Economically Improving Crash Worthiness of a Large Propane Tanker

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Approximately every three years a 65,000 lb propane tractor-trailer crashes resulting in explosion that usually kills several people. The study presented in this paper first simulates the effects observed at one of these accident sites. This was simulated in LS-DYNA by building a full length model of the tanker trailer and also including the liquid in the tanker. The presence of the liquid in the model provide the initial effects of liquid on the tanker. The resulting model correlated very closely with the actual observation seen at the crash site. Then a variety of options where explored to determine how to improve the crash worthiness of the tanker for several crash scenario's. The result of this work illustrated that for less than $20,000 the velocity that would cause failure could be raised from 20 mph to over 55 mph through the use of energy absorbing materials.

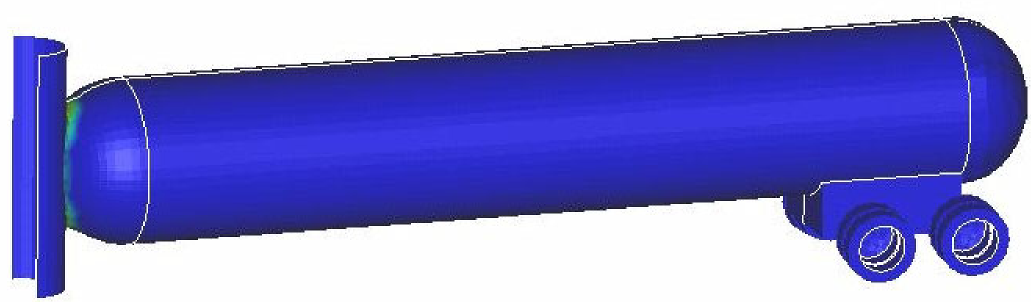

Figure 1. Illustration of the Full Length Tanker Model as it Crashes in to Rigid Bridge Pier

Introduction

About every three years a propane tanker is involved in a accident that results in a breaching of the pressure boundary containing the propane. The result of these accidents is usually multiple fatalities. In almost all of these cases the tanker hits a relatively rigid structure on the highway. When the pressure boundary is breached , the liquid propane inside the tanker will instantly turn into a gas, and thereby greatly increases the pressure that the vessel experiences. The increased pressure causes the explosive effect referred to as fluid hammer has been seen at the site of previous accidents involving these tankers. Previous research on the fluid hammer effect has illustrated that the best way to prevent it is prevent the breach of the pressure boundary in the first place.

The current design of these tankers has been shown from both accident investigations and model simulations to survive only a accident of less than 20mph. In this research project it was illustrated that by attaching eighteen inches of energy absorbing foam to the front of the tanker that the tanker would be able to survive a 55mph impact into a rigid structure. The cost of doing this would a loss of 3200 pounds of load carrying capability and a cost of $20,000.

The Models of the Tanker

The worst-case scenarios could be defined by three cases. These are a head on impact into a rigid flat wall, a head on impact into a rigid round column, and an impact at 45 degree angle to a rigid flat wall. As part of these research, various energy absorbing systems where explored to improve the crash worthiness of these tankers. This was done by evaluations of various head thick nesses, multiple heads and energy absorbing materials between heads and energy absorbing materials over existing head designs.

The initial part of the research was done with quarter and half symmetry models of just the front part of the tanker. This was done to greatly reduce the run time for each sequence of runs that where used to determine the point that the pressure boundary would be breached. In addition to half and quarter symmetry, only the first ten feet of the tanker was modeled in the smaller models. The balance of the mass and stiffness of the tanker was simulated in the smaller model by a high strength high-density section of the tanker and liquid propane components of the model. The total weight was then verified to ensure that tanker model weighted the prescribed 65,000 lbs. These quarter and half symmetry models took about two hours to run per case explored. The quarter symmetry model is illustrated in figure 2.

At the end of the research project the results where validated by running significantly large model of the full length tanker as illustrated in figure 1. This model took over 15 hours to run, and as such was not deemed to be a viable model for doing the hundreds of cases needed to determine an optimal design for an energy absorbing system to increase the survivability of the tanker.

The head on impact simulations were done with a quarter symmetry model since in these cases there are two planes of symmetry for both the model and impact condition. For the simulations of impacts that are occurring at an inclined angle, a half symmetry model is used since there is only one plane of symmetry relative to the impact event. To verify the accuracy of these front-end models a full-length model of the final proposed tanker design for improving the crash worthiness was built. A run was completed to verify those results are the same as the small model. All of these models where created by using a parametrically laid out input file for the ANSYS 5.6 to LS-DYNA preprocessor. This file is written in the ANSYS Parametric Design Language format to facilitate rapid construction of various design options of the tanker model.

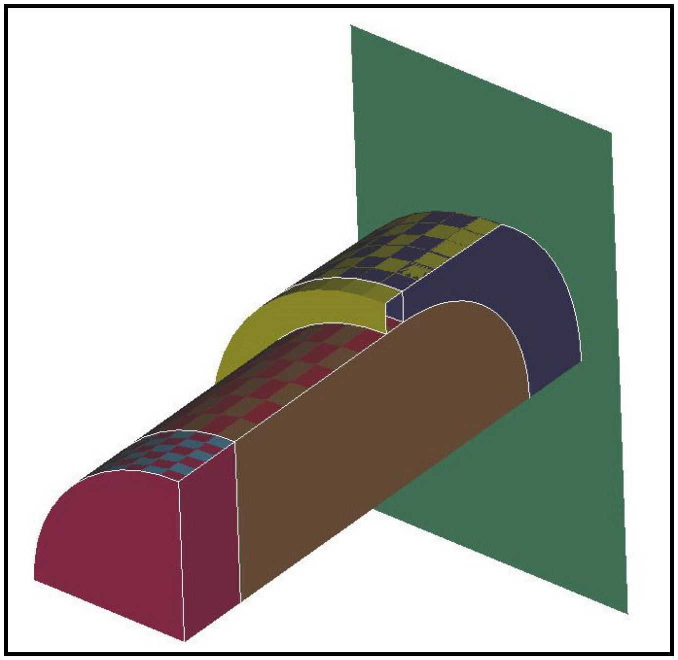

Figure 2. Quarter Symmetry Model for Evaluation Straight Impact into a Flat Rigid Wall

Impact Scenarios

A review of previous papers about crashes of pressurized tankers illustrated that their failure mode is almost always the result of a forward velocity into a structure that is effectively rigid. Furthermore, it was noticed that three primary types of events have lead to pressure boundary failures in the past. The first scenario is a crash straight or almost straight into a basically flat rigid surface. The second scenario is a crash straight or almost straight into a round column that again is rigid and unyielding to the impact. Finally, the third scenario is an impact at a 45-degree impact. This was chosen because at this angle the peak force is achieved in the combination of both the longitudinal and lateral forces into the tanker body.

