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MASSIVELY PARALLEL COMPUTATIONS OF DAMAGE TO A THIN-WALLED STRUCTURE FROM BLAST

Anay Luketa-Hanlin
Sandia National Laboratories
P.O. Box 5800, Albuquerque, NM 87185
(505) 284-8280, aluketa@sandia.gov

Stephen Attaway
Sandia National Laboratories
P.O. Box 5800, Albuquerque, NM 87185
(505) 844-9288, swattaw@sandia.gov

ABSTRACT

The objective of this work is to determine initial structural response from a blast threat for the newer class of liquefied natural gas (LNG) vessels. Import of LNG by ship is expected to significantly increase in the coming decade and there is concern over vulnerability. Current vessels hold up to 160,000 m^3 of LNG, while the new vessels will hold up to 266,000 m^3. These vessels are double-hulled and have an insulating containment system which keeps the LNG at a temperature of 111 K.

Calculations were performed to determine the structural response of these ships from blast using CTH, a shock-physics code, developed at Sandia National Laboratories. The calculations were performed on massively parallel computing platforms (~1000 processors) due to the number of elements required (~10^9). Detailed geometry of the stiffeners, framing, and changing hull thickness with elevation were included, as well as the insulation, LNG, and water. Thus, there is multi-phase interaction with the structure.

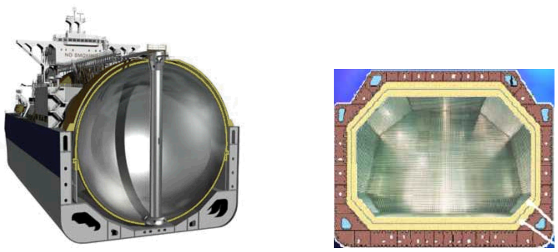
The geometry of these ships fall within a class of problems termed 'thin-walled problems' since they require resolution of length scales from ~10 mm to ~10 m. In order to capture the smallest length scales an adaptive mesh refinement (AMR) feature was used. This feature allows for cells to be concentrated in active regions as the calculation progresses. This paper will discuss the resolution challenges of simulating thin-walled problems, as well as regimes in which shock-physics codes, such as CTH, are appropriate for application. Results will be provided without disclosure of threats.

INTRODUCTION

The demand of natural gas is expected to significantly increase over the coming decade to meet energy needs in the U.S. Consequently, import of natural gas by way of shipment in its liquid form, termed liquefied natural gas (LNG), is expected to significantly increase. It is shipped as a liquid since its volume is 1/600th of that in its gaseous state. LNG is comprised mostly of methane (85-95% vol.) with ethane, propane, and small amounts of heavier hydrocarbons comprising the rest.

Currently, LNG is transported in a class of ships that carry up to 160,000 m^3 of fuel at a temperature of 111 K. It is kept at this temperature due to insulation and not to pressurization. Future ships now under design are expected to carry up to 266,000m^3 of LNG and are roughly 65 m longer (345 m) and 8 m wider (55 m) than current ships. There is concern of vulnerability of these older and newer classes of ships to external blast events. Blast threats of the current LNG ships have been assessed in a previous study by Sandia National Laboratories [1]. The objective of this work is to extend this previous study to the larger class of LNG ships. The larger ships have differences in hull thickness, as well as inner and outer hull separation, hence the need for an additional study. The area of the hole in the inner hull resulting from a blast event will determine the amount of LNG spilled onto the water, which consequently provides a key boundary condition for hazard analyses of subsequent events such as fire and explosion. The properties and description of the hazards related to an LNG spill on water is provided in [2]. The following first provides a general description of the types and structure of LNG ships, then specifications about the simulations are described, and finally results are presented and discussed.

In general, LNG ships are classified according to the type of system that contains the LNG. The containment type of the new ships will be primarily membrane versus Moss spherical, thus the membrane containment system is the focus of this work. The main difference between the two designs is that the Moss system carries spheres built with aluminum alloy that contain the LNG and have a structural integrity independent of the ship, while for the membrane type the LNG is contained within thin, stainless steel, rectangular membranes directly supported by the hull structure (Fig. 1).



