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Rail Vehicle Cab Car Collision and Corner Post Designs according to APTA S-034 Requirements

Ronald A. Mayville
R.A. Mayville & Associates, Inc.

Kent N. Johnson
Premiere Engineering

David C. Tyrell
Volpe Center

Richard G. Stringfellow
TIAX LLC

ABSTRACT

The American Public Transportation Association standard for rail passenger equipment, S-034, includes requirements for the collision and corner posts of cab cars that are consistent with new federal requirements and substantially different than what has been required in the past. This paper describes the development and evaluation of two cab car end frame designs that were generated to investigate the implications on crashworthiness and operations of the new standards. A review was undertaken of prior cab car crashworthiness research and of existing and planned cab car designs for North American operation. The two designs were then generated and both hand and finite element analysis, including analysis for large deformations, was conducted to demonstrate that the designs meet the requirements. Of particular interest is the issue of providing large deformation capacity of the posts and the implications of eliminating the stairwell to meet the strength requirements.

INTRODUCTION

The issue of strength requirements for cab cars has been a topic of discussion for some time. 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 essentially requires that the cab car have nearly the same layout as a passenger coach car, with the result that the operator is located immediately adjacent to the flat end wall of the vehicle. This end wall includes collision posts and corner posts that provide some protection against intrusion. 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 cars have been required to possess collision posts of substantial strength since around 1940. Around the 1980's it became standard practice – but not a Federal requirement – to also require strong corner posts at the end of passenger and cab cars.

Since the mid 1990's there has been renewed research into determining if and to what extent increasing the strength of passenger end frames would improve rail vehicle crashworthiness in a practical manner. This research has included design layout development, finite element analysis and component testing [1-4]. The results have demonstrated that a substantial improvement is possible without incurring an undue penalty in weight and cost.

Recently, discussions and research have led to the adoption of higher strength requirements for both the collision and corner posts for passenger (coach) and cab cars. These new requirements are now given in the American Public Transportation Association (APTA) SS-C&S-034-99, Revision 1, Standard for the Design and Construction of Passenger Railroad Rolling Stock, and the Code of Federal Regulations, Title 49, Part 238 [5,6].

Because the requirements are relatively new, there is a desire to better quantify the improvement they provide in collisions as well as the added design effort and weight (and, therefore, cost) associated with the changes. As a result, the Federal Railroad Administration with the Volpe Center conducted full-scale tests to investigate this matter. The tests approximate an accident [7] in which a cab car struck a trailer truck on which was carried a 20 ton steel coil. The coil in the accident penetrated the cab and passenger compartments and resulted in three fatalities.

This paper summarizes the designs that were eventually tested with particular emphasis on the collision and corner posts and the associated support structure. Also discussed are the implications on design requirements. Two designs – the 1990's design and the State-of-the-Art (SOA) design – were developed. The intent of the1990's design was to represent structural requirements in practice for cab car end frames in the early to mid 1990's. 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 general approach taken in the project was to review existing and planned designs, define design requirements, develop and fabricate the designs, and validate the analyses. More detail about the program from which this paper is derived can be found in [8]. In addition, other papers have been written on the full-scale tests that employed these designs [9,10].

STRUCTURAL REQUIREMENTS

The requirements for the two designs were developed with input from several sources. These included:

- Federal requirements
- industry standards
- specifications for existing and planned rail vehicles
- discussions with industry personnel active in rail vehicle design (particularly, members of the APTA Passenger Rail Equipment Safety Standards Construction/Structural Committee.)

Table 1 summarizes the structural crashworthiness requirements used for the two versions of the cab car end frame reported here. The State-of-the-Art requirements are essentially those found in APTA S-034 with the exceptions given below.

The intent behind the increases in strength defined in the state-of-the-art design is, in large part, to raise the amount of energy that can be absorbed in a collision. Some car specifications, but not the standard, have gone so far as to require that the posts must sustain a deformation equal to the depth of the post without causing failure in the post or the connections. Similar language for S-034 was under consideration during the course of this end frame design project and so such a requirement is included the SOA design. The most recent revision of S-034 does not include the deformation requirement but states instead that the posts must achieve the required strength without causing fracture in the post or at the connections.

