SAND2022-5751C

HYDRODYNAMIC RAM SIMLUATIONS OF THIN-WALLED LIQUID-FILLED 7 L AND 15000 L CONTAINERS

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ABSTRACT

When liquid-filled containers are impacted by projectiles moving at high speed, the transfer of kinetic energy can cause container failure and release of the liquid. The hydrodynamic ram (HRAM) of a container is a coupled fluid dynamics and structural dynamics problem that is an important consideration for failure of fuel tanks in aircraft and ground vehicles. We present peridynamics HRAM simulation results of container response and liquid spray. We consider response of seven liter (two gallon) and ~15000 liter (4000 gallon) thin-walled steel containers subject to fragment impacts. Experimental data of the spray pattern and container shape are available for 7 L containers and compare well with simulation results. The results demonstrate the ability of peridynamics simulations to capture HRAM effects on containers. Two applications of the work are better understanding of fuel tank structural damage and fire risk to vehicles.

Acknowledgements

Funded by: Defense Threat Reduction Agency, Henry Marcinowski

BACKGROUND

The work presented in this paper addresses an area of research pertaining to hydrodynamic ram and its effect on liquid-filled containers. Hydrodynamic ram occurs when a high speed projectile impacts a liquid-filled container. An illustration of the steps in hydrodynamic ram are shown in Figure 1. The container response and liquid spray are of interest when estimating the potential for fires in vehicles including aircraft. Veras et. al. 2009 describes previous work in the field including applications and simulations of container response. Previous researchers have primarily focused on the dynamics inside the tank such as the fragment deceleration, cavity growth, and cavity collapse. There are fewer publications describing the liquid spray which we believe could be very important for understanding fire risk. The timing, spray velocity, spray angles, and droplet sizes are all important factors for ignition of fuel.

Figure 1 Hydrodynamic ram on a fuel tank illustration.

Vehicles at risk from hydrodynamic ram of fuel tanks and potential fires include: airplanes, helicopters, and ground vehicles. An example of aircraft damage is shown in Figure 2. Vehicle survivability is of interest to the military and civilian aviation authorities as well as understanding the risks of crew or equipment loss from threats.

ARA and Sandia National Labs have applied a peridynamics code called EMU to study hydrodynamic ram. Peridynamics is an extension of continuum mechanics to media with cracks and long-range forces (Silling 2000).

Figure 2 Aircraft damage (Yang et. al. 2016).

SIMULATION SETUP

Three container configurations were considered in the present paper. The nomenclature for volume (V) in liters and number of fragments (F) are used to distinguish runs. A seven liter container impacted by one fragment is designed V7F1. The first two configurations are seven liter containers and the third is a 15000 L container. The first configuration involves a steel cylinder impacted by one, four, or seven fragments. The diameter was 20.6 cm with a 26 cm height. The walls were 0.58 mm thick with 1.9 cm ullage (air) above the liquid. The total volume of water was roughly 7 liters. The first three cases considered are: 1) V7F1: single fragment impact (v=1983 m/s), 2) V7F4: four fragment impacts (v=1836 m/s), and 3) V7F7: seven fragment impacts (v=1836 m/s). Each steel fragment was 1.28 g with dimensions: 12.7 x 6.4 x 1.6 mm. The fragment velocities were obtained from timing data between impact of two break screens. Experiments for each case were repeated three times. The simulation setup is shown in Figure 3. The simulation used 5 mm nodes.

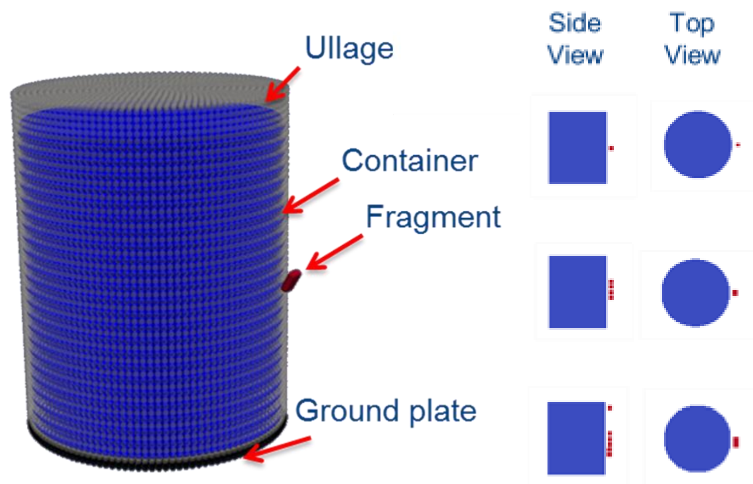

Figure 3 Simulation setup for V7F1 (top) V7F4 (middle) and V7F7 (bottom).