(a) (b)

FIGURE 1: CONTAINMENT SYSTEMS OF LNG SHIPS, (A) MOSS SPHERICAL (B) MEMBRANE.

The number of cargo tanks, each separated by twin bulkhead cofferdams, varies with the capacity of the ship (Fig. 2). Current ships typically have four to six separate tanks, while the larger ships will have five, each holding about 50,000 m^3 of LNG.

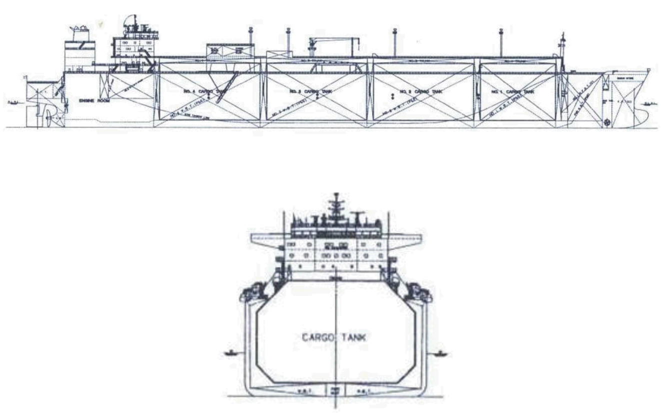


FIGURE 2: MEMBRANE-TYPE LNG SHIP.

The containment system is comprised of a primary and secondary barrier, and insulation. Figure 3 shows a cross section of the various layers of a membrane system. The insulation is either polyurethane foam (PUF) or perlite encased in plywood and typically has a thickness ranging between 2.5 – 5 m. In addition to the layers that comprise the cargo tanks, there is a surrounding double hull construction of an inner and outer hull separated by an air space distance of about 2 to 2.5 m. The thickness of the inner and outer hull is in the range of 15 – 20 mm, while the primary and secondary barriers are in the range of 0.7 – 1.2 mm.

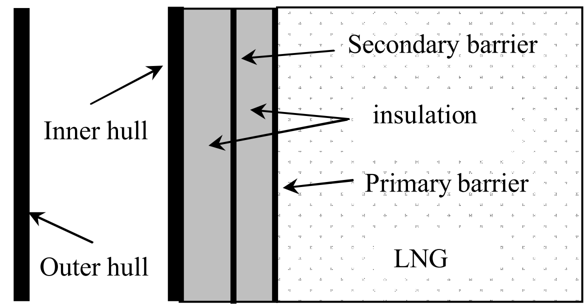


FIGURE 3: CROSS SECTION OF A LNG MEMBRANE TANKER

SIMULATIONS

To perform the calculations the shock physics code, CTH, developed at Sandia National Laboratories was used. CTH can model multi-dimensional, multi-material, large deformation, strong shock wave physics problems. The conservation of mass, momentum, and energy, along with equations of state and constitutive model equations are solved. A two-step solution method is used in which the first step is a Lagrangian description of cell distortion to follow material motion, and the second is a remesh step where the distorted cells are mapped back to an Eulerian mesh. The code can model multi-phase and mixed phase materials, elastic-plastic, visco-plastic, and visco-elastic behavior, high explosive detonation and initiation, shock propagation, fragmentation, fracture, and structural failure for 1D, 2D, and 3D geometries [2]. It can be run on Wintel PCs, all serial workstations, workstation networks and clusters, and parallel supercomputers.

As previously mentioned, the thickness of the inner and outer hull is on the order of 10s of millimeters. The dimension of the required domain is on the order of 10s of meters. Thus, the resolution requirement spans length scales differing by a factor of 1000. Consequently, this is considered a thin-walled problem. To capture the difference in length scales an adaptive mesh refinement (AMR) capability was utilized. This feature allows the mesh to be concentrated in significant dynamic regions as the calculation proceeds. A uniform grid or a stretched unstructured grid would require significantly more computational resources for this type of problem. The dynamic regions are determined through indicators specified by the user for values and differences of values for any variable. The user can also specify regions of concentration via subdomains in conjunction with indicators. Typically, it is difficult to determine the optimum specification of indicators for any particular problem. Thus, the use of AMR requires that the user perform some exploratory trial runs to optimize indicators. The code also has the feature of discarding or inactivating material regions that are no longer significant at a certain time in a calculation and would be otherwise expensive to include.

