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STRATEGY FOR ALTERNATIVE OCCUPANT VOLUME TESTING

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ABSTRACT

This paper describes plans for a series of quasi-static compression tests of rail passenger equipment. These tests are designed to evaluate the strength of the occupant volume under static loading conditions. The research plan includes a detailed examination of the behavior of conventional equipment during the 800,000-pound buff strength test. The research will also include a demonstration of an alternative static test that is designed to load and test the occupant volume at a location other than the buff lugs. The alternative test will demonstrate a testing and evaluation method for the occupant volume strength of passenger rail cars that accounts for the collision load path through the occupant volume.

Per current Federal Railroad Administration (FRA) regulations, all passenger cars must support an 800,000-pound static load applied to the car's line of draft without undergoing permanent deformation. However, more operators are looking to introduce equipment built to foreign standards. Many international manufacturers are implementing alternative designs that make use of crash energy management design features, articulated truck designs that span two cars, and low floor designs. These changes in the form and function of the designs require alternative means of applying a compressive load to assess occupant volume strength.

FRA has reviewed several proposed alternatively designed equipment under requests for waivers for specific corridors of operation. Because the number of requests has increased significantly, FRA is trying to establish reasonable alternative means for assessing adequate and equivalent occupant volume strength to conventional equipment. This paper proposes an alternative static test procedure that will provide a means of evaluating a similar level of occupant volume integrity and passenger protection during a collision. The test will allow for greater design variation for newer rail cars and cars built to foreign standards.

For the alternative test, the load may be introduced through the available structure at the floor level and at the roof level. These loading locations will enable the load to be applied directly into key longitudinal members in the load path of collision loads through the occupant volume. Finite element models are used before testing to determine appropriate alternative load levels and locations.

The test article is a modified Budd Pioneer car. No significant modifications are planned for the longitudinal members of the car, or for the occupant volume.

INTRODUCTION

Passenger-carrying equipment operating on the general railroad system is subject to regulations promulgated by FRA. These regulations include structural strength requirements for the equipment, and can be found at Title 49 Code of Federal Regulations (CFR) 238.203. The compressive strength requirement ("buff strength requirement") reads, in part:

> (a)(1) Except as further specified in this paragraph or in paragraph (d), on or after November 8, 1999 all passenger equipment shall resist a minimum static end load of 800,000 pounds (lb) applied on the line of draft without permanent deformation of the body structure.

A development in the design of passenger railcars has been the introduction of crash energy management (CEM) systems. These systems are designed to absorb collision energy through controlled permanent deformation of a sacrificial unoccupied space, preserving occupant volume. The compressive strength evaluation for passenger equipment with CEM systems is altered slightly:

> (2) For a passenger car or a locomotive, the static end strength of unoccupied volumes may be less than 800,000 pounds if:
>
> (i) Energy absorbing structures are used as part of a CEM design of the passenger car or locomotive, and

> (ii) The passenger car or locomotive resists a minimum static end load of 800,000 pounds applied on the line of draft at the ends of its occupied volume without permanent deformation of the body structure.

For conventional equipment both with and without CEM systems, the 800,000-pound load is applied to the underframe of the car over a fairly small area along the line of draft. This load is shown schematically in Figure 1.

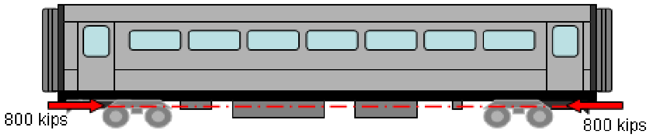

Figure 1. 800,000 lb Applied Along Line of Draft

Safety concerns arise when a vehicle that was not designed to support an 800,000-pound load is to be operated in the same environment with equipment that was designed to support the load. In the case of a car equipped with CEM, it is possible for a design to feature a load path along the line of draft for service loads, but a completely different load path through the occupant volume for collision loads. Collision loads are likely more severe than normal operating loads; the occupant volume should be designed to maintain its integrity when subjected to the more severe loading.

The current 800,000-pound load was developed over the early half of the 20th century and included as an Association of American Railroads (AAR) Recommended Practice in 1939. The buff strength requirement was adopted as a result of fatal accidents involving equipment built to different strength standards. In these accidents, “lightweight” equipment generally suffered greater loss of occupant volume than the equipment that was considered “heavyweight” [1]. By establishing a minimum level of required carbody strength along the line of draft, the equipment was thought to fare better in accidents involving high forces. The essential purpose of this requirement was to ensure sufficient occupant volume is preserved for occupants to ride out a collision.

