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Transit IDEA Program

SLEEVED COLUMN SYSTEM FOR CRASHWORTHINESS OF LIGHT RAIL VEHICLES

Final Report for Transit IDEA Project 22

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

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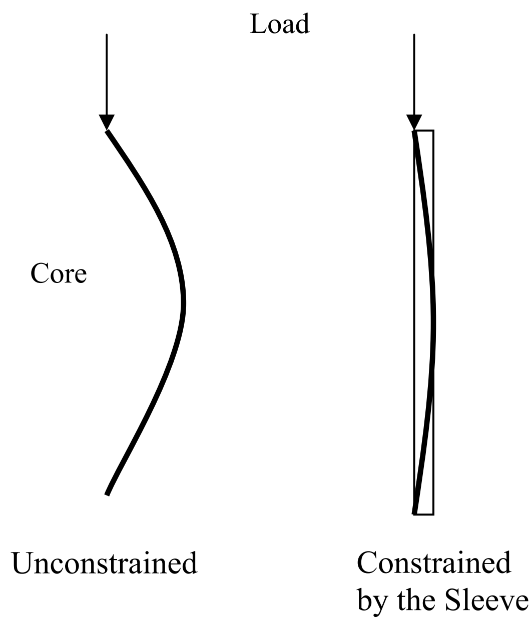
Executive Summary

This report describes the research and development undertaken in this Transit IDEA project to determine the applicability of a new sleeved column energy absorber system for improving crashworthiness of rail transit vehicles. The new technology is an efficient energy absorber with the potential for low weight, low cost, and easy replacement at low impact speeds using materials commonly employed in light rail transit vehicle construction.

Energy is absorbed by the permanent compression of one or more relatively long core elements that are constrained against buckling by an outer sleeve. The absorbers can be completely independent energy absorption elements or, by using existing members for the sleeve, integral with the primary structure of the vehicle.



The Sleeved Column Concept

This project included analytical and experimental stages and an assessment of how the sleeved column would be designed for rail vehicles. Nonlinear finite element analysis was used successfully to investigate various structural shapes for both the core and the sleeve, with a focus on single core piece construction. Analysis results and input from our rail vehicle manufacturer, Siemens-Duewag, indicated that sleeves with a square or rectangular cross section are most appropriate.

Rail vehicle impacts were simulated by conducting drop tower impact tests conducted on 2m (6ft) long, steel absorbers over a range of energy absorption of 25-100 kJ and impact speeds of 17-34 km/hr. These tests demonstrated that the core element could be replaced at low collision speeds and that collision energies were absorbed with little lateral support in these long elements. The tests also showed that the peak crush load during energy absorption was greater than anticipated because of the effects of friction between the core and the sleeve and because the true stress-strain properties were substantially higher than assumed. The analysis and design approaches were modified to account for these effects.

Our assessment supports the applicability of the sleeved column energy absorption technology to rail vehicles. Review of light rail vehicle construction shows that the absorbers could be used as independent elements on each side of the coupler pocket or at the sides of the vehicles, in which case the side sill structural elements could be used as the sleeves. In fact, during the course of this project, the basic concept of the sleeved column was used for independent absorbers on each side of the coupler for the proposed Southern New Jersey Light Rail Vehicle Project.

This report provides information needed for practitioners in the rail vehicle industry to design sleeved column energy absorbers. It includes a design approach for achieving desired energy absorption levels with the sleeved column. Included are true stress-strain curves for both a steel and an aluminum alloy measured as part of this project for use in the design. Procedures are also provided for estimating weight and cost. This novel design approach is available for use in designing light rail transit vehicles.

Introduction

The objective of this project is to demonstrate the feasibility of incorporating a new structural energy absorption technology into transit rail vehicles. The new system, called the sleeved column energy absorption system, has the potential to be light, low cost and to provide replaceable elements for low speed impacts.

The overall project included three stages: (1) the development of a design suitable for transit vehicles; (2) dynamic testing for demonstration and refinement; and (3) specific assessment of adaptability to transit and other rail systems.

This report summarizes the results of the entire effort. Appendices provide the information needed for practitioners in the rail vehicle industry to design sleeved column energy absorbers for specific applications.

Description of the Sleeved Column Technology

The sleeved column energy absorption system is a novel, low cost, light weight replaceable element [1] that can be incorporated into modern transit rail vehicles to provide substantial protection in collisions. The system is based on the sleeved column technology, in which one or more core elements carry load and efficiently absorb energy within a sleeve (Figures 1 and 2.) The greatest efficiency-to-cost ratio is generally achieved when materials such as ductile high strength steel are used for the core element and low strength steel is used for the sleeve. This patented technology [2] is unique. It is currently being incorporated into U.S. civil engineering codes for use as energy damping systems for seismic applications (c.f. [3]) and has also been applied in structural support systems for water towers [1].

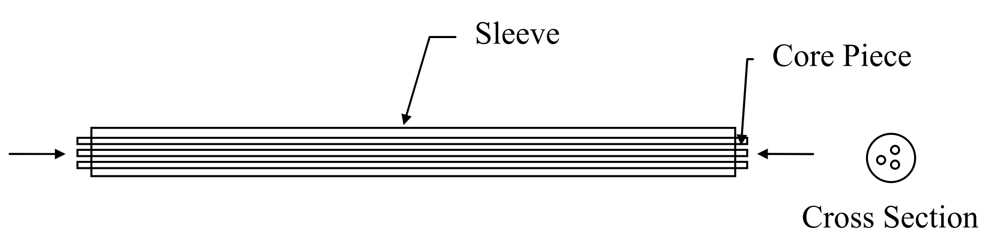


Figure 1: Schematic Illustration of the Sleeved Column System

The basis of the sleeved column system is that the relatively long core elements carry the entire load and absorb all of the energy. It is efficient, because the entire cross section and length of the core elements can participate in absorbing energy. (Rather than just the folds in conventional elements that deform like an accordion.) The sleeve, which carries little or no load, prevents the core elements from buckling so that they can absorb the design energy.

