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DETAILED IMPACT ANALYSES FOR DEVELOPMENT OF THE NEXT GENERATION RAIL TANK CAR

Part 2 –Development of Advanced Tank Car Protection Concepts

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ABSTRACT

Significant research has been conducted over the past few years to develop improved railroad tank cars that maintain tank integrity for more severe accident conditions than current equipment. The approach taken in performing this research is to define critical collision conditions, evaluate the behavior of current design equipment in these scenarios, and develop alternative strategies for increasing the puncture resistance. The evaluations are being performed with finite element models of the tank cars incorporating a high level of detail. Both laboratory scale and full-scale impact tests were performed to validate the modeling and ultimately compare the effectiveness of current and alternative equipment designs.

This paper describes the use of the detailed finite element impact and puncture analyses to assess the performance of advanced puncture protection concepts.

INTRODUCTION

Over the last few years, there has been significant attention on the potential for release of hazardous materials from railroad tank cars. This attention is primarily a result of a series of three accidents or derailments between 2002 and 2005 involving the release of hazardous material [1-3]. In response, a research program was initiated to develop strategies for improving railroad tank cars so they can maintain tank integrity for more severe accident conditions than current equipment. The research was initiated by The Dow Chemical Company (Dow), Union Pacific Railroad, and Union Tank Car Company, working under Memoranda of Cooperation (MOC) with the Federal Railroad Administration, and Transport Canada, and separately with the U.S. Transportation Security Administration.

The Next Generation Rail Tank Car (NGRTC) Project was organized to include a Core Team (consisting of representatives from the signatories to the Memorandum of Cooperation) and a group of Lead Contractors. The Core Team and Lead Contractors worked together to: 1) evaluate and select candidate materials, components, subsystems and systems with the potential to provide large performance improvements in the safety and security of rail tank cars; 2) select conceptual tank car designs incorporating appropriate materials, components and systems for improved safety and security; and 3) develop and use appropriate models, analytical techniques and testing protocols to demonstrate the efficacy of the tank car concepts. The goal of the NGRTC program was to develop a conceptual tank car that had a five to ten times improvement in the impact energy required to puncture the tank car.

A key effort in this program is the development and application of detailed finite element models of tank car equipment which can accurately predict the puncture resistance under different impact conditions. These analysis tools were developed and validated for the puncture of the baseline tank cars for both side and head impact conditions [4, 5].

This paper describes the results of the NGRTC efforts to develop advanced strategies for improving railroad tank cars so they can maintain tank integrity for more severe accident conditions than current equipment.

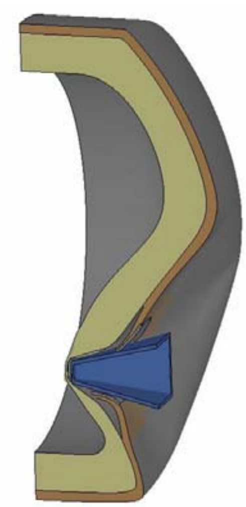
ANALYSES OF ADVANCED PROTECTION SYSTEMS

The first task in this research was to develop and validate a modeling capability that can be used to analyze the impact response of a tank car. The results of the model development and validation effort are provided in a companion paper [4] and in the NGRTC analysis final report [5].

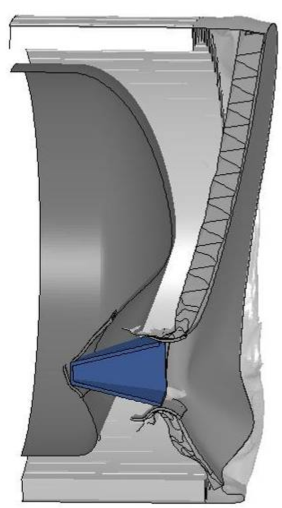
The validated puncture modeling capabilities were subsequently applied to analyze a series of advanced tank car protective structure concepts. Included in these were multi-layered foam systems, engineered metal structures (EMS) systems, and advanced material (composites) options.