Because of this need to protect occupant space during a collision, the load path taken by collision forces during an accident is considered important. Although the line of draft is an important load path for service loads, accident loads may take a very different load path through the occupant volume, especially in the case of a CEM system. The load path may include some level of force along the line of draft, but the total force on the occupant volume will be shared across a larger portion of the cross-section. Because the collision loads are of concern, a new evaluation criteria that accounts for the load path through the occupant volume during the collision loading would be appropriate.

Conventional Car Crush Behavior

As part of FRA’s Passenger Equipment Safety Research Program, full-scale impact tests of passenger rail equipment have been conducted. A key result of each test has been the measurement of force-crush characteristics for conventional railroad equipment [2]. This characteristic represents the force necessary to collapse the carbody as a function of distance along the length of the car. The force-crush behavior of the carbody is a key input used in other computer simulation and modeling, including train-level collision dynamics models. This characteristic describes the passenger car’s response to particular collision conditions and can be used to estimate the amount of occupant volume lost for a given collision scenario.

A typical, idealized force-crush characteristic for a conventional single-level car is shown in Figure 2. Typical features of such a characteristic include a high peak force (“crippling force”) at low displacement, followed by a significant drop in crush resistance of the occupant volume. Once the crippling force has been exceeded, the occupant volume is considered compromised. Further crush will result in the loss of survival space for occupants. Although this particular force-crush behavior may be thought of as typical for single-level passenger equipment, particular design elements of cars may result in behavior that is different from that shown here.

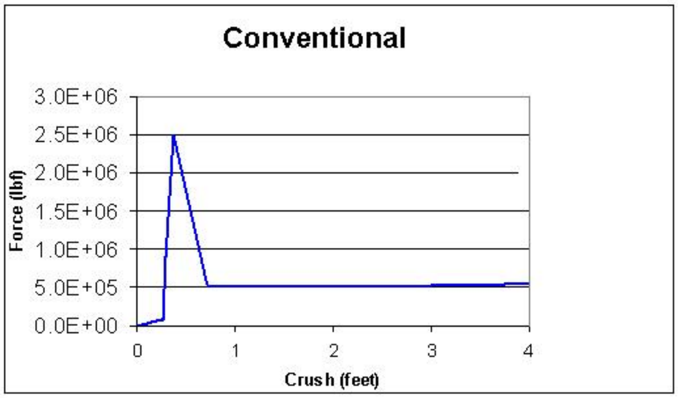

Figure 2. Idealized Force-crush Characteristic

Quasi-static finite element (FE) analyses of the occupant volume loaded until the point of crippling have indicated three regions of deformation—elastic, localized plastic, and global crippling. These three regions are indicated on a force-displacement characteristic in Figure 3.

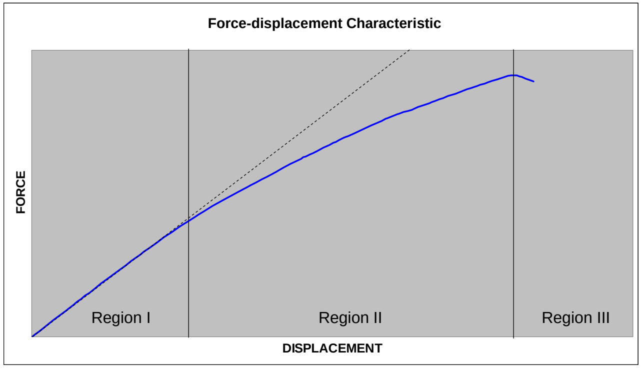

Figure 3. Force-displacement Characteristic Regions

As in the current 800,000-pound compressive strength test, an elastic relationship exists between load applied and deformation of the carbody for loads within Region I. The carbody does not experience permanent deformation when loaded within this region. Ideally, strength testing on railcars is performed within this region, as the carbody will not sustain damage and may be placed into service following testing.

Once the carbody begins to experience permanent deformation, the force-displacement behavior is no longer within Region I. The force-displacement behavior has now entered Region II, the region of plastic deformation before crippling of the carbody. In general, when loaded within Region II, the carbody experiences areas of local plastic behavior, but the carbody has not yet reached its ultimate load-carrying capacity.

At some value of applied load, the carbody's structural integrity has been compromised. This load, the crippling load, represents the maximum force the carbody can sustain. Any loading beyond this maximum will result in large-scale deformation and significant loss of occupant volume.

During a test of occupant volume integrity, load levels that remain within Region I would result in a test that is non-destructive. Whereas this is desirable for future use of the test article, this region represents only a small portion of the total load-deformation behavior of the car. Conducting a test into Region II and continuing up to the crippling load would provide a more complete force-displacement characteristic, but result in destruction of the test article.