The sleeved column differs from other energy absorption systems in a number of ways:

a) The use of solid or thick-walled tube core elements provides a very high absorbed energy per unit-volume, -weight and -amount crushed.
b) Core and sleeve elements are relatively inexpensive to produce and fabricate into the vehicle structure through conventional manufacturing methods familiar in the U.S.
c) Under mild to medium collision conditions, only the core rods are damaged and these are easily replaced at low cost.

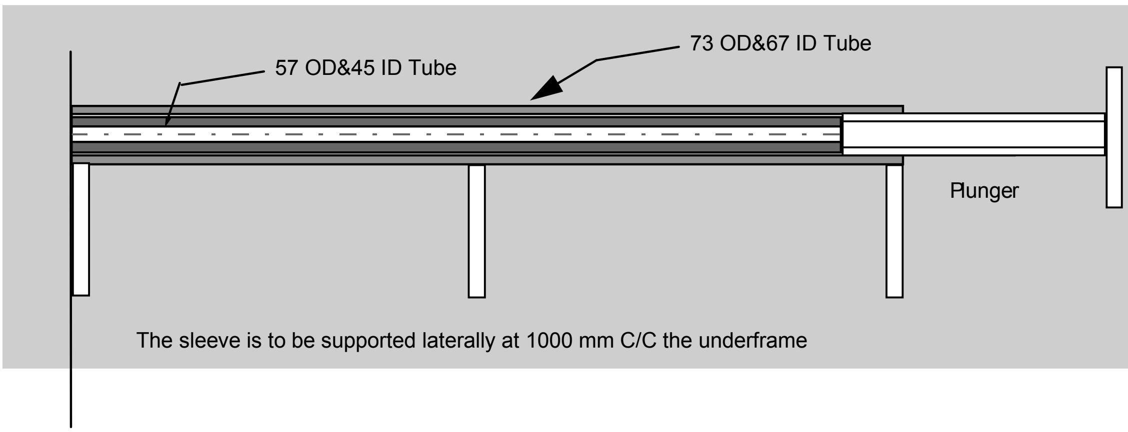


Figure 2: An Example of a Sleeved Column Design with a Tubular Core Element

Summary of Stage 1 Results

Stage 1 included a feasibility study (through finite element analysis) and the further development of a design methodology for the sleeved column system. The original design specifications for the absorber are listed in Table 1.

Table 1: Design Specifications for Each Sleeved Column Energy Absorber

Maximum Crush Load:	450kN
Energy Absorption:	200kJ
Maximum Crush Length (goal)	1m
Maximum Total Length (goal):	3m

These specifications and others like them are based on a consideration of the collision scenario against which protection is desired.

The required energy absorption for a collision between two objects (train-to-train or train-to-highway vehicle)can be estimated from the equation for collision energy:

$$E_c \approx \frac{1}{2}\frac{m_1 m_2}{m_1 + m_2}(V_2 - V_1)^2 ,$$

where m_1 and m_2 are the masses and V_1 and V_2 are the speeds of the colliding objects. For the case of one LRV with a mass of 45,300kg (100,000 lbm) traveling at 20 km/hr (12.5 mph) striking a standing like vehicle, the collision energy is:

$E_c =$ 350 kJ (2.58×10^5 ft-lbf.)

This energy is to be divided between four energy absorbers: two per vehicle end with two vehicle ends. This results in a required energy absorption of 88 kJ/absorber. Similar calculations can be conducted for other scenarios and vehicle types. The maximum force that can be induced in the absorber is generally determined by the strength of the structure that supports it. However, it may also be determined by the need to keep peak accelerations (decelerations) low during the collision. Finally, the amount of allowable energy absorber crush is determined by the available space at the ends of the vehicles, which is generally less than 1 m (3 ft.)

The results of Stage 1 supported the merits of the proposed system. The device was shown to have promise not only for light rail vehicles but also as an energy absorber for general rail vehicle crashworthiness applications over a wide range of speeds. A specific configuration was developed that utilizes a plunger to apply load to a single deformable core element (Figure 2, above.) We estimated that the design energy could be absorbed with about 0.5 m of crush without exceeding the design load. This amount of crush is more favorable for light rail vehicle application because of the limited space between vehicle front and the operator volume.

Two comments in particular from the reviewers altered the approach taken in Stage 2:

- Conduct a low speed test to assess the ability of the system to sustain impacts without requiring repair.
- Utilize a tube of square or rectangular cross section for the sleeve, since this form, and not a circular one as studied in Stage 1, is most commonly used in rail vehicle construction.

Summary of Stage 2 Results

In Stage 2 we developed a detailed design and fabricated three, single-core-element sleeved columns with the characteristics shown in Table 2.

Figure 3 shows the elements of the sleeved column prior to assembly. No material was used between the core and the inner surface of the sleeve, although the outer surface of the core was coated with a molybdenum disulfide coating prior to insertion. Nonlinear finite element analysis was used to verify and refine the design of the absorbers.

Table 2: Sleeved Column Energy Absorber Characteristics Tested in Stage 2

Sleeve length	2.3 m (90 inches)
Sleeve cross section	51x51x7.9 mm (2.0x2.0x0.312 inches) tube
Sleeve material	A500 Gr.B steel
Core length	2.0 m (80 inches)
Core cross section	25x25 mm (1.0x1.0 inches) solid
Core material	A36 steel

Figure 3: Sleeve (upper) and Core (lower) Pieces Used for Testing

These energy absorbing elements were then tested in the test configuration shown in Figure 4. Table 3 lists the test conditions applied.

Table 3: Conditions for Actual Tests

Test	Drop Height (m)	Input Energy (kJ)	Impact Speed (km/h)
1	1.1	25	16.8
2	3.4	75	29.1
3	4.5	100	33.6

Figure 5, for the first test, and Figure 6, from the second test, show that the finite element predictions are quite good. Comparable agreement was obtained for the other test.

Figure 4: The Test Configuration used in Stage 2 Impact Testing; the Sleeved Column is in the Center of the Support Frame

A key observation from these tests was that the peak load was greater than anticipated. This was caused by core material strengths that were greater than assumed in the design and because of friction between the core and the sleeve. Nevertheless, the results of Stage 2 showed that:

a) the sleeved column is efficient at absorbing energy using low cost, easily fabricated materials
b) the core can absorb energy and be removed for low speed impacts.

Conclusions from the Stage 2 work and comments from the reviewers that had an impact on the Stage 3 work include:

- It is important to know the true stress-strain curve of the core material
- Substantially better results will be obtained if the core material has a flat stress-strain curve
- Friction between the core and the sleeve must be accounted for or deliberate means to reduce friction, such as an interlayer of low-friction grout, must be employed

- There is a shift in the light rail vehicle industry to aluminum construction; it would be useful to determine the applicability of the technology to aluminum vehicles.

Figure 5: Comparison between Core Deformation Observation and Prediction for Test 1.

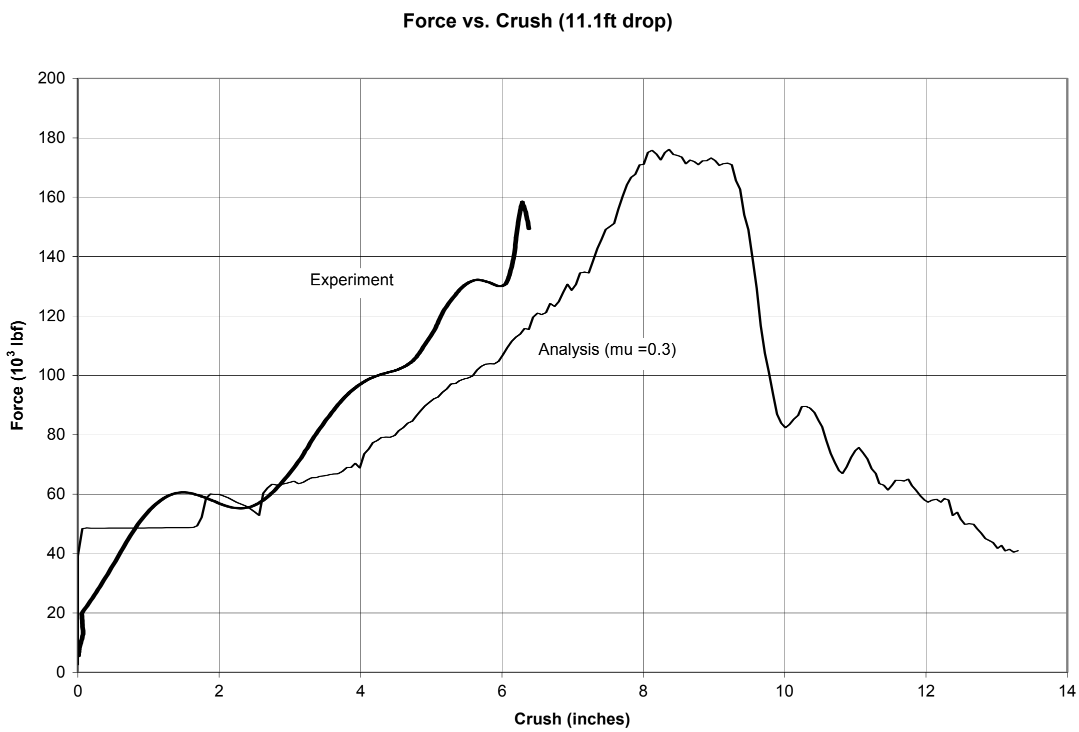


Figure 6: Comparison of Nonlinear Finite Element Predictions with Test Measurements for a Drop Tower Impact Test on a Sleeved Column Energy Absorber

Summary of Stage 3 Results

In this stage of the project we investigated how the sleeved column can be designed for rail vehicle applications and present an example on how it could be incorporated into a light rail vehicle. It is the intention of the owners of the sleeved column patent, Tube Investments, that users would license the technology rather than purchasing energy absorbers from another party. This is consistent with the fact that the sleeved column provides the greatest benefit when it is adapted to the structure of interest. Thus, this report strives to provide some basic design rules and a set of material data that the user can apply to incorporate the sleeved column energy absorber into a rail vehicle structure. In order to license the technology the user should contact Tube Investments directly using the information included at the end of this report.

Sleeved Column Energy Absorbers for Rail Vehicles

Table 4 lists the material, geometry, and weight of three different specific configurations that were designed using the calculation approach and the material property and cost data given in the appendices below.

