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BLAST AND BALLISTIC SURVIVABILITY ANALYSIS TOOLS FOR DESIGN OPTIMIZATION DEVELOPED IN DARPA'S ADAPTIVE VEHICLE MAKE (AVM)

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ABSTRACT

As part of DARPA's Adaptive Vehicle Make (AVM) portfolio of programs, blast and ballistic survivability analysis tools were developed. The intent of these tools was to facilitate design and design optimization by making it possible for designers to perform survivability analysis from CAD and to automate the survivability analysis pipeline to allow optimization codes to invoke the survivability tools and obtain results. This paper describes some of the tools and their capabilities through highlighting five innovations utilized in the program: multi-fidelity modeling; automated meshing and welding; uncertainty quantification and 95% bounds; a large material property database and more accurate blast loads; and automating the entire computational pipeline.

INTRODUCTION

The Defense Advanced Research Projects Agency (DARPA) launched the Adaptive Vehicle Make (AVM) portfolio of programs with the ambitious goal of reducing the time from concept to rolling vehicle by a factor of five. By changing the design paradigm and achieving "correct by construction," the first vehicle rolling off an assembly line would be fully functional, and thus time fixing, redesigning, and related requirements creep would not occur. As a specific way of speeding up the design process, DARPA wanted survivability analysis integrated in such a way that the designer or automated optimization software could carry out survivability studies. This paper outlines how the Southwest Research Institute (SwRI) team delivered analysis tools for AVM that allowed designers to do just that: perform survivability analysis from CAD in an automated fashion.

The SwRI team provided survivability analysis tools, in this case for ballistic, blast, and corrosion protection. The development of these tools was a large effort. DARPA referred to this program as the Component, Context, and Manufacturing Model Library (C2M2L-2) [1]. We produced significant advances in software tools for survivability analysis. To exercise the software, DARPA held test and design exercises and competitions, with participants from industry, government laboratories (including TARDEC), and academia. The survivability software development for AVM is now complete (it ended at the end of 2014), and the software that was developed can be obtained from DARPA.

The automated, designer-invoked survivability tools are best presented by highlighting five major innovations that were incorporated in their development:

- Innovation #1: Multi-fidelity Analysis/Varying Levels of Refinement
- Innovation #2: Automated Meshing and Connecting of Parts for Complex Vehicle Structure
- Innovation #3: Uncertainty Quantification and Development of 95% Bounding Models
- Innovation #4: Sophisticated Large Deformation/Material Failure Material Model Library and Better Blast Loads
- Innovation #5: Connecting the Whole Pipeline Together so It Executes Automatically

A major goal of ours was to make the survivability analysis tools easy for the designer to use. For example, for ballistics we developed the Shotline Viewer to allow the designer to explore the effects of ballistics impacts and the results of the terminal ballistics analysis models (Fig. 1). For blast analysis, our software pipeline produced movies of the blast event showing the ensuing structural deformation. These capabilities allowed the designer, likely a person with limited background in survivability, to quickly understand the results of these threat environments on their design. In addition, by automating the tools, it was possible for a higher level of automated optimization software to exercise the tools and return numerical scores for use in design optimization studies.

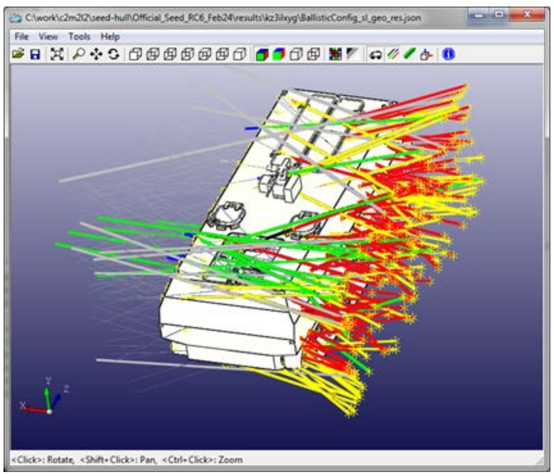

Figure 1: Screen image from the Shotline Viewer showing color-coded shot lines through the vehicle.

Another major goal of the tool development was to remain CAD agnostic as far as possible. The ballistics and blast tools that we developed used STEP files. Though the overarching META AVM software suite used CREO for assembly, our survivability tools can be easily interfaced with other CAD tools.

We now discuss the highlighted innovations.

INNOVATION #1: MULTI-FIDELITY ANALYSIS/VARYING LEVELS OF REFINEMENT

A major innovation that SwRI included in AVM was a multi-fidelity modeling approach, employing different tier levels of analysis. Each of the models had different levels of accuracy and uncertainty in exchange for different amounts of computational time. The approach allowed the rapid exploration of the design space by using fast-running, lower tier models that sped up the conceptual design phase. In addition, by developing the different tiers of models, lower-tier simpler models were quickly completed and thus in the software development process working survivability analysis models were always available. This was extremely beneficial in the concurrent development of other pieces of software by other contractors in AVM and the definition of software interfaces.

Figure 2 shows an overview of the notion of increasing fidelity of the model vs. computational time. It should be noted that the physics models were of differing fidelity. In all cases the complete geometry being passed to the survivability pipeline was used – i.e., there was no need to produce lower fidelity geometry models to use any of the tiers of survivability solvers. Further, the various tiers of solvers could be used at a conceptual level, where only a concept hull with plate thicknesses and additional mass was specified. This allows a rapid initial design space exploration to determine the amount of armor and structure required to survive a specified threat, and then as the design proceeds to more detailed design the survivability analysis can be redone many times to allow the designer to make adjustments, such as at welds and joins, to ensure designated levels of protection are achieved. By performing survivability analysis at the conceptual level, it is feasible to automate the design-space exploration.

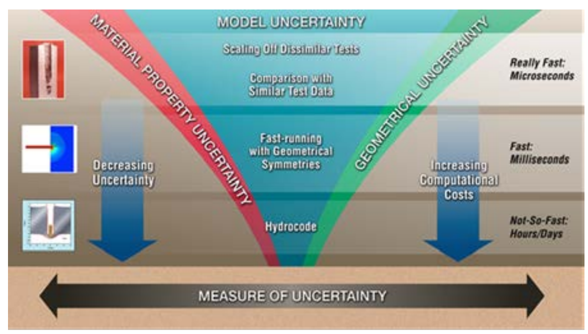

Figure 2: Multