THE EFFECT OF CARGO ON THE CRUSH LOADING OF RAM TRANSPORTATION PACKAGES IN SHIP COLLISIONS

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Introduction

Recent intercontinental radioactive material shipping campaigns have focused public and regulatory attention on the safety of transport of this material by ocean-going vessels. One major concern is the response of the vessel and onboard radioactive material (RAM) packages during a severe ship-to-ship collision. These collisions occur at velocities less than the velocity obtained in the Type B package regulatory impact event and the bow of the striking ship is less rigid than the unyielding target used in those tests (Ammerman and Daidola, 1996). This implies that ship impact is not a credible scenario for damaging the radioactive material packages during ship collisions. It is possible, however, for these collisions to generate significant amounts of crush force by the bow of the impacting ship overrunning the package. It is the aim of this paper to determine an upper bound on the magnitude of this crush force taking into account the strength of the radioactive material carrying vessel and any other cargo that may be stowed in the same hold as the radioactive material.

During ship collisions, the kinetic energy of the striking ship is initially absorbed by plastic deformation of the struck side of the hull. If the striking ship has sufficient kinetic energy, the hull will be penetrated and further energy will be absorbed by plastic deformation of the decks, bulkheads, and cargo. Eventually, again if the striking ship has enough kinetic energy, the RAM package will be impacted. Initially, this will be merely an impact load due to the inertia of the RAM package. The RAM package will then be torn from its tiedowns, and subsequently experience crushing between the contacting ship and cargo on the side of the hull away from the point of impact. The magnitude of this crush force is limited by the strength of the bulkheads, decks, hull structure of the ship, and the material properties of the cargo. Previous studies have shown that, for a vessel with no other cargo, the maximum crush force that can be applied to a package is equal to the force required to push the package through the far hull of the ship into the ocean (Ammerman and Ludwigsen, 1998). An upper-bound for this force is about the same as the inertial crush force seen during the regulatory impact accident. This paper extends the research, using finite element analysis, to the crush forces that may develop when there is other cargo in the hold with the RAM package.

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There are two ways that other cargo effects the crush loading on the radioactive material package. First, the surrounding cargo absorbs some of the energy of the collision before the RAM package is ever contacted and, thus, has a tendency to decrease the magnitude of the loads transmitted to the package. Second, the surrounding cargo distributes the contact force over a larger area of the ship hull. Instead of the RAM package punching a relatively small hole through the side of the ship, the combination of the RAM package and cargo causes deformations over a much greater portion of the ship hull prior to failure.

Finite Element Model

Figure 1 shows the finite element mesh used in this study. All of the elements in the ship hull are 4-node shell elements with 5 integration points through their thickness. The hull elements are 0.75 inches (19 mm) thick, the stiffener elements are 0.5 inches (13 mm) thick. The stiffeners are 18 inches (457 mm) tall by 6 inches (152 mm) wide and spaced 40 inches (1.02 m) on center. The 100 inch (2.54 m) "deep" cargo is modeled with 8-node hexahedral elements and is constructed in three distinct blocks: a region directly behind the RAM package, a thin transition region around this section, and the remaining large surrounding volume. This particular configuration was chosen to allow the cargo elements in the transition region to fail due to a shearing load while not allowing the remainder of the cargo, particularly in the region directly below the cask, to fail due to a compressive load. The RAM package is also modeled with 8-node hexahedral elements and has dimensions 36 inches (914 mm) in diameter by 100 inches (2.54 m) long. Boundary conditions are applied to the "front" plane of the model to enforce symmetry. The boundaries at the "back" and each side of the hull are the floor deck of the hold above the package (or the deck of the ship) and the bulkheads at either end of the hold containing the RAM package.