Each of the configurations utilizes sleeve and core elements of square cross section, is designed to a maximum load of 450kN($100x10^3$ lbf) and contains no low-friction grout between the core and sleeve. The shortest absorber, 1.2 m (3.9 ft) in length, is envisioned as a dedicated energy absorber located adjacent to the coupler hardware of the vehicle. The design crush is low, 0.25 m (10 inches), so that no underframe structure is damaged to meet the energy absorption requirements. The other two absorbers in Table 4 are envisioned as being integral to the underframe of the rail vehicle; that is, the sleeve would also serve the function of carrying other operational loads. In addition, the design crush is large enough that some of the underframe structure would also be crushed. The third design applies more to rail vehicles that operate at higher speeds, such as in commuter trains. Both energy absorber locations are shown schematically in Figure 7. Figure 8 illustrates how the side sill energy absorbers might appear in a light rail vehicle before any decorative shrouding was placed over them.

Table 4: Examples of Sleeved Column Energy Absorbers for Use in Rail Vehicles

Type	Location in Vehicle	Core and Sleeve Material	Design Energy Absorption	Length	Design Crush	Added Weight
A	At coupler	Steel	100kJ	1.2m(47in.)	0.25m(10in.)	19.8kg (43.5lbm)
B	At side sill	Aluminum	100kJ	1.9m(75in.)	0.38m(15in.)	13.8kg* (30.4lbm)
B	At side sill	Steel	600kJ	5.0m(197in.)	1.0m(39in.)	116kg* (257lbm)

*If an independent sleeve were required.

These designs are intended to provide prospective users with an idea of the general characteristics of the sleeved column energy absorbers; it will be more efficient to adapt the design to the specific rail vehicle in question.

Specific Application

During the course of this project we learned that the new Southern New Jersey light rail vehicle will likely include an embodiment of the sleeved column system. In this case the absorbers are located adjacent to the couplers, similar to the type A absorbers in Figure 7. Both the sleeve and the core have a rectangular cross section. The core is an aluminum piece designed to crush by folding rather than uniform compression. Total crush distance before the plunger contacts the sleeve is 0.4m (1.3 ft) and the energy absorbed is approximately 200kJ. Figure 9 shows a side view of the configuration.

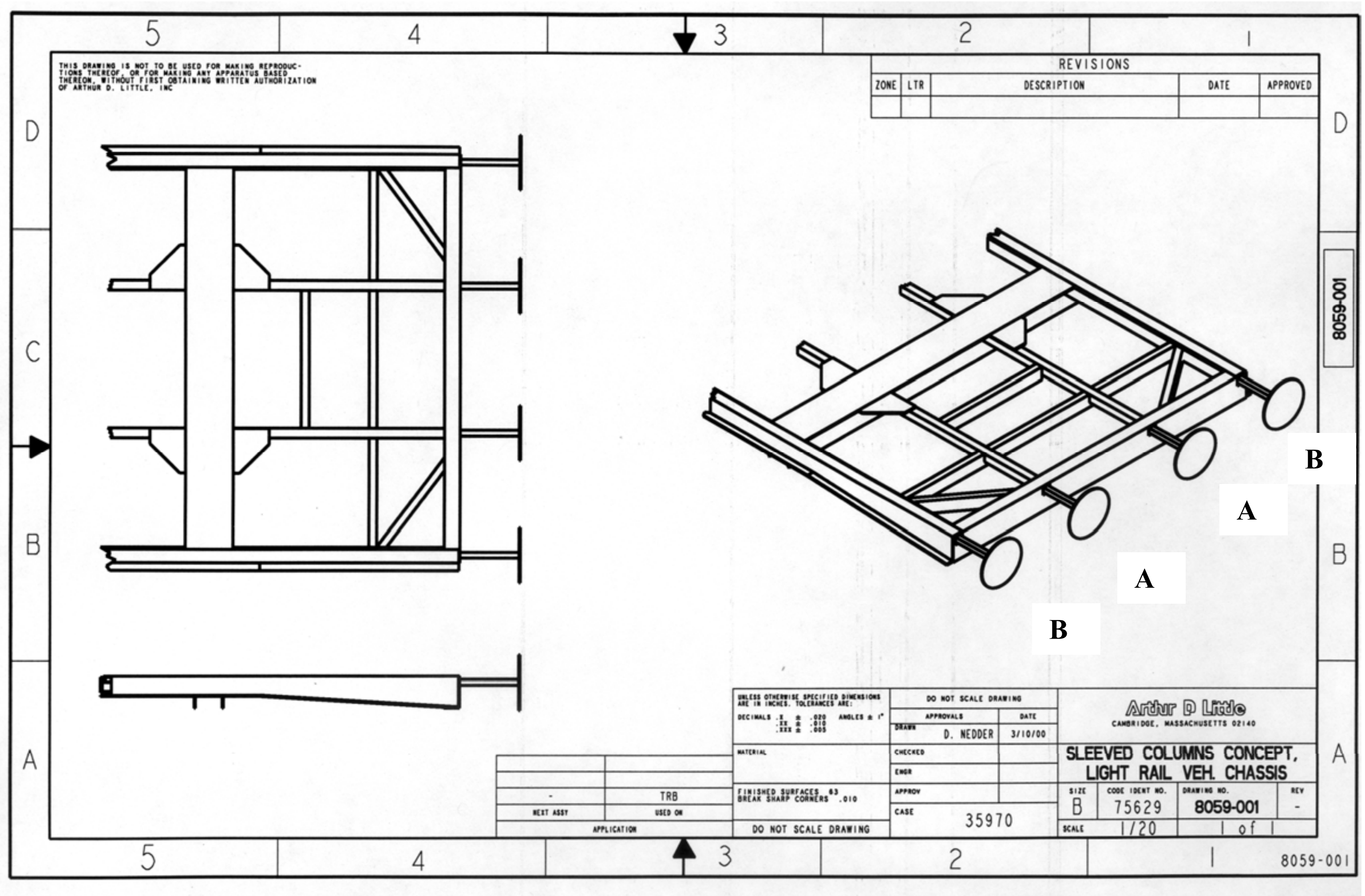


Figure 7: Candidate Locations for Sleeved Column Energy Absorbers in Rail Vehicles

