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DYNAMIC AND QUASI-STATIC GRADE CROSSING COLLISION TESTS

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ABSTRACT

To support the development of a proposed rule [1], a full-scale dynamic test and two full-scale quasi-static tests have been performed on the posts of a state-of-the-art (SOA) end frame. These tests were designed to evaluate the dynamic and quasi-static methods for demonstrating energy absorption of the collision and corner posts. The tests focused on the collision and corner posts individually because of their critical positions in protecting the operator and passengers in a collision where only the superstructure, not the underframe, is loaded. There are many examples of collisions where only the superstructure is loaded.

For the dynamic test, a 14,000-lb cart impacted a standing cab car at a speed of 18.7 mph. The cart had a rigid striking surface in the shape of a coil mounted on the leading end that concentrated the impact load on the collision post. During the dynamic test the collision post deformed approximately 7.5 inches, and absorbed approximately 137,000 ft-lbs of energy. The SOA collision post was successful in preserving space for the operators and the passengers.

For the quasi-static test of the collision post, the collision post was loaded in the same location and with the same fixture as the dynamic test. The post absorbed approximately 110,000 ft-lb of energy in 10 inches of permanent, longitudinal deformation. For the quasi-static test of the corner post, the post was loaded at the same height as the collision post, with the same fixture. The corner post absorbed 136,000 ft-lb of energy in 10 inches of permanent, longitudinal deformation.

The series of tests was designed to compare the dynamic and quasi-static methods for measuring collision energy absorption during structural deformation as a measure of crashworthiness. When properly implemented, either a dynamic or quasi-static test can demonstrate the crashworthiness of an end frame.

INTRODUCTION

Three tests were designed to demonstrate test methods and to measure the crashworthiness of the Federal Railroad Administration (FRA) prototype end frame design. The prototype design, referred to as the state-of-the-art (SOA) design, has enhanced loading capabilities. A proposed rule allows for either quasi-static or dynamic evaluation scenarios for the two major end frame components: the collision and corner posts. By requiring energy absorption capabilities for new end frames, the rule aims to improve survivability for operators and passengers at higher collision speeds.

This paper covers work done to support a proposed rule: a dynamic test of a collision post, a quasi-static test of a collision post, and a quasi-static test of a corner post. The work is used both to support the development of the rule and to assist the government and industry in building and evaluating structures built to the standards of the proposed rule.

BACKGROUND

Several collisions have occurred where the super structure of a leading cab car has been loaded and the underframe of the car has not been loaded. These collisions demonstrate a need for better protection for the cab engineer and passengers to external threats.

In Yardley, Pennsylvania in 1975, a cab car-led commuter train hit a semi-tractor carrying coils of steel at a grade crossing [2]. The cab car impact velocity was 15 mph. Two coils, which were loaded on the semi-trailer, weighing 5 tons and 8 tons, penetrated into the first passenger car and killed three occupants. In this accident, only the collision and/or corner post were loaded, not the underframe.

In 1996, in Secaucus, New Jersey, a cab car-led consist and a locomotive-led consist collided at a switch. At the collision interface, the locomotive pushed in or tore loose the collision and corner posts of the cab car. During this collision, the underframe was not loaded. There were three fatalities [3].

In Silver Spring, Maryland in 1996, there was a collision between a cab car-led consist and a locomotive-led consist at a switch. There were eleven fatalities in this collision, some resulting from a fire in the cab car. In the accident, the collision and corner post were pushed in and torn loose, but the underframe was not loaded [4].

In Tarrytown, New York in 2004, a cab car-leading railroad train collided with an outrigger secured in a gondola car fouling right-of-way by 12 inches. Although there were no fatalities, two cars required car body repairs and five cars sustained minimal damage [5].

On June 18, 1998, a cab car-led, two-car MU commuter train collided with a highway truck at a grade crossing [6] in Portage, Indiana. The highway truck consisted of a tractor with two trailers. The trailers were loaded with coils of sheet steel. The second trailer, the one furthest from the tractor, was stopped on the tracks. The train collided with the second trailer, and during the impact, a coil of steel broke free and struck the end of the car. The steel coil penetrated down half the length of the car and killed three people [7].

Figure 1 shows the exterior and the interior of the cab car after the collision. The picture in the top right shows the interior of the car. The collision post had been severed and pushed back into the car. Figure 1 also shows the 6-foot diameter, 19-ton steel coil. In this collision, the coil loaded the superstructure of the car, not the underframe.

Figure 1. Cab car and steel coil involved in the grade crossing collision in Portage, Indiana.

The preceding collisions were used to characterize types of loading conditions, which led to the development of a simplified, generalized test scenario. The goal of the research conducted is to establish methods for measuring the crashworthiness performance of end frame structures and to develop strategies for incrementally improving the survivability of end frame structures under a range of impact conditions.

PREVIOUS TESTS

Both the Federal Railroad Administration (FRA) and car builders have done testing on super structure crashworthiness. In support of the American Public Transportation Association (APTA) Standard for the Design and Construction of Passenger Railroad Rolling Stock [8], Bombardier conducted a series of qualifying quasi-static tests on a mock-up front end structure of an M7 cab car. The end frame of the M7 car was developed to be compliant with applicable FRA regulations [9] and APTA standards. In total, four quasi-static tests were conducted on the front end structure: a 100,000-lbf load applied longitudinally on the corner post at 18 inches above the top of the end sill, a 100,000-lbf load applied transversally on the corner post at 18 inches above the top of the end sill, a load up to the elastic limit of the collision post applied longitudinally at a distance 30 inches above the end sill, and an ultimate load case applied 30 inches above the end sill. The first three loads were elastic in nature and the last load case was designed to evaluate the large deformation collapse response of the collision post [10].

The M7 designs provide improved crashworthiness protection for the operator in a collision where the superstructure, not the draft sill or side sills, is loaded. The design is capable of gracefully deforming in the post-buckling regime. This mode of deformation with subsequent failure helps assure that in the event of a collision with an object that has the majority of its mass above the draft sill and side sills of a cab car in the push-mode of operation, the operator is protected from bulk crushing.

Observations from these tests were:

- the graceful crush of cab car end frames can be objectively measured by large-deformation quasi-static testing and by large-deformation dynamic testing, however
- further quasi-static and dynamic tests are necessary to validate quasi-static and dynamic analyses.

FRA has also conducted tests. An ongoing objective of FRA's passenger crashworthiness program has been to evaluate the existing passenger car designs and offer potential improvements. There have been two full-scale dynamic tests using a grade-crossing scenario. Two tests focused on the corner post, testing a generalized 1990s design and an improved SOA design.

Many of the key structural elements are similar for the 1990's and SOA designs. The principal differences are the size of the corner posts, the presence of a bulkhead sheet attached to the lateral member/shelf to the collision post to the corner post and to the end beam on the SOA design, and the length of the side sill on the SOA design, which extends past the operator compartment to the end beam, removing the step well. The SOA end frame is a specific end frame prototype design developed for this series of tests. The SOA end frame was designed to absorb more energy during a collision and provide a survivable space for the operator and passengers. The SOA design, shown in Figure 3, includes more substantial collision and corner posts. The connections between the corner and collision posts and the anti-telescoping (AT) beam along the top of the end frame, and the buffer beam along the bottom of the end frame, are made stronger by running the posts through the entire AT beams and bufferbeam. Shelves and bulkhead sheets connect the collision and corner posts, allowing some load to be shared between the two posts. The end frame is better supported by a continuous side sill and robust roof rails [11, 12].

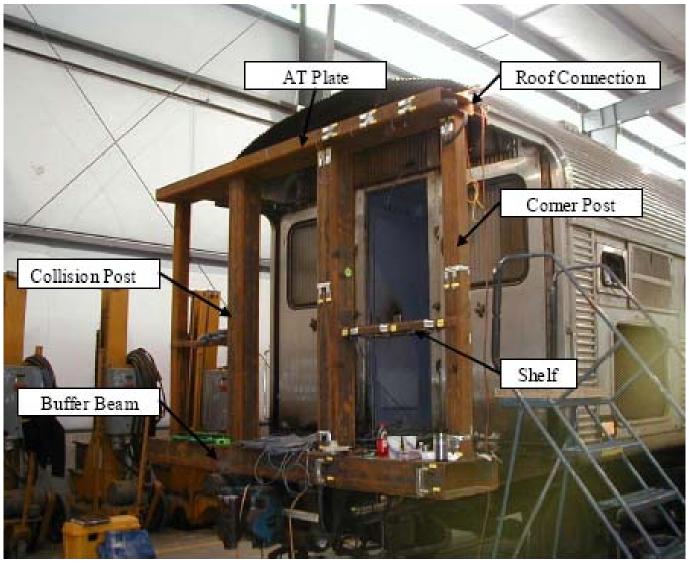

Figure 2. Important features of the1990s end frame design.