For some of these concepts, additional material characterization testing was required. For example, detailed characterization testing was performed on the crushable energy absorbing foams [6-8]. The tests were then used to develop suitable constitutive models for the various strength foams [5].

Example head impact puncture analyses on both a layered foam system and a corrugated EMS system are shown in Figure 1. A variety of designs were investigated using the detailed analyses capabilities. In addition, a full scale head test was also performed for both of the concepts shown in Figure 1 [9]. However, neither of the foam or EMS systems was optimized.



(a) Layered foam protection system

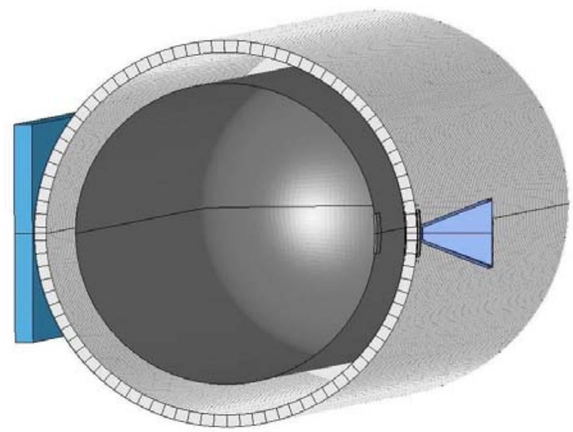


(b) Corrugated EMS protection system

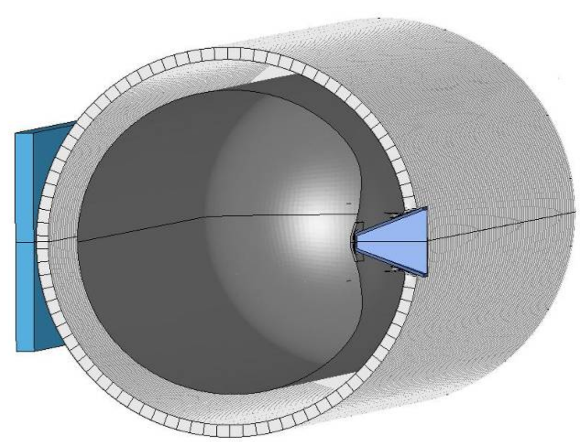
Figure 1. Analyses of advanced protection concepts.

The failure mode of the layered foam and EMS systems was similar to that of the baseline tank systems when impacted by the 6x6 inch impactor. When the load acting on a layer of the advanced protective system exceeded the shear capacity of the layer, the layer would be punctured. For many of the advanced concepts, the system design would increase the stiffness of the support for the outer layers. The increased support structure stiffness would result in outer layer penetration at reduced ram displacements. As a result, the protection system and commodity tank would be penetrated independently at lower peak forces and lower puncture energies than could be obtained in an optimized system.

An example of this failure mode is seen in the impact response of an egg-crate core sandwich EMS structure shown in Figure 2. The outer EMS sandwich structure consists of a core that is a rectangular grid of axial and radial webs with a 4 inch spacing and face sheets that are fully bonded to the core. The face sheets are made of 8 gauge (0.1644”) steel and the core webs are made of 5 gauge (0.2092”) steel.



(a) Calculated impact response



(b) Calculated impact response

Figure 2. Calculated side impact response and penetration for a 4-inch egg crate EMS system.

The intermediate stage of deformation for the egg-crate EMS is shown in Figure 3. At this point in the response the outer face sheet has already been punctured and the core under the penetrator face is being crushed. These sandwich structures are very efficient for developing stiffness and strength for distributed loading conditions or under uniform crushing. However, the high stiffness of the system subjected to the localized punch load results in a penetration at relatively low levels of displacement. Thus, under these localized loading conditions the EMS structure absorbs very little impact energy for the total amount of weight required for the protective sandwich structure.

