# Revising US passenger railcar occupant volume integrity requirements

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## ABSTRACT

The Federal Railroad Administration (FRA) is developing new regulations addressing the occupant volume integrity (compressive end strength) of passenger rail cars. The new rules are being adopted to accommodate the introduction of rail equipment designed to alternate standards that will provide a level of safety equivalent to that of conventionally-designed vehicles. The fundamental change in the regulations involves applying the proof load on the collision load path rather than on the line of draft, as has been longstanding U.S. practice. Alternatively-designed passenger equipment must be shown to comply with one of the following loading scenarios:

- 3,560 kN (800,000 lbf) with no permanent deformation
- 4,450 kN (1,000,000 lbf) with limited plastic deformation
- 5,340 kN (1,200,000 lbf) without exceeding the crippling strength of the car.

Full-scale tests have been performed to determine whether these scenarios adequately represent the compressive end strength of conventionally-designed passenger equipment. This paper includes a description of and selected results from the full-scale crippling load test program and illustrates that the proposed load levels and performance requirements are reasonably reflective of the strength of conventional equipment. Alternatively-designed equipment compliant with the new requirements will achieve the safety-equivalence goal.

## 1 BACKGROUND

The FRA Office of Research and Development conducts research to inform rulemaking to improve crashworthiness and occupant protection for passenger railroad equipment operated in the U.S. Acknowledging that equipment designed to more modern, performance-based standards is highly desired by U.S. passenger railroads, FRA is focusing on implementing crashworthiness regulations that are compatible with emerging safety technologies. In a passenger train collision or derailment, the principal crashworthiness risks include the loss of survival space inside the passenger compartment due to crushing of the carbody structure and, as the train decelerates, the risk of secondary impacts of passengers with interior surfaces. Resistance to loss of survival space is referred to as occupant volume integrity (OVI). Since May 2003, FRA, with the assistance of the Volpe Center, has conducted substantial research on rail equipment crashworthiness to establish the technical basis for more performance-based regulations to respond to the needs of the industry. Ensuring that equipment designed to alternate standards possesses OVI equivalent to that of conventionally-designed passenger equipment is the cornerstone of the revised regulatory philosophy.

Current FRA regulations require that Tier I passenger equipment (with maximum operating speed of 200 km/h [125 mph]) sustain a static compressive end-load of 3,560 kN (800,000 lbf) applied longitudinally on the line of draft without permanent deformation (1). This traditional approach to demonstrating OVI is relatively simple to accomplish. Since it is intended to be non-destructive to the test article, the required load is applied and released, and measurements and visual observations confirm or refute the absence of permanent deformation. Passenger rail equipment built to alternative design standards generally incorporates crash energy management (CEM) principles and employs crush zones and deformable structures outboard of the occupant volume which collapse during impact and absorb collision energy while preserving passenger survival space. In order to provide maximum effectiveness, CEM-equipped vehicles must possess a strong occupant volume to ensure that vehicle crushing is restricted to areas outboard of the occupant compartment. As such, this equipment will generally not pass the traditional line of draft buff strength test since permanent deformation cannot be avoided.

FRA convened the Engineering Task Force (ETF) of the Passenger Safety Working Group of the Railroad Safety Advisory Committee (a government-labor-industry body formed to develop consensus rulemaking) in 2009 to conceive new standards for assessing crashworthiness generally, and OVI in particular, of alternatively-designed equipment not built according to traditional U.S. practice (2). The primary goal of the new standards is to ensure OVI equivalence of new equipment with that of existing rolling stock. This new standard differs from the conventional approach primarily in that loads are introduced into the occupant volume through the collision load path, whereas the conventional requirement places loads along the line of draft. For passenger vehicles equipped with crash energy management (CEM) components, collision loads are applied at the interface between the occupant volume and the CEM components. Originally conceived as guidance for railroads seeking a waiver of the conventional FRA regulations in order to deploy alternatively designed passenger equipment, the ETF criteria and procedures describe the analysis and testing which must be performed and submitted to FRA to demonstrate compliance with the new requirements. The ETF criteria and procedures are now in the process of being codified into regulation.

The ETF OVI requirements for alternatively-designed passenger equipment require compliance with one of the following loading scenarios:

- 3,560 kN (800,000 lbf) with no permanent deformation
- 4,450 kN (1,000,000 lbf) with limited plastic deformation
- 5,340 kN (1,200,000 lbf) without exceeding the crippling strength of the car.

