Proceedings of the 2020 Joint Rail Conference
JRC2020
April 20-22, 2020, St. Louis, MO, USA

JRC2020-8088

RAKING IMPACT OF A DIESEL MULTIPLE UNIT FUEL TANK: TESTS AND ANALYSIS

Karina Jacobsen
Michael Carolan
Volpe National Transportation Systems Center
United States Department of Transportation
Cambridge, Massachusetts, USA

ABSTRACT

The Federal Railroad Administration (FRA) sponsors research on safety topics to address and to improve safety regulations and standards. This paper focuses on the latest research and testing conducted to evaluate passenger locomotive fuel tank integrity. Fuel tank integrity regulations, in the form of a series of static load conditions, currently exist to set a minimum level of protection against an impact to the fuel tank that might puncture the tank and cause the release of diesel fuel. The current research program involves a series of dynamic impact tests and quasi-static tests that measures the forces required to deform a fuel tank and investigate the types of loading conditions experienced by fuel tanks.

The objective of the testing program is to establish the baseline puncture resistance of current locomotive fuel tanks under dynamic impact conditions and to develop performance requirements for an appropriate level of puncture resistance in alternative fuel tank designs, such as Diesel Multiple Unit (DMU) fuel tanks. The tests are divided into two loading scenarios identified from accidents: blunt impact and raking impact. The blunt impact scenario in the form of a full-scale dynamic impact test, have been completed on both conventional passenger locomotive fuel tanks and a DMU fuel tank.

DMU fuel tank quasi-static tests, conducted in December 2018 and November 2019, are designed to simulate a raking impact scenario of a fuel tank. The Transportation Technology Center Inc. (TTCI), with support from the Volpe Center designed a test setup using a fuel tank mounted to a boxcar placed within the “squeeze frame”. An indenter, shaped like a broken rail, is fixed to the ground and the fuel tank is slowly pushed into the indenter using a series of hydraulic rams. Load cells and string potentiometers are used to measure the force/displacement. Cameras capture the deformation profile of the fuel tank. The Volpe Center develops and performs finite element analysis to evaluate the loading scenario prior to testing.

The results of pre-test analyses for the raking impact tests are presented to highlight the critical position on the fuel tank to be impacted. The analysis gives an estimate of the force required to puncture the fuel tank as well as the resultant tear of the fuel tank. Additionally, finite element analysis may be used to evaluate the effect of the fuel on the fuel tank integrity. These results highlight the detailed differences of quasi-static versus dynamic loading of fuel tanks, which supports defining trade-offs between specifying static load requirements versus scenario-defined performance based standards.

INTRODUCTION

With the rise in popularity and availability of self-propelled passenger rail cars, small-scale railroads such as start-up commuter lines or extension lines, are purchasing DMUs with higher regularity. These vehicles give railroads the flexibility to have varying consist lengths to accommodate their travelers’ schedules. These start-up railroads and extension lines to existing railroads, provide some urban/suburban communities an alternative to road traffic congestion increasing from population growth and urban sprawl. DMUs are unique passenger rail cars from a regulatory perspective because they classify as “locomotives” [1] though they weigh significantly less, contain more occupants, and carry a smaller fuel tank than vehicles fitting the traditional concept of a locomotive.

In support of the regulatory process the FRA's Train Occupant Protection Research Program focuses research on evaluating the safety performance of existing railroad equipment as well supporting the advancement of new rail technologies and improved designs. Current research is focused on assessing fuel tank crashworthiness during dynamic impacts in order to assess the applicability of current fuel tank standards on the growing number of alternative passenger equipment fuel tank designs, like those on DMUs. A research program has been set up to assess conventional passenger locomotive fuel tanks and alternatively-designed passenger equipment fuel tanks.

The research program follows the methodology illustrated in Figure 1. Conducting forensic field investigations allows safety issues to be observed and documented. An issue observed over a series of accidents illustrates patterns and likelihood. Known issues can then be scoped for research programs when necessary. The existing equipment can be evaluated using testing and/or modeling. Alternate designs can then be evaluated against the established baseline performance. These results are shared with industry to aid in development of new standards or regulations. The cyclic approach enables a feedback loop in which the performance of equipment designed to new standards and regulations can be followed in the field and accidents.

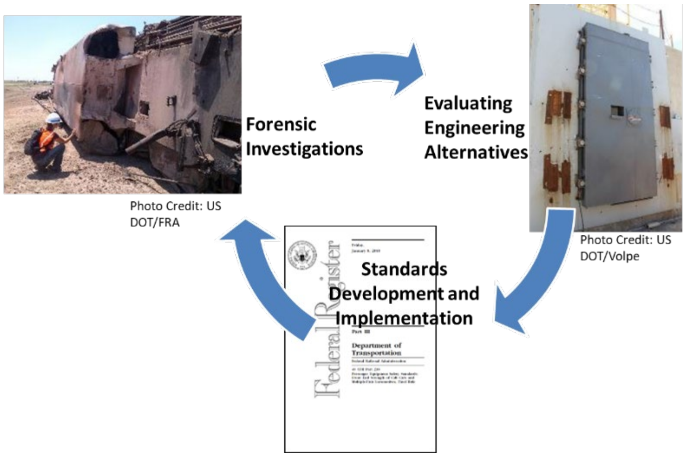


Figure 1. Flow Diagram of Crashworthiness Research Methodology

As part of the FRA research effort, a survey was conducted of accidents and derailments in the U.S. over the last two decades in which fuel tanks were punctured [2]. The information on incidents was found using a combination of the FRA accident database and in-person field investigations conducted by FRA inspectors and support staff from the Volpe Center. The surveys consisted of freight and passenger trains involved in accidents or derailments during which one or more fuel tanks ruptured; some sources surveyed contained limited detailed information. Two key findings should be noted from the results of this survey. First, a fuel tank rupture during a train collision or derailment may result in a fire, which presents additional threats to the survivability of passengers and crew as they egress from the collision wreckage. For passenger operations that utilize DMUs the risk associated with a diesel spill, fire and injuries and/or fatalities is higher with the presence of more people on board the consist and their proximity to the ejected fuel. The second key finding is that each fuel tank impact scenario can be categorized by its resultant loading type, of which there are two general loading conditions leading to punctures: blunt impacts and raking impacts.

