

## THE DEVELOPMENT OF A RAIL PASSENGER COACH CAR CRUSH ZONE

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### ABSTRACT

This paper presents information on the design of a rail vehicle crush zone for better occupant protection. The overall design requirements and characteristics are described and the configuration for the various structural subsystems is presented. The paper also includes information on full-scale component tests carried out to support the development of the design, particularly for the primary energy absorbers. Comparisons between test and finite element analysis are presented and there is a discussion of how the test results have affected the design.

### INTRODUCTION

In supporting the U.S. Federal Railroad Administration's research program into rail passenger car crashworthiness, the Volpe Center has managed numerous analytical studies, component tests and a series of full-scale passenger car collision tests. Several of the full-scale tests on conventional equipment have now been completed. The next phase of testing will be to carry out full-scale tests of passenger cars equipped with improved crashworthiness features. Most important of these features is an integrated crash energy management system. Such systems, incorporating crush zones in vehicle ends, have been applied to passenger cars around the world (c.f. [1]), and have been shown to be effective in improving the protection of car occupants from injury in a collision.

The objective of the program described here is to develop a detailed design of a coach car crash energy management system that can be applied to a modified existing passenger car and subjected to a full-scale collision test. The system is to include a pushback coupler, an anticlimber, and a primary energy absorption system. Tasks in the program included developing and evaluating strategies for the system, preparing and analyzing a preliminary design, fabricating and testing some of the critical components of the design, and finalizing the design in light of

test and analysis results. The end product will be a detailed design ready to be fabricated and installed on the selected test vehicle.

### SUMMARY OF DESIGN REQUIREMENTS

The overall crush zone design specifications were derived from the need to satisfy several categories of requirements. These include service/operational, strength, energy absorption, fabrication and test requirements. The discussion here focuses on the strength and energy absorption specifications and presents many of the characteristics that were used to develop detailed component designs.

The basic strength and energy absorption requirements for the crash energy management (CEM) system were developed in recognition of current requirements for strength-based designs in the U.S. and with knowledge of the approaches used in other CEM systems throughout the world. Currently, vehicles intended for operation in the U.S. must be designed according to the Code of Federal Regulations (CFR) [2]. Furthermore, the current practice is to design according to the American Public Transportation Association, APTA SS-C&S-034-99 Standard for the Design and Construction of Passenger Railroad Rolling Stock [3]. These latter requirements meet or exceed those in the CFR. The strength-based requirements used in developing the CEM design described here differ in some cases from those in the APTA document as shown in Table 1.

The buff strength requirement for the present design is the same as that currently applied to conventional equipment; this is a conservative approach. The anticlimbing requirements are more severe than those of the CFR or APTA, in part because of a desire to determine the extent to which a higher vertical strength could be achieved. Incidentally, the anticlimbing requirements adopted here are the same as those required for the Acela power car.

**Table 1: Comparison of Some of the Structural Requirements for the CEM Design**

Category/Component	APTA Requirement	Requirement used for this CEM Design
Buff strength	<ul style="list-style-type: none"> <li>▪ A load of at least 125% of the pushback coupler system's peak load applied to the line of draft; no yield.</li> <li>▪ 800,000 lbf applied on the buffer beam over an area not greater than 6 inches x the distance between the outboard webs of the collision posts; no yield.</li> </ul>	<ul style="list-style-type: none"> <li>▪ 800,000 lbf applied to the line of draft; no yield. (Note: the peak design load for the pushback coupler system is 600,000 lbf.)</li> <li>▪ 800,000 lbf applied on the buffer beam over an area not greater than 6 inches x the distance between the outer webs of the collision posts; no yield.</li> </ul>
Anticlimber	<ul style="list-style-type: none"> <li>▪ There must be a structural arrangement that resists a vertical load of 100,000 lbf up or down; no yield</li> </ul>	<ul style="list-style-type: none"> <li>▪ 100,000 lbf, up or down, applied to a ribbed anticlimbing element, before or during crush of the crush zone; no yield of support system</li> <li>▪ 200,000 lbf, up or down, applied to a ribbed anticlimbing element, after complete crush of the crush zone; ultimate strength</li> </ul>
Collision posts	<ul style="list-style-type: none"> <li>▪ 300,000 lbf applied at the top of the underframe or at 18 inches above the top of the underframe; ultimate strength</li> <li>▪ 50,000 lbf applied anywhere along the post above the underframe; no yield</li> </ul>	<ul style="list-style-type: none"> <li>▪ 500,000 lbf applied at the top of the underframe; ultimate strength</li> <li>▪ 200,000 lbf applied 30 inches above the top of the underframe; ultimate strength</li> <li>▪ 50,000 lbf applied anywhere along the post above the underframe; no yield</li> </ul>