Understanding the crippling load magnitude and the load path taken in reaching that load can be key pieces of information for ensuring a robust railcar design. While the current 800,000-pound requirement provides a minimum strength level for loads along the line of draft, collision loads may enter the occupant volume through a different load path. Prior research into the behavior of cars involved in train-to-train collisions has shown that once the occupant volume crippling strength of a given car has been exceeded, crush continues through that car rather than being passed back through the consist [3]. Understanding the crippling load of the occupant volume is important to understanding the train-level behavior during a collision.

Although conducting an occupant volume integrity test up to and beyond the crippling load would provide the most complete description of the load-deformation behavior of the occupant volume during collision loading, a destructive test is not practical for a new car design. The crippling behavior may be calculated using FE analyses, but a purely analytical approach would inspire less confidence than test data.

A satisfactory solution may be found through a combination of physical testing and detailed analyses. The occupant volume could be loaded along the collision load path to some significant compressive load not to exceed the elastic limit of the car. This load case could be simulated using detailed FE analysis. If the elastic FE results are verified through this test, further FE analysis can be performed to estimate the crippling load of the occupant volume. This approach maintains the carbody testing as a non-destructive evaluation while providing greater confidence in the analytical results versus analysis alone.

PLANNED TESTS

An alternative test is planned to evaluate the occupant volume strength of a car that is compliant with existing FRA regulations for buff strength. This test is intended to consider the load path through the occupant volume that is likely during collision loading. Previous analyses by Carolan, et al have been performed to study the behavior of a generic single-level passenger car when subject to various compressive loads [4]. This work indicated that the carbody behaved like a simple beam under the 800,000-pound load, and that this behavior could be replicated through loading at alternate locations such as the lower energy absorber supports.

The selected test car has been modified to be equipped with a CEM system. While normal service loads travel through the coupler and into the underframe, collision loads of sufficient strength to trigger the CEM system will follow a different load path into the occupant volume. Since collision loads present the greatest challenge to the occupant volume's integrity, the compressive testing should occur at the location these loads enter the occupant volume. The locations of the energy absorber support structures on the test car, Budd Pioneer Car 244, are indicated in Figure 4.

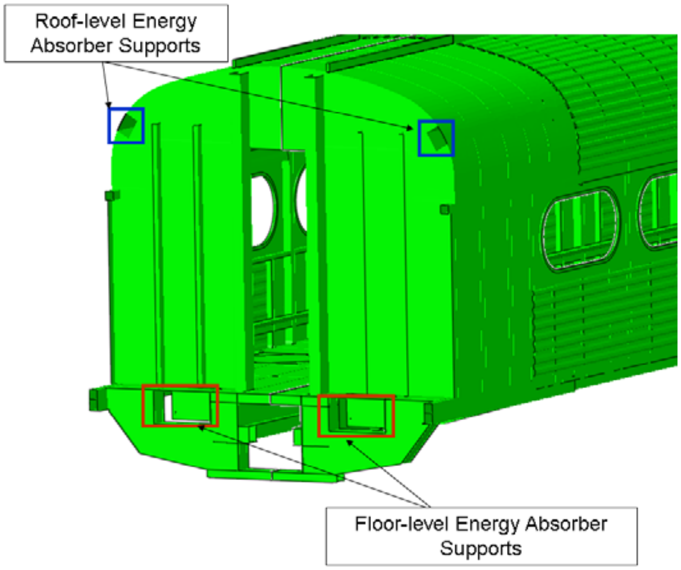

Figure 4. Energy Absorber Support Locations

800,000-pound Buff Test

The first test to be performed will be a conventional 800,000-pound compressive load test. Because this particular car is designed for a CEM system, the load will be reacted at a suitable location along the line of draft of the railcar. The loading location is the back of the coupler pocket. This loading location will be consistent with 49 CFR 238.203(a)(2). The load will travel through the sliding sill portion of the CEM design. The trigger mechanism, an arrangement of shear bolts, is designed to support the 800,000-pound load without activating the CEM system.

The CEM system is described in detail in Martinez, et. al [5]. A CEM crush zone of the type previously installed on the test car is shown in Figure 5. For this particular design the load is introduced through the couplers during an in-line train-to-train collision. Upon impact, the load initially triggers the shear bolts of the pushback coupler, causing the coupler to slide into the underframe of the car end. The impact load then transfers to the buffer beam and anti-telescoping plate of the end frame. A second set of shear bolts between the fixed sill and sliding sill is designed to fail at a specified force level. Once these bolts fail, the entire end frame slides back along a sliding sill while crushing the primary energy absorbers and the roof absorbers. These energy absorbers are supported by the occupant volume.

