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IDEA

High-Speed Rail IDEA Program

**Metal Foams for Improved Crash Energy
Absorption in Passenger Equipment**

Final Report for High-Speed Rail IDEA Project 34

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Metal Foams for Improved Crash Energy Absorption in Passenger Equipment

IDEA Program Final Report
for the Period March 2002 Through June 2004
HSR-34

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ABSTRACT

Crashworthiness of passenger vehicles has gained increased attention and progress over the last three to four decades. New strategies of crash energy management and new materials have provided a safer traveling environment, but national and international statistics indicate that there is still more to do. Metallic foams with a high fraction of porosity, which typically range from 40-97 volume percent (this is the portion of the metal foam that is filled with air or a gas), are a rapidly emerging class of novel materials for various engineering applications. Some examples of proposed applications are ultra-lightweight structural components, impact energy absorbers in automotive applications, thermal and sound insulation, and filters or heat exchangers for chemical processing. The attributes of metallic foams especially lend themselves to applications requiring high stiffness-to-weight ratio and efficient crash energy absorption.

The goal of this project was to identify and demonstrate specific applications for aluminum foam in high speed rail equipment. The main focus was on improvement of crush energy absorption of structures in rail passenger cars. Four application areas were discussed and explored through analytical studies, redesign and sub-scale testing of components. A single application was selected for full scale testing based on test results, cost-of-fabrication modeling, and the ability to produce a full-scale component within the boundaries of this project.

Lightweight aluminum foam sandwich panels, railcar primary crash energy dissipation, head impact injury mitigation, and a passenger-seat-mounted sliding rail to reduce passenger secondary impact injury were explored. All applications showed promise, except aluminum foam strips to mitigate head impact injury. The passenger seat sliding rail device was chosen for full scale testing after positive sub-scale tests. In an 8g pulsed sled test with 50th percentile male instrumented dummies, Head Injury Coefficient (HIC) values were reduced by 80% with an aluminum foam-filled sliding rail mounted to the seat pedestals.

Keywords: Aluminum foam, metal foam, crash energy management, crashworthiness, passenger railroad equipment, secondary impact, Head Injury Coefficient, occupant safety.

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EXECUTIVE SUMMARY

Crashworthiness of passenger vehicles has gained increased attention and progress over the last three to four decades. Significant vehicle and regulatory improvements have been achieved. Higher speeds and volumes of traffic, however, have increased the challenge to vehicle and passenger survivability. New strategies of crash energy management and new materials have provided a safer traveling environment, but national and international statistics indicate that there is still more to do. The goals of crashworthiness design focus on the passenger first and on the equipment as a secondary priority. The current philosophy adopted in the automobile industry is to structurally harden the passenger compartment against collapse and intrusion. The passenger compartment must also protect the passenger against secondary collision. This same approach has been adopted in railcar design.

The challenge is to employ innovative materials and designs that can dissipate large amounts of crash energy in a controlled manner that insures the safety of the passengers. Metallic foams with a high fraction of porosity (i.e. more pores per volume of metal foam) are a rapidly emerging class of novel materials for various engineering applications, such as ultra-lightweight structural components, impact energy absorbers in automotive applications, thermal and sound insulation, and filters or heat exchangers for chemical processing. The attributes of metallic foams especially lend themselves to applications requiring high stiffness-to-weight ratio and efficient crash energy absorption. The latter two make use of the unique characteristics of metallic cellular materials (i.e. a combination of its comparatively high strength and its characteristic non-linear deformation behavior) and can lead to many unique structural applications. As the porosity of a metal foam increases its density decreases. For example, aluminum foam at 80% porosity has a density that is 0.54 grams per cubic centimeter or a density that is 20% of the solid. The physical and mechanical properties of the metal foam are proportional to its level of porosity and can thus be tailored. In compression, a metal foam can be designed to yield at a specific loading and continue to yield at that same loading over a 50 to 60% displacement. This is the non-linear deformation behavior mentioned earlier. This is a result of each metallic bubble collapsing and dissipating crush energy. Also, as porosity increases other properties change, such as thermal conductivity decreases (i.e. becomes a better insulator), and vibrational damping improves.

A powder metallurgy method for fabricating metallic foams was developed at the Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM) and further improved at the Fraunhofer USA Center for Manufacturing and Advanced Materials – Delaware (FC-DE). This method allows direct net-shape fabrication of foamed parts with a relatively homogeneous pore structure. Metallic foams fabricated by this approach exhibit closed-cell microstructures with higher mechanical strength compared to the open-cell foams. This type of microstructure is particularly attractive for applications in the field of lightweight construction and energy absorption.

The goal of this project was to identify and demonstrate specific applications for aluminum foam in high speed rail equipment. The main focus was on improvement of crush energy absorption of structures in rail passenger cars. Four application areas were explored through analytical studies, redesign and sub-scale testing of components. A single application was selected for full scale testing based on test results, cost-of-fabrication modeling, and the ability to produce a full-scale component within the boundaries of this project. Lightweight aluminum foam sandwich panels, railcar primary crash energy dissipation, head impact injury mitigation, and a passenger seat mounted sliding rail to reduce passenger secondary impact injury were explored.

We found that aluminum foam sandwich panels have outstanding performance in terms of bending stiffness, vibration damping, and relatively good thermal insulation. However, there are two attributes that need development to make it a feasible candidate material—cost and a relatively malleable surface. There is no production capability currently in the U.S. Pilot plant manufacturing exists in Germany with a few promising commercial applications. The success of these projects should allow a reduction in cost that is competitive with the incumbent materials now in passenger railcars. The malleable surface issue regards the aluminum face sheets that are softened in processing. In this condition, the face sheets are prone to dents and scratches. This would not be suitable in high density public transportation equipment. Development of the proper face sheet alloy and post-process heat treatment to achieve the right balance of properties should be achievable in the near future.

We have demonstrated in this study and in previous a previous HSR-IDEA concept exploration contract (HSR-20) that placing aluminum foam within aluminum or steel tubing provides good structural components for crash energy dissipation. The combination of the foam inside the tube can absorb more energy than the two materials separately. An interaction between the two materials during uniaxial crushing delays yielding of the tube and the inner core offers resistance to the inward movement of folds. Thus, more deformation energy is required to accomplish crushing. We believe that this could be optimized with the proper combination of tubing wall thickness, tubing diameter, yield strength and foam density. Aluminum foam-filled steel tubing is a good means of crush energy absorption and still appears to be a good candidate to

reduce personal injury and equipment damage on passenger railcar accidents. It, however, requires more investigation to optimize usage in this application

Flat strips of one inch thick aluminum foam in a range of densities between 0.40 and 0.49 grams/ cc were used as an impact energy absorbing material in a FMVSS 201U test. This is a Federal Motor Vehicle Safety Standards (FMVSS) test used to assess head impact injury on A-pillars in automobiles. The test results were double the recommended HIC (head injury coefficient) value. The broad impact area of the 2" wide flat aluminum foam strip required too large a load for crush. A crowned geometry would have allowed a smaller initial impact area and perhaps better results. Nonetheless, this did not prove itself to be a promising application.

Dynamic impulse testing was conducted on a steel cylinder and plunger assembly with aluminum foam in the cylinder. A 100-pound block of steel was projected at the plunger so that the contact velocity was 24.6 mph. This provided 1400 ft-lbs of impact energy. The most promising results were obtained in an aluminum foam sample with a density of 0.296 g/cc. With dynamic loadings less than 1200 pounds force, over five inches of crush was attained and 370 ft-lbs of energy dissipated. This would allow a passenger to safely decelerate from 24.6 mph to 17.6 mph without exceeding 20 g's deceleration. A sliding seat rail mechanism was designed to utilize these results.

The sliding seat rail was designed to collapse a core of aluminum foam after passengers impacted the seat backing in front of them. As in the dynamic impulse, it was intended to safely decelerate a passenger to a lower velocity. The rails were attached to passenger rail car seats on test sleds. Two 50th percentile male instrumented dummies provided test data as the sled was given an 8-g impulse. Although the aluminum foam did not crush as much as was expected, good results were obtained. An 80 % reduction in HIC (head injury coefficient) value was obtained over the baseline sled test without aluminum foam. The lack of complete crush of the foam was attributed to uneven movement of the two rails attached to the front row seats. Some design improvements should maintain forward movement of the rails. Further development of the sliding rail design may allow a greater delay in head impact yielding greater benefits at higher speeds.

1. BACKGROUND

Metallic foams with a high fraction of porosity (typical range from 40-97 volume percent) are a rapidly emerging class of novel materials for various engineering applications, such as ultra-lightweight structural components, impact energy absorbers in automotive applications, thermal and sound insulation, and filters or heat exchangers for chemical processing. The attributes of metallic foams especially lend themselves to applications requiring high stiffness-to-weight ratio and efficient crash energy absorption. The latter two make use of the unique characteristics of a metallic cellular material, i.e. a combination of its comparatively high strength and its characteristic non-linear deformation behavior (*1*), and can lead to many unique structural applications. Two examples of aluminum foam applications explored respectively by automobile and railcar producers in Europe are the back dashboard in a convertible in which lightweight stiffness is needed at this point without the structural roof line and low speed crush-zones at the front and rear of suburban railcars.

A powder metallurgy method for fabricating metallic foams was developed at the Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM) (*2*) and further improved at the Fraunhofer USA Center for Manufacturing and Advanced Materials – Delaware (FC-DE). This method allows direct net-shape fabrication of foamed parts with a relatively homogeneous pore structure. Metallic foam fabricated by this approach exhibits closed-cell microstructures with higher mechanical strength compared to the open-cell foams. This type of microstructure is particularly attractive for applications in the field of lightweight construction and energy absorption.

Fraunhofer's prior experience in the production of foamed aluminum indicates that the foamed component provides a substantial increase in the stiffness-to-weight ratio (SWR) with a low fractional density. The aluminum foam has a relatively homogeneous closed-cell microstructure which is responsible for the high SWR of the foam. Under deformation, this microstructure features localized cell collapse and rapid compaction energy dissipation, which leads to unique deformation behaviors.