The required collision post base shear strength is substantially greater than that currently required by the CFR and APTA for coach cars (vs. cab cars.) This was felt to be important for the crush zone to function as intended even if the vehicle is loaded above the underframe. If the collision post shear strength were 300,000 lbf/post (600,000 lbf total), then it would be possible to fail the collision posts before the crush zone were activated; the pushback load and, indeed, the average crush force for the crush zone is about 800,000 lbf. All other components have strength requirements that are the same as those required by the CFR or APTA standard for coach cars.

The CEM system includes three key elements, consistent with the prevailing philosophy of crash energy management passive protection. These are: a pushback coupler and an interlocking anticlimber to ensure that the underframes of interacting vehicles transfer load through their primary load-bearing structure; and a zone at the end of the car designed to crush and absorb energy in a controlled manner without endangering the occupant volume. Table 2 lists some of the characteristics of the crush zone elements used to develop the detailed component designs.

The pushback coupler activation load was selected to minimize the chances of pushback for minor impacts and to ensure that the shear system would have adequate fatigue strength for normal operation. Although anticlimbing systems are sometimes used to also absorb energy, a strength-only design was chosen to avoid the complications of designing to achieve

sufficient vertical strength. Most of the energy in the system is absorbed by elements that are within the underframe; a relatively small amount of energy is absorbed in the roof structure.

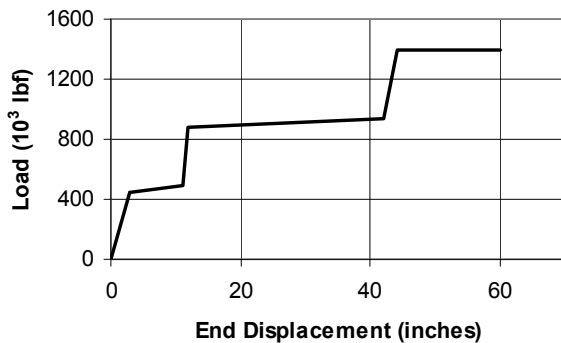
The requirement for total design energy absorption is  $2.5 \times 10^6$  ft-lbf (3.4 MJ) in about three feet (0.9 m) of crush. This can be compared to existing systems and requirements. The current energy absorption requirement for systems operated in the U.K. [4] is  $0.75 \times 10^6$  ft-lbf (1 MJ). On the other hand, the Code of Federal Regulations [2] requires that the lead end of the first trailing coach car for Tier 2 equipment absorb at least  $3.7 \times 10^6$  ft-lbf (5 MJ) of energy; Tier 2 refers to equipment operated at speeds greater than 125 mph but less than 150 mph (200-240 km/hr.) There are no energy absorption requirements for Tier 1 equipment, under which the subject coach car falls.

The crush zone must also possess other characteristics besides the amount of energy absorption. The load should increase as crush proceeds so crush is shared between coupled ends. In particular, the resistance to crush must increase substantially — about 50% — after the deformation in the crushable structure is exhausted, at about 40 inches (1 m), so that the occupant volume is protected and other vehicle end crush zones absorb the remainder of the overall collision energy. These characteristics are depicted schematically in Figure 1.

**Table 2: Some of the Characteristics of the Coach Car Crush Zone Design**

Crush Zone Element	Pushback/Activation Strength (lbf)	Energy Absorption (10 <sup>6</sup> ft-lbf) [MJ]	Stroke (inches)
Pushback coupler	450,000	0.3 (0.41)	8
Anticlimber	Not applicable	0.0	0
Primary energy absorbers (at underframe level)	900,000	2.0 (2.70)	30
Roof structure absorbers	120,000	0.2 (0.27)	30
Total:		2.5 (3.38)	38

### Target Vehicle End Crush Response



**Figure 1. The Target Vehicle End Crush Zone Response**

One of the challenges of this project is the need to incorporate the crush zone into existing older vehicles: Budd Pioneer cars fabricated in the 1950's. These cars were designed to a buff strength of 800,000 lbf (3.56 MN), but they have a limited number of load paths and attachment points for connecting the crush zone to the vehicle. In addition, these cars have also been used in other full-scale crash tests and have experienced substantial end damage. The final design will include the details by which the existing vehicles are to be modified to accept the crush zone and to provide the reinforcement needed to achieve a load-crush response close to that depicted in Figure 1.