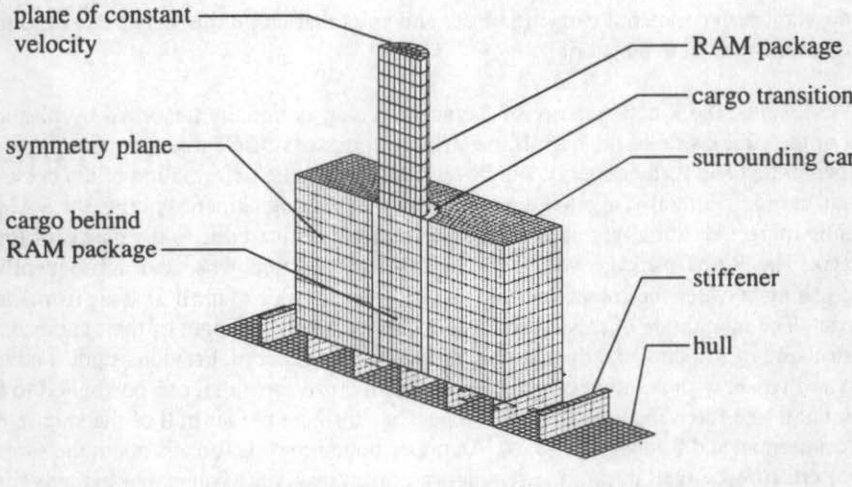


Figure 1: Schematic of the Finite Element Model

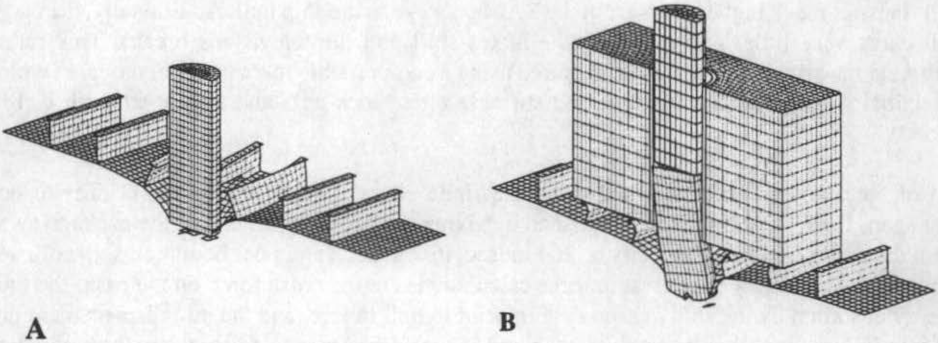
The hull, stiffeners, and cask are modeled using an isotropic hardening material model, which is typical for steel structures. The choice of material model for the cargo, however, is more complex. Assuming that the cargo is not a single large piece of massive machinery (earth moving equipment for example), a collection of many discrete small items (boxes of televisions for example) should behave like a compressible fluid. That is, in compression the material will deform quite easily under a fairly low load (the boxes will move out of the way and the televisions will shatter) up to the point at which it "locks-up". At this point, the material becomes much more stiff (the televisions and boxes are a compacted block of useless junk) and will transmit much higher loads from the RAM package to the ship hull. Additionally, the cargo will carry very little load in shear (the boxes shift and the televisions break). This rather elaborate material response can be captured using a compressible foam material model in which the initial stiffness, crush strength, the stiffness after "lock-up", and failure strength can be varied.

All of the analyses are performed using the finite element code PRONTO-3D (Taylor and Flanagan, 1987). Loading is accomplished by giving the nodes on the end of the package away from the cargo a constant velocity of 264 in./sec. (6.7 m/sec.) an upper bound on ship collision velocities. The results of interest in these calculations are the crush force on the cask, the total energy absorbed by the ship / cargo system prior to hull failure, and the hull displacement just prior to failure. For all of the analyses, the hull is considered to have failed when the equivalent plastic strain in any of the hull elements exceeds 20%. All of energy that would be absorbed by the ship and cargo prior to the cask being contacted by the striking ship is neglected. The actual deformation of the RAM package is not considered in this analysis, it is merely serving as an appropriately shaped load cell. The total load on the package is calculated by multiplying the axial stress of each element on the constant velocity plane by its cross sectional area and summing over all of the elements on the plane. Displacements are recorded at a node along the centerline at the top and bottom of the cask, and at a point at the base of the stiffener directly below the cask. The energy absorbed by the system is then calculated by numerically integrating a curve representing the load vs. the displacement of the bottom of the cask.