The three dimensional calculations include ship framing, stiffeners, difference in hull thickness with vertical distance, insulation, LNG, and water. CTH has the capability of reading in geometry files created with a CAD program such as SolidWorks or Pro/Engineer. The use of CAD packages allows geometric details such as stiffeners, framing, lightening holes, and difference in hull thickness with vertical distance, to be easily generated and modified if required. The alternate method to creating the ship geometry is to specify within the input file an enormous number of points, thereby significantly increasing time requirements. For this work, a geometry model was created using SolidWorks as shown in Fig. 4 which indicates the stiffeners and framing of the inner and outer hull. The water, LNG, and insulation were also included, but not shown in Figure 4.

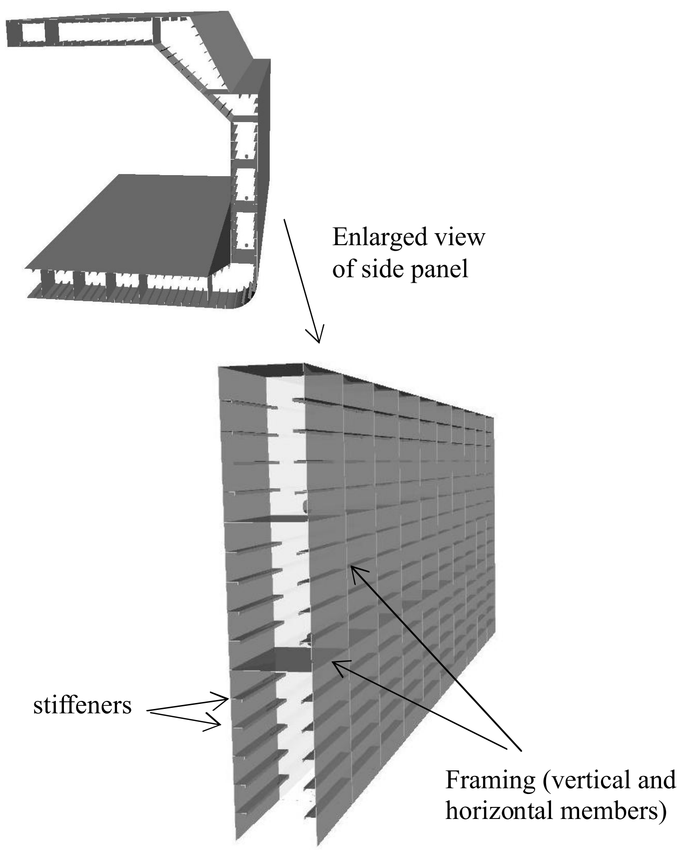


FIGURE 4: GEOMETRY MODEL OF LNG SHIP, (A) CROSS SECTION OF A TANK HALF, AND (B) ENLARGED VIEW OF SIDE PANEL.

A total of six simulations was performed using 920 processors, taking approximately two weeks for each simulation, which required on the order of billions of computational elements over 5 – 10 milliseconds of real time. All of the simulations were performed on the Razor cluster at Sandia National Laboratories. The cluster has 280 Dell 1950 compute nodes with four processors giving a total of 1120 CPUs. The CPUs are Dual Core 3.0 GHz Intel Woodcrest processors with 16 GB RAM having four FLOPS per clock cycle, which provides a theoretical peak performance of 13.44 TFLOPS.

A symmetry plane was utilized on a domain of approximately 15 x 15 x 15 m, for all but one simulation. A non-transmitting boundary condition which linearly extrapolates pressure and allows material to flow out of the domain was used at all boundaries but the symmetry boundary.

