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FULL-SCALE SHELL IMPACT TEST OF A DOT-113 TANK CAR

SUMMARY

On November 19, 2019, the Federal Railroad Administration (FRA) conducted a full-scale shell impact test of a DOT-113C120W (DOT-113) tank car at the Transportation Technology Center (TTC) in Pueblo, CO. A DOT-113 is a tank within-a-tank designed to transport specified cryogenic materials by rail. The outer tank is carbon steel and the inner tank is stainless steel with insulation and vacuum in between the tanks, in order to keep the lading cold. The shell of the outer tank was struck by a 297,000 pound ram car equipped with a 12-inch by 12-inch impactor at its mid-height and longitudinally offset 11 feet towards the A-end, because a centered impact would have fouled a track adjacent to the impact wall due to the DOT-113's length. Figure 1 shows the tank car in its pre-test position against the impact wall at the TTC.

Figure 1. Pre-test Photo of DOT-113 Tank Car

The tank car was filled with water to 82.4 percent of its capacity. The car was sealed and pressurized with air to a targeted pressure of 45 psig; however, the actual initial test pressure was ~50 psig. The pressure and outage were chosen to be in the middle of the allowable pressure and outage range proposed for a DOT-113 tank car carrying liquefied natural gas (LNG) as specified in a Pipeline and Hazardous Material Safety Administration (PHMSA) 2019 notice of proposed rulemaking (NPRM). Based on pre-test finite element analyses (FEA), the target test speed of 16.5 +/- 0.5 mph was chosen so that puncture of both tanks was a likely outcome. The actual impact occurred at 16.7 mph. This speed corresponds to an impact energy of approximately 2.8 million foot-pounds.

The tank was punctured after an indentation of ~47 inches, at a force of ~750 thousand pounds. Review of the test measurements showed that the impactor had slowed to ~8.4 mph when puncture occurred, corresponding to a residual kinetic energy of ~0.7 million foot-pounds. The residual kinetic energy corresponded to approximately 25 percent of the initial kinetic energy of the ram car. Figure 2 shows the punctured tank car outer shell.

Figure 2. Post-test Photo of the Punctured Shell

BACKGROUND

FRA has an established program to evaluate the puncture resistance of various tank car designs. This program supports examining strategies to lower the potential for loss of lading of tank cars involved in derailments. FRA seeks to develop standardized test and simulation methodologies for quantifying the puncture resistance of tank car designs. This program has previously tested DOT-105 [1][2], DOT-111 [3], DOT-112 [4], and DOT-117 [5] tank cars under similar shell impact conditions. A companion FEA is performed alongside each test, and the test results are used to both validate the pre-test model and improve future finite element (FE) models.

OBJECTIVES

This test was intended to impact the DOT-113 tank car at a speed that was close to the threshold speed necessary to cause puncture of both tanks. A target test speed between 16 and 17 mph was chosen so that puncture was a likely outcome, but not the only possible outcome.

METHODS

The DOT-113 tank car was loaded with water in a manner that approximated the mid-range of the proposed allowable service conditions. The targeted outage of 17.6 percent and pressure of 45 psig (~50 psig actual) were chosen to be approximately midway between the pressure (15 psig) and outage (~21%) when the car is offered for transportation and the pressure (75 psig) and outage volume (15%) that would correspond to the pressure relief valve starting to discharge (as proposed in PHMSA's NPRM). Key parameters for the tested car are summarized in Table 1.

Table 1. Summary of Tank Car Parameters

Parameter	Value
Commodity in Test	Water
Tank Capacity (water)	32,900 gallons (nominal)
Outage in Test	17.6%
Outage Pressure in Test	Target 45 psig Actual 50 psig
Outer Shell Thickness	7/16 inch
Outer Shell Material	American Society for Testing and Materials (ASTM) A516, Grade 70
Inner Shell Thickness	1/4 inch
Inner Shell Material	ASTM A240, Type 304

Both the moving ram car and the stationary tank car were instrumented for this test. The acceleration, force, velocity, and displacement of the ram car were derived from accelerometers positioned on structural members of the ram car. Speed sensors on the ram car recorded its speed just prior to impact. Laser displacement transducers on the impact wall were positioned in-line with laser displacement transducers on the ram car to measure the external compression of the tank car at its vertical centerline. The tank car was instrumented internally with pressure transducers in the air and water. Externally, the tank car was instrumented with string potentiometers at the ends of the tank and at its support skids to measure the car's overall motion. The test was recorded by both conventional- and high-speed cameras. The instrumentation is summarized in Table 2.

