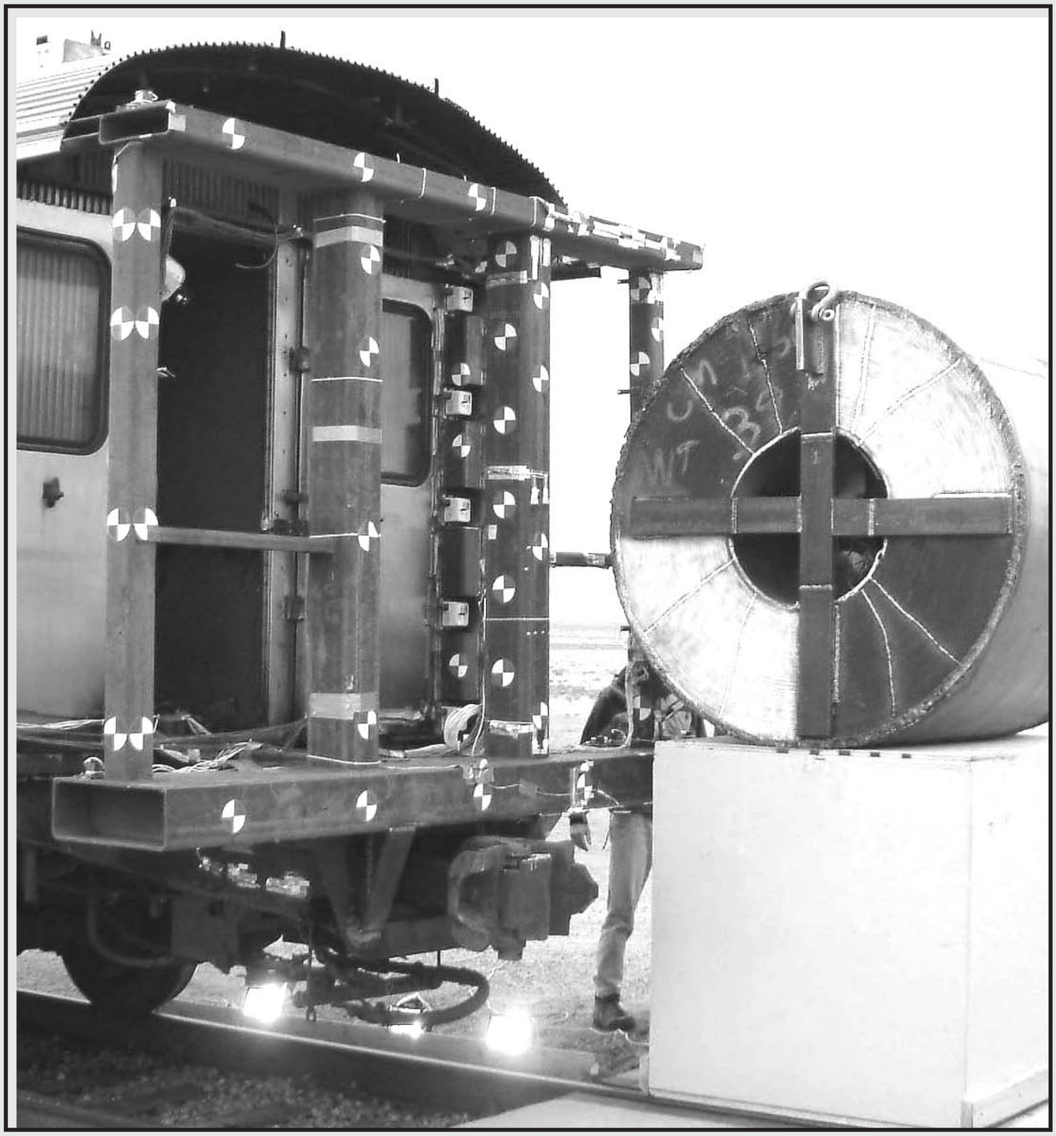
U.S. Department of Transportation

Federal Railroad Administration

Development of Conventional Cab Car End Structure Designs For Full Scale Testing

Rail Passenger Equipment Impact Tests

Office of Research
and Development
Washington, DC 20590



DOT/FRA/ORD 06/20

Final Report
December 2006

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (LEAVE BLANK)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 2006	Final Report

4. TITLE AND SUBTITLE
Development of Conventional Passenger Cab Car End Structure Designs for Full Scale Testing

5. FUNDING NUMBERS
CB035/RR28

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-FRA-07-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
1120 Vermont Avenue NW – Mail Stop 20
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-06/20

11. SUPPLEMENTARY NOTES
* under contract to:
U. S. Department of Transportation
John A. Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142-1093

12A. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the U.S. public through the National Technical Information Service, Springfield VA 22161
This document is also available on the FRA web site at www.fra.dot.gov.

13. ABSTRACT (MAXIMUM 200 WORDS)

The Volpe Center is supporting the Federal Railroad Administration's full-scale testing program to understand and improve rail vehicle crashworthiness. The objective of one of the sets of tests in this program is determining the behavior of cab car end structures in simulated grade crossing collisions. The project described in this report supported these tests by developing ready-to-fabricate designs for the ends of passenger cars to represent a State-of-the-Art (SOA) and a 1990s cab car design, both of which are primarily strength-based designs. The report includes a description of prior research on cab car crashworthiness, the requirements for the designs, the designs themselves and the analyses used to demonstrate that the designs meet the requirements. Also included is a comparison between strains measured from quasi-static load tests and from finite element analyses. The results of the project show that the SOA end frame provides substantially greater strength and energy absorption capability than the 1990s design with little penalty in weight.

14. SUBJECT TERMS
Transportation, safety, crashworthiness, passenger rail vehicles, cab car end structure

15. NUMBER OF PAGES
92

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

Preface

This report describes the development and evaluation of two cab car end frame designs that were generated to investigate the implications of new industry standards and Federal regulations on crashworthiness and operations. Prior cab car crashworthiness research and existing and planned cab car designs for North American operation were reviewed. The two designs were then generated. Both hand and finite element analysis, including analysis for large deformations, were conducted to demonstrate that the designs meet the requirements. The end frames were then fabricated, integrated into existing cars, and instrumented and loaded to validate the design analyses. Finally, the end frames were used in full-scale grade crossing collision tests as part of a separate task.

This work was performed as part of the Equipment Safety Research Program sponsored by the Office of Research and Development of the Federal Railroad Administration. The authors would like to thank Dr. Tom Tsai, Program Manager, and Claire Orth, Division Chief, Equipment and Operating Practices Research Division, Office of Research and Development, Federal Railroad Administration, for their support. The authors would also like to acknowledge the contributions of David Tyrell, Project Manager of the Volpe Center, for contributions in design and analysis, Patricia Llana, TIAX, who developed the finite element models, and Ebenezer Railcar Services, who fabricated the end frames. In addition the authors would like to acknowledge the contributions to design work from Kent Johnson and Scott Landrum from Premiere Engineering Inc.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

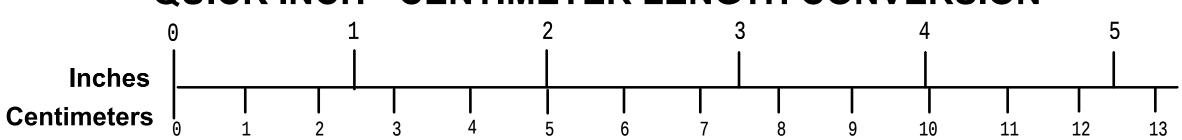
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286 **Updated 6/17/98**

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Executive Summary

This report describes the results of a program to design passenger rail car end frames for testing the differences in crashworthiness performance for cab cars that meet early to mid 1990s structural standards and cab cars designed to the current American Public Transportation Association (APTA) and Federal Railroad Administration (FRA) structural requirements, known as State-of-the-Art (SOA) design. The program is part of a larger one being conducted to investigate how crashworthiness of rail vehicles in various configurations and collision scenarios can be improved. The end frames discussed here were used to evaluate the increase in cab car protection for a particular grade crossing collision scenario. The development of the designs relied on a review of industry practice over the last few decades and on prior research in the area of cab car crashworthiness. A detailed set of design requirements was developed that included the applicable structural requirements, the need to meet operability requirements and the need to adapt to existing test cars. Hand and beam element finite element analyses were used to develop the 1990s design, while detailed finite element analyses, including large deformation calculations, were carried out to develop the SOA design. The end frames were fabricated from A710 steel and shipped to the Transportation Test Center (TTC) in Pueblo, Colorado, where they were attached to existing Budd Pioneer cars. Quasi-static loading tests were conducted on the frames after instrumentation by strain gages. Finally, the end frames were used in full-scale grade crossing collision tests in a separate program.

The results of this project demonstrate that the new APTA requirements can be met with designs that are very similar to those needed to satisfy the requirements used in the 1990s. For example, there is only a 250 lbm (113 kg) difference between the 1990s and SOA end frame designs. In addition, the analyses and the full-scale tests demonstrate that stronger end frames provide a significant improvement in crashworthiness provided care is taken to assure that the collision and corner posts are designed to deform in a controlled and predictable manner under significant crush distances. For the purposed of this program 'severe deformation' of a post is taken as one times the depth of the post.

A number of important issues were raised in the course of this program. The SOA design relied on the use of the side sill to support the back of the end beam at the base of the corner post. This is possible because of the general acceptance by industry to eliminate the step well at the operator's corner. If a step well were present so that such a structural detail could not be used, the weight penalty would be much greater. The ability to achieve a prescribed amount of deformation in the end frame posts has also been raised as an important issue. The SOA design was developed with the requirement that the post deform an amount equal to one times its depth without cracking. This requirement was originally part of an accepted standard released by APTA in 1999, but eventually it was changed to a recommended practice. The recommended practice addresses deformability in an indirect manner by requiring very strong connections between the posts and their connections.

The very successful performance of the SOA design in the full-scale test relative to the 1990s end frame demonstrates the potential for crashworthiness improvement.

1. Introduction

The Volpe National Transportation Systems Center (Volpe Center) is supporting the FRA's analysis and full-scale testing program to understand and improve rail vehicle crashworthiness. The objectives of these tests are to establish the crashworthiness of vehicles built to current standards and to assess the improvements provided by new requirements and new technologies. Several tests have already been conducted and more are planned, as shown in Table 1. These include crash tests in which a single car, and two coupled cars collide with a rigid surface, and a test in which a moving, cab car-led train collides with a standing locomotive-led train. The tests characterize vehicle trajectories, deformation modes, secondary impact environment and energy absorption. The tests for equipment essentially built to today's standards are complete and the tests with crash energy management systems began at the end of 2003. Another set of completed tests focused on the behavior of cab car end structures in simulated grade crossing collisions. The project described in this report supported these tests by developing ready-to-fabricate designs for the ends of passenger cars to represent an SOA and a 1990s cab car design, both of which are primarily strength-based designs.

Table 1. Full-Scale Passenger Equipment Tests to Assess Improvements in Crashworthiness

Test Conditions	Conventional Design Equipment	Improved Crashworthiness Design Equipment
Single car collision into a rigid, flat barrier	November 16, 1999	December 3, 2003
Two coupled car collision with a rigid, flat barrier	April 4, 2000	February 26, 2004
Cab car led train collision with a locomotive led train	January 31, 2002	March 2006
Single car collision with a steel coil	June 4, 2002	June 7, 2002

Cab cars are passenger-carrying rail vehicles located at the very end of the train. The operator is positioned at the end of the cab car where he or she has good visibility of the track. In the United States, the cab car is designed to also be used as a passenger car within the train. This requires that the cab car have the same layout as a pure passenger car. This results in the operator being located immediately adjacent to the flat end wall of the vehicle. Figure 1 shows an example of a cab car operated in the U.S. The end wall does include two collision posts, one on each side of a doorway and a post at each corner. Nevertheless, the proximity of the operator to the very end of the car puts him or her at greater risk in the event of a collision with an object or another train.

Passenger car ends have been required to possess collision posts of substantial strength since the 1950s. The need for such structures was highlighted by a serious collision in which override and penetration of the passenger compartment occurred [1]. Around the 1980s it became standard practice – but not a Federal requirement – to also require strong corner posts at the end of passenger and cab cars.

Figure 1. An Example of a Cab Car in which the Operator is Positioned Immediately Adjacent to the Vehicle End

Since the mid 1990s there has been renewed research into determining how increasing the strength of passenger end frames would improve rail vehicle crashworthiness in a practical manner. This work has in part been motivated by some serious accidents in which there were fatalities because of the crush and intrusion into the ends of the cars. For example, a collision between a cab car-led train and a steel coil on a trailer truck in Portage, Indiana in 1998 resulted in penetration of the coil into the car and three fatalities [2]. (The full-scale grade crossing tests were modeled after this accident.) There was also a collision between a locomotive-led train and a cab car-led train at a switch in Secaucus, New Jersey in 1996 that crushed the corner of the cab car and also resulted in three fatalities [3]. The research that has been conducted includes design layout development, finite element analysis and component testing [4-6]. The results have demonstrated that a substantial improvement in crashworthiness is feasible.

In the past few years, this research together with industry group discussions on the development of new standards and recommendations have led to the adoption of higher strength requirements for both the collision and corner posts for both passenger and cab cars. These new requirements are given in the APTA SS-C&S-034-99, Standard for the Design and Construction of Passenger Railroad Rolling Stock, and the Code of Federal Regulations, Title 49, Part 238 [7,8].

Since the requirements are relatively new, there is a desire to better quantify the improvement they provide in collisions. The full-scale grade crossing tests described earlier are one method that was pursued to demonstrate this.

The objective of the project described in this report was to develop two cab car end frame designs: the 1990s design and the SOA design. The intent of the 1990s design was to represent structural requirements in practice for cab car end frames in the early to mid 1990s, prior to the passage of the new 49 CFR Part 238 or the adoption of APTA SS-C&S-034-99. The SOA design is meant to represent the structural requirements for vehicles that are and will be designed to the recent APTA and Federal requirements.

The approach taken in the project was to review existing and planned designs, define design requirements, develop and fabricate modification designs, quasi-statically test the two designs, and compare the test results between the conventional and modified designs. Information on existing and planned designs was obtained from industry sources, particularly from members of the APTA Passenger Rail Equipment Safety Standards Construction/Structural (PRESS-C&S) committee. The designs were developed after generating concepts for the various structural elements. Each element or system of elements was then analyzed using simple strength of material hand calculations or finite element analysis. Industry participants provided review of these designs. The detailed engineering was then carried out and a company specializing in rail vehicle structures fabricated the end frames. The finite element models were also used to generate values of strain corresponding to the quasi-static test loads, and these were compared to the test data. Information on the full-scale grade crossing collision tests may be found in references [9,10].

2. Prior Research Summary

Several studies related to the strengthening of cab car end structures have been conducted previously under the FRA/Volpe Center crashworthiness program. The projects demonstrated that increased strength provides a benefit in occupant protection in grade crossing and offset collisions. The work has also explored the feasibility of increasing strength practically for various approaches, including the use of the side sill to support the corner loads. This section provides a summary review of these studies, particularly as they apply to the issue of end frame strengthening.

2.1. Locomotive Crashworthiness Research

Cab car crashworthiness was first investigated in 1995 as part of a larger project on locomotive crashworthiness [11]. The objective was to determine the crashworthiness of cab cars in centered and offset collisions and to investigate the potential benefit of increasing component strength. In particular, collision dynamics analyses were conducted to simulate the impact between the underframe of a single locomotive and a cab car-led train for two cab car corner post strengths: one in which the ultimate strength at the underframe was 150×10^3 lbf (667 kN) ─ the structural practice at the time ─ and one in which the strength was 600×10^3 lbf (2,669 kN). The deformation response for the 150×10^3 lbf (667 kN) strength case was determined from approximate, nonlinear finite element analysis. This response was then scaled by a factor of four for the 600×10^3 lbf (2,669 kN) corner post strength case. There was no expectation at the time that a 600×10^3 lbf (2,669 kN) strength could be practically achieved; it was selected to determine the effect of a large increase in strength on crush. No work was conducted in that study on exactly how such a high strength could be achieved or on the implications on the support structure, weight and cost.

The results of the analyses indicated that the amount of corner post crush could be reduced from over 6 ft. to less than 2 ft. at a closing speed of 15 mph (24 km/h) for impact with a locomotive. The effects of fracture were not treated in the analysis predictions, but the importance of a ductility measure was considered.

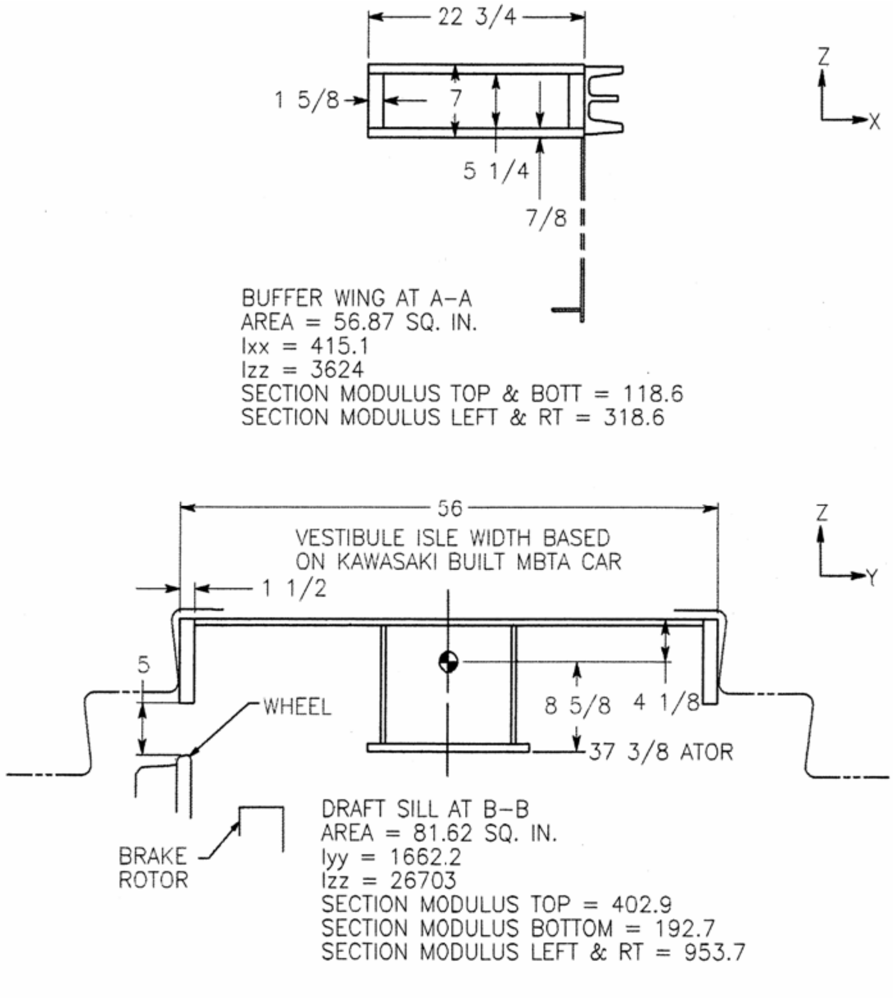
2.2. Evaluation of Cab Car Crashworthiness Design Modifications

Some additional work on corner strength was conducted subsequent to the locomotive crashworthiness study [11]. This work involved approximate calculations on the increase in section size that would be needed to achieve an end beam strength, for a load applied at the base of the corner post, of 300×10^3 lbf (1334 kN). Side sill support was not included. The additional weight was estimated to be only 150 lbm (68 kg), but it is now recognized that the analysis did not properly account for the structure needed to resist the loads within, for example, the draft sill. Nevertheless, the collision analyses demonstrated the benefits on crashworthiness that increased corner strength could provide.

2.3. Approaches to Preventing Override and Lateral Buckling in Passenger Trains

Some information applicable to the strength of corner structures in passenger cars may be found in a study completed in 1999 on methods to prevent override and lateral buckling. One of the approaches investigated in that study was a push back and locking coupler, which, together with a stronger corner structure, was intended to provide moment resistance against the yaw motion associated with lateral buckling. In particular, a structural concept was developed to achieve corner strengths of 300×10^3 and 600×10^3 lbf (1,334 and 2,669 kN), with and without step wells; these strengths refer to the ultimate strength for a longitudinal load applied at the end of the end beam, at which the base of the corner post would be located. The analysis utilized beam element finite elements and was considerable more detailed than the analysis conducted in [12].

Figure 2 shows the concept structure developed for the case in which the end beam must carry a load of 300×10^3 lbf (1,334 kN) without the benefit of a side sill load path. There are, of course, many other ways in which such a strength could be achieved. (Note: an existing Massachusetts Bay Transportation Authority (MBTA) car was used for the platform on which the analysis was based.) Table 2 lists the estimated increase in weight associated with two levels of increased corner strength for the cases in which the side sill can and cannot be used as a load path. These weight estimates agree closely with the estimates of the present study.



Source: [12]

Figure 2. Schematic of the Cab Car End Structure Required to Support a 300x10^3 lbf Corner Load without a Step Well

Table 2. Estimated Weight Increases for Higher Corner Post Support Structure Strengths

	WEIGHT INCREASE FOR CORNER STRENGTH*	
Configuration	**300x10^3 lbf (1334 kN)**	**600x10^3 lbf (2669 kN)**
Stepwell	1,100 lbm (499 kg)	4,650 lbm (2109 kg)
No stepwell	150 lbm (68 kg)	500 lbm (227 kg)

Source: [12]
*per vehicle end

2.4. End Beam Study

Around 1998, the authors conducted an experimental study to further investigate the feasibility of increasing the strength of a rail car corner structure under impact conditions [5]. The focus in that project was on the end beam, which ultimately must support any load placed at the base of the corner post. Two end beam designs were developed: one whose design ultimate strength was $150x10^3$ lbf (667 kN) at its end (where the corner post would be) and one with a design ultimate strength of $400x10^3$ lbf (1,779 kN). The strength in the latter case was achieved by utilizing a structural member that corresponds to the side sill having been brought to the rear face of the end beam. Extending the side sill eliminates the opportunity for a step well at the particular corner in question. However, in 1998, discussions had begun in industry about eliminating the step well at the operator's corner just for this purpose.

Two end beam structures were fabricated and then tested. The baseline ($150x10^3$ lbf, or 667 kN, strength) design was tested both quasi-statically and in a drop tower apparatus. The modified ($400x10^3$ lbf, or 1,779 kN, strength) design was tested only in the drop tower apparatus.

The results of these tests and of the accompanying finite element analyses were at first surprising. The modified end beam was found to absorb only twice as much energy as the baseline design in about 0.5 ft. (0.2 m) of crush, even though the ratio of the design strengths was four. As it turns out, the reason for this difference in ratios has to do with the difference in load path for the two designs. In the baseline case, the load is carried only by bending of the end beam. On the other hand, the extended side sill in the modified design carries most of the load in the initial portion of the deformation, but, due to a folding-type buckling that occurs, the side sill's load carrying capacity drops off as the load in the end beam increases. Figure 3 shows the beginning of the folding deformation in the modified test article 'side sill' after an impact in the drop tower.

The test results also showed that the baseline end beam fractured after about 0.5 ft. (0.2 m) of end displacement. Although not tested to fracture, the end beam in the modified design would also have fractured at this displacement, since its mode of deformation was not substantially different than in the baseline case.

Another result from this study was that the measured ultimate strength of the end beam was substantially greater than the design value: the peak load in the quasi-static test, for a load applied at the very end of the beam, was $240x10^3$ lbf (1,068 kN) compared to the design value of $150x10^3$ lbf (667 kN). This difference is directly attributable to material properties that were substantially greater than the minimum required values that were used in design. On the other hand, use of the actual material properties in the nonlinear finite element analysis, which, in this case, did include the effects of material fracture, provided accurate predictions of the end beam strength.