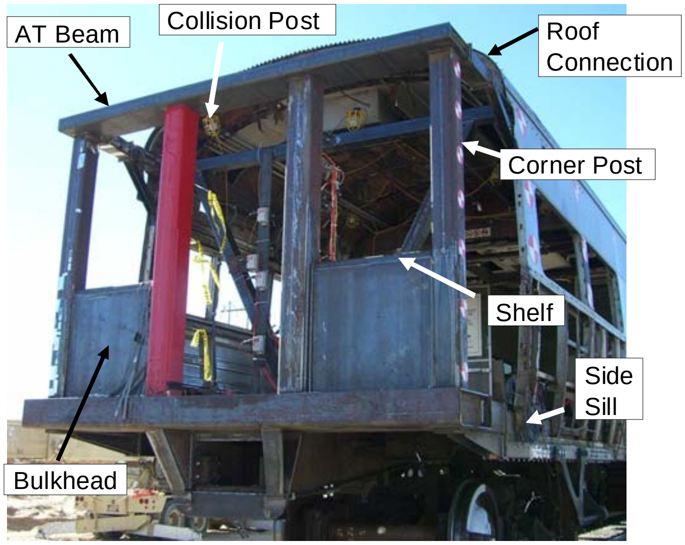

Figure 3. Important features of the SOA end frame.

Table 1 shows the previous full-scale tests that have been performed as part of the grade-crossing scenario research. Two dynamic tests were performed on the corner posts. One test was performed on a 1990s design, which was designed to be a typical end frame structure of the 1990s. The second dynamic corner post test was conducted on a SOA design. This paper discusses the dynamic test of the collision post and the two quasi-static tests.

Table 1. Previous end frame tests

Test Type	Post	Design	Date
Dynamic	Corner	1990s	June 4, 2002
Dynamic	Corner	SOA	June 7, 2002

In the test performed on the 1990s end frame, the car had an initial velocity of approximately 14 mph and collided with a 6-foot diameter, 40 kip steel coil. The coil was mounted on a frangible wooden table. The center of the coil hit the corner post at a height of 30 inches above the top of the finished floor. During this test the connection between the corner post and the AT beam failed.

A second dynamic test was conducted on the corner post of a SOA end frame. For the corner post test, the SOA design was retrofit onto a Budd Pioneer car [13]. The same test setup was used as in the 1990s design test. During this test, the corner post and attachments did not fail. After impact, the coil rolled under the train, tipping the car. The car did not derail, but the unexpected tipping was a cause of concern for future tests [14].

PROPOSED RULE AND CURRENT TESTS

The proposed rule includes performance requirements for the end frame of a cab car or Mu locomotive. The rule includes two separate scenarios which load at two locations on the end frame: the collision post, offset 19 inches from the center of the car, and the corner post, located at the outer edge of the end frame. Dynamic and quasi-static methods can be used to demonstrate compliance with the rule. For either method, the minimum amount of energy to be absorbed and the maximum amount of permanent deformation is the same.

Three tests, listed in Table 2, were recently conducted to show the performance of the prototype SOA end frame performance under the tests in the proposed rule.

Table 2. Recent end frame tests

Test Type	Post	Design	Date
Dynamic	Collision	SOA	April 16, 2008
Quasi-static	Collision	SOA	June 25, 2008
Quasi-static	Corner	SOA	August 13, 2008

For each test, a pretest analysis was performed. A concurrent paper discusses in detail the modeling methods and results for these analyses [15].

DYNAMIC COLLISION POST TEST

The dynamic test set up and requirements are derived from the proposed FRA rule on end frames. Based partially on the lessons learned during this testing program, the rule has been changed from the published version. At the time that this paper is being written, the proposed ruled has been accepted by the full Rail Safety Advisory Committee. The requirements discussed in this paper are based on the updated rule, which is set to be published in the near future.

Several methods for a dynamic test were considered, including running the car into a stationary coil shape, mounting the coil shape onto a pendulum, and hitting the collision post. After considering the test cost, control, and repeatability, a method of mounting the coil shape onto an existing cart was chosen. A rigid cart design allows the same cart to be used for multiple tests, either on the corner or collision post. The test facility is familiar with running dynamic tests and can reliably set the speed of the cart. Figure 4 shows a schematic of the test layout. The cab car is on the right in the figure and the cart is on the left.

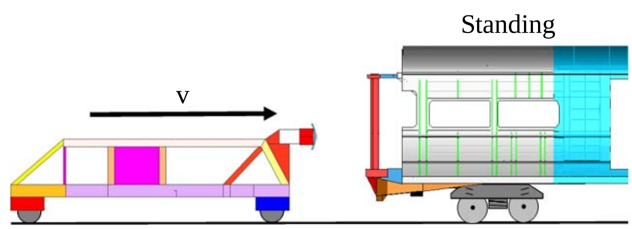

Figure 4. Schematic of the dynamic test layout.