The second configuration was a steel cylinder with 20.9 cm diameter, 24.1 cm height, and wall thickness of 0.28 mm. The container was filled with 7 L of water and 1.1 cm ullage. This container was constrained above and below by thick steel plates and a steel support beam behind. The container was impacted by two 0.38 g fragments traveling at 2353 m/s, and the case is designated as V7F2. The velocity was obtained from impact timing of two break screens. A pressure gauge was placed inside the container as shown in Figure 4. The PCB model 138A25 gauge was at mid-height near the wall at 135 degrees from the impact location. The simulation was run with 5 mm and 3 mm nodes, and the 3 mm node results are shown here.

The first configuration calculations used 8 cores and 48 hours of DoD High Performance Computer (HPC) time. The second configuration (V7F2) used 32 cores and 72 hours of DoD HPC time.

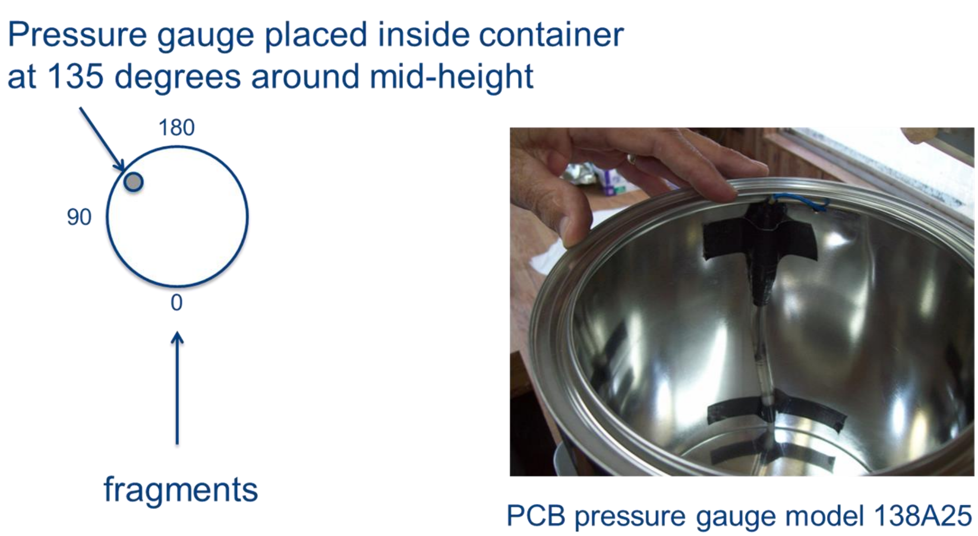

Figure 4 Pressure gauge placement for V7F2.

The third configuration was a 15000 L cylindrical container 1.8 m in diameter, 6.1 m tall with a wall thickness of 6.35 mm. The container volume was 15000 L and filled with approximately 13000 L of liquid leaving an ullage of ~1.4 m. The fragment was a steel cube with 0.71 kg mass. The first case: V15000F1 had a single fragment with velocity 1800 m/s. The second case: V15000F10 had ten fragments with velocity of 2000 m/s. The simulation setup is shown in Figure 5. This simulation used 4.5 cm nodes and used 8 cores and about 72 hours of DoD HPC time.