Conventional structural steel, A572-50, was used to fabricate the designs and the weight increase for the modified design was approximately 80 lbm (36 kg), per corner.

There are several implications of the study. First, it is feasible to increase the strength of a cab car supporting corner structure substantially without a significant weight penalty, particularly when the side sill can be used to carry load. Furthermore, this strength increase provides an increase in energy absorption, and therefore, crashworthiness. However, when the load is applied at the base of the post, and, therefore, to the end of the end beam, the increase in energy absorption is less than what would be predicted by the ratio of the strengths for the particular design approach in which the side sill is used to provide strength. Furthermore, the energy absorption is limited by the deformability of the structure; in the case of these end beam designs, fracture occurred after 0.5 ft. (0.2 m) of corner displacement. Another important implication is that the use of nonlinear finite element analysis, which is becoming common in the rail vehicle industry, provides an opportunity to reduce weight while improving crashworthiness.

Figure 3. Full-Scale End Beam/Side Sill Corner Post Support Element Designed and Tested to Demonstrate Substantial Energy Absorption Capability

2.5. Evaluation of Protection Strategies for Cab Car Crashworthiness

A study completed in 2000 specifically addressed the potential crashworthiness benefits of increasing corner strength for laterally offset, or corner, collisions [4]. The work was primarily a finite element study that accounted for large deformations in the collisions. The two relevant scenarios investigated were: a collision between a locomotive and the corner of a cab car (as occurred in an accident in Secaucus, NJ); and a collision between a cab car corner post and a steel coil (similar to what occurred in the Portage, IN accident). In the case of the simulated locomotive collision, the load is applied at the base of the corner post, while for the steel coil, the load is applied at about 36 in. (911 mm) above the underframe. The baseline strength for the corner structure was again 150×10^3 lbf (667 kN), and increased corner strengths of 300×10^3 lbf, (1,334 kN) and 500×10^3 lbf (2,224 kN) were analyzed. Detailed structural designs were not developed for the modified structures. Rather, elements within the finite element model were either extended, for the side sill, or simply increased in thickness, for the end beam, until the desired strengths ─ as determined by the finite element analysis ─ were achieved. The effects of increasing the strength of other elements, such as the AT plate and the lateral shelf, were also investigated. The increase in structural weight associated with these modifications was not calculated.

Several different combinations of collision object, impact location, strength modification approach and collision speed were analyzed. An example set of results is shown in Table 3. The results in this table are given in terms of the collision speeds that produced 1 ft. and 3 ft. (0.3 m and 0.9 m) of predicted crush for a collision of a 40×10^3 lbm (18×10^3 kg) object with the very base of the corner post; 1 ft. (0.3 m) of crush is intended to correspond approximately with the crush beyond which the cab operator is seriously threatened, and 3 ft. (0.9 m) corresponds to the crush beyond which the passengers are expected to be threatened.

Table 3. A Comparison of the Predicted Collision Speeds Required to Produce 1 ft. and 3 ft. of Vehicle Crush for the Baseline and Modified End Structures.

Case	Corner Strength at Base (10^3 lbf (kN))	Collision Speed at 1 ft. of Crush (mph (km/h))	Collision Speed at 3 ft. of Crush (mph (km/h))
Baseline	150 (667)	11.5 (18.5)	18.7 (30.1)
Extended side sill only	300 (1334)	13.6 (21.9)	22.3 (35.9)
Extended side sill and stronger end beam	500 (2224)	15.4 (24.8)	26.1 (42.0)

Source:[2]

The results of Table 3 indicate that there is a significant although small improvement in crashworthiness by increasing the strength of the corner structure for this collision scenario. The analyses also indicated that fracture would occur after about 20 in. (508 mm) of end beam displacement in contrast to the 6 in. (152 mm) observed in the end beam study described above. This is likely attributable to differences in end beam design and the approximate manner in which fracture was predicted in the finite element analyses.

Finally, the protection strategy study also examined the use of crash energy management, or crush zone, approaches in providing increased cab car protection. In this case, the entire end of the car absorbs energy and displaces backward during the collision. The operator is then either provided with an escape route or a refuge area. Such an approach more directly addresses the physical requirement that energy must be absorbed in all collisions. Rather than requiring the corner structure to absorb all of this energy, the entire end participates in the process.

2.6. Summary

The primary result of the previous studies just described is that cab car occupant protection against crush in offset collisions can be improved by increasing the strength of the end frame components. This benefit comes from the ability of the stronger corner structures to absorb more energy.

Less clearly demonstrated was the feasibility of increasing the strength in a practical manner. When the side sill can be used as a load path to support the required load at the base of the corner post, there appears to be little weight penalty in the structure. Of course, in this case the stepwell must be eliminated and this has an effect on operations. Nevertheless, such an approach has been accepted in industry, at least for the operator's corner. If the side sill cannot be used as a load path to support the corner loads then the previous work indicates that there will be a significant weight penalty.

In either case, some of the previous work suggests that the potential increase in crashworthiness protection is limited by the deformability of the structural elements. Even though the strength may be increased substantially, the effective amount of energy absorption may still be relatively low, thus providing only a small increase in tolerable collision speed. This suggests that the crash energy management approach, in which the entire end of the cab car absorbs energy, be examined in greater detail. It also suggests that developing end frame designs, which deform gracefully under '*severe deformations*' prior to failure of the support structure is warranted.

3. Requirements

A requirements document was generated as part of the design process to provide guidance for generating concepts and quantitative measures for evaluating the design. The requirements for the two designs were developed from group discussions with industry and review of existing car structures. Important input included:

- Federal requirements;
- industry standards;
- specifications for existing and planned rail vehicles; and
- discussions with industry personnel active in rail vehicle design.

Input from members of APTA's PRESS-C&S Committee was very useful in this regard. The detailed requirements for the two designs, which include crashworthiness, operational, testing, fabrication, and physical requirements, are included in Appendix B. This section provides a summary of the key requirements.

Several cab cars have been designed and built over the last 10-15 years. A partial list of single-level passenger rail cars is given in Appendix A. For some of these cars, the design team had access to the specifications and drawings. These were reviewed to glean features common to the various designs.

3.1. Crashworthiness Requirements

Table 4 summarizes the crashworthiness requirements used in this project for the two the cab car end frame designs. Figures 4 and 5 provide some of the information schematically.

Table 4. Summary of Cab Car End Structure Crashworthiness Standards and Requirements

	Standard/Requirement	
Component	**1990s Design**	**SOA Design**
Collision Post (must be present at the 1/3 points along the width of the vehicle)	• $300x10^3$ lbf (1,334 kN) at the floor without exceeding the ultimate shear strength • $300x10^3$ lbf (1,334 kN) at 18 in. (457 mm) above the floor without exceeding the ultimate strength • Both requirements apply for loads applied ±15° inward from the longitudinal • If reinforcement is used to achieve the strength it must extend fully to 18 in. (457 mm) and then taper to 30 in. (762 mm) above the underframe	• $500x10^3$ lbf (2,224 kN) at the floor without exceeding the ultimate shear strength • $200x10^3$ lbf (890 kN) at 30 in. (762 mm) without exceeding the ultimate strength • $60x10^3$ lbf (267 kN) applied anywhere without yield • All requirements apply for loads applied ±15° inward from the longitudinal • Strengths must be achieved without failing connections • The post must be able to deform substantially without failing the connections
Corner Post (must be present at the extreme corners of the vehicle)	• $150x10^3$ lbf (667 kN) at the floor without exceeding the ultimate shear strength • $30x10^3$ lbf (134 kN) at 18 in. (457 mm) above the floor without exceeding the material yield strength • Both requirements apply for loads applied anywhere between longitudinal to transverse inward	• $300x10^3$ lbf (1,344 kN) at the floor without exceeding the ultimate shear strength • $100x10^3$ lbf (445 kN) at 18 in. (460 mm) above the floor without exceeding the yield strength • $45x10^3$ lbf (200 kN) applied anywhere along the post without yield • All requirements apply for loads applied anywhere between longitudinal inward to transverse inward
Lateral Member (must be present between the corner and collision posts just below the cab window)	• $15x10^3$ lbf (66.7 kN) applied in the longitudinal direction anywhere between the corner and collision post without yield	• $15x10^3$ lbf (66.7 kN) applied in the longitudinal direction anywhere between the corner and collision post without yield • Include a bulkhead in the opening below the shelf.

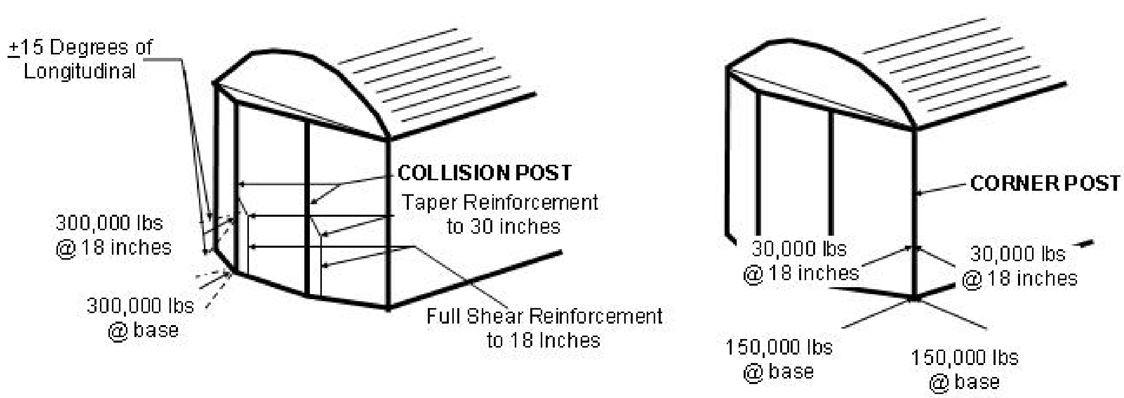


Figure 4. Some of the Structural Requirements for the 1990s Design

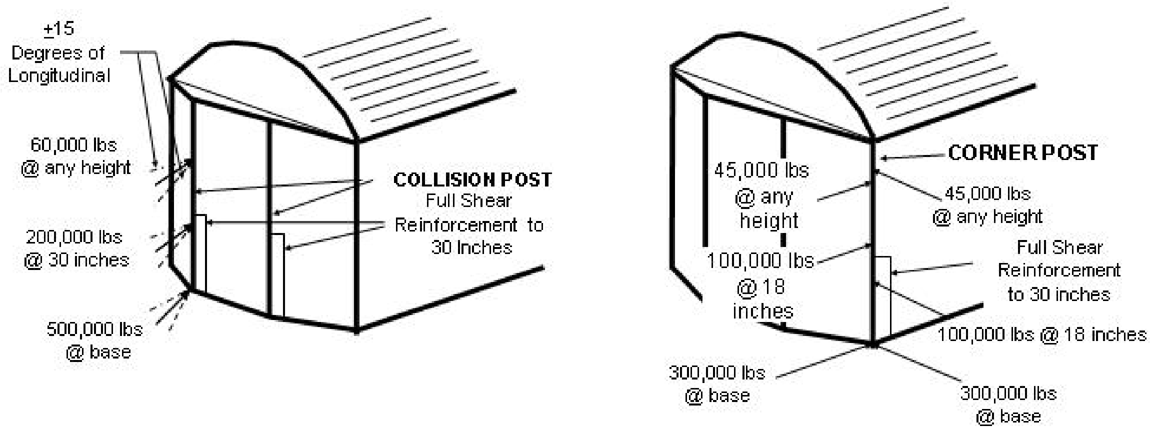


Figure 5. Some of the Structural Requirements for the SOA Design

The intent behind the increases in strength defined in the SOA design is, in large part, to raise the amount of energy that can be absorbed in a collision. At one point, the APTA standard included the following paragraph:

> *'… post and its supporting structure shall be designed so that when it is overloaded … failure shall begin as bending or buckling in the post. The connections of the post to the supporting structure, and the supporting car body structure, shall support the post up to its ultimate capacity. The ultimate shear and tensile strength of the connecting fasteners or welds shall be sufficient to resist the forces causing the deformation, so that shear and tensile failure of the fasteners or welds shall not occur,* ***even with severe deformation*** *of the ... post and its connecting and supporting structural elements.'*

The APTA standard did not specify how much severe deformation the structural members must sustain. Engineers in the industry suggested that deformation equal to the depth of the structural member is considered 'severe.' A deformation requirement was not explicitly included in the APTA standard. The subject remains a topic of debate due to a change in the standard based upon requests from rail car manufacturers. The standard has been changed to a recommended practice. This occurred because the manufacturers desired an explicit definition of '*severe deformation*.' In addition to the definition, the manufacturers requested clearer guidance in terms of how to demonstrate compliance to transportation authorities that specify testing of 'severe deformation.'

Another area for which there was and continues to be discussion relates to the elimination of the stepwell at the end of the car to enable the use of the side sill to support the required $300x10^3$ lbf (1334 kN) corner post load. The research to date, including the prior research summarized above and the results of the present study, demonstrate that use of the side sill for direct support of the load permits a design with little weight penalty. Yet there are evidently situations in which a step well is still required. To accommodate this case, the APTA standard permits the use of a lower longitudinal strength requirement at the non-operator side of the car, provided the adjacent body corner post (usually located on the inboard side of the doorway) is designed to meet the $300x10^3$ lbf (1,334 kN) longitudinal strength requirement. It remains a topic of debate whether the operator's side can be practically designed with a step well and meet the current strength requirements.

Still another area of discussion was whether the collision and corner posts should be required to penetrate and be joined with the upper and lower surfaces of the end beam. Older standards did not require this for the corner post but the current standard requires it explicitly. It is an important requirement because it ensures a substantially stronger and more deformable connection to the end frame as demonstrated by the full-scale grade crossing tests that were eventually conducted.

There are some requirements that are now in the APTA standard that were not accepted at the time the project being described in this report was conducted. These came about as a compromise for repealing the then accepted '*severe deformation*' requirement. These are strength requirements for the connections between the collision and corner posts and the AT plate. The shear strength for the joint between the collision post and the AT plate must be $70x10^3$ lbf (311 kN). In addition, the connection must carry a tensile load (downward along the post) of $30x10^3$ lbf (133 kN) for the collision post and $22.5x10^3$ lbf (100 kN) for the corner post. These requirements are another indirect way of ensuring that the post deforms before the connection fails. Although not checked, it is likely that the SOA design satisfies these requirements.

3.2. Other Requirements

In addition to the crashworthiness requirements, it was also important to ensure that the designs were practical with regard to other operational and physical requirements. These requirements include accommodation for conventional coupling components and restricting dimensions to fit into standard vehicle envelopes.

The designs also had to be adaptable to two similarly built test cars (one for each design) located in Pueblo, Colorado at TTC. These Budd Pioneer vehicles were used for the two previous full-scale collision tests but still each had one end in a condition usable for this program as revealed by examination of the cars and the corresponding drawings. The vehicles, built in the 1950s, possess stairwells on each side of a draft sill that meets the $800x10^3$ lbf (3,559 kN) buff load requirement. There is a buffer beam, or end beam, at the very end that contains the bellmouth and to the sides of which the collision posts are attached. Only a light plate structure protruded laterally from the end beam and there were no significant corner posts. Figure 6 shows a photograph of the structure prior to modification. The preliminary assessment conducted in this study indicated that the collision posts, end beam and corner structure would need to be replaced for both the 1990s and SOA design test cars.

Figure 6. One of the Budd Pioneer Cars Prior to Modification for this Program. (The Stairwell has been Removed)

4. Design Descriptions

The sections that follow provide summary descriptions of the 1990s and SOA designs developed in this program. There are a number of common features to the two designs. These include the geometry of the end beam and the use of A710 Class 3 steel for all components. The connection detail between the end beam and the draft sill of the existing Budd car is also the same for both designs. These will be described in greater detail in the sections that follow. Sections from the drawings corresponding to some of the individual components are included in this section and in Appendix C.

4.1. 1990s Design

A photograph of the fabricated 1990s end frame provides an overview of the design and its attachment to the existing test car, Figure 7.

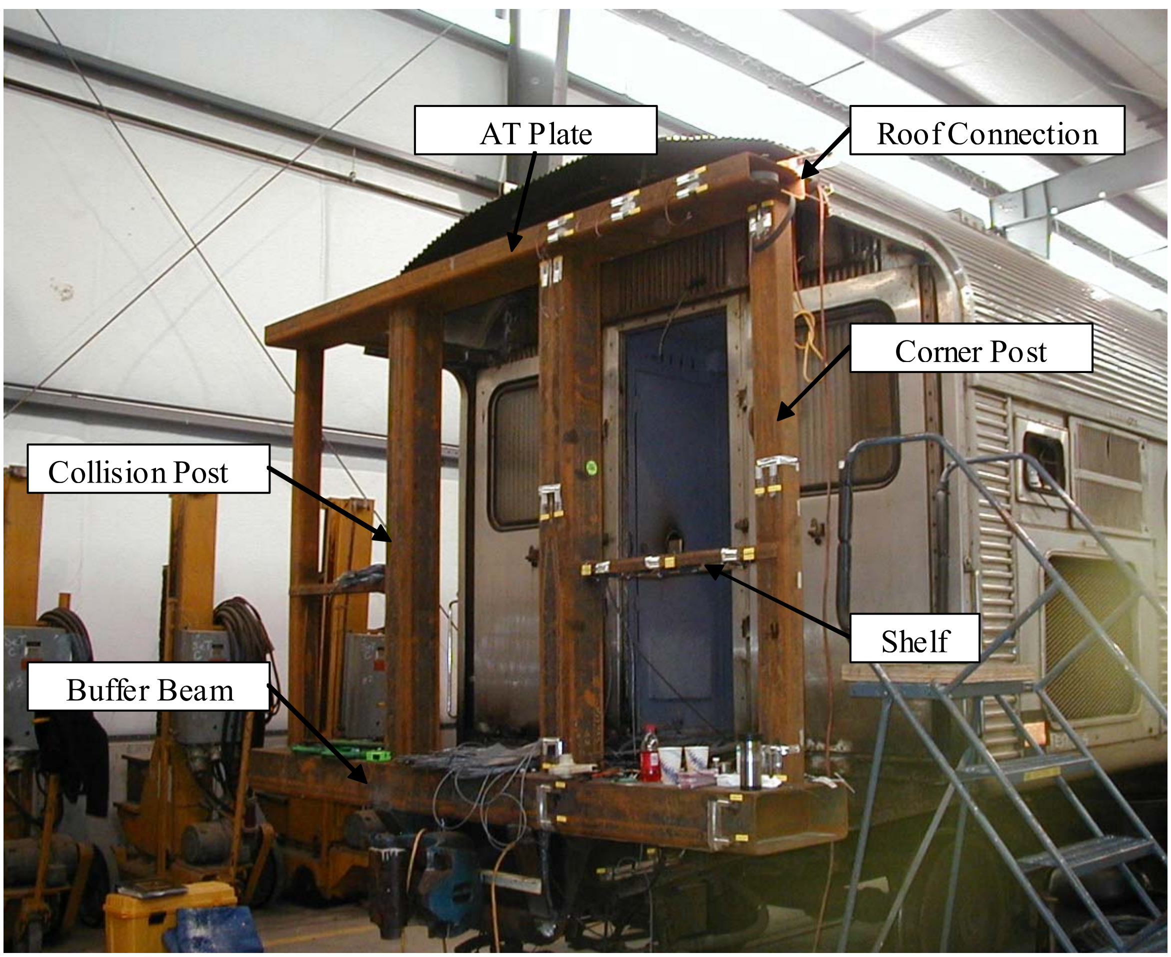


Figure 7. Fabricated 1990s End Frame Design

The end beam consists of a closed rectangular cross section, 7.31 x 19.0 in. (186 x 483 mm), fabricated from 0.375-inch (9.5-mm) thick plate as shown in Figure 8. It contains internal gussets, some of which line up with the webs of the draft sill on the existing car. The collision posts penetrate both the upper and lower flanges of the end beam, while the corner posts penetrate only the upper flange, consistent with some of the 1990s era designs we reviewed. The end frame includes a new bellmouth as part of the assembly. (Additional sections from the drawings used to fabricate the end frames are included in Appendix C.)

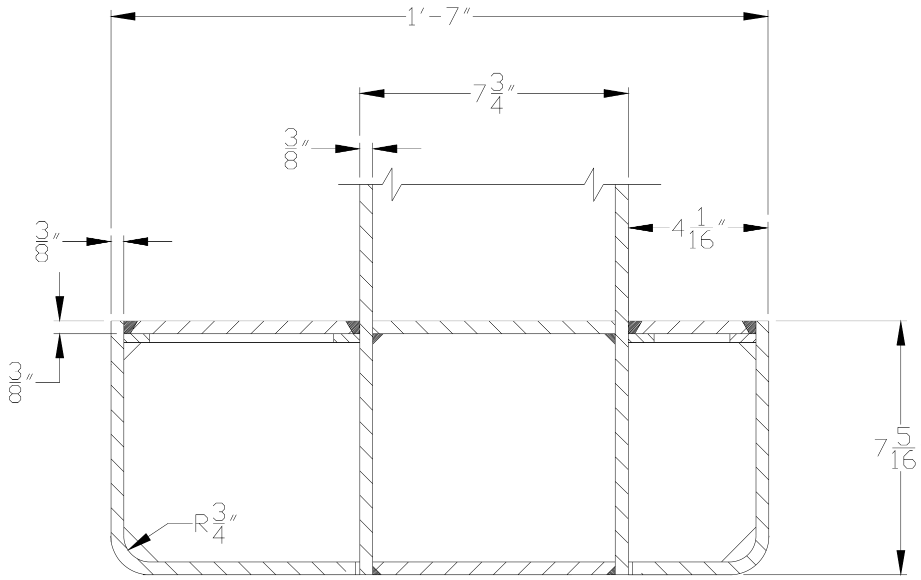


Figure 8. Cross Section for the 1990s Design End Beam (Through the Collision Post)

The collision post has a rectangular cross section, 7.75 x 6.5 in. (197 x 165 mm), fabricated from 0.375-inch (9.5-mm) plate, as shown in Figure 9. The post is reinforced by two lugs, each 0.25 in. (6.4 mm) thick and extending to 34 in. (864 mm) above the underframe on the front and back of each post.

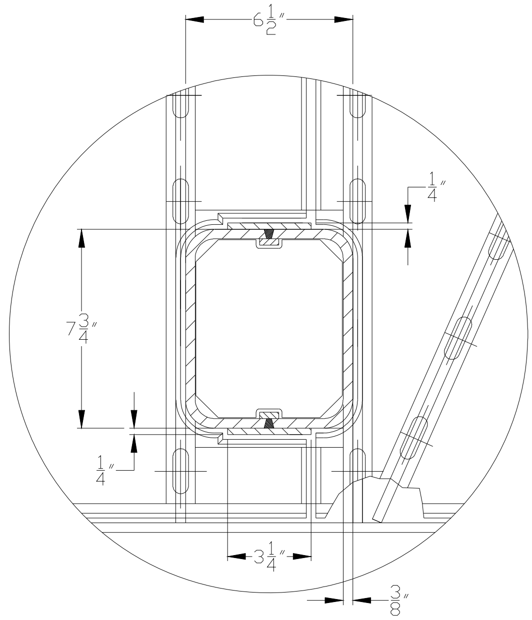


Figure 9. Cross Section of the 1990s Collision Post (Projections of the Gussets within the End Beam are Also Shown)

The corner posts have a square cross section, 4.5 in. (114 mm) on a side, fabricated from 0.25-inch (6.4-mm) plate, as shown in Figure 10. The corner posts are reinforced on two adjacent sides by 0.25-inch thick (6.4 mm) lugs that extend 27.25 in. (692 mm) above the underframe.