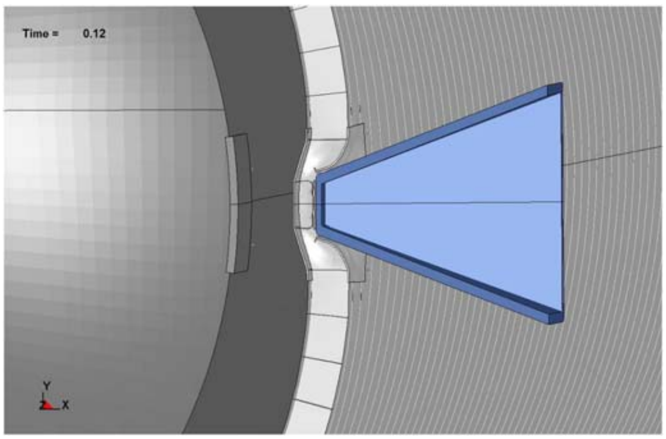


Figure 3. Calculated intermediate impact damage for a 4-inch egg crate EMS system.

A variety of different approaches were evaluated to improve the puncture protection capabilities of the foam and EMS systems. The performance of advanced protective systems was typically improved when the thickness of the outer layer was increased to resist puncture and the stiffness of the supporting structure was reduced to increase the displacements of the system before the puncture level was exceeded. These effects are seen by considering the three protections concepts shown in Figure 4. The concepts include two different corrugated EMS designs and a single monolithic plate, all of which have approximately equivalent weight. The different corrugated EMS designs illustrate the approach of moving weight from the inner face sheet and core structure to lower the system stiffness and increasing the outer face sheet thickness to improve the penetration resistance. The maximum extrapolation of this concept is to move all of the EMS weight into a single thicker outer jacket.

The calculated puncture behavior of the three protection options are compared in Figure 5. The ram punctures the baseline 6-inch corrugated EMS structure at a load of approximately 200,000 lbs and a ram displacement of approximately 6 inches. Thus, the energy dissipation of this EMS structure is quite small. The ram punctures the modified 3-inch corrugated EMS structure at a load of approximately 600,000 lbs and a ram displacement of approximately 12 inches. Thus, the energy dissipation of this EMS structure is approximately 5 times that of the original 6-inch EMS concept. Alternatively, the 0.5625-inch-thick jacket is not penetrated until a force of approximately 1.1 million lbs and an impactor displacement of approximately 30 inches. Thus, the jacket absorbs significantly more impact energy than either of the corrugated EMS structures for the 6-inch impactor.

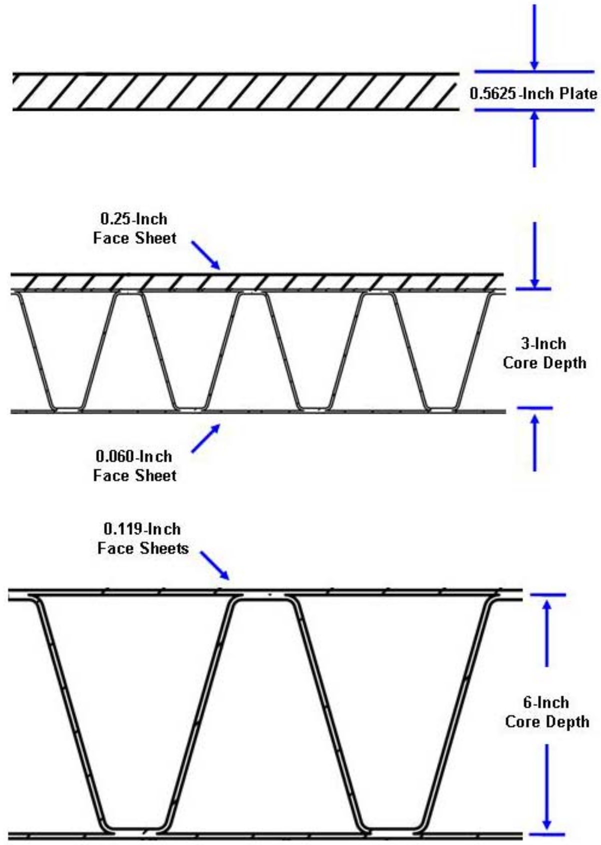


Figure 4. Alternative EMS tank protection concepts.