Crash into a Rigid Flat Wall at 90 Degree Angle to the Line of Travel

The first case considered in the evaluations of various designs of the crash worthiness of the propane tankers was the head on impact of a tanker into a rigid flat wall. In this scenario the tanker is assumed to be traveling at a given velocity directly into the rigid flat wall. The simulation then lets the tanker move along the line action through the time frame of the impact. The total time duration of the crash was less than 100 milliseconds. The simulation uses a quarter symmetry model of the front end of the tanker as previously described. This is illustrated in Figure 2.

Crash into a Rigid 42" Diameter Column at 90 Degree Angle to the Line of Travel

The second case considered in the evaluations of various designs of the crash worthiness of the propane tankers was the head on impact of a tanker into a rigid bridge column. In this case the tanker is assumed to be traveling at a given velocity directly at the rigid bridge column. The simulation then lets the tanker move along the line action through the time frame of the impact. Again the total amount of time actually simulated is less than 100 milliseconds. This simulation uses a quarter symmetry model of the front end of the tanker. This is illustrated in Figure 3.

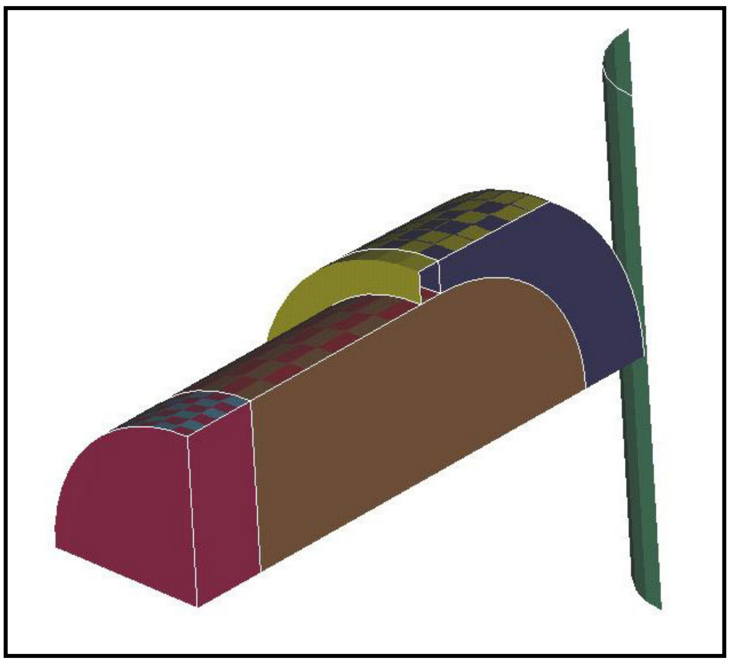

Figure 3. Quarter Symmetry Model for Evaluation Straight Impact into a Rigid Cylindrical Wall

Crash into a Rigid Flat Wall at 45 Degrees to Direction of Travel

The third and final case considered in the evaluations of propane tankers was the 45 degree inclined impact of a tanker into a rigid flat wall. In this scenario the tanker is assumed to be traveling at a given velocity and at a 45-degree angle to the rigid flat wall just prior to impact. The simulation then lets the tanker move along the line action. Again the time duration of the event simulation is less than 100 milliseconds. This simulation uses a half symmetry model of the front end of the tanker because the impact and load path is only symmetrical about one plane. This is illustrated in Figure 4.

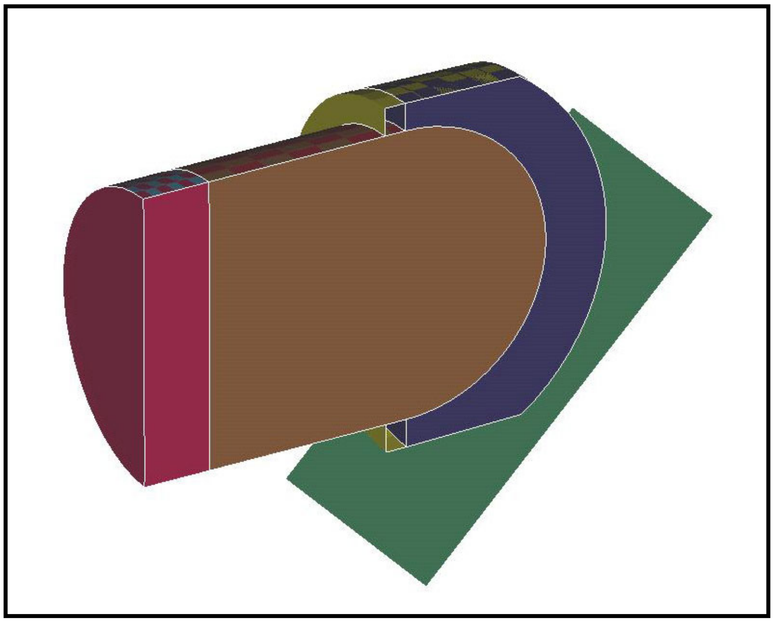

Figure 4. Half Symmetry Model for Evaluation 45° Angled Impact into a Rigid Flat Wall

Bare Head Model of Tanker

The initial models of the front end of the propane tanker worked well at predicting the shape of the deformation due to a given type of impact. The models accurately predicted the three impacts that have occurred on US highways with full propane tankers.