A proxy object cart mounted with a coil shape was developed as an alternative to the steel coil on a frangible table. The striking surface has a 48-inch diameter and 36-inch width. This surface was mounted on a box beam on the leading end of the cart, at the required height of 30 inches above the finished floor of the cab car. The beam supporting the coil shape was designed so that the coil shape could be moved horizontally in order to impact the corner post, if necessary. The coil shape could also be moved vertically a few centimeters in either direction for proper location for impact. The finished cart weighed approximately 14,000 lb. The cab car weighed 70,000 lb.

The proposed rule requires that the energy absorbed during the test be greater than 135,000 ft-lb. The post cannot have more than 10 inches of permanent, longitudinal deformation in the impact. The energy absorbed during the test is calculated using the following equation: $E_a = E_0 - E_f$

Where—

E_0 = Energy of initially moving object at impact = ½ $m_1 * V_0^2$.

E_f = Energy after impact = ½ $(m_{1+}m_{2)} * V_f^2$.

V_0 = Initially moving object impact speed.

V_f = Speed of both objects after collision = $m_1 * V_0/(m_1+m_2)$.

m_1 = Initially moving object mass.

m_2 = Initially standing object mass.

The target initial velocity of 19 mph, ensured that the end frame would absorb a minimum of 135,000 ft-lb of energy during the collision. The anticipated final speeds were less than 3 mph for both the cab car and the cart.

The test article and test design performed as predicted and the test was a success. The actual test speed was 18.7 mph. The end frame exceeded the energy absorption requirement by absorbing 137,000 ft-lb of energy. The collision post indented approximately 7.5 inches, meeting the requirement that there be less than 10 inches of permanent deformation. The desired modes of deformation were observed.

Figure 5 shows still frames of the test taken from the high-speed video. The top photo shows the cart at the initial contact. The middle photo shows the cart and collision post at the maximum amount of collision post deflection. The photo on the bottom shows the cart and end frame at the end of the test, after some elastic energy has been recovered from the collision post. The cab car moved back approximately 6 feet after the test and stopped. The cart lifted vertically and moved laterally on recoil. When the cart came down after impact, the wheels missed the track and the cart derailed. Since the cart came down off the tracks, it stopped and did not move backwards.

Figure 5. Still photographs from high-speed video.

Figure 6 shows the end frame after the test. The impacting object pushed in the collision post, lateral shelf and bulkhead sheet. The bottom oval shows where the collision post and bulkhead sheet partly separated from the buffer beam. The shelf separated from the collision post and the corner post. The AT beam, which runs laterally at the top of the end frame, bent down at the connection to the collision post, as shown in the top oval. The welds between the collision post and the AT beam did not crack or fail. The middle oval surrounds the impact area, and the crack in the collision post behind the impact location.

Figure 6. A photograph of the end frame after the dynamic collision post test.

Figure 7 and Figure 8 show important details of the mode of deformation. The collision post fractured in two places during the test: at the back of the post at the impact point and at the connection to the buffer beam. The top photo in Figure 7 shows the back of the collision post and the connection to the shelf before the test. A shelf tab extends from the shelf and is welded to the back of the collision post. There is a gap between the side of the post and the shelf. The post is a box cross section formed by two U-sections welded together at the front and back of the post. There are several internal gussets in the horizontal plane. The back of the post fractured at this location during the test. The front of the post did not fracture. This fracture was not predicted in the pretest modeling, but the end frame was still able to meet the energy absorption requirements. The tab connecting the shelf failed as well.

Figure 7. The back of the collision post, at the connection to the shelf, pre-test (left) and post-test (right).

The collision post also fractured at the connection to the buffer beam. Figure 8 shows the fracture. The bulkhead sheet tore from the buffer beam at the corner. The crack on the left side of the post (as seen in the picture) extends behind the bulkhead sheet. The crack is circled in the figure. On the right side of the post, the crack extends almost down the entire side. The buffer beam was distorted and the top plate of the buffer beam pushed down at the location of the collision post and the bulkhead sheet. Despite fracture in this location, the post still met the test requirements.

Figure 8. Fracture at the connection between the collision post and the buffer beam.