In this context, the crippling strength is the maximum load (applied on the collision load path) that can be sustained by the occupant volume. The ETF crippling strength requirement is the extreme means by which OVI equivalence between conventionally- and alternatively-designed equipment is determined, and is founded on previously-performed testing and analysis of typical US passenger equipment (3).

## 2 MOTIVATION and APPROACH

FRA conducted a test program culminating in a destructive test of a conventionally-designed passenger car in order to:

- provide additional validation of the ultimate (crippling) strength of the occupant volume of conventional equipment,
- provide the opportunity for two independent teams to perform the analysis that would be expected to be provided to FRA to demonstrate compliance with the ETF criteria and procedures related to OVI, and
- produce documentation which could serve as a model for railroads seeking approval from FRA to acquire and place into service equipment not compliant with the existing regulations.

Confirmation of the crippling strength of conventionally-designed equipment is important since the ETF OVI requirements are based in part on this metric. Previous testing was performed on a pair of cars of identical construction. In this test, a different design was used to provide additional validation of the ETF criterion.

A manufacturer must supply information to its customer demonstrating that the equipment it is providing is compliant with applicable regulations; this information is subsequently provided to FRA for the same purpose. Regulatory compliance demonstration is increasingly reliant on numerical analysis and simulation, which is validated by elastic structural tests. The validated model is used to show compliance with requirements for which tests were not performed. Although carbody destructive tests, such as the one described here, are rarely performed by manufacturers when developing data to demonstrate compliance with structural requirements, FRA sought to use this opportunity to develop information, which can be publicly shared, illustrating how the ETF criteria and procedures could be applied in practice. Two modelling teams were organized to perform analyses, informed by the calibration test data, of the crippling test and produce mock documentation representative of that which would be presented to FRA to demonstrate compliance with the regulations.

The testing was conducted in two parts:

- an elastic test in which 3,560 kN (800,000 lbf) was applied to the carbody to ensure that it was sufficiently structurally sound for the crippling test and to develop calibration data for the modelling teams, and
- a crippling (destructive) test which involved loading the occupant volume to the point at which it could no longer sustain load to establish its OVI.

The general approach is shown in Figure 1 and generally follows the ETF recommendations. The final crippling load test has been added to this program in order to provide the additional information on OVI described above.

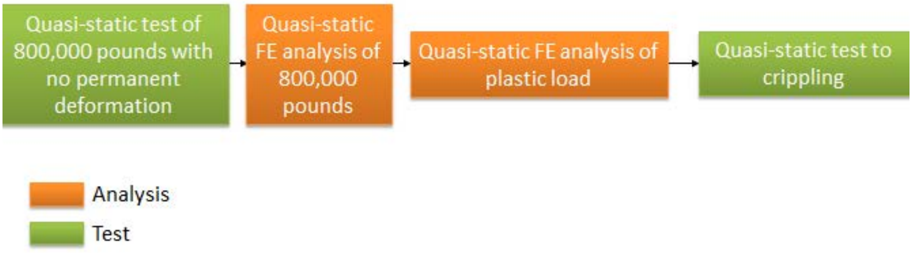


**Figure 1. ETF approach to OVI assurance with additional crippling test component added as part of this research program.**

## 3 TEST PROGRAM

### 3.1 Overview

Transportation Technology Center, Inc. (TTCI) performed two full-scale tests on a Budd M1 Car 9614 at the Transportation Technology Center in Pueblo, CO. This particular car had been previously modified to include CEM elements on both ends. In order to evaluate OVI, the CEM elements were removed to allow loads to be placed where they would be introduced into the occupant volume in the event of a collision.

In the first test, conducted on March 13, 2013, a 3,560 kN (800,000 lbf) load was applied through the two floor-level CEM pockets. This test was performed to assess the integrity of the test article (since it had been damaged during a previous train-to-train collision test) and to develop data which would be provided to the analysis teams to calibrate their respective models in advance of the crippling load test. The crippling load test was performed on July 17, 2013 during which loads were introduced through the floor and roof level CEM pockets. The test setup is shown in Figure 2 and is identical to that used in prior similar tests (3).