Part of the discussion in the APTA committee on feasibility of increasing corner post strength practically was whether such strength increases could be achieved with a step well. The step well located in many cab cars interrupts a path through which load could be transferred from the corner to the vehicle structure inboard of the doorway. In the end, there was general consensus that the step well could be eliminated on the operator's side at the cab end thereby enabling a load path to the side sill in the vehicle. There is still a question about the conditions under which the currently required corner strength can be achieved with a step well and this topic is addressed later in this paper.

It is interesting to note that the new collision post strength requirements represent a substantial increase over previous requirements and are now the same as those that were required for locomotives in AAR S580 [11]. (However, that standard is now in the process of also being modified.) Likewise, corner posts are now required to possess strengths equal to the former values for the collision posts. Finally, both posts are now required to explicitly withstand substantial loads applied anywhere along their height.

In addition to the crashworthiness requirements, the designs were developed to be practical (consistent with operational requirements and current fabrication practices) and adaptable to existing rail vehicles that would be used in the full-scale tests.

DESIGN DESCRIPTIONS

The sections that follow provide summary descriptions of the 1990's and SOA designs developed in this program with emphasis on the posts and their supporting structure. Additional information can be found in [8-10]. There are a number of common features to the two designs. These include the geometry of the buffer beam and the use of A710 Class 3 steel for all components. The connection detail between the buffer beam and the draft sill of the existing Budd car is also the same for both designs.

1990's Design

A photograph of the fabricated 1990's end frame provides an overview of the design and its attachment to the existing test car, Figure 1.

The collision post has a rectangular cross section, 7.75x6.5 inches, fabricated from 0.375 inch plate. The post is reinforced by two lugs, each 3.25 inches wide and 0.25 inches thick and extending to 34 inches above the underframe on the front and back of each post. The collision posts penetrate both the upper and lower flanges of the buffer beam, while the corner posts penetrate only the upper flange, consistent with some of the 1990's era designs reviewed. The corner posts have a square cross section, 4.5 inches on a side, fabricated from 0.25 inch plate. The corner posts are reinforced on two adjacent sides by 2.62 inch wide, 0.25 inch thick lugs that extend 27.25 inches above the underframe. The collision and corner posts penetrate only the lower flange of the antitelescoping plate.

The 1990's 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 1990's design as there is in the SOA design.

State-of-the-Art Design

A photograph of the fabricated SOA end frame provides an overview of the design and its attachment to the existing test car, Figure 2. The primary features of the SOA design that differ from the 1990's design are:

Table 1: Summary of Cab Car End Frame Structural Requirements for This Study

	Standard/Requirement	
Component	**1990's Design**	**State-of-the-Art Design**
Collision Post (must be present at the 1/3 points along the width of the vehicle)	300×10^3 lbf at the floor without exceeding the ultimate shear strength 300×10^3 lbf at 18 inches 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 inches and then taper to 30 inches above the underframe	500×10^3 lbf at the floor without exceeding the ultimate shear strength 200×10^3 lbf at 30 inches without exceeding the ultimate strength 60×10^3 lbf 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)	150×10^3 lbf at the floor without exceeding the ultimate shear strength 30×10^3 lbf at 18 inches above the floor without exceeding the material yield strength Both requirements apply for loads applied anywhere between longitudinal to transverse inward	300×10^3 lbf at the floor without exceeding the ultimate shear strength 100×10^3 lbf at 18 inches above the floor without exceeding the yield strength 45×10^3 lbf 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)	15×10^3 lbf applied in the longitudinal direction anywhere between the corner and collision post without yield	15×10^3 lbf applied in the longitudinal direction anywhere between the corner and collision post without yield Include a bulkhead in the opening below the shelf. (not required in S-034)

- The corner posts extend through both the top and bottom flanges of the buffer beam.
- The collision and corner posts penetrate both flanges of the antitelescoping plate.
- There is a side sill element that extends up to the buffer beam.