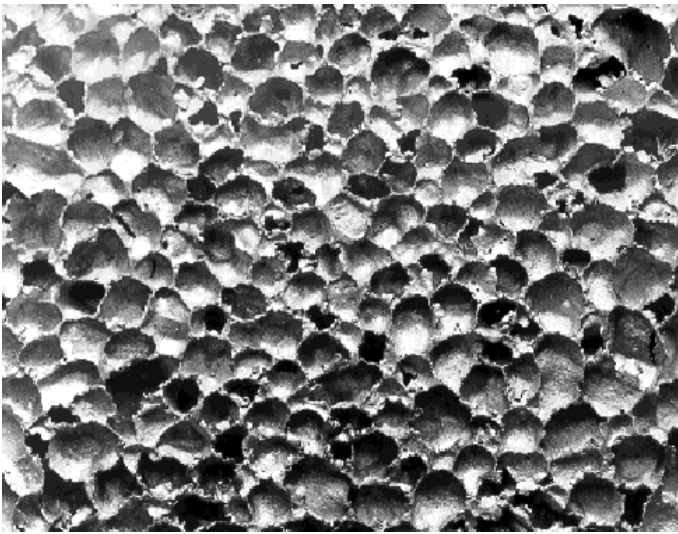


FIGURE 1: An example of 80% porous aluminum foam with an average pore size of 2 to 5 mm.

2. OBJECTIVES

Crashworthiness of passenger vehicles has gained increased attention and progress over the last three to four decades. Accompanied with the vehicle and regulatory improvements have been higher speeds and volumes of traffic that have increased the challenge to vehicle and passenger survivability. New strategies of crash energy management and new materials have provided a safer traveling environment, but national and international statistics indicate that there is still more to do.

The goals of crashworthiness design focus on the passenger first and on the equipment as a secondary priority. The current philosophy adopted in the automobile industry is to structurally harden the passenger compartment against collapse and intrusion. The passenger compartment must also protect the passenger against secondary collision. Secondary collision is caused by the abrupt change in vehicle velocity that brings the unrestrained occupants in contact with the interior of the car. The key to this concept is crash energy management in both the primary and secondary collisions.

Exterior structure is utilized to absorb, delay and redirect crash energy to a level that the passenger compartment can manage. Air bags, collapsible steering wheels, padded dashes, lap/shoulder harnesses and head rests are just a few

examples of energy management devices added to the interior. The lessons learned by the automobile industry have been considered for passenger railcar design over the last few years.

Prior design philosophy in passenger railcars required high uniform strength along the length of the car. This provides for a long, useful equipment life under normal conditions. In the event of a collision, however, this construction tends to result in buckling of the cars both vertically and horizontally. If buckling does not occur, large deformations in the cars closest to the collision result in loss of passenger compartment space and severe injuries or fatalities. The effect decreases as a function of the cars distance from the impact point. In either mode, extensive damage to equipment and passengers occurs.

Relatively new thinking in passenger railcar crashworthiness design by Tyrell, et al (3, 4), Chatterjee, et al (5, 6), and others calls for a crush zone at the end of each car to manage impact energy along the length of the train set. This approach minimizes damage to all the passenger compartments. Comparison of conventional design versus crash energy management designs in varying crash scenarios has been demonstrated by many researchers. The crush zone concept of Mayville, Johnson, Stringfellow and Tyrell has reached an advanced level of design and testing (7). The crash energy is managed by a sliding sill on either end of a Tier 1 passenger car with energy absorbing components. (Tier 1 passenger cars operate at speeds up to 125 mph.) The sill area on either end of the railcar is not normally occupied by passengers during transit and is considered sacrificial to preserve the occupied internal compartment.

In this sliding sill design, the cumulative energy absorption of 3.4 MJ over a stroke length of 40 inches is accomplished in the pushback coupler, primary energy absorber, and the roof structure absorbers (reference figure 9). This quantity of energy absorption was chosen based on CFR (Code of Federal Regulations) and APTA (American Public Transportation Association) regulations on railcar design in the U.S. as well as the concept requirement of maintaining the passenger compartment structure in a collision. The majority of the energy (2.7 MJ) is absorbed by two heavy-wall square steel tubes with cut-outs for controlled crush. They are mounted in the underframe. The balance of the energy is absorbed by the pushback coupler (0.41 MJ) and the roof structure absorbers (0.27 MJ) constructed of aluminum honeycomb. For reference, energy absorption of 1 MJ is required in the U.K. on Tier 1 operating equipment, while 5 MJ is required by the Code of Federal Regulations on Tier 2 equipment. Tier two classified equipment operates at speeds between 125 mph and 150 mph. While the ability to absorb 3.4 MJ is impressive for Tier 1 railcars, it is not sufficient for greater speeds and crash energy attained in Tier 2 train sets.

The energy absorbing components in the sliding sill dissipate the overall crash energy sufficiently to assure the integrity of the passenger compartment for Tier 1 equipment. Aluminum foam-filled extruded aluminum tubing could serve the same purpose as the primary energy absorbers and dissipate higher crash energy at lower forces. This would increase the duration of the crash pulse and reduce the velocity at which the passenger impacts the back of the seat in front of him. In a previous HSR-IDEA concept exploration contract (HSR-20), Fraunhofer USA demonstrated that aluminum foam inserts in extruded tubing can absorb significantly more crash energy than the two components separately.

With the passenger compartment intact, the safety of the unrestrained occupants in the railcar is a function of velocity, deceleration, crash pulse and the coach design. As was mentioned in the introduction, a combination of restraints and soft, compliant surfaces has reduced injury in automobile accidents. Required use of seat belts as is done in air travel would in large part benefit the safety of the passengers. If this is not practical, a coach environment designed to minimize failed velocity and safely decelerate unrestrained passengers may be sufficient.

The goal of this project was to identify and demonstrate specific applications for aluminum foam in high speed rail equipment. The main focus is on improvement of crush energy absorption of structures in rail passenger cars. Four application areas are discussed and explored through analytical studies, redesign and sub-scale testing of components. A single application was selected for full scale testing based on test results, cost-of-fabrication modeling, and the ability to produce a full-scale component within the boundaries of this project.

3. IDEA PRODUCT & CONCEPT

SPECIFIC APPLICATIONS OF ALUMINUM FOAM

3.1 Aluminum Foam Sandwich Panels

An efficient design for utilization of aluminum foams is in the form of aluminum foam sandwich (AFS) panels. AFS panels consist of aluminum foam cores with about 80-90 vol % porosity metallurgically bonded to thin outer face sheets of aluminum or steel. The sandwich panel design provides very high specific stiffness (stiffness per unit weight), excellent vibration damping, and very good thermal and sound insulation. In addition, energy absorption associated with plastic deformation of the aluminum foam core under impact and crash conditions provides improved crashworthiness to structures fabricated from AFS panels. The crashworthiness enhancement of AFS panels was studied at the MIT Impact and Crashworthiness Laboratory (8). AFS panels may serve in a multifunctional manner as an enhanced replacement of heavy stainless steel panels and "Plymetal" panels currently used in passenger railcar interiors.

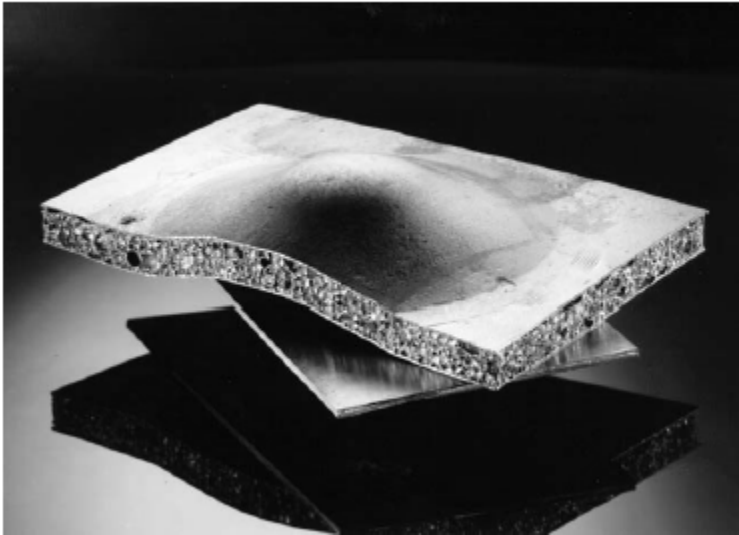


FIGURE 2: Aluminum foam sandwich (AFS) cross-section that was shaped before foaming.

3.2 Primary Impact Energy Absorber

An analysis of the dynamic deformation of aluminum foam as an energy absorber entitled, “On the Effectiveness of Aluminum Foam as an Energy Absorber for Rail Car Crush Zones” (9), was performed by the Center for Composite Materials at the University of Delaware. A sliding sill crush zone design reported in “Test Results and Analyses for Coach Car Crush Zone Components” by Mayville, Stringfellow and Tyrell was used as a baseline comparison. In the analysis the following properties were determined and found to be pertinent in this application of aluminum foam:

1. Progressive collapse of aluminum foam is 40 to 60% more efficient than homogeneous collapse. The collapse and densification of aluminum foam in a moving zone from one end of a component to the other is defined as progressive collapse. Homogeneous collapse is defined as uniform deformation throughout the aluminum foam component as force is applied.
2. It has been demonstrated that the predominant mode of failure in aluminum foam placed in extruded aluminum or steel tubing is progressive collapse.
3. Aluminum foam-filled thin walled extrusions produce a smoother force/displacement curve when taken to failure under a compressive load. This reduces the significant G load perturbations above the average deceleration, thus decreasing peak decelerations.
4. The best results in terms of mass, volume, and number of constituent elements was found to be steel tubes filled with foam.
5. Filling the baseline energy absorbing components from the Mayville, et al, design with aluminum foam could increase the energy absorbing capability by 28%.

The application of aluminum foam-filled extrusions to dissipate primary impact energy in a crash event will be investigated. This use of metal foam at either end of a passenger car may increase the quantity of energy absorbed without increased loading of the passenger compartment.

3.3 Secondary Impact Head Injury

As a result of a crashpulse generated as two consists collide, unrestrained passengers are accelerated in the passenger compartment until they impact a surface. This is referred to as secondary impact. The rate of deceleration of the passenger is dependent on the velocity attained and the properties of the surface. After an 8g crash pulse, the head of a passenger that has moved just 2.5 feet through open space attains a velocity relative to the passenger compartment of about 26 mph. The accelerated unrestrained passenger continues to move at an increasing rate of velocity until an interior surface of the passenger compartment is impacted. This is known as Secondary Impact Velocity (SIV). Striking hard surfaces at this

velocity can do significant damage. The automobile industry has addressed this by providing softer impact surfaces in the passenger compartment. The surface must be compliant, but capable of absorbing large amounts of crash energy over a short distance to minimize head and neck injury to the passenger.

The application of aluminum foam as an energy absorber in automobile interiors was investigated by Kretz and Goetzinger (10). It was found that the proper density of aluminum foam in an A-pillar design could significantly reduce injuries as measured by Head Injury Criterion (HIC) values. Lower density aluminum foam was found to densify too soon during the deceleration of the occupant and higher densities required higher deformation forces that caused injury. Appropriate density aluminum foam could be used in train interior surfaces to reduce head injury. Testing of aluminum foam panels will be conducted in accordance with Federal Motor Vehicle Safety Standard (FMVSS) 201U. A 10 pound Free Motion Headform (FMH) with tri-axial acceleration was used to impact samples at 15 mph.

3.4 Energy Absorbing Sliding Seat Rail

The proposed sliding sill crush zone which is part of a Crash Energy Management (CEM) design ensures the survival of the passenger compartment under specified crash conditions. Based on modeling reported at the April, 2003 ASME/IEEE Joint Railroad Conference in a paper entitled, "Collision Safety Comparison of Conventional and Crash Energy Management Passenger Rail Car Design", there is an increase in occupant Secondary Impact Velocity (SIV) in a CEM modified train over that expected in a conventional design. This seems to be most severe in the first two cars behind the impact. The cushioning effect of the crush zone on each car reduces the occupant SIV incrementally in the cars behind the first two passenger cars.

The increased potential injury to the passengers in the first two cars needs to be addressed. Injury occurs when unrestrained passengers impact the back of forward facing seating after attaining unsafe velocities. While requiring restraints is effective in reducing injury, it is not considered practical. Compartmentalization strives to minimize SIV and provide safe deceleration.

An aluminum foam-filled piston/cylinder design that can be placed at the seat mounting point(s) was tested to assess its ability to safely decelerate passengers after they have come in contact with the seat backing. The aluminum foam will begin to crush, minimize loading to the passenger at points of contact and dissipate crash energy before the seats have fully deflected. A July, 2002 study sponsored by the FRA entitled, "Commuter Rail Seat Testing and Analysis" (report # DOT-VNTSC-FRA-02-10) provides a good basis on which to compare and quantify possible reduction in injury to passengers.

4. INVESTIGATION

4.1 ALUMINUM FOAM SANDWICH PANELS

Based on our discussions with Talgo designers and with engineers at Alstom (Hornell, NY) who are refurbishing Comet 2 aluminum passenger cars for the New Jersey Transit Authority, there is significant interest in evaluating AFS panels to replace current materials used for floors, overhead panels, ceilings, and bulkheads.

Sandwich panels that are currently used, for example as floors and overhead panels, consist of either aluminum or stainless steel outer face sheets with inner cores of various materials, including marine grade plywood, polymer foams, or aluminum honeycomb. This material, referred to in the industry as "Plymetal", is the same material that was specified in the original cars built by Bombardier about 20-25 years ago. A report issued by NIST and the Volpe National Transportation Systems Center in 2001 indicates that the majority of rail car floors are constructed of Plymetal (plywood/metal) panels (11).

A number of long-term performance and reliability issues have been identified with the baseline Plymetal panels using plywood cores. The issues include:

- Permeable to moisture and water leading to rotting, potentially dangerous mold growth, and overall structural deterioration
- Relatively heavy weight – core density of 0.6 – 0.8 g/cm³
- Produced in batch process at low production rates
- Flammability of plywood core
- Poor ductility and impact resistance of plywood core
- Delamination of adhesively bonded outer face sheets during long 20 year lifetimes of rail passenger equipment
- Complex edge joining techniques
- Poor recyclability

In Fraunhofer's discussions with the Talgo R&D and Engineering Group in Spain, it was learned that Talgo is planning to use a newer material for floor panels in its next generation of aluminum body passenger coaches. The floor panel material that Talgo has tentatively selected is HEREX C70 sandwich panel produced by Alcan Airex AG, a division of Alcan

Aluminum. This sandwich material consists of an inner core of rigid, closed-cell polyvinyl chloride polymer foam with outer face sheets of aluminum alloy. The HEREX C70 sandwich panel is superior to Plymetal in terms of stiffness per unit weight and fire resistance. However, it still has short-comings in terms of giving off noxious/toxic fumes of chloride compounds when exposed to fire. In addition, it is not expected to provide as great energy absorption for improved crashworthiness, compared to aluminum foam sandwich (AFS) panels.

Fraunhofer USA CMAM collaborated with a local design and engineering company (Advantek LLC) to develop a simple Finite Element Analysis model for calculating the stiffness and load deflection behavior of AFS panels for a range of panel cross-sectional designs and panel loading conditions. An example of such model calculations is shown in Figures 3 - 5 below (12).

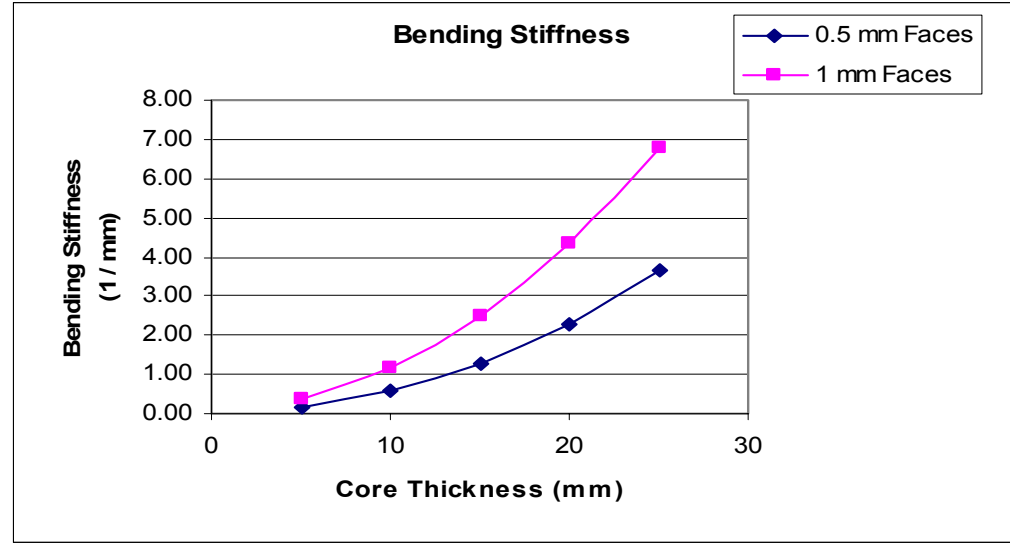


FIGURE 3: Relative bending stiffness of AFS panels vs. thickness of aluminum foam core for 0.5 and 1.0 mm thick aluminum outer face sheets.

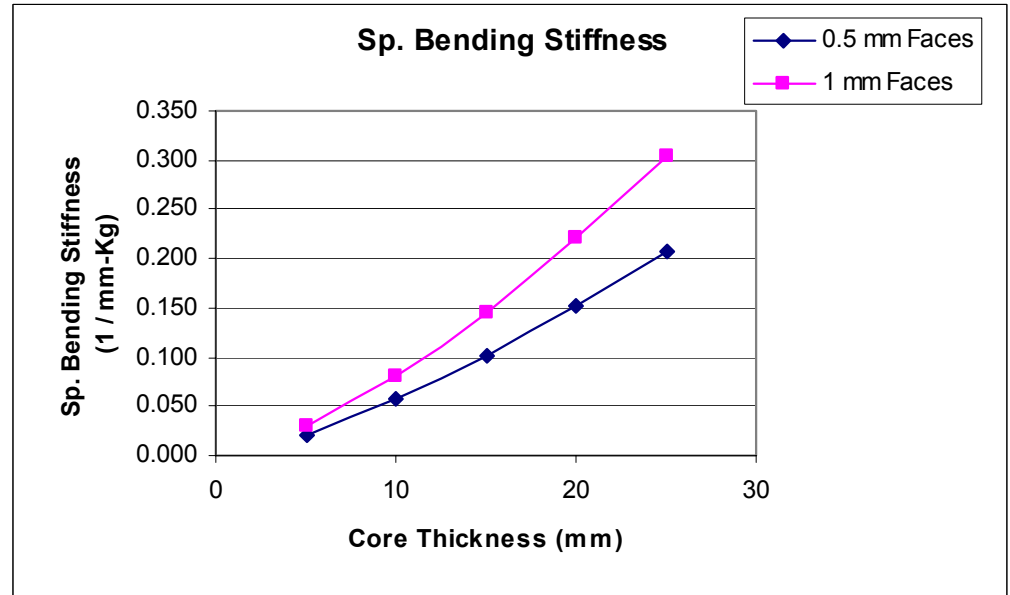


FIGURE 4: Relative specific bending stiffness of AFS panels vs. thickness of aluminum foam core for 0.5 and 1.0 mm thick aluminum outer face sheets.

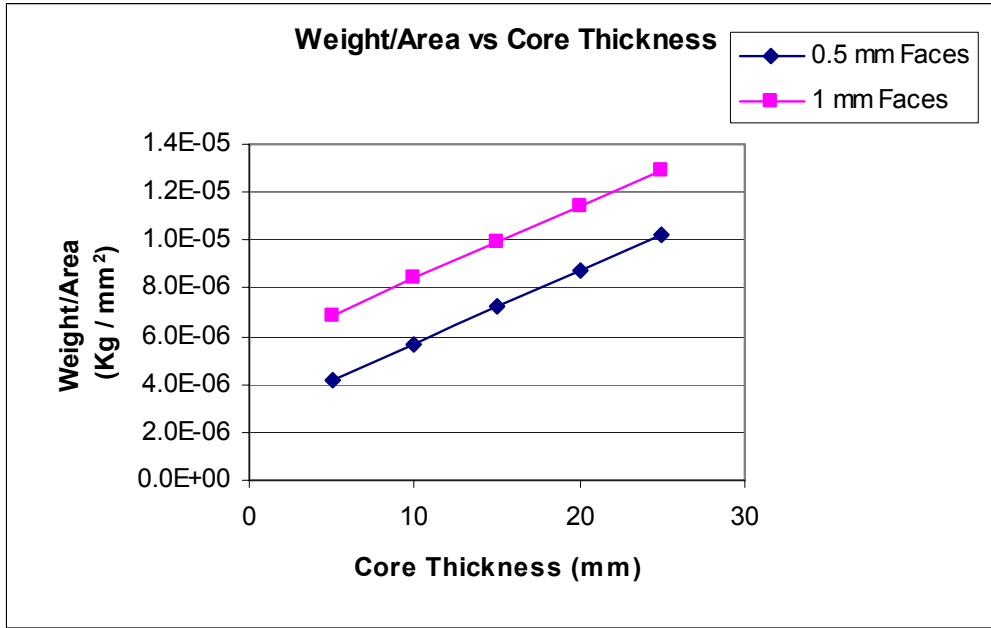


FIGURE 5: Weight per unit area of AFS panels vs. thickness of aluminum foam core for 0.5 and 1.0 mm thick aluminum outer face sheets.