**Figure 2. Test car in loading fixture. Arrows indicate approximate location at which loads are applied for crippling load test.**

Before testing, all significant damage observed on the car was repaired. A patch was applied to one location on the right side sill, and to maintain structural symmetry, an identical patch was applied in the same location on the opposite side of the car. Material characterization tests were performed on selected structural members using specimens excised from a sister car. These data were provided to the analysis teams for incorporation into their respective finite element models. The squareness of the car in the test fixture was surveyed prior to commencing testing. The survey indicated that the car was not precisely aligned within the fixture, resulting in slightly non-perpendicular alignment between loading rams and the end structure of the car. This information was provided to the modelers to allow for appropriate corrections.

### 3.2 Instrumentation

Arrays of strain gauges and displacement transducers (string potentiometers) were applied to the test car. The instrumentation arrangement was the same for both tests. Strain gauges (81) were installed at nine longitudinal stations along the length of the car. A typical cross-sectional strain gauge distribution is shown in Figure 3. At certain locations, individual strain gauges were shifted slightly from their desired positions to avoid structural details. The spatial position of each gauge was recorded and provided to the analysts to permit extraction of model results at the relevant locations.

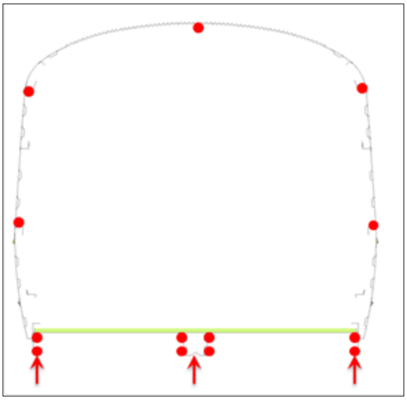


**Figure 3. Cross-sectional distribution of strain gauge instrumentation at typical longitudinal station**

String potentiometers (63) were arranged in triads to permit measurement of the three-dimensional displacement and were installed along the center and side sills at each cross section, with the exceptions of cross-sections 2 and 8 since these sections coincided with the bolster locations. The displacement transducer arrangement is shown in Figure 4. The spatial position of each triad was recorded and provided to the analysts to permit extraction of model results at the relevant locations.

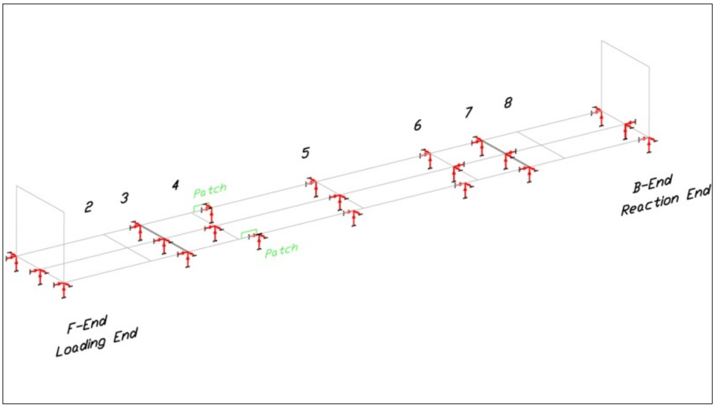


**Figure 4. Layout of string potentiometer arrays**

The four load actuators were equipped with pressure and displacement transducers to monitor the stroke and applied load at each corner on the F-end of the car to which loads were applied, as shown in Figure 2.

### 3.3 Proof test

The 3,560 kN (800,000 lbf) test was performed first in order to provide calibration data for the modelers. The load was applied to the floor-level CEM pockets only in gradually-increasing increments and reduced to 90 kN (20,000 lbf) after each load increment. This strategy allows for verification that the measurement equipment is functioning properly. Since the instrumentation is monitored in real-time, cycling the load allows comparisons to be made at the same load level multiple times throughout the test. Substantially different measurement observations at the same load would indicate problems with the test setup or instrumentation which might warrant suspending the test. Prior to application of the final (maximum) load, the load was reduced to 9 kN (2,000 lbf) as required by the American Public Transportation Association (APTA) Standard PR-CS-S-034-99, Rev 2 (4). Reduction of the load to nearly zero allows for confirmation that permanent deformation has not occurred before application of the maximum load. The loading rate was approximately 1.8 cm/min (0.7 in/min). Load, strain and displacement sensor readings were collected. Review of the data following the test suggested locations at which buckling could be expected during the crippling test.

Following the proof test, slight buckling of the left and right side sills was observed at station 6 as shown in Figure 5. However, upon removal of the load a mere 0.25 cm (0.1 in) permanent change in length of the car was measured, providing evidence (despite the pre-existing damage) that the car was suitable for use in the crippling test.