A bulkhead exists in the opening defined by the collision post, shelf, corner post, and underframe. The collision post again has a rectangular cross section, 7.75x6.5 inches, fabricated from 0.375 inch plate, but the two reinforcing lugs have a width of 5.12 inches and a thickness of 0.375 inches, and extend to 46 inches above the underframe on each side of each post. The corner posts have a square cross section, but for the SOA design they are 6.0 inches on a side, and fabricated from 0.31 inch plate. The corner posts are reinforced on all four sides by 3.25 inch wide, 0.31 inch thick lugs that extend 27.25 inches above the underframe. Note that the APTA standard requires reinforcement to extend to at least 30 inches above the floor, if it is needed to meet the strength requirement. In this design the reinforcement is used to achieve a strong and ductile connection, not for strength.

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 1990's design. Each side sill is a closed rectangular section, 4.94x5.81 inches, fabricated from two 0.25 inch thick angles.

Use of an extended side sill in the SOA design provides an additional and important load path to help satisfy the required corner post loads. Again, such a structural approach was made possible when industry participants agreed ─ in the context of the APTA committees ─ that the stairwell at the cab end of the cab car could be eliminated. In fact, for the SOA design described here, the side sill carries the majority of the 300,000 lbf required corner post base load.

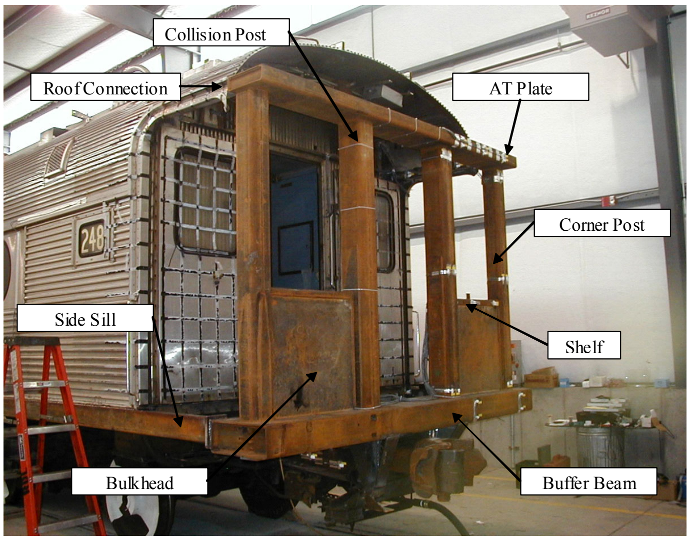

Figure 2. A Photograph of the Fabricated SOA End Frame Design

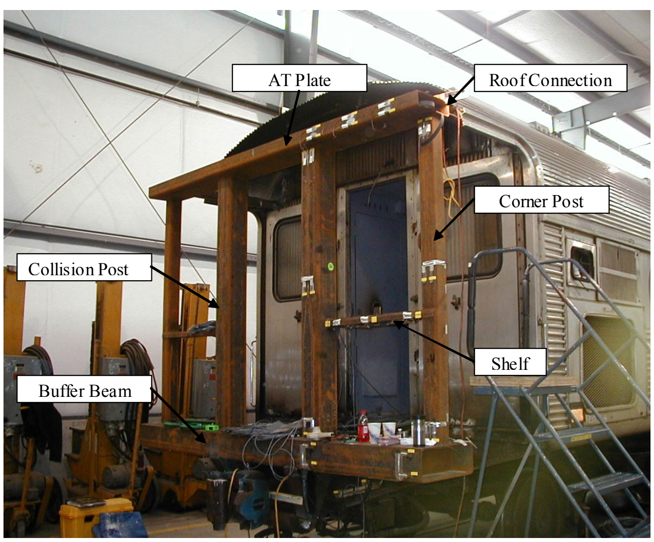

Figure 1. A Photograph of the Fabricated 1990's End Frame Design

DESIGN ANALYSIS

This section describes some of the analyses conducted to demonstrate that the collision and corner post strengths are achieved for the 1990's and SOA designs. Also discussed are the implications of utilizing the extended side sill to achieve the required corner strength for the SOA design and the effect of these changes on vehicle weight.