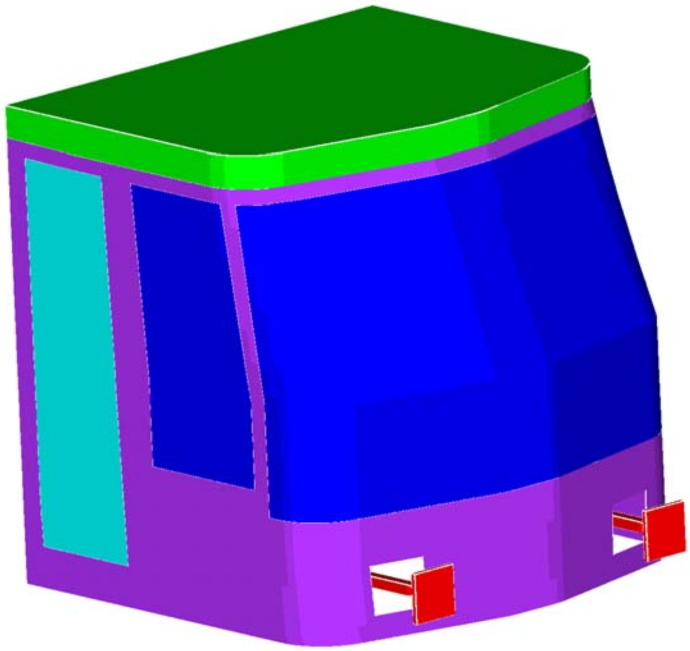


Figure 8: Illustration of Two Sleeved Column Energy Absorbers in a Light Rail Vehicle (without a shroud)

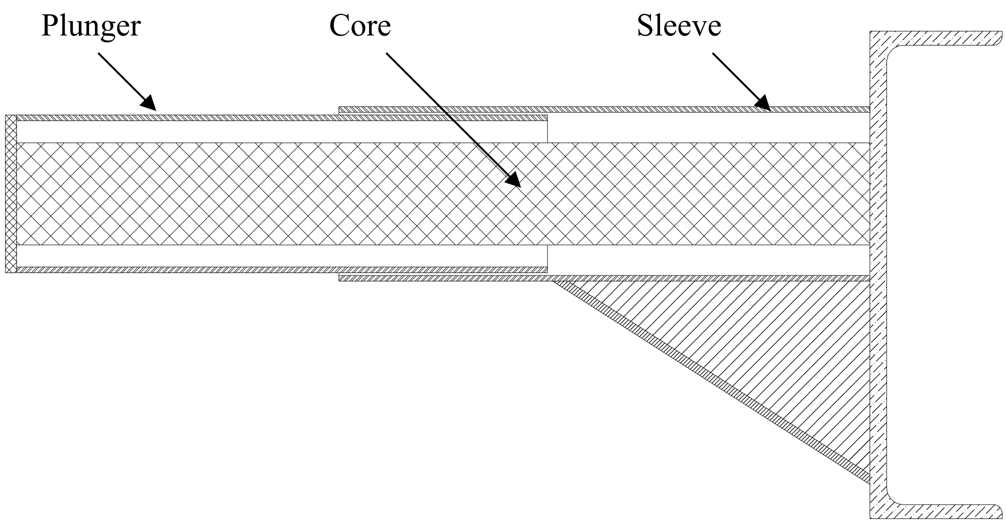


Figure 9: Schematic of the Sleeved Column Energy Absorber Planned for Use in the New Jersey Transit Light Rail Vehicle

Summary

The work in this project has focussed primarily on demonstrating how the sleeved column energy absorber can be designed and incorporated into light and general rail vehicles. Key material property data were measured for both a steel and aluminum and a design procedure was developed and described. In addition, approximate sleeved column element cost data were collected. This information is intended to provide the rail vehicle crashworthiness designer with the information needed to investigate the feasibility of the sleeved column technology to provide the design energy absorption needed for his or her application.

Overall the study has demonstrated some important characteristics and limitations of the sleeved column technology for application to rail vehicle crashworthiness. These include:

Characteristics

- The sleeved column is an efficient, relatively low cost approach to energy absorption.
- Its efficiency is comparable to other approaches currently being used, such as thin-walled tubular members that fold in an accordion mode.
- The sleeved column core element can be replaced for relatively low speed impacts, facilitating repair.
- The technology can be potentially adapted to existing cars.
- We believe it is currently necessary to verify the sleeved column design using nonlinear finite element analysis to ensure that the design goals can be met.

Limitations

- It is also essential to have true stress-strain properties for the core material to be used; these should be determined from compression tests.
- While the sleeved column is efficient, it has the property of a substantially increasing load with crush rather than the more ideal flat or mildly rising load-crush response of other absorber designs.
- Better response is obtained if a low-friction grout can be incorporated between core and sleeve, but this adds a fabrication cost.

Contact Information

For more information about the sleeved column technology and ways in which it can be utilized, designed, and fabricated the reader is invited to contact the following organizations.

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References

1. Kalyanaraman, V., Sridhara, B.N. and Mahadevan, K.,"Sleeved Column System," Proceeding of the Structural Stability Research Council, 20-22 June 1994, Lehigh University, Bethlehem, PA (June 1994) 15 pages.
2. United States Patent 5,175,972, Sleeved Compression Member, Jan.. 5, 1993.
3. Reina, P. and Normile, D.,"Fully Braced for Seismic Survival,", Engineering News Record (July 21, 1997)34-36.