Analysis Results

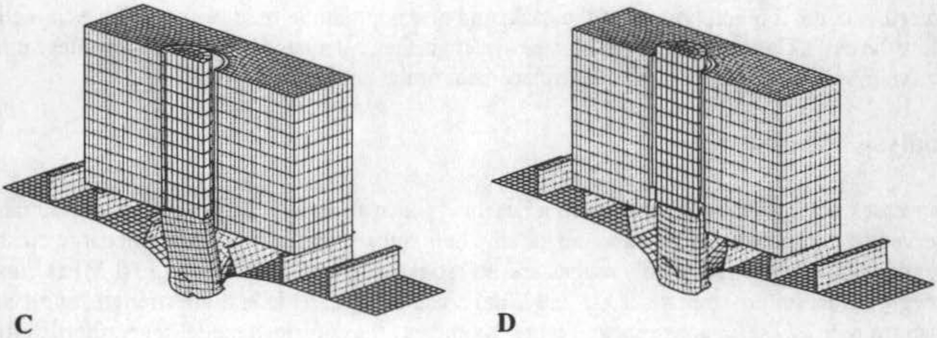
Four cases are considered. To develop a baseline, the analysis is first performed without any intervening cargo between the cask and the ship hull. Subsequently, three different cargo crush-strength / failure strength combinations are investigated, specifically; 2 ksi (13.8 MPa) crush strength / 2 ksi failure strength, 1 ksi (6.9 Mpa) crush strength / 1 ksi failure strength, and 1 ksi crush strength / 2 ksi failure strength. Figure 2 compares the deformed model shape shortly after hull failure for the baseline and three different cargo cases. Careful inspection will reveal that there are more elements in the cask of the baseline case than for the cases with cargo. This has no effect on the results of interest because, as previously stated, the cask merely serves as a load cell.

Several behaviors are noteworthy in Figure 2. First, and most obvious, is that the RAM package is merely punching out a cylindrical plug through the cargo which subsequently fails the ship hull in a manner similar to the case without cargo. Second, comparing Figures 2B and 2C demonstrates that the crush strength of the cargo dictates the final length of this plug of cargo before the foam material that simulates the cargo "locks up" and becomes solid enough to fail the hull. Additionally, the cargo crush strength affects the time required to generate enough displacement to fail the ship hull. Finally, a very careful comparison of Figures 2B, 2C, and 2D reveals that the failure strength of the cargo dictates the size of the hull region affected by the cargo. This is more clearly seen in Figure 3. Note that higher cargo failure strengths create a much larger damage area in the ship hull. This occurs because after impact by the cask, the entire block of cargo moves as unit for a finite length of time and causes gross deformation of the ship hull over an area approaching the size of the entire cargo block. After the cargo fails in



time = 15 ms
no cargo

time = 26 ms
cargo crush strength = 2 ksi
cargo failure strength = 2 ks



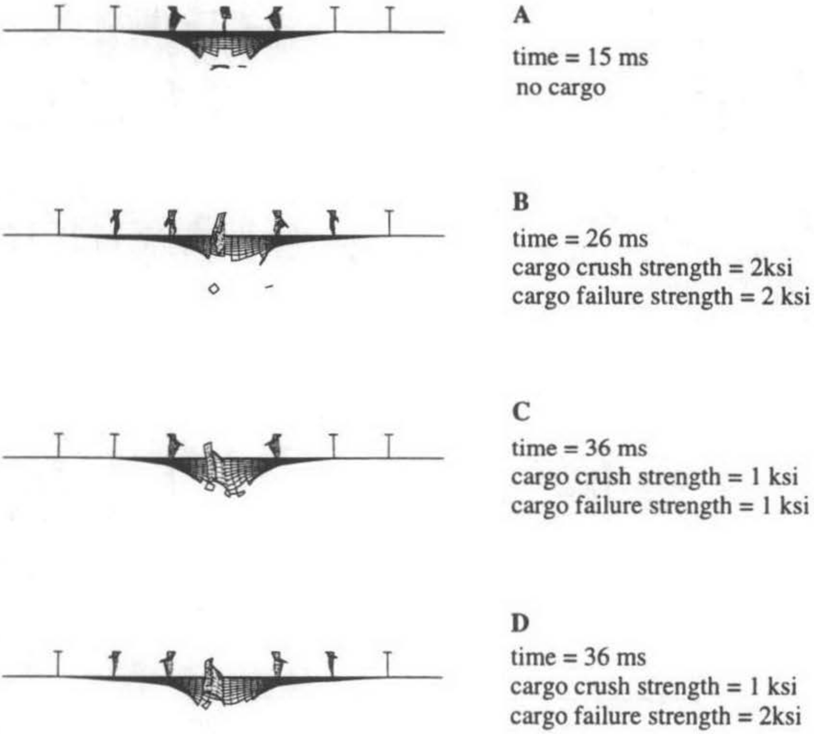
time = 36 ms
cargo crush strength = 1 ksi
cargo failure strength = 1 ksi

time =36 ms
cargo crush strength = 1 ksi
cargo failure strength = 2ksi

Figure 2: The effect of cargo material properties on the deformed shape of entire model after hull failure

shear and the "plug" is punched out by the cask, loads are no longer transmitted to the remainder of the cargo block and the hull deforms in regions much more local to plug contact.