The calculated forces to puncture the outer layer of the foam and EMS systems are added to the plot of the puncture force versus system thickness in Figure 6. The difference in the data for the advanced systems is that the thickness used is the layer thickness only (e.g. outer head shield or outer face sheet thickness) rather than the sum of the total tank and jacket layer thicknesses. The comparison shows that the foam and EMS structures had the effect of making each layer act independently rather than coming in contact and working together to resist the high shear stresses around the edge of the impactor. With this effect the impactor is able to puncture each layer of the system sequentially without fully engaging the other layers in the system. As a result, the maximum achievable puncture forces were reduced and the systems that were analyzed did not reach the desired puncture energies.

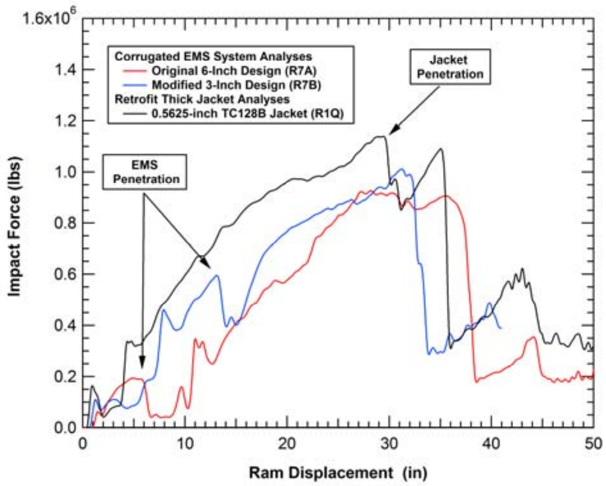


Figure 5. Comparison of the force-deflection behaviors for the Corrugated EMS concepts.

Although the systems with a monolithic jacket performed better than the corrugated EMS structures in this example, the conclusion can not be generalized to all EMS designs and impact scenarios. The EMS structures would be expected to perform significantly better under a more distributed loading. Other benefits of the EMS concepts are that the structural stiffness can be used to efficiently carry the train service loads in a "tank within a tank" design. Further analysis of other EMS concepts (e.g. core geometries, materials) and more general impact conditions would be required to obtain an optimized design.

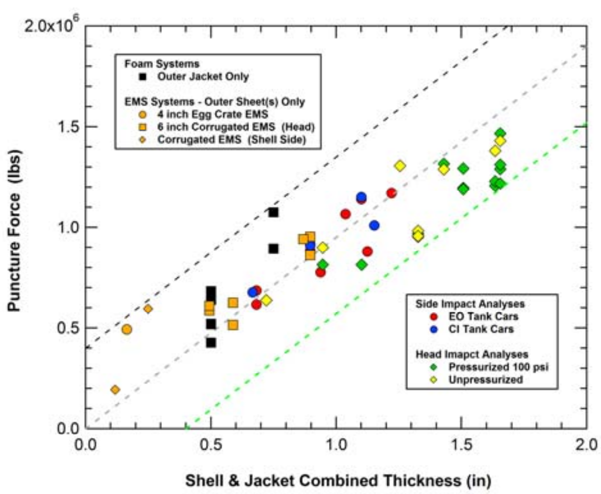


Figure 6. EMS puncture forces as a function of outer layer thickness.

A similar set of observations was obtained from the analysis of layered foam systems. In general, the systems analyzed did not outperform a single monolithic plate of equivalent protection system weight for the 6x6 inch impactor. However, the performance for larger impactors and the optimum foam and interface properties to maximize performance were not fully explored. In addition, low density foams can contribute to improved thermal insulation. If a foam system can maintain a lower average shipping temperature (and thus a lower average tank pressure), the overall tank puncture energy could potentially be increased.

Composite Material Protection Systems

The above analyses indicate that a tank protection system developed using only traditional tank car designs will have difficulty reaching the five to ten times protection goal of the NGRTC program. To achieve a five times increase in the puncture energy of tank cars while maintaining a comparable level of utility will require new design approaches and advanced materials. The candidate materials for advanced protection concepts include polymeric composite materials.