The schematics in Figure 2 illustrate two idealized loading scenarios identified in this research that can penetrate an exposed surface of a fuel tank. In this research a "blunt" impact is characterized by a rigid object aligned relative to a fuel tank such that it imparts a primarily perpendicular force to the fuel tank surface. A "raking" impact is characterized by a rigid object initially aligned at a primarily tangential force applying a tearing load upon the tank.

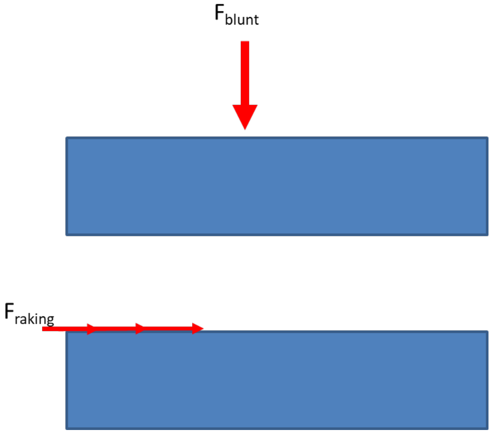


Figure 2. Force Diagrams of Fuel Tank Loading Types

This paper describes the efforts conducted to launch the evaluation of a raking impact scenario. To highlight the raking loading scenario, an incident from a rail yard in Newark, New Jersey from April 2012 is shown in Figure 3. In this incident two locomotives impacted the side of another train at a switch. Through the sequence of events a doortrack of the trailing freight car was dragged along the side of the lead locomotive fuel tank [2]. The resulting damage to the fuel tank is shown in Figure 4.

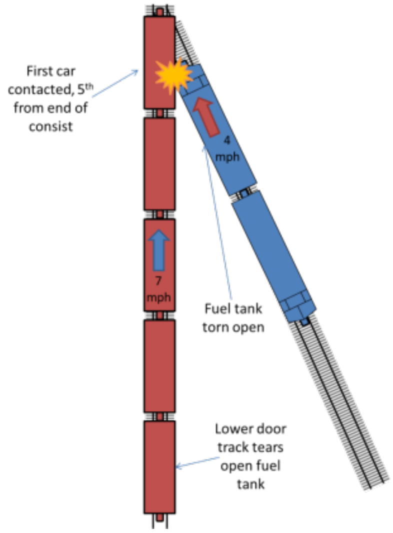


Figure 3. Schematic of Raking Impact in Oak Island Yard in Newark, NJ

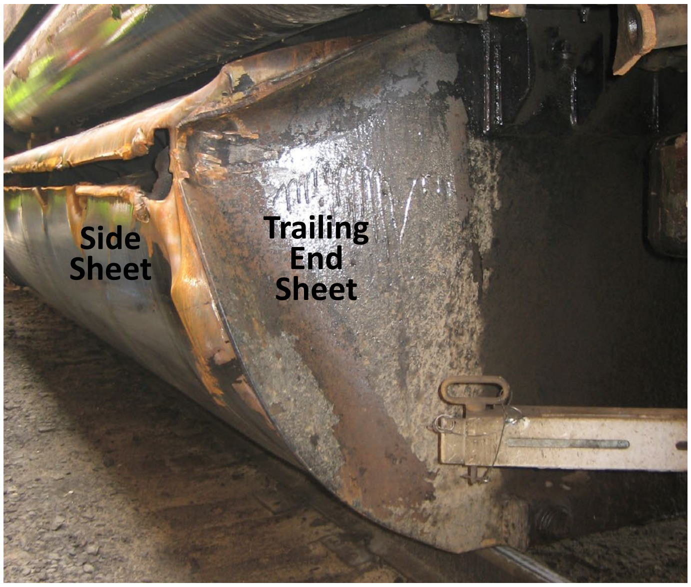
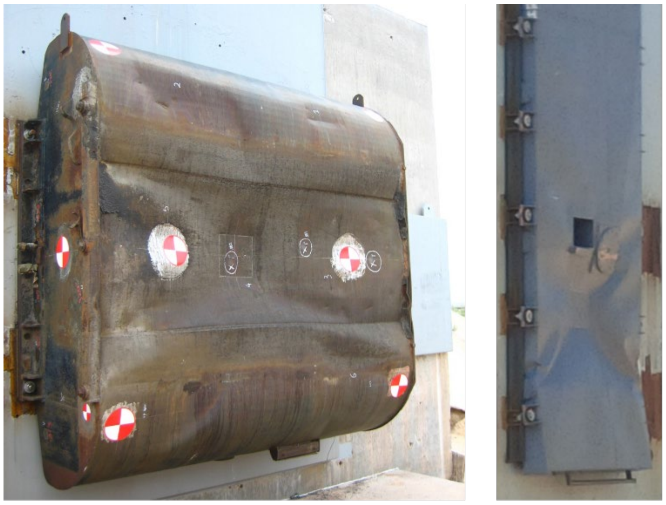


Figure 4. Damage to Trailing Locomotive Fuel Tank

FRA funded a series of full-scale tests to evaluate fuel tanks under the identified loading scenarios: a blunt and raking impact. In the first phase of the research, a test setup for a blunt impact was designed and used to test three retired passenger locomotive fuel tanks and one DMU fuel tank. The first two tests were performed on conventional passenger locomotive fuel tanks in October 2013 and August 2014 at low speeds, 4.5 and 6.2 mph. The targeted speeds were chosen to impart permanent deformation to the tank. The force-deflection characteristics of the impact were measured [3]. These tests provided valuable initial information on the variance of tank performance based on design details.