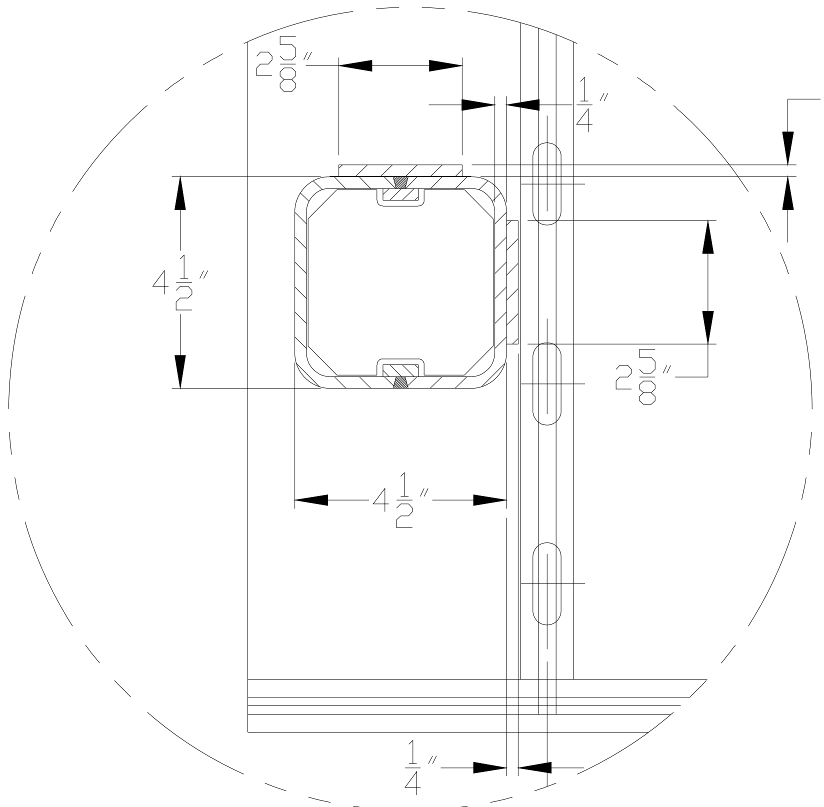


Figure 10. Cross Section of the 1990s Corner Post

A lateral shelf member spans between the collision and corner post on each side. It consists of a channel, 5.0 x 1.75 in. (127 x 44.5 mm) formed from 0.25-inch (6.4-mm) plate. The top of the shelf is 30 in. (762 mm) above the underframe.

The collision and corner posts are supported at the top by an AT plate that also has a closed, rectangular cross section. Its dimensions are 12.0 x 3.75 in. (305 x 95 mm) and it is fabricated from 0.25-inch (6.4-mm) plate (Figure 11). The collision and corner posts penetrate only the lower flange of the AT plate.

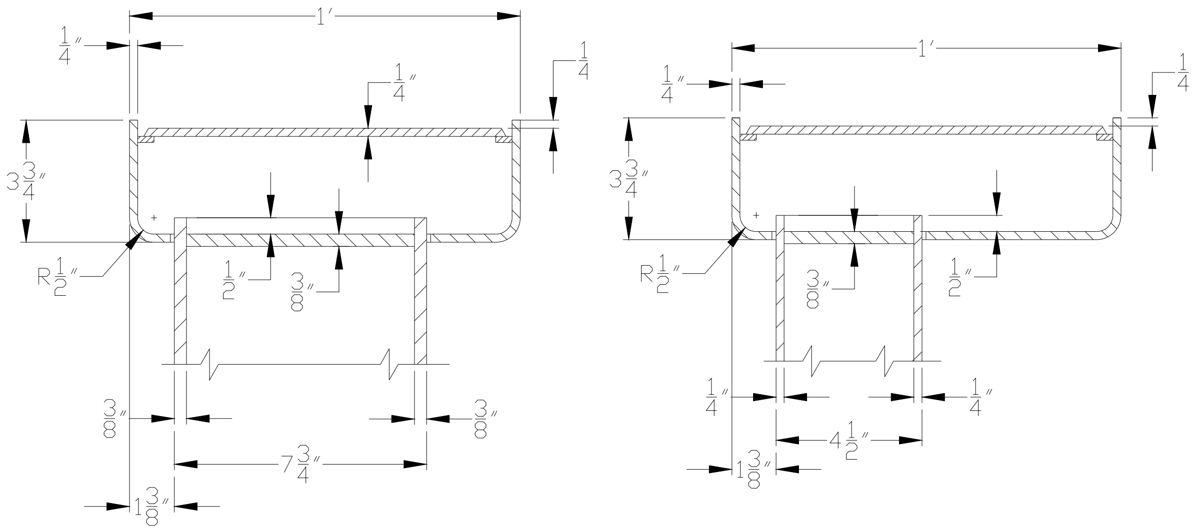


Figure 11. Cross Sections of the 1990s Design AT Plate at the Collision Post (left) and Corner Post (right)

The end frame is attached to the existing car at three locations: the draft sill and the two longitudinal roof members. There is no connection at the side sill in the 1990s design as there is in the SOA design. The connection at the draft sill is made at both webs and the top flange. There are also two, transverse reinforcing gussets between the end beam and the end of the draft sill.

The connection of the longitudinal roof members to the existing car structure was designed but then modified to fit the existing vehicle in its present condition. Each roof member extending from the rear of the anti-telescoping plate is essentially a channel section fabricated from an angle and a bar. The open part of the channel is attached to the existing (outer) roof sheet. The end of this built-up member bears against a flat plate welded onto the vestibule wall. Another angle and a transverse gusset reinforce the end connection.

4.2. State-of-the-Art Design

Figure 12, the fabricated SOA end frame, provides an overview of the design and its attachment to the existing test car. The primary features of the SOA design that differ from the 1990s design are as follows:

- The corner posts extend through both the top and bottom flanges of the end beam
- The collision and corner posts penetrate both flanges of the AT plate
- There is a side sill element that extends up to the end beam
- A bulkhead exists in the opening defined by the collision post, shelf, corner post, and underframe.

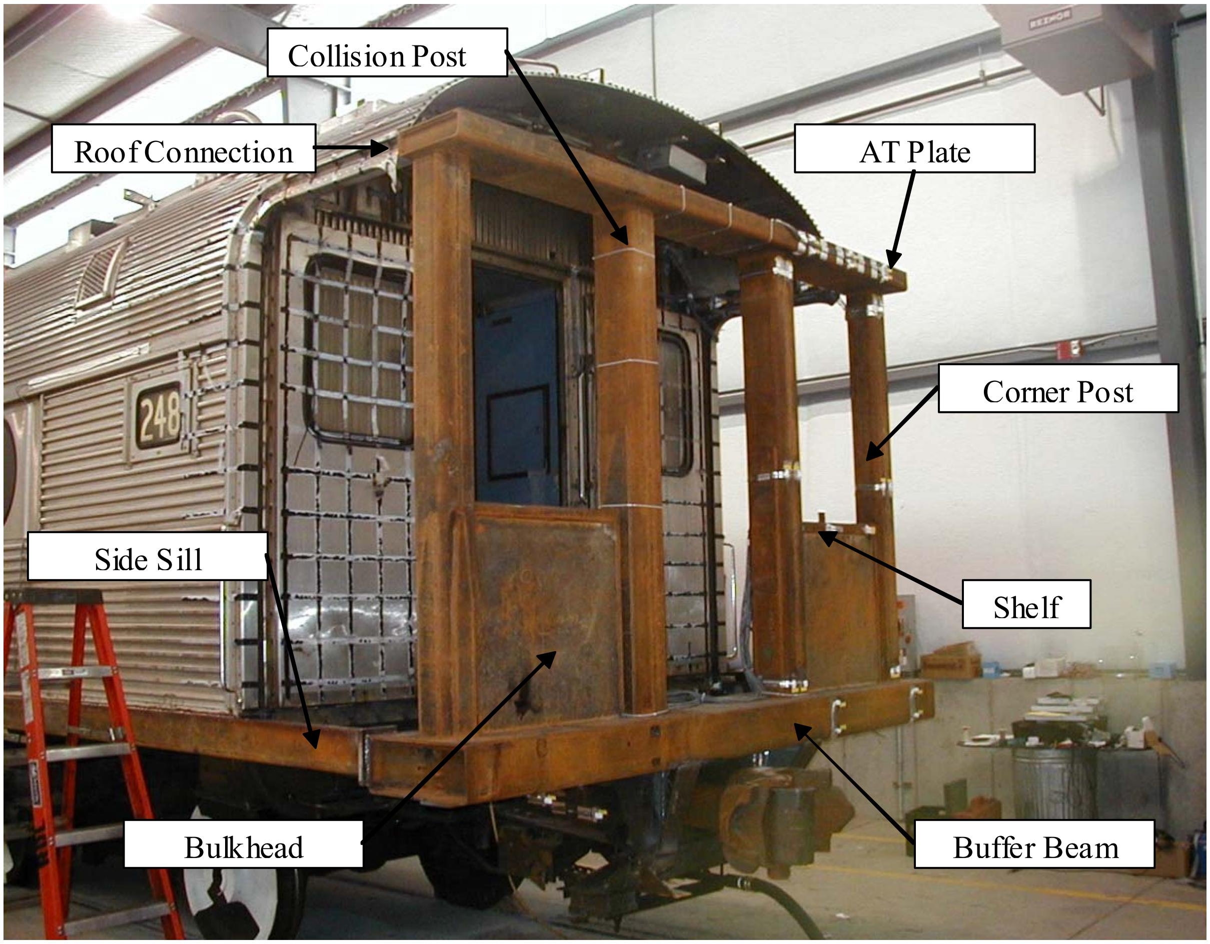


Figure 12. Fabricated SOA End Frame Design

The end beam has the same dimensions as for the 1990s design. In the case of the SOA design the collision posts and the corner posts penetrate both the upper and lower flanges of the end beam.

The collision post again has a rectangular cross section, 7.75 x 6.5 in. (197 x 165 mm), fabricated from 0.375-inch (9.5-mm) plate, but the reinforcing lugs have a thickness of 0.375 in. (9.5 mm), and extend to 46 in. (1,168 mm) above the underframe on each side of each post (Figure 13).

The corner posts have a square cross section, but for the SOA design they are 6.0 in. (152 mm) on a side, fabricated from 0.31-inch (7.9-mm) plate (Figure 14). The corner posts are reinforced on all four sides by 0.31-inch (7.9-mm) thick lugs that extend 27.25 in. (692 mm) above the underframe. The lugs are not required for shear reinforcement; instead they are present for '*severe deformation*' bending requirements.

A lateral, shelf member is the same in this design as in the 1990s design. However, the SOA design includes a 0.25-inch (6.4-mm) thick bulkhead plate welded to the collision post, shelf, corner post and underframe; a part of this can be seen in Figure 13.

The AT plate has the same dimensions as in the 1990s design. In the SOA design, the collision and corner posts penetrate both the lower and upper flanges of the AT plate.

The SOA end frame is attached to the existing car at five locations: the draft sill, the two roof rails, and the two side sills. The connections to the draft sill and roof rails are essentially identical to the 1990s design. Each side sill is a closed rectangular section, 4.94 x 5.81 in. (125.5 x 147.6 mm), fabricated from two 0.25-inch (6.4-mm) thick angles, as shown in Figure 15. The connection to the back of the end beam includes a 0.75-inch (19-mm) thick pad to distribute the bearing load. The connection of the side sill is made to the rest of the car by: a) welding the end of the inside angle to a plate on the face of the cross tie; and b) by extending the outer angle to the body bolster and welding the edges to the side plate and side sill.

The SOA end frame weight is 250 lbm (113 kg) more than the 1990s design.

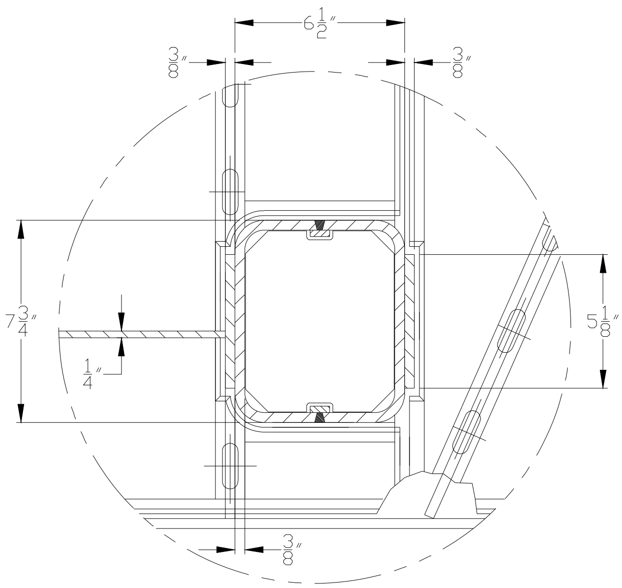


Figure 13. Cross Section of the SOA Collision Post (projections of the gussets within the end beam are also shown)

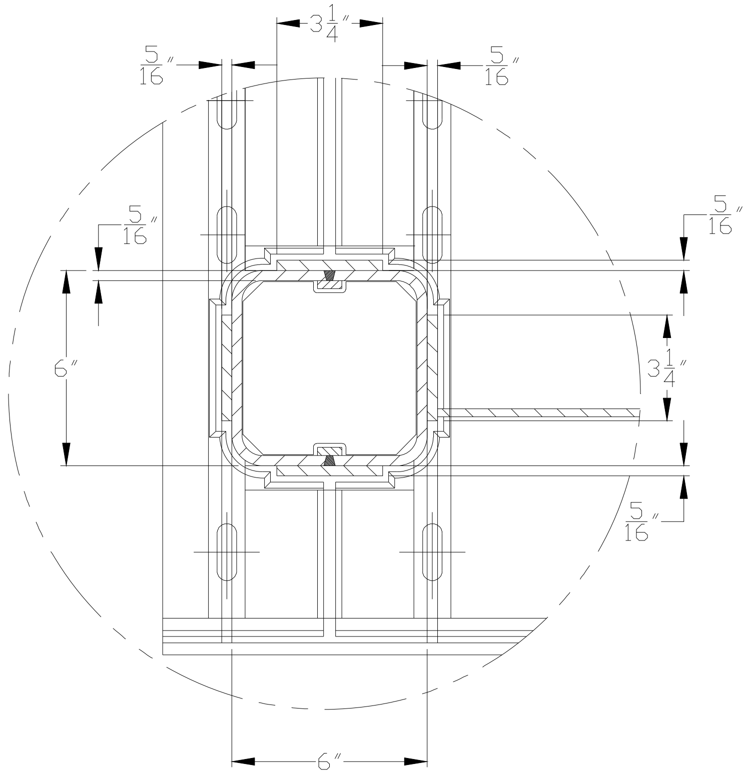


Figure 14. Cross Section of the SOA Corner Post

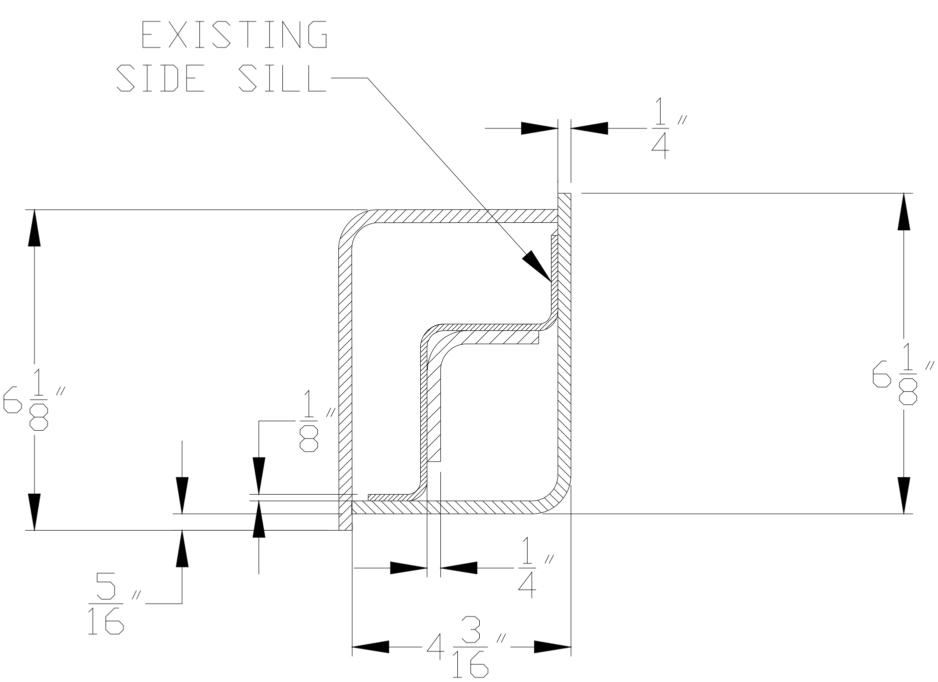


Figure 15. Cross Section of the SOA Side Sill (Taken Between the Vestibule and the End Beam)

5. Design Analysis

The preliminary design of the various structural members was initially carried out by conducting hand and beam element finite element analysis for both the 1990s and the SOA designs. No other analysis was carried out for the 1990s design, consistent with the design techniques generally used in the 1990s design era. However, a detailed finite element model was generated for post-test analysis of the 1990s design. On the other hand, finite element analysis, including the simulation of detailed shapes of each structural member, was conducted for the SOA design after the draft engineering drawings had been generated. The SOA design was then modified, as needed, to satisfy the various requirements and the detailed finite element analysis repeated.

This section describes the analysis conducted to demonstrate that the final SOA design meets the new strength requirements.

For some structural members and load cases, even for the SOA design, only hand calculations were used to demonstrate that a particular requirement was satisfied. These components and load cases included:

- Collision post shear strength at the base
- Collision post strength for the cases in which the load is applied up to 15 degrees to the longitudinal axis
- Corner post shear strength at the base
- Shelf strength under longitudinal loading anywhere along its length.

Appendix D gives an example of the hand calculation approach used to calculate the ultimate strength of the collision post when loaded above the underframe.

Table 5 lists the load cases for which detailed finite element analysis was used to demonstrate compliance of the SOA design with the requirements.

Table 5. Detailed Finite Element Analysis Load Cases Conducted for the SOA Design

Component	Load Case
Collision Post	Longitudinal load at 30 in. (762 mm) above the underframe; ultimate strength must be at least 200,000 lbf (890 kN); deformation of at least one times the depth of the post
	60,000 lbf (267 kN) at a height of 75 percent of the distance between the underframe and the AT plate; longitudinal direction; no yielding
	60,000 lbf (267 kN) at a height of 75 percent of the distance between the underframe and the AT plate; transverse direction; no yielding
Corner Post	100,000 lbf (445 kN) at 18 in. (457 mm) above the underframe in the longitudinal direction; no yielding
	100,000 lbf (445 kN) at 18 in. (457 mm) above the underframe in the lateral direction; no yielding
	45,000 lbf (200 kN) at the AT plate; longitudinal direction; no yielding
	45,000 lbf (200 kN) at the AT plate; lateral direction; no yielding
	Longitudinal load at 18 in. (457 mm) above the underframe; deformation of at least one times the depth of the post

Only a few of the collision and corner post results are described here as examples of the finite element calculations. Figure 16 shows part of the model used in the analysis. Approximately 20 ft. (6.1 m) of the vehicle length was simulated in these calculations. The back (inboard) end of this model was fixed against all degrees of freedom in the analyses. The load was applied as a line load for all of the linear elastic cases. For the nonlinear cases, which include determination of ultimate strength and deformation capacity, the load was applied to the post through an 'indenter' that had a 3-inch (76-mm) radius at the point of contact, was 6 in. (152 mm) high and spanned the entire width of the post. This shape was chosen because it facilitates the contact modeling; there is, to the authors' knowledge, currently no standard or recommended practice for the geometry of such a loading device.

Figure 17 shows the load-load point displacement plot for the case in which a load is applied to the collision post in the longitudinal direction at 30 in. (762 mm) above the underframe. Note that the maximum predicted strength is about 250×10^3 lbf (1,120 kN), well in excess of the required 200×10^3 lbf (890 kN) requirement. Figure 18 shows a deformed geometry plot from the finite element analysis. The collision post has been deformed 7.75 in. (197 mm), a value equal to the depth of the post. Figure 19 shows a plot of the equivalent plastic strain as a measure of the likelihood of fracture. Note that the strains at the lower connection, which is the most highly strained connection in this case, are less than 25 percent. Typical elongation values for the A710 material exceed 30 percent. This indicates that significant cracking is unlikely to occur for a deformation equal to one times the depth of the post.

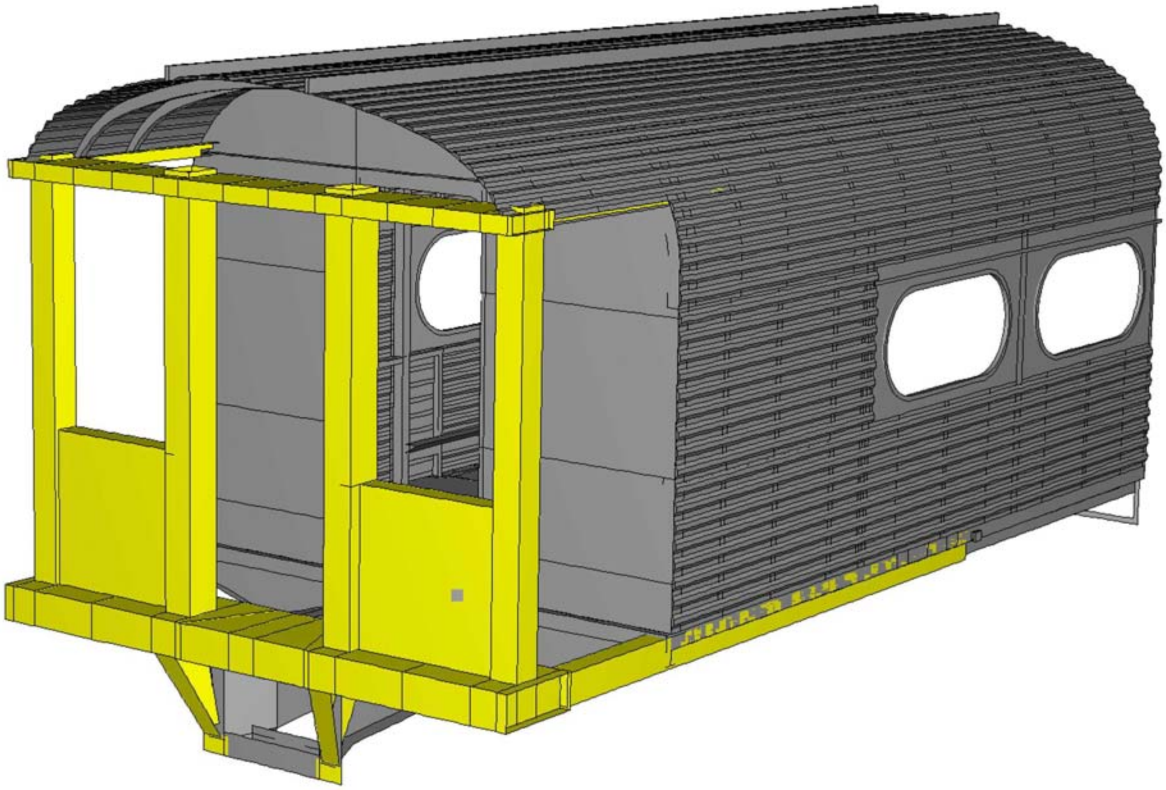


Figure 16. Model Used to Assess Various Load Cases for the SOA End Frame Design

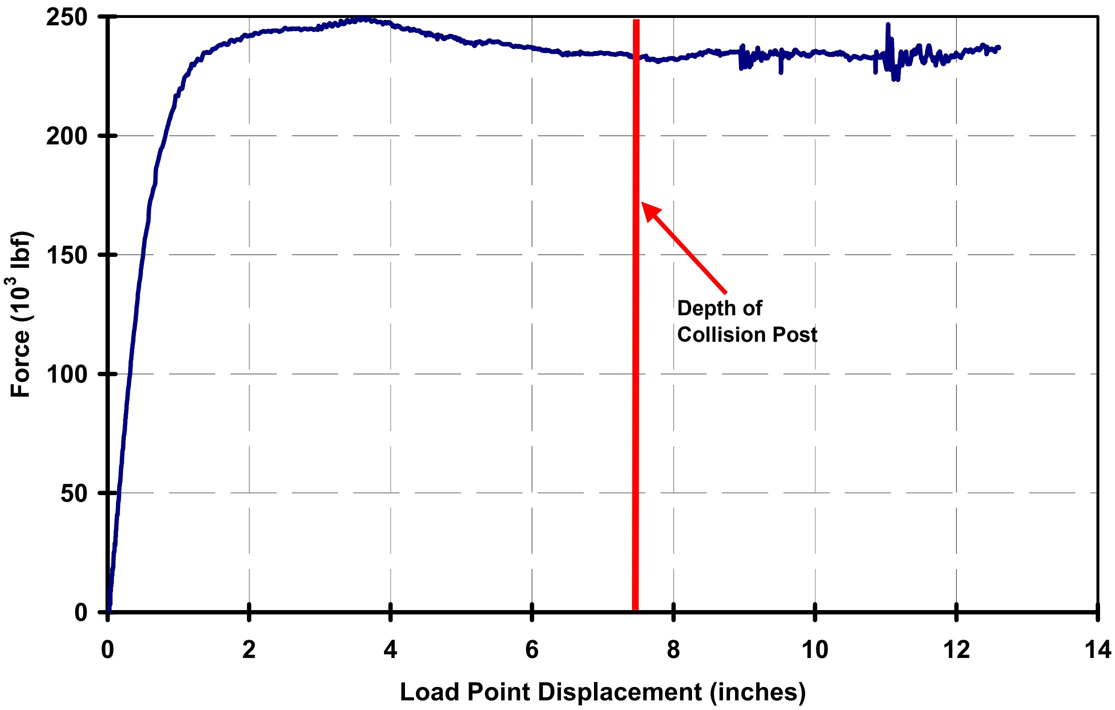


Figure 17. Calculated Load-Load Point Displacement Plot for a Longitudinal Load Applied on the Collision Post 30 in. (762 mm) above the Floor (Load is for One Post)

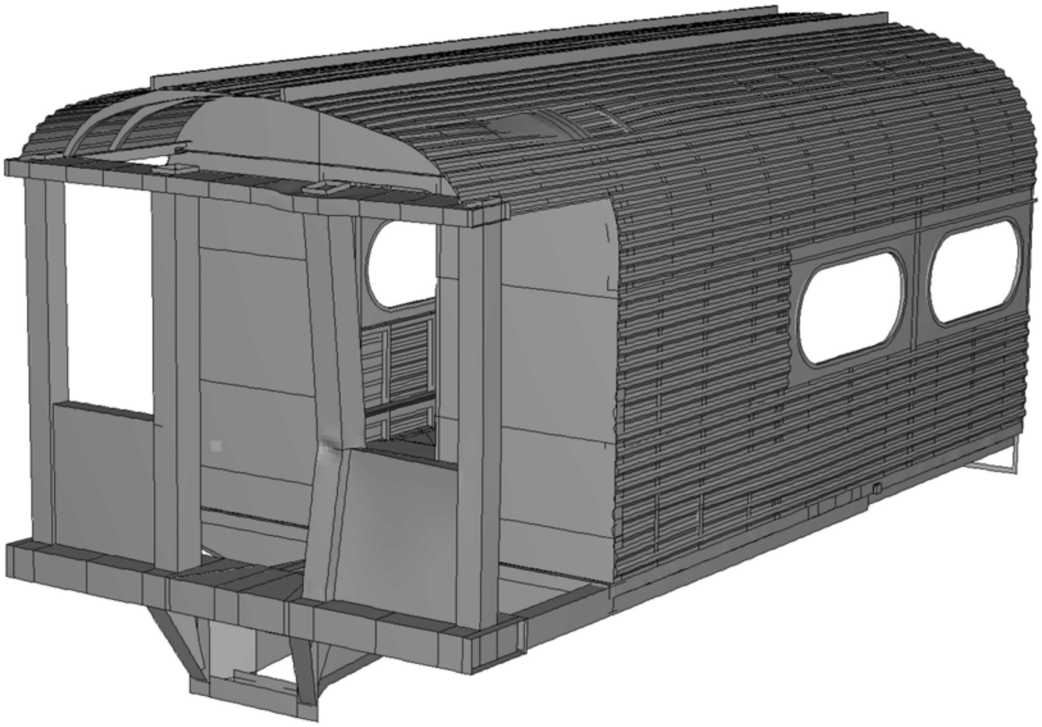


Figure 18. Deformed Model Corresponding to a Load Point Displacement of 7.75 in. (197 mm) on the Collision Post

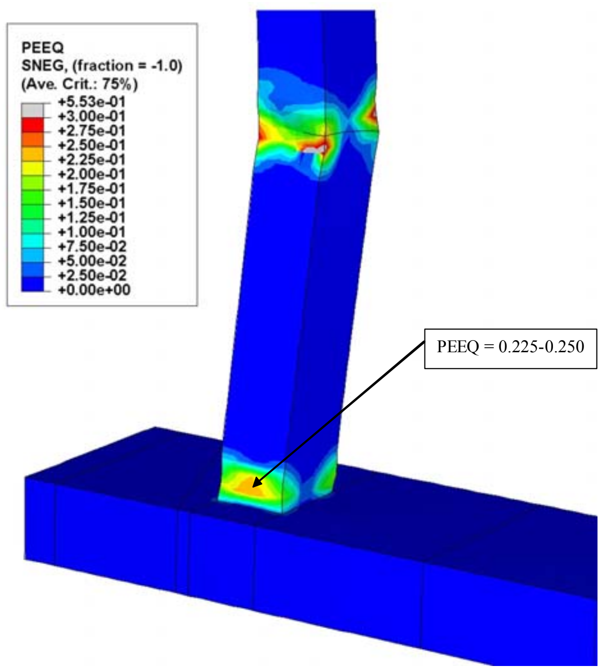


Figure 19. Equivalent Plastic Surface Strain Contours Corresponding to a Load Point Displacement of 7.75 in. (197 mm) on the Collision Post

Figure 20 shows the load-load point displacement plot for the case in which a load is applied to the corner post in the longitudinal direction at 18 in. (457 mm) above the underframe. In this case the maximum predicted strength is approximately 230x10^3 lbf (1,023 kN). A strength comparable to that obtained for the collision post, represented in Figure 17, is explained by the fact that the corner post is loaded at about one-half the height as the collision post and the strength requirement for a load above the underframe is based on a yield criterion for the corner post rather than the ultimate strength criterion for the collision post. There is no requirement for the ultimate strength of the corner post for a load applied at 18 in. (457 mm). However, there is a requirement for deformation. Figure 21 shows a plot of the deformed geometry, and Figure 22 shows a plot of the equivalent plastic strain on the post surface corresponding to a load point displacement of 6 in. (152 mm), the depth of the corner post. The bulkhead has been removed from the figure for clarity. Here, there is a small area over which the plastic strain exceeds the nominal 30 percent elongation of the A710 material. This indicates that some cracking could occur for a deformation equal to one times the depth of the post. However, it is unlikely that the integrity of the corner post – end/buffer beam connection is significantly compromised. For ultimate load conditions, it is expected that some cracking of material may occur.

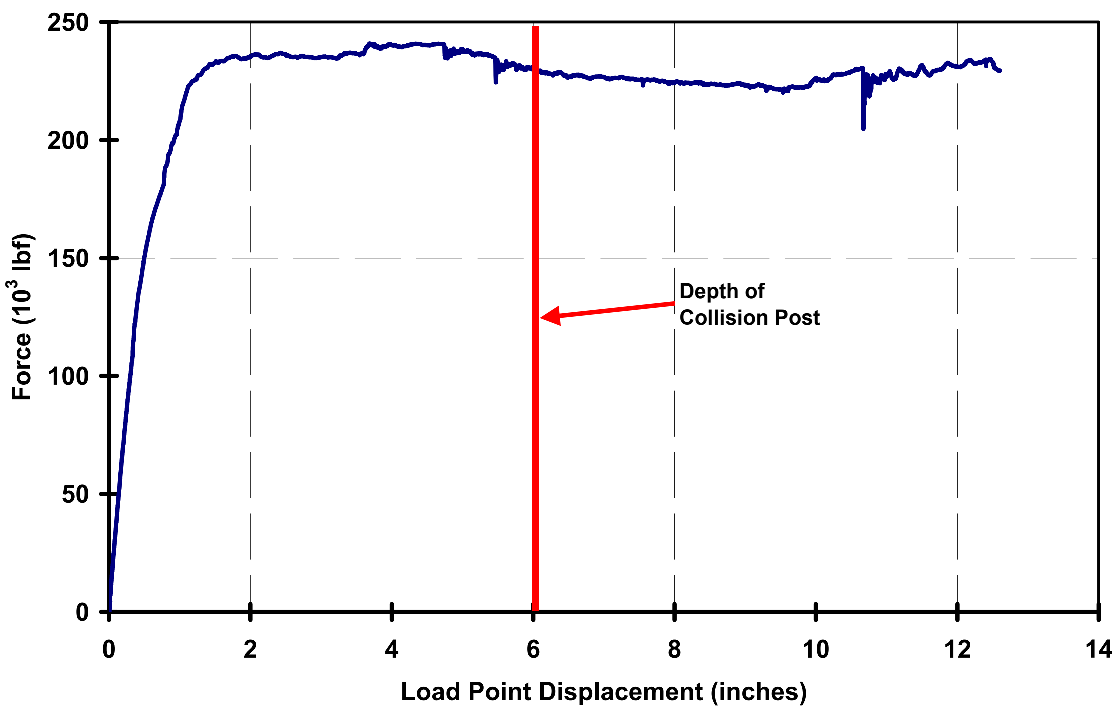


Figure 20. Load-Load Point Displacement Plot for a Longitudinal Load Applied on the Corner Post 18 in. (457 mm) above the Floor

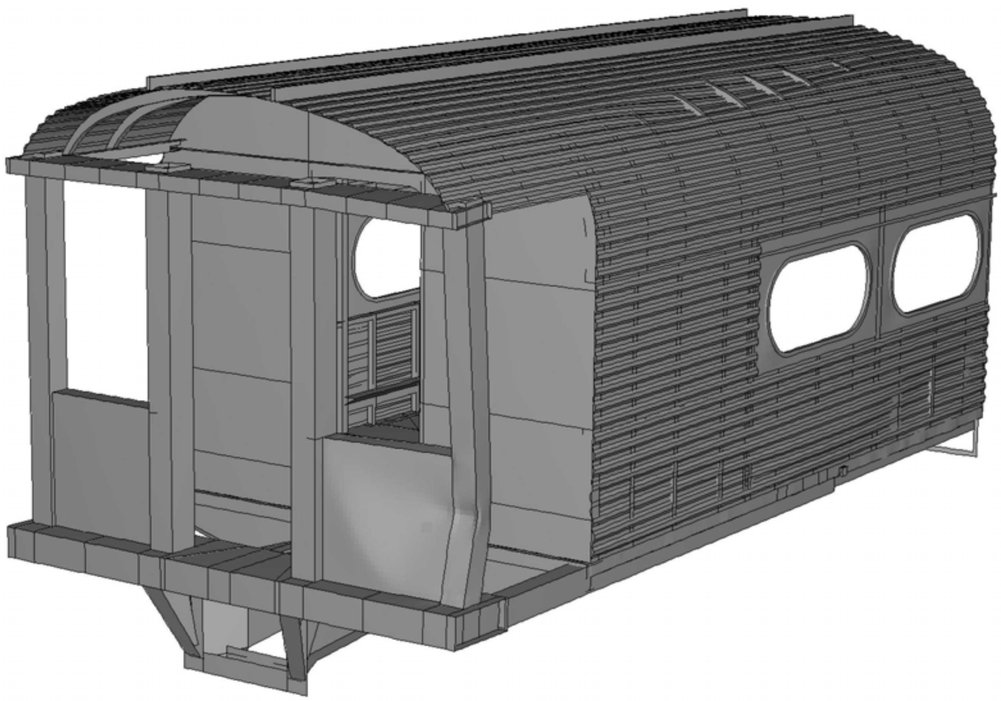


Figure 21. Deformed Model Corresponding to a Load Point Displacement of 6 in. on the Corner Post at 18 in. (457 mm) above the Floor

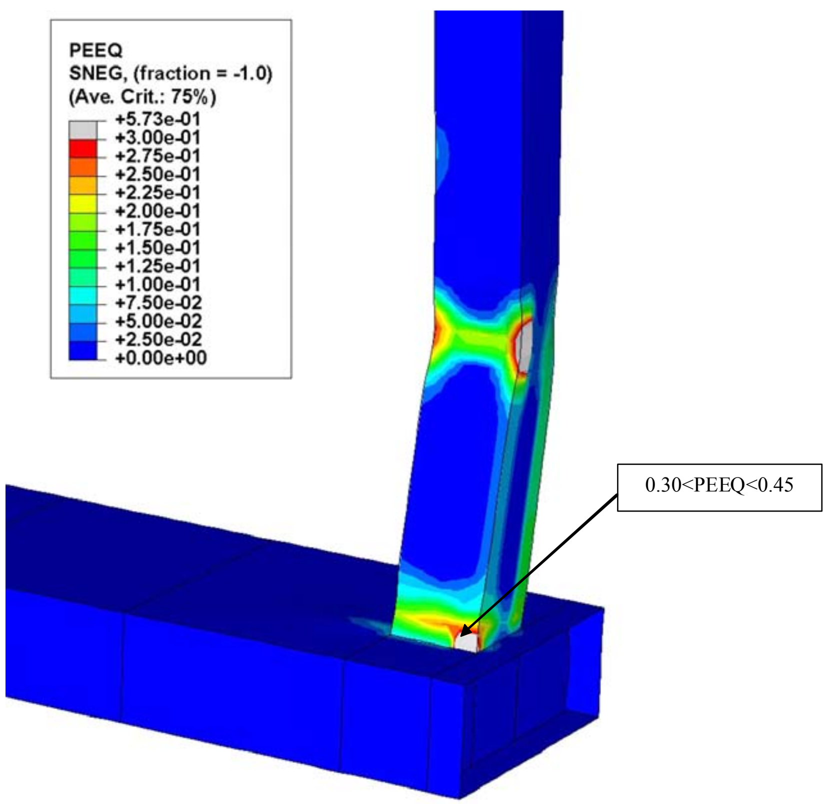


Figure 22. Equivalent Plastic Surface Strain Contours Corresponding to a Load Point Displacement of 6 in. (152 mm) on the Corner Post

Figure 23 shows the stress contour plot for the load case in which 100×10^3 lbf (445 kN) is applied to the corner post in the transverse direction 18 in. (457 mm) above the underframe. Only some of the structural components are shown in the half-model in the figure: the end beam, the collision and corner posts, the shelf, the bulkhead, the AT plate, the side sill and the roof member. The draft sill, in which stresses are well below yield, is removed for clarity. The Mises (effective) stress is plotted for the surface of the structural components. The results show that there are no stresses greater than 75×10^3 psi (517 MPa) the minimum required yield strength of the A710 material used, except at the point of load application. Very small localized areas of plasticity at the load point locations can occur without affecting the global performance of the system and are therefore acceptable.

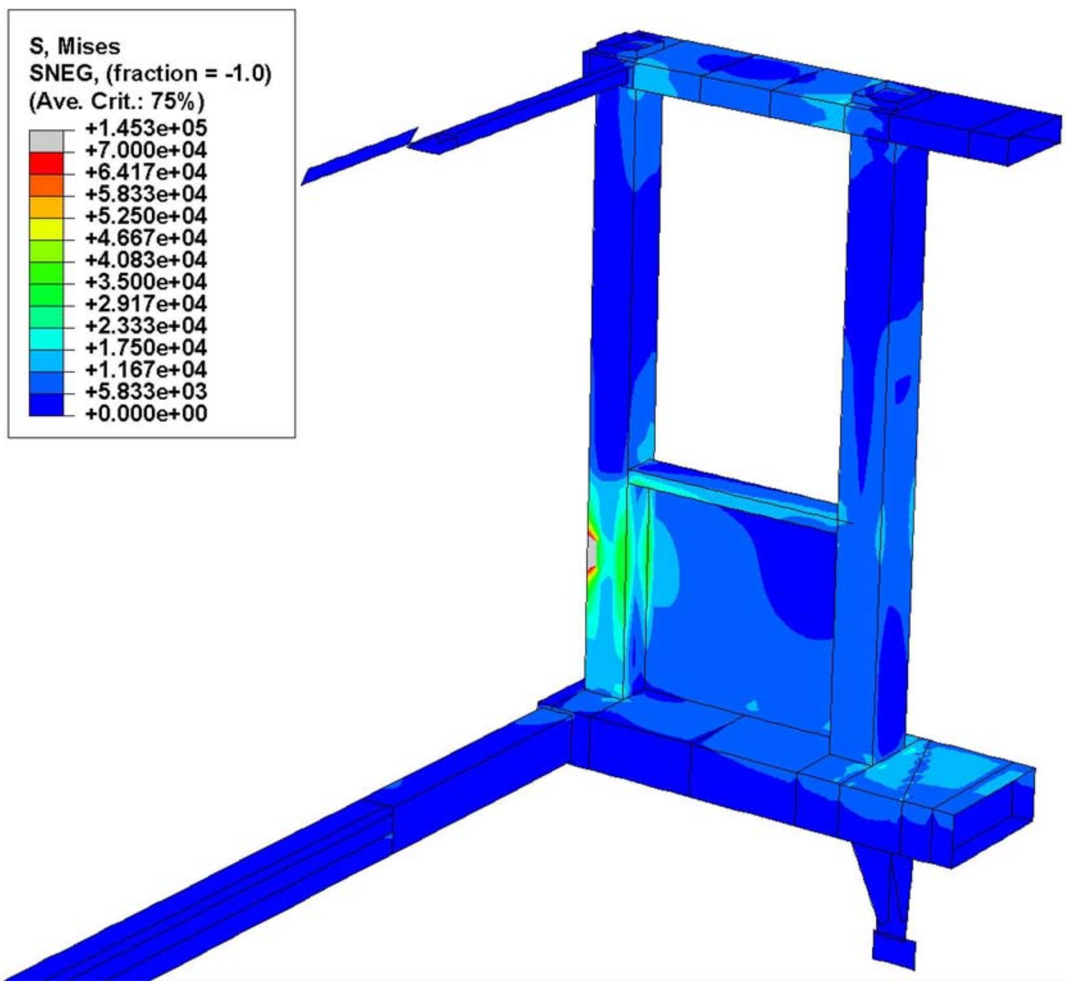


Figure 23. Mises Surface Stress Contour Plot for the 100×10^3 lbf (445 kN) Lateral Corner Post Load at 18 in. (457 mm)

6. Fabrication

Ebenezer Railcar Services, West Seneca, New York, fabricated the end frames and then shipped them to the TTC in Pueblo, Colorado, for integration into the existing cars. The general sequence of fabrication was as follows:

1. Plate pieces were ordered from the material vendor
2. Pieces requiring it were then beveled and formed into the required shape
3. The pieces were then welded together
4. Inspection was carried out throughout the fabrication process.

The primary material of construction, A710, was selected because it is now commonly used in the construction of rail vehicles for North American operation. The material was obtained from a few different heats, each with slightly different mechanical properties. Table 6 lists typical values for the primary material based on the different heats and thicknesses.

Table 6. Average Mechanical Properties for the A710, Gr. A, Class 3 Steel Used to Fabricate the 1990s and SOA Endframes

Property	Average Value
Yield Strength	87×10^3 psi (600 MPa)
Tensile Strength	93×10^3 psi (640 MPa)
Elongation (in 2 in. or 51 mm)	30 percent

The minimum required strengths for this material are: 75×10^3 psi (517 MPa) for the yield strength; and 85×10^3 psi (586 MPa) for the tensile strength. The minimum elongation (in 2 in. or 51 mm) is 20 percent. The values for the material used to fabricate the end frames are significantly greater than what is probably used in the rail vehicle industry (except for elongation). However, a source of material was not found with properties that were closer to the minimum required values in the quantities and for the schedule needed. The minimum properties were used in the design calculations.

Welding was carried out using the MIG process following the requirements of AWS D1.1. Figures 24 and 25 show photographs of one of the end frames during fabrication. These figures show part of the internal structure of the end beam and the AT plate. The completed end frames were shown in Figures 7 and 12 in Section 4 on Design Descriptions.

As part of the fabrication process, parts were inspected prior to all operations. Material certifications were also obtained to ensure that minimum properties were met. Measurements were also made of the end frames after fabrication. As stated earlier, the integration of the end frames onto the existing rail vehicles was carried out by TTC staff. However, the authors of this report comprehensively inspected the end frames after integration.

Figure 24. SOA End Frame in Fabrication; This is the End Beam Before the Top Plate was Welded on

Figure 25. SOA End Frame in Fabrication; This is the AT plate Before the Top Plate was Welded on

7. Static Testing Results: Comparison With Analysis

Both the 1990s and SOA end frames were extensively instrumented with strain gages and subjected to a set of static loads at TTC. This section provides a brief description of the static test procedure and reports the agreement between the finite element analyses and test results for the two end frame designs and three load cases.

Approximately 90 strain gages were applied to each end frame and its supporting structure for the tests. The locations of many of the gages are shown schematically in Figure 26 and included:

- Both the front and rear surfaces on the corner post that was to be loaded were strain gaged at three locations along its length.
- Both the front and rear surfaces on the collision post that was to be loaded were strain gaged at three locations along its length.
- The front and rear faces of the AT plate were strain gaged at three locations along its width on the side that was to be loaded.
- The front and rear surfaces of the lateral shelf at three locations along its width on the side that was to be loaded.
- The front and rear surfaces of the end beam at two locations along its width on the side that was to be loaded.
- Three locations along the length of the draft sill on both sides.
- Three locations along the length of the roof (cant) rail and on the inside and outside surfaces between the vestibule and the end frame.

Three of the test loads applied are listed below and shown schematically in Figure 27. Each was applied to the right side of the end frame for an observer looking at the end of the car from the outside.

- A longitudinal load applied 30 in. (762 mm) above the floor on the front of the collision post in the inward direction. This load was equal to 100×10^3 lbf (445 kN) for both the 1990s and the SOA end frames.
- A longitudinal load applied 18 in. (457 mm) above the floor on the front of the corner post in the inward direction. This load was 30×10^3 lbf (133 kN) for the 1990s end frame, and 100×10^3 lbf (445 kN) for the SOA end frame.
- A lateral load applied 18 in. (457 mm) above the floor on the side of the corner post in the inward direction. Again, this load was 30×10^3 lbf (133 kN) for the 1990s end frame, and 100×10^3 lbf (445 kN) for the SOA end frame.

The load was applied through a loading ram and load cell in series. Figure 26 shows an example for the collision post loading. The load was applied quasi-statically and the car was reacted at the opposite end through the coupler, for the case of longitudinal loads, and by a symmetric structural support for the case of the lateral load. The loads were applied over an area on a square bearing plate with an edge length equal to the width of the post. It is important to apply the loads over a minimum area to prevent excessive localized yielding or crimping of the posts webs.

Figure 26. End Frame Quasi-static Loading Test Arrangement; Strain Gage Locations are Shown by the Small Colored Points

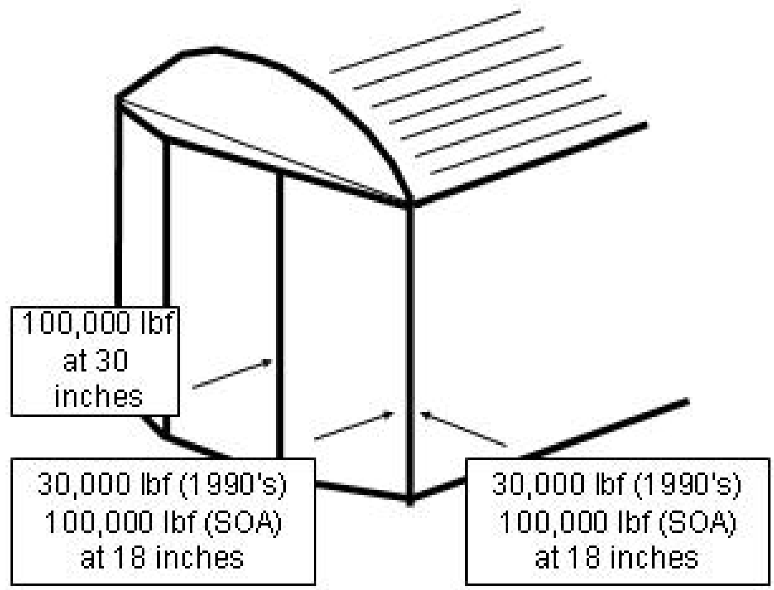


Figure 27. Static Loads Applied to the End Frames

In the analysis, the load was applied to the post through an 'indenter' that had a 3-inch (76-mm) radius at the point of contact, was 6 in. (152 mm) high and spanned the entire width of the post. Strains were interpolated from the analysis to correspond to the reported locations of the center of the gages.

Figures 28-33 show examples of strain comparisons between test and finite element analysis for a set of load cases and locations. The individual measurement and analysis results are provided in Appendix E. The analysis results agree well with the test measurements, particularly when the strain magnitudes are relatively large.

Review of the data in Appendix E shows that there is some disagreement in results for the draft sill and roof rail locations. In part, these strains are relatively low and poorer agreement is expected. In addition, the details of the car structure to which the end frame was attached were not characterized in detail and so there are likely differences between the actual test geometry and the geometry simulated in the model.

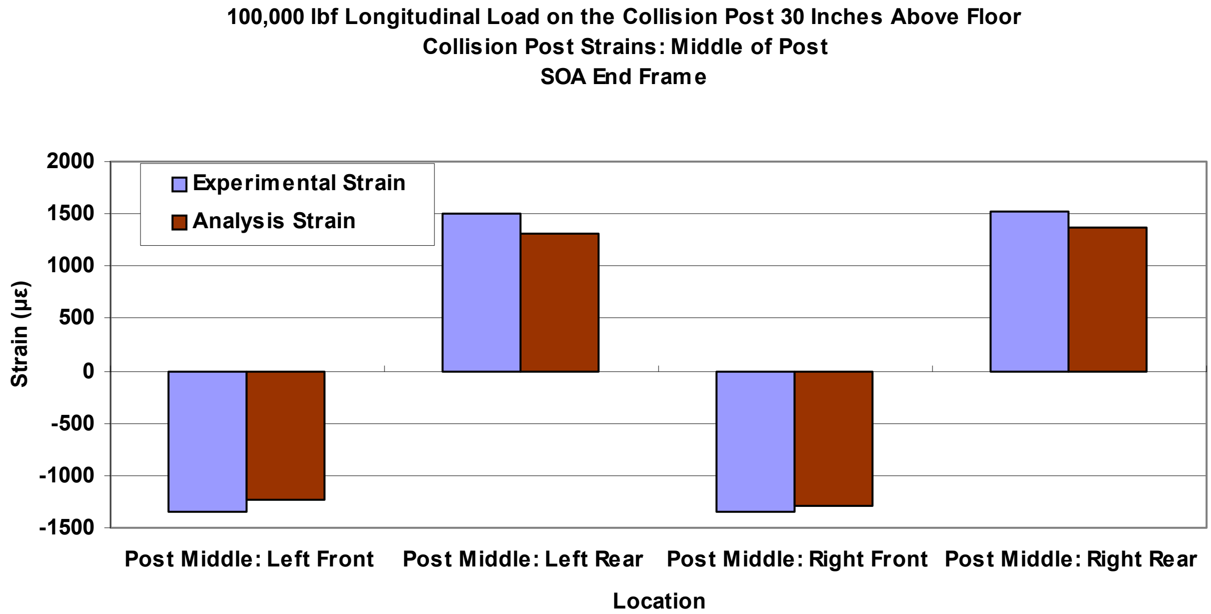


Figure 28. Comparison of Test to Analysis Results for the SOA Collision Post Loading Case: Strains at the Middle (Vertically) of the Collision Post

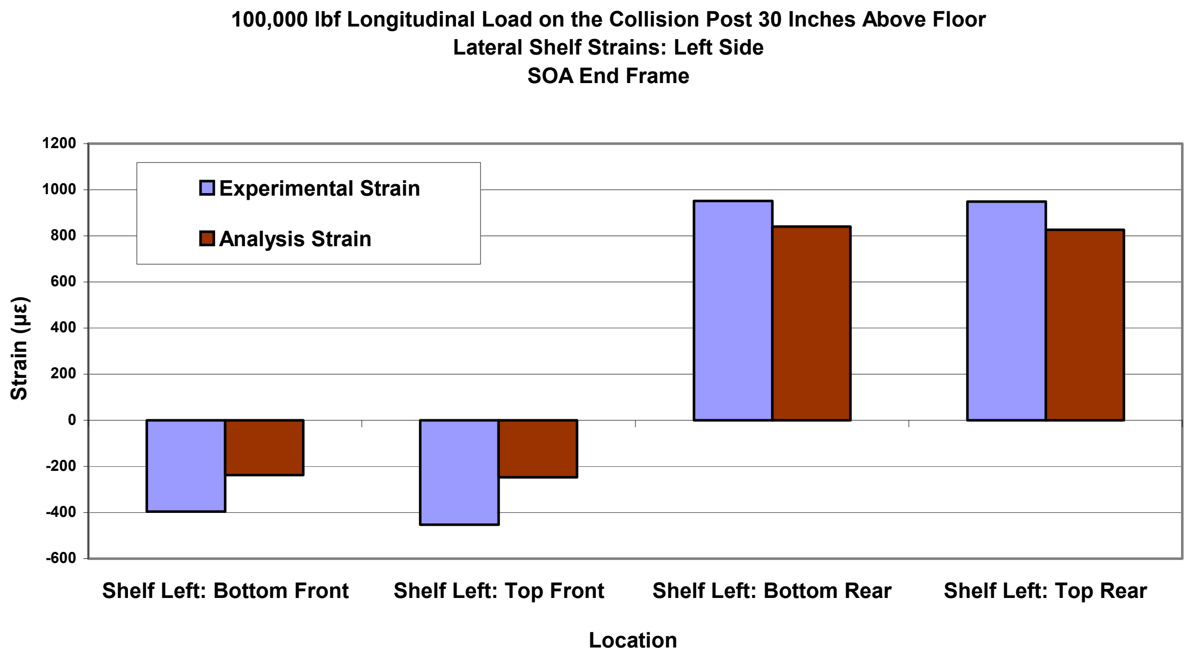


Figure 29. Comparison of Test to Analysis Results for the SOA Collision Post Loading Case: Strains at the Left-Hand (Collision Post) Side of the Lateral Shelf

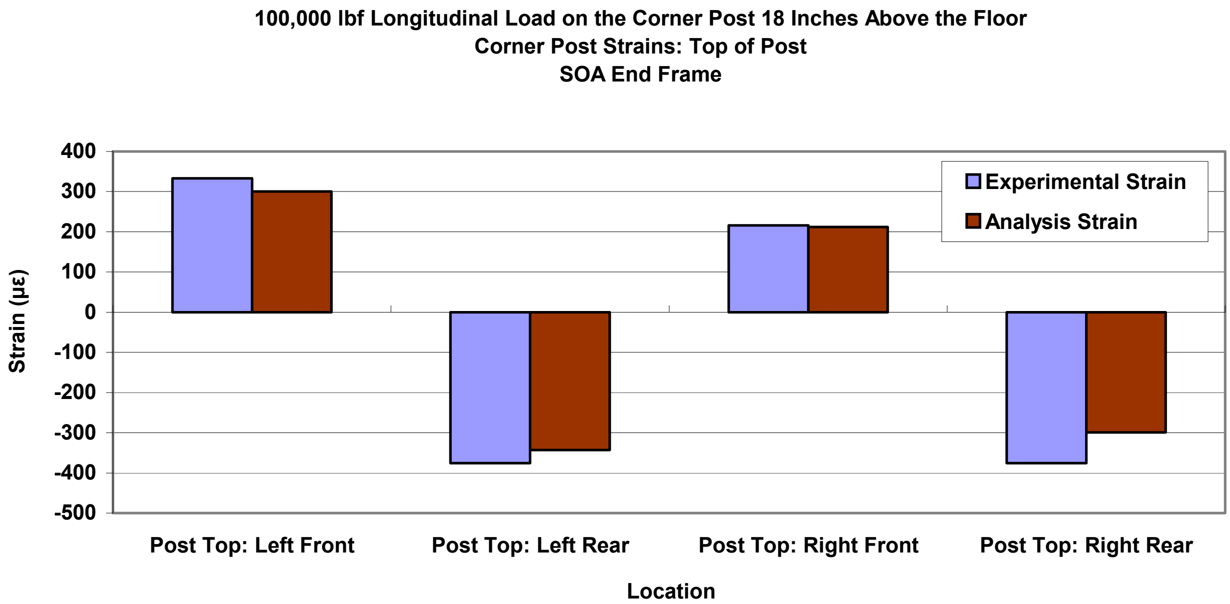


Figure 30. Comparison of Test to Analysis Results for the SOA Corner Post Loading Case: Strains at the Top of the Corner Post

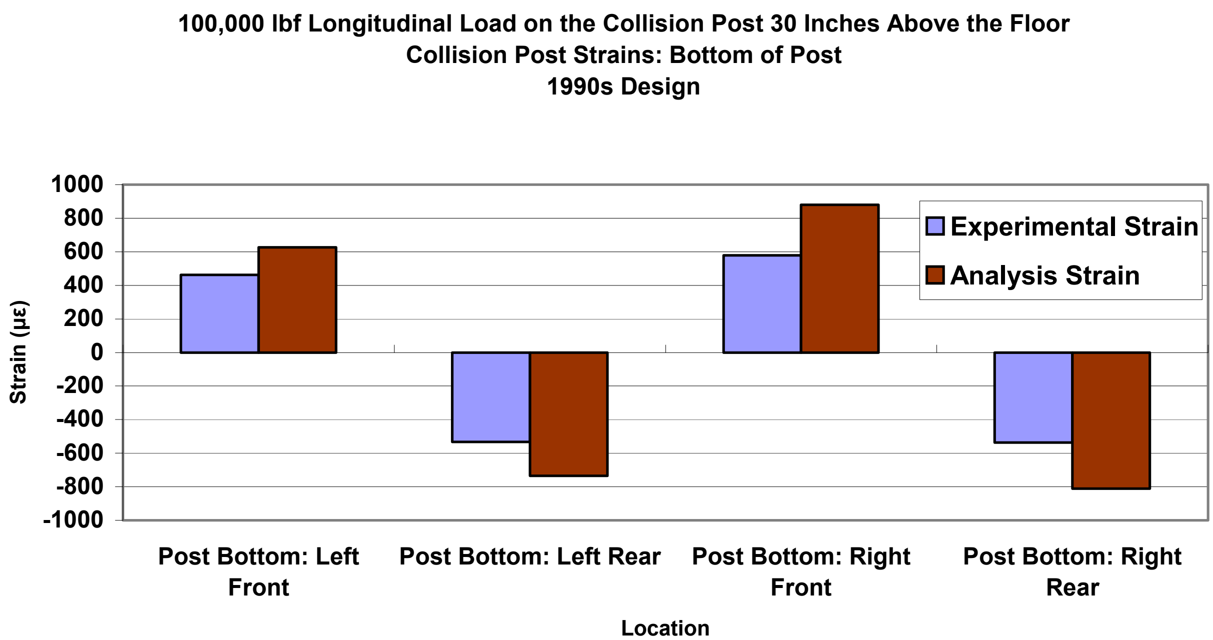


Figure 31. Comparison of Test to Analysis Results for the 1990s Collision Post Loading Case: Strains at the Bottom of the Collision Post

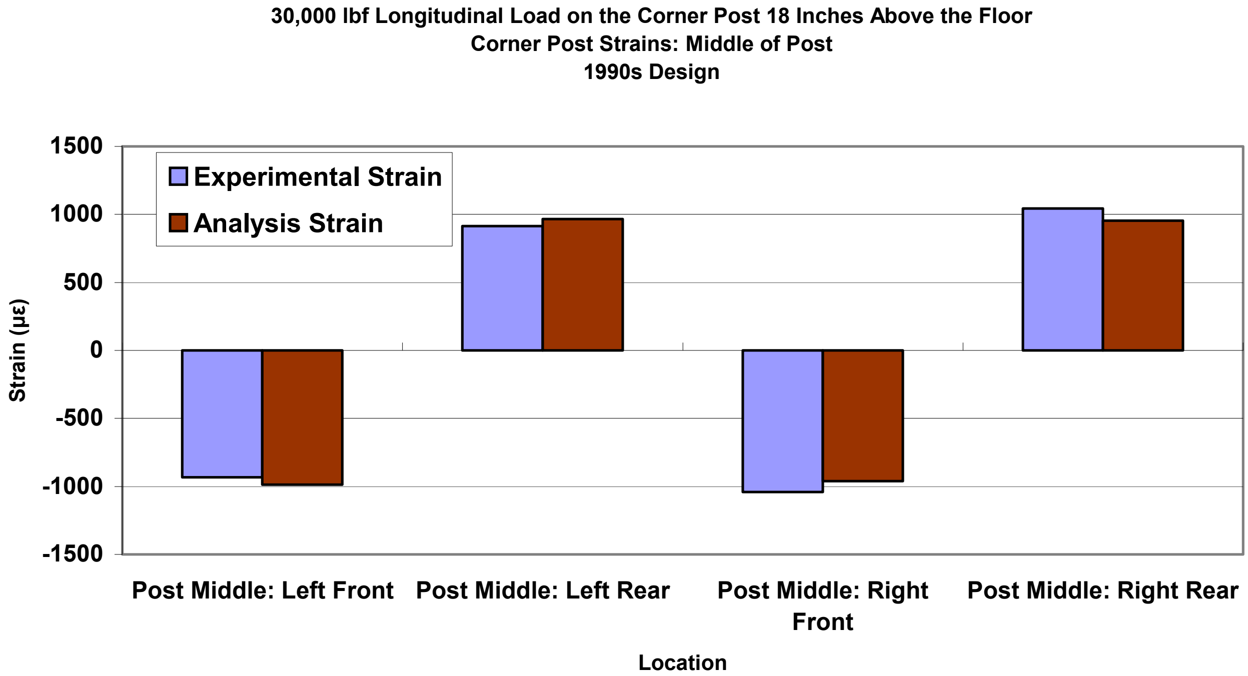


Figure 32. Comparison of Test to Analysis Results for the Lateral Corner Post Loading Case: Strains in the Shelf

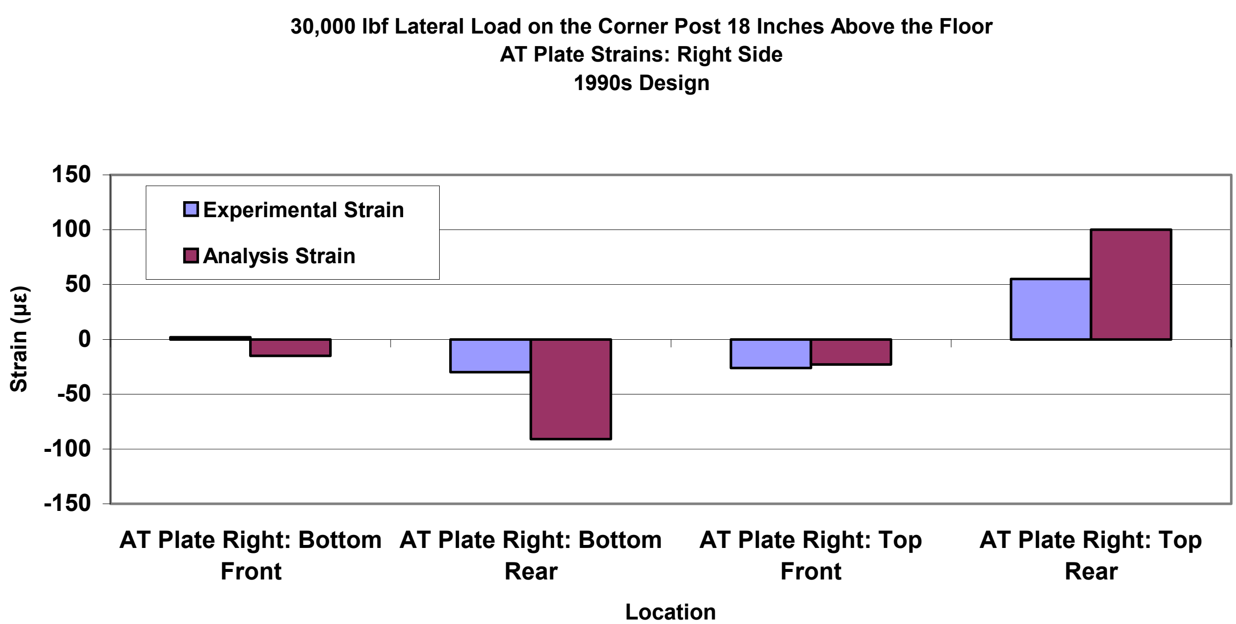


Figure 33. Comparison of Test to Analysis Results for the Lateral Corner Post Loading Case: Strains in the Shelf (Rear Surface)

8. Summary

This report describes the results of a program to design end frames for testing the differences in crashworthiness performance for cab cars that meet early to mid 1990s structural standards and cab cars designed to the current APTA and FRA structural requirements (SOA design). The program is part of a larger one being conducted to investigate how crashworthiness of rail vehicles in various configurations and collision scenarios can be improved. The end frames discussed here were used to evaluate the increase in cab car protection for a particular grade crossing collision scenario. The development of the designs relied on a review of industry practice over the last few decades and on prior research in the area of cab car crashworthiness. A detailed set of design requirements was developed that included the applicable structural requirements, the need to meet operability requirements and the need to adapt to existing test cars. Hand and beam element finite element analyses were used to develop the 1990s design, while detailed finite element analyses, including large deformation calculations, were carried out to develop the SOA design. The end frames were fabricated from A710 steel and shipped to the Transportation Test Center in Pueblo, Colorado, where they were attached to existing Budd Pioneer cars. Quasi-static loading tests were conducted on the frames after instrumentation by strain gages. Finally, the end frames were used in full-scale grade crossing collision tests in a separate program.

The results of this project demonstrate that the new APTA requirements can be met with designs that are very similar to those needed to satisfy the requirements used in the 1990s. For example, there is only a 250 lbm (113 kg) weight difference between the 1990s and SOA end frame designs. In addition, the analyses and the full-scale tests demonstrate that the stronger end frames provide a significant improvement in crashworthiness.

A number of important issues were raised in the course of this program. The SOA design relied on the use of the side sill to support the back of the end beam at the base of the corner post. This is possible because of the general acceptance by industry to eliminate the step well at the operator's corner. If a step well were present so that such a structural detail could not be used, the weight penalty would be much greater [11].

The ability to achieve a prescribed amount of deformation in the end frame posts has also been raised as an important issue. The SOA design was developed with the requirement that the post deform an amount equal to one times its depth for a load applied at 30 in. (762 mm) above the underframe (for the collision post) and 18 in. (457 mm) above the underframe (for the corner post) without cracking. This requirement was originally under discussion within APTA but eventually was not adopted. Instead, deformability is achieved in an indirect manner by requiring very strong connections between the posts and the end beam and the AT plate. In other words, the design can still be developed by considering only strength-based criteria. The concept of addressing energy absorption directly remains a topic of discussion.

The very successful performance of the SOA design in the full-scale test relative to the 1990s end frame demonstrates the potential for crashworthiness improvement [9,10].

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10. Jacobsen, K., Tyrell, D. and Perlman, B., "Rail Car Impact Tests with Steel Coil: Collision Dynamics," in Proceedings of ASME/IEEE Joint Railroad Conference, April 22-24, 2003, Chicago, IL (2003) 10 pages.
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Acronyms

AAR	American Association of Railroads
APTA	American Public Transportation Association
AT	Anti-Telescoping
CFR	Code of Federal Regulations
FRA	Federal Railroad Administration
MBTA	Massachusetts Bay Transportation Authority
SOA	State-of-the-Art
SS-C&S	Safety Standards-Construction/Structural (APTA)
TTC	Transportation Technology Center

Appendix A. Examples of Single Level Cab Cars

Table A-1. Examples of Single Level Cab Cars

Owner, Service Area	Manufacturer Car Series	Delivery Date	Quantity: Cabs (C) No cab (N)	Comments
MARC Baltimore-Washington	Nippon Sharyo	1991/2	6 C 28 N	Cars operate at up to 110mph on Northeast Corridor with cab leading
MBTA Boston	Bombardier	1989/90	53 C 54 N	Ex-Pullman aluminum body car design. End doors with stairwell
NICTD Chicago	Sumitomo	1992	7 C 10 N	Electric MU cars. Cab cars have two cabs. End doors with stairwell
NICTD Chicago	Nippon Sharyo	2000-01	10C	Electric MU cars. All cars have cabs End doors with stairwell
Connecticut DOT New Haven	Bombardier	1991	10 C	Ex Pullman aluminum design, 2 cabs, end doors with stairwell
MNCR New York	Bombardier	1991-9	58 C 95N	Ex Pullman aluminum design. Most have end doors with stairwell plus a floor-height center door.
MNCR New York	Morrison Knudsen M6	1995-6	60 C	Electric MU cars with 2 sets of center doors and no stairwells for high platform operation
NJT Northern New Jersey	Bomb Comet III/IV	1990-97	31 C 119 N	Ex-Pullman aluminum design. End doors with stairwell
NJT Northern New Jersey	Alstom Comet V	2001-3	200 Total 130 Firm, incl 50 C	New design, probably with stairwells at non-cab ends. Required to be compliant with new FRA/APTA requirements
SEPTA Philadelphia	Bombardier	1999-2000	10 N	Ex-Pullman aluminum design. End doors with stairwell.
VRE Washington	Morrison Knudsen	1992	10 C 28 N	Have end doors with stairwells
VRE Washington	Kawasaki	1999	4 C 9 N	End doors with stairwell
Amtrak	Morrison Knudsen view-liners	1993-4	51 N	All sleepers for eastern routes. Door with stairwell at one end of car only. No cab cars
LIRR/ MNCR New York	Bombardier M7	2001 on	Up to 808 326 firm for LIRR	New design of electric MU car for high-level platforms. No stairwells. Originally ordered May 1999, before new FRA/APTA regulations

Appendix B. Requirements for the Cab Car End Frames

B-1. Introduction

B-1.1. Purpose

The purpose of this specification is to define the requirements for the rail passenger cab car end structures to be fabricated onto an existing rail vehicle.

B-1.2. Definitions

B-1.2.1. Budd Pioneer Car

The vehicles to which the designs of this project must be adapted. These vehicles were used in the first two full-scale collision tests at TTCI in Pueblo, Colorado. The vehicles conform to the design defined by the drawings in Appendix A.

B-1.2.2. Permanent deformation

There is technically no permanent deformation if a stress analysis shows that the Mises stress does not exceed the minimum specified yield strength.

B-2. Reference Documents/Drawings

B-2.1. Budd Pioneer Drawings

See attached list, Appendix A.

B-2.2. Standards

B-2.2.1. AWS D1.1

B-2.2.2. APTA SS-C&S-034-99, Standard for the Design and Construction of Passenger Railroad Rolling Stock, The American Public Transportation Association, Washington, D.C.

B-2.2.3. Code of Federal Regulations, Title 49, Part 238, Various Sections (Last Revised October 1, 2003.)

B-2.2.4. AAR-S-034, Specifications for the Construction of New Passenger Equipment Cars, The Association of American Railroads, Last Revised, 1969.

B-3. General Description

The cab car end structures, whose specifications are outlined in this document, are for use in full-scale tests to be conducted in late 2001. These tests will be used to investigate the collision performance of cab cars in simulated grade crossing collisions. One design will emulate a structure typical of those cab cars designed in the 1990s timeframe; the other design will emulate cab car end structures that satisfy the most recent, 'State-of-the-Art' (SOA) designs as defined, for example by the APTA SS-C&S-034-99 standard. The cab cars equipped with these end structure designs will be tested either alone or in a consist representing a commuter train. The cab car will collide with some type of object intended to simulate an object in a grade crossing. The most likely such object, as of this writing, is a steel coil whose center of mass is offset laterally from the centerline of the vehicle at the instant of collision. The cars must also satisfy certain operational requirements in addition to the strength characteristics so that they could be used (mechanically) in actual service if incorporated into a modern rail coach car.

The requirements listed here are derived from two sources: (1) actual car requirements from operating companies; and (2) industry and federal requirements. The former is, in part, represented by the specifications for the Bombardier MBTA single level cars that have been in operation in the 1990s. The latter requirements are partly contained in APTA SS-C&S-034-99, Standard for the Design and Construction of Passenger Railroad Rolling Stock and its predecessor, AAR S-034, and the Code of Federal Regulations, Title 49, Part 238.

B-4. Specific Requirements

The requirements are divided into three major sections:

- Requirements specific to the 1990s design (Section 4.1)
- Requirements specific to the State-of-the-Art (SOA) design (Section 4.2)
- Requirements common to both designs (Section 4.3)

B-4.1. 1990s Design Requirements

B-4.1.1. Coupler Carrier

The coupler carrier shall be capable of resisting a downward force applied to the coupler shank of $100x10^3$ lbf (445 kN), for any position of the coupler, without permanent deformation.

B-4.1.2. Coupler

The coupler and its supporting structure shall be capable of resisting an upward force of $100x10^3$ lbf (445 kN) without permanent deformation.

B-4.1.3. End Strength

The strength of the vehicle end shall be at least $800x10^3$ lbf (3,560 kN) without permanent deformation. This load shall be applied to the rear draft stops ahead of the bolster on the centerline of draft.

B-4.1.4. Collision Posts

B-4.1.4.1. Description

There shall be two full height collision posts extending from the underframe to the cant rail or roofline. They shall be located at the approximate 1/3 points across the width of the vehicle and shall, in their entirety, be forward of the seating position of any crew person.

B-4.1.4.2. Strength

The collision post shall resist each one of the following horizontal inward loads individually applied at any angle within 15 degrees of the longitudinal axis:

a) Minimum $300x10^3$ lbf (1,330 kN) applied at a point even with the top of the underframe, without exceeding the ultimate shear strength of the post.
b) Minimum $300x10^3$ lbf (1,330 kN) applied at a point 18 in. (457 mm) above the top of the underframe, without exceeding the ultimate strength.

Any reinforcement required to provide the specified $300x10^3$ lbf (1,330 kN) shear strength at the top of the underframe, shall extend with its full section from the bottom of the end sill to a distance of 18 in. (457 mm). The reinforcement must then taper to a point approximately 30 in. (762 mm) above the top of the underframe. In addition, the connection of the post to the anti-telescoping plate/roof structure shall have sufficient ultimate strength to sustain loads produced by bending the collision post to its ultimate strength. Each collision post and any shear reinforcement, if used, shall be welded to the top and bottom plates of the end sill with the equivalent of AWS pre-qualified welded joints.

B-4.1.5. Corner Posts

B-4.1.5.1. Description

The vehicle end shall have two structural corner posts, one located at each extreme corner of the car body structure. The corner posts shall extend from the bottom of the underframe structure to the bottom of the roof structure.

B-4.1.5.2. Strength

Each corner post and intervening connections shall resist each of the following horizontal loads individually applied toward the inside of the vehicle in any direction from longitudinal to transverse:

a) Minimum $150x10^3$ lbf (667 kN) applied at a point even with the top of the underframe, without exceeding the ultimate shear strength of the post.

b) Minimum $30x10^3$ lbf (133 kN) applied at a point 18 in. (457 mm) above the top of the underframe, without permanent deformation.

In addition, the connection of the post to the anti-telescoping plate/roof structure shall have sufficient ultimate strength to sustain loads produced by bending the corner post to its ultimate strength.

B-4.1.6. Horizontal Framing Members

B-4.1.6.1. Description

There shall be a horizontal structural member between the collision post and the corner post at a height equivalent to the bottom of the windshield.

B-4.1.6.2. Strength

The horizontal member shall be capable of carrying a longitudinally oriented load of $15x10^3$ lbf (66.7 kN) anywhere along its length without causing permanent deformation.

B-4.1.7. Stepwell

The vehicle end shall include space for a stepwell. However, an actual stepwell need not be included.

B-4.2. State-of-the-Art Design Requirements

B-4.2.1. Coupler Carrier

The coupler carrier shall be capable of resisting a downward force applied to the coupler shank of $100x10^3$ lbf (445 kN) without permanent deformation.

B-4.2.2. Coupler

The coupler and its supporting structure shall be capable of resisting an upward force of $100x10^3$ lbf (445 kN) without permanent deformation.

B-4.2.3. End Strength

The strength of the vehicle end shall be at least $800x10^3$ lbf (3,560 kN) without permanent deformation. This load shall be applied longitudinally over an area not exceeding 6-in. (152 mm) high and a width not exceeding the distance between outboard webs of the collision posts, centered vertically and horizontally on the underframe end sill or end beam construction.

B-4.2.4. Collision Posts

B-4.2.4.1. Description

There shall be two full height collision posts extending from the underframe to the cant rail or roofline. They shall be located at the approximate 1/3 points across the width of the vehicle and shall, in their entirety, be forward of the seating position of any crew person.

B-4.2.4.2. Strength

The collision post shall resist each one of the following horizontal inward loads individually applied at any angle within 15 degrees of the longitudinal axis:

a) Minimum $500x10^3$ lbf (2,224 kN) applied at a point even with the top of the underframe, without exceeding the ultimate shear strength of the post.
b) Minimum $200x10^3$ lbf (890 kN) applied at a point 30 in. (762 mm) above the top of the underframe, without exceeding the ultimate strength.
c) Minimum $60x10^3$ (267 kN) applied at any height along the post above the top of the underframe, without permanent deformation.

The area properties of the collision posts, including any reinforcement required to provide the specified $500x10^3$ lbf (2,224 kN) shear strength at the top of the underframe, shall extend from the bottom of the end sill to at least 30 in. (762 mm) above the top of the underframe. Each collision post and any shear reinforcement, if used, shall be welded to the top and bottom plates of the end sill with the equivalent of AWS pre-qualified welded joints.

The collision post and its supporting structure shall be designed so that if overloaded at a point 30 in. (762 mm) above the underframe, failure shall begin as bending or buckling in the post. The connections of the post to the supporting structure, and the supporting car body structure, shall support the post at its ultimate capacity. The ultimate shear and tensile strength of the connecting fasteners or welds shall be sufficient to resist the forces causing the deformation, so that shear and tensile failure of the fasteners or welds shall not occur, even with '*severe deformation*' of the collision post and its connecting and supporting structural elements. For purposes of design, severe deformation shall mean the depth of the post of inward deformation at 30 in. (762 mm) above the underframe.

B-4.2.5. Corner Posts

B-4.2.5.1. Description

The end structure shall have two structural corner posts, one located at each extreme corner of the car body structure. The corner posts shall extend from the bottom of the underframe structure to the bottom of the roof structure.

B-4.2.5.2. Strength

Each corner post and intervening connections shall resist each of the following horizontal loads individually applied toward the inside of the vehicle in any direction from longitudinal to transverse:

a) Minimum $300x10^3$ lbf (1,330 kN) applied at a point even with the top of the underframe, without exceeding the ultimate shear strength of the post.
b) Minimum $100x10^3$ lbf (445 kN) applied at a point 18 in. (457 mm) above the top of the underframe, without permanent deformation.
c) Minimum $45x10^3$ lbf (200 kN) applied anywhere between the top of the post at its connection to the roof structure, and the top of the underframe, without permanent deformation.

The area properties of the corner posts, including any reinforcement required to provide the specified $300x10^3$ pound (1,330 kN) shear strength at the top of the underframe, shall extend from the bottom of the end sill to at least 30 in. (762 mm) above the top of the underframe. Each corner post and any shear reinforcement, if used, shall be welded to the top and bottom plates of the end sill with the equivalent of AWS pre-qualified welded joints.

The corner post and its supporting structure shall be designed so that if overloaded at a point 30 in. (762 mm) above the underframe, failure shall begin as bending or buckling in the post. The connections of the post to the supporting structure, and the supporting car body structure, shall support the post at its ultimate capacity. The ultimate shear and tensile strength of the connecting fasteners or welds shall be sufficient to resist the forces causing the deformation, so that shear and tensile failure of the fasteners or welds shall not occur, even with '*severe deformation'* of the collision post and its connecting and supporting structural elements. For purposes of design, severe deformation shall mean the depth of the post of longitudinal, inward deformation at 30 in. (762 mm) above the underframe.

B-4.2.6. Horizontal Framing Members

B-4.2.6.1. Description

There shall be a horizontal structural member between the collision post and the corner post at a height equivalent to the bottom of the windshield.

B-4.2.6.2. Strength

The horizontal member shall be capable of carrying a longitudinally oriented load of $15x10^3$ lbf (66.7 kN) anywhere along its length without causing permanent deformation.

B-4.2.7. Stepwell

The vehicle end shall not include space for a stepwell.

B-4.3. Operational Requirements (Both Designs)

B-4.3.1. Coupler System

B-4.3.1.1. Coupler

The coupler shall be a Type H tightlock coupler. There is no specific requirement on shank length except that it must be compatible with the other requirements of this specification.

B-4.3.1.2. Coupler Carrier

A coupler carrier must be provide that includes a spring loaded device to ensure that the coupler remains level during normal use.

B-4.3.1.3. Draft Gear

The coupling system shall include a draft gear capable of absorbing low speed impacts**.**

B-4.3.1.3.1. General
The coupling system shall include a draft gear capable of absorbing low speed impacts.

B-4.3.2. Uncoupling
The vehicle end shall be equipped with an AAR Style No.6 uncoupling mechanism.

B-4.4. Test Requirements

B-4.4.1. General
The vehicle ends designed and built to this specification will be used for full-scale testing. Therefore, it is important that the design facilitate measurements and observations to be made during the tests. The types of tests envisioned include:

a) a single vehicle colliding with an object representing a grade crossing obstacle;
b) a multiple vehicle consist colliding with the rigid surface; and
c) a multiple vehicle consist colliding with a grade crossing obstacle.

The tests will be conducted at TTC in Pueblo, Colorado.

B-4.4.2. Visibility
The vehicle end shall be designed in such a way that it will be possible to view the collision and corner posts during crush deformation in the test. For example, parts of the roof and sides must remain open to facilitate viewing by cameras mounted on the ground or on the vehicle.

B-4.5. Fabrication Requirements

B-4.5.1. General
The design should utilize materials and fabrication methods that a normal metal fabrication company could use.

B-4.5.2. Materials and Construction Methods
B-4.5.2.1. Materials
The materials of construction for the primary structure shall be either high strength low alloy (also known as low-alloy, high tensile) or austenitic stainless steels commonly used in the fabrication of modern railway vehicles for operation in North America. The energy absorbing elements shall be constructed from either the steels mentioned above and/or aluminum honeycomb.

B-4.5.2.2. Construction Methods
All primary structural members shall be welded in accordance with AWS D1.1.

B-4.5.2.2.1. Overall vehicle integration.
The end structure shall be designed so that it can be integrated into the existing Budd Pioneer coach cars. The goal of the design shall be to minimize the amount of effort required for building the end structures into the existing cars.

B-4.6. Physical Requirements

B-4.6.1. Envelope

The end structures are to be attached to the end of one of the existing Budd Pioneer cars. Its outer boundaries should not exceed those of the as-built Budd Pioneer cars with the possible exception of the length beyond the bolster center point.

B-4.6.2. Curving

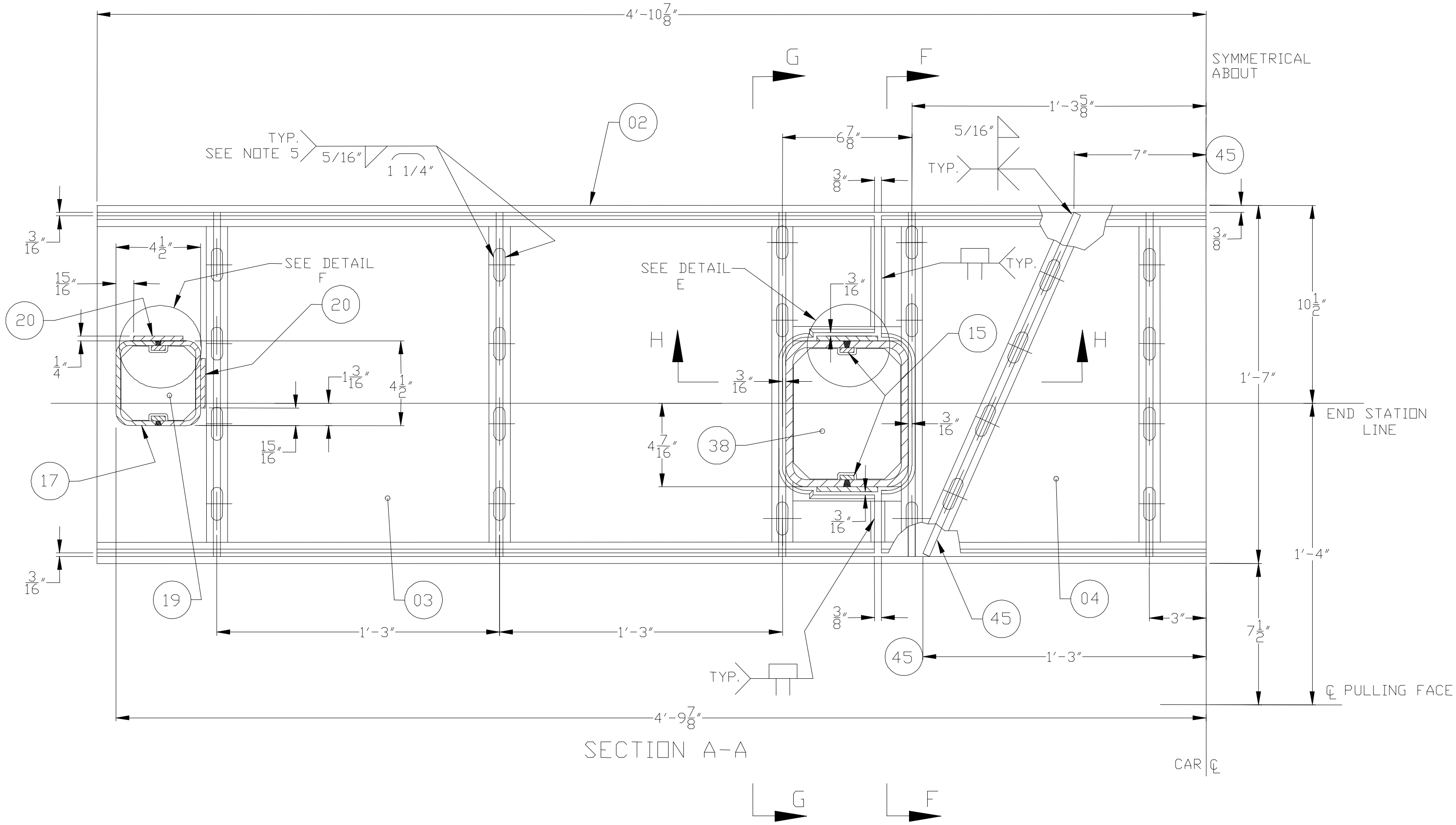
The components of the vehicle end shall not interfere for operation with nominally identical cars operating on curves as tight as a 250-foot (76.2 m) radius.

B-4.6.3. Space for Normal Equipment

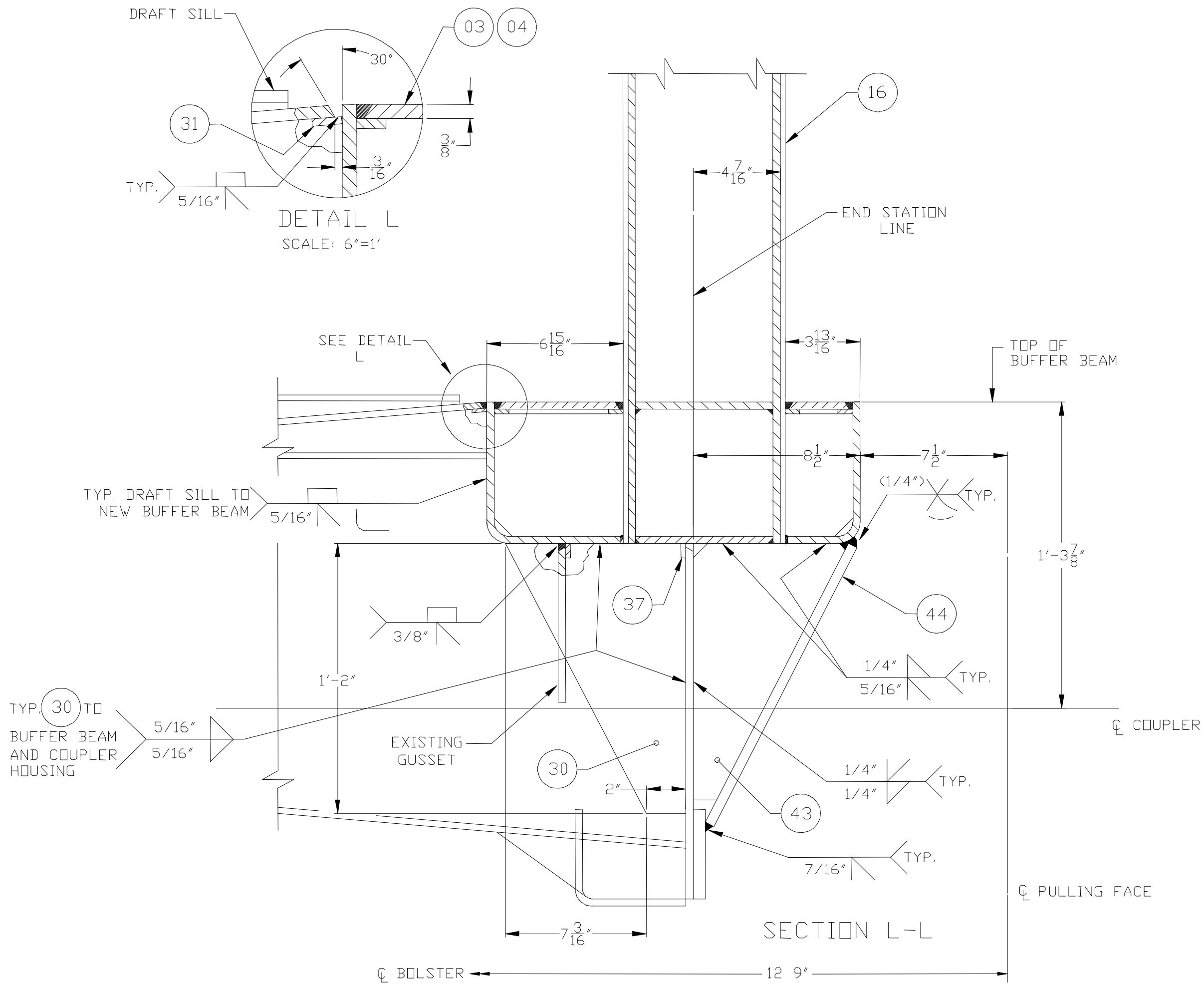
Although much of the usual equipment found on passenger rail cars will not be included in this design, the design shall provide space for this equipment. Openings, piping and other equipment normally associated with this equipment need not be included. The equipment not already specified includes:

- Hand brake
- HEP (head end power)
- 27-point communication line
- Trainline box
- Electronic brake box
- Diaphragm

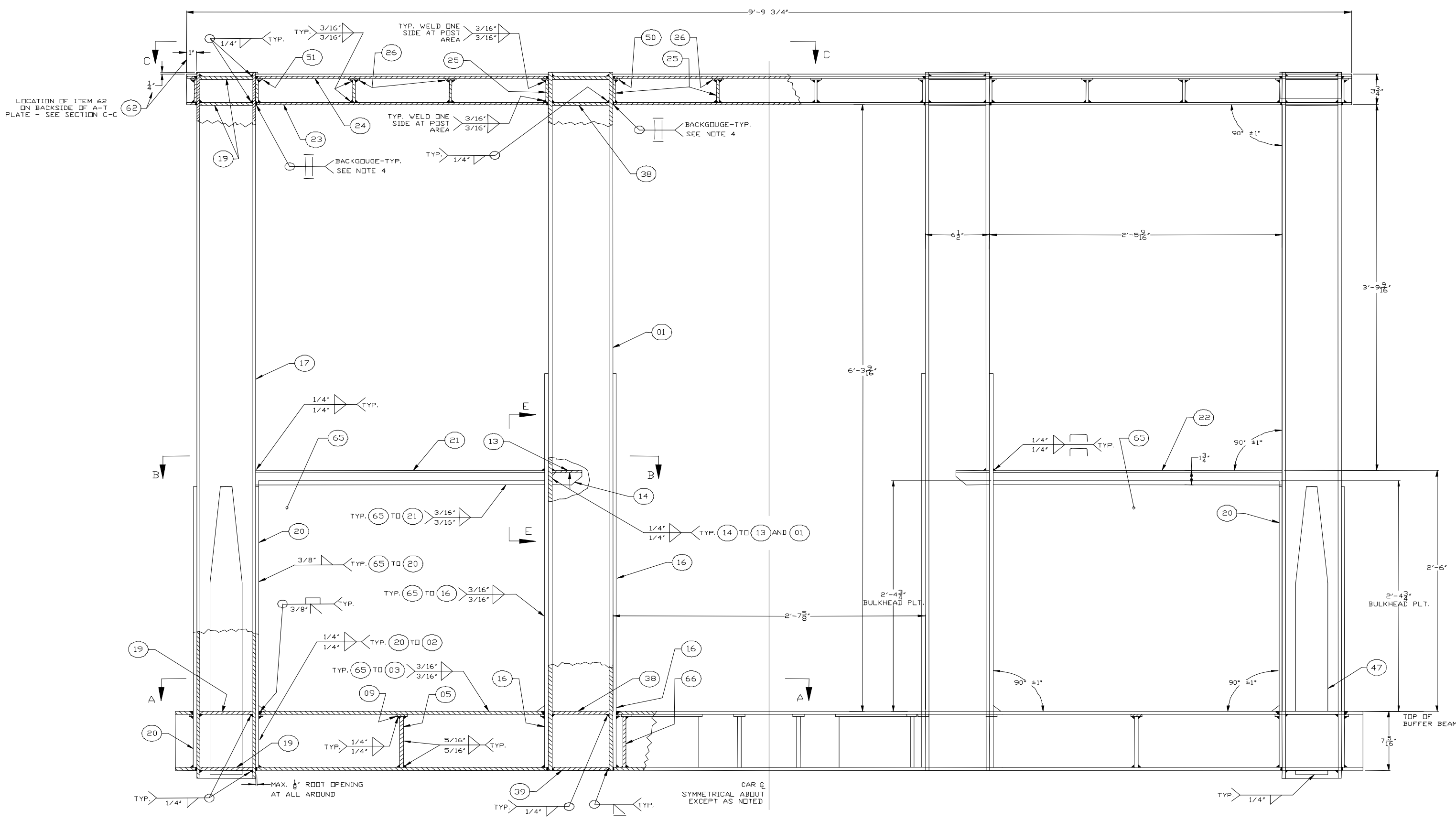
Appendix C. Sections from the Drawings Used to Fabricate the End Frames