Table 2. Summary of Instrumentation

Type of Instrumentation	Channel Count
Accelerometers	11
Speed Sensors	2
Pressure Transducers	8
String Potentiometers	4
Laser Disp. Transducers	15
Total Data Channels	**40**
Digital Video	4 high-speed 4 conventional-speed

An FEA was performed in conjunction with the test. A schematic of the FE model is shown in Figure 3. This model featured simplified modeling of the water and the air within the tank. The water was modeled using a hydraulic cavity approach, and the air was modeled as an ideal gas using a pneumatic cavity. The tanks were modeled using shell elements, except in the impact zone. The impact zones of both the inner and outer shells were modeled using solid elements, with elastic-plastic and ductile failure material properties defined. This combination of shell and solid element types allowed puncture of the tank car to be modeled while reducing the model's run-time.

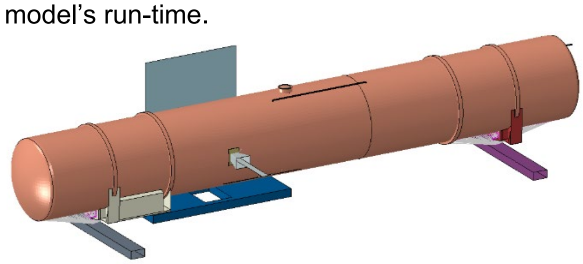

Figure 3. DOT-113 FE Model

Since the exact material properties for the ASTM A516, Grade 70 carbon steel (outer shell) and the ASTM A240, Type 304 stainless steel (inner shell) were not known before the test, pre-test simulations were performed using estimated carbon steel and stainless-steel behaviors. These estimates were based on publiclyavailable tensile test results [2][6][7]. The pre-test models using varied combinations of material behaviors resulted in an estimated speed range of 16 to 20 mph to cause puncture of both inner and outer tanks for the expected test conditions. Thus, a target test speed of 16.5 +/- 0.5 mph was expected to result in puncture of the tank car without imparting excess energy (i.e., residual kinetic energy as close to zero as possible).

RESULTS

The impact occurred at 16.7 mph and resulted in puncture of the inner and outer tanks. The force-displacement results from the test are shown in Figure 4, along with annotations denoting where the outer and inner shells punctured. The force/acceleration results are taken from the average of four of the five longitudinal accelerometers on the ram. A CFC-60 filter was used on these results in accordance with the Society of Automotive Engineers (SAE) J211-1 standard. Examination of the test data revealed that the outer tank punctured after ~31 inches of impactor travel and the inner tank punctured after ~47 inches. The impactor continued to penetrate the inner tank after puncture.

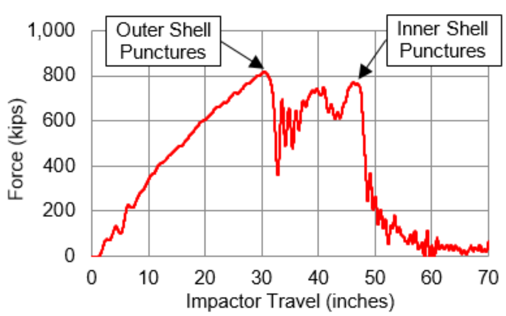

Figure 4. Test Force-displacement Results at 16.7 mph (CFC-60)

Figure 5 shows the tear in the outer shell after the removal of the ram car. The tear appears to have initiated under a corner of the impactor and propagated vertically, which is consistent with previous tests and pre-test FEA for this test. No welds were involved in tearing of the outer tank. Red paint transfer from the impactor's tip is highlighted in this image as evidence of impactor contact.

Figure 5. Post-test Tear in Outer Tank

Figure 6 shows the tear on the inner tank from the inside of the tank, prior to the ram's removal. Vertical tears are visible above the head of the impactor and a longitudinal tear is visible on the right of the image. The tear ran close to but did not open a stainless steel longitudinal weld seam in the inner tank.

Figure 6. Post-test Tear in Inner Tank

CONCLUSIONS

A full-scale impact test resulting in puncture of both tanks of a DOT-113 tank car was conducted on November 19, 2019. The impact occurred at 16.7 mph with a 297,000-pound ram car equipped with a 12-inch by 12-inch impactor. The impact resulted in puncture of both tanks of the tank car with a residual kinetic energy of 0.7

million foot-pounds, or 25 percent of the initial kinetic energy.

FUTURE ACTION

Material samples will be cut from both tanks and characterized by tensile testing. The pre-test FE model will be updated to include the actual impact conditions, measured material properties of the tank car shells, and test speed then re-run. The test data, photos, and videos will be reviewed and further compared with the behaviors from the FEA in a model validation effort. The test results will also be compared with the corresponding measurements from previously-conducted tank car impact tests to understand the similarities and differences in the structural responses of different tank cars under substantially-similar impact conditions. An additional post-test FEA is planned to investigate the impact response of the DOT-113 when loaded under service conditions (e.g., cryogenic lading, temperature, and inner tank material properties).

REFERENCES

[1] Federal Railroad Administration, "Full-Scale Shell Impact Test of a DOT-105 Tank Car (RR 18-06)," March 2018.

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[7] Kirkpatrick, S. and McKeighan, P., "Correlating Material Properties to Puncture Resistance to Enhance the Safety and Security of Tank Cars," March 2018.

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