A third test was conducted on August 20, 2014 with an identical test setup, on a retired conventional passenger locomotive fuel tank, at a speed of 11.2 mph. A fourth test was conducted on June 28, 2016 on a DMU fuel tank at 11.1 mph. The objectives of these tests were to measure the performance of conventional fuel tanks and DMU fuel tanks under a dynamic blunt impact [3][5][6][7][8]. For this research, new DMU fuel tanks were purchased from a manufacturer of DMU equipment operated in the U.S. The conventional locomotive fuel tanks were repurposed from test locomotives owned by the FRA and located at the Transportation Technology Center (TTC).

While the impact conditions of the third and fourth tests were nearly identical, the impact responses were very different. The details of the fuel tank internal baffle construction proved to contribute to the progression of each tank's response to the load. Results of one blunt impact test, a conventional fuel tank from an F40 locomotive (#234), featured a very low initial force after impact, attributed to the gap between the interior of the bottom of the tank and the lateral baffles followed by climb up to the peak force. Contrastingly, the DMU fuel tank features baffles that are spot-welded to the bottom sheet. The DMU fuel tank experienced a high initial force, while the conventional tank does not experience a significant increase in stiffness until the bottom sheet closes the gap to the baffles. Both tanks experienced buckling of their respective baffles, which resulted in a temporary decrease in force. The deformed shapes of the F40 fuel tank and the DMU fuel tank are shown in Figure 5. Because it was so much stiffer, the DMU fuel tank experienced much less deformation compared to the conventional fuel tank. However, because the DMU fuel tank had a smaller overall height than the conventional fuel tank, the maximum indentation experienced by the DMU tank was a much larger reduction in height as a percentage of the initial height of the tank.


Post-test Photograph
Tank 234

Post-test Photograph
DMU Tank

Figure 5. Deformed Shapes of Tank 234 (left) and DMU Fuel Tank (right)

TEST – RAKING SCENARIO

The second phase of testing in this research program is focused on understanding the details of a raking loading scenario. On December 18, 2018, a preliminary test designed to simulate a raking impact was conducted on a DMU tank. The subsequent sections of this paper describe the test design process, test setup, pre-test modeling, test and model results, and planned next steps for this preliminary DMU fuel tank raking test. Discussion of the previous tests and analyses on fuel tank test specimens can be found in References [3] through [8].

Objective

The key objective of the impact testing of fuel tanks is to examine the gross response of the fuel tanks to a given impact type. The testing program is meant to characterize each test specimen's deformation behavior when impacted on different surfaces and in different ways. The overall approach to characterizing the deformation behavior includes:

1. Develop an analytical model of the fuel tank specimen based upon known design details.
    - Use an analytical model to plan for test.
    - Estimate possible fuel tank behavior under test impact conditions.
2. Apply loading scenario to the surface(s) of a fuel tank specimen.
    - Measure the force-deformation behavior of the tank with specified instrumentation.
    - Record mode of deformation and material failure with video cameras.
3. Conduct post-test examination to characterize structural deformation of tank exterior and interior.
4. Update model with actual conditions and tank properties.

The outcome of this process can be used to make a comparison between fuel tanks of different designs, with analysis techniques being used to provide additional information on the fuel tank behavior. Modeling can also be used to simulate additional impact conditions beyond what was tested, providing additional points of comparison between different designs.

The initial approach was to conduct the raking impact test in a dynamic impact test similar to the blunt impact scenario. However, because of the required controllability of the load application and the lower force required to initiate and propagate a raking tear, it was determined that a load applied quasi-statically within a fixture would be a better option for designing a successful test. The key objectives, as stated above, were to measure and document the force required to puncture a fuel tank and to document the material and structural behavior of the tank.

Test Development and Setup

The raking test scenario was designed to simulate a DMU fuel tank loaded along an edge by a relatively rigid object, chosen to be an indenter dimensioned like a piece of broken rail. To date, minimal research can be found evaluating a raking load scenario of fuel tanks. To achieve the desired loading scenario and test objectives a test had to be designed that was controllable and repeatable. The challenge involved creating a setup to apply a sustained force to an object moving longitudinally along the rails. A dynamic collision scenario using a rolling cart with a fuel tank mounted on it was considered; an impact object would be mounted to the ground along the tracks. Unlike the blunt impact test, the required peak force was lower which would require a very low speed, making it harder to ensure the tolerance of the impact speed with a rolling impact vehicle. Additionally, pre-test modeling revealed that the raking impact response of the tank was highly-sensitive to the position of the indenter. The amount of overlap between the raking indenter and the bottom of the tank was another critical component that was considered difficult-to-control under dynamic impact conditions. Thus, concepts for developing a quasi-static test setup were then considered.

Figure 6 shows the conceptual test setup developed by TTCI for applying a load along the bottom of the tank. Figure 6 shows a schematic illustration of the test setup with the empty fuel tank mounted to a rail vehicle within the "squeeze frame" and an indenter mounted to the ground. The rail vehicle is advanced by a hydraulic cylinder within the squeeze frame, causing the fuel tank to slowly "rake" across the indenter. The indenter is positioned such that it contacts the fuel tank in the desired location, with the desired amount of vertical overlap between the bottom of the tank and the top of the indenter. The reaction load is measured by a load cell supporting the rear of the indenter.