## CRUSH ZONE DESIGN

### Concept

Figure 2 illustrates the manner in which the majority of the crush motion is controlled in the crush zone concept; it is referred to as a sliding sill crush zone. The 'sliding' part of the crush zone includes the end frame (not all of which is shown in

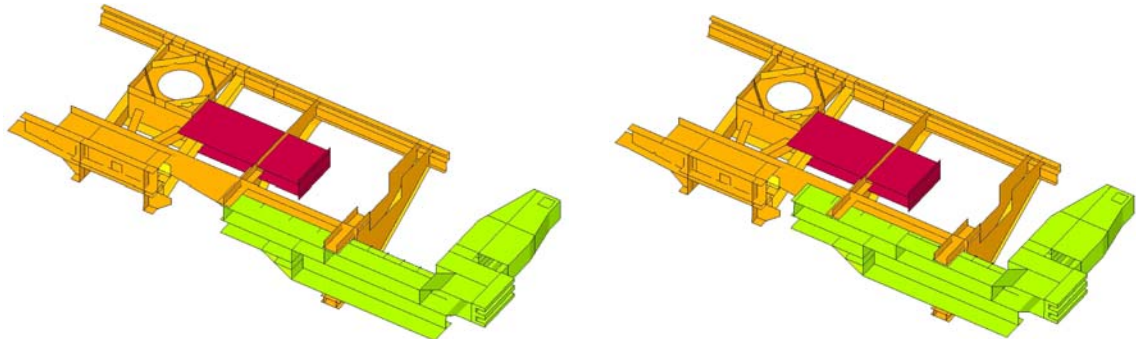
Figure 2) and the center sliding sill. The fixed part is integral with the underframe. When the load at the outer surface of the buffer beam reaches a certain value, a set of bolts shear and the sliding motion is allowed to proceed. The sliding motion is accompanied by the crush of energy absorbers. Figures 3 and 4 illustrate the overall crush zone geometry and the manner in which the primary energy absorbers crush. Similar sliding mechanisms are used for both the pushback coupler and the roof structure.

There are definite advantages to the sliding sill approach. The sliding sill/fixed sill connection carries the majority of the longitudinal load prior to activation of the shear bolts, so that there is neither steady nor cyclic loading on the primary energy absorbers during normal operation. The sliding sill/fixed sill interface carries vertical, lateral and offset longitudinal loads and the bending moments associated with these during crush. In other words, there is no need for plastically deforming elements to carry these loads. The difficulty is to develop a robust design for the various shear bolt systems, which must possess both reliable minimum and maximum strengths and be resistant to failure by fatigue.

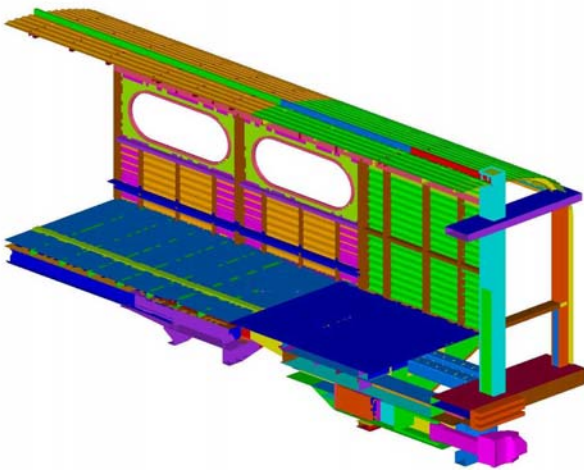
### Pushback Coupler

The pushback coupler consists of a conventional U.S. (tightlock) coupler and draft gear. The buff (compression) lug is connected to the sliding sill element through a set of eight bolts whose total design shear load is  $450 \times 10^3$  lbf (2000 kN). A total of 8 inches (200 mm) of pushback motion occurs, after the shear bolts fail, during which a block of aluminum honeycomb is crushed. The energy absorbed by this pushback motion is approximately  $0.3 \times 10^6$  ft-lbf (0.4 MJ).