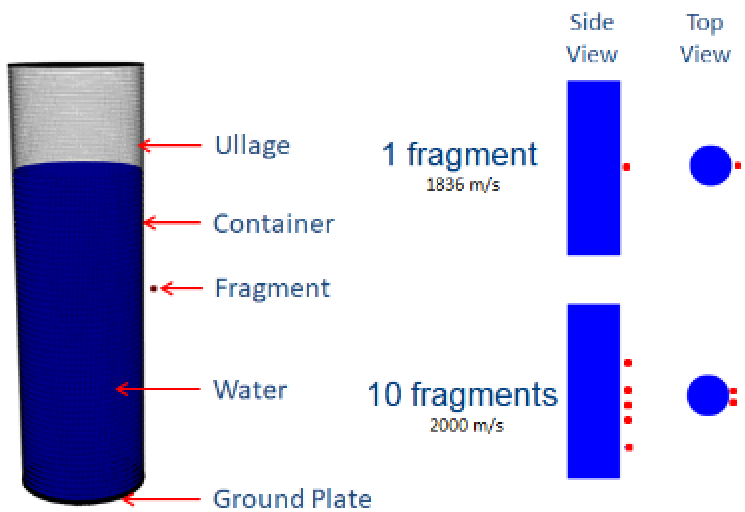

Figure 5 Setup for 15000 L container (V15000F1 and V15000F10).

A summary of the three configurations is shown in Table 1.

Table 1. Simulation setup details for the three configurations.

Configuration 1	Volume (L)	Fragment mass (g)	Number of Fragments	Fragment Velocity (m/s)
V7F1	7	1.28	1	1983
V7F4	7	1.28	4	1836
V7F7	7	1.28	7	1836
Configuration 2				
V7F2	7	0.38	2	2353
Configuration 3				
V15000F1	15000	710	1	1836
V15000F10	15000	710	10	2000

The range of kinetic energy from the fragments is shown in Figure 6. The smallest kinetic energy was V7F2 at 2.1E+03 J while the largest was V15000F10 at 1.42E+07 J. Metrics such as kinetic energy per mass of liquid could be useful for comparing HRAM in different container sizes.

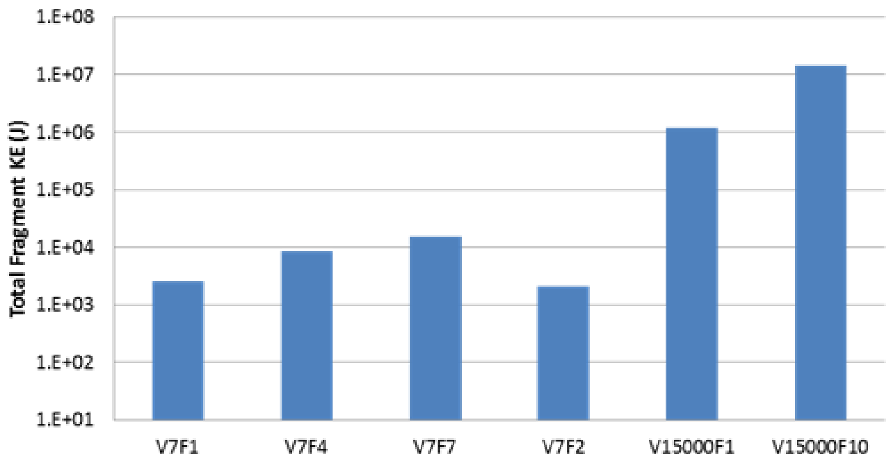

Figure 6 Kinetic energy of fragments for the simulations.

SIMULATION RESULTS

The results for the first configuration (V7F1, V7F4, and V7F7) are compared with high speed video images of the liquid spray pattern and the final container shape. In each of the three repeats for V7F1, V7F4 and V7F7, the fragments that hit below the water line did not exit the back of the container. Therefore all the kinetic energy from the fragment(s) was deposited into the container. In the simulations, like the experiments, the fragment did not exit the back of the container. Figure 7 shows the spray pattern for the experiment (left) and simulation (right) for V7F1, V7F4, and V7F7 at 50 ms, 25 ms, and 25 ms, respectively. The fragment is travelling right to left, and the spray is directed back towards the fragment source. Note that the simulation captures the vertical displacement from the stand in V7F1. The "jump" occurs when the bottom of the container interacts with the stand as the liquid pressure increases and displaces the bottom of the container.

A comparison of the container shapes for V7F1, V7F4, and V7F7 is shown in Figure 8. The EMU simulations generally capture the container shape observed in the experiments.