To model damage of the inner and outer steel hull the Johnson-Cook fracture model was used which has a failure criteria based on equivalent plastic strain. The Johnson-Cook fracture model describes cumulative damage and accounts for pressure, p, temperature, T, and strain rate, $\dot{\varepsilon}$, along the loading path for each material particle with a specified yield stress, Y. Damage is a scalar variable which is determined by integrating the ratio of the equivalent plastic strain rate, $\dot{\varepsilon}^{p}$, to the equivalent local plastic strain at fracture, ε^{pf} over time. That is,

$$D = \int \frac{\dot{\varepsilon}^{p}}{\varepsilon^{pf}(p, Y, T, \dot{\varepsilon})} dt \qquad (1)$$

If damage accumulates to a maximum value of 1 then material failure occurs. The model only predicts failure involving shear deformation for damage levels greater than zero, but for materials with zero damage, failure due to excessive hydrostatic tensile stress is also accounted for. The yield strength in a mixed material cell is determined by the sum of the volume fraction weighted yield strengths of the individual materials.

The thermodynamic equations of state (EOS) with phase changes are obtained from tabular or analytic equations of state using the Helmholtz potential in which thermodynamic properties (pressure and internal energy) of a material are related to its density and temperature. The thermodynamic behavior of the air and water are determined by a tabular EOS library called SESAME. The Jones-Wilkins-Lee (JWL) analytic EOS formula was used to model high explosive reaction products.

A porosity model was used to model the compaction of pores from pressure in the PUF insulation. This model utilizes a pressure dependent parameter to describe pore compaction which relates the density of the porous material to the density of the nonporous solid. The model accounts for reversible elastic and unloading/reloading partial compaction behavior, as well as an irreversible compaction. As the insulation becomes more and more compact the strain rate decreases resulting in a stiffer material. The LNG was modeled as pure methane using the Mie-Grüneisen analytic equation of state formula with appropriate constants.

The high explosive was initiated by an ideal detonation wave with a specified velocity and initiation point. A programmed burn model was used to model the initial explosive burn which provides the appropriate amount of energy into the explosive as a function of burn wave speed. Shock pressures are based on the explosive materials and geometry.

RESULTS AND DISCUSSION

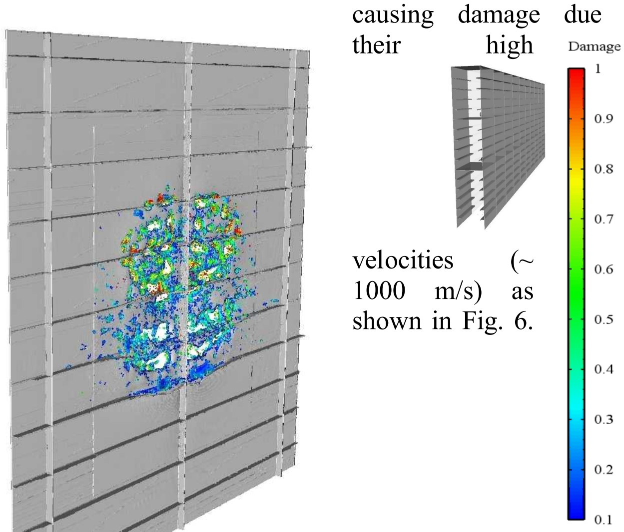
The simulations investigated damage to the inner and outer hull resulting from different charge sizes placed at different locations and stand-off distances. The details regarding the charge threat cannot be disclosed. However, the final results for damage in terms of breach area of the inner and outer hull can be provided. Table 1 provides the results for the area of hole in the outer and inner hull resulting from a blast event for all scenarios.

TABLE 1: RESULTS FOR BREACH SIZE IN INNER AND OUTER HULLS

Scenario	*Outer Hull Hole area (m^2)*	*Inner Hull Hole area (m^2)*
1	18	16
2	18	16
3	14	12
4	16	12
5	18	13
6	13	12

Figure 5 shows damage to a section of the inner hull from an external blast event for one of the scenarios considered. The bottom portion of the damage region is wider and indicates a greater amount of tearing compared to the upper damage region. The irregular pattern is due to the difference in mediums that the blast wave travels through and consequently to different failure mechanisms. For wave propagation in air the blast will initially fail the outer hull resulting in fragments.