APPENDIX A: CALCULATION PROCEDURE

The sleeved column energy absorber is ideally designed in a two-step process in which hand calculations are used for preliminary selection of dimensions and materials, and nonlinear finite element analysis is used for design verification. The 'hand' calculation procedure can be easily incorporated in a spreadsheet format.

Hand Calculation Design:

Hand calculations proceed by iterations until a satisfactory set of dimensions is achieved that meet both the performance requirements but are consistent with available material forms and the structure into which the absorber is to be built.

Step 1: Ensure performance requirements are consistent.

The energy absorber will be picked as part of a system. For example, the system may include the coupler and several other sleeved columns or other structural energy absorbers. Each energy absorber has its own specification in the following terms:

Required energy absorption: E_{abs}
Maximum allowable force (as determined by the support structure and acceleration requirements): F_{max}
Maximum allowable crush (to ensure that other components are not damaged or occupant volumes are not crushed): D_{max}.

These are not independent parameters because:

$$F_{avg} = E_{abs}/D_{max} < F_{max}.$$

That is, the average force, which is determined by the amount of energy that must be absorbed and the allowable energy absorber crush, must be less than the maximum allowable force. In fact, our experience is that having F_{avg} less than about $0.7F_{max}$ will more quickly lead to a robust design. If the average force requirement above is not satisfied, the fundamental requirements for the absorber must be changed.

Step 2: Select materials

The core and sleeve materials should be chosen to be inexpensive, readily available and compatible with other materials in the structure. Structural steel will be the most likely used material for vehicles in North America although there is an increasing use of extruded aluminum. Appendix B provides the data needed for sleeved column design for one material in each of these categories.

Step 3: Select core element cross-sectional area

The core element or elements are designed to absorb all of the energy, although, in reality, some energy will be absorbed by friction between the core and the sleeve. We need to determine the length and cross-sectional dimensions of the core element. The maximum allowable force, the material selected and the design maximum strain, determine the cross-sectional area. We suggest a design maximum strain of 20%, because our observations are that the core elements deform uniformly and it is not difficult to obtain material data up to this strain. When the material and design maximum strain have been selected, the true stress-strain curve for that material (see, for example, Appendix B) is used to determine the corresponding stress, S_{max}. Given these parameters we can calculate the design maximum cross-sectional area. The force resisted by the sleeved column will consist of a component due to deformation of the core and a component due to friction between the core and the sleeve.

The first force component is the product of the stress and the actual cross-sectional area at the design maximum strain. The final cross-sectional area as a result of plastic deformation is,

$$A_f = A_c/(1 - e_{max}),$$

Where A_c = the initial core cross-sectional area. For example, if $e_{max} = 0.2$ (compression is taken as positive), then the cross-sectional area after crush to this strain is $A_f = 1.25A_c$; there is a 25% increase in area.

The contribution due to friction is difficult to estimate accurately. We suggest using a multiplication factor of $(1 + \mu)$ with:

No low friction grout between core and sleeve:	$\mu = 0.3$
Low friction grout between core and sleeve:	$\mu = 0.1$.

Thus, in order to ensure that the maximum force is less than the design maximum force,

$$A_c < [F_{max} (1 - e_{max})]/[(1+\mu)S_{max}].$$

Note that the use of the friction force in this manner is approximate; the actual contribution of friction is best treated with the finite element analysis.

Step 4: Select core element length

The core element length selected must be consistent with several constraints and this is often the point in design at which iterations must be made. We first determine the volume of material needed, which is determined by the ability of the core material to absorb energy on a unit volume basis:

$$Vol_c = E_{abs}/e_{abs}$$

where e_{abs} is the specific energy absorbed (energy absorbed per unit volume). The parameter e_{abs} is determined from the true stress-strain curve of the core material for a particular maximum strain (see Appendix B for sample material properties.) Generally, the higher the core element material strength, the less volume of material is needed.

The core length must then satisfy the following constraints:

$$A_c L_c = Vol_c$$

$$e_{max} = D_{max}/L_c,$$

where L_c is the core element length. Furthermore, the core length must be consistent with the structure into which it is built. For example, if a side sill is used as the sleeve, then the core cannot be longer than the greatest length of unobstructed sleeve. In addition, there must be sufficient structure at the back end of the core to support the maximum core load.

Again, we suggest using a design maximum strain of 20% (0.2), which, with the design maximum energy absorber crush,

$$L_c = D_{max}/e_{max} = 5D_{max}.$$

If a different core length is used, then one must ensure that the other constraints are satisfied.

Step 5: Select core element geometry.

The required core element cross-sectional area can be obtained from many geometric forms. For example, one can use solid round, square or rectangular shapes or tubes. If tubes are selected, it is important to ensure that the ratio of wall thickness-to-diameter, in the case of a circular cross section, or edge dimension in the case of a square or rectangular cross section, is low enough to avoid accordion-type crush of the core if this is not desired. Such deformation could lead to binding between core and sleeve (if insufficient annular space is present) with the negative consequence that the sleeve carries a high axial load and buckles.

Example. E_{abs} = 100kJ, F_{max} = 450kN, D_{max}< 0.5m, no grout between core and sleeve (μ = 0.3).

Step 1 (Example)
- $F_{avg} = E_{abs}/D_{max}$ = 100/0.5 = 200kN
- This is less than 0.7(450) = 315kN, so there is a comfortable margin.

Step 2 (Example)
- We will use the cold-drawn 1018 steel whose properties are given in Appendix B
- e_{abs}(at e=0.2) = 0.134J/mm^3
- S_{max} = S(at e=0.2) = 710MPa.

Step 3 (Example)
- $A_c < [F_{max} (1 - e_{max})]/[(1+\mu)S_{max}] = 450x10^3(1-0.2)/[(1+0.3)710] = 390mm^2$.

Step 4 (Example)
- First try. $L_c = 5D_{max}$ = 5(0.5) = 2.5m. (based on a design maximum strain of 20%)
- Assume this length fits the vehicle structure and the back of the core can be well supported at a length of 2.5m from the impact point.
- $Vol_c = E_{abs}/e_{abs} = 100x10^3/0.134 = 7.5x10^5$ mm^3 (required volume of material to absorb 100kJ)
- $L_c = Vol_c/A_c = 7.5x10^5/634 = 1.2x10^3$ mm (1.2m). Since the calculation leading to this value of L_c assumes a maximum strain of 20%, the maximum crush would have to be 0.2(1.2) = 0.24m. In other words, the energy absorption and peak force requirements for the energy absorber can be met with a lower crush than anticipated. If a crush of 0.5m is permissible, more energy could be absorbed and the design calculations redone.

Step 5 (Example)

- Select a square solid rod.
- The edge dimension should be smaller than, $c = \sqrt{A_c} = \sqrt{390} = 19.7$ mm
- This is quite close to the readily available size of 19.1mm (0.75 inch) in the U.S. and is acceptable.

Step 6: Select the inner dimension of the sleeve.

The inner dimension of the sleeve is selected to provide a minimum of clearance with the outer dimension of the core, while accommodating the growth in cross section of the core that results from plastic deformation during crush. The clearance will also depend on whether a low friction separation material is used between the core and sleeve. We assume for the moment that it is not.

The sleeve cross section should have an inner dimension, whether it is a diameter or a straight segment given by,

$$c_i = [c_c/(1 - e_{max})] + \delta$$

where δ = 4-8 mm. The additional clearance between the crushed core and the sleeve has been observed from experiment to be needed. Smaller clearances lead to binding during crush, and larger clearances permit too much bending and nonuniform deformation of the core during crush. (Note: If a folding-type crush of a thin-walled tubular core is desired, greater clearances are needed.)

Step 7: Select the outer dimension of the sleeve.

The outer dimension of the sleeve is selected to avoid Euler buckling during crush of the core.

The Euler buckling load is given by:

$$P_{cr} = \frac{\pi^2 EI}{(kl)^2}$$

where k = a factor to account for how the column is fixed at its supports
E = sleeve elastic modulus
I = sleeve moment of inertia
l = length of sleeve between lateral supports.

Our test experience indicates that, F_{max} should be less than $0.5P_{cr}$ to meet the design requirements. That is,

$F_{max} < 0.5P_{cr}$

This equation can be used with the buckling formula to calculate the required sleeve moment of inertia (about the weak axis),

$$I_{req} = \frac{(kl)^2 F_{max}}{0.5\pi^2 E}.$$

It is helpful if the lateral supports provide not only resistance to lateral motion but also resistance to rotation at the support point.

The sleeve should generally have the same inner shape as the outer shape of the core, although this is not strictly necessary. When the sleeve shape is known then the appropriate formula for the moment of inertia can be used to calculate the minimum outer dimension. For example, the bending moment of inertia of a square tube is,

$$I = \frac{1}{12}(c_o^4 - c_i^4).$$

And the minimum outer dimension can be calculated from

$$c_o \geq (12I + c_i^4)^{1/4}.$$

Step 8: Calculate weight and cost.

These are straightforward calculations, which one can carry out with the knowledge of the core and sleeve volumes, the material density and information from suppliers.

Example (continued): Use a structural steel sleeve, such as A500, Gr. B, with lateral supports at the ends and at the center (l = 0.6m).

Step 6 (Example)

- $c_i = [c_c/(1 - e_{max})] + 4\text{-}8$ mm = 19.1/(1 - 0.2) + 4-8 mm = 25.4 – 29.4mm.
- A standard 1.0 inch (25.4 mm) inner square tube is likely to be available. (This must be checked again when the required outer dimension is calculated.)

Step 7 (Example)

- $I_{req} = \frac{(kl)^2 F_{max}}{0.5\pi^2 E} = \frac{[(1)(600)]^2 (450x10^3)}{0.5(\pi^2)(207x10^3)} = 15.8x10^4 mm^4$.
- $c_o \geq (12I + c_i^4)^{1/4} = [12(15.8x10^4) + (25.4)^4]^{1/4} = 39.0mm.$
- An outer edge equal to 38.1mm (1.5 inches) could be a readily available size and would provide the required resistance to buckling.

Step 8 (Example)

- The weight of the core (no grout case) would be 3.4kg (7.5lbm).
- The weight of the sleeve required (no grout case) would be 16.4kg (36 lbm).
- If the sleeve were part of the underframe used for another purpose, then the added weight of the sleeve, which might require reinforcement to act as part of an energy absorber, would be less.

Additional Steps

In addition to the core and sleeve design it is necessary to design a plunger that transfers the load to the core elements. In general, the plunger should be a solid cross section that fits into the sleeve with closer tolerance than the core. The plunger should also be substantially harder than the core to prevent bending or mushrooming at the end that contacts the core element. For the same reason, it is helpful to chamfer the end of the core elements that contact the plunger. It is also useful to check for the possibility of large sleeve deformation due to contact between core and sleeve, although we have not found this to be a problem.

Finite Element Analysis

In this section we provide some discussion on the method we have used to simulate the sleeved column energy absorber under impact loading. This analysis is used to verify and, if necessary, refine the detailed design.

