Int. J. mech. Sci., Vol. 19, pp. 595–602. Pergamon Press 1977. Printed in Great Britain

DESIGN OF A METAL SKINNING ENERGY ABSORBER FOR THE U.S. CAPITOL SUBWAY SYSTEM

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(*Received* 20 *June* 1977)

Summary—The design of a metal skinning emergency overshoot stopping device for the U.S. Capitol Subway System is discussed. The kinetic energy of the vehicle is dissipated by pulling a round rod through a circular cutting tool. The design procedure used in the selection of critical components is reviewed and a systematic method for their selection is shown. Photographs of the final design hardware are shown. A subway collision test was conducted and the results of the test are shown to agree well with predictions.

NOTATION

σ_w	working stress, Pa
σ_y	yield stress, Pa
a	vehicle acceleration, m/s^2
D	outside diameter of rod, m
F	retarding force of Energy Absorber, N
l	distance energy absorber moves, m
l_a	deceleration limited stopping length, m
l_s	space limited stopping length, m
l_{stop}	stopping length of vehicle also energy dissipation length, m
N	number of cutting tool units, —
t	radial depth of cut, m
U	cutting energy per unit volume of chips, Nm/m^3
V	vehicle velocity after moving a distance, l, m/s
W	weight of impacting vehicle, N
g	acceleration of gravity, 9.80 m/s^2

INTRODUCTION

The U.S. Capitol–Rayburn House subway system operates between a terminal located at the Southwest corner of the Capitol and the Rayburn House Office Building. The track length is approximately 198 m (650 ft) and the one way running time is approximately 42 sec. A photograph of the subway car and the passenger loading platform is shown in Fig. 1.

A failure of the automatic dynamic and mechanical braking systems can cause a subway car to overshoot the unloading platform and impact a concrete barrier. Fig. 2 shows a photograph of the overshoot area—note in particular the concrete barrier at the end of the tracks.

Because of the catastrophic effects of subway overshoot, it is important to provide an ultimate stopping system that would absorb the vehicle energy in a safe and reliable manner. The design parameters, provided by the Capitol subway engineering staff, are shown in Table 1. In addition, it was also important that the ultimate stopping system,

(1) be as inconspicuous as possible—to avoid undue alarm (and unsightliness) to passengers, and

(2) be extremely reliable, all mechanical, and require minimum upkeep.

METAL SKINNING ENERGY ABSORBER

A kinetic energy absorber should provide a predictable and reliable means of dissipating the kinetic energy of a moving vehicle. The energy should be removed so that the maximum deceleration levels do not exceed design specifications.

TABLE 1. CAPITOL SUBWAY DESIGN PARAMETERS

Maximum Impact Velocity	--	7.6 m/s (1500 ft/min)
Maximum Impact Weight	--	102,000 N (23,000 lbf)
Maximum Deceleration Level	--	1 g (32.2 ft/sec^2)
Maximum Stopping Distance	--	6.1 m (20 ft.)
Maximum Kinetic Energy	--	.30 MJ (2.23 x 10^5 ft-lbf)

A schematic diagram of a general absorber system is shown in Fig. 3. The best manner of dissipating the vehicle kinetic energy (K.E.) is to convert it to non-recoverable work. Under these conditions, no residual usable energy will remain in the system and springback is eliminated. If it is assumed all the vehicle kinetic energy is dissipated as work, then the change in vehicle kinetic energy must equal the work done on the vehicle.