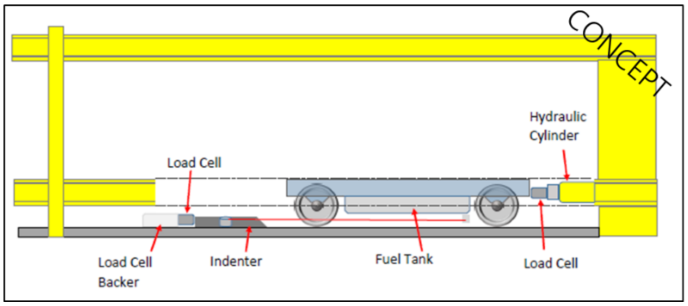


Figure 6. Schematic Showing Test Setup

For the test of the DMU fuel tank, the fuel tank is mounted to the underframe of a railcar, in this test a boxcar. Two C-channels were welded to the underframe structure of the boxcar. The tank was bolted to two C-channels through mounting hardware that was provided by the DMU tank manufacturer and which featured a rubber bushing through which the attachment bolt passed. Details of the typical mounting arrangement are described in a previous paper of the blunt impact test on the DMU fuel tank [8].

A series of indenter designs were considered for the test. The indenter characteristics were evaluated via modeling to determine the approximate size that could penetrate the DMU fuel tank. The indenter was constructed to approximate the shape of a rail which has had its head broken off. The indenter was fabricated with A514 Grade B steel to minimize the amount of permanent deformation the indenter would undergo as a result of the focused raking load. The concept for positioning the indenter beneath the tank is shown in Figure 7. The indenter would be braced against a base plate with a load cell between the indenter end and the base plate. The free end of the indenter is positioned to align with the leading edge of the fuel tank. The indenter would be supported by a base anchored into the ground and a low friction surface between the indenter and the ground.

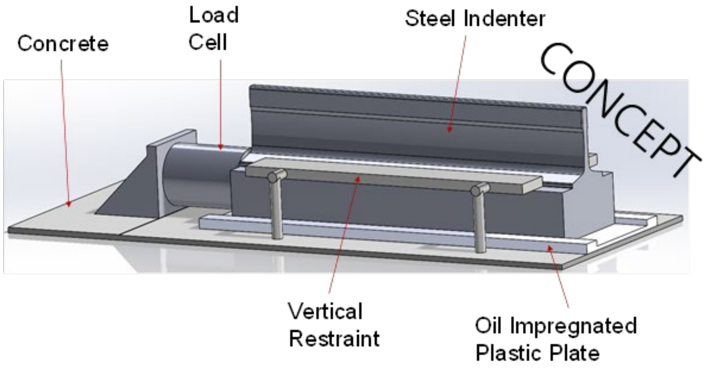


Figure 7. Concept for Indenter Fixture

The final test setup is shown in the photographs below. Figure 8 shows the indenter layout as finalized for the test. The indenter fixture comprises a thick steel base plate bolted into the concrete slab beneath the crossties. The bottom edges of the indenter are held with polytetrafluoroethylene (PTFE), a soft low-friction plastic, to minimize sticking of the indenter in the support structure. The indenter is shown in position prior to the test. There is a 2-inch vertical overlap between the bottom edge of the fuel tank and the top edge of the indenter. This is to ensure contact and puncture of the fuel tank. At the right side of this figure the load cell is visible as a dark cylinder. The load cell is positioned to measure the longitudinal load reacted through the indenter. The PTFE shims (white rectangles on the base of the indenter) are intended to provide vertical restraint to the indenter while reducing the longitudinal load that is transmitted into the base plate outside of the load cell.

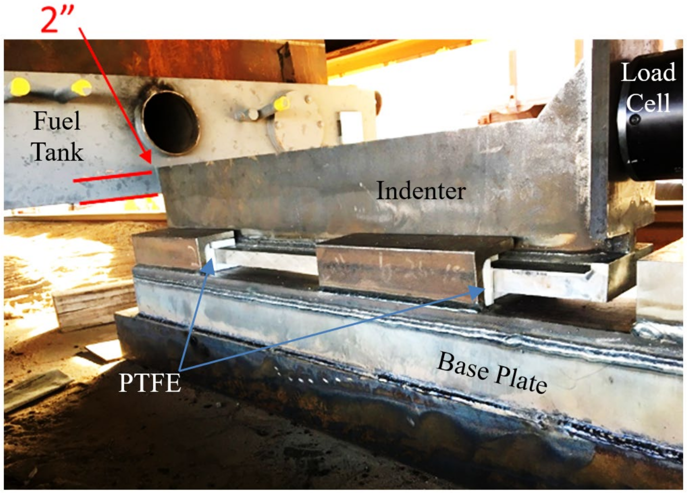


Figure 8. Final Test Setup Indenter Fixture

Figure 9 shows the box car positioned on the rails within the squeeze frame. The hydraulic ram pushes the boxcar toward the left, as indicated with the annotation. The fuel tank is mounted to the underframe of the boxcar about midway between the trucks. The indenter (not visible) is located beneath the boxcar between the rails.

Figure 9. Box Car Positioned in Squeeze Frame Prior to Test

Figure 10 shows the detail of the live end of the test frame. A sled assembly is shown that rests on the lateral side sills of the squeeze frame. The sliding surface was lubricated and tested to provide a low-friction sliding contact. Two hydraulic cylinders are positioned between the sled and a fixed support of the squeeze frame end. The hydraulic cylinder control system pushes the sled assembly, which presses against the boxcar drawbar fixed in the draft pocket and advances the boxcar along the rails at 1.2 inches per minute. A load cell is positioned between the sled assembly and the boxcar drawbar to measure the load applied to the boxcar.

Figure 10. Photograph of Hydraulic Cylinders and Sled in Squeeze Frame

INSTRUMENTATION

The objectives of the test were to characterize the fuel tank deformation behavior and assess the details of the test setup in creating a controllable dynamic impact condition. The primary measurement made during this test was the force-versus-displacement behavior of the fuel tank raking along the indenter, which equates to measuring the load reacted and the advancement of the boxcar into the indenter. Table 1 lists instrumentation used in the quasi-static raking test of DMU fuel tank.