During development of the AFS technology the following standard material dimensions have been established by Fraunhofer IFAM as a compromise between optimum design and process capabilities:

- Total thickness: 11 mm
- Thickness of surface layers: 1 mm
- Foam core layer density: 0.4 g/cm³
- Overall AFS density: 0.8 g/cm³
- Mass per unit area: 8.8 kg/m²

Since the AFS is a composite of three layers the mechanical properties depend on the loading direction. The following table gives an overview of standard AFS properties:
Loading direction Orthogonal to surfaces and Parallel to surfaces.

| Loading direction | Orthogonal to surfaces | Parallel to surfaces |
|---|------------------------|----------------------|
| Young's Modulus [GPa] | 2.5 | 15 |
| σ_{\max} , tension [MPa] | 4 | 90 |
| σ_{\max} , compression [MPa] | 8 | NA |
| τ_{\max} [MPa] | 4 | NA |
| Thermal expansion [1/°K] | 23×10^{-6} | 23×10^{-6} |
| Heat conductivity [W/mK] | 12 | 235 |
| Heat capacity (20 to 100°C) [J/gK] | 0.9 | 0.9 |
| Max. operating temperature [°C] | 430 | 430 |
| Sound Absorption (1 to 10kHz) [%] | 30 | 30 |
| Electrical conductivity [m/Ωmm ²] | 2.1 | 34 |

TABLE 1: Properties of standard aluminum foam sandwich.

While AFS has many attractive properties in a panel application, there are two attributes that need development to make it a feasible candidate material—cost and a relatively malleable surface. There is no production capability currently in the U.S.

Pilot plant level manufacturing exists in Germany with a few promising commercial applications. The success of these projects should allow a reduction in cost that is competitive with the incumbent materials now in passenger railcars. The second area mentioned alludes to the aluminum face sheets that are softened in processing. In this condition, the face sheets are prone to dents and scratches. This would not be suitable in high density public transportation. Development of the proper face sheet alloy and post-process heat treatment to achieve the right balance of properties should be achievable in the near future.

4.2 PRIMARY IMPACT ENERGY ABSORPTION

This application is a continuation of the work begun in phase 1. It was demonstrated in that study that the specific energy absorption of a square metal tube could be increased by as much as 50% by filling the interior of the tube with aluminum foam. This is not just an additive effect, but a multiplying one. In other words, the crush energy dissipation of the materials combined is significantly greater than the crush energy dissipation of the two materials added together when tested separately. The aluminum foam is a lightweight approach to providing stability to the tubing sidewalls when placed in compression. It also offers resistance to the inward folding of the tube as it progressively deforms, thus requiring more work. Moreover, the presence of the metal foam insert causes more folds to form per unit length than without the foam. An illustration of this can be seen in the cross-section of a crushed aluminum foam-filled stainless steel tube shown in figure 6. Compare the number of folds created in figure 6 to that in figure 7 in the same stroke length.

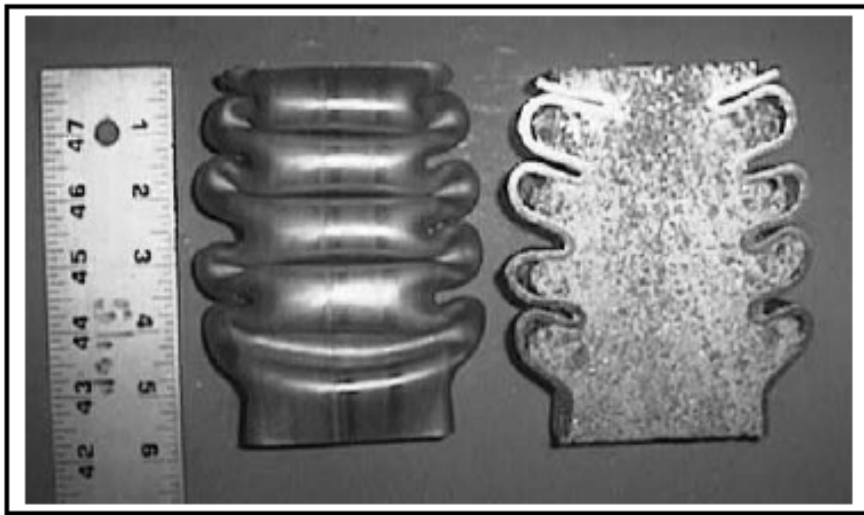


FIGURE 6: Deformed aluminum foam-filled 304 stainless steel tube after axial compression. (178 mm axial displacement/ 305 mm initial length = 58% strain).

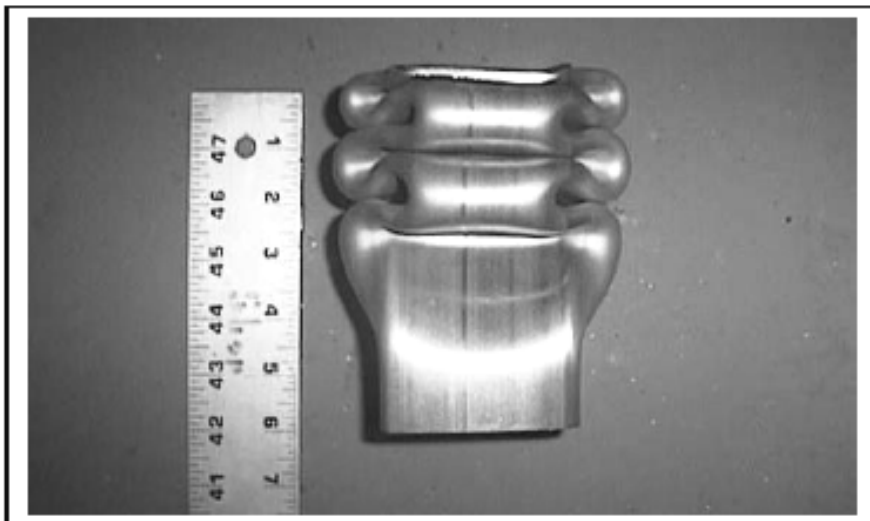


FIGURE 7: Deformed empty 304 stainless steel tube at 58% strain.

The application proposed was to use aluminum foam in steel tubing profiles as major crash energy absorbers at the ends of the railcars. As was presented in the IDEA Concept earlier, this use of aluminum foam may produce a more weight efficient means of dissipating large quantities of crash energy. For an absorber made from pure foam, the necessary mass of metal foam to dissipate the target 2.7 MJ (discussed in section 2) for the primary energy absorber is equal to 325 kg. The necessary volume of foam is approximately equal to 0.54 cubic meters of foam. If one takes into account that the length of the absorbing device is equal to 1 m (40 inches), the working area of the block of metal foam must be equal to 0.54 sq. m. (e.g., a square area about 28 inches per side).

4.2.1 Absorbers made from aluminum and steel tubes.

The cross-sections of aluminum and steel tubes used in experiments are presented at the Figure 8.

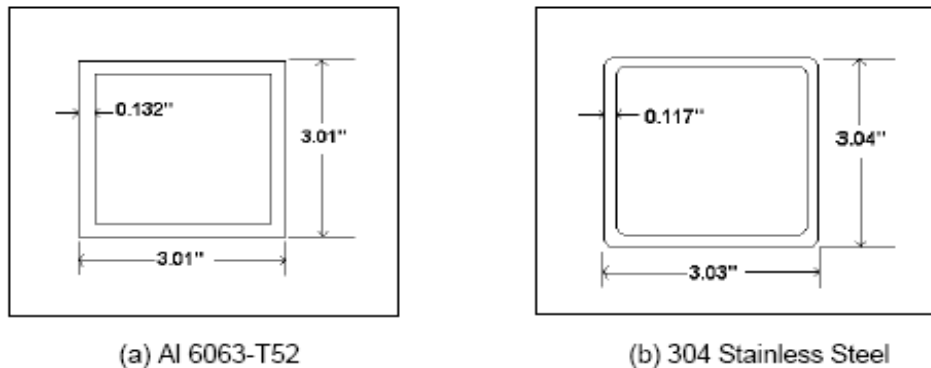


FIGURE 8: Cross-sections of aluminum and steel tubes.

The area of one element is approximately equal to 70 sq.cm. The aluminum element having a length of 12 inches absorbs approximately 10 kJ. The steel element absorbs approximately 27 kJ per element. These results are scaled to 1m lengths by assuming the energy absorption is proportional to the volume of absorbing material. Thus, an absorbing element having the same cross-section and longer lengths (40 inches) than used in the experiment (12 inches) will absorb 3.3 time greater energy. The energy absorbed is 33 KJ per aluminum tube and 90 KJ per steel tube.

Consequently, one needs to use 82 aluminum elements and roughly 30 steel elements to absorb 2.7 MJ. These one-meter tubes will occupy an overall cross-sectional area of 0.57 square meters for the aluminum tubes and 0.21 square meters for steel tubes. The mass of empty tube absorbers will be approximately 125 kg for the aluminum and 111 kg for the steel. Based on prior testing, the energy absorbed by a one meter aluminum foam-filled aluminum tube with a 70 sq. cm. cross-section is equal to 83 KJ. The mass of combined aluminum tube/metal foam absorber able to absorb 2.7MJ of energy is equal to approximately 94 kg. The device must contain 32 elements and will occupy an area 0.22 square meters.

The energy absorbed by an aluminum foam-filled steel tube one meter in length is equal to 183 KJ. The mass of combined steel tube/metal foam absorber able to absorb 2.7MJ of energy is equal to approximately 80.4 kg. The device must contain 15 elements and will occupy the area 0.11 square meters.

4.2.2 Standard absorbing elements.

In the sliding sill design proposed by Mayville, Johnson, Stringfellow and Tyrell each of two primary energy absorbers consists of two tubes of square cross-sections. Figure 9 shows one absorber on one side of the train. Figure 10 illustrates a close up view of one of these absorbers. The material of construction is A572-50 steel. This is a structural steel with a yield strength of 50,000 psi. The cut-outs and diaphragms are designed to allow the tubing to yield over a range of impact velocities and loadings. At higher impacts this feature allows the absorber to yield sooner in the crash event and dissipate more energy as the absorbers continue to be loaded. The total length of the 0.25 inch (6.4 mm) thick tubes is 40 inches (1 m). The cross-section of tubes is nominally 6 x 6 inches (12.7 x 12.7 cm). A total of 2.7MJ is absorbed by the 2 primary absorbers through the crush of these 4 tubes.

