hardness material than the bar stock.

Now, consider loaded railway cars weighing approximately 125 tons traversing a steep incline on a cog railway. In the event of power and brake failures, the cars roll downhill with the maximum velocity at end of the track reaching 40 fps. A horizontal barricade is to be constructed at the end of the track. The railway car can withstand a deceleration of 30 g. Design an energy absorbing system to prevent damage to the cars.

The minimum stopping distance from Equation 1*a* and applying the 30% correction factor is

$$l_s = \frac{1.3[40\,(1.4667)]^2}{2\,(30)\,(32.2)}$$

$$= 2.4 \text{ ft}$$

Because of the relatively short stopping distance, the honeycomb core process is selected. Required retarding force (reducing deceleration by 30%) is $F = 0.7Wa/g = 5.25 \times 10^6$ lb. Geometry to be determined is core thickness (length) and cross sectional area.

Two types of honeycomb materials meet the requirements for energy absorbers: corrugated 5052 aluminum and expanded-core 5052 aluminum. Their crush strength to density properties are shown in the crush strength graph.

Required core thickness depends on stopping distance and stroke efficiency. A factor of safety should be applied to the thickness calculation to account for variations in crush strength from manufacturing tolerances. A factor of 1.25 is reasonable for this application.

Selection of the core material is mainly an intuitive process based on data available from manufacturers. For preliminary calculations, it is sufficient to arbitrarily select a crush strength falling about in the middle of available strengths and base the remaining calculations on this value. If a honeycomb with this strength is not actually available, the thickness and area calculations can be altered after consulting a manufacturer.

For this application, an expanded aluminum honeycomb with a crush strength of 2,000 psi and a density of 18.1 lb/ft³ (from the graph) is selected. Core thickness, then, is

$$t_c = l_s f_s/\beta$$

$$= 62.6 \text{ in.}$$

And cross sectional area from Equation 4 is

$$A = \frac{(5.25)\,(10^6)}{2{,}000\,(144)}$$

$$= 18.2 \text{ ft}^3$$

MD

Nomenclature

A = Honeycomb cross sectional area
a = Allowable deceleration
B = Calculation constant
b = Strip width
D = Original rod diameter
D_f = Final rod diameter
D_m = Mean tube diameter
D_t = Cutting tool ID
E = Energy or work
E_y = Young's modulus
F = Retarding force
f_{cr} = Crush strength
f_s = Safety factor
g = Gravitational constant
h = Drop distance in free fall
h_p = Original height of single pleat
l_s = Stopping distance
m = Mass
N = Number of rods
r = Mean radius of curvature
t = Depth of cut
t_c = Honeycomb core length
t_k = Strip thickness
t_w = Tube wall thickness
U = Specific energy of cutting
V = Object velocity
W = Object weight
α = Tool rake angle
β = Stroke efficiency
γ = Honeycomb weight density
μ = Coefficient of friction
σ_y = Yield strength
ϕ = Die included half angle