Table 1. Instrumentation for Quasi-static Raking Test of DMU Tanks

Type of Instrumentation	Channel Count
String Potentiometers	6
Load Cells	2
Displacement from Hydraulic Cylinders	2
Pressure from Hydraulic Cylinders	2
Force from Hydraulic Cylinders	2
Total Data Channels	**14**
Digital Video	2 Cameras

String potentiometers and load cells were mounted on the boxcar and test fixture arrangement as illustrated in the schematic in Figure 11. The red lines indicate the positions of the string potentiometers. These measure the longitudinal displacement of the boxcar on left and right sides and a laser sensor (not shown) measures the vertical displacement of the boxcar. The hydraulic ram on the right side of the figure advances the boxcar longitudinally into the indenter. The reaction load is measured with the load cell behind (to the left) of the indenter.

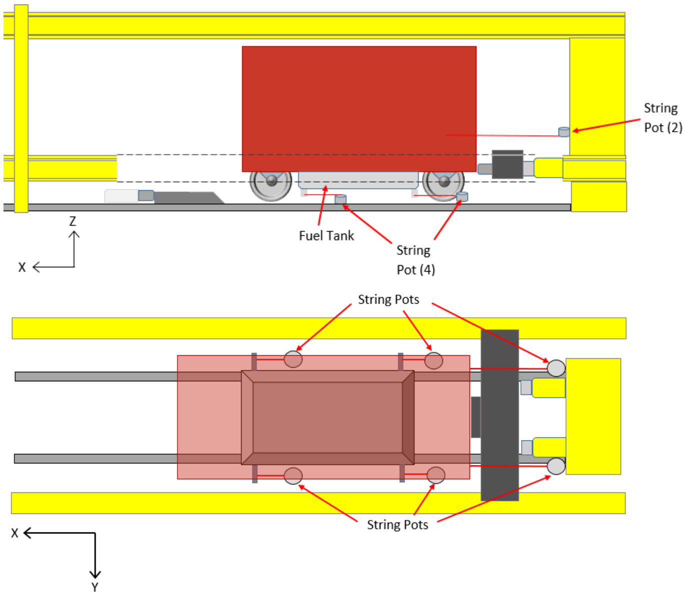


Figure 11. Schematic Showing Side and Plan Views of Test Fixture with String Potentiometers Indicated

The top photograph of Figure 12 shows the load cell positioned between the sled assembly and the boxcar draw bar, measuring the load applied. The bottom view of photograph of Figure 12 shows the load cell positioned between the back of the indenter and the backing plate, measuring the reaction load.

Figure 12. Load Cells Measuring the Load Applied (top) and Load Reacted (bottom)

Two digital cameras were used to record the test. One was placed beneath the bottom of the tank just forward of the indenter to capture the contact zone between the indenter and the tank. The second camera was located to the side of the indenter with an oblique view of the indenter, front edge of the tank and bottom of the tank.

TEST SPECIMENS

A set of new DMU tanks were purchased by FRA as part of the passenger locomotive fuel tank research project. The fuel tanks are of a design that is currently in operation in the U.S. The DMU fuel tanks do not meet FRA's existing requirements for locomotive fuel tanks (49 CFR 238, Appendix D) and are subject to operation under a waiver granted by FRA's Office of Safety.

Figure 13 shows a side and bottom view of the DMU fuel tank used for the testing program, taken from the finite element (FE) model. The fuel tank is relatively shallow in comparison to a conventional locomotive tank and its shorter bottom surface dimension spans almost the full width of a DMU railcar. The longitudinal and lateral dashed black lines along the bottom of the tank indicate the locations of the internal baffles. The diagonal lines are reflective of the fuel tank's non-planar bottom surface. The bottom of the fuel tank slants slightly downward toward the center.

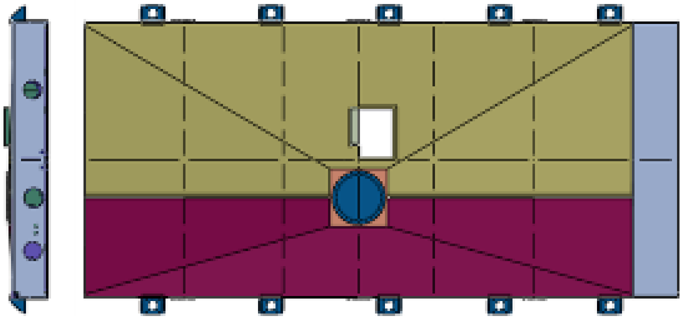


Figure 13. Side (left) and Bottom (right) Views of DMU Fuel Tank

TEST RESULTS

The preliminary raking impact test was conducted on December 18, 2018 at TTC. The boxcar was positioned in the squeeze frame with the leading end plate just about against the edge of the indenter. The front surface of the indenter was aligned against the front of the fuel tank with two inches of overlap, as can be seen in Figure 12. During the test, the indenter punctured into the end plate of the front of the tank and tore through the bottom of the tank. The indenter was pushed at a rate of 1.2 inches per minute for a length of 21 inches. The internal baffles deformed in the interior of the tank as the indenter passed through the cross-section of the tank containing the baffles.

Figure 14 and Figure 15 show post-test photographs of the torn area on the edge and bottom surfaces of the DMU fuel tank. As the indenter made initial contact with the leading end plate, the material pulled back and down. As the applied force increased, the end plate eventually began to tear. Once the end plate tore, the fuel tank was able to continue raking over the indenter with contact mainly between the bottom sheet of the tank and the indenter. The path of the indenter is particularly pronounced in Figure 15, where the tear in the bottom sheet is clean and approximately the width of the indenter. The position of the first set of lateral baffles inboard from the end plate is apparent in this figure as the roughly triangular tear in the bottom sheet. When the indenter reaches the first internal baffle the material "catches" and pulls back until the indenter continues to tear the material cleanly.