The crush zone design is based on the sliding sill mechanism.

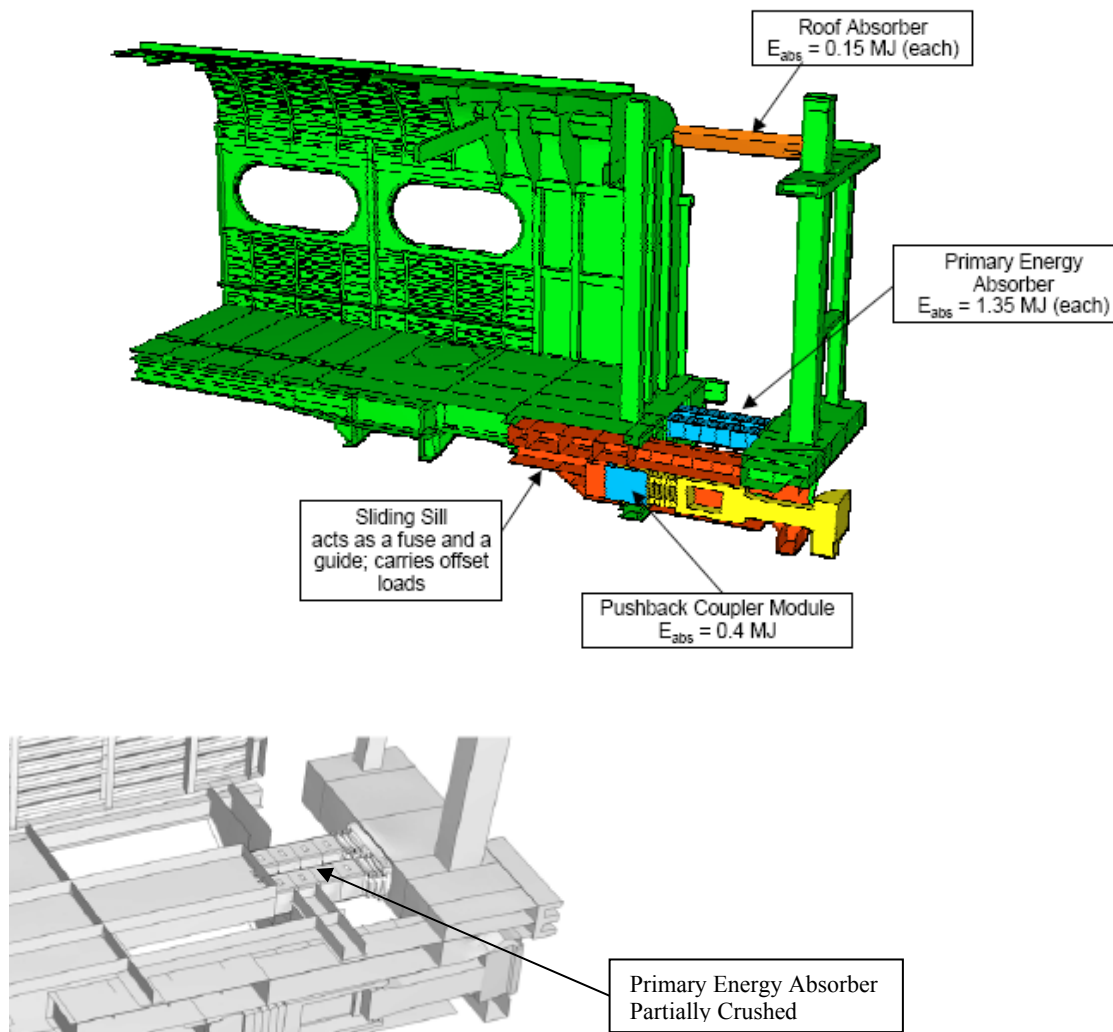


FIGURE 9: The crush zone design.

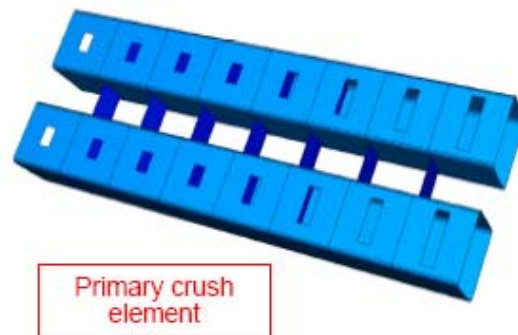


FIGURE 10: Primary energy absorbing assembly.

The total energy absorbed by a system of two primary energy absorbers is equal to 2.7MJ under deformation of 36 inches. Each primary energy absorber absorbs 1.35MJ. Each individual tube absorbs (4 total) 0.675MJ. The summary of the data is presented in Table 2 for the case of 2.7MJ to compare to other configurations being considered in this study.

Another practical option to consider is the filling of the 4 primary absorbers just described with foam to improve energy absorption at higher velocities. Let us suggest that we fill these tubes with aluminum foam at the density 0.6 g/cm^3 .

The volume of foam in a single tube is thus:

$$V = 14\text{cm} * 14\text{cm} * 100\text{cm} = 19600\text{cm}^3$$

Here we took into account the approximate thickness of walls estimated to be 0.25 inches (0.65 cm.)

Thus, the mass of foam is equal to:

$$M_f = 19600 * 0.6 = 8640\text{g} = 11.76\text{kg}$$

The total mass of the single tube filled with aluminum foam will be $27.00 + 11.76 = 38.76 \text{ kg}$.

Using the phase I experimental data for energy absorption by aluminum foam during progressive collapse, the energy absorbed per 1 kg of foam can be estimated as:

$$8.3 / 0.52 \approx 16 \text{ kJ/kg}$$

Thus, the total energy absorbed by aluminum foam per tube will be equal to:

$$E_f = 16 \text{ kJ/kg} * 11.76 = 188\text{kJ} = 0.188\text{MJ}$$

The baseline design consisting of two primary energy absorbers (where each assembly consists of two tubes each) can absorb 2.7 MJ of energy in 36 inches (0.91 m) of crush. One tube will absorb approximately 0.675 MJ of energy.

Thus, filling the tubes with aluminum foam will increase the energy absorption to

$$0.675 + 0.188 = 0.863\text{MJ}$$

This corresponds to a 28% increase in the energy absorption compared to the empty tube. In addition the mass of tube will increase by 35%:

$$\frac{38.76}{27} = 1.35$$

These improvements are approaching a level where one could eliminate one of the four tubes to absorb 2.7MJ of energy with only a slight weight increase. Alternatively, the higher energy absorption would allow a 14% increase in crash velocity with tube crush in the same distance or a 28% higher mass of the rail car.

Referring to table 2, One can conclude that the best results are provided by the foam-filled steel tubes which exhibit superior results with respect to all parameters. Interestingly, the steel foam filled tubes and the aluminum-foam-filled tubes are the lightest weight. The trade-off is in the number of tubes needed to absorb the specified energy. It is important to notice that the tube designs have not been optimized, but that significant improvements are possible. The major advantage is offered by the foam in reducing the G load perturbations above the average deceleration level commonly observed during crush of the steel baseline. In the Table 2 the results of analyses are summarized.

| E=2.7MJ Length =1m | Pure aluminum foam | Empty Al- tubes | Empty Steel Tubes | Foam-filled Al-tube | Foam-filled Steel tube | Existing Absorbers (2 primary absorbers with 4 individual tubes |
|-----------------------|--------------------------|--------------------|----------------------|------------------------|---------------------------|---|
| Number of elements | 1 | 82 | 30 | 32 | 15 | 4 |
| Weight (kg) | 325 | 125 | 111 | 94 | 80.4 | 108 |
| Area (sq.meters) | 0.54 | 0.57 | 0.21 | 0.22 | 0.11 | 0.0645 |

TABLE 2: Parameters of energy absorbers.

There is evidence to support investigating a bitubal design as well as the monotubal structures studied in phase I of this program. The tube within a tube design (i.e. bitubal) is thought to be more efficient when aluminum foam fills the space between the tubes. An example of a compressively tested and sectioned bitubal arrangement is shown in figure 11. Notice the uniform progressive buckling that is desired in an application such as this. Samples were constructed as follows: All samples were made with electrical resistance welded square steel tubing with a side wall thickness of 0.083 inches. Each sample was 12 inches long. The aluminum foam used in the filled samples was the same nominal density.



FIGURE 11: Uniaxially compressed aluminum foam-filled and empty bitubal designs. Notice the uniform folds of the sectioned sample with the sandwiched aluminum foam revealed.

The samples were all uniaxially compressed in a universal testing machine at a strain rate of 0.5 inches per minute through a 7.5 inch stroke. The test results are shown in table 3.

Contrary to our expectations the most weight efficient energy absorbing sample was the single tube with aluminum foam filling the interior. There was a slight increase in total energy absorbed in sample 3 with the addition of aluminum foam. Sample 5 demonstrated a much greater increase over samples 1A and 1B, but on a weight basis fell far short of just filling the tube with aluminum foam as in sample 2.

The advantages anticipated by the successes reported elsewhere in aluminum foam sandwiched in bitubal designs were not realized to the degree reported by other researchers. Sample sizes used in those experiments, however, were much smaller than the sample sizes used here.

| Sample ID | Sample Description |
|-----------|---|
| 1A and 1B | 2" square steel tubing centered inside 3" tubing – no aluminum foam. Bitubal baseline |
| 2 | 3" square steel tubing filled with aluminum foam – monotubal design |
| 3 | 1" square steel tubing inside of 3" tubing with a 0.938" layer of aluminum foam between |
| 4 and 5 | 2" square steel tubing inside of 3" tubing with a 0.438" layer of aluminum foam between |

| Sample ID | Mass(kg) | Energy (kJ) | Specific Energy (kJ/kg) |
|-----------|----------|-------------|-------------------------|
| 1A | 2.60 | 29.0 | 11.2 |
| 1B | 2.61 | 30.7 | 11.8 |
| 2 | 2.36 | 42.9 | 18.1 |
| 3 | 2.29 | 32.7 | 14.3 |
| 4 | 2.81 | 0.00 | 0.00 |
| 5 | 2.80 | 40.2 | 14.4 |

TABLE 3: Energy absorption efficiency in bitubal and monotubal steel and aluminum foam components in uniaxial compression.