The pushback coupler system includes a coupler carrier whose ultimate longitudinal strength is relatively low. The need for this arises because of the interference between the coupler head and the coupler carrier during the coupler pushback motion. It is important to ensure that the combined load from crush of the honeycomb element and the coupler carrier remain below the sliding sill-to-fixed sill connection strength until the



**Figure 2: The Sliding Sill Component of the Crush Zone Concept (One-Half Model Symmetric about the Centerline of the Underframe)**



**Figure 3. A Finite Element Model of the Overall Coach Car Crush Zone Design (Half Model)**

anticlimbers of coupled vehicles interlock. Use of a ribbed anticlimber rather than the coupler carrier as the ‘anticlimbing arrangement’ for downward acting loads facilitates the design of a carrier with relatively low longitudinal strength.

**Interlocking Anticlimber**

The approach taken to meet the anticlimbing requirements is to use a ribbed anticlimber element mounted on the end of the underframe over the coupler. No energy absorption is associated with the anticlimber element. The vertical strength of the ribs and their attachment to the car as well as the supporting structure is:

- a)  $100 \times 10^3$  lbf (445 kN) for crush values up to the design crush of 38 inches (0.97 m).

- b)  $200 \times 10^3$  lbf (890 kN) for a crush value of 38 inches (0.97 m).

The sliding and fixed sill structures are designed to support the vertical load without yielding.

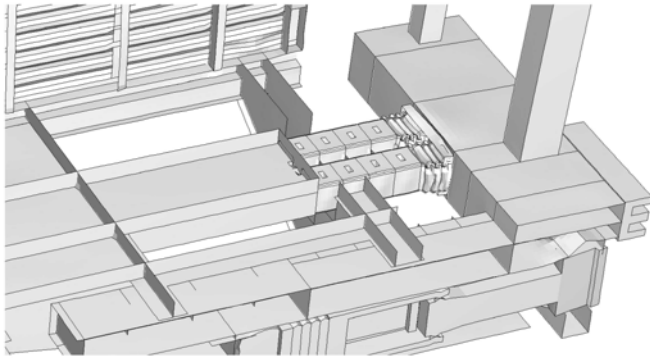
Positioning the anticlimber element in line with the vehicle centerline facilitates meeting the requirement for combined longitudinal and vertical loads. However, there is still an issue of how to incorporate a longitudinally flexible walkway support, normally in the position of this anticlimber, for permitting passage between cars. The engineering of such a system appears feasible but has not been addressed in detail in this program. This issue was also addressed in part in [5].

**Sliding Sill/Fixed Sill Connection**

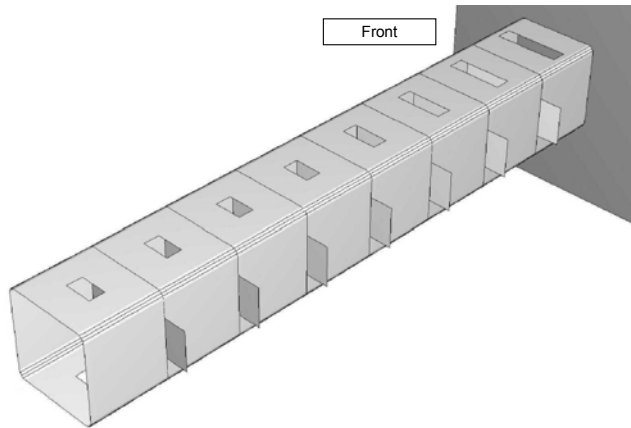
The sliding sill element is connected to the underframe of the vehicle through a set of 12 bolts that are loaded in shear. The longitudinal failure load of this bolted system is approximately  $1000 \times 10^3$  lbf (4,500 kN.) Once the bolts have failed, offset loads are carried at steel bearing surfaces within the sliding connection. The sliding sill also contains the pushback coupler and associated hardware as described in the section above.

**Primary Energy Absorbers**

Each of the two primary energy absorbers consists of two tubes of square cross section. Figure 5 illustrates one of these absorbers. The material of construction is currently A572-50 steel. The total length of the 0.25 inch (6.4 mm) thick tubes is 40 inches (1.0 m). Lateral, internal diaphragms and cutouts are included to achieve the desired crush response for a variety of collision speeds.