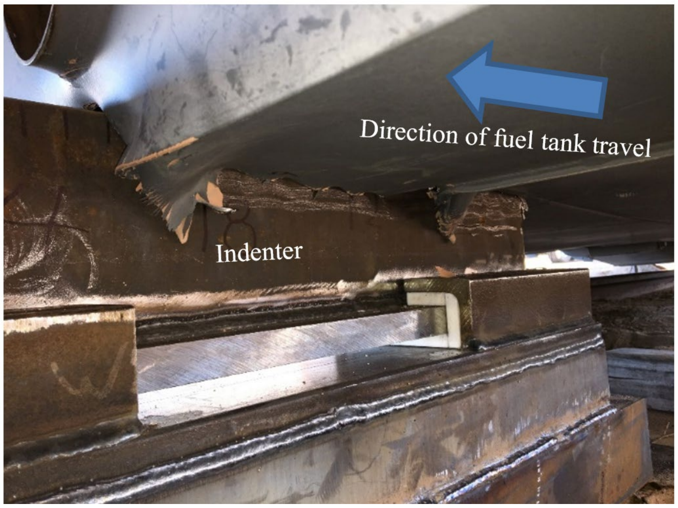


Figure 14. Post-test Photograph of Indenter and Tank

Figure 15. Post-test Photograph of DMU Fuel Tank; Bottom of Tank

<u>TEST MEASUREMENTS</u>

Figure 16 shows the measured forces of the two load cells versus time. The load cell placed between the hydraulic cylinder/sled assembly and the boxcar is labeled "BF" ("boxcar force") and the load cell between the indenter and base plate is labeled "IF" ("indenter force"). The load application load cell was about 30 feet away from the reaction load cell. The plot shows force over the full duration of the test. The plot shows very good agreement between these two load cells, indicating that there was no significant force lost due to the test frame setup.

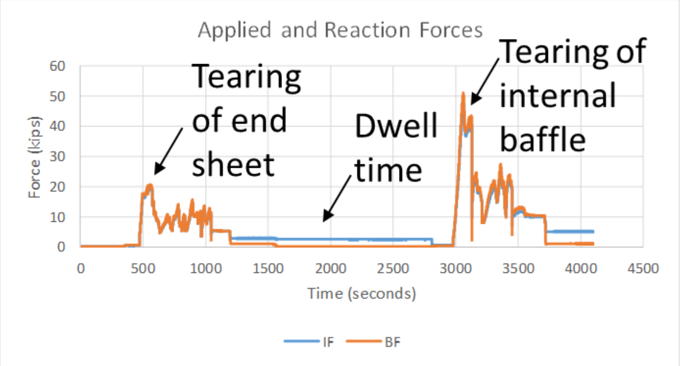


Figure 16. Comparison of Applied and Reaction Forces

The indenter makes contact with the edge of the fuel tank and as the force begins to climb to an initial peak load of about 20 kips at 500 seconds the end sheet tears. The force then drops to an average load of around 10 kips as the indenter is pushing through the bottom surface of the tank more cleanly. The hydraulic actuator used in this test had a stroke of 11 inches. The "dwell time" shown on the plot marks the period when the hydraulic actuator had to be reset to allow for a second "push" up to 21 inches of raking. At about 3000 seconds the test resumes and the force climbs to a second peak load of around 40 to 50 kips as the indenter reaches the next internal baffle. The indenter tore through the baffle and the force dropped off to about 10 kips. The test was terminated at 21 inches of stroke.

Figure 17 is a plot of the measurement of vertical displacement of the boxcar for the duration of the test. A laser displacement transducer was aligned with the side sill of the boxcar to track any potential for the boxcar to climb during the test. As seen in this data, the vertical movement was negligible.

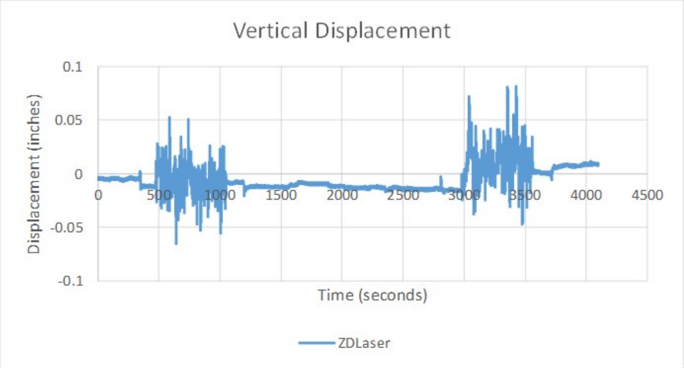


Figure 17. Laser Scan Measurement of Vertical Displacement

Figure 18 shows the measurements from the four longitudinal string potentiometers. It is clear that the four string potentiometers measured a consistent longitudinal displacement on left and right sides of the boxcar.

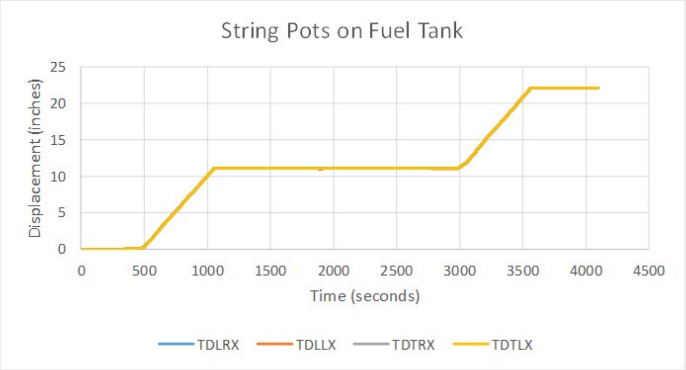


Figure 18. Comparison of String Potentiometer Measurements

MODELING AND COMPARISONS

Pre-test finite element analysis (FEA) was performed to help establish the desired indenter-to-fuel tank overlap. The pre-test model was assembled and meshed using the Abaqus/CAE software, and the simulation was executed in Abaqus/Explicit software [9]. The initial pre-test analysis for examining how a fuel tank responds to a raking impact used the DMU model developed for the first phase of blunt impact testing. The DMU model was initially developed and material properties defined based upon drawings and information provided by the manufacturer at the time of purchase. The information included manufacturing drawings as well as digital geometry that was used as a starting point for the fuel tank geometry in the FE model. The fuel tank model includes detailed geometry of the outer surfaces of the tank, internal baffles, and external mounting brackets and pads. The fuel tank was modeled as a series of discrete parts that are attached to one another via tied constraints at the locations where actual parts would be attached via welding in the tank assembly. The tied constraints between parts constrain all six degrees-of-freedom (three translational and three rotational) and cannot fail. In this way, the constraints represent a perfectly-welded connection between parts.