1990's and SOA Designs

The preliminary design of the various structural members was initially carried out by conducting hand and beam element, elastic finite element analysis for both the 1990's and the SOA designs. No other analysis was carried out for the 1990's design, consistent with the design techniques used in the 1990's era. (However, a detailed elastic-plastic finite element model was generated for post-test analysis of the 1990's design; see [9].) On the other hand, finite element analysis, including the simulation of detailed shapes of each structural member and elastic-plastic material behavior, were 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. For some of the load cases, even for the SOA design, only hand calculations were used to demonstrate that a particular requirement was satisfied. These load cases included: a) collision and corner post shear strengths at the base; b) collision post strength for the cases in which the load is applied up to 15 degrees to the longitudinal axis.

Figure 3 shows the finite element model used to evaluate the SOA design. A vehicle length of approximately 20 ft 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, elastic-plastic cases, which include determination of ultimate strength and deformation capacity, the load was applied to the post through a rigid body that had a 3 inch radius at the point of contact, was 6 inches high and spanned the entire width of the post.

Figure 4 shows the load – load point displacement plot for the cases in which a load is applied to the collision and corner posts (separately) in the longitudinal direction above the underframe at 30 inches, for the collision post, and at 18 inches for the corner post. The maximum predicted strength for the collision post is about 250,000 lbf, well in excess of the required 200,000 lbf requirement. The ultimate strength for the corner post at 18 inches is nearly the same as the ultimate strength for the collision post at 30 inches. This similar load-displacement response is explained by the fact that the corner post is loaded at about one-half the height as the collision post and the $100\text{x}10^3$ lbf strength requirement for the corner post is based on a yield criterion rather than the ultimate strength criterion for the collision post. The analysis predicted that there are no stresses above the specified minimum yield strength for the case in which the corner post is loaded to $100\text{x}10^3$ lbf at 18 inches above the underframe. That is, yielding does not occur in the post or in the supporting end beam or other components.

The highest strains in the collision and corner posts for the two load cases under consideration occur in the vicinity of the base connection. (There are high strains at the point of load application but these do not affect strength.) Figures 5 and 6 show plots of the equivalent plastic strain at the base of the posts for a load point displacement equal to the depth of the post; the plastic strain is one measure of the likelihood of fracture. The strains at the lower connection of the collision post are less than 25%. Typical elongation values for the A710 material exceed 30%. This indicates that failure by cracking is unlikely to occur for a deformation equal to one times the depth of the post.

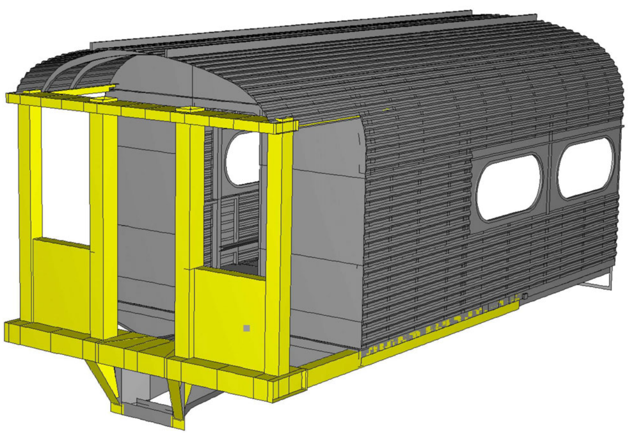

Figure 3. The Model Used to Assess Various Load Cases for the State-of-the-Art End Frame Design

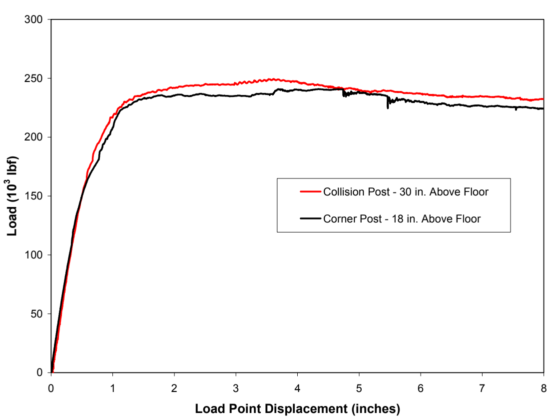

Figure 4. The Load-Load Point Displacement Plot for a Longitudinal Load Applied Either on the Collision Post 30 inches above the Floor, or the Corner Post 18 inches above the floor. (load is for one post only.)