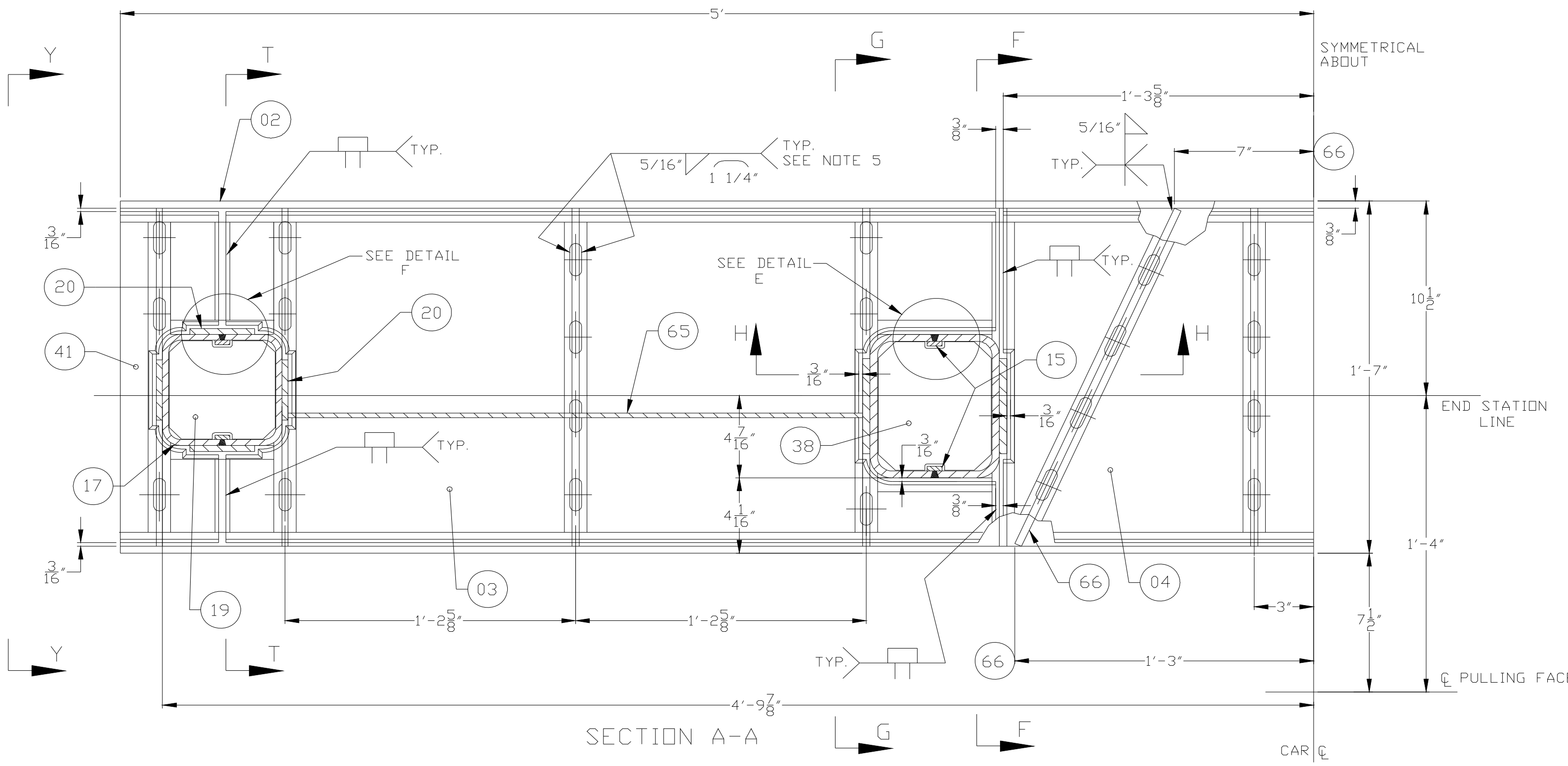
Plan View of the Left Side of the Buffer Beam with Collision and Corner Posts in Section; 1990s Design



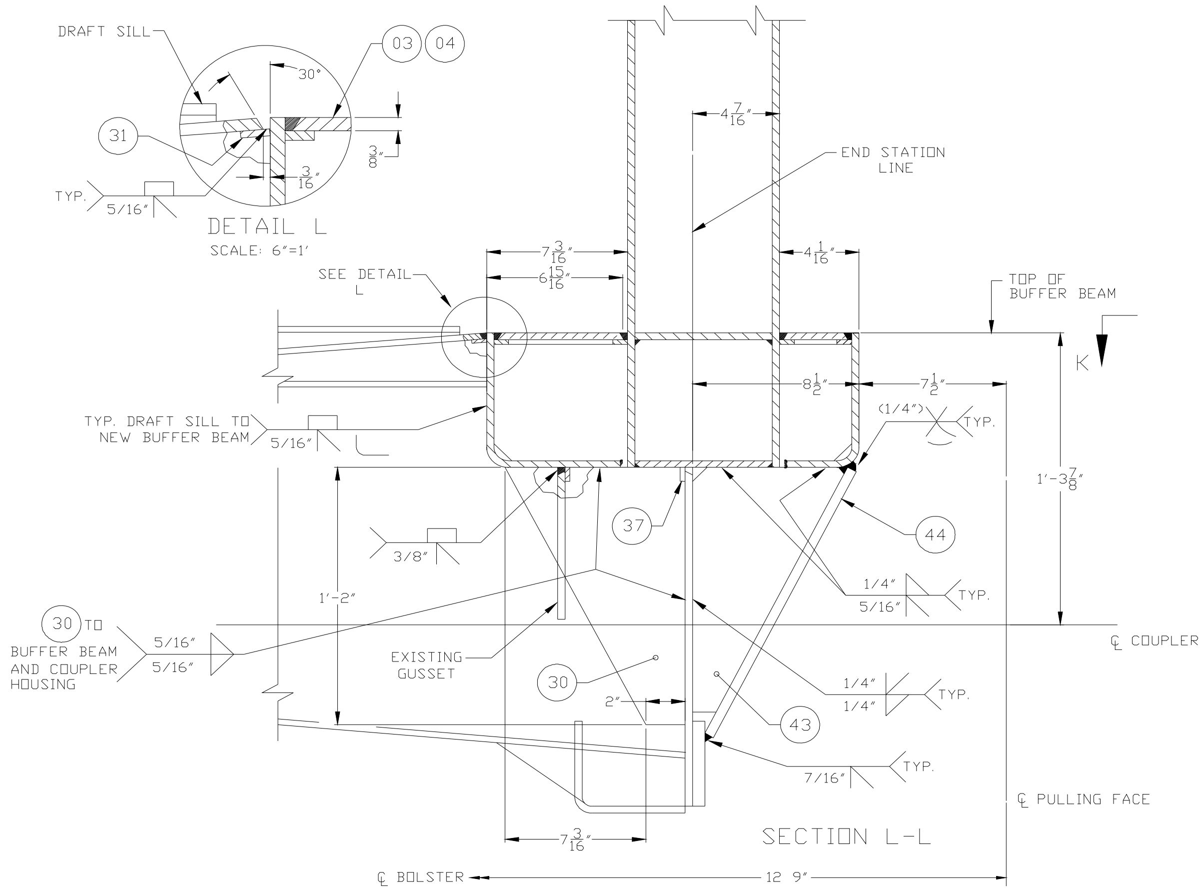
Side View Section Through the Collision Post and Buffer Beam; 1990s Design



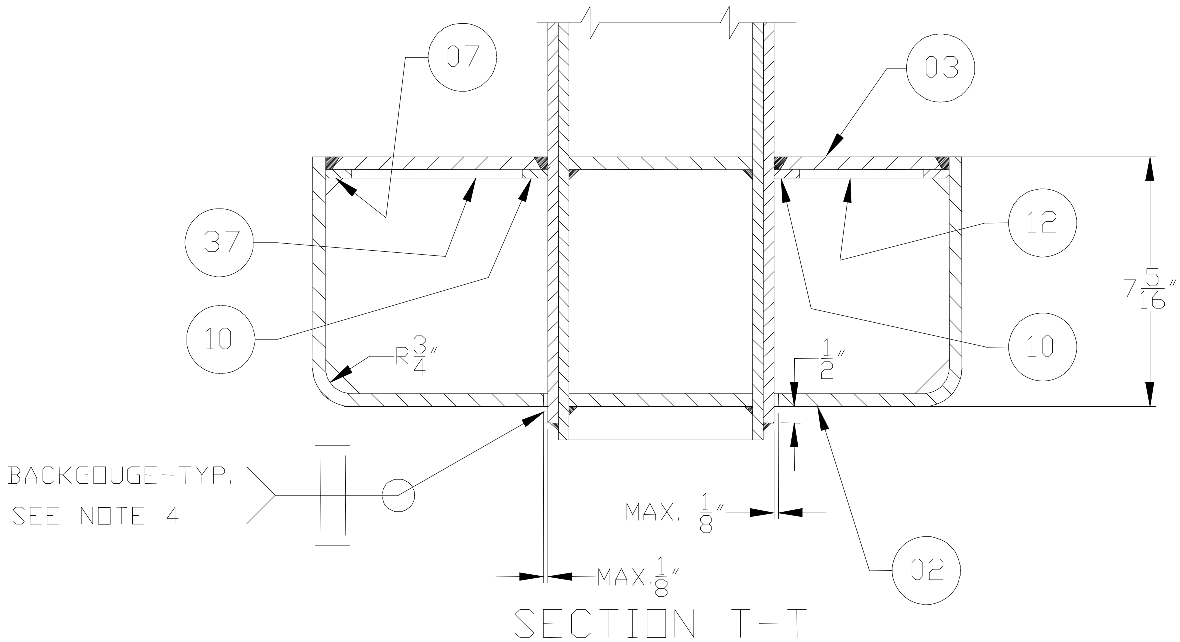
Front Elevation of the State-of-the-Art End Frame



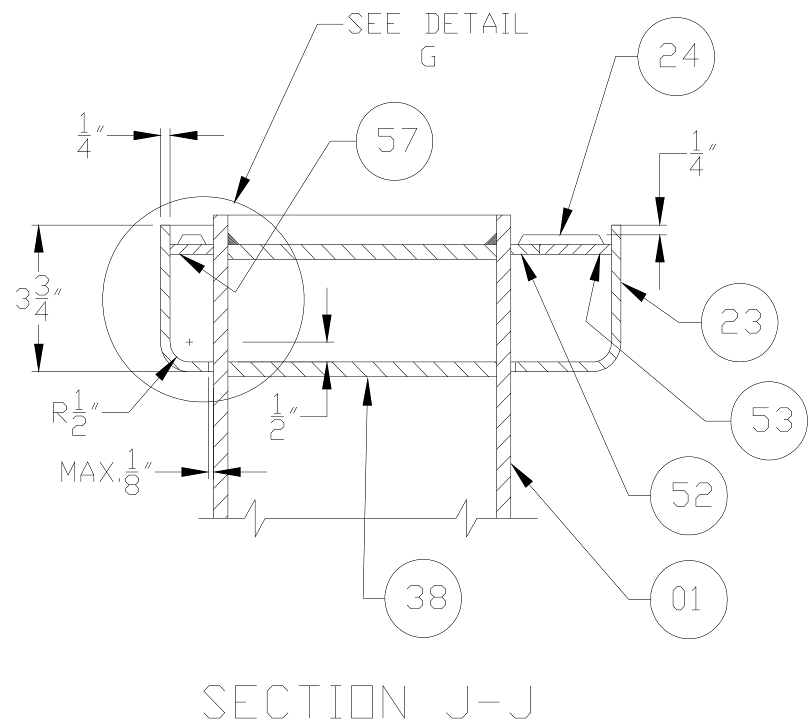
Plan View of the Left Side of the Buffer Beam with Collision and Corner Posts in Section; State-of-the-Art Design



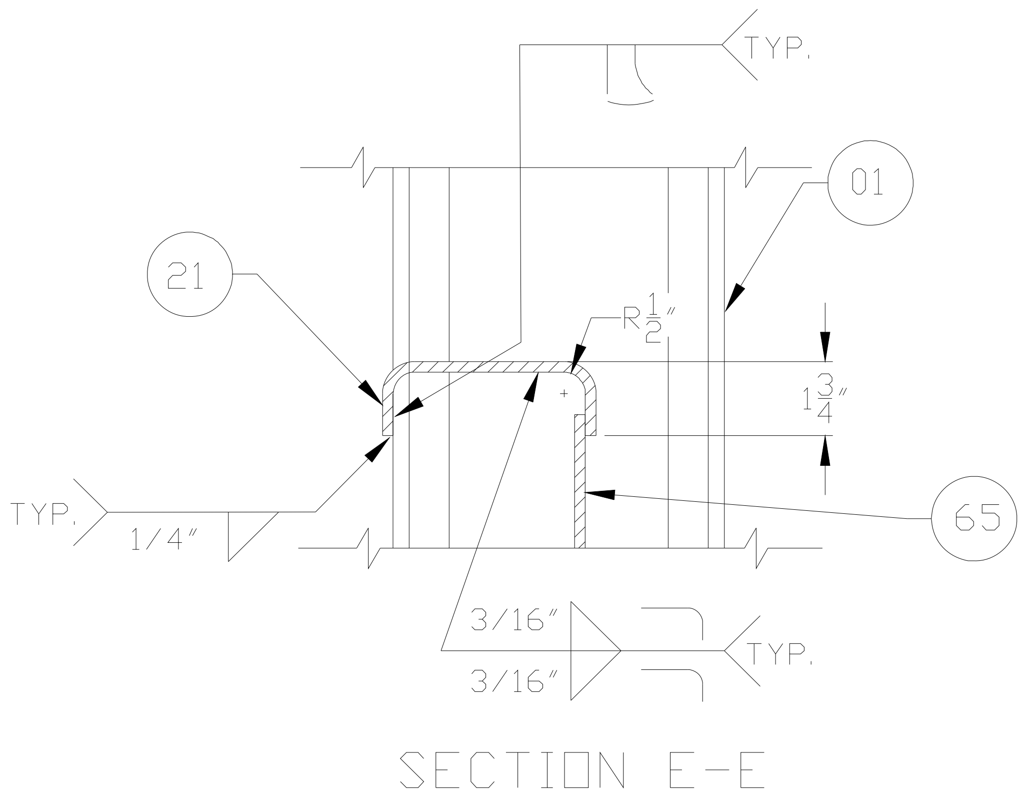
Section through the Buffer Beam and Collision Post at the Draft Sill; State-of-the-Art Design



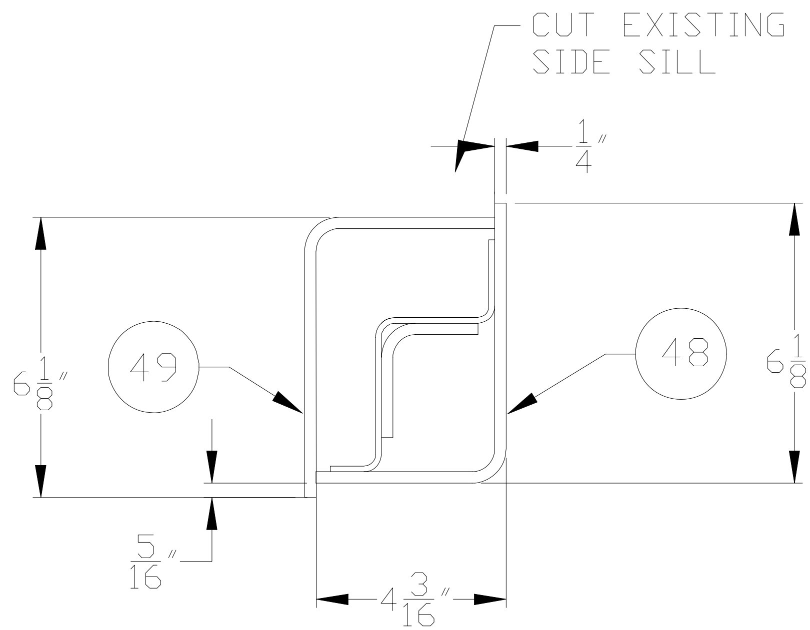
Section through the Corner Post and Buffer Beam; State-of-the-Art Design



Section through the Collision Post/AT Plate; State-of-the-Art Design



Section through the Lateral Shelf and Bulkhead; State-of-the-Art Design



SECTION V-V

Section of the Side Sill between the Buffer Beam and Bolster; State-of-the-Art Design

Appendix D. Example Calculation for Collision Post Strength

This section provides an example of one of the hand calculation procedures used in the design of the end frames. It is for the case in which the collision post must possess an ultimate strength for a longitudinal load applied at and above the underframe. The example given here is for the SOA design for which the collision post must possess an ultimate strength of 500x10^3 lbf (2,224 kN) for a longitudinal load applied at the underframe, and 200x10^3 lbf (890 kN) for a longitudinal load applied 30 in. (762 mm) above the underframe.

The 500,000 lbf shear load determines the area of the webs of the post:

$$A_w \geq \frac{F_u}{\tau_u} = \frac{F_u}{0.58\sigma_u} = \frac{500{,}000}{0.58(90{,}000)} = 9.58 in^2$$

where A_w is the area of the webs
F_u is the ultimate load
τ_u is the ultimate strength in shear of the post and lug material
σ_u is the ultimate tensile strength of the post and lug material.

The collision post cross section is shown in Figure D-1. The area of the webs in this case is:

$$A_w = 2[(0.375)(7.75) + (0.375)(5.125)] = 9.66 in^2,$$

which is greater than the required area.

The ultimate strength for a load applied at 30 in. (762 mm) above the underframe is, by the requirements, to be determined by a plastic collapse bending mechanism. For this particular geometry and loading, the first plastic hinge in the post forms at the underframe. Plastic collapse then occurs when a hinge forms at the load point; the attachment to the AT plate is assumed to behave as simply supported for the entire loading.

The ultimate strength in this case can be determined by the equilibrium method of plastic limit load analysis (c.f. [D1]) The beam is assumed to be in equilibrium at the point that a mechanism is formed for which the bending moment at the hinges is equal to the plastic moment. (In the collision post case the hinge at the AT plate is taken as a true hinge.) Then the plastic moment required to balance the applied load is given by:

$$M_p = \frac{l_1 l_2}{l + l_2} P_u$$

where, l_1 = the distance from the applied load to the plastic hinge at the support

l_2 = the distance from the applied load to the true hinge
$l = l_1 + l_2$
P_u = the applied load.

In the present case then, the required plastic moment is:

$$M_p = \frac{(30)(45.56)}{75.56 + 45.56}(200{,}000) = 2.26x10^6\, in - lbf\,.$$

The plastic moment for the collision post section with lugs, which extend to 45 in. (1140 mm) above the underframe, is 2.28×10^6 in-lbf (257×10^3 N-m).

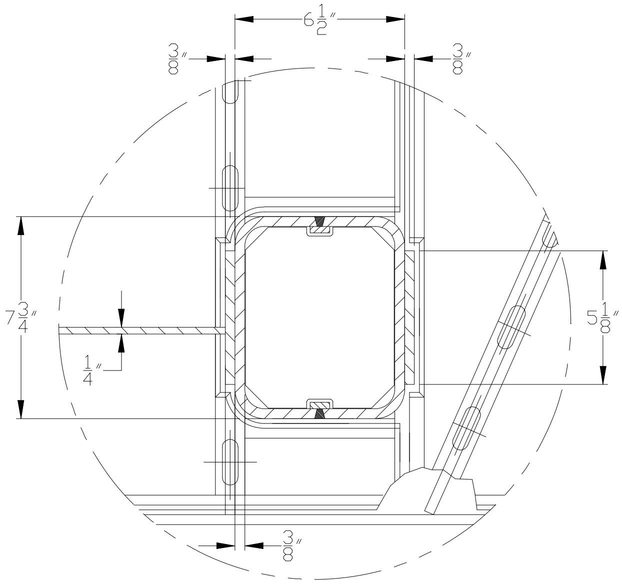


Figure D-1. The SOA Collision Post Cross Section

Reference

1. Steel Structures; Design and Behavior, 3rd Edition (HarpersCollins)1990.

Appendix E. Tables of Strains from Test Measurements and Finite Element Analysis

(See Section 7 of the main text for a description of the strain gage locations.)