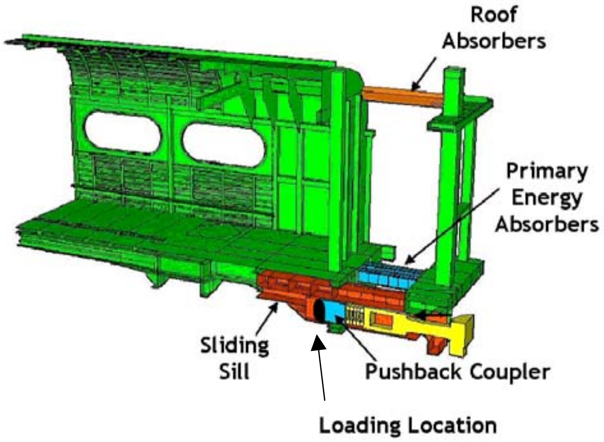

Figure 5. Coach Car Crush Zone

For the 800,000-pound test, the coupler and its energy absorber will be removed and the buff lugs will be loaded. The load will travel through the sliding sill's shear bolts and continue into the center sill. The crush zone should not be activated, as the shear bolts are designed to fail at a load greater than 800,000 lb.

The purpose of loading the car in this manner is to establish the baseline behavior of the occupant volume during a test that the car was designed to pass. Although significant structural modifications have been made to both ends of the railcar, the structures between the body bolsters are left as they were originally. The carbody should not experience permanent deformation during this compressive test. As a result of numerous high energy tests this car has been subjected to, it may have sustained damage greater than pretest inspections have discovered. The 800,000-pound buff test will help determine if this car is still structurally sufficient.

Combined-loading Test

Because the CEM system on the Pioneer car features energy absorbers at the roof and the floor levels, a loading case that takes advantage of both of these locations simultaneously is desired. The carbody would be restrained at its rear end at the roof and floor energy absorber supports. This load case is shown schematically in Figure 6.

Figure 6. Schematic Showing High and Low Load

By loading the occupant volume across both sets of CEM supports, this load case attempts to simulate the carbody's behavior during a collision of sufficient severity to trigger the leading and trailing end CEM components. The loads are introduced into the occupant volume at the locations where collision loads will be introduced. This test will initially be run in the elastic range of the car. If the test fixture design allows for loads of sufficient magnitude the car will also be loaded to its crippling load.

TEST SPECIMEN

The cars used in FRA's full-scale test program have been donated by various railroads during the past 10 years. The program has used Budd M1, Budd Pioneer, and Bombardier multilevel cars for a total of 10 full-scale crash tests. Some vehicles were tested "as is" to establish a baseline level of crashworthiness and some cars received modifications to demonstrate improved crashworthiness designs.

Several cars have been crash tested and repaired multiple times, while others have been damaged beyond repair. The cars that remain were inspected to determine the best choice for this test. The ideal candidate would be an unaltered car that has been designed and tested to the 800,000-pound buff strength test. The ideal car would also not be damaged on any of its structural members.

The best available candidate was Budd Pioneer Car 244. The car features a stainless steel body structure and a high-strength low-alloy steel underframe, and was constructed to meet the 800,000-pound buff strength requirement. This car has been used in four full-scale crash tests. The car crushed 5 feet in a dynamic one-car conventional test [2]. It was then retrofitted with a CEM non cab crush zone and tested in a one-car CEM test [6]. The car and its CEM crush zone were then repaired and the car was used as the second car in the two car CEM test [7]. In its fourth and final test to date, the car and its crush zones were repaired and used as the fourth car in the CEM train to train test [8]. Budd Pioneer Car 244, with CEM crush zones, is shown in Figure 7.

Figure 7. Budd Pioneer Car with CEM

During the CEM retrofit, the end structures of the car, including the endframe and portions of the draft sill, were removed and replaced with energy-absorbing components. However, the carbody structure between the body bolsters was left unmodified. Because the occupant volume is principally located between the body bolsters, this railcar represents a typical occupant volume arrangement for single-level railcars of conventional construction. A cross-section of the occupant volume, taken from the FE model, is presented in Figure 8 with structural members of interest indicated.