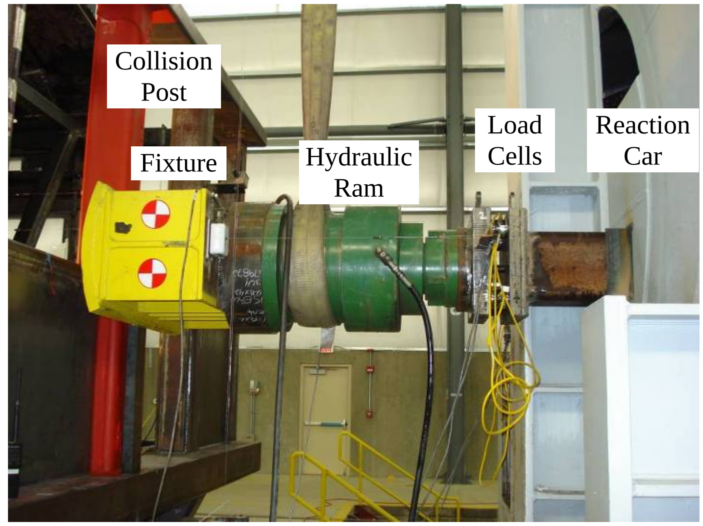

Figure 9. Hydraulic ram configuration for the collision post test.

QUASI-STATIC COLLISION POST TEST

The proposed rule allows for either static load conditions and a quasi-static test, or a dynamic test to asses the performance of an end frame. A quasi-static collision post test was run to compare the dynamic test and the quasi-static test and to demonstrate the quasi-static test method.

The proposed rule requires that the collision post and frame absorb 135,000 ft-lb of energy in no more than 10 inches of longitudinal, permanent deformation. Load is applied with the same fixture from the dynamic test. This fixture has a diameter of 48 inches and a width of 36 inches. The fixture is made of a thick, stiff material and reinforced so that it does not deform or absorb energy. Longitudinal string potentiometers at several locations recorded the deformation of the post. Four load cells, connected in parallel, measured the load being applied into the post. The force and the displacement were cross-plotted and the integral was used to calculate the energy absorbed during the test.

For the quasi-static test, the test car is coupled to a reaction car. Figure 9 shows the configuration for the test. The collision post, on the left, is painted red. The rigid fixture, in yellow with targets, was taken from the dynamic test cart. The hydraulic ram is suspended from a crane. Four load cells, connected in parallel, connect the hydraulic ram to the solid block, which acts as a spacer between the ram and the reaction car. The solid block is removable, and when the stroke of the ram is reached, the solid block was replaced with a longer solid block to continue the test. Figure 10 shows a schematic of the test with the cars coupled together. As the load from the hydraulic ram is introduced to the car through the collision post, is it reacted through the couplers. During the test, the force reading from the load cells and the displacement readings from the string potentiometers is displayed real time for test observers.

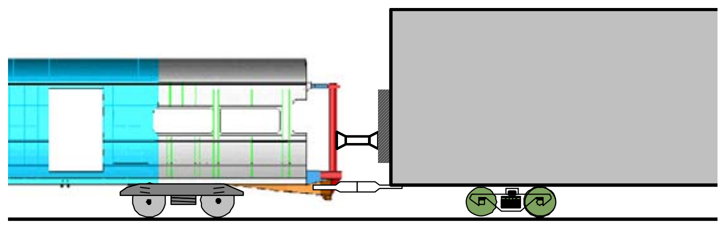

Figure 10. Schematic of the quasi-static test set up.

The mode of deformation in the quasi-static collision post test is very similar to the mode of deformation seen in the dynamic collision post test. The top circle in Figure 11 shows where the collision post pulled down on the AT beam. The middle circle shows the post deformation at the loading location. The post was loaded past 15 inches of deformation and did eventually fail completely in the middle. The bottom circle in the figure shows where the collision post fractured as it separated from the buffer beam.