$$\frac{1}{2}\frac{W}{g}(V^2 - V_i^2) = -\int_0^l F\,dl. \tag{1}$$

Shaw[1] was the first to suggest that metal cutting could be used for absorbing vehicle kinetic energy. He proposed a specific design, for automobile bumpers, utilizing a round bar which is pushed through a circular cutting tool (typical impact speed 5 mph = 7.3 ft/sec = 2.24 m/sec). The force of pushing the bar through the cutting tool would expend energy in chip formation—and bring the vehicle to a stop. Shaw's development relies on two important assumptions. The first is that the metal cutting force is independent of velocity and displacement. The second is that a value for specific cutting energy (the total energy expended per unit volume of chips, U) is not affected by the circular geometry and conventional steady state values may be used for U. The first assumption was later verified by Pleck and Von Turkovich,[2] using a decelerative orthogonal metal cutting aparatus and evaluating 3 different materials. They showed that the cutting force and U is approximately constant over cutting velocity ranges from 0.75 m/s to 3.1 m/s. Conry, Metz and Pleck[3] have also shown that metal cutting is an optimal energy absorption process and they present design principles which suggest how the process can be applied. The authors show that U generally decreases with increasing cutting speed. They suggest that for weak velocity dependent materials U will increase to approximately 110% of the high speed asymptotic value, at low cutting speeds.

For the Capitol subway application, a metal "skinning" operation, as shown in Fig. 4, was utilized. For this design, it was assumed that U is independent of velocity and the geometry of the configuration. It should also be noted that U is weakly dependent on the depth of cut and tool rake angle.[4] For reasonable rake angles (5–20°) and depths of cut (0.006–0.020 in.) U is assumed constant and independent of these parameters. Typical steady state values for U are $2.1 \times 10^9\,\mathrm{Nm/m^3}$ (300,000 in lbf/in^3) for steel and $0.7 \times 10^9\,\mathrm{Nm/m^3}$ (100,000 in lbf/in^3) for aluminum.[5]

A value for U may be obtained by evaluating the Brinell indentation hardness of the material being cut ($U \cong H_B$).[6]

Knowing the value for U, the magnitude of the pulling force F (Fig. 4) may be estimated as

$$F = U\pi Dt \tag{2}$$

independent of velocity, displacement and time.

There is a second component of force, perpendicular to F in Fig. 4, which arises due to the mechanics of the cutting process. This force does no work in stopping the vehicle but it will help to keep the rod centered in the cutting tool. For conventional metal cutting this force is approximately 0.5 of the power force.[4]

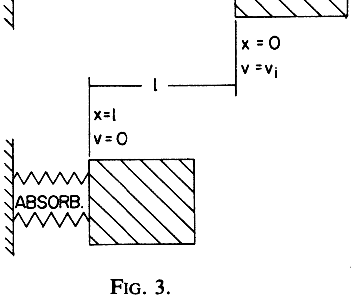

FIG. 3.

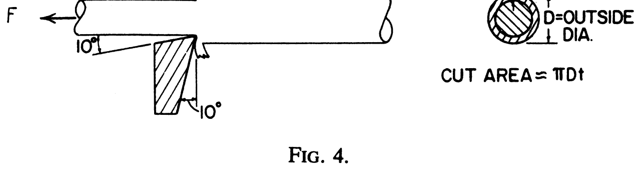

FIG. 4.

FIG. 3. Schematic diagram of an energy absorber system.

FIG. 4. Schematic diagram of metal skinning geometry.

FIG. 1. U.S. Capitol—Rayburn House Subway Loading Platform.

FIG. 2. U.S. Capitol–Rayburn House Subway Overshoot Area. The end of the overshoot is 6.1 m (20 ft) beyond the normal stopping position of the subway car.

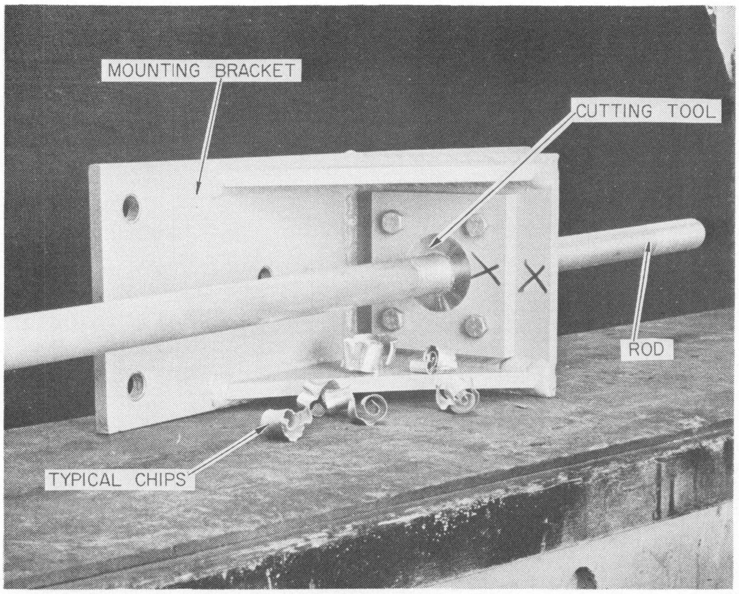

FIG. 7. Metal skinning unit.

SELECTION OF METAL SKINNING PARAMETERS

Since the vehicle retarding force, F, depends only on U and geometry parameters, equation (1) may be simplified to:

$$F \cdot l_{\text{stop}} = \frac{1}{2}\frac{W}{g} V_i^2. \tag{3}$$

For a constant magnitude retarding force, the vehicle will decelerate according to the equation:

$$F = \frac{W}{g} \cdot a. \tag{4}$$

Combining equations (3) and (4) allows the energy dissipation stopping length to be obtained

$$l_{\text{stop}} = \frac{V^2}{2a}. \tag{5}$$

The energy dissipation stopping length (l_{stop}) is either limited by the space available (l_s) or the maximum deceleration allowed (l_a). For any particular design the largest possible energy dissipation length (between these two values) should be used. For the Capitol subway $l_a = 3.0$ m (9.7 ft) and $l_s = 6.1$ m (20 ft). For this applicaton an energy dissipation length of 4.3 m (14.5 ft) was chosen. The value of deceleration (a) for this energy dissipation length is shown in Table 2.

The design for the Capitol subway uses four metal skinning devices with 6061-T6 Aluminum rods as the material being cut. For this material U was estimated[6] as the Brinnell hardness ($H_B = 95$ kg/mm^2 = 135,000 in lbf/in^3). Two rod and cutting tool units are mounted on each sidewall, parallel, one above the other, as shown in Fig. 5. The units on each sidewall work together when a striker bar, projecting laterally on each side of the subway car, impacts a short beam connecting the two rods together. This interaction can only occur when the vehicle overshoots the platform.

To calculate the pulling force per rod equation (4) can be modified as,

$$F = \frac{1}{N}\frac{W}{g} \cdot a \tag{6}$$

where N = number of individual cutting units. Using the data from Table 1 and a 0.67 g, gives the value for pulling force shown in Table 2.

TABLE 2. DESIGN TABULATION FOR METAL SKINNING ABSORBERS

Parameter	English		SI	
Space limited stopping length (ℓ_s)	20 ft		6.1 m	
Deceleration limited stopping distance (ℓ_a)	9.7 ft		3.0 m	
Energy dissipation length (ℓ_{stop})	14.5 ft		4.3 m	
Deceleration level (a)	21.6 ft/sec^2 (.67 g)		6.5 m/sec^2 (.67 g)	
Pulling force (F) per rod	3860 lbf		17293 N	
6061-T6 yield stress (σ_y)	40,000 psi		276 MPa	
Working stress (σ_w)	6667 psi		46 MPa	
Calculated rod cut diameter (D')	.859 in		2.182 cm	
Standard rod diameter (D)	1.000 in		2.540 cm	
Calculated depth of cut (t)	.0091 in		.231 mm	
Cutting tool I.D. (ID)	.982 in		2.494 cm	
Tolerances:				
Δ D (rod)	± .002 in	± .002 in	± .051 mm	± .051 mm
Δ ID (tool)	± .002 in	± .0005 in	± .051 mm	± .013 mm
Variations:				
Pulling force (ΔF)	848 lbf	530 lbf	3773 N	2357 N
deceleration (Δa)	4.8 ft/sec^2	3.0 ft/sec^2	1.46 m/sec^2	.91 m/sec^2
length (Δℓ)	4.1 ft	2.3 ft	1.25 m	.70 m

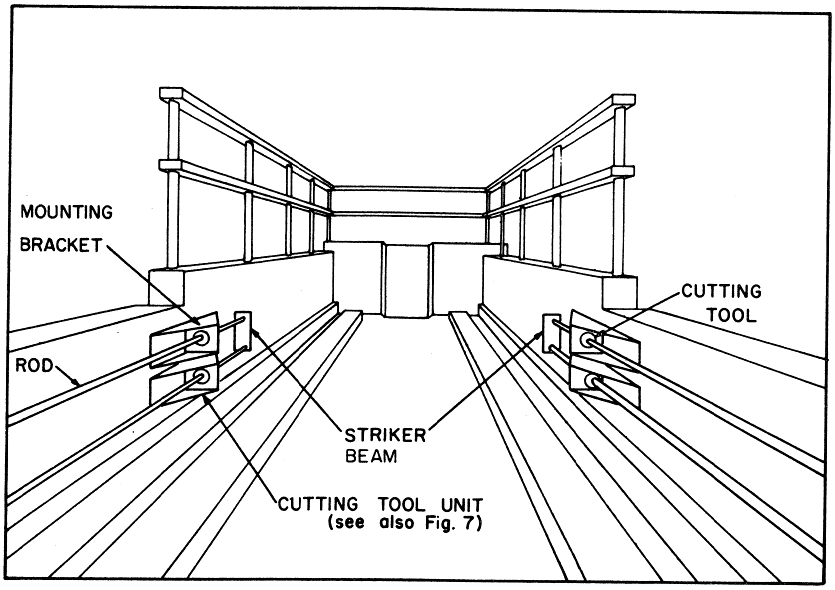

FIG. 5. Schematic diagram of metal skinning device placement for the capitol subway system.

A factor of safety (on rod stress) of 5 was assumed for this design. This value was applied to the rod yield stress, resulting in the working stress (σ_w) shown in Table 2.

It is necessary that the cut rod diameter (D') satisfy the following inequality.

$$D' \geq \sqrt{\frac{F}{\frac{\pi}{4}\sigma_w}} \tag{7}$$

D' is shown in Table 2.

The next step involves choosing an uncut diameter (D) (preferably a standard size) as indicated in Table 2. The radial depth of cut is then calculated from equation (2) and the cut rod diameter ($DCUT = D - 2t$) is compared to D'. If $DCUT > D'$, the design is acceptable. If $DCUT < D'$, a larger D would be chosen. The value for the calculated depth of cut is also shown in Table 2.

The cutting tool diameter is the same as the cut rod diameter and this value is rounded off to the nearest 0.025 mm (0.001 in.) as shown in Table 2. This is the tool diameter which was used for the subway design.

The tolerances on both the cutting tool and rod diameters cause variations in the magnitude of the cutting force, deceleration and energy dissipation length. These variations can be calculated using the following equations:

$$\Delta F = U\pi D(\Delta D + \Delta ID)/2 \tag{8}$$

$$\Delta a = \frac{N\Delta F}{(W/g)} \tag{9}$$

$$l_{\max} = \frac{V_i^2}{2(a - \Delta a)}, \quad \Delta l = l_{\max} - l_{\text{stop}} \tag{10}$$

where a positive ΔD is a larger rod and a positive ΔID is a smaller tool. For tolerances of ±0.051 mm (±0.002 in.) on the rod and ±0.051 (±0.002 in.) on the tool the variations are shown in Table 2. These variations were considered excessive so the tolerance on the tool ID was tightened to ±0.013 mm (±0.0005 in.) giving the variations shown. These were the final design dimensions. Kirk and Gay[7] have developed a design flowchart which summarizes the design steps discussed above; additional information on these steps may be found there.

