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FULL-SCALE SHELL IMPACT TEST OF A DOT-105J500W TANK CAR DESIGNED TO CARRY LIQUID CARBON DIOXIDE

SUMMARY

On March 6, 2024, the Federal Railroad Administration (FRA) sponsored a full-scale shell impact test (Test 14) of a DOT-105J500W (DOT-105) specification tank car at Transportation Technology Center (TTC) in Pueblo, CO. The DOT-105 tank car was designed for service with refrigerated liquid carbon dioxide (liquid CO2) and included different design features from other DOT-105 tank cars due to the cold temperature (-20°F) of the refrigerated commodity. The tank car featured 5 inches of foam thermal insulation around the tank and a full-length center sill instead of the typical stub sills due to thermal expansion of the tank during loading and unloading.

The tank car had a volume of approximately 21,500 gallons. During the test, a ~297,000-lb ram car equipped with a 12x12-inch impactor struck the tank at its mid-height and longitudinal center. Figure 1 shows the tank car in its pre-test position against the impact wall at TTC.

Figure 1. Pre-impact DOT-105

Researchers filled the tank car to approximately 95.2 percent by volume with water as a stand-in for refrigerated liquid CO2. The remaining (i.e., outage) 4.8 percent volume contained a mixture of air and nitrogen. The outage was pressurized to 225 psig, typical of conditions in liquid CO2 transportation. Researchers targeted a test speed of 16.0 ± 0.5 mph, intending to puncture the tank car. However, the impact did not result in puncture of the tank car. The measured impact speed was 15.5 mph. This speed and ram mass corresponds to 2.4 million ft-lb of impact kinetic energy.

The peak force developed by the impact was approximately 1.8 million pounds, and the impactor indented the tank car to a depth of approximately 35 inches. The impactor rebounded at a speed of 8 mph after making contact with the tank car. Figure 2 shows the state of the DOT-105 tank car following the shell impact test and removal of the jacket around the impact zone.

Figure 2. Post-impact DOT-105 (Jacket Removed)

BACKGROUND

FRA has established a program to evaluate the puncture resistance of various tank car designs. This program supports examining strategies to reduce the potential for release of hazardous materials from tank cars involved in derailments. The program seeks to develop standardized test and simulation methodologies for quantifying the puncture resistance of tank car designs, and has previously tested DOT-105, DOT-111, DOT-112, DOT-117, and DOT-113 specification tank cars under similar shell impact conditions. Companion finite element (FE) analysis is performed prior to each test. The test results are used to both validate the pre-test model and improve future FE models. A well validated FE model can then be used to investigate other impact conditions and hazardous materials.

Previous FRA-sponsored shell impact tests of DOT-105 tank cars used tank cars that were designed for chlorine service. Test 6 [1] used a 12x12-inch impactor and resulted in puncture at 15.2 mph, while Test 8 [2] used a 6x6-inch impactor and resulted in puncture at 9.7 mph. Table 1 summarizes the recent DOT-105 shell impact tests.

Table 1. Recent DOT-105 Shell Impact Test Series

Test #	Impactor Size	Intended Service	Impact Speed (mph)	Puncture	Ref.
6	12x12 inches	Chlorine	15.2	Yes	[1]
8	6x6 inches	Chlorine	9.7	Yes	[2]
14	12x12 inches	CO2	15.5	No	

OBJECTIVES

In Test 14, researchers planned to impact a DOT-105 tank car designed for refrigerated liquid CO2 service and result in puncture of the tank with a 12x12-inch impactor. The initial pressure (225 psig) and outage (4.8 percent) for Test 14 were intended to be representative of liquid CO2service, and the impact conditions were intended to facilitate comparisons with previous shell impact tests.