Tank car concepts with composite protection systems were not evaluated as thoroughly as the layered foam and EMS concepts and no testing of composite systems was performed in the NGRTC program. However, some preliminary evaluations were performed to assess the potential of composites for puncture resistance.

A brief literature search was performed to identify candidate composite systems that can be used for tank car impact protection and data that can be used to assess the potential protection levels. One of the promising material systems is an S-2 glass fiber composite for which a range of punch tests had been previously performed and reported in open literature sources [10-15]. This material has been used in applications requiring penetration resistance and the published information included results from various punch test configurations. In addition, a detailed composite damage model for this material system had been developed and implemented in LS-DYNA [16, 17]. Published material parameters were available and the model had been validated against the punch test results.

A summary of the normalized peak punch test loads for the S-2 Glass composite system and various candidate tank car steels are plotted against aerial density is shown in Figure 7. The normalized punch loads are the shear stress around the punch perimeter scaled by the material density since many tank car designs are operationally constrained by the amount of additional weight that can be added to the protection system. As a result, the punch shear resistance is compared on an equivalent weight basis rather than an equivalent thickness basis. The data in the figure were taken from the punch tests performed on steels in the NGRTC program [18-20] and composite punch tests reported in open literature sources for a woven S-2 glass fiber SC-15 polymeric matrix composite system.

The comparisons in Figure 7 are not perfect due to some differences in the punch test protocols between steels and composites. For example, the punch used in the composite tests had a sharp edge around the face and the NGRTC punch had a radius applied around the perimeter of the punch face. However, the comparison indicates that there is potential for puncture resistance improvements using composite materials. At the largest aerial density testing for the composite, a direct comparison can be made with 11 gauge A1011 steel and the HSLA 90XF. The composite out performs A1011 by approximately 70% and HSLA 90x by roughly 10%. Further improvements in the performance of the composite system could likely be obtained by optimizing the composite material and/or layup for these types of impact conditions.

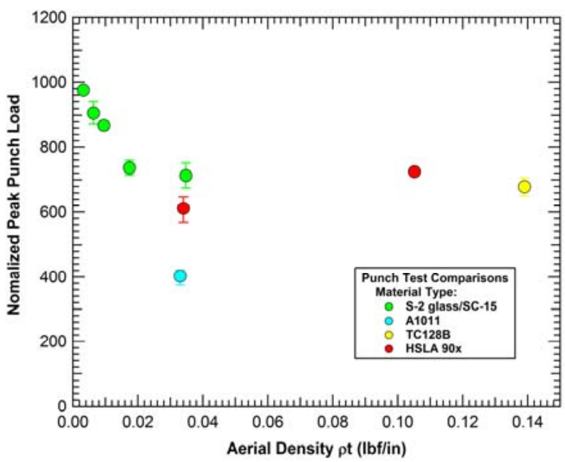


Figure 7. Normalized peak punch test loads versus aerial density for various materials.

Some preliminary tank car impact analyses were performed with LS-DYNA to assess the potential puncture protection of the composite material. The first step in this process was to validate the implementation of the composite damage model in the current version of LS-DYNA being used for the puncture analyses. Models of the punch tests were developed to validate the *MAT_COMPOSITE_MSC_DMG material model in LS-DYNA. Our approach was to model the same experiments performed by Xiao et al [12] and confirm the agreement between simulations and experiments reported. The LS-DYNA models of the punch simulations were developed based on descriptions provided by Xiao et al in Reference 12.

When the simulations of the punch test were repeated in this study, the agreement of the model with the punch tests was not obtained. An example of the performance is shown in Figure 8. The agreement is good in the initial loading of the specimen and the onset of damage. However, in all of the cases analyzed, the model predicts a premature failure and the full puncture force and punch displacement prior to failure was not achieved.