The top and side view comparisons of the liquid spray in V7F4 as a function of time are shown in Figure 9 and Figure 10. The liquid in the simulation is colored by velocity magnitude. The simulation captures the major features of the spray pattern observed in the high speed video frames.

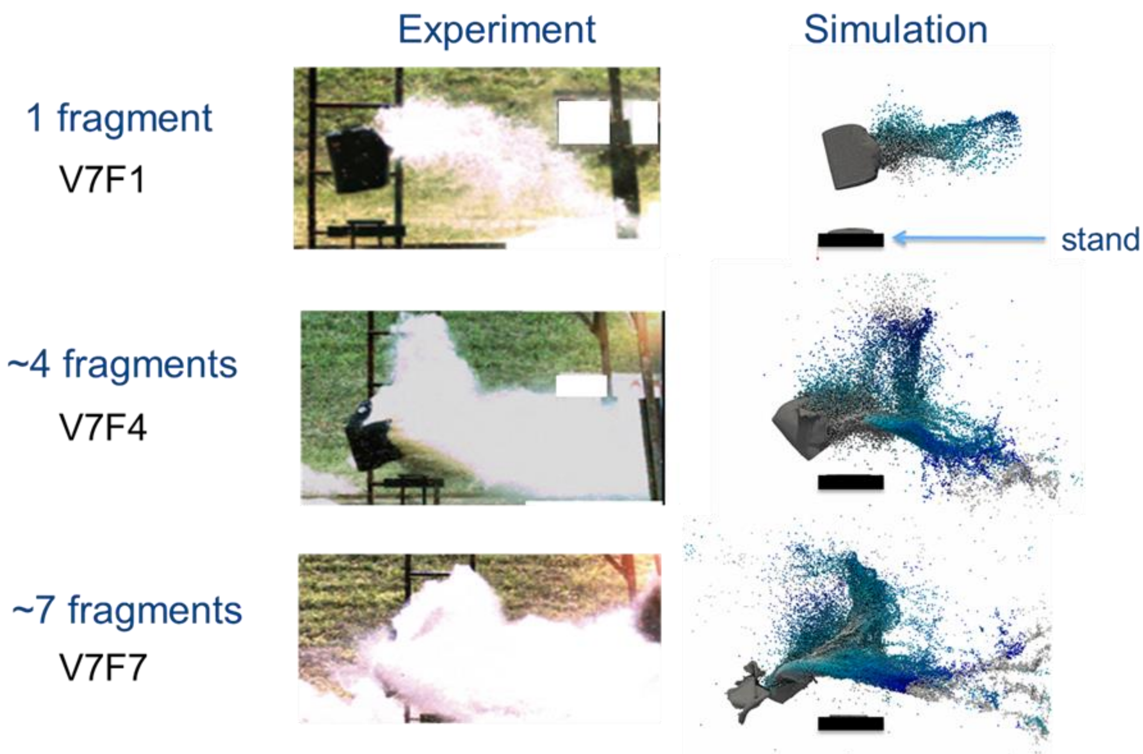

Figure 7 Spray pattern for V7F1, V7F4, and V7F7 at 50 ms, 25 ms, and 50 ms (from top to bottom). The liquid in the simulation is colored by displacement.