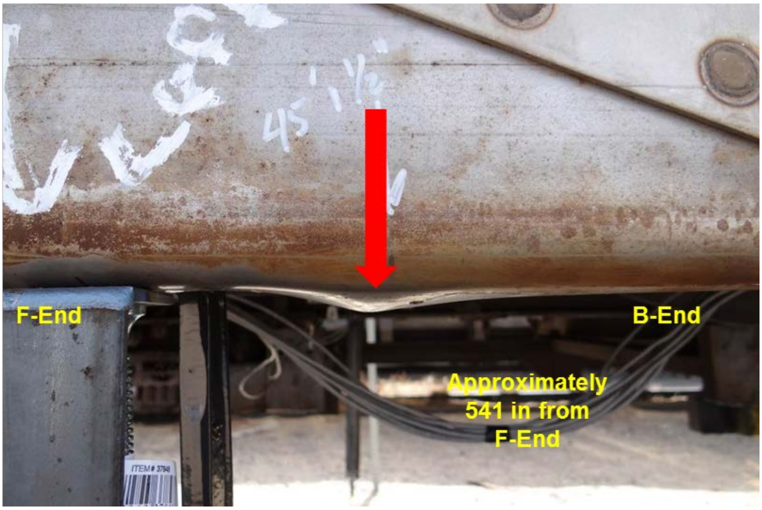


**Figure 5. Slight buckle on lower flange of left side sill following proof test. Similar damage observed on right side sill at same location.**

### 3.4 Crippling test

The loading procedure for the crippling test generally followed the same protocol employed for the proof test with one exception. Following application of the 2,670 kN (600,000 lbf) load increment, the load was reduced to 9 kN (2,000 lbf). The remainder of the test was performed under stroke control. The actuators were advanced in 0.64 cm (0.25 in) increments, with a dwell after each increment, until crippling of the carbody occurred.

Buckling first occurred in the roof at a total load of approximately 3,115 kN (700,000 lbf) followed by a corresponding buckle at 4,272 kN (1,000,000 lbf) at approximately the same position on the roof at the opposite end of the car as shown in Figure 6 and Figure 7. Roof buckling did not occur during the 3,560 kN (800,000 lbf) proof test because in that test the loads were applied to the floor-level CEM pockets only which resulted in upward bending of the carbody, putting the roof structure in tension.

At a total load of approximately 4,700 kN (1,100,000 lbf), complete crippling of the center sill and side sills occurred. Previous results obtained from similarly-performed tests of a Budd Pioneer cab car indicated crippling strength of this conventionally-designed passenger car to be between 5,120 – 5,296 kN (1,150,000 – 1,190,000 lbf) (2). Recall that M1 car 9614 had sustained damage during a previous test program. The major damage was repaired prior to commencing testing; however some local areas of damage remained, which initiated critical buckling of the underframe and lowered the apparent crippling strength of the carbody.

The test results provide additional validation of the extreme carbody strength requirement proposed by the ETF. Additionally, based upon the results of the three crippling tests performed to date, the crippling strength of conventional equipment operated in the U.S. can be conservatively estimated to be 5,340 kN (1,200,000 lbf).