In addition to modeling the fuel tank, the pre-test FE model included the indenter, the fixture for the indenter and the mounting hardware and C-channels that attached the fuel tank to the boxcar. These components were included to assist in evaluating not only the fuel tank's performance in the test, but also in developing the test setup. The pre-test FE model also featured deformable rubber bushings and bolts to represent the mounting of the fuel tank to the C-channels. An illustration of the pre-test FE model is shown in Figure 19.

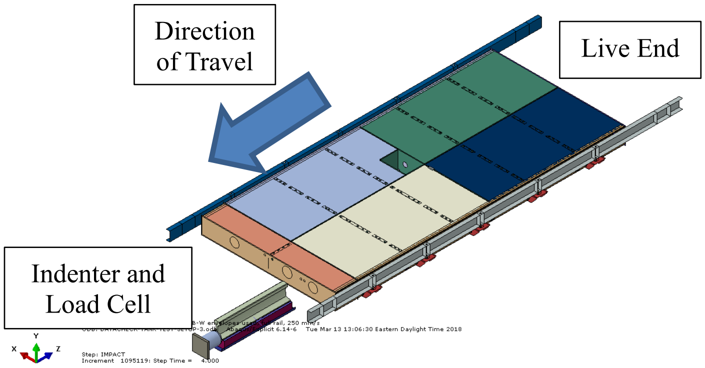


Figure 19. Pre-test FE Model Showing Fuel Tank Mounted to C-channels and Indenter

For each type of steel defined in the model, a value of 200 GPa was used for Young's modulus. Results of previous material tensile testing performed after the blunt impact test of the DMU tank were defined in the raking model. The material properties included elastic-plastic stress-strain behavior, and a triaxiality-based damage initiation and progression failure model that would simulate tearing of the tank. Further details on developing the material models can be found in Reference [10].

Following the test, post-test adjustments were made to the pre-test model including refining the mesh size at the area around the impact and adjusting the material failure model to correspond to using finer elements in the failure zone. Figure 20 shows a detail of the area where the indenter contacts the edge of the tank in the post-test FE model. Note that this image has been inverted, looking down on the bottom of the fuel tank.

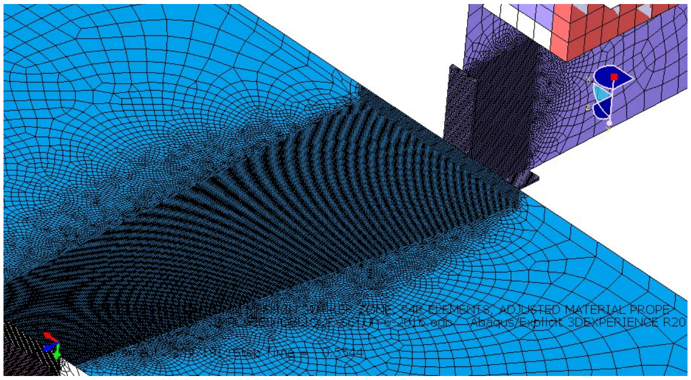


Figure 20. Image from Model Showing Refined Mesh (Inverted View)

Figure 21 shows the extents of the tearing to the end plate and bottom sheet from the post-test FE model. Note that the model terminated after approximately 15 inches of travel, while the test continued through 21 inches of travel. This termination is associated with the large amount of deformation and element failure occurring in the model by this point. The tearing shown in Figure 21 exhibits some similarities as the tearing observed in the test (Figure 15). In general, the FE model exhibited more widespread damage and less-clean tearing of the bottom sheet than what was observed in the test.

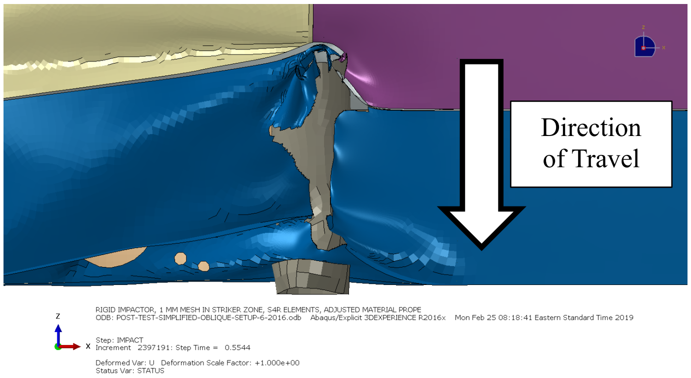


Figure 21. Deformed Shape of Post-test FE Model

Figure 22 shows a comparison of the test measurements and corresponding results from the FEA. For both the test and the FEA, the indenter force is plotted against the travel of the fuel tank. The model does a reasonable job of predicting the peak force required to initially puncture into the DMU fuel tank. This section of the test is highlighted with a red box. There are several possible sources of discrepancy between test and model. The initial tear represents the initiation of puncture to the tank, while continued movement of the tank past the indenter is damage propagation. The material model chosen for damage initiation may not be as well suited to capturing the continued propagation as it is to capture the initial tearing. Separately, the damage mode is a highly complicated combination of folding, shearing, and ultimately tearing the material. Further mesh refinement or exploration of additional material failure modeling strategies may be necessary to better capture the failure modes observed in the test.