We have used the ABAQUS™ non-linear finite element code to model the sleeved column energy absorber. The finite element model is generally composed of 8,800 elements and approximately 11,000 nodes. The sleeve is modeled by four-noded quadrilateral elements; eight-noded brick elements are used to model the core. Both the sleeve and the core models are fully constrained at the back end of the device. Constraints against lateral motion are applied by simulating the supports (for example, the back, middle and impacted end of the sleeve.) Mass elements with defined initial velocities are used to impart the desired energy to the free end of the core. Contact conditions are defined between the sides of the core and the inside surfaces of the sleeve. A simple isotropic Coulomb friction model is used to define the interaction between the sleeve and the core via the definition of a single coefficient of friction. True stress-strain curve data are used for the core and, if available, for the sleeve.

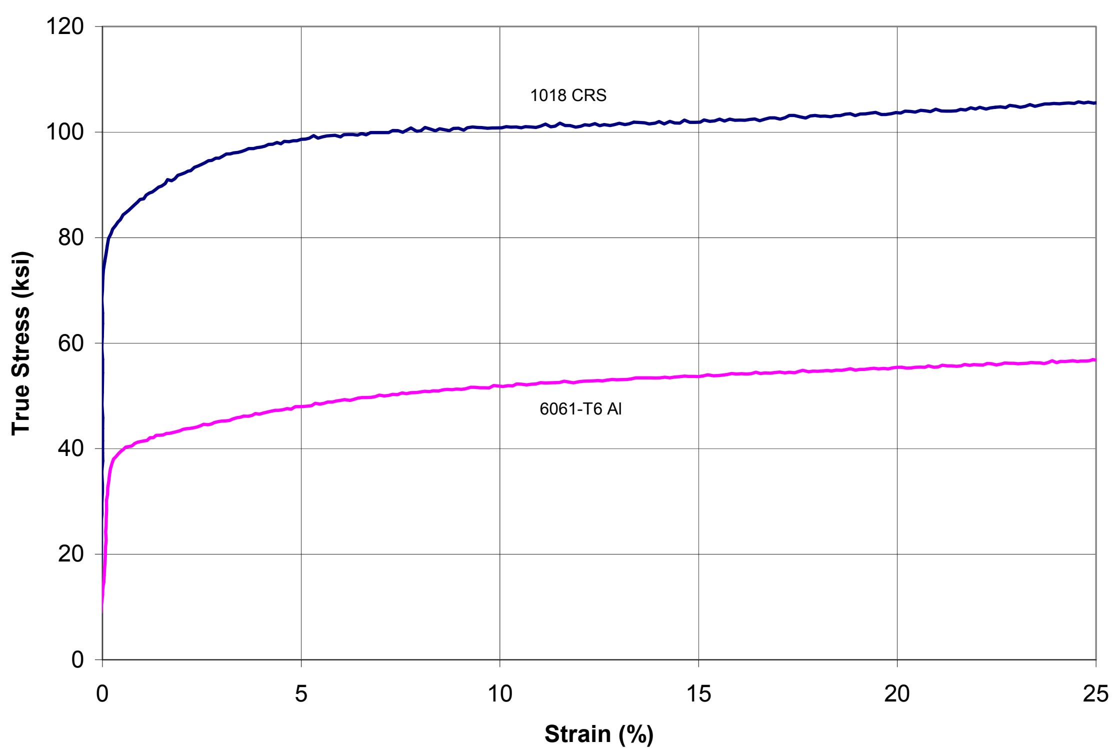
The model is used to calculate the load-crush response, to determine if or under what conditions sleeve buckling occurs, to check loads and deformations of the lateral support structure and to calculate stresses in the sleeve.

APPENDIX B: MATERIAL PROPERTIES FOR DESIGN

There are many material possibilities for the core and sleeve elements of the sleeved column energy absorber. In general, it is desirable to optimize between the following characteristics for the core element(s):

- high strength
- low cost
- in readily available forms (especially for low volume applications, such as rail vehicles)
- flat stress-strain curve.

We find that there are currently not many materials that meet these requirements. Two of the best we have found are 1018 cold-rolled steel and 6061 T6 aluminum. As part of our Stage 3 work, we determined the true stress-strain curve for these materials from uniaxial compression tests. The results are shown in the figure below and key results are tabulated in the table below.



Sample Core Element Material Data for Use in Sleeved Column Energy Absorber Design (Metric units)

Material	True Stress at e = 0.2	Volumetric e_{abs} at e = 0.2	Weight e_{abs} at e = 0.2
1018 CRS	710 MPa	0.13 J/mm^3	17 kJ/kg
6061-T6 Aluminum	380 MPa	0.07 J/mm^3	26 kJ/kg

Sample Core Element Material Data for Use in Sleeved Column Energy Absorber Design (English units)

Material	True Stress at e = 0.2	Volumetric e_{abs} at e = 0.2	Weight e_{abs} at e = 0.2
1018 CRS	103 ksi	19,400 lbf in/in^3	68,800 lbf in/lbm
6061-T6 Aluminum	55 ksi	10,000 lbf in/in^3	100,000 lbf in/lbm

APPENDIX C: COST DATA

The table below lists some example core element material costs as obtained in November 1999 for quantities of 800 pieces, each 2m long. This is enough material to produce four energy absorbers (two on each end) for each of 200 rail vehicles.

Material	Edge Size (in.)	Cost($)/Core Element
6061 T6 Al	1.000	10.40
6061 T6 Al	1.125	13.20
6061 T6 Al	1.250	16.30
1018 Cold Drawn	0.875	6.35
1018 Cold Drawn	1.000	8.30