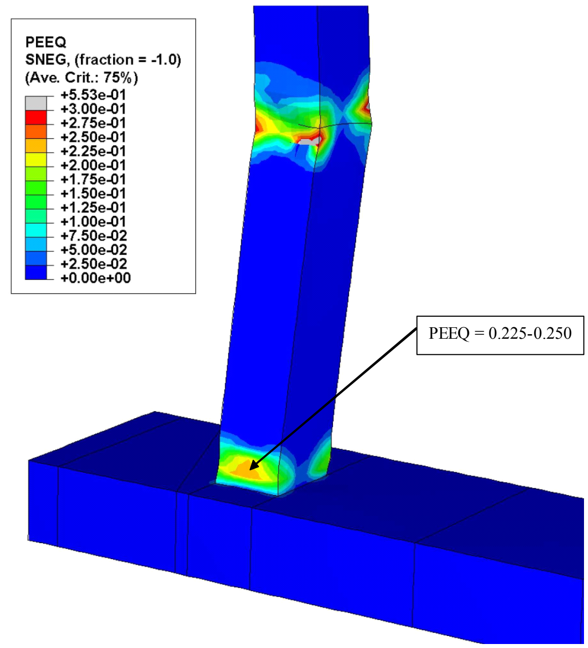

Figure 5. The Equivalent Plastic Surface Strain Contours Corresponding to a Load Point Displacement of 7.75 inches on the Collision Post.

Figure 6 shows a plot of the equivalent plastic strain on the corner post surface corresponding to a load point displacement of 6 inches, the depth of the corner post. (The bulkhead has been removed from the figure for clarity.) Here there is a small area, immediately adjacent to the outside lug, over which the plastic strain exceeds the nominal 30% elongation of the A710 material. This indicates that some cracking could occur at deformations equal to one times the depth of the post. (An earlier analysis without the bulkhead showed that the strain at the base of the corner post was about 25% for 6 inches of deformation.) No failure is predicted in the connection to the buffer beam. Thus, some refinement in design should be considered to eliminate this problem. (This issue is discussed further below.)

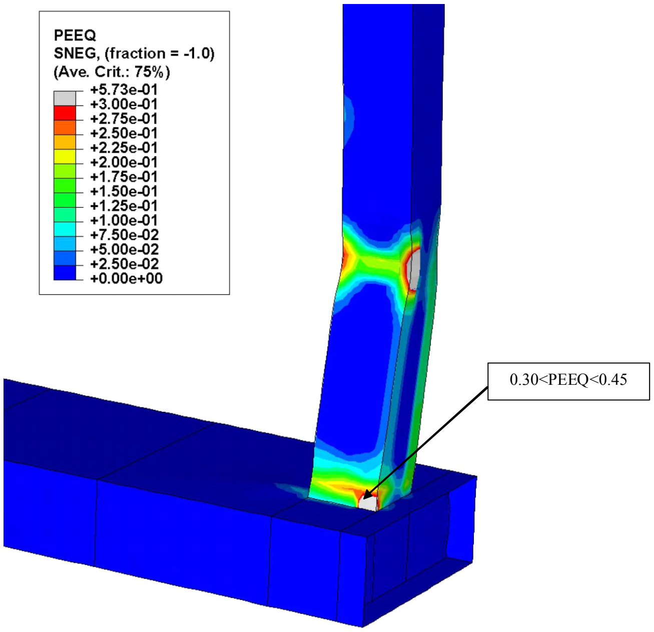

Figure 6. The Equivalent Plastic Surface Strain Contours Corresponding to a Load Point Displacement of 6 inches on the Corner Post.