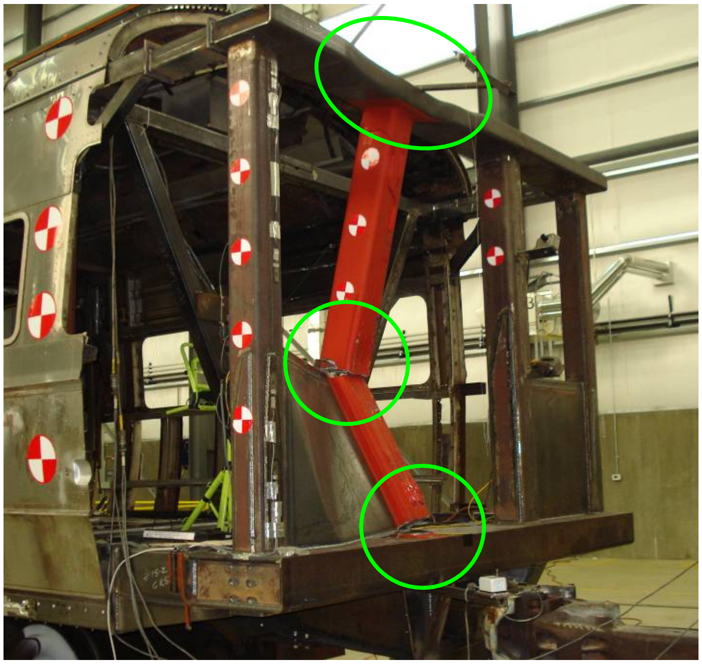

Figure 11. Post-test quasi-static collision post test.

The force-displacement characteristic is required to assess the energy absorption of the collision post and end frame. This characteristic is shown in Figure 12. The force, shown as the solid blue line, increases until approximately 2.25 inches. When the post had deformed this far (location 1 on the graph), the back of the collision post fractured, resulting in a sharp decline in load. As the post continues to crush, the back of the post continues to fracture, resulting in a declining force. After approximately 3.5 inches, fracture occurred at the connection of the post to the buffer beam (location 2 on the graph). After this point, the load continues to decrease as the post crushes. When the crush of the post reaches 8 inches, the force begins to increase, due to tension in the post connection. After 11 inches of crush, the post has absorbed 110,000 ft-lb of energy, as circled on the dashed green line. Based on the unloading characteristic measured during the test, 11 inches of crush is approximately equal to 10 inches of permanent deformation.

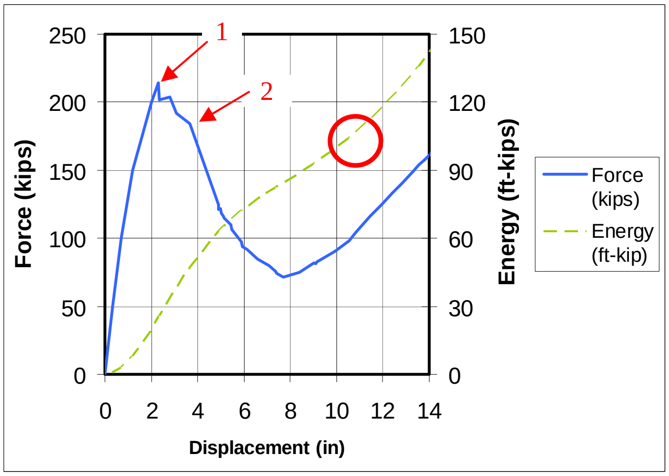

Figure 12. Force-displacement and energy-displacement graphs for the quasi-static collision post test.

Since the collision post and end frame were required to absorb 135,000 ft-lb of energy in 10 inches of permanent deformation, but only absorbed 110,000 ft-lb of energy, the test article did not pass the requirements. A closer look was given to the test set-up and the SOA end frame design and manufacturing.

The premature fracture at the back of the collision post is of concern. The fracture kept the collision post from absorbing enough energy during the test. Three potential contributing factors were explored: material properties, fabrication quality, and design details. As part of the post-test autopsy, material samples were taken from various locations on the collision and corner posts from the dynamic and quasi-static test of a collision post. Three-point bending tests of the specimens demonstrated that the ductility of the material was within specification. Material properties were ruled out as a contributing factor to the fracture. A visual inspection of the specimens confirmed that the welds were within specification, so fabrication quality was also ruled out as a cause of fracture.

The design details warranted a closer look. The specimens taken at the location of the fracture revealed that an internal gusset on the post coincided with an exterior shelf tab. Figure 13 shows specimens taken from the collision posts in the dynamic and quasi-static tests. The gusset locations were within specification for these posts. However, there is some flexibility with the location of the gusset relative to the location to the shelf tab. In both the dynamic and quasi-static tests, the fracture occurred at the location of both the gusset and the shelf welds. The rigid gusset did not allow the post to oval as it deformed, causing the fracture at the back of the post.