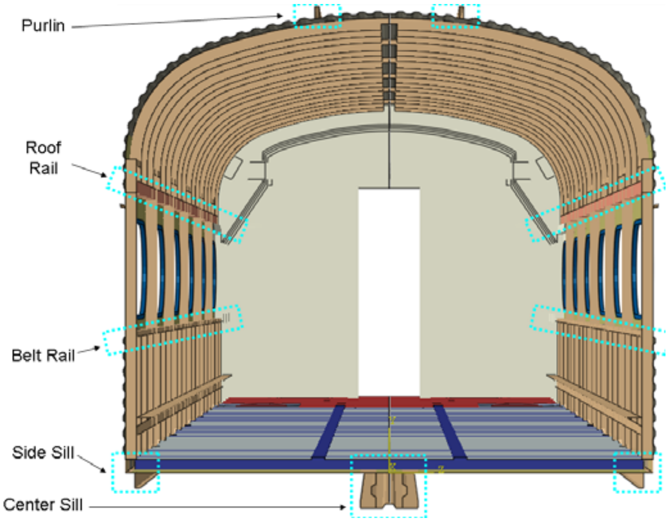

Figure 8. Occupant Volume Cross-section

PRETEST MODELING AND SIMULATION

Detailed FE models have been used to assist in the selection of load magnitudes and locations. A detailed FE model of a conventional Pioneer car was developed as part of the full-scale testing program [9]. This model was later modified to include CEM components [6]. The CEM Pioneer model is the starting point for the modeling efforts supporting these tests.

The commercial software ABAQUS/CAE was used to modify the existing model [10]. Modifications include removal of the endframe, pushback coupler, and primary energy absorber components. These modifications were anticipated as necessary to accommodate the physical testing of the railcar, as access would be needed to the energy absorber supports. Additionally, the suspension is not modeled as part of this effort.

Because the quasi-static tests are intended to evaluate the occupant volume strength of the passenger car, the CEM components do not need to be included in either the model or the test car. Likewise, the suspension components are not necessary to capture an accurate response from the occupant volume during this test. The loads that would be reacted through the CEM system are to be applied directly to the supports for the energy absorbers, located at the ends of the occupant volume. An oblique view of the modified full car geometry is shown in Figure 9.

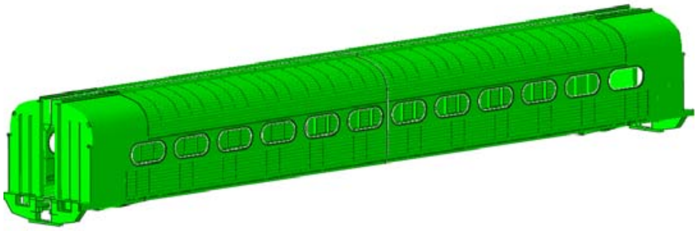

Figure 9. FE Model Geometry (Modified Full Car)

Taking advantage of the symmetry of the railcar at its longitudinal and lateral midplanes, only one quarter of the car is modeled. This model is adequate for simulating load cases where the carbody is being reacted at the same location as the load application on the front end. The materials used in this model are represented as elastic-plastic. Material failure and element removal are not included in the material definitions.

The non-linear finite element solver ABAQUS/Explicit was utilized to perform the analyses on this vehicle [10]. Analyses were performed for the load cases described in the preceding section, as well as load cases designed to overload the occupant volume to the point of collapse. These crippling analyses were conducted to provide an estimate of the upper limit of force that can be applied to the vehicle body during the test, so that the test conditions may be specified below this level for any test where crippling is not desired.

Preliminary FE Model Results

The first load case simulated using the FE model was the conventional buff strength test. In this case, the load was placed in-line with the center sill at the intersection of the center sill and the body bolster. This location is indicated in Figure 10.

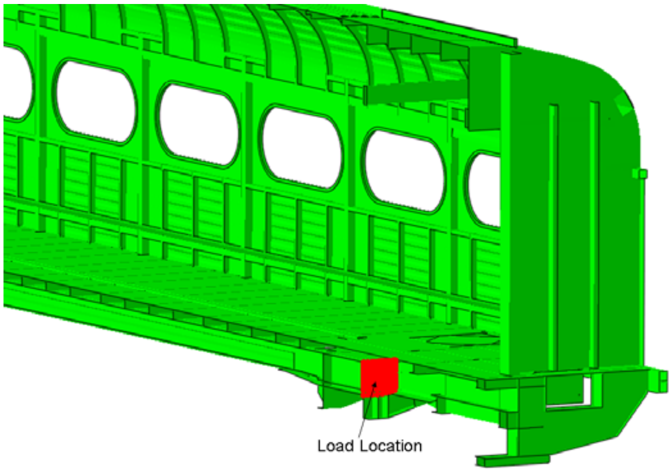

Figure 10. Line of Draft Load Location

Loading was accomplished by prescribing a displacement value for the nodes at the load location. The displacement was applied gradually over time, simulating an external load application where displacement is controlled. Load magnitude was calculated at the lateral symmetry plane as well as at the load application location. The estimated force-displacement characteristics at both locations are shown in Figure 11. The crippling load is estimated at 1.4 million

Figure 11. Line of Draft Force-displacement Characteristics

The next load case analyzed featured simultaneous loading of both the floor and roof energy absorber supports. The carbody was restrained at similar locations on the back end. Estimated force-displacement characteristics for this load are plotted along with the estimated characteristic for the line of draft load in Figure 12.