A likely reason for the lack of agreement between simulations and tests was the functionality of the material model in different versions of LS-DYNA. Significant effort was expended in working with LSTC and MSC to have a version of LS-DYNA functioning correctly with material 162. Material 162 is formally supported by MSC, but LSTC provides versions of LS-DYNA with this material model. A request was made to MSC for LS-DYNA models that could be used to validate that the material model was functioning correctly in the versions of LS-DYNA built for ARA. MSC provided single element models to proof various functions of the model. However, these single element tests do not provide a comprehensive way of assessing the models functionality as there is damage growth that occurs based on the state of surrounding elements. Several requests were made to MSC for additional models to test the functionality of material 162. Unfortunately, none were provided that could be validated against other results.

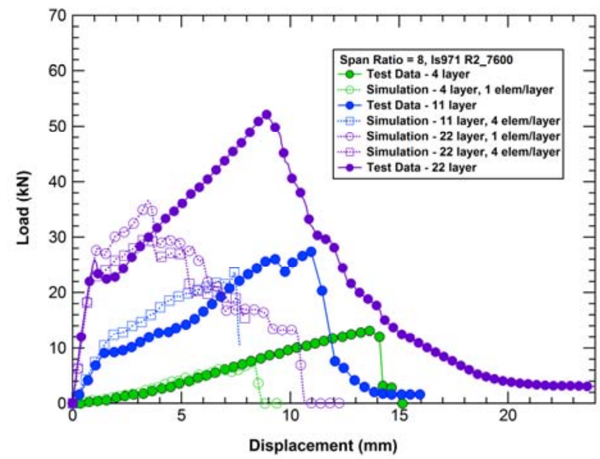


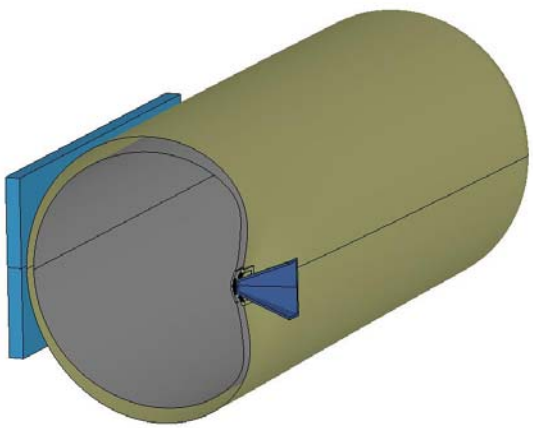
Figure 8. Comparison of punch test data and simulations.

Given these limitations in the composite damage model, it was still desirable to perform an analysis of a composite tank car system. A model was developed to assess the puncture resistance of the 500 lb chlorine tank car with a composite jacket retrofit. A 1.5-inch thick composite jacket was placed around the commodity tank. A composite with this thickness has approximately the same weight as a steel jacket with a thickness of 0.355 inches (that the same tank car retrofit with a 0.375-inch steel jacket was previously analyzed in the NGRTC Program [5]). A (0/90) layup with principal material directions coincident with the hoop and axial tank directions and equal numbers of 0 degree and 90 degree layers was used. The model for the commodity tank is the same as discussed in the previous analyses.

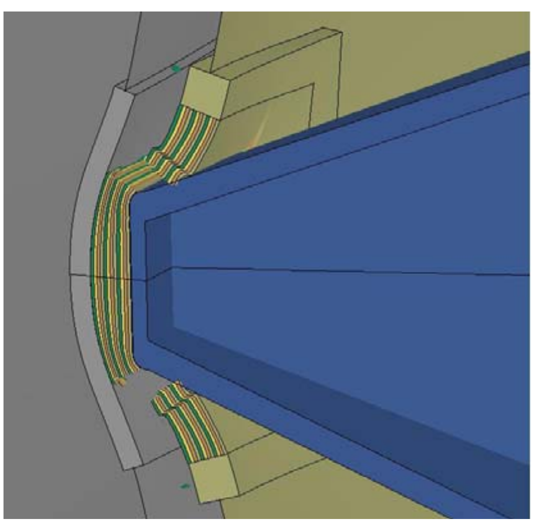
The model developed for the composite jacket is similar to the approach used for steel materials. Inside the impact zone, a very fine mesh of solid elements was used where the detailed damage and failure behavior can be assessed. Outside the impact zone, the jacket was modeled with shell elements. These were connected to solid elements in the impact zone, much like the approach used for modeling the commodity tank.