METHODS

The Test 14 DOT-105 tank car consisted of a 0.818-inch thick TC128, Grade B steel tank having an approximate capacity of 21,500 gallons. The tank was surrounded by 5 inches of polyurethane foam thermal insulation, which was surrounded by an 11-gauge A1011 steel jacket. Unlike DOT105J500W tank cars used to transport other commodities, the tested tank car featured a full-length center sill which was necessary to accommodate the thermal contraction of the tank when loading refrigerated liquid CO2.

The team instrumented both the moving ram car and the stationary tank car. Accelerometers mounted on the ram car measured its acceleration during the impact, and the force, velocity, and displacement of the ram car were derived from the measured acceleration. Speed sensors on the ram car recorded its speed just prior to impact. A laser displacement transducer on the impact wall measured the displacement of the ram car as a check on the displacement derived from the accelerometers. Inside the tank, pressure transducers measured the pressures in the air and water, and string potentiometers measured the deformation of the tank. String potentiometers mounted on the exterior of the tank car measured its overall motion. Conventional-speed and high-speed cameras on the ground and a drone-mounted, conventional-speed camera in the air recorded the shell impact test. The instrumentation is summarized in Table 2.

Table 2. Summary of Instrumentation

Type of Instrumentation	Count
Accelerometers	11
Speed Sensors	2
Pressure Transducers	15
String Potentiometers	10
Laser Disp. Transducers	1
Total Data Channels	**39**
High Speed Video	3
Conventional Speed Video	4

Even though this was the sixth shell impact test of a DOT-105 tank car, there were uncertainties in the puncture resistance of the tank car due to the elevated pressure and unique design of the liquid CO2 tank car. Researchers estimated a range of impact speeds that could puncture the tank car by varying the outage pressure, outage volume, and TC128 material properties in a model sensitivity study prior to the test.

Figure 3 shows a snapshot of the Test 14 FE model. The FE model is a half-symmetric representation of the DOT-105 tank car sitting on skids and centered against the crash wall. The impactor, wall, skids, and ground are represented as rigid bodies.

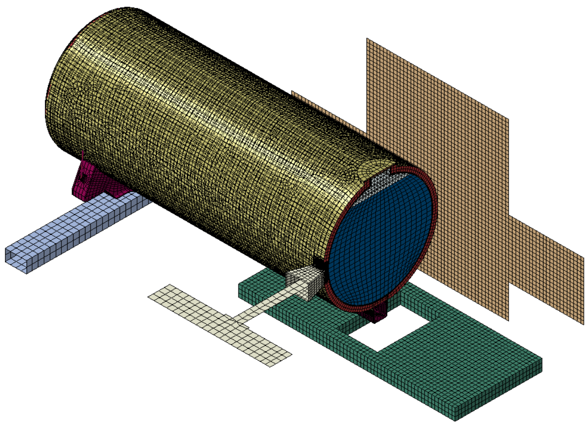

Figure 3. DOT-105 FE Model

Researchers modeled the tank car primarily using shell elements with elastic-plastic material properties except in the impact zone. The impact zone of the tank has solid elements with elastic-plastic and ductile failure material properties. This combination of shell and solid element types allows puncture of the tank car to be modeled while considering variations in the stress state across the thickness of the tank without drastically increasing the model's run-time. The foam insulation and water were also modeled using solid elements.

RESULTS

Figure 4 shows a comparison between the force- and absorbed energy-displacement responses in Test 14 and the pre-test FE model with an impact speed of 15.5 mph. The test results were calculated by averaging the longitudinal accelerometers on the ram car. The acceleration data were filtered using a CFC-60 filter in accordance with SAE J211-1.

The overall shapes of the force-displacement curves from the test and model were generally in agreement up to 30 inches of impactor displacement. After 30 inches of displacement, the test had a sharper dip in impactor force while the model had a shallower dip in force. After the dip in force, the test achieved a peak force of 1.8 million pounds without puncturing, while the model predicted that the tank car would puncture after reaching a peak force of approximately 1.6 million pounds. During the post-test investigation of the tank car, researchers hypothesized that the model disagreement could be due to more blunting of the impactor than expected. The additional blunting could be due to added thickness in the jacket, not accounted for in the model, and the foam insulation being more resilient in the test than expected.