These fragments will then be propelled into the inner hull causing damage due to their high velocities (~ 1000 m/s) as shown in Fig. 6.



The effect of overpressures causes damage as

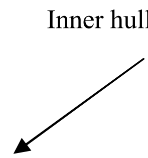


FIGURE 5: DAMAGE TO INNER HULL FROM EXTERNAL BLAST EVENT.

Figure 6: Provide a figure showing fragments. Awaiting transfer approval..

well, but is secondary to the damage from fragments. The blast wave also partially propagates through water resulting in a significant mass of water thrown towards the outer hull and subsequently the inner hull. The water provides a high momentum impact due to the combination of a velocity of around 100 m/s and density of 1000 kg/m^3. The initially displaced water from the blast will result in a void which will be filled by surrounding water thereby resulting in secondary water waves. These calculations do not capture pressure damage from subsequent water impacts; however, the impact from the initial water wave will cause the most severe damage.

These calculations provide initial blast damage, not subsequent long duration structural response of the ship. A Finite Element Method (FEM) code is more appropriate to use for late time response. If knowledge of early and late time structural response is needed, a one-way coupling can be utilized in which pressure distributions from a shock physics code can be provided as input into an FEM code. The type of code required for capturing early and late time structural failure will depend upon the charge standoff from the impact surface. For small standoff a shock physics code is appropriate, while for large standoff and late time structural failure an FEM code is appropriate, or a combination of both such as in a one-way coupling. Two-way coupling is currently an area of active research. Shock physics codes are appropriate to capture initial structural response from close in explosives since they can more accurately capture shock, fragmentation, and stress concentrations than FEM codes. However, since time steps are explicitly controlled by the minimum cell thickness within shock physics codes such as CTH, it would be computationally cost prohibitive to model long duration behavior.

The number of cells across a thin walled structure required for adequate resolution depends upon what physical feature of the blast-structure event is trying to be captured. These physical features include: air shock, blast impulse, through thickness shock, fragmentation, debris tracking, spall, ductile tearing, bending strength, welds, and internal blast pressures. Resolution requirements will be code and problem dependent, however, a previous study applying CTH to a thin-walled structural problem of isotropic materials indicates that a resolution of 1 to 2 cells will capture the air shock at the impact surface and some blast impulse and blast pressures inside of the structure, with the structural response being mostly hydrodynamic [4]. A resolution of 3 – 5 cells will allow better prediction of the blast impulse and some resolution of structural mechanics and through thickness shock pressure, while increasing up to 7 cells will allow for some wall bending, fragmentation, debris tracking, and spall to be captured. A resolution of 7 – 15 cells will allow all of these physical features to be captured, but can be computationally cost-prohibitive even on massively parallel platforms. For these calculations the inner and outer hulls were resolved with 3 cells.

Experimental data is needed to determine the degree to which the code can capture all of the aforementioned physical features as a function of the number of through thickness cells. Currently, experimental data required for validation of more detailed physical features such as fragmentation and debris tracking does not exist for this problem. However, there have been documented blast events occurring for both a double-hulled and single-hulled ship, the details of which cannot be disclosed, that can be used for approximate validation of the hole size. Comparison to these cases indicates that the code provides a reasonable estimate for breach areas resulting from a blast event.

CONCLUSION

The objective of this work is to obtain short-time initial structural response to determine breach areas in the inner and outer hulls of an LNG ship resulting from various blast events. The configuration of the inner and outer hull of an LNG ship represents a thin-walled problem. Due to the range of length scales, it is very computationally challenging to simulate a 3-D thin-walled structure involving blast. Typically, billions of elements are required for a simulation. Consequently several weeks of CPU time on a massively parallel system (~1000 processors) is required for these type of simulations.

A shock physics code can be used to calculate short-time structural response for close proximity blast events. FEM codes are appropriate for late-time or long duration structural response. Both types of codes can be coupled to obtain a structures short and long time response to blast.

The results indicate the range of hole sizes from various blast events are from blank for the inner hull, and blank for the outer hull for the newer class of LNG ships.

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