To reduce the model size, this region was modeled with 12 thick plies of the composite fabric. In reality, a composite this thick would require approximately 64 plies of fabric where delamination could occur between each layer. To model each ply, a minimum of 64 elements would be needed through the thickness. Instead, the composite was modeled with 12 layers with 3 elements through the thickness of each ply, resulting in 36 elements through the thickness. Elements therefore have a characteristic length of about .042 inches (1 mm). Delamination can still occur in the model, but only between each of the 12 layers.

Preliminary analyses with the composite jacket and tank model are shown in Figure 9. The time shown corresponds to a ram displacement of 18 inches and the current impact load is in excess of 500,000 lbs. The composite jacket has significant damage and has failed around much of the perimeter of the contact patch. Based on the observed level of damage, it is not expected that the calculation would predict puncture forces that are significantly greater than that of an equivalent weight steel jacket. However, the composite model is also expected to under predict the composite strength in this analysis.



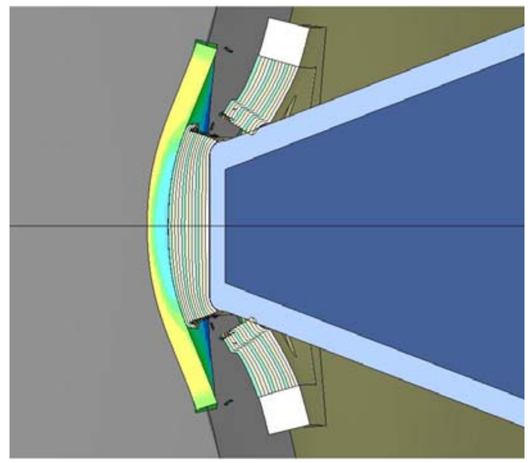
(a) Calculated impact response



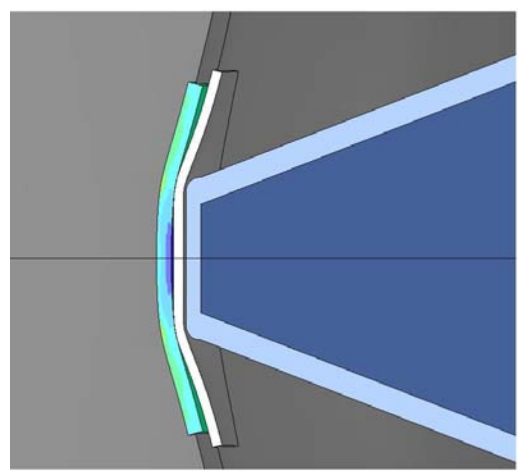
(b) Detail of the puncture behavior

Figure 9. Punch-shear mode in composite jacket at 18 inches of displacement.

One effect seen in the analyses is the potential for the composite to provide a blunting of the impact loads on the commodity tank. A comparison of the impact behavior of a 1.5-inch thick composite jacket with an equivalent weight steel jacket is shown in Figure 10. The comparison clearly shows a blunting of the loads on the commodity tank for the same level of impact displacement and this effect has potential for delaying the development of damage and penetration of the tank. The magnitude of this blunting effect would be expected to increase as the thickness of the composite jacket becomes greater.



(a) 1.5 inch composite jacket



(b) 0.375 inch A1011 steel jacket

Figure 10. Composite jacket blunting effect for a tank side impact.

Impact Performance Summary

A summary of the current state of tank car side impact performance is provided in Figure 11. From the full scale side impact Test 2, the 105J500W tank car puncture energy was slightly less than one million ft-lbs. This corresponds to a 10 mph impact with a 286,000 lb ram car and the 6x6 inch impactor. From analyses, the puncture energies of the 105J300W and 105J600W tank cars are approximately 30 percent less and 40 percent greater than the 105J500W tank car, respectively.