Initially, an improved bare head model was created to develop a mesh of the tanker and the propane that would provide a more stable simulation of the movement of the liquid propane during an impact. The three impact scenarios were then run with this revised model to verify that the solutions of the improved models agreed with the previous work.

In the first case it was noted that the impact on the rigid flat wall was a basic head buckling problem that caused the front of the main head to pop inward until a critical area/strain is reached that causes failure to occur. This shape is illustrated in Figure 6. Then various thick nesses of head were evaluated to determine the effect of increased head thickness on the crash worthiness. The results are illustrated on the chart in Figure 6. Based on these results it was concluded that head thickness does not improve crash worthiness on a bare head.

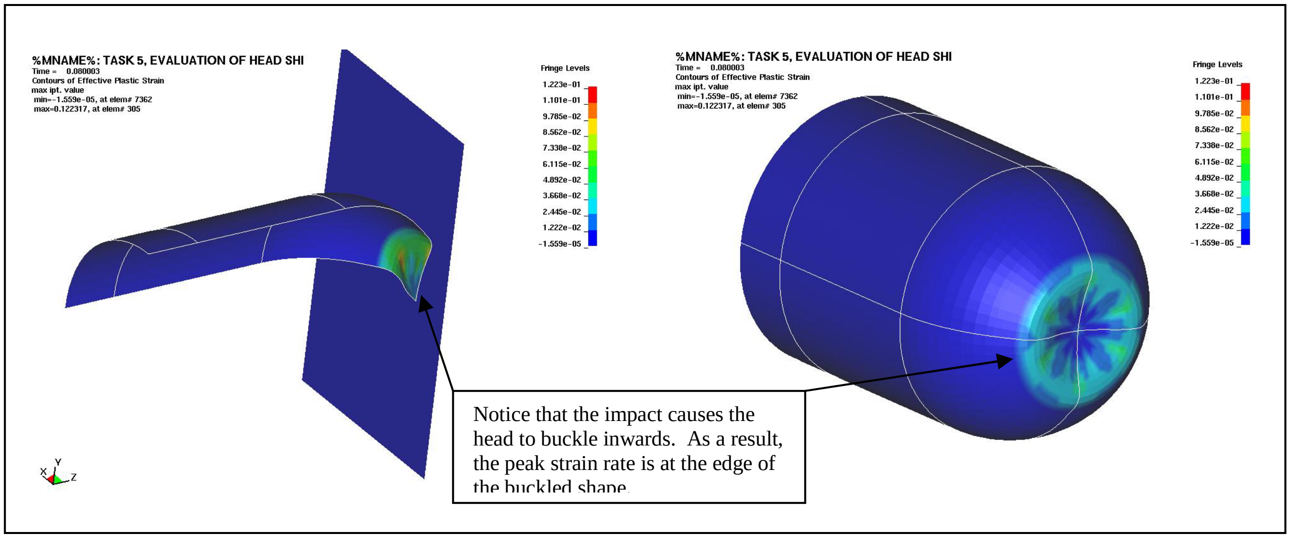

Figure 5. Scenario One: Head on Impact of Bare Head on a Rigid Flat Surface

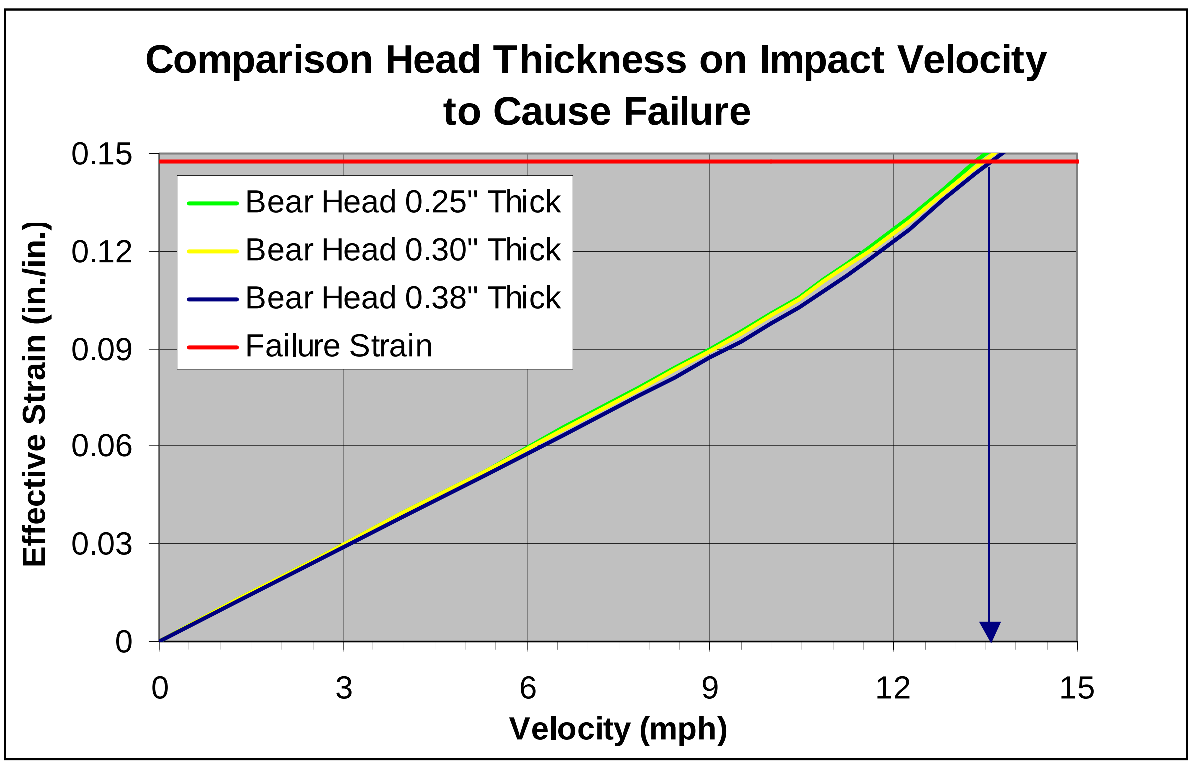

Figure 6. Chart to illustrate the effect on primary head thickness on the critical failure Velocity

The bare head design was run into a column. In this case the deformed shape of the model also agreed with both previous models and the details of the accident in White Plains, NY where a tanker ran into a bridge column. The results at the critical speed, just before failure of the primary pressure boundary, are illustrated in Figure 6. In this model the folding that occurred in the head material during the accident at the White Plains, NY is seen in this model.