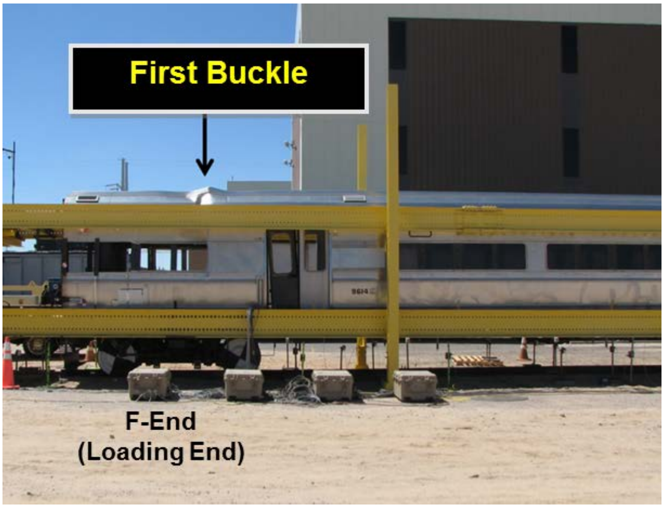


**Figure 6. First roof buckle at 3,115 kN (~700,000 lbf)**

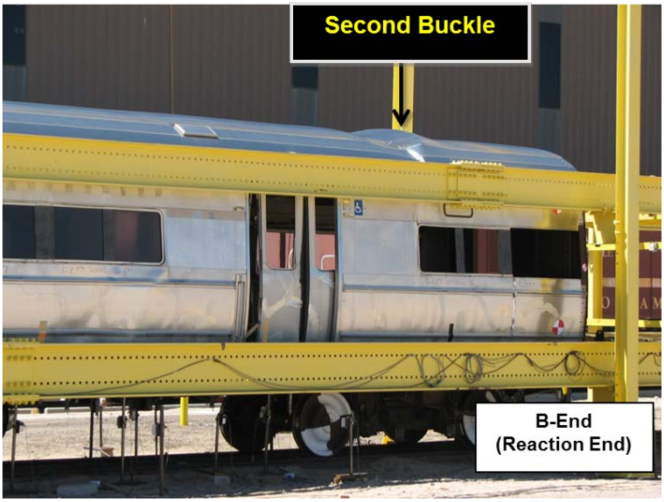


**Figure 7. Second roof buckle at 4,272 kN (~1,000,000 lbf)**

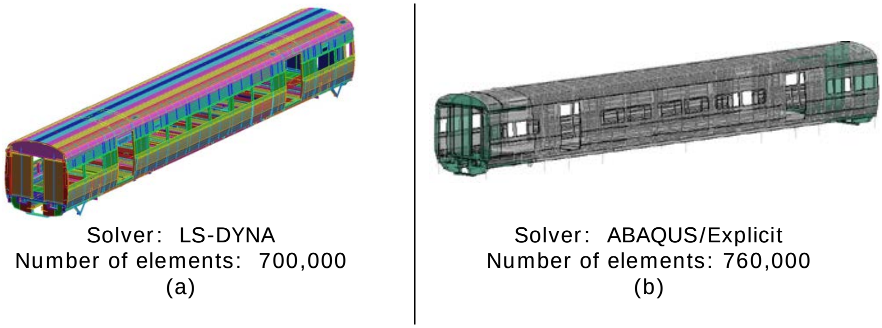
## 4 ANALYSIS

Since demonstration of the OVI of modern passenger rail equipment designed to alternative standards (especially those incorporating CEM technology) cannot be practically achieved using the conventional proof test approach, the ETF criteria and procedures acknowledge that extensive computer modelling supported by limited physical testing is necessary to accomplish this. The modelling activity associated with this test series was conceived to provide publishable results that could be used as guidance for manufacturers in developing information to present to FRA to show compliance with FRA structural requirements.

Generally, such testing and analysis would be performed by the equipment manufacturer and submitted to FRA for review and acceptance, with that information treated confidentially. Destructive tests, such as the one described here, are typically not performed by manufacturers. Instead, elastic tests are performed on instrumented equipment and the results are validated with a numerical (i.e., finite element) model. Once validated against the test data to within a reasonable tolerance (ETF recommendations are ±10% for displacements and ±20% for strains), the model can be used to demonstrate vehicle response to loading conditions not tested. Demonstration of compliance with regulations is achieved through submission to FRA of the test plan, test data, a demonstration of model validation, and model results that illustrate compliance with the relevant regulations.

Two modeling teams were assembled to develop prototype analyses and documentation of the crippling test according to the ETF procedures. The teams operated independently, and were provided the same information related to the car design, and the proof and material test results. The teams included Arup (in collaboration with TTCI) and the Volpe Center. This parallel modeling effort was devised to demonstrate that two different modelers, utilizing different approaches (e.g. different modeling techniques, different software packages, etc.) could each produce results comparable to the test measurements.

The complete details of each team's approach, methodology and results will be published in the final report describing the entire activity. Selected results are presented here . The finite element (FE) models prepared by each team are shown in Figure 8.