**Figure 4. Finite Element Prediction of the Deformation of the Crush Zone (the floor elements have been removed for clarity.)**



**Figure 5. An Illustration of One-Half of One of the Primary Energy Absorbers**

### **Roof Structure**

The crushable roof structure consists of two sliding elements, one on each side. Each element consists of a sliding part, which is attached to the back of the antitelescoping plate above the corner post, and a fixed part, which is built into the body of the car. The inboard end of the sliding element is framed into the side to transfer load to the roof rail of the car. The fixed and sliding parts of the element are attached by shear bolts. When the shear bolts fail, the sliding part moves back into the fixed part, crushing aluminum honeycomb pieces as it moves back. The energy absorption in this element is relatively low:  $0.1 \times 10^6$  ft-lbf (0.14 MJ) per side. This is equivalent to an average crush force of  $40 \times 10^3$  lbf (180 kN) per side for the 30 inches (0.76 m) of crush.

### **COMPONENT TESTING**

The development of the crush zone design has included testing of three of the key structural components: the pushback coupler, the primary energy absorber and the sliding sill-to-fixed sill connection. Each component was full scale. Only the details of the primary energy absorber component testing will be described here. Tests on the pushback coupler revealed the need to provide better support for the honeycomb block, which satisfied the performance requirements, but kinked during deformation. The sliding sill-to-fixed sill test article appeared to fail at a load lower than the design strength and exhibited failure in some of the internal components. A revision of this design is in preparation.

The components were tested in a drop tower facility by Simula Technologies, Phoenix, AZ; Figure 6 shows an illustration of the tower. The falling mass was 11,000 lbm (5,000 kg) and load was measured at the base of each test article using a set of four load cells. Instrumentation included high speed cameras, accelerometers and strain gages.

The test conditions for the primary energy absorber test were as follows. The drop height was 75 ft (23 m), which provided an impact speed of 47 mph (75 km/hr) and an impact energy of  $0.8 \times 10^6$  ft-lbf (1.1 MJ); this is 80% of the design energy absorption.

Figures 7 and 8 show comparisons between finite element predictions and test results. Figure 7 is a comparison of the deformation and Figure 8 shows a comparison between the predicted and measured crush responses. The predicted total crush was 25 inches (0.64 m) and the observed total crush was 21 inches (0.53 m). Figure 7 shows that the test article deformed at its base, particularly on one side, in contrast to the predictions. This difference has been attributed to a different attachment method used in the test in comparison to that simulated in the analysis. Despite this difference, the finite element analysis predicted the crush response quite well and the primary energy absorber successfully fulfilled its performance requirements.

Nevertheless, the results of the test indicated that some changes should be made to the primary energy absorber to improve the probability that it will perform as intended. Subsequent finite element calculations with a modified trigger-hole pattern show that the new design is much more resistant to imperfections than the one tested.

### **SUMMARY**

This paper has provided a description of the current status of a project to develop a detailed design of a crash energy management system for a rail vehicle passenger coach car. The design is now being finalized. When completed, the system will be fabricated and installed onto the end of an existing car for planned full-scale testing in 2003.

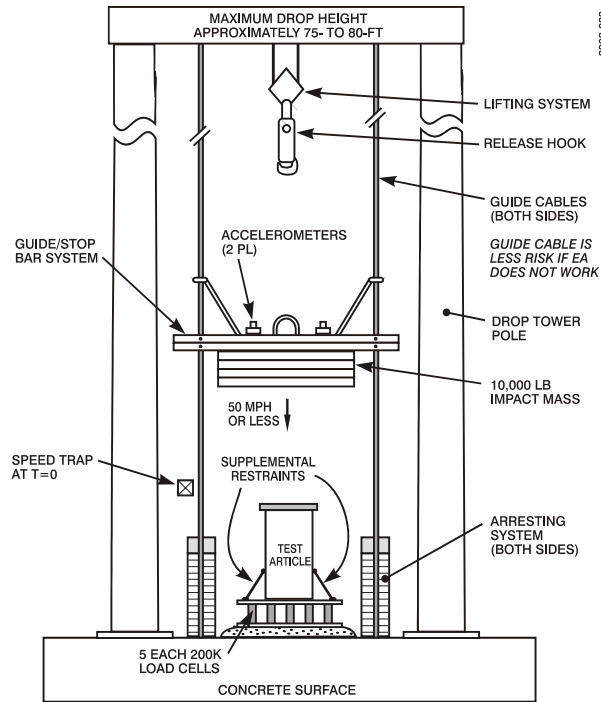


Figure 6. An Illustration of the Drop Tower Facility Used to Impact the Test Articles (Note: Some of the parameters in this figure were modified for the test.)