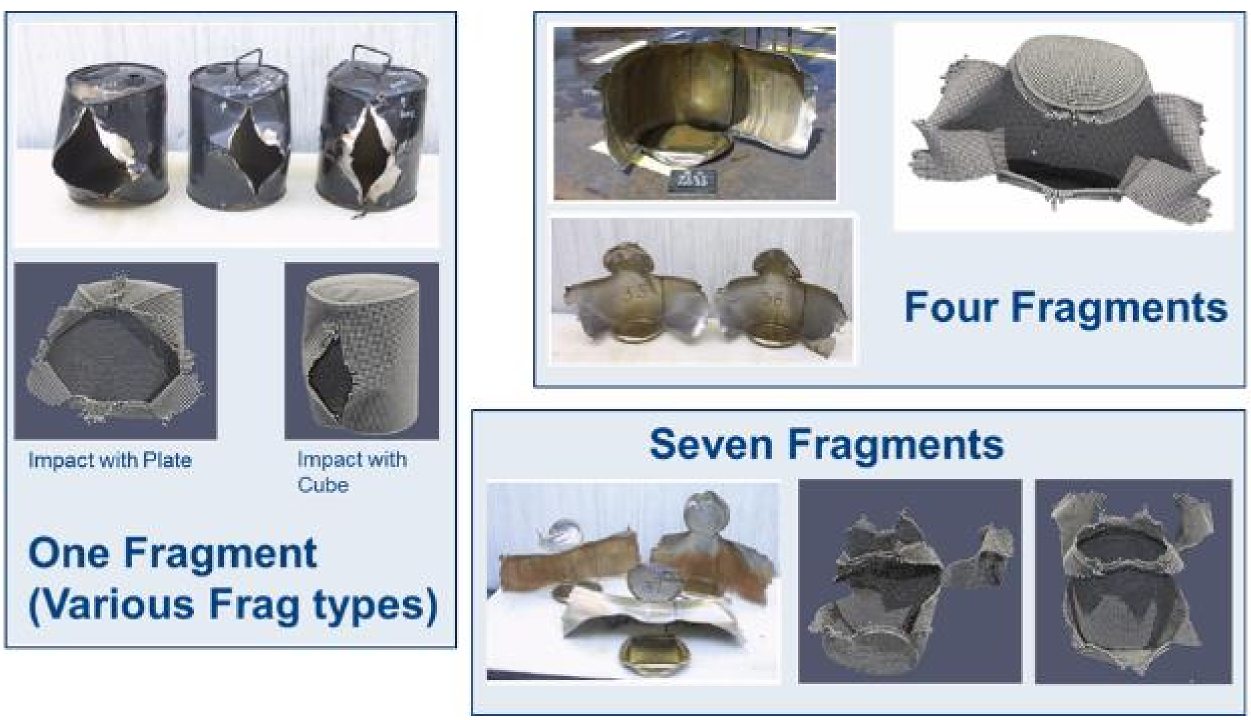

Figure 8 Container shape for V7F1, V7F4, and V7F7.