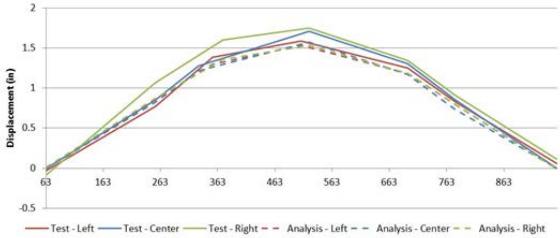


Solver: LS-DYNA
Number of elements: 700,000
(a)

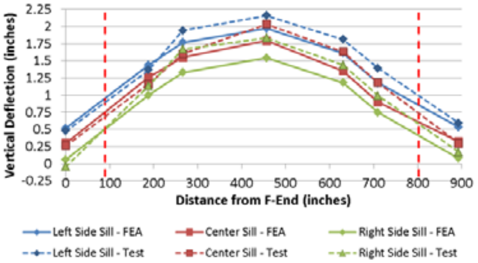
Solver: ABAQUS/Explicit
Number of elements: 760,000
(b)

**Figure 8. Finite element models developed by Arup (a) and Volpe (b).**

The first test performed on car 9614 was a 3,560 kN (800,000 lbf) load applied to the floor-level energy absorbers. The data from this test were used by both Arup and Volpe to calibrate their respective FE models. Once calibrated, these models could be used to predict the expected response of the car during the crippling load test. Figure 9 shows the results for vertical deflection under the 3,560 kN (800,000 lbf) axial proof load as provided by each team. It should be noted that each team has chosen to present the results differently. For example, Arup has adjusted the test data in its comparison to remove rigid body motion of the carbody observed during the test. In Figure 9(b) the Volpe results are presented in raw form. For each plot, the test data have also been plotted alongside the FE results.



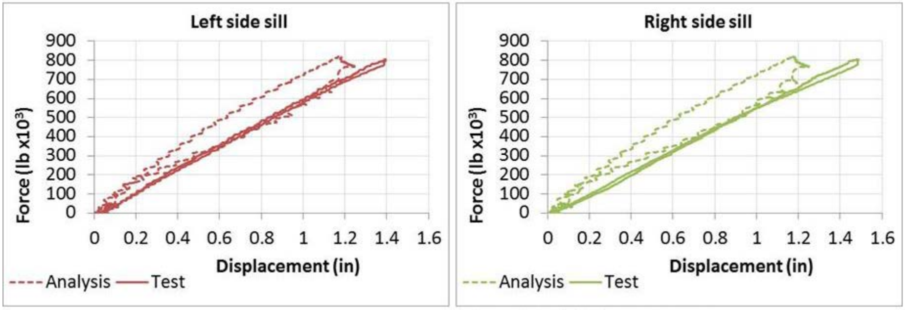
(a) Arup



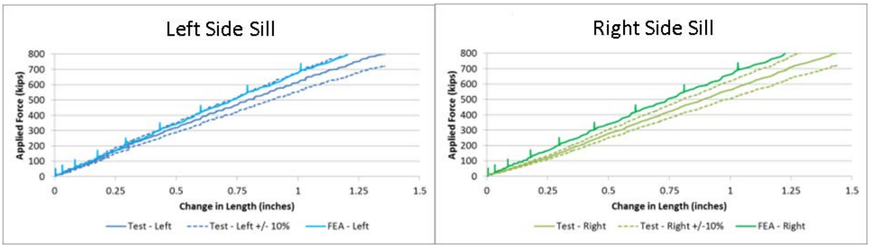
(b) Volpe

**Figure 9. Comparison of Arup-Volpe vertical displacement results from 3,560 kN (800,000 lbf) center, left and right side sills (1 in = 2.54 cm).**

Figure 10 contains force-versus-displacement plots for the left and right side sills from both sets of finite element results as well as the 3,560 kN (800,000 lbf) validation test. Arup's results are on the top of this Figure, and Volpe's results are on the bottom. For both set of results, the applied force is plotted against the change-in-length of the car obtained from both the left side sill and the right side sill.



(a) Arup



(b) Volpe

**Figure 10. Comparison of Arup-Volpe force-displacement results in 800,000 lbf test for left and right side sills (1 kip = 4.448 kN; 1 in = 2.54 cm).**