In the final case the bare head is impacting a flat rigid surface at a 45-degree angle. The flattening of the one side of the head can be seen in Figure 7. This model also illustrates that the bare head will fail on the leading edge of the impact zone due to a buckling and folding of the head material.

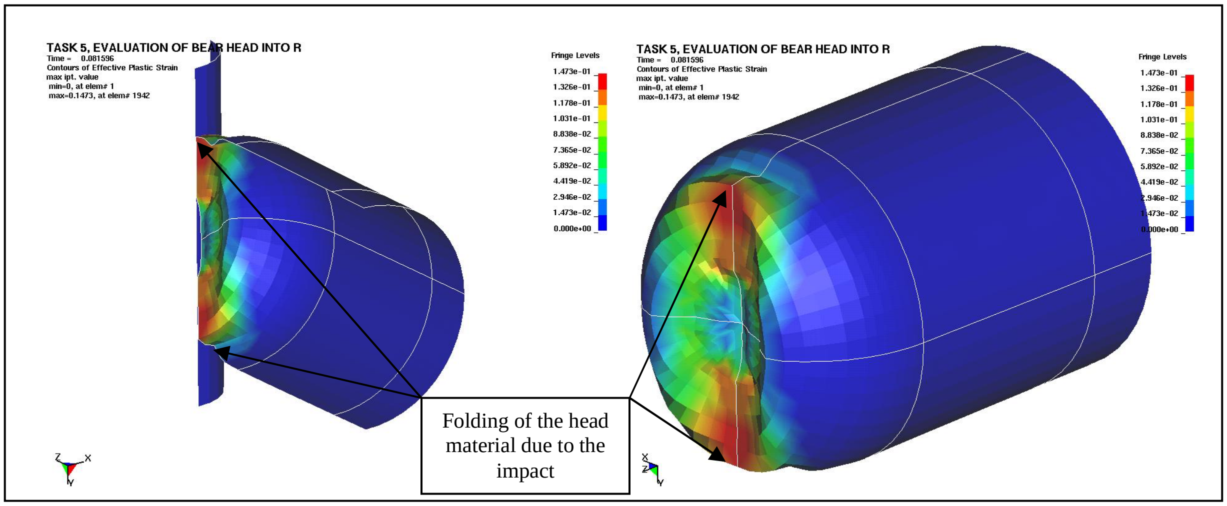

Figure 7. Scenario Two: Head on Impact of Bare Head on a rigid 42 Inch Diameter Bridge Column

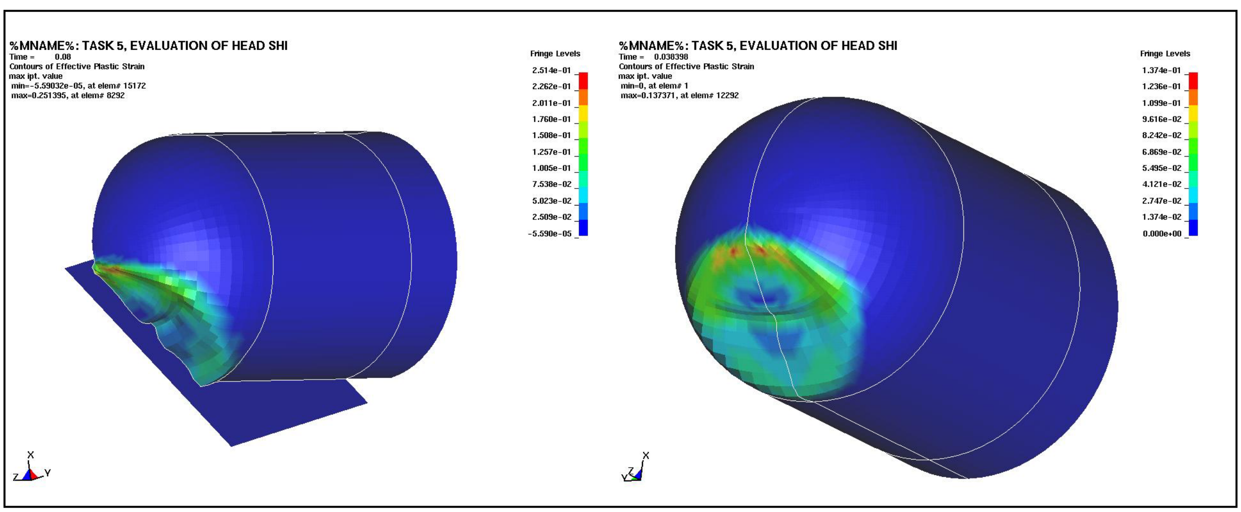

Figure 8. Scenario Three: 45 Degree Impact of Bare Head on a rigid Flat Surface

Energy Absorbing Material over Primary Head

Several options for absorbing the energy of the impact where explored using this cases. The addition of second off set head did almost nothing to improve the crash worthiness of the tanker. A second option was also explored where energy absorbing material called HEXCEL that is used in the aircraft industry to build lightweight structures was tried. This product requires the material in the honeycomb structure to buckle to use up the energy. This system improved the crash worthiness by about ten mile per hour. This was nowhere near the 55 mph goal. As a result it became obvious that a material that could spread out the energy of the crash over a larger area was needed if any significant improvements to crash worthiness was to be expected.