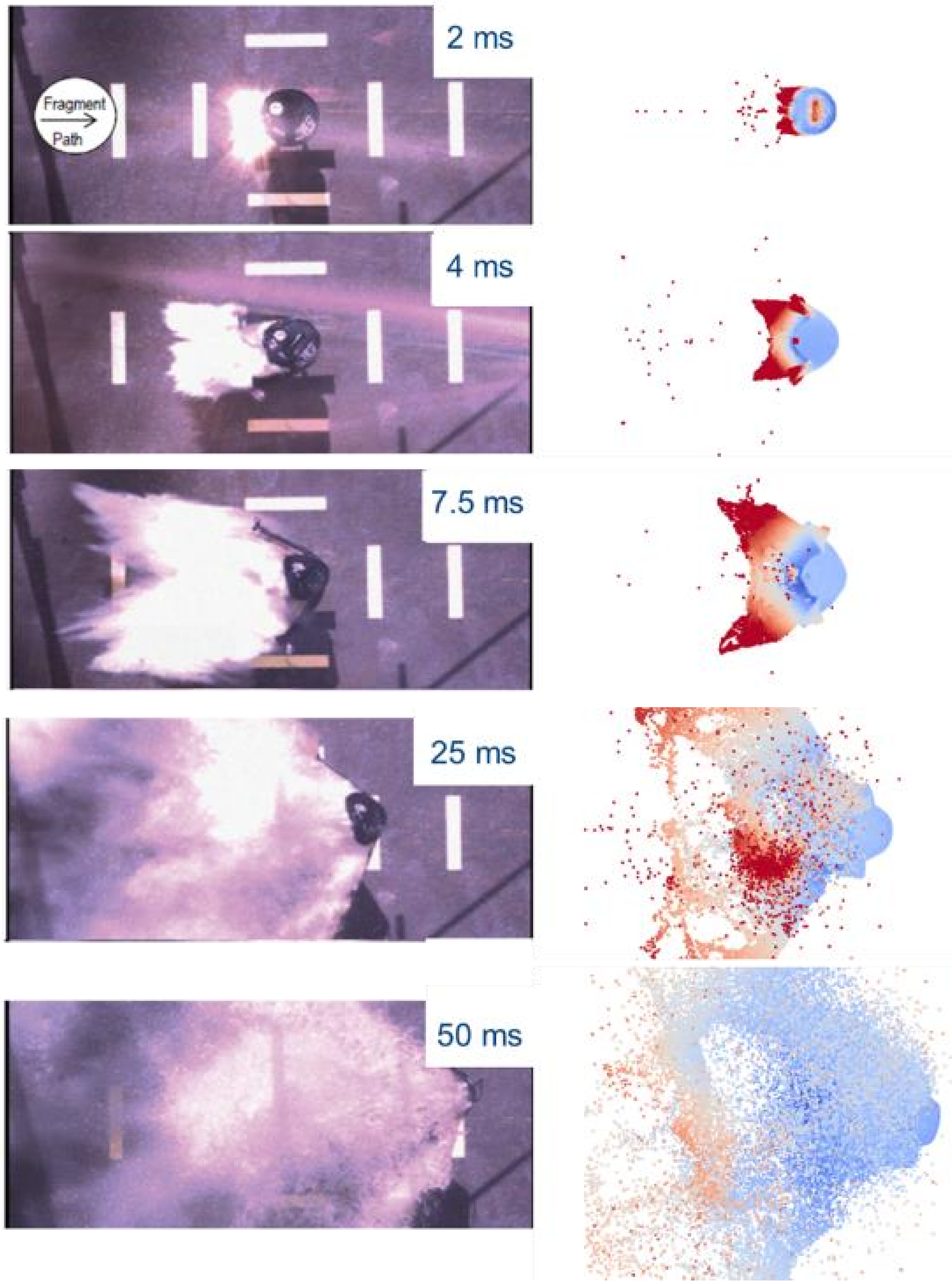

Figure 9 Top view of spray pattern from V7F4 at 2, 4, 7.5, 25, and 50 ms. The fragment path is from left to right. Liquid in the simulation is colored by velocity magnitude.