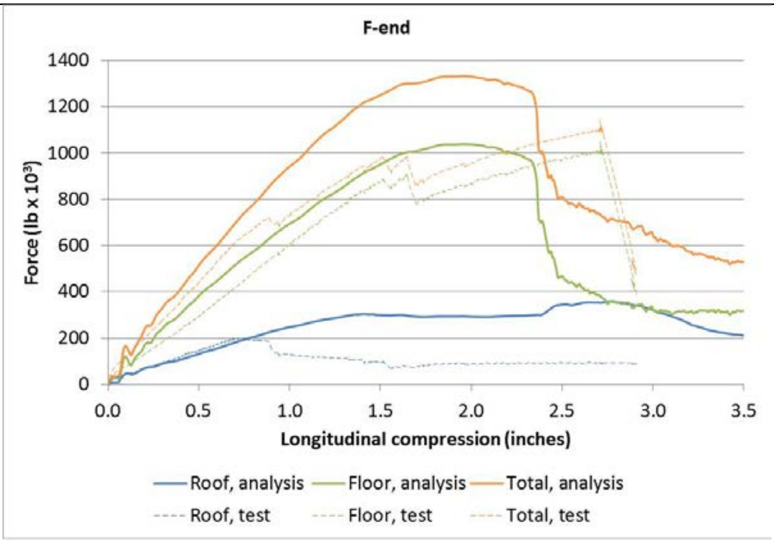
Once the FE models were calibrated using data from the first test, the models were used to simulate the crippling response of the car.

Table 1 displays several key results from both numerical models and the crippling test. This Table includes the roof buckling load, which is the maximum load introduced into the car through the two roof-level loading points. The crippling load is the maximum load the occupant volume sustained during the test, and is equal to the sum of the loads applied at the four loading locations. These data suggest similar outcomes from the analysts, whereas the test values are lower for the reasons described in Section 3.4.

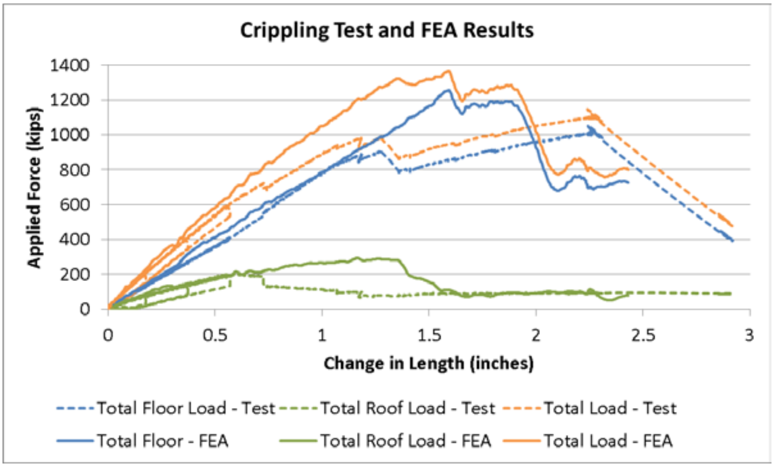
**Table 1. Crippling strength estimates.**

| Parameter | Arup | Volpe | Test |
|---|---|---|---|
| Roof buckling load, kN, (klbf) | ~1,335 (300) | 1,312 (295) | 890 (200) |
| Crippling load, kN (klbf) | 5,921 (1,331) | 6,072 (1,365) | 4,272 (1,100) |

Figure 11 contains two sets of force-versus-displacement plots from the crippling test and analyses. The top portion of this figure contains Arup's force-versus-displacement results and the bottom portion contains Volpe's results. Three curves have been plotted for each set of data. The total floor load is the sum of the loads applied by the two floor-level actuators, the total roof load is the sum of the loads applied by the two roof-level actuators, and the total load is the sum of all four actuators.



(a) Arup



(b) Volpe

**Figure 11. Comparison of Arup-Volpe force-displacement results in crippling test for floor, roof, and total loads (1 kip = 4.448 kN; 1 in = 2.54 cm).**

It is important to note that a crippling test would not likely be performed by a manufacturer as part of its compliance demonstration. Elastic analyses require very simple material characterization and the companion validation tests are simple (and inexpensive) to perform. The material model in the crippling test requires much more sophistication to properly establish both the elastic and plastic behaviors of the materials of construction. If the material properties are not appropriately modeled, the simulation may predict crippling loads in excess of what the physical carbody can sustain (a non-conservative estimate). This is especially relevant when carbodies are constructed of alternative materials. The carshells tested in this program were of stainless steel construction.

Figure 12 shows the force versus displacement results for three crippling tests performed by FRA. The crippling load is denoted by the peak force. These data suggest that the ETF criterion for equivalent occupant volume integrity (5,340 kN or 1,200,000 lbf) is a conservative estimate of the structural capacity of conventionally-designed passenger rolling stock. Applying this criterion to an alternative design will, at the occupant volume level, result in equivalent safety.