Energy Absorbing Foam Material

Based on previous papers a material called LAST-A-FOAM FR-3700 a rigid polyurethane was chosen for it's energy absorbing abilities. General Plastics Manufacturing Corporation of Tacoma, Washington manufactures this material in a variety of densities. This material can be formed into any geometric form. In this study the application of various densities and thick nesses over the end of the tanker were studied. The optimal density and thickness determined that tanker's crash worthiness could be increased from 20 mph to 55mph and greater for the three impact scenarios previously discussed. The actual shape of the foam over the head used in this study is illustrated in Figure 9. This material was modeled using the LS-DYNA software's Foam material model.

Results of Various Foam Densities and Thick nesses

Various densities and thick nesses of LAST-A-FOAM FR-3700 foam for a head-on, angled collision, and a collision with a cylindrical bridge column were studied to determine what configuration would increase the tankers crash worthiness from 20 mph to 55 mph. The density of the foam was varied from 14 lbs/ft^3 to 35 lbs/ft^3 for a constant thickness of eighteen inches. Based on a constant thickness of 18 inches, it was determined that a density of 22 lbs/ft^3 would be the optimal density of foam. These results are summarized in Figure 10. In addition, it can be seen in Figure 15 that increasing the tanker's head thickness would actually reduce the crash worthiness of the tanker. To verify this, the thickness of the foam was varied from 9 to 24 inches with a density of 22 lbs/ft^3. This is illustrated in Figure 11. The results of these simulations illustrated that 18 inches is the optimal thickness for 22 lbs/ft^3 density foam. Based on this work an ideal thickness for each foam density could then be determined. Then the crash worthiness of the tanker as a function of foam thickness and density could be used to define the benefits versus the weight cost on the tanker design.

This optimization of the thickness and density of the foam was done on the front end model impacting into a rigid flat wall. These results are illustrates in Figure 12. The final results of this optimization of foam thickness and density were then used for the impact scenarios of the tanker hitting a cylindrical bridge column and a rigid wall at a 45 degree angle. The impact of the tanker into the bridge column is illustrated in Figure 13. The impact of the tanker into the rigid wall at a 45 degree angle is illustrated in Figure 14.