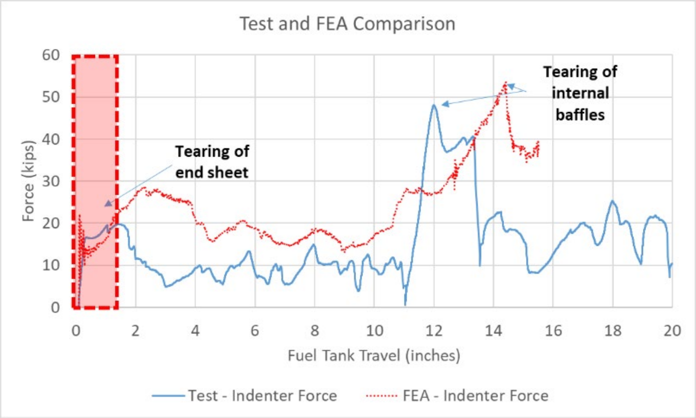


Figure 22. Test and Post-test Model Comparison

SUMMARY, CONCLUSIONS AND NEXT STEPS

The described research efforts are performed to assess the performance of fuel tanks under idealized scenarios representing loads experienced in accident and impact incidents. The testing described in this paper shares the results of the preliminary test developed of a raking scenario for a DMU fuel tank.

The outcomes of this effort further the understanding of how fuel tanks of an alternative design may respond to the loads experienced in investigated collisions/incidents. These results can then be compared with the load and material requirements defined in the CFR [11]. This test effort also demonstrated the viability of the test setup at loading the fuel tank in a controlled manner and successfully measuring the applied forces and displacements.

A second test of the idealized raking scenario is planned. The squeeze frame test setup that was successfully tested in the December 18, 2018 test will be used to perform another test of the DMU fuel tank at another location on the fuel tank. The second test is intended to load the fuel tank in such a manner as the impactor bypasses the end sheet and strikes the bottom sheet directly, raking along the bottom of the tank without directly loading the end sheet. These tests show how the internal construction of the fuel tank, such as baffle location and attachments can affect the outcome of the fuel tanks performance.

The results of the test further indicated a need to carefully consider the FEA techniques that may be appropriate to modeling a complex mode of failure initiation and propagation.

ACKNOWLEDGEMENTS

The fuel tank research is part of the Equipment Safety Research Program sponsored by the Office of Research and Development of the FRA. This work is monitored by Program Managers in the Office of Rolling Stock Research. FRA staff at TTC helps to coordinate efforts between FRA, Volpe and TTCI.

The authors would like to acknowledge Volpe Center colleague Dr. A. Benjamin Perlman for his ongoing technical advice and support in the research discussed in this paper. The authors would also like to acknowledge Volpe Center colleagues, Dr. Shaun Eshraghi for his contributions to the development of the fuel tank models.

Mr. Travis Gorhum and Dr. Przemek Rakoczy lead the fuel tank testing effort at TTCI.

REFERENCES

[1]. U.S. Department of Transportation, Federal Railroad Administration, Code of Federal Regulations, Title 49, Part 238.5, “Definitions”.

[2]. Jacobsen, K., "Fuel Tank Crashworthiness: Loading Scenarios," American Society of Mechanical Engineers, Paper No. JRC2011-56077, March 2011. http://ntlsearch.bts.gov/tris/record/ntl/37914.html

[3]. Jacobsen, K., "Passenger Locomotive Fuel Tank Integrity Research," Proceedings from the 4th International Conference on Fires in Vehicles FIVE 2016, October 2016.

[4]. Jacobsen, K., Carolan, M., Perlman, A.B., “Conventional Fuel Tank Blunt Impact Tests: Test and Analysis Results,” Proceedings of the 2014 Joint Rail Conference, JRC2014-3786, April 2014. http://ntlsearch.bts.gov/tris/record/ntl/51599.html

[5]. Jacobsen, K., Llana, P., Carolan, M., Sullivan, L., “Fuel Tank Integrity Research: Fuel Tank Analyses and Test Plans,” Proceedings of the 2013 ASME/IEEE/ASCE Joint Rail Conference, JRC2013-2425, April 2013. http://ntlsearch.bts.gov/tris/record/ntl/50984.html

[6]. Jacobsen, K., Carolan, M., Llana, P., “Test Requirements of Locomotive Fuel Tank Blunt Impact Tests,” Proceedings of the 2013 ASME Rail Transportation Division Fall Technical Conference, RTDF2013-4701, October 2013. http://ntlsearch.bts.gov/tris/record/ntl/48594.html

[7]. Jacobsen, K., Carolan, M., "Results of a Conventional Fuel Tank Blunt Impact Test," American Society of Mechanical Engineers, Paper No. JRC2015-5759, March 2015. http://ntlsearch.bts.gov/tris/record/ntl/54927.html

[8]. Jacobsen, K., Carolan, M., "Results of a Diesel Multiple Unit Fuel Tank Blunt Impact Test," American Society of Mechanical Engineers, Paper No. JRC2017-2248, April 2017. http://ntlsearch.bts.gov/tris/record/ntl/54927.html

[9]. Abaqus version 6.14. Dassault Systems Simulia Corp, Providence, RI, 2014.

[10]. Gorhum, T., Carolan, M., Rakoczy, P., Jacobsen, K., Eshraghi, S., and Shurland, M. “Blunt Impact Testing of a Diesel Multiple Unit Fuel Tank.” United States Department of Transportation, Federal Railroad Administration. DOT/FRA/ORD-18/22. July, 2018. https://railroads.dot.gov/elibrary/blunt-impact-testing-diesel-multiple-unit-fuel-tank.

[11]. U.S. Department of Transportation, Federal Railroad Administration, Code of Federal Regulations, Title 49, Part 238, Appendix D— “Requirements for External Fuel Tanks on Tier I Locomotives”.