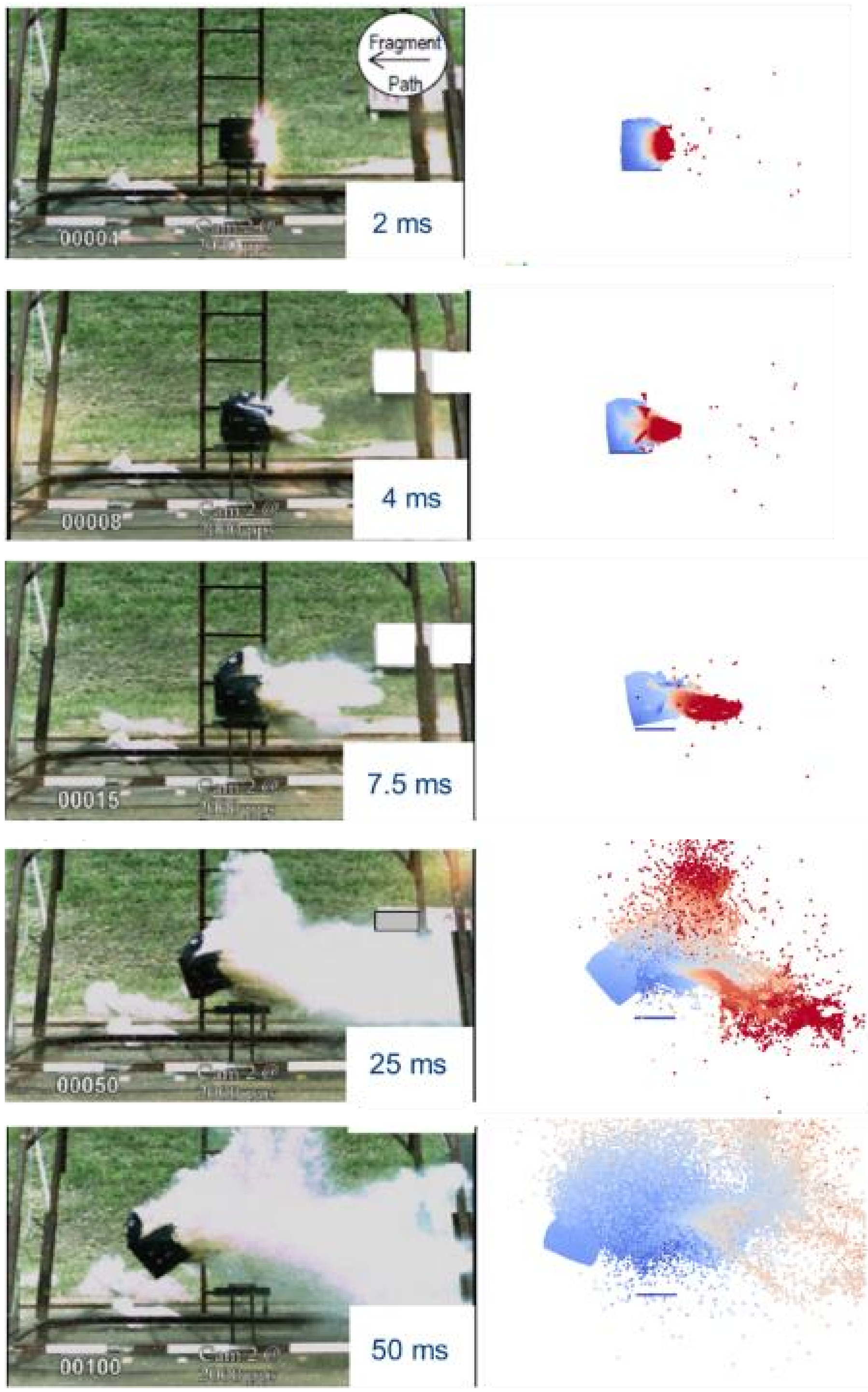

Figure 10 Side view of spray pattern from V7F4 at 2, 4, 7.5, 25, and 50 ms. The fragment path is from right to left. Liquid in the simulation is colored by velocity magnitude.

Hydraulic pressure versus time data inside the container was available for the second configuration (V7F2). Figure 11 shows the comparison between the EMU simulation and the experiment. The simulation captures the peak pressure and waveform shape seen in the data, illustrating the ability of peridynamics to simulate the dynamics of hydrodynamic ram events.

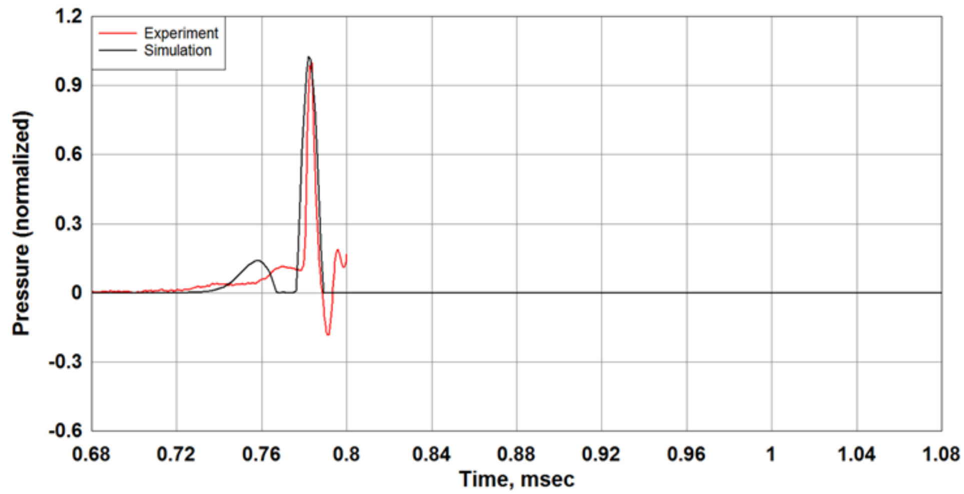

Figure 11 Hydraulic pressure versus time for V7F2. The experimental data (red) and the EMU simulation (black) are in good agreement.