All of the aforementioned behaviors are important because they each contribute to the total energy absorbed by the system prior to hull failure, previously defined as the area under the load vs. deflection curve. Figure 4 shows the load vs. deflection curves and the energy absorbed for each case discussed above. The same general trends are present in all of the load vs. displacement curves, but they are most easily seen in Figures 4B and 4C. Upon contact with the cargo, the load on the cask increases quite rapidly and oscillates about a value approximately



A
time = 15 ms
no cargo

B
time = 26 ms
cargo crush strength = 2ksi
cargo failure strength = 2 ksi

C
time = 36 ms
cargo crush strength = 1 ksi
cargo failure strength = 1 ksi

D
time = 36 ms
cargo crush strength = 1 ksi
cargo failure strength = 2ksi

Figure 3: Section view through hull after failure showing the effects of cargo material properties

equal to the failure strength (in shear) of the cargo in the transition region. The load then drops off to zero for a short period of time and then increases again to a value around 2.5 million pounds (11.2 MN). The relatively constant initial portion of the curve is due to the cargo crushing behind the cask and the elements in the transition region slowly failing. As the last elements in the transition region fail, the resulting cargo plug is free from the restraining forces of the cargo, buckles the center stiffener, and then impacts the ship hull. These two events occur in the region where the load drops off and stays briefly around zero. The RAM package and cargo plug now directly load the ship hull, which displaces and then fails due to membrane tensile stress. Notice that in Figure 4C and 4D the RAM package displacement is approximately 90 inches (2.3 m) before hull failure but in Figure 4B the displacement is only around 65 inches 1.7 m. This is directly attributable to the crush strength of the cargo and explains why case B absorbed the least amount of energy. The cargo "locked-up" and created a solid plug more quickly. The system in figure 4D absorbed almost 50% more energy than that of Figure 4C. This is due to the increased failure strength of the cargo. The solid plug is the same size in each case, however, the cargo block stayed intact much longer for the case shown in Figure 4D. This caused larger gross deformation of the ship hull, and hence higher loads for a longer period of time, before the cargo plug broke free.