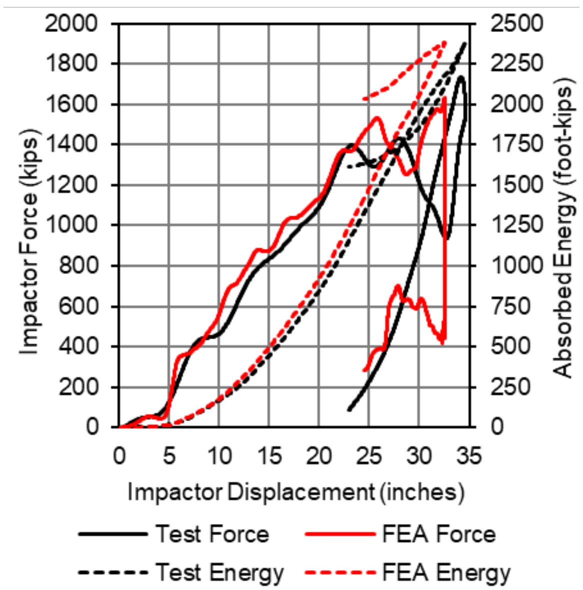

Figure 4. Force- and Energy-displacement Results from Test 14 and the FE Model (CFC-60)

Figure 5 shows a comparison of the outage pressure response in Test 14 and the pre-test FE model with an impact speed of 15.5 mph. The test result was calculated by averaging pressure transducers in the outage of the tank.

Again, the overall shapes of the two curves were in agreement. The model predicted a slightly lower peak outage pressure because it resulted in puncture while the test did not. After reaching the peak pressure, the puncture in the FE model resulted in a sharper decrease in pressure relative to the test.

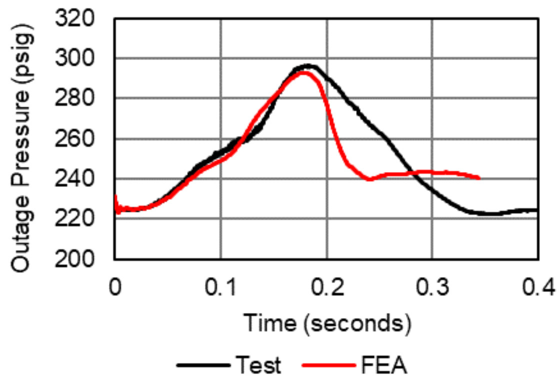

Figure 5. Outage Pressure Results from Test 14 and FE Model

CONCLUSIONS

FRA sponsored a full-scale shell impact test of a DOT-105 tank car designed for refrigerated liquid CO2 service. The tank car was filled to 95.2 percent with water and pressurized to 225 psig. The impact occurred at 15.5 mph with a 297,000-pound ram car equipped with a 12x12-inch impactor. The impact had a kinetic energy of approximately 2.4 million foot-pounds, and the tank car resisted the impact without puncturing. The pre-test model predicted puncture under the tested conditions. The shapes of the force versus displacement and pressure versus time responses from the pre-test model were generally in agreement with the test results.

FUTURE ACTION

Researchers will review test data, photos, and videos and compare them with the behaviors from the FE model for validation. Researchers will update the pre-test FE model to reflect the measured material properties of coupons extracted from the tank car. Researchers will validate the updated FE model against the test results and then use the validated FE model to investigate the puncture resistance of the DOT-105 tank car under actual service conditions for refrigerated liquid CO2.

REFERENCES

[1] FRA (2018). Full-Scale Shell Impact Test of a DOT-105 Tank Car (Report No. RR 18-06).

[2] FRA (2019). Full-scale Shell Impact Test of a DOT-105 Tank Car (Report No. RR 19-04).

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KEYWORDS

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