Sample 4 began to fail in bending in the early stages of the compression test and had to be aborted. This new testing combined with past testing led to several conclusions:

- The lack of good results and the added work and expense to assemble a bitubal component is not worth pursuing any farther in this application.
- The length-to-width ratio of the 12" long x 3" wide samples is just sufficient to expect the tubes to fail in progressive buckling without a bending component. This instability was seen in several samples in past testing and again in sample 4 here. The length of a full scale energy absorber would need to approach 1 meter. The probability of bending in uniaxial compression would be greatly increased. A failure like this would dissipate very little energy.
- A wider component filled with aluminum foam would make more sense in anticipation of scale up.

The design requirement for crash energy absorption in the sliding sill primary energy absorber is 675 kJ per tube. This must be accomplished in a 50 to 60 percent decrease in length of a 1 meter component during crush. A six inch diameter DOM (Drawn Over Mandrel) steel tube with 0.250" thick walls was calculated to be sufficient when filled with aluminum foam. Two aluminum foam-filled tubes 12 inches long and two empty tubes of the same length were tested in uniaxial compression in a universal testing machine at a strain rate of 0.5 inches per minute. All four of the samples were crushed through a 7.5 inch stroke. Two of the tested samples can be seen in figure 12. Uniform progressive buckling was observed in both the filled and unfilled tubes.

The unfilled tubes yielded at an average of 260,000 pounds force with a uniformly cyclic failure over the remaining folds. The aluminum foam-filled tubes began yielding at an average of 340,000 pounds force and in contrast to the empty tubes increased in yield strength with each fold. This produced a 40 percent increase in energy dissipated from 170 kJ in the empty tube to 238 kJ in the filled tube. At this rate a one meter aluminum foam-filled tube could absorb over 780 kJ. This does not offer a significant weight advantage over the baseline design that can absorb 25 kJ per kg. The aluminum foam-filled 6 inch diameter tube which weighs 32 kg can only absorb 24 kJ per kg.

Another benefit expected of the aluminum foam was a decrease in the range of peak-to-valley failure mode of the tube. It was speculated that a "smoother" crushing action would minimize deceleration peaks in a railcar crash event. There was no decrease observed in the testing of these samples.



FIGURE 12: A sectioned aluminum foam-filled 6 inch diameter steel tube with an empty tube after compression testing.

While current and past work indicates promising results, the relationship between the steel tube properties and the aluminum foam core requires more study. An aluminum foam-filled, thick walled tube, it appears, tends to dominate the performance of the composite tube. A thinner walled tube will have a lower yield and won't dissipate as much energy on crushing. Perhaps a cluster of lighter weight tubes would produce the optimum results of high specific energy absorption accomplished under a continuous load (i.e. a smooth flow stress during crushing). It was not felt that this could be treated properly in the present scope of this project and another application was pursued as will be discussed in section 4.4.

4.3 SECONDARY HEAD IMPACT ENERGY ABSORPTION

The intended application for the third component was to reduce head impact injury. Prior testing had been preformed by Kretz and Goetzinger in an automobile A-pillar design with some promising results. Aluminum foam strips shown in figure 13, 12 inches long x 2 inches wide x 1 inch thick were sent to MGA Research for standard FMVSS 201U head impact testing. The test stand can be seen in figure 14. The test consists of projecting a 10 pound instrumented dummy head into the test material with an impact velocity of 15 mph. A HIC (head injury coefficient) value is calculated from the test data. The value should be below 1000 to keep head and neck injuries to a minimum per the AIS (Abbreviated Injury Scale) chart shown in table 6. As can be seen in table 4, the test results were much higher than would be considered beneficial. The testing was stopped after two samples because the results were not expected to improve with the densities of the next two samples.

Aluminum Foam FMVSS 201U Test Samples

| Sample | Mass (gms) | Volume (cc) | Density (g/cc) | HIC value |
|--------|------------|-------------|----------------|-----------|
| 1 | 158.5 | 392.5 | 0.404 | 2381 |
| 2 | 168.2 | 404.2 | 0.416 | 2296 |
| 3 | 161.7 | 404.2 | 0.400 | ---- |
| 4 | 197.0 | 404.2 | 0.487 | ---- |

TABLE 4: Results of aluminum foam strips in a head impact test.

The test engineers did point out two factors that would tend to yield higher numbers:

- The test stand seen in figure 14 is more rigid than testing that is typically done in a car frame. The car frame has more flexibility and this reduces deceleration of the head.

- The flat surface of the aluminum foam requires a higher loading to crush the foam, absorb energy and improve deceleration. The domed or crowned cross-section that is seen in A-pillars would begin crushing sooner and progressively slow the head.



FIGURE 13: Aluminum foam samples, 12" x 2" x 1", used in 201U head impact test at MGA Research.

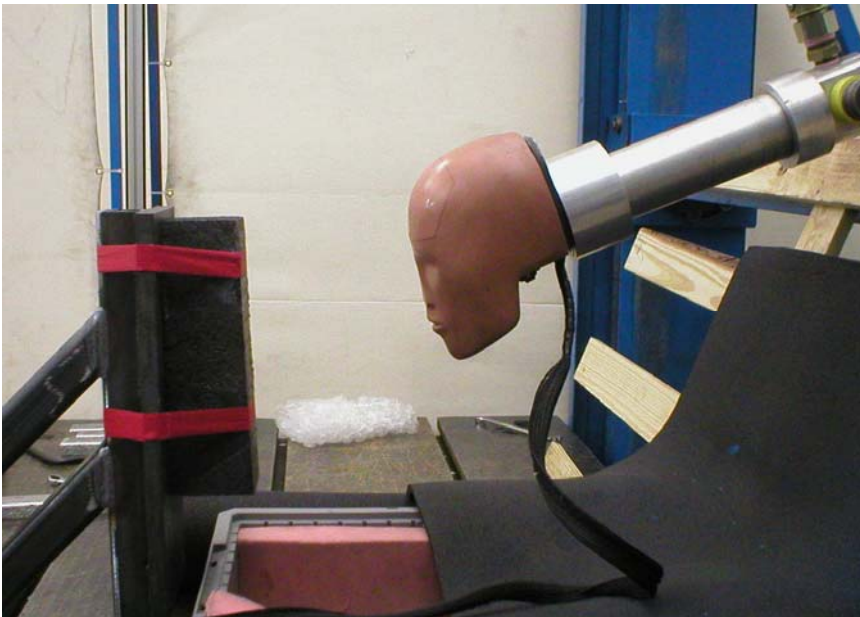


FIGURE 14: Test set-up for 201U test conducted outside of an automobile frame. The aluminum foam was mounted at left on a rigid stand.

Based on the previous work cited above regarding the use of aluminum foam in A-pillar design, an extension to railcar interiors seemed reasonable. The initial results do not support continued work with this application.

4.4 ENERGY ABSORBING SLIDING SEAT RAIL

An aluminum foam-filled piston/cylinder first generation prototype that could eventually be placed at the seat mounting point(s) was built and tested to assess its ability to safely decelerate passengers after they have come in contact with the seat backing. The assembly can be seen in figure 15 with the plunger extracted from the tube. The aluminum foam samples were charged in the tube for each test.

Dynamic impulse testing was conducted at MGA Research, Inc. in Troy, Michigan. The test set-up is illustrated in figure 16. After an aluminum foam cylinder was inserted into the tube, the plunger was seated on the foam. A 100 pound block was projected at the plunger end so that the contact velocity was 24.6 mph. This was the maximum mass and velocity that could be used safely in this test equipment. The impulse energy applied was nearly 1900 joules or 1400 ft-lbs. This approximates a fifth percentile female passenger contacting the back of a rail car seat after a 10 g crash impulse and 2.5 feet of travel. It was felt at the time that this was a good starting point to assess the minimum requirements for the application. The test results are summarized in table 5.

| Sample | Mass (gms) | Vol. (cc) | Density (g/cc) | Displacement (cm) at 1200 lbs load | Energy (J) | Deceleration Time below 20g (msec) |
|--------|------------|-----------|----------------|------------------------------------|------------|------------------------------------|
| 1 | 68.3 | 258.2 | 0.265 | 13.0 | 500 | 22 |
| 2 | 118.5 | 258.2 | 0.459 | 1.0 | 50 | 6 |
| 3 | 101.8 | 258.2 | 0.394 | 6.2 | 250 | 13 |
| 4 | 111.9 | 258.2 | 0.433 | 7.6 | 230 | 12 |

TABLE 5: Characteristics of aluminum foam cylinders and seat deceleration test results.

All of the samples were able to dissipate this amount of crash energy. However, the maximum loadings reached as high as 8300 lbs. force as densification of the foam approached an end point. Because the passenger's knees typically contact the back of the seat first, a femur loading limit of 1200 pounds was used to analyze the test data. This is just short of the maximum axial femur loading of 1530 pounds specified by Federal Motor Vehicle Safety Standard (FMVSS) 208 in a recent modification of the criteria for the 5th percentile female. The 1200 pound criteria was also chosen based on static loadings at which a number of passenger rail seat backings failed just beyond 1200 pounds as reported by VanIngen-Dunns and Manning (13). For example, sample 1 was able to crush a linear distance of 13 centimeters



FIGURE 15: Tube and plunger prototype for passenger secondary crash energy absorption.

(5.12 inches) and dissipate 500 joules before exceeding 1200 pounds force as it continued to crush. This would have slowed the passenger from 24.6 mph to 17.5 mph. Additional energy would be dissipated in seat deflection in a full scale test on passenger seats. It is also interesting to note that the crushing foam in sample 1 kept deceleration below 20 g for 22 msec.

The remaining samples with higher aluminum foam densities exceeded the 1200 pound criteria much more quickly. They also dissipated much less energy before exceeding that limit. The deceleration characteristics increased over a shorter period of time for these samples.



FIGURE 16: The 100 pound impactor at right was contacted the plunger shaft at an initial velocity of 24.6 mph. In the actual test the plunger shaft was a greater distance from the impactor.

The density range between 0.265 g/cc and 0.394 g/cc was not tested. A longer aluminum foam cylinder at an optimum density in this range may absorb more energy and safely decelerate the hypothetical passenger to even lower velocities and greatly reduce injury. Another advantage in the seat moving after knee contact may be a delay in head contact with the seat until the passenger's relative velocity has decreased somewhat.