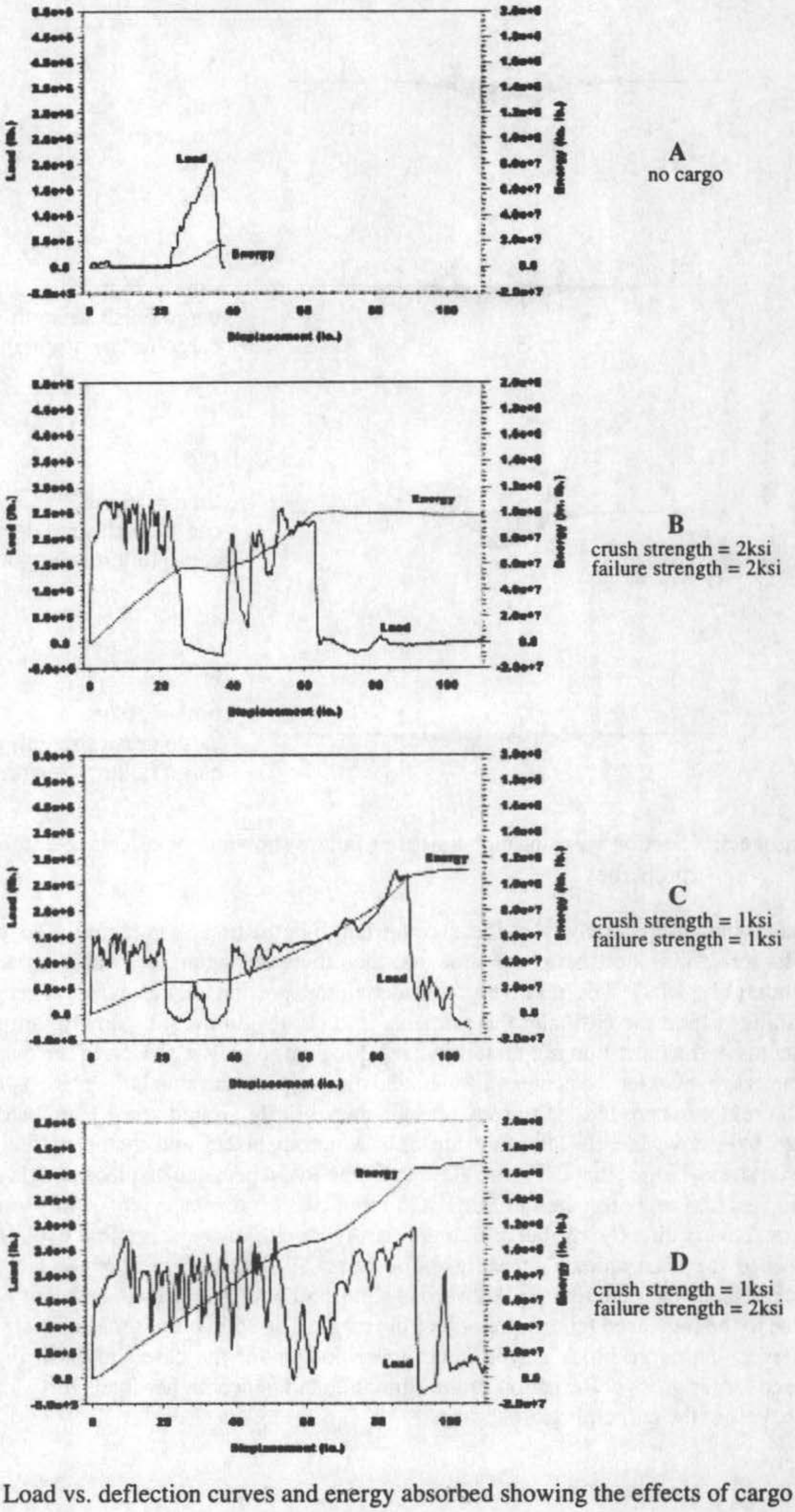


Figure 4: Load vs. deflection curves and energy absorbed showing the effects of cargo

Although it is not possible to directly relate these crush forces to the impact forces generated during the regulatory 30 foot (9m) drop test, the relative magnitudes can be compared. Assuming a package weight of 25 tonnes (typical for truck casks), the peak loads shown in this paper correspond to accelerations ranging from 50-60 G's. Equivalent static loads for truck casks are generally in the range of 50 G's during regulatory drop tests, with peak accelerations often 4 times higher.

Figure 5 compares the ship hull displacement to the cask displacement for each of the three cargo combinations. Each curve has been truncated at the point of hull failure.

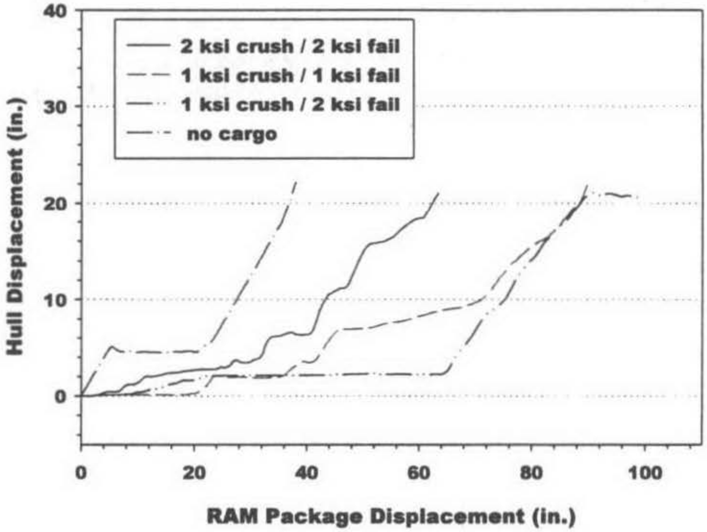


Figure 5: Comparison of hull displacement vs. RAM package displacement for various cargo material properties

The important thing to note is that, despite the distinctly different cargo and hull responses, the total hull displacement at failure is approximately the same for all three case. This implies a consistent failure mode across all three cases, specifically, membrane tensile failure of the ship hull.

Conclusions

The results of this study indicate several important things about the effect of cargo on the crush loading of RAM packages during ship collisions. The material properties of the cargo can have a profound effect on both the total energy absorbed by the ship during a collision, and the deformed shape of the hull prior to failure. However, varying both the cargo crush-strength and failure-strength by a factor of two reveals very little effect on the crush force actually transmitted to the RAM package. Because the primary failure mode of the system is membrane tensile failure of the ship hull, the magnitude of crush force that RAM packages transported by sea are likely to be subjected to during severe ship-to-ship collisions is limited by the strength of the hull of the transporting vessel. Additionally, the inertial crush force generated during the regulatory drop test can be used as a conservative upper-bound for this crush force.

References

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