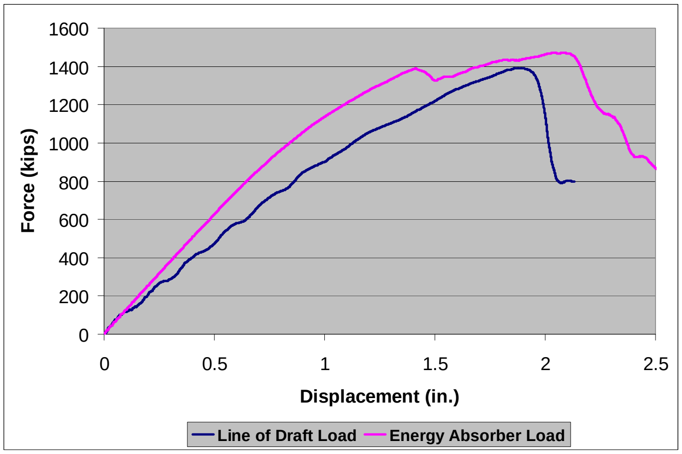

Figure 12. Force-displacement Characteristics for Two Load Cases

For the dual energy absorber load case, the general shape of the force-displacement characteristic is the same as the line of draft load. The occupant volume is stiffer under this loading, as more of the structure is being engaged by loads at the floor and roof. The characteristic features a dip in force level corresponding to buckling of the roof structure that occurs before the crippling load is reached. The crippling load for the entire occupant volume is slightly above 1.4 million lbs for this load case.

TEST IMPLEMENTATION

Anticipated Modifications

On the basis of the results of the finite element modeling, certain modifications may need to be made to the structure of the railcar to accept significant loads over relatively small areas. It is not anticipated that any modifications will be made to the longitudinal members making up the occupant volume.

Budd Pioneer Car 244 has already been retrofit with CEM crush zones on either end, outside of the body bolsters. In the last test that Car 244 underwent, the CEM crush zone was triggered and crushed. During that test, shear bolts that held the sliding sill in place failed in shear at the prescribed force level. As the sill will be loaded in this test, repairs will be made to the sliding sill and crush zone as necessary. Anticipated repairs include boring out the holes where the old shear bolts were and installing new bolts. Crush zone components that were bent in previous testing will also be straightened prior to this test. The energy absorbing components, which were crushed during the train-to-train test, will not be replaced, as the crush zone will not be triggered during the test.

Test Fixtures

The primary test article for each structural test is the occupant volume of the railcar. The current squeeze test fixture requires that the car be lowered to align the line of draft with the loading structures on the frame. To achieve a lowered line of draft, the carbody will likely have its trucks removed and be supported at the body bolsters where the suspension components would be attached. The carbody will be supported in such a way as to allow it to lift upward as a result of bending moments generated during the test.

The carbody will also require restraint in the longitudinal direction. Depending on the test, this restraint will be provided at one or more locations at the rear end of the car. The testing location will require either a significant testing frame or fixed walls to react the loads into the carbody at multiple locations. The scenario will be analyzed using finite element models to develop a rigid test fixture.

To apply the load in the combined loading test, fixtures will be designed to load the left and right sides of the car evenly. In using these fixtures, the load in the two lower energy absorber supports will be equal, and the load in the two roof absorber supports will be equal.

Planned Instrumentation

The primary output from the testing portion of this research program is the force-displacement characteristic for the occupant volume for each loading setup. Additional output of interest includes the overall deformation mode of the carbody and stress-strain behavior for key members making up the occupant volume.

The carbody is expected to arch upward as a result of the bending moments generated during loading [6]. String potentiometers will be placed at five locations along the length of the car, between the center sill and fixed points along the ground to measure this behavior. This arrangement is shown schematically on one half of the car in Figure 13.

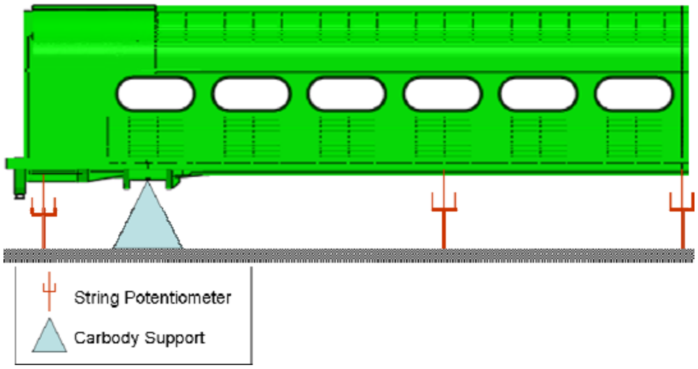

Figure 13. Vertical String Potentiometer Placement

The loads being reacted through the occupant volume will be generated through the use of hydraulic cylinders attached to a rigid test fixture or wall. The stroke length of the cylinders will be measured through string potentiometers placed between the rigid fixture and the loading location. Additional potentiometers may be used to measure deflection of the endframe at some intermediate height. The hydraulic cylinder and string potentiometer setup is shown for the live end of the car in Figure 14.