Results for the third configuration are shown in Figure 12 and Figure 13. In V15000F1 the fragment penetrates the container but there is limited additional container damage and minimal liquid spray. The V15000F10 case has significant container damage and the simulation shows liquid spray directed back towards the fragment source. The effect of fragment shape, impact location, and impact timing could change the container response and could be investigated with the simulation tool.

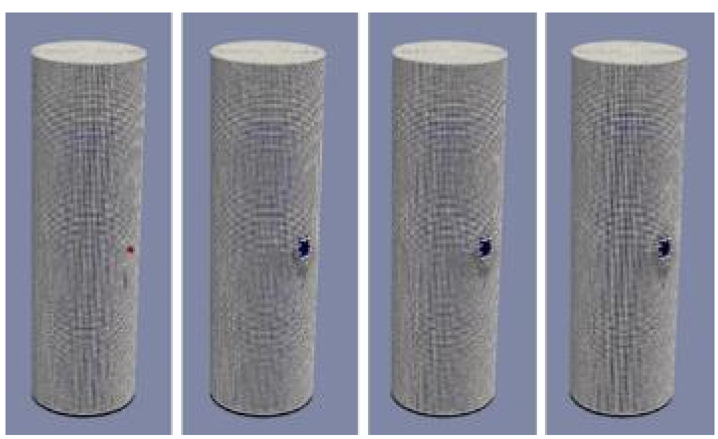

Figure 12 Isometric view of the container response for V15000F1 0, 10, 25, and 50 ms.

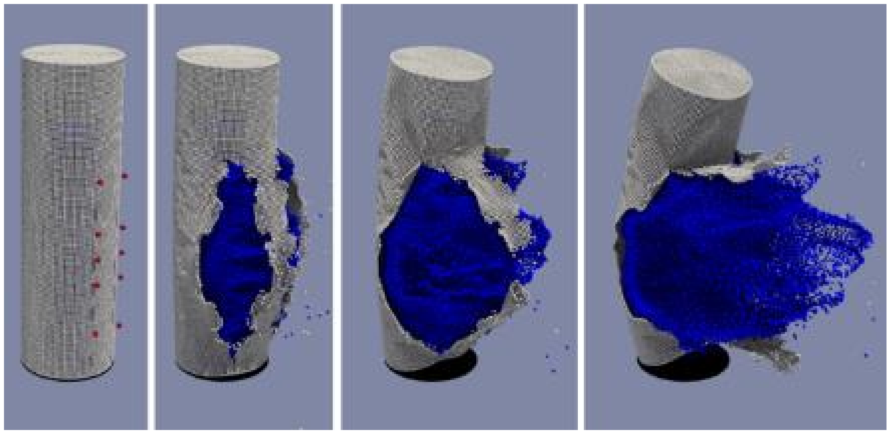

Figure 13 Isometric view of the container response for V15000F10 at 0, 10, 25, and 50 ms.

CONCLUSIONS

The paper reports advances to simulating response of liquid-filled containers to high speed fragment impacts. The hydrodynamic ram and subsequent container response and liquid spray are important for aircraft survivability and understanding risk of fires. A new approach using peridynamics simulations with EMU was shown to capture the liquid spray pattern and container shape for a range of kinetic energy levels. The simulations also match the peak hydraulic pressure versus time inside a container undergoing HRAM. Results were presented for a large container with two fragment kinetic energy loads to show the approach can be used for a range of container sizes. The peridynamics simulations run in a few days on 36 CPU cores which is much faster than other approaches such as coupled CFD/CSD tools. Future work includes studying the liquid drop sizes created during HRAM events and looking at scaling of container size, container thickness, container material, fragment conditions, and ullage.

REFERENCES

Veras, D., Zaera, R.., Lopez-Puente, J. 2009, Numerical modelling for the hydrodynamic ram phenomena. Int. J. Impact Eng. 36 363-374.

Silling, S.A., 2000, Reformulation of elasticity theory for discontinuities and long-range forces, J. of the Mechanics and Physics of Solids, Vol. 48, Iss. 1, 175-209.

Yang, K., Kwon, Y.W., Adams, C., and Liu, D., 2016, Modeling and simulation of hydrodynamic ram for aircraft survivability, JASP online, Aircraft Survivability, Fall.