Table E-1. 1990s Design: 30,000 lbf (9,140 N) Longitudinal Load on Corner Post, 18 In. Above Floor

Component (Orientation)	Location	Forward Surface Gage	Forward Surface Measured Strain (με)	Forward Surface Model Strain (με)	Rear Surface Gage	Rear Surface Measured Strain (με)	Rear Surface Model Strain (με)
Corner Post (Vertical)	Bottom Left	SG-COR-BFL	455	265	SG-COR-BRL	-308	-389
	Bottom Right	SG-COR-BFR	-227	-281	SG-COR-BRR	262	257
	Middle Left	SG-COR-MFL	-933	-987	SG-COR-MRL	914	965
	Middle Right	SG-COR-MFR	-1040	-961	SG-COR-MRR	1042	954
	Top Left	SG-COR-TFL	551	302	SG-COR-TRL	-636	-313
	Top Right	SG-COR-TFR	-66	-71	SG-COR-TRR	-268	-518
Collision Post (Vertical)	Bottom Left	SG-COL-BFL	-203	-97	SG-COL-BRL	160	78
	Bottom Right	SG-COL-BFR	-214	-171	SG-COL-BRR	221	169
	Middle Left	SG-COL-MFL	-232	-184	SG-COL-MRL	234	183
	Middle Right	SG-COL-MFR	-226	-176	SG-COL-MRR	227	160
	Top Left	SG-COL-TFL	-6	-1	SG-COL-TRL	11	-2
	Top Right	SG-COL-TFR	-15	-26	SG-COL-TRR	17	23
AT Plate (Lateral)	Left Top	SG-ATP-LFT	0 (failed)	-72	SG-ATP-LRT	177	123
	Left Bottom	SG-ATP-LFB	-166	-107	SG-ATP-LRB	147	95
	Middle Top	SG-ATP-MFT	-65	-37	SG-ATP-MRT	48	43
	Middle Bottom	SG-ATP-MFB	-61	-39	SG-ATP-MRB	82	51
	Right Top	SG-ATP-RFT	78	36	SG-ATP-RRT	-168	-109
	Right Bottom	SG-ATP-RFB	-17	9	SG-ATP-RRB	154	-21
Lateral Member/Shelf (Lateral)	Left Top	SG-LM-LFT	973	-279	SG-LM-LRT	-1013	333
	Left Bottom	SG-LM-LFB	667	-325	SG-LM-LRB	-1025	334
	Middle Top	SG-LM-MFT	192	184	SG-LM-MRT	-225	-245
	Middle Bottom	SG-LM-MFB	152	140	SG-LM-MRB	-210	-247
	Right Top	SG-LM-RFT	-613	-399	SG-LM-RRT	632	422
	Right Bottom	SG-LM-RFB	-444	-394	SG-LM-RRB	571	487
End beam (Lateral)	Center Top	SG-BB-CFT	261	248	SG-BB-CBT	-229	-217
	Center Bottom	SG-BB-CFB	261	256	SG-BB-CBB	-251	-249
	End Top	SG-BB-EFT	-4	20	SG-BB-EBT	4	1
	End Bottom	SG-BB-EFB	4	5	SG-BB-EBB	-4	-3
Component (Orientation)	**Location**	**Outer Surface Gage**	**Outer Surface Measured Strain (με)**	**Outer Surface Model Strain (με)**	**Inner Surface Gage**	**Inner Surface Measured Strain (με)**	**Inner Surface Model Strain (με)**
Draft Sill (Longitudinal)	Top Forward	SG-DS-TRF	-495	-223	SG-DS-TLF	443	227
	Bottom Fwd.	SG-DS-BRF	-12	197	SG-DS-BLF	166	-126
	Top Middle	SG-DS-TRM	-354	-130	SG-DS-TLM	340	171
	Bottom Middle	SG-DS-BRM	-112	100	SG-DS-BLM	249	-15
	Top Rear	SG-DS-TRR			SG-DS-TLR		
	Bottom Rear	SG-DS-BRR			SG-DS-BLR		
Cant Rail (Longitudinal)	Top Forward	SG-CR-TRF			SG-CR-TLF	-160	-87
	Bottom Fwd.	SG-CR-BRF			SG-CR-BLF	-309	-317
	Top Middle	SG-CR-TRM			SG-CR-TLM	-170	-33
	Bottom Middle	SG-CR-BRM			SG-CR-BLM	-164	-59
	Top Rear	SG-CR-TRR			SG-CR-TLR		
	Bottom Rear	SG-CR-BRR			SG-CR-BLR		

Table E-2. 1990s Design: 30,000 lbf (9,140 N) Lateral Load on Corner Post, 18 In. (460 mm) Above Floor

Component (Orientation)	Location	Forward Surface			Aft Surface		
		Gage	Measured Strain (με)	Model Strain (με)	Gage	Measured Strain (με)	Model Strain (με)
Corner Post (Vertical)	Bottom Left	SG-COR-BFL	125	13	SG-COR-BRL	-23	42
	Bottom Right	SG-COR-BFR	-42	-32	SG-COR-BRR	-12	-43
	Middle Left	SG-COR-MFL	-42	-30	SG-COR-MRL	-29	-45
	Middle Right	SG-COR-MFR	4	27	SG-COR-MRR	23	-35
	Top Left	SG-COR-TFL	-42	5	SG-COR-TRL	4	5
	Top Right	SG-COR-TFR	6	20	SG-COR-TRR	96	-85
Collision Post (Vertical)	Bottom Left	SG-COL-BFL	-31	-160	SG-COL-BRL	-162	-194
	Bottom Right	SG-COL-BFR	162	220	SG-COL-BRR	93	224
	Middle Left	SG-COL-MFL	129	118	SG-COL-MRL	91	117
	Middle Right	SG-COL-MFR	-81	-112	SG-COL-MRR	-145	-132
	Top Left	SG-COL-TFL	12	10	SG-COL-TRL	6	-7
	Top Right	SG-COL-TFR	-14	-3	SG-COL-TRR	27	-5
AT Plate (Lateral)	Left Top	SG-ATP-LFT	0 (failed)	-76	SG-ATP-LRT	-118	-69
	Left Bottom	SG-ATP-LFB	89	28	SG-ATP-LRB	91	43
	Middle Top	SG-ATP-MFT	-19	-28	SG-ATP-MRT	-25	-7
	Middle Bottom	SG-ATP-MFB	23	-16	SG-ATP-MRB	15	6
	Right Top	SG-ATP-RFT	-26	-23	SG-ATP-RRT	55	100
	Right Bottom	SG-ATP-RFB	2	-15	SG-ATP-RRB	-30	-91
Lateral Member/Shelf (Lateral)	Left Top	SG-LM-LFT	-278	90	SG-LM-LRT	-318	107
	Left Bottom	SG-LM-LFB	-145	77	SG-LM-LRB	-259	109
	Middle Top	SG-LM-MFT	-350	-337	SG-LM-MRT	-375	-291
	Middle Bottom	SG-LM-MFB	-438	-372	SG-LM-MRB	-438	-328
	Right Top	SG-LM-RFT	-499	-447	SG-LM-RRT	-419	-317
	Right Bottom	SG-LM-RFB	-659	-522	SG-LM-RRB	-579	-339
End beam (Lateral)	Center Top	SG-BB-CFT	-10	-13	SG-BB-CBT	-34	-10
	Center Bottom	SG-BB-CFB	-29	-38	SG-BB-CBB	-50	-22
	End Top	SG-BB-EFT	-2	-3	SG-BB-EBT	0	-1
	End Bottom	SG-BB-EFB	6	4	SG-BB-EBB	6	4
Component (Orientation)	**Location**	**Outer Surface**			**Inner Surface**		
		Gage	**Measured Strain (με)**	**Model Strain (με)**	**Gage**	**Measured Strain (με)**	**Model Strain (με)**
Draft Sill (Longitudinal)	Top Forward	SG-DS-TRF	-10	-7	SG-DS-TLF	-4	-7
	Bottom Fwd.	SG-DS-BRF	12	-2	SG-DS-BLF	-10	3
	Top Middle	SG-DS-TRM	66	-13	SG-DS-TLM	-73	12
	Bottom Middle	SG-DS-BRM	-8	-4	SG-DS-BLM	14	0
	Top Rear	SG-DS-TRR			SG-DS-TLR		
	Bottom Rear	SG-DS-BRR			SG-DS-BLR		
Cant Rail (Longitudinal)	Top Forward	SG-CR-TRF			SG-CR-TLF	69	61
	Bottom Fwd.	SG-CR-BRF			SG-CR-BLF	103	45
	Top Middle	SG-CR-TRM			SG-CR-TLM	39	32
	Bottom Middle	SG-CR-BRM			SG-CR-BLM	46	14
	Top Rear	SG-CR-TRR			SG-CR-TLR		
	Bottom Rear	SG-CR-BRR			SG-CR-BLR		

Table E-3. 1990s Design: 100,000 lbf (30,500 N) Longitudinal Load on Collision Post, 30 In. (760 mm) Above Floor

Component (Orientation)	Location	Forward Surface			Aft Surface		
		Gage	Measured Strain (με)	Model Strain (με)	Gage	Measured Strain (με)	Model Strain (με)
Corner Post (Vertical)	Bottom Left	SG-COR-BFL	-567	-264	SG-COR-BRL	374	275
	Bottom Right	SG-COR-BFR	-13	10	SG-COR-BRR	-13	-3
	Middle Left	SG-COR-MFL	-446	-355	SG-COR-MRL	345	282
	Middle Right	SG-COR-MFR	-354	-296	SG-COR-MRR	345	312
	Top Left	SG-COR-TFL	139	30	SG-COR-TRL	-195	-33
	Top Right	SG-COR-TFR	-10	14	SG-COR-TRR	-189	-65
Collision Post (Vertical)	Bottom Left	SG-COL-BFL	462	626	SG-COL-BRL	-533	-735
	Bottom Right	SG-COL-BFR	578	879	SG-COL-BRR	-537	-812
	Middle Left	SG-COL-MFL	-1432	-1564	SG-COL-MRL	1838	1572
	Middle Right	SG-COL-MFR	-1573	-1638	SG-COL-MRR	1865	1674
	Top Left	SG-COL-TFL	-50	-64	SG-COL-TRL	-55	44
	Top Right	SG-COL-TFR	-41	-60	SG-COL-TRR	-46	27
AT Plate (Lateral)	Left Top	SG-ATP-LFT	0 (failed)	-728	SG-ATP-LRT	1147	867
	Left Bottom	SG-ATP-LFB	-921	-802	SG-ATP-LRB	825	651
	Middle Top	SG-ATP-MFT	-490	-369	SG-ATP-MRT	499	424
	Middle Bottom	SG-ATP-MFB	-533	-421	SG-ATP-MRB	509	371
	Right Top	SG-ATP-RFT	-32	-42	SG-ATP-RRT	-40	-2
	Right Bottom	SG-ATP-RFB	-162	-40	SG-ATP-RRB	255	-146
Lateral Member/Shelf (Lateral)	Left Top	SG-LM-LFT	-829	172	SG-LM-LRT	909	-187
	Left Bottom	SG-LM-LFB	-819	168	SG-LM-LRB	800	-204
	Middle Top	SG-LM-MFT	-194	-115	SG-LM-MRT	211	153
	Middle Bottom	SG-LM-MFB	-139	-78	SG-LM-MRB	206	163
	Right Top	SG-LM-RFT	474	274	SG-LM-RRT	-450	-263
	Right Bottom	SG-LM-RFB	596	342	SG-LM-RRB	-451	-309
End beam (Lateral)	Center Top	SG-BB-CFT	59	49	SG-BB-CBT	55	18
	Center Bottom	SG-BB-CFB	-95	-52	SG-BB-CBB	48	55
	End Top	SG-BB-EFT	0	0	SG-BB-EBT	2	-2
	End Bottom	SG-BB-EFB	2	26	SG-BB-EBB	6	3
Component (Orientation)	**Location**	**Outer Surface-53**			**Inner Surface**		
		Gage	**Measured Strain (με)**	**Model Strain (με)**	**Gage**	**Measured Strain (με)**	**Model Strain (με)**
Draft Sill (Longitudinal)	Top Forward	SG-DS-TRF	-634	-53	SG-DS-TLF	414	527
	Bottom Fwd.	SG-DS-BRF	271	232	SG-DS-BLF	373	-115
	Top Middle	SG-DS-TRM	-489	-91	SG-DS-TLM	282	272
	Bottom Middle	SG-DS-BRM	230	266	SG-DS-BLM	529	111
	Top Rear	SG-DS-TRR			SG-DS-TLR		
	Bottom Rear	SG-DS-BRR			SG-DS-BLR		
Cant Rail (Longitudinal)	Top Forward	SG-CR-TRF			SG-CR-TLF	-636	-435
	Bottom Fwd.	SG-CR-BRF			SG-CR-BLF	-840	-756
	Top Middle	SG-CR-TRM			SG-CR-TLM	-507	-245
	Bottom Middle	SG-CR-BRM			SG-CR-BLM	-444	-230
	Top Rear	SG-CR-TRR			SG-CR-TLR		
	Bottom Rear	SG-CR-BRR			SG-CR-BLR		

Table E-4. SOA Design: 100,000 lbf (30,500 N) Longitudinal Load on Corner Post, 18 In. (460 mm) Above Floor

Component (Orientation)	Location	Forward Surface			Rear Surface		
		Gage	Measured Strain (με)	Model Strain (με)	Gage	Measured Strain (με)	Model Strain (με)
Corner Post (Vertical)	Bottom Left	SG-COR-BFL	2	765	SG-COR-BRL	-698	-905
	Bottom Right	SG-COR-BFR	484	729	SG-COR-BRR	-461	-645
	Middle Left	SG-COR-MFL	-1124	-1224	SG-COR-MRL	1135	1260
	Middle Right	SG-COR-MFR	-1175	-1235	SG-COR-MRR	1177	1091
	Top Left	SG-COR-TFL	333	300	SG-COR-TRL	-376	-343
	Top Right	SG-COR-TFR	216	212	SG-COR-TRR	-376	-299
Collision Post (Vertical)	Bottom Left	SG-COL-BFL	-192	-95	SG-COL-BRL	142	98
	Bottom Right	SG-COL-BFR	-275	-166	SG-COL-BRR	321	217
	Middle Left	SG-COL-MFL	-317	-251	SG-COL-MRL	317	282
	Middle Right	SG-COL-MFR	-287	-266	SG-COL-MRR	300	232
	Top Left	SG-COL-TFL	-23	-69	SG-COL-TRL	79	57
	Top Right	SG-COL-TFR	-173	-101	SG-COL-TRR	119	109
AT Plate (Lateral)	Left Top	SG-ATP-LFT	-12	-107	SG-ATP-LRT	148	161
	Left Bottom	SG-ATP-LFB	-158	-157	SG-ATP-LRB	85	171
	Middle Top	SG-ATP-MFT	-15	-86	SG-ATP-MRT	48	133
	Middle Bottom	SG-ATP-MFB	-40	-104	SG-ATP-MRB	34	122
	Right Top	SG-ATP-RFT	-27	-49	SG-ATP-RRT	-57	100
	Right Bottom	SG-ATP-RFB	82	-25	SG-ATP-RRB	21	64
Lateral Member/Shelf (Lateral)	Left Top	SG-LM-LFT	392	437	SG-LM-LRT	-956	-982
	Left Bottom	SG-LM-LFB	356	400	SG-LM-LRB	-1036	-1054
	Middle Top	SG-LM-MFT	177	159	SG-LM-MRT	-105	-124
	Middle Bottom	SG-LM-MFB	152	148	SG-LM-MRB	-101	-121
	Right Top	SG-LM-RFT	-95	-127	SG-LM-RRT	823	860
	Right Bottom	SG-LM-RFB	-206	-233	SG-LM-RRB	933	933
End beam (Lateral)	Center Top	SG-BB-CFT	155	113	SG-BB-CBT	-120	-91
	Center Bottom	SG-BB-CFB	160	146	SG-BB-CBB	-164	-129
	End Top	SG-BB-EFT	-15	-3	SG-BB-EBT	195	-442
	End Bottom	SG-BB-EFB	-10	5	SG-BB-EBB	25	12
Component (Orientation)	**Location**	**Outer Surface**			**Inner Surface**		
		Gage	**Measured Strain (με)**	**Model Strain (με)**	**Gage**	**Measured Strain (με)**	**Model Strain (με)**
Draft Sill (Longitudinal)	Top Forward	SG-DS-TRF	-98	223	SG-DS-TLF	117	373
	Bottom Fwd.	SG-DS-BRF	292	228	SG-DS-BLF	238	211
	Top Middle	SG-DS-TRM	-46	150	SG-DS-TLM	81	142
	Bottom Middle	SG-DS-BRM	290	272	SG-DS-BLM	292	129
	Top Rear	SG-DS-TRR	58		SG-DS-TLR	40	
	Bottom Rear	SG-DS-BRR	102		SG-DS-BLR	92	
Cant Rail (Longitudinal)	Top Forward	SG-CR-TRF	85		SG-CR-TLF	-79	-55
	Bottom Fwd.	SG-CR-BRF	54		SG-CR-BLF	-606	-562
	Top Middle	SG-CR-TRM	-10		SG-CR-TLM	-234	
	Bottom Middle	SG-CR-BRM	-37		SG-CR-BLM	-260	
	Top Rear	SG-CR-TRR	-148		SG-CR-TLR	-110	
	Bottom Rear	SG-CR-BRR	10		SG-CR-BLR	-27	

Table E-5. SOA Design: 100,000 lbf (30,500 N) Lateral Load on Corner Post, 18 In. (460 mm) Above Floor

Component (Orientation)	Location	Forward Surface			Aft Surface		
		Gage	Measured Strain (με)	Model Strain (με)	Gage	Measured Strain (με)	Model Strain (με)
Corner Post (Vertical)	Bottom Left	SG-COR-BFL	13	47	SG-COR-BRL	-299	-297
	Bottom Right	SG-COR-BFR	-27	-65	SG-COR-BRR	200	279
	Middle Left	SG-COR-MFL	131	201	SG-COR-MRL	11	97
	Middle Right	SG-COR-MFR	-238	-343	SG-COR-MRR	-118	-145
	Top Left	SG-COR-TFL	-160	-195	SG-COR-TRL	-166	-273
	Top Right	SG-COR-TFR	129	176	SG-COR-TRR	139	131
Collision Post (Vertical)	Bottom Left	SG-COL-BFL	6	-2	SG-COL-BRL	-90	-67
	Bottom Right	SG-COL-BFR	137	90	SG-COL-BRR	88	49
	Middle Left	SG-COL-MFL	265	135	SG-COL-MRL	265	88
	Middle Right	SG-COL-MFR	-154	-60	SG-COL-MRR	-275	-120
	Top Left	SG-COL-TFL	-144	-57	SG-COL-TRL	-135	-58
	Top Right	SG-COL-TFR	167	84	SG-COL-TRR	158	89
AT Plate (Lateral)	Left Top	SG-ATP-LFT	-307	-129	SG-ATP-LRT	-409	-171
	Left Bottom	SG-ATP-LFB	204	97	SG-ATP-LRB	226	102
	Middle Top	SG-ATP-MFT	-40	-25	SG-ATP-MRT	-55	-29
	Middle Bottom	SG-ATP-MFB	13	-15	SG-ATP-MRB	-10	-13
	Right Top	SG-ATP-RFT	190	48	SG-ATP-RRT	349	148
	Right Bottom	SG-ATP-RFB	-164	-87	SG-ATP-RRB	-349	-164
Lateral Member/Shelf (Lateral)	Left Top	SG-LM-LFT	-322	-264	SG-LM-LRT	-286	-345
	Left Bottom	SG-LM-LFB	-299	-245	SG-LM-LRB	-145	-211
	Middle Top	SG-LM-MFT	-190	-139	SG-LM-MRT	-507	-484
	Middle Bottom	SG-LM-MFB	-175	-141	SG-LM-MRB	-541	-515
	Right Top	SG-LM-RFT	-173	24	SG-LM-RRT	-743	-701
	Right Bottom	SG-LM-RFB	-154	17	SG-LM-RRB	-1147	-887
End beam (Lateral)	Center Top	SG-BB-CFT	-205	-169	SG-BB-CBT	-234	-167
	Center Bottom	SG-BB-CFB	56	17	SG-BB-CBB	6	-30
	End Top	SG-BB-EFT	-66	-6	SG-BB-EBT	-73	60
	End Bottom	SG-BB-EFB	54	6	SG-BB-EBB	48	-47
Component (Orientation)	**Location**	**Outer Surface**			**Inner Surface**		
		Gage	**Measured Strain (με)**	**Model Strain (με)**	**Gage**	**Measured Strain (με)**	**Model Strain (με)**
Draft Sill (Longitudinal)	Top Forward	SG-DS-TRF	-67	-19	SG-DS-TLF	37	-17
	Bottom Fwd.	SG-DS-BRF	12	5	SG-DS-BLF	12	-5
	Top Middle	SG-DS-TRM	-13	-2	SG-DS-TLM	0	-9
	Bottom Middle	SG-DS-BRM	-23	-16	SG-DS-BLM	42	-15
	Top Rear	SG-DS-TRR	33		SG-DS-TLR	-21	
	Bottom Rear	SG-DS-BRR	17		SG-DS-BLR	-31	
Cant Rail (Longitudinal)	Top Forward	SG-CR-TRF	-12		SG-CR-TLF	46	38
	Bottom Fwd.	SG-CR-BRF	-19		SG-CR-BLF	42	-35
	Top Middle	SG-CR-TRM	-2		SG-CR-TLM	19	28
	Bottom Middle	SG-CR-BRM	-2		SG-CR-BLM	23	20
	Top Rear	SG-CR-TRR	0		SG-CR-TLR	4	
	Bottom Rear	SG-CR-BRR	13		SG-CR-BLR	8	

Table E-6. SOA Design: 100,000 lbf (30,500 N) Longitudinal Load on Collision Post, 30 In. (760 mm) Above Floor

Component (Orientation)	Location	Forward Surface			Aft Surface		
		Gage	Measured Strain (με)	Model Strain (με)	Gage	Measured Strain (με)	Model Strain (με)
Corner Post (Vertical)	Bottom Left	SG-COR-BFL	0	-173	SG-COR-BRL	281	273
	Bottom Right	SG-COR-BFR	-197	-148	SG-COR-BRR	173	88
	Middle Left	SG-COR-MFL	-430	-396	SG-COR-MRL	331	262
	Middle Right	SG-COR-MFR	-326	-297	SG-COR-MRR	410	379
	Top Left	SG-COR-TFL	-46	-55	SG-COR-TRL	35	102
	Top Right	SG-COR-TFR	-71	-89	SG-COR-TRR	-39	0
Collision Post (Vertical)	Bottom Left	SG-COL-BFL	812	856	SG-COL-BRL	-806	-861
	Bottom Right	SG-COL-BFR	769	877	SG-COL-BRR	-817	-893
	Middle Left	SG-COL-MFL	-1342	-1237	SG-COL-MRL	1510	1308
	Middle Right	SG-COL-MFR	-1350	-1285	SG-COL-MRR	1521	1361
	Top Left	SG-COL-TFL	88	21	SG-COL-TRL	-46	-22
	Top Right	SG-COL-TFR	6	15	SG-COL-TRR	-54	-13
AT Plate (Lateral)	Left Top	SG-ATP-LFT	-680	-687	SG-ATP-LRT	733	717
	Left Bottom	SG-ATP-LFB	-694	-675	SG-ATP-LRB	648	670
	Middle Top	SG-ATP-MFT	-333	-370	SG-ATP-MRT	331	388
	Middle Bottom	SG-ATP-MFB	-326	-369	SG-ATP-MRB	331	388
	Right Top	SG-ATP-RFT	-31	-49	SG-ATP-RRT	-60	55
	Right Bottom	SG-ATP-RFB	36	-38	SG-ATP-RRB	40	81
Lateral Member/Shelf (Lateral)	Left Top	SG-LM-LFT	-453	-247	SG-LM-LRT	949	826
	Left Bottom	SG-LM-LFB	-396	-238	SG-LM-LRB	952	840
	Middle Top	SG-LM-MFT	-78	-24	SG-LM-MRT	211	82
	Middle Bottom	SG-LM-MFB	-72	-27	SG-LM-MRB	213	92
	Right Top	SG-LM-RFT	223	163	SG-LM-RRT	-541	-580
	Right Bottom	SG-LM-RFB	196	162	SG-LM-RRB	-670	-703
End beam (Lateral)	Center Top	SG-BB-CFT	-162	-185	SG-BB-CBT	151	158
	Center Bottom	SG-BB-CFB	-211	-182	SG-BB-CBB	243	264
	End Top	SG-BB-EFT	-37	-4	SG-BB-EBT	75	-182
	End Bottom	SG-BB-EFB	-35	-6	SG-BB-EBB	10	-32
Component (Orientation)	**Location**	**Outer Surface**			**Inner Surface**		
		Gage	**Measured Strain (με)**	**Model Strain (με)**	**Gage**	**Measured Strain (με)**	**Model Strain (με)**
Draft Sill (Longitudinal)	Top Forward	SG-DS-TRF	-162	194	SG-DS-TLF	8	546
	Bottom Fwd.	SG-DS-BRF	385	110	SG-DS-BLF	279	263
	Top Middle	SG-DS-TRM	-113	73	SG-DS-TLM	-2	105
	Bottom Middle	SG-DS-BRM	402	224	SG-DS-BLM	337	124
	Top Rear	SG-DS-TRR	-6		SG-DS-TLR	-4	
	Bottom Rear	SG-DS-BRR	77		SG-DS-BLR	79	
Cant Rail (Longitudinal)	Top Forward	SG-CR-TRF	131	-318	SG-CR-TLF	-494	-388
	Bottom Fwd.	SG-CR-BRF	210	-552	SG-CR-BLF	-831	-617
	Top Middle	SG-CR-TRM	2	-219	SG-CR-TLM	-421	-229
	Bottom Middle	SG-CR-BRM	75	-214	SG-CR-BLM	-404	-218
	Top Rear	SG-CR-TRR	-133		SG-CR-TLR	-175	
	Bottom Rear	SG-CR-BRR	10		SG-CR-BLR	-101	