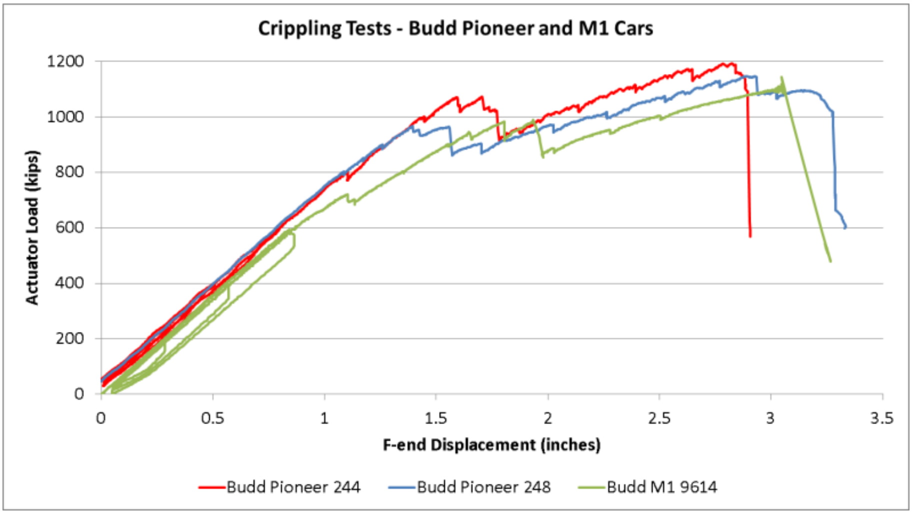


**Figure 12. Force-displacement results for three crippling tests performed by FRA (1 kip = 4.448 kN; 1 in = 2.54 cm).**

## 5 CONCLUSIONS

This occupant volume integrity test program generally accomplished the goals it sought to achieve. The destructive crippling test produced additional information on the strength of the occupant volume of conventional US passenger equipment. Although the occupant volume strength observed in this test was slightly lower than that derived from prior testing, it is believed that the difference is due to pre-existing damage sustained during previous high-energy impact tests which was not repaired prior to the crippling test.

From an analytical perspective, the two teams present high-level results which are in reasonable qualitative agreement. Each was able to produce estimates of the deflected shape of the carbody under the 3,560 kN (800 klb) elastic load which were is good agreement with the test results. Each team, however, overestimated the crippling strength of the car. This was likely due to the fact that the analytical models do not account for preexisting damage, the presence of which resulted in reduced crippling strength.

As the final report will reveal, the details provided by each analyst team are substantially different. Each took different approaches in how the finite element model was constructed and degree of structural detail accounted for (weldments, roof corrugations, etc.) as well as how the material data derived from coupon tests were treated. Thus, particular results differ between the two analysts. As a practical matter, compliance documentation will be prepared by the equipment manufacturer according to internal methodologies and best practices.

It should also be noted that the purpose of this exercise was not to compare the model results directly, since in practice FRA would never be in the position of reviewing compliance documentation submitted by two entities for the same piece of equipment. Rather, the activity was intended to show how the ETF criteria and procedures could be applied in practice in a form that could be made publically available.

FRA intends to use the “mock” submittals developed during this research program to inform planned activities to develop a “suggested practices” document which will serve as industry guidance in the preparation of compliance documentation for FRA review and acceptance.

## REFERENCE LIST

1. Code of Federal Regulations, Title 49, Transportation, Volume 2, Subtitle B (Parts 200-299) Federal Railroad Administration, Department of Transportation.

2 Carolan, Michael et al. “Technical Criteria and Procedures for Evaluating the Crashworthiness and Occupant Protection Performance of Alternatively Designed Passenger Rail Equipment for Use in Tier I Service,” DOT/FRA/ORD-11/22, October 2011. http://www.fra.dot.gov/eLib/details/L01292

3 Carolan, M., Perlman, B., and Tyrell, D., “Alternative Occupied Volume Integrity (OVI) Tests and Analyses,” U.S. Department of Transportation, DOT/FRA/ORD-13/46, October 2013. http://www.fra.dot.gov/eLib/details/L04847

4 APTA PR-CS-S-034-99, Rev 2, Standard for the Design and Construction of Passenger Railroad Rolling Stock, American Public Transportation Association, Washington, DC.