The actual circular cutting tools for each unit were manufactured from ANSI-M4 tool steel which was quenched and tempered to R_c62. A 10° rake and clearance angle was used for each tool—a reasonable value considering the material being cut.

Because of the severity of impact, the actual rods were shaped with a taper as shown in Fig. 6. The purpose of this taper was to reduce impact stresses and to gradually apply the retarding force to the vehicle, to minimize "jerk" to the vehicle occupants. The choices of a linear taper and the length of taper were arbitrary. The effect of the linear taper also causes the calculated energy dissipation length to increase by 1/2 the actual taper length. This should be accounted for and sufficient stopping space should be provided.

EXPERIMENTAL RESULTS AND DISCUSSION

A photograph of one of the four metal skinning units is shown in Fig. 7. The frame is constructed of mild steel plates which are welded together. The cutting tool is AISI-M4 tool steel that has been heat treated to R_c62. It is lightly pressed into a holder which is bolted to the bracket.

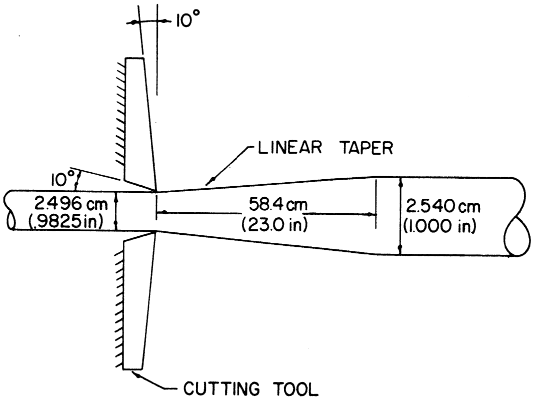

FIG. 6. Tapered rods used in the capitol subway design (material 6061-T6 aluminum).

Four of the units were installed on the U.S. Capitol–Rayburn House subway and a collision test was conducted. Prior to the test, the actual tool and rod parameters, of all units, were measured—these results are shown in Table 3.

A Bolex movie camera, running at 64 frames/sec, was used to record the vehicle motion during the collision test. Identification marks were placed every 15.2 cm (6.0 in.) along the side of the car, and the camera was set up perpendicular to the direction of subway car motion. The subway vehicle was placed in a coasting mode before impact. The vehicle weight and approximate impact speed are shown in Table 3. Note that the impact velocity is less than the worst case conditions specified in Table 1. It turns out that the initial specifications were overly conservative and the Capitol subway engineering staff decided that 4.5 m/s (10 mph) represented a more "typical" impact speed. Since the cutting force is not affected by impact speed, this change simply reduces the energy dissipation length, and less rod is pulled through the tool.

After impact, when the depth of cut becomes constant, the vehicle retarding force should be constant. If this is assumed true then the vehicle velocity at any length, l, after impact, is given by:

$$V^2 = (\text{CONSTANT}) - 2al. \tag{11}$$

Therefore, a plot of velocity squared vs stopping length (after impact) should be a straight line. The slope of the line is twice the vehicle deceleration.

The collision test was conducted and the energy absorber worked very well. The movie film was analyzed and the distance that the car moved between frames (approximately 7.6 cm (3 in.) at the impact speed) divided by the time between frames, was used to determine vehicle velocity. The stopping length was easily obtained by keeping track of how far the vehicle had moved beyond impact. The velocity data vs stopping length is plotted in Fig. 8.

The results shown in Fig. 8 indicate that the plot of V^2 vs stopping length decreases linearly. The slope of the line is equivalent to -0.6 g deceleration. The slope for other values of deceleration is also shown indicating that small changes in the position of the line drawn through the experimental data will not drastically affect the deceleration value. It was not possibly to obtain velocity readings over the initial length of taper because the resolution of the camera was not adequate.