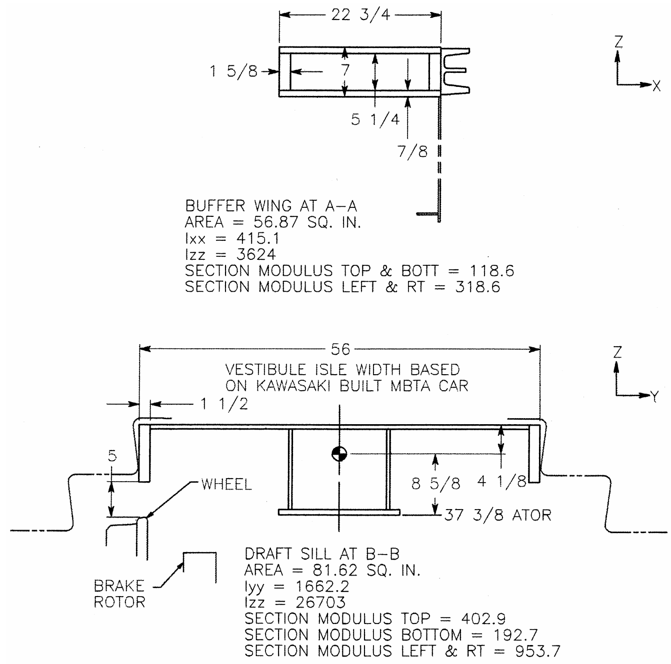

Figure 7. The Buffer Beam and Draft Sill Sections Required to Support a 300x10^3 lbf Load at the Corner Post Base Without Side Sill Extension (from [1].)

No Side Sill Case

In a previous study [2] the authors investigated the structural arrangement that would be needed if the side sill could not be extended to support the corner post loads. The design from that study required that the draft sill and the buffer beam have substantially larger sections in order to prevent yielding in these components, which were directly in the load path. This is because substantial bending moments arise in these members when the corner post is loaded near its base. Finite element analysis was not conducted as part of that study. Figure 7 shows an illustration (from [1]) of the section required for the case in which the side sill is not extended to provide a load path for the corner post load.

Weight Increases

It is difficult to state precisely how much weight would be added to a car structure for different requirements since in many cases the designs would evolve in different manners. In this study, the incremental change in weight was calculated by modifying the baseline designs. Table 2 shows the comparison of estimated additional weight for the higher corner post (and collision post) strength design of the SOA end frame. This table shows that the estimated increase in weight is significant when the side sill cannot be extended.

Table 2: Estimated Weight Increases Associated with Increased Corner Post Strength

	Weight Increase/Vehicle End* (from baseline)	
Design	**This Study (SOA)**	**From [1]**
Extended Side Sill	250 lbm	150 lbm
Side Sill Not Extended	NA	1100 lbm

* Based on the requirement that both corners must carry the design loads separately.

DISCUSSION AND CONCLUSIONS

This paper describes some of the results of a program to design end frames for testing the differences in crashworthiness performance for cab cars that meet early to mid 1990's structural standards and cab cars designed to the current APTA and FRA structural requirements. Particular attention is paid to the design of the corner posts and their supporting structure. 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 were developed that included the applicable structural requirements, the need to meet operability requirements and the need to adapt to existing test cars. Hand and simple beam model finite element analyses were used to develop the 1990's design, while detailed finite element analyses, including large deformation calculations, were carried out to develop the State-of-the-Art (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 and included in full-scale crash tests.

The results of this project demonstrate that the new APTA requirements can be met with designs that are very similar geometrically to those needed to satisfy the requirements used in the 1990's. For example, there is only an 250 lbm weight difference between the 1990's and SOA end frame designs of this study when the side sill is extended to support the back of the buffer beam at the base of the corner post. One the other hand, if a stairwell were included at that location, the weight penalty would be much greater.

The SOA design was also shown to be able to sustain large deformations of both the collision and corner posts without failure; this is a requirement that was considered but then eventually dropped by the APTA Construction and Structural subcommittee in its development of the S-034 standard. It is important to acknowledge that the SOA corner post design falls just short of completely satisfying the requirement set forth in this study, that there be no fracture up to the point at which the corner post is displaced by an amount equal to its depth. Under such conditions, the analysis predicts that the equivalent plastic strain at the base of the corner post exceeds the minimum required elongation for the A710 material.

Clearly, a more detailed design process is needed when, in addition to meeting strength requirements, the plastic strain associated with limit conditions must be distributed over significant lengths of the post. Nevertheless, the tools required to develop such designs are at hand as demonstrated by this study.

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