These test results seemed sufficient to support the design of an aluminum foam-filled sliding rail that could mount to the bottom of a seat for the purposes of absorbing the impact energy of a passenger on contact with the back of a seat. The concept was to allow the seat to move in a controlled manner when the passenger impacted the back of the seat. This would not only reduce injury to the passenger through a longer deceleration, but also reduce damage to the seats and the possibility of the seats breaking free of their mountings. The piston and tube idea was carried forward from the sub-scale tests. Modifications were made to allow mounting to the floor or side wall. The stroke length was increased to allow an expected maximum of 10 inches of seat travel. The prototype used in the "full-scale" tests can be seen in figure 17.

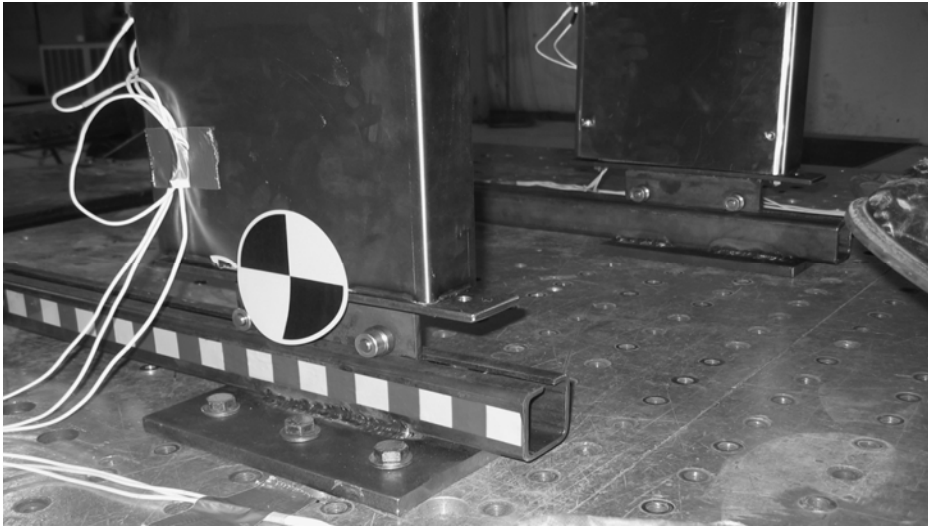


FIGURE 17: Seat pedestals mounted to sliding rails.

The device was expected to function in the following manner. Aluminum foam is loaded into the front end of the tube. The piston inside the tube is attached to the t-section seat mounting. A shear pin holds the sliding rail in place as the seat is loaded under the 8 g pulse. The pin shears with the additional load of the passenger impacting the rear of the seat and the foam begins to deform as the rail moves. Some of the energy is dissipated through the crushing of the foam in the tube. The horizontal movement of the seat reduces the resistance that the passenger would typically encounter. This alone is not expected to stop the passenger. It is intended to maintain compartmentalization of the passenger, now at a lower velocity, with the balance of the deceleration accomplished by the flexing of the seat.

After discussions with MGA Research, it was decided that this configuration could be studied on the test sled used for rail seat testing at their Burlington, Wisconsin facility. The test conditions specified in APTA SS-C&S-016-99, revision 1, which covers the Standard for Row-to-Row Seating in Commuter Rail Cars were used as follows:

- Two rows of commuter seats were mounted on a test sled.
- Two Hybrid III, 50th percentile male ATDs were placed in the seats facing the back of the next row.
- The dummies were instrumented with head and chest accelerometers and femur load cells.
- The seat struck by the ATDs contained accelerometers.
- Two high-speed cameras recorded the test.
- The sled was accelerated with an 8g, 250 msec pulse to APTA (American Public Transit Association) specifications.
- Tests were conducted with aluminum foam in the sliding rail and with steel rod blanks to obtain a baseline for comparison.

The seats were supplied by Technical Metal Specialties (TMS) of Milwaukee, Wisconsin. MGA Research has a good working relationship with TMS and was very familiar with their seats. The seats were fixed position, two-passenger, dual pedestal, floor-mounted design as shown in figure 18. The use of two hybrid III, 50th percentile male ATDs were specified in the APTA standard mentioned above. It was also decided that the combined mass of these two dummies would present fairly stringent test conditions on the equipment being tested.



FIGURE 18: Test set-up with two male ATDs and the front row seats mounted to the sliding rails.

4.2.1 Test Results and Analysis

The 8g pulse shown in figure 19 was applied to the sled to simulate a crash condition that approximates the deceleration of the first coach car behind the locomotive in an in-line train-to-train collision with a closing speed of 70 mph (14). The resultant HIC values, chest deceleration and femur loadings obtained from each of the ATDs (Anthropomorphic Test Dummies) during the course of the test were used to compare the effectiveness of the aluminum foam against the baseline. The Abbreviated Injury Scale (AIS) shown below in table 6, published by the American Association of Automotive Medicine, is used to interpret the test data relative to potential passenger injury. A maximum axial loading of the femur specified by the FAA as 2250 pounds-force is used.

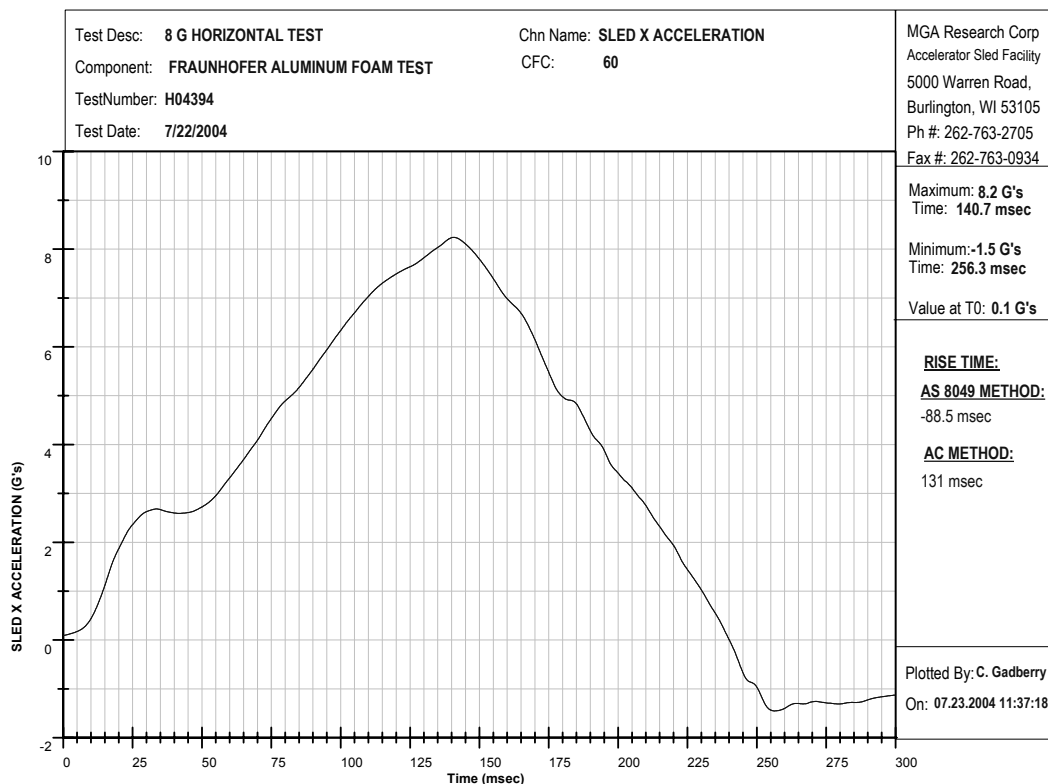


FIGURE 19: The 8g pulse applied over 250 msec used to accelerate the test sled.

| AIS Code | HIC | Head Injury | Chest Deceleration | Chest Injury |
|----------|-----------|--|--------------------|--|
| 1 | 135-519 | Headache or dizziness | 17-37 G's | Single rib fracture |
| 2 | 520-899 | Unconscious less than 1 hour; linear fracture | 38-54 G's | 2 to 3 rib fractures; sternum fracture |
| 3 | 900-1254 | Unconscious 1 to 6 hours; depressed fracture | 55-68 G's | 4 or more rib fractures; 2 to 3 rib fractures with hemothorax or pneumo-thorax |
| 4 | 1255-1574 | Unconscious 6 to 24 hours; open fracture | 69-79 G's | greater than 4 rib fractures with hemo-thorax or pneumo- thorax; flail chest |
| 5 | 1575-1859 | Unconscious more than 24 hours; large hematoma | 80-90 G's | Aorta laceration (partial transection) |
| 6 | >1860 | Non-survivable | >90 G's | Non-survivable |

TABLE 6: AIS code for HIC and chest deceleration.

Data collected from the ATDs and the sled can be seen in tables 7 and 8. All of the values for both test conditions were well below the specified acceptable levels mentioned above. The most noticeable effect demonstrated by the aluminum foam-filled sliding rail is the significant reduction in the HIC value. This was consistent in both ATDs. A comparison of the charted data for the complete simulated event exhibits a lower deceleration over a longer time period for the aluminum foam test and higher, more abrupt decelerations for the baseline test. This would help to explain the 80% reduction in the HIC value. Femur loading and chest deceleration, however, don't seem to be changed to any significant degree. In fact, the involvement of the aluminum foam may have increased these numbers slightly.

| Test Conditions | Baseline - Sled Test Without Aluminum Foam | | Sled Test With Aluminum Foam | |
|------------------------------|---|--------|------------------------------|--------|
| Subject ATD | ATD #1 | ATD #2 | ATD #1 | ATD #2 |
| Head x-direction Max. (g's) | 105.3 | 125.7 | 56.7 | 40.5 |
| Head y-direction Max. (g's) | 13.1 | 8.4 | 7.6 | 4.2 |
| Head z-direction Max. (g's) | 15.4 | 14.9 | 15.1 | 7.6 |
| Head Resultant (HIC) | 234.5 | 354.1 | 42.6 | 72.4 |
| Chest x-direction Max. (g's) | 23.5 | n.a. | 25.3 | n.a. |
| Chest y-direction Max. (g's) | 1.9 | 3.5 | 1.2 | 2.7 |
| Chest z-direction Max. (g's) | 13.8 | 14.1 | 21.1 | 15.6 |
| Chest Resultant (g's) | 23.6 | 22.9 | 32.9 | 25.2 |
| Right Femur (lbs) | 1245 | 1173 | 861 | 1230 |
| Left Femur (lbs) | 1339 | 1208 | 1035 | 1487 |

TABLE 7: ATD test results with and without aluminum foam in sliding rail

| Test Conditions | Baseline - Sled Test Without Aluminum Foam | Sled Test With Aluminum Foam |
|--|---|---------------------------------|
| Sled Acceleration Max. (g's) | 8.2 | 8.2 |
| Sled Velocity Max. (mph) | 22.8 | 22.9 |
| Front Bench Right Resultant Acceleration(g's) | 19.8 | 39 |
| Front Bench Left Resultant Acceleration (g's) | 45.4 | 34 |

TABLE 8: Sled conditions during test.