Based on the data shown in Table 3, and a deceleration of 0.6 g, it is possible to calculate U for the metal cutting process. Equation (6) may be used to calculate F and equation (2) can be used to obtain U. These values are shown in Table 4. The calculated value of U is between the two values of U which were discussed in the section on the "Metal Skinning Energy Absorber." This indicates that steady conventional values of U could be successfully applied to predict cutting forces with the circular cutting tool geometry used in this design.

If the value of U shown in Table 4 is used to recompute the energy dissipation stopping length (for the data in Table 1) then $l_{\text{stop}} = 6.04$ m (19.8 ft). When the effect of the taper is added to this length, it exceeds the maximum available space. This suggests that for future designs it is better to use the U values given in the section "Metal Skinning Energy Absorber" and not the Brinnell hardness approximation. Fortunately

TABLE 3. MEASURED PARAMETERS OF METAL SKINNING ABSORBERS

Parameter	English	SI
Rod O.D.	1.0000 in	2.5400 cm
Cutting Tool I.D.	.9825 in	2.4956 cm
Total rod length	18.0 ft	5.49 m
Length of taper	23. in	58.4 cm
Vehicle test weight	18,650 lbf	82,955 N
Approximate impact speed	10 miles/hr (14.7 ft/sec)	4.5 m/s

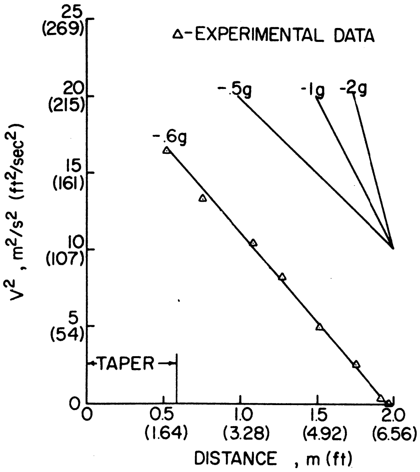

Fig. 8. Vehicle velocity squared vs stopping length.

Table 4. Calculated metal skinning parameters

Parameter	English	SI
Pulling force per rod (F)	2798 lbf	12443 N
Cutting Energy per unit volume (U)	$1.01 \cdot 10^5$ in lbf/in^3	$.7 \cdot 10^9$ Nm/m^3

for the subway passengers a more realistic maximum impact speed is 6.7 m/sec (15 mph) which gives an energy dissipation length of 4.68 m (15.3 ft).

It was interesting to see that the chips which were generated by the ring cutter were curled and continuous in length, typically as long as 30–60 cm (1 or 2 ft). Each chip varied irregularly in width over its entire length. Typical width variations were 1–1.5 cm, for an individual chip. The chip thickness appeared quite uniform and a number of these individual curled chips were found around the circumference of the cut, where the rod entered the cutting tool. The cutting tool showed no dulling after the test and it appears reasonable to make the cutting tool from a medium carbon steel in future applications.

CONCLUSIONS

A metal cutting energy absorber system has been designed for the U.S. Capitol–Rayburn House subway system. The design, utilizing a round bar which is pulled through a circular cutting tool, applies a constant retarding force to the subway vehicle.

A design methodology has been discussed for the systematic selection of critical parameters in the metal cutting/energy absorber design.

The results of a collision test have shown that steady state metal cutting data can be successfully used to predict the performance for a circular cutting tool energy absorber.

Acknowledgements—The technical assistance of Mr. J. Raymond Carroll, P.E., Director of Engineering and Mr. Elmer White, Head, Elevator Engineering Department of the Architect of the Capitol Office, is gratefully acknowledged. The informative and useful technical discussions with Mr. John Gay are also gratefully acknowledged.

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