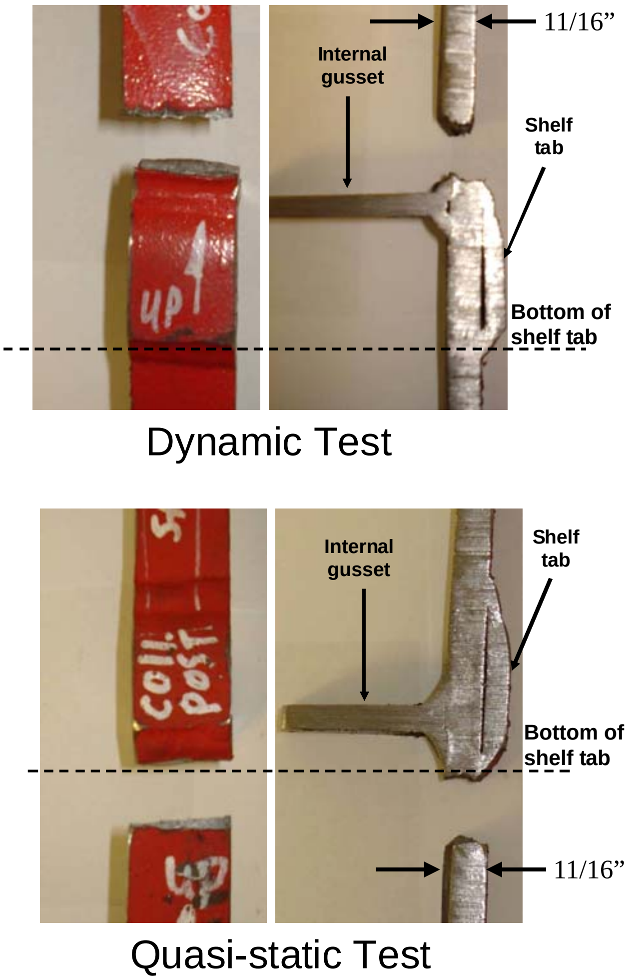

Figure 13. Gusset, shelf, and fracture locations on the collision post for the quasi-static and dynamic tests.

QUASI-STATIC CORNER POST TEST

Similar to the collision post requirements, the proposed rule allows for either static load conditions and a quasi-static test, or a dynamic test. A quasi-static corner post test was run to demonstrate the quasi-static test method. For this test, the corner post and end frame were required to absorb 120,000 ft-lb in less than 10 inches of permanent, longitudinal deformation. The same fixture was used for this test as in the collision post tests. The fixture was centered on the corner post.

In response to the results of the quasi-static test of the collision post, the shelf was redesigned so the tab was removed and the depth of the shelf was decreased. The circle in Figure 14 shows the tab before modification and the arrows show the decreased shelf size after modification. This reduced the amounts of welds at the corner and back of the post. The corner post was not designed with internal gussets, so the design detail did not need to be addressed.

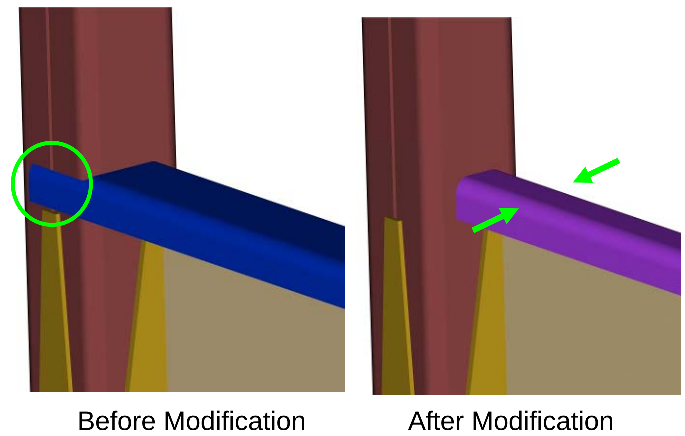

Figure 14. Schematic showing shelf modifications.

In the quasi-static corner post test, the end frame deformed as expected and absorbed energy while deforming. Figure 15 shows an overview of the deformation of the end frame at the end of the test. Circles show the areas where the AT plate has been pulled down significantly and where the shelf and bulkhead have deformed. Figure 16 shows the details of the fracture locations. The photo on the bottom shows a close up of the fracture at the bottom of the corner post. The photo on the top shows the connection of the shelf to the corner post. Although the connection between the shelf and the post has fractured, the post itself has not fractured.

Figure 15. Quasi-static corner post post-test overview photo.

Figure 16. Quasi-static corner post post-test detail photos.

The force-displacement characteristic is shown in Figure 17. After about 4.5 inches of crush, as pointed out in Figure 17, failure initiated at the connection of the post to the buffer beam. The post and end frame absorbed 136,000 ft-lb of energy in 11 inches of crush. After elastic recoil, 11 inches of crush results in 10 inches of permanent deformation. The hydraulic ram loaded the corner post through 14 inches of deformation. The post would have continued to deform past 14 inches, but the hydraulic ram was out of stroke.