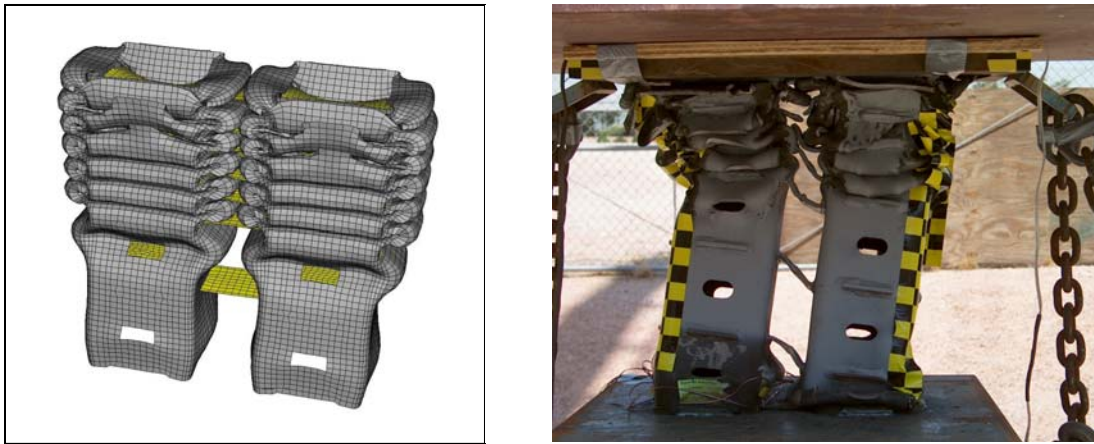
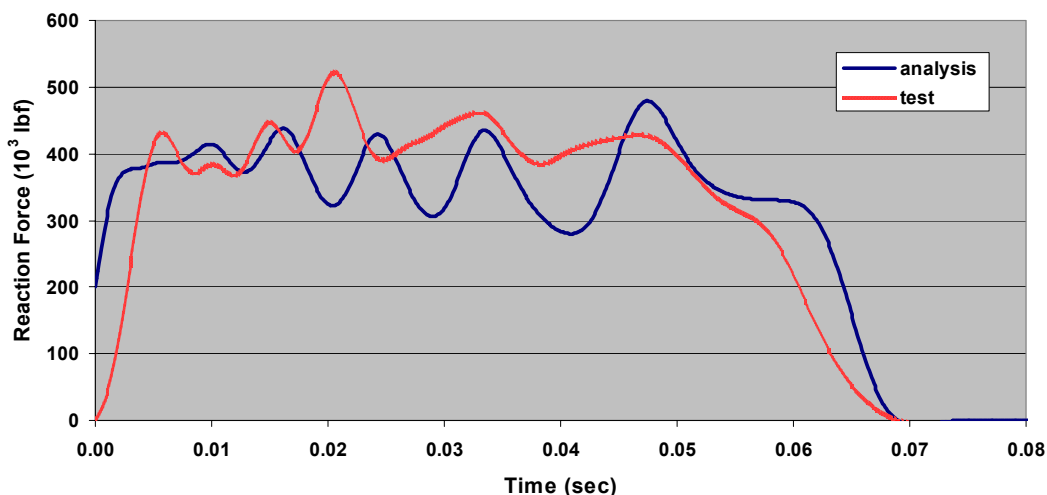


Figure 7. A Comparison of the Deformation Predicted by Finite Element Analysis and the Observed Deformation in the Drop Tower Test of the Primary Energy Absorber.

**Primary Energy Absorber Test Article Crush  
Reaction Force -- Comparison of Test and Analysis  
Filtered/SAE 60**



**Figure 8. A Comparison of the Predicted and Measured Load vs. Time Response of the Primary Energy Absorber in the Drop Tower Test.**

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