Matching the sequence of events in the high-speed videos taken during testing to the ATD real-time data for head, chest and femur some differences between baseline and foam loaded tests were noticed. A synopsis of timeline events in table 9 helps to represent some of these differences. It is obviously more evident with the charts in-hand and the high-speed videos. The following is apparent:

- In the aluminum foam case, the rail movement delays loading of the ATD femurs by about 15 msec. The femur loading is at maximum when the head begins to go through deceleration.
- In the baseline case, the femurs are substantially unloaded before the head begins pushing on the seat back causing the head to perform most of the deflection of the seat after 180 msec.
- Also in the baseline case, after the initial abrupt loading of the femur and then the head, they unload and don't see any significant reloading.
- In contrast, the head and femurs reload again in the aluminum foam event to values that are about one-third the initial loadings, but for time spans about twice the original.

In both cases, the loading applied first by the knees tends to exert a largely horizontal force on the seat pedestals and mountings. A small moment force exists at these points. The moment force becomes much larger as the head impacts the top of the seat back. The extent of this rotational force was not anticipated and is speculated influenced the continued forward movement of the foam-filled sliding rail. The effect of this force can be seen in figure 20.

Some variation is noted in the test data obtained from the two ATDs. This is due to small differences in seat construction, seat mounting, and the manner in which the dummies strike the back of the seat. A systematic difference between the seating arrangements of ATDs 1 and 2 may have been introduced because of the need to mount the front row seats on the sliding rail. Typically, the seats are mounted flush with the floor and the feet of the ATD are placed flat on the floor of the sled. The sliding rail caused the seats to be raised several inches off of the sled floor. So that the ATDs feet were properly positioned a foot rest was provided (figure 18). On reviewing the high speed films of the test, we observed that the feet of the dummies cannot always remain in the appropriate positioning after impact. This changes the angle of impact of the knees on the back of the seat and subsequent differences in head deceleration.

| Timeline | Baseline - Sled Test Without Aluminum Foam | Sled Test With Aluminum Foam |
|-----------|--|---|
| 145 msec. | ATDs knees contact the seat back. Femurs begin loading. Seat back is being pushed away by leg engagement. Face touches cushion on seat back. | ATDs knees contact the seat back. The shear pin in the sliding rail breaks and the rail begins to move. |
| 150 msec. | | Face touches cushion on seat back. |
| 158 msec. | Femur load is maximum | |
| 160 msec. | Femur begins to unload. Face begins to push into the top of the seat | Femur begins to load. The rail has moved 2 inches. |
| 170 msec. | | Rail stops moving after more 1 inch. Femur begins to unload. Head begins deceleration. |
| 180 msec. | Head deceleration begins. | |

TABLE 9: Timeline comparison of ATD test data for two test conditions.



FIGURE 20: Deformation of seat mounting caused by ATD impact on seat back.

5. CONCLUSIONS

The goal of the project was to identify, investigate and demonstrate specific applications for aluminum foam in high speed rail equipment. Four application areas were explored through analytical studies, redesign and sub-scale testing of components:

- Lightweight aluminum foam sandwich (AFS) panels for flooring, partitions and electrical panel doors.
- Primary impact energy absorption in sliding sills or crushable zones at the end of passenger cars.
- Secondary head impact energy absorption to reduce head injury.
- Energy absorbing sliding seat rail to reduce injury to passengers on impact with seat backings.

It was found that aluminum foam sandwich panels have outstanding performance in terms of bending stiffness, vibration damping, and relatively good thermal insulation. However, there are two attributes that need development to make it a feasible candidate material—cost and a relatively malleable surface. There is no production capability currently in the U.S.

Pilot plant level manufacturing exists in Germany with a few promising commercial applications. The success of these projects should allow a reduction in cost that is competitive with the incumbent materials now in passenger railcars. The second area mentioned alludes to the aluminum face sheets that are softened in processing. In this condition, the face sheets are prone to dents and scratches. This would not be suitable in high density public transportation. Development of the proper face sheet alloy and post-process heat treatment to achieve the right balance of properties should be achievable in the near future.

It was demonstrated in this study and previous work by Fraunhofer USA that placing aluminum foam within aluminum or steel tubing provides a good component for crash energy dissipation. The combination of the foam inside the tube can absorb more energy than the two materials separately. An interaction between the two materials during uniaxial crushing delays yielding of the tube and the inner core offers resistance to the inward movement of folds. Thus, more deformation energy is required to accomplish crushing. It is believed that this could be optimized with the proper combination of tubing wall thickness, tubing diameter, yield strength and foam density. More study is needed to bring this system to its full potential.

Flat strips of one inch thick aluminum foam in a range of densities between 0.40 and 0.49 grams/cc were used as an impact energy absorbing material in a FMVSS 201U test. This is a Federal Motor Vehicle Safety Standards (FMVSS) test used to assess head impact injury on A-pillars in automobiles. The test results were double the recommended HIC (head injury coefficient) value. The broad impact area of the 2" wide flat aluminum foam strip required too large a load for crush. A crowned geometry would have allowed small initial impact area and perhaps better results. Nonetheless, this did not prove itself to be a promising application.

Dynamic impulse testing was conducted on a steel cylinder and plunger assembly with aluminum foam in the cylinder. A 100 pound block of steel was projected at the plunger so that the contact velocity was 24.6 mph. This provided 1400 ft-lbs of impact energy. The most promising results were obtained in an aluminum foam sample with a density of 0.296 g/cc. With dynamic loadings less than 1200 pounds force, over five inches of crush was attained and 370 ft-lbs of energy dissipated. This would allow a passenger to safely decelerate from 24.6 mph to 17.6 mph without exceeding 20 g's deceleration. A sliding seat rail mechanism was designed to utilize these results.

The sliding seat rail was designed to collapse a core of aluminum foam after a passenger impacted the seat backing in front of them. As in the dynamic impulse, it was intended to safely decelerate a passenger to a lower velocity. The rails were attached to passenger rail car seats on test sleds at MGA Research. Two 50th percentile instrumented dummies provided test data as the sled was given an 8 g impulse. Although the aluminum foam did not crush as much as was expected, good results were obtained. Significant reductions in head injury coefficient (HIC) values were noted with the aluminum foam when compared with the baseline tests. The lack of complete crush of the foam was attributed to uneven movement of the two rails attached to the front row seats. Some design improvements should maintain forward movement of the rails.

The following conclusions are offered:

- An 80 % reduction in HIC value was obtained using aluminum foam in a sliding rail device mounted to the base of commuter seats.
- Further development of the sliding rail design may allow a greater delay in head impact yielding greater benefits at higher speeds.
- An optimized sliding rail system could be built into the floor of the railcar.
- Aluminum Foam Sandwich panels offer attractive multifunctional properties. Still developing production capabilities and high cost (e.g. \$12 per pound) make it difficult to implement in current railcar construction.
- Aluminum foam-filled steel tubing is a good means of crush energy absorption and still appears to be a good candidate to reduce personal injury and equipment damage on passenger railcar accidents. It, however, requires more investigation to optimize usage in this application.

REFERENCES

- 1) G. J. Davies and S. Zhen, "Review of Metallic Foams: Their Production, Properties and Applications," *Journal of Materials Science*, 18, pp.1899-1911 (1983).
- 2) J. Baumeister and H. Schrader, "Method for Manufacturing Foamable Metal Bodies," U.S. Patent No. 5,151,246.
- 3) D. Tyrell, K. Severson-Green, and B. Marquis, "Evaluation of Selected Crashworthiness Strategies for Passenger Trains", pp. 50-58, Transportation Research Record 1489.
- 4) D. Tyrell, K. Severson-Green, and B. Marquis, "Crashworthiness of Passenger Trains", Report #DOT-VNTSC-FRA-97-4, National Technical Information Service, Springfield, VA, Feb., 1998.
- 5) S. Chatterjee and J. F. Carney, "Passenger Train Crashworthiness – Primary Collisions", pp. 1-12, Transportation Research Record, 1531.
- 6) S. Chatterjee and J. F. Carney, "Passenger Train Crashworthiness – Secondary Collisions", pp. 13-19, Transportation Research Record, 1531.
- 7) R. A. Mayville, K. Johnson, R. Stringfellow, and D. Tyrell, "The Development of a Rail Passenger Coach Car Crush Zone", Proceedings of the 2003 IEEE/ASME Joint Rail Conference, April, 2003.
- 8) L. Zheng, "Numerical Simulation of Crush Behavior of Aluminum Sandwich Panels for Train Collisions", MIT ICL Report No. 92, November 2002.
- 9) S. Lapatnikov, C. Krauthauser, J. W. Gillespie, Jr., Ken Kremer, "On the Effectiveness of Aluminum Foam as an Energy Absorber for Rail Car Crush Zones", Analytical Study requested by Fraunhofer USA, January 2004.
- 10) R. Kretz and B. Goetzinger, Proceedings of the International Conference on Cellular Metals and Metal Foaming Technology, June 2001, Ed. Banhart, Ashby, Fleck, MIT Publishing.
- 11) R.D. Peacock, R.W. Bukowski, P.A. Reneke, and J.D. Averill (NIST) and S.H. Markos (Volpe), "Development of a Fire Hazard Assessment Method to Evaluate the Fire Safety of Passenger Trains," Fire and Materials 2001. 7th Int. Conf. and Exp. Proc., San Antonio, TX , pp. 67-78, January 22-24, 2001.
- 12) T. D. Claar, "Bending Stiffness Analysis of Aluminum Foam Sandwich Panels for Potential Weight Savings in Bulkhead Panel Applications," Fraunhofer Internal Report (2002).
- 13) C. VanIngen and J. Manning, "Commuter Rail Seat Testing and Analysis", Report #DOT-VNTSC-FRA-02-10, National Technical Information Services, Springfield, VA, July, 2002.
- 14) D.C. Tyrell, K.J. Severson, B.P. Marquis, "Train Crashworthiness Design for Occupant Survivability", American Society of Mechanical Engineers, AMD-Vol. 210, BED-Vol, 1995.