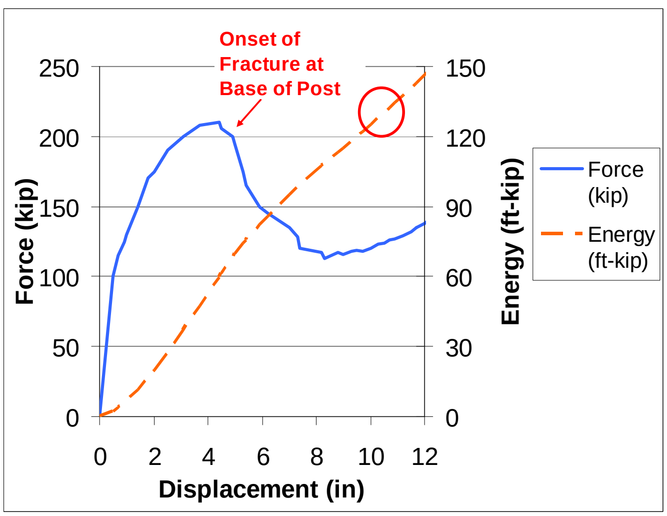

Figure 17. Force-displacement and energy-displacement characteristics for the corner post

SUMMARY

Three tests were performed on a SOA end frame to support development of a rulemaking on cab car end frames. During the dynamic test of a collision post, a cart weighing 14 kip with a cylinder-shaped striking surface on the end traveled at 18.7 mph and hit the collision post of a standing cab car weighing 70 kip. The cart did not deform plastically during the test. The cab car end frame absorbed 137,000 ft-lb of energy, exceeding the requirement of 135,000 ft-lb of energy. The collision post plastically deformed approximately 7.5 inches, meeting the requirement of less than 10 inches of deformation.

For the quasi-static test of a collision post, a hydraulic ram loaded the collision post using the same coil shape from the dynamic test. During the test, early failure on the back of the collision post at the loading location led to a decreased force-crush characteristic. The end frame absorbed approximately 110,000 ft-lb in 10 inches of permanent deformation, which did not meet the requirement of 135,000 ft-lb in 10 inches. A stiff gusset in the collision post did not allow the post to deform into an oval shape and caused an early fracture in the post. Although the test article did not meet the requirements, the test setup and implementation was successful.

The results of the quasi-static collision post test led to changes in the SOA design for the corner post test. The shelf was modified to reduce the amount of welding on the post. There are no internal gussets in the corner post. The corner post absorbed 136,000 ft-lb of energy in 10 inches, surpassing the requirement of 120,000 ft-lb.

The collision post design passed the dynamic test but did not pass the quasi-static test. The dynamic test is useful in showing how the end frame performs under a loading condition similar to a collision. The quasi-static test is useful in pointing out design flaws that may have been missed with the dynamic loading scenario. The successful results from the quasi-static corner post test indicate that with proper modification to the end frame design, the collision post would have passed the quasi-static test.

The testing program demonstrated repeatable methods for assessing the energy absorbing capability of end frame structures. These methods include both dynamic and quasi-static tests where energy absorption and permanent deformation are used as limiting criteria. The tests also show the improved crashworthiness of an SOA design. The test results are being used in support of the new FRA end frame crashworthiness rule.

The series of tests established the effectiveness of both the dynamic and the quasi-static test, such that either will be allowed to show that a design meets the requirements. The dynamic test allows for testing of alternative designs.

The setup and the results of these tests have established for the industry and FRA's Office of Safety a protocol for running and evaluating large deformation tests.

The results of the tests in comparison with pretest analyses show that, at this time, testing is necessary to demonstrate performance. However, as modeling methods improve and are shown to accurately predict failure and energy absorption, there is potential that analyses will in the future be acceptable for demonstrating crashworthiness performance.

ACKNOWLEDGMENTS

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Richard Stringfellow and Chris Paetsch, of TIAX, ran a pretest finite element model and monitored the purchase and manufacturing of the parts of the end frame, under contract to the Volpe Center.

Gabriel Amar of Taylor, Raynauld, Amar and Associates provided the cut drawings and the SOA design drawings.

Mark White of Transportation Technology Center, Inc. (TTCI) led the team that implemented the test. Tom Roderick of TTCI, led the fabrication of the end frames and retrofit onto the existing cars.

Long Island Railroad donated the Budd M1 car used in this test.

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