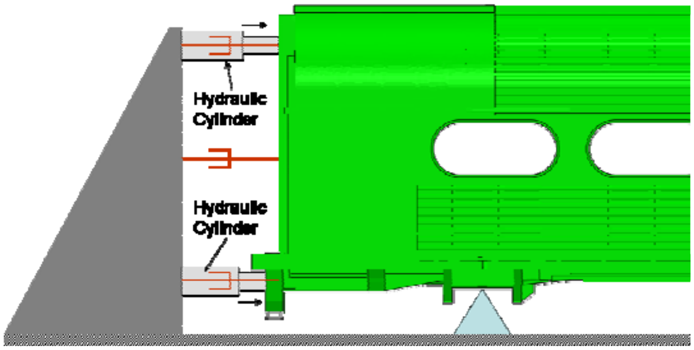

Figure 14. Live End Instrumentation

At the fixed end of the car, rigid supports will be placed between the rigid test fixture and the appropriate reaction location or locations on the carbody. Load cells will be placed at each reaction location to measure the force being transmitted through the carbody. Additional string potentiometers will be placed at each reaction location to measure any deflection between the rear end of the car and the rigid support fixture. This arrangement is shown in Figure 15.

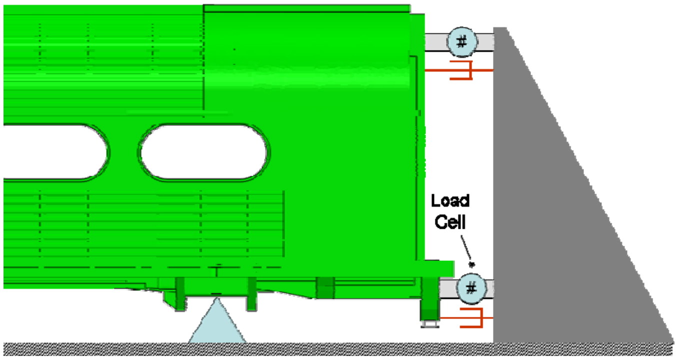

Figure 15. Fixed End Instrumentation

In addition to the force-deflection behavior of the carbody, another key output from this test will be the stress-strain behavior of key structural members. At a minimum, the center sill, side sills, belt rail, and roof rail will be instrumented with strain gages at each longitudinal location where a string potentiometer will be placed. This will provide strain data in the major longitudinal members of the car at five cross-sections of the car. Strain gages will be placed on both the left and right hand sides of the car, providing a level of redundancy.

Additional strain gages will be necessary for critical areas likely to experience large strains and/or buckling behavior. While the load path through the occupant volume will vary with the load and reaction locations, the same strain gages will be used throughout the testing sequence. These critical areas will be indicated by the results of the detailed finite element simulations of the tests.

In addition to the instrumentation already discussed, the testing sequence will be video recorded. The video will be uncompressed digital video, with a target recording rate of one frame of video for 0.01 inch of actuator displacement. The cameras will be focused on the load application locations. Oblique and head-on views will be recorded.

Data Acquisition

The primary outputs of this test will include the force-deflection behavior of the occupant volume during each load case, as well as vertical and lateral deflections of the carbody and stresses and strains in critical members. Load cells capable of reacting the load magnitudes anticipated in these tests (approximately 1,000 kips) will be utilized at the reaction end of the car to measure applied force. The load cells can be used in parallel to measure the total load through a single location. String potentiometers will be used on the front and rear ends of the car to measure carbody deflection as the load is applied. Strain gages will be applied to the longitudinal structural members along the length of the carbody to provide an indication of the overall stress state of the car throughout the tests.

Test Procedures

For these quasi-static tests, loading will be accomplished through one or more hydraulic rams, capable of generating the necessary loads. Testing apparatus and procedures already exist for testing the car to 800,000 lb along the line of draft. The low-level load at the floor energy absorber supports will likely utilize a similar test setup as the existing 800,000-pound test. However, it is anticipated a testing rig will be necessary for the load case involving the roof absorbers. Additional care must be taken to ensure loading of the floor and roof absorbers occurs at the same rate.

Procedures for the existing 800,000-pound test are described in APTA Standard SS-C&S-034-99, “Standard for the Design and Construction of Passenger Railroad Rolling Stock” [11]. According to the APTA Standard, the carbody is incrementally loaded over a series of loads that measure less than 800,000 lb, and is held at each load along the way until stable strain readings are achieved. This procedure allows stress values to be extrapolated to the stresses anticipated at 800,000 lb. The test may be terminated if it is believed the carbody will sustain permanent deformation during subsequent loadings.