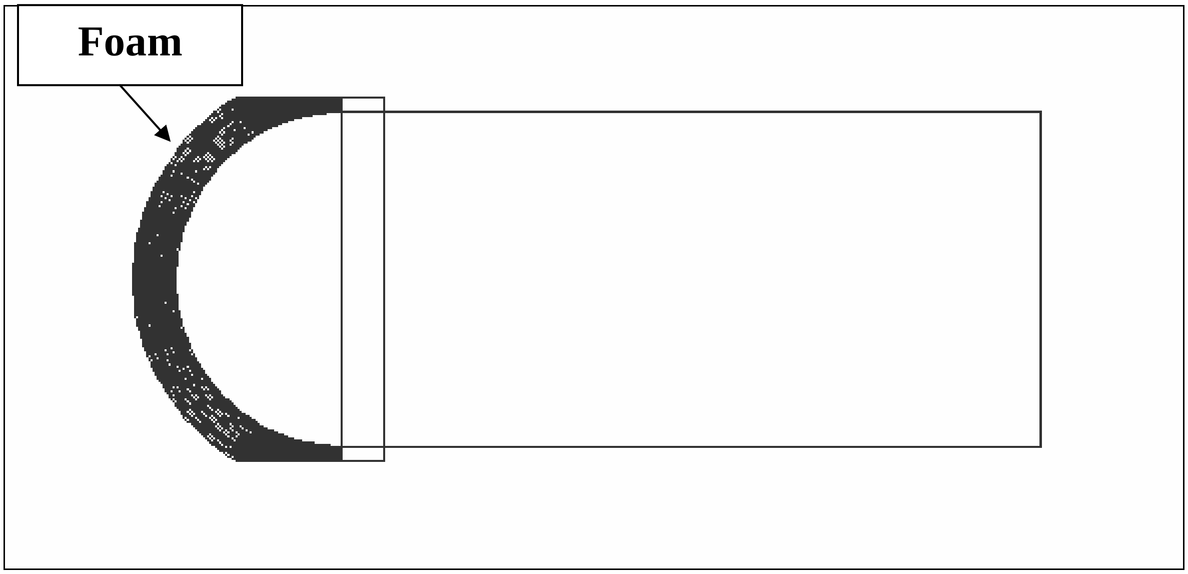

Figure 9. Illustration of the Foam Covering of the Tanker

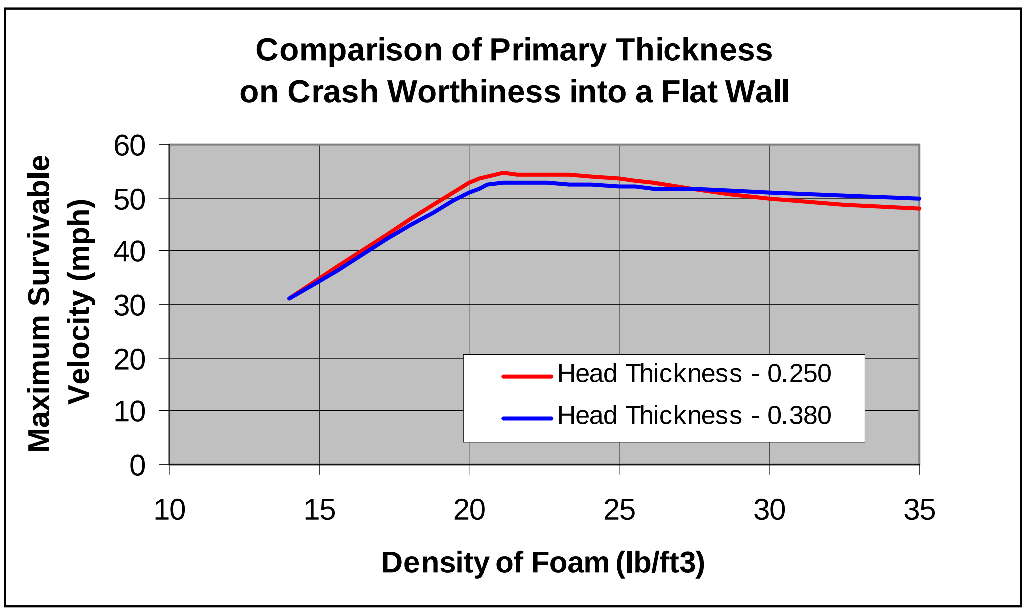

Figure 10. Comparison of Foam Density vs. Primary Head Thickness

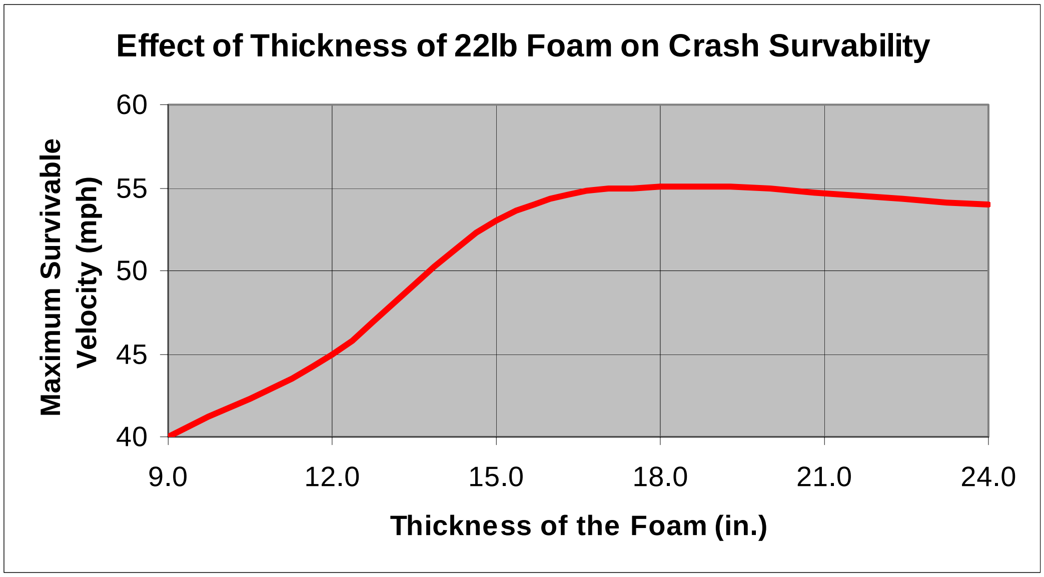

Figure 11. Comparison of Various Thickness of 22-lb/ft^3 Density Foam

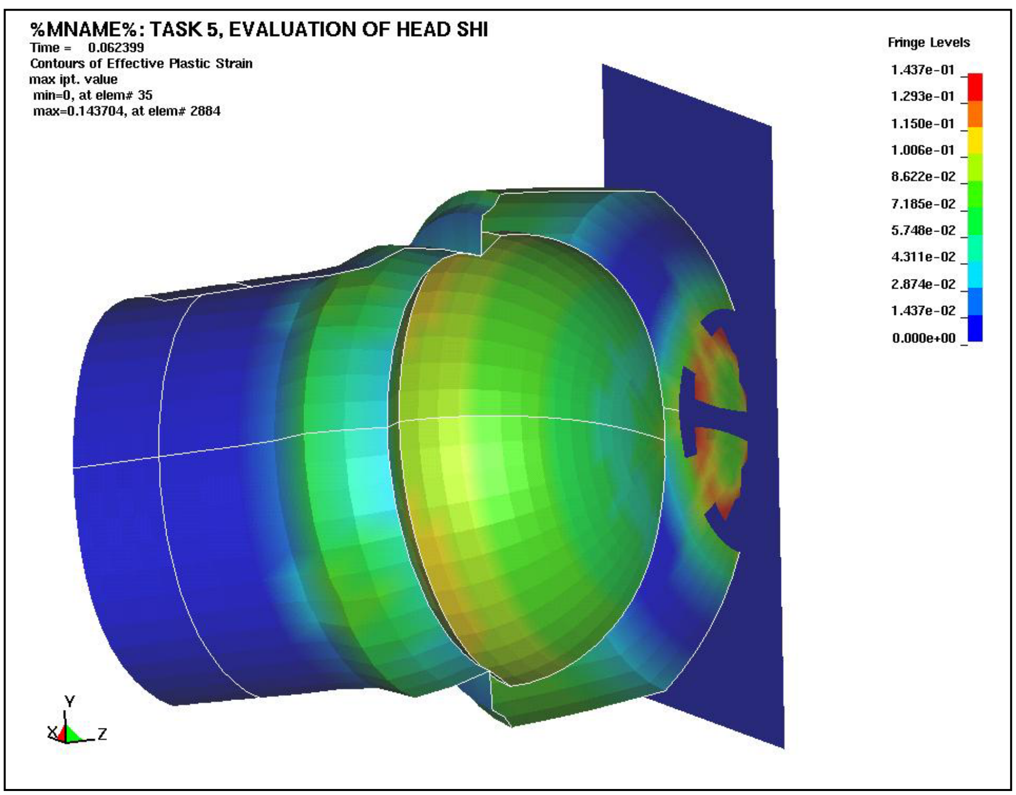

Figure 12. Impact of the Tanker Model with 18” Thick 22lb. Energy Absorbing Foam into a Flat Wall