The goal of the Next Generation Railroad Tank Car Project was to increase the puncture energy of the tank car by five to ten times over the baseline 105J500W tank car design. This target is outlined by the red box in Figure 11. The proposed toxic inhalation hazard (TIH) tank car standard [21] fell within this range (25 mph impact), requiring a puncture energy that is 6 times that of the baseline tank car. However, the levels that were found to be achievable with the first generation concepts in the NGRTC project are more consistent with two to three times the puncture energy of the baseline design.

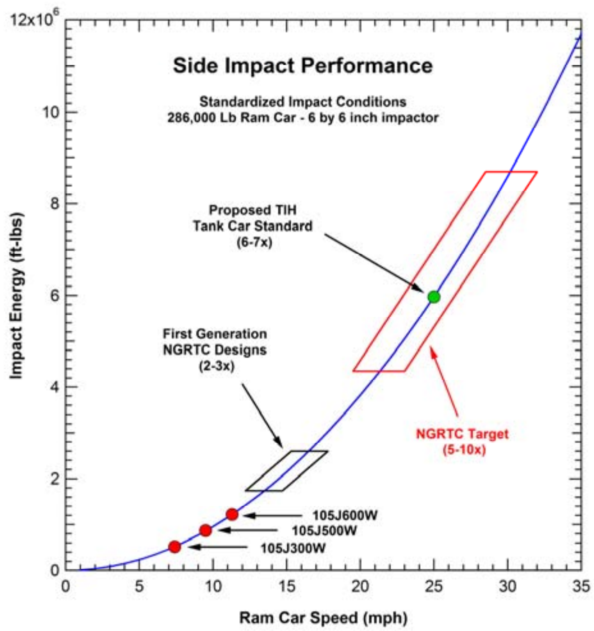


Figure 11. Summary of side impact puncture performance and goals.

A similar summary of the current state of tank car head impact performance is provided in Figure 12. The calculated puncture energy for a pressurized (100 psi) 105J500W tank head with an 11-gauge head jacket is 610,000 ft-lbs [4, 5]. This corresponds to an 8 mph impact with the 286,000 lb ram car and the 6x6 inch impactor. For comparison, the puncture energy of a 105J600W tank head with a 0.50 inch full height head shield is 1.1 million ft-lbs.

The goal of the Next Generation Railroad Tank Car Project was to increase the puncture energy of the tank car by five to ten times over the baseline 105J500W tank head as outlined by the red box in Figure 12. The proposed TIH tank car standard is above this range, requiring a puncture energy that is approximately 14 times that of the baseline tank head (30 mph impact). However, the levels that were found to be achievable with the first generation concepts in the NGRTC project are more consistent with 2.5 to 4 times the puncture energy of the baseline design.

ACKNOWLEDGMENTS

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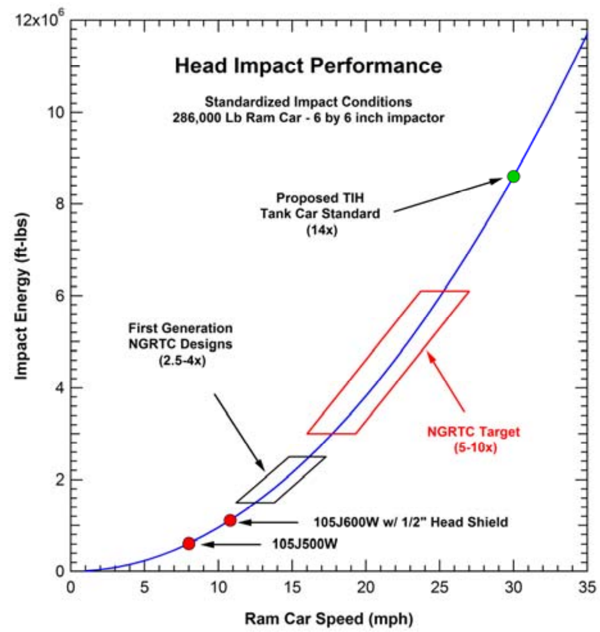

Figure 12. Summary of head impact puncture performance and goals.

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