A similar methodology will be used to load the car at alternate locations. The loading of the car will be graduated, with intermittent loads used to help identify critical areas of likely failure. The load will be applied gradually in increments and held for a period of one minute. The load may then be lowered to a nominal level of 5 to 10 kips before loading to the next increment.

After the car has been tested to its elastic limit, the car will then be loaded to its crippling load.

The APTA standard also requires ballasting of the carbody to simulate the presence of interior fixtures within the occupant volume. The car will be ballasted during the test to simulate the running weight of the vehicle.

SUMMARY

A series of quasi-static compression tests are planned to evaluate the occupant volume integrity of passenger equipment. In addition to performing a conventional 800,000-pound buff strength test, the occupant volume will be tested for its response to loads typical of those developed during CEM system use. These loads will be applied to the energy absorber supports at the ends of the occupant volume, giving consideration to the load path collision loads will take through the occupant volume.

Before conducting this test, FEA will be performed on the carbody to establish boundary load magnitudes and locations. Additionally, the results of the FE work will assist in determining what, if any, modifications to the carbody are necessary to react the loads envisioned in this test. The FE results will also be used to assist in identifying significant areas of strain and/or buckling. These areas will be appropriately instrumented during the test.

The key output from each test is the force-displacement characteristic for the occupant volume. Additional output data that will be requested includes vertical displacement along the length of the carbody as well as strain data in structural members along the load path.

The combined loading test explores an alternative loading scenario to the traditional 800,000-pound buff test. This test should provide guidance on evaluating cars without traditional buff stops. It is important that the occupant volume strength of new equipment built to foreign standards be compatible with cars currently operating on U.S. rail corridors.

FUTURE PLANS

On the basis of the outcome of this test, additional tests may be implemented to further understand the behavior of the occupant volume. To better understand the applicability of these tests to a variety of vehicles, they may be run on another suitable carbody. Additionally, loading another carbody until its structural integrity has been crippled would further enhance the understanding of carbody collapse behavior at fairly large loads and displacements.

ACKNOWLEDGEMENTS

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REFERENCES

1. White, J.H. “*The American Passenger Railway Car.*” Baltimore, MD: The John Hopkins University Press, 1978.

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2. Tyrell, D., Severson, K., and Perlman, A.B. “Single Passenger Rail Car Impact Test Volume I: Overview and Selected Results,” U.S. Department of Transportation, DOT/FRA/ORD-00/02.I, March 2000.

3. Tyrell, D. “Passenger Rail Train-to-Train Impact Test Volume I: Overview and Selected Results.” US Department of Transportation, DOT/FRA/ORD-03/17.I, July 2003.

4. Carolan, M., Perlman, B.A., Tyrell, D., "Evaluation of Occupant Volume Strength in Conventional Passenger Railroad Equipment" American Society of Mechanical Engineers, Paper No. RTDF2008-74026, September 2008.

5. Martinez, E., Tyrell, D., Perlman, A.B. , "Development of Crash Energy Management Designs for Existing Passenger Rail Vehicles," American Society of Mechanical Engineers, Paper No. IMECE2004-61601, November 2004.

6. Jacobsen, K., Tyrell, D., and Perlman, A.B. “Impact Test of a Crash-Energy Management Passenger Rail Car.” American Society of Mechanical Engineers, Paper No. RTD2004-66045, April 2004.

7. Jacobsen, K., Tyrell, D., and Perlman, A.B. “Impact Tests of Crash Energy Management Passenger Rail Cars: Analysis and Structural Measurements.” American Society of Mechanical Engineers, Paper No. IMECE2004-61252, November 2004.

8. Tyrell, D., Jacobsen, K., and Martinez, E., “A Train-to-Train Impact Test of Crash Energy Management Passenger Rail Equipment: Structural Results.” American Society of Mechanical Engineers, Paper No. IMECE2006-13597, November 2006.

9. Kirkpatrick, S., and MacNeil, R. “Development of a Computer Model for Prediction of Collision Response of a Railroad Passenger Car.” Proceedings of the 2002 IEEE/ASME Joint Railroad Conference, Institute of Electrical and Electronics Engineers, Catalog Number CH37356-TBR, 2002.

10. ABAQUS Version 6.9-1, 2009, Dassault Systemes Simulia Corp. Providence, RI.

11. American Passenger Transportation Association, “APTA SS-C&S-034-99, Rev. 2. Standard for the Design and Construction of Passenger Railroad Rolling Stock,” June 15, 2006.