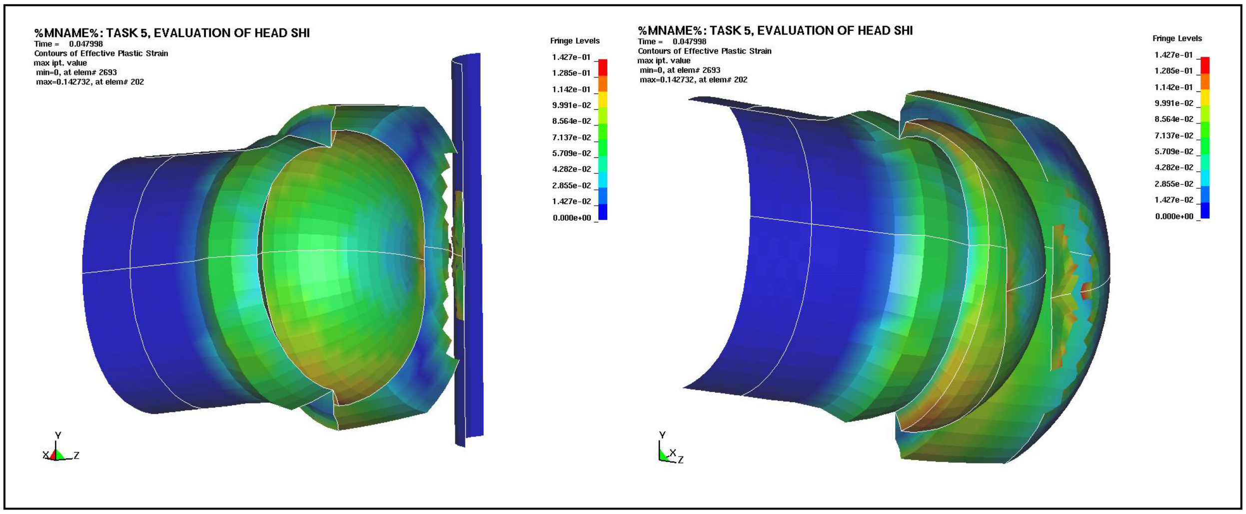

Figure 13. Impact of the Tanker Model with 18" Thick 22 lb/ft^3 Density Energy Absorbing Foam into a Bridge Column

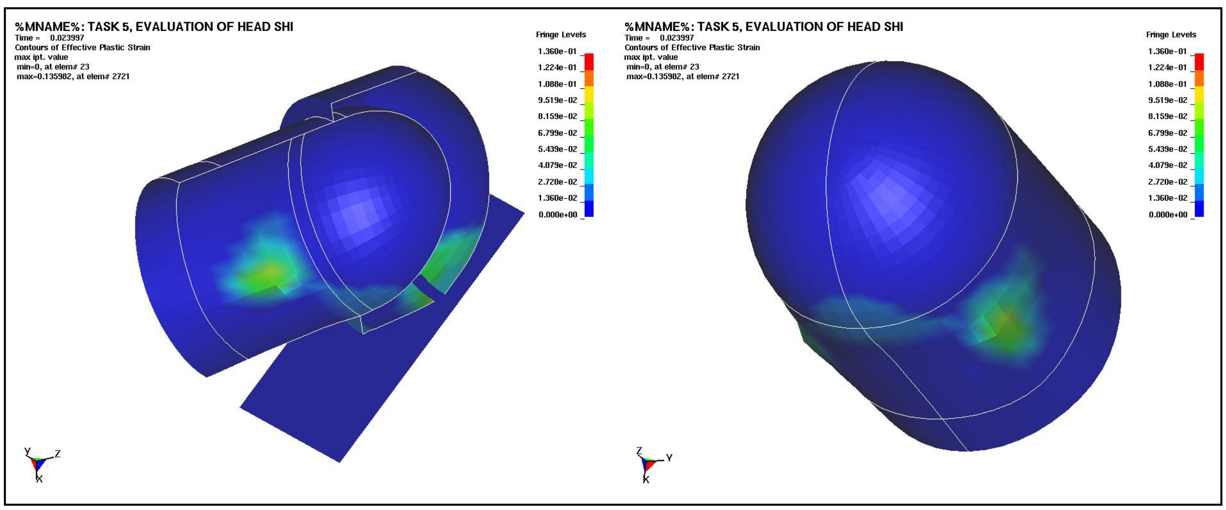

Figure 14. Impact of the Tanker Model with 18" Thick 22 lb/ft^3 Density Energy Absorbing Foam into a Flat Wall at 45 Degree Angles

3.6 Full Length Model of the Tanker

To verify that the smaller front end model would pick up all of the effects that would be caused by the presence of the whole tanker, a full model was built and solved with the previously optimized solution with the foam material. The model used an 18 inch thick 22lb/ft^3 density energy absorbing foam to cover the current design head that is 0.250 inches thick. The foam is then covered with 0.060-inch thick sheet metal to protect it.

The results of the full-length simulations illustrated that the smaller models where good approximations of the results that a full length model would provide. The full-length models also captured the little details of the impact that would ultimately be needed to completely describe a refined test of a given tanker design. In fact, the full-length models indicated that the improvement to the crash worthiness of the tanker would be a few mph greater than the front-end model had predicted. However, it should be noted that this model takes more than four times the computer resources. The model of the full-length tanker into the rigid flat wall is illustrated in Figure 15. The model of the full-length tanker into the rigid bridge column is illustrated in Figure 16. The model of the full-length tanker into the rigid flat wall at a 45 degree angle is illustrated in Figure 17.

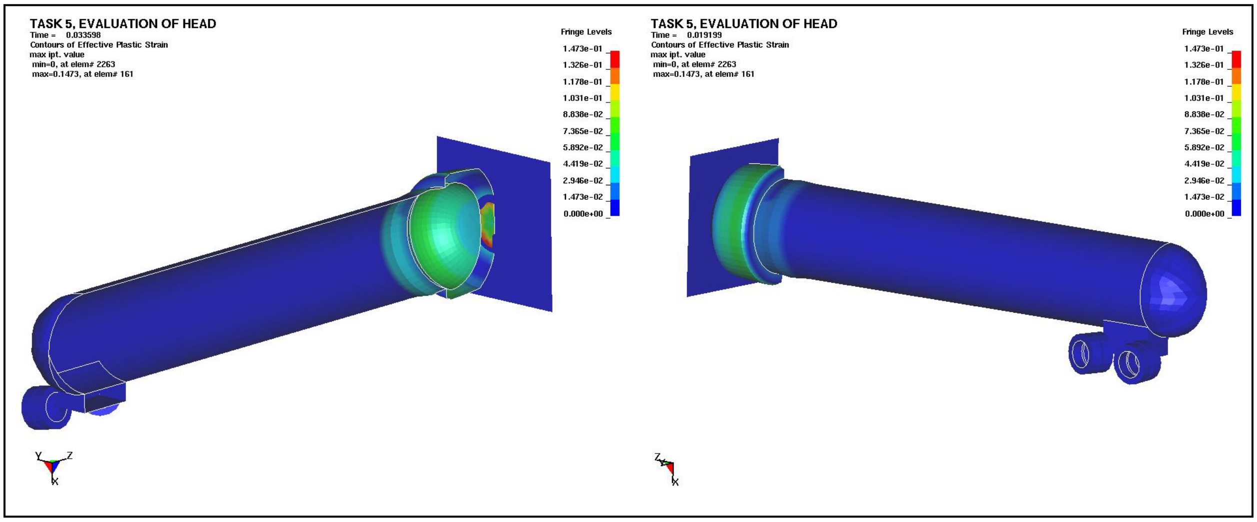

Figure 15. Impact of the Full Length Tanker into a Rigid Flat Wall

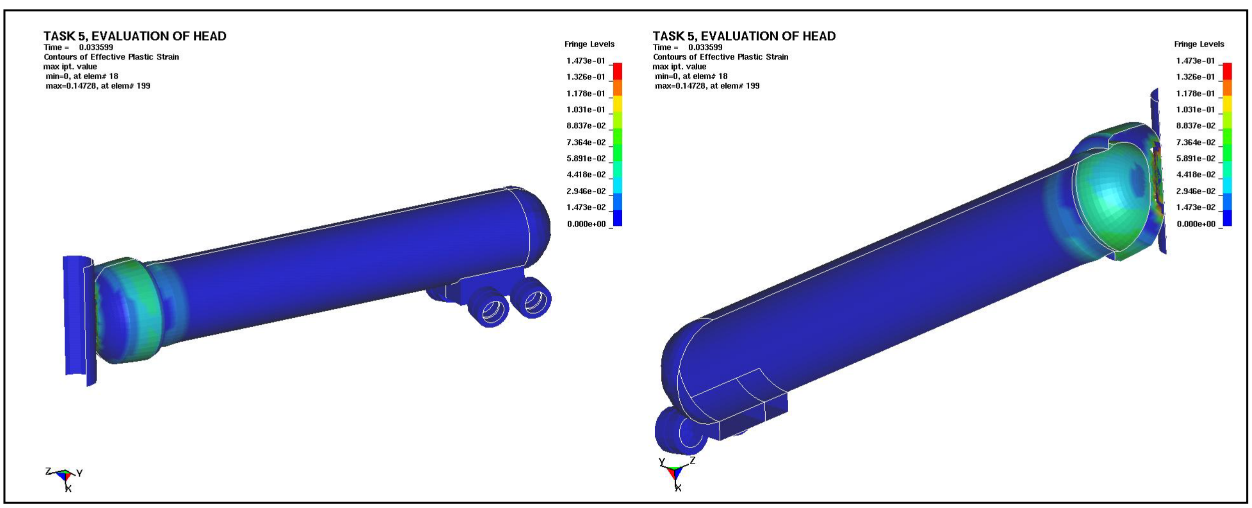

Figure 16. Impact of the Full Length Tanker into a Rigid Bridge Column

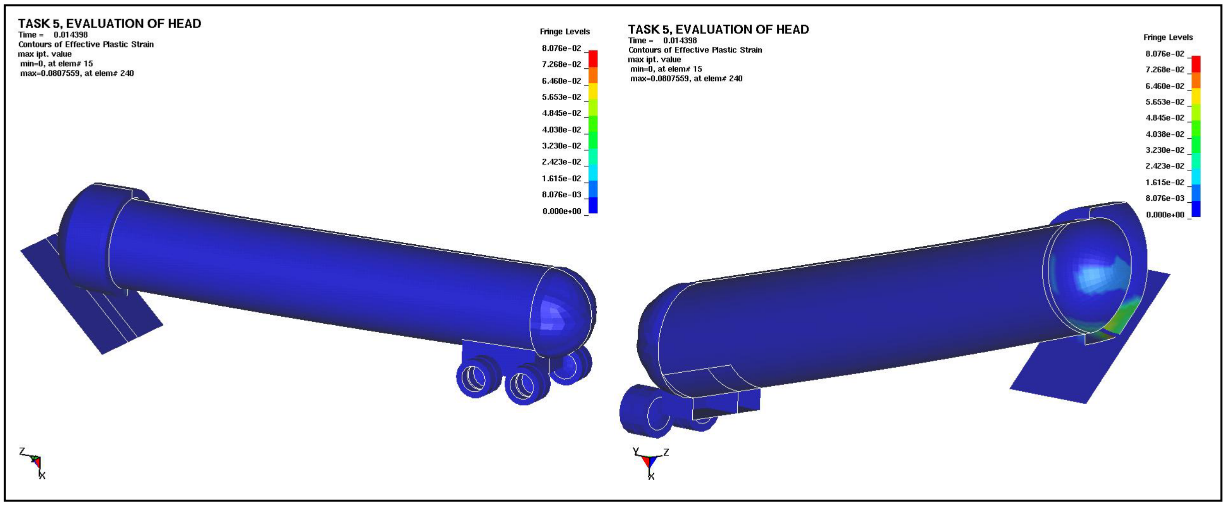

Figure 17. Impact of the Full Length Tanker into a Rigid Flat Wall at a 45-Degree Angle

General Conclusions

LAST-A-FOAM FR-3700 foam is the ideal choice for dramatically improving the crash worthiness of the tanker. At a thickness of 18 inches of LAST-A-FOAM FR-3700 at 22 lb/ft^3 density will provide an impact protection speed of over 55 mph. It must be noted however that while the thicker foams will increase the impact protection speed, there is an accompanying increase in the weight of the tanker thereby reducing the carrying capacity of the tanker. Furthermore, it should also be noted that this design can be retrofitted onto existing tankers and provide the same level of crash protection as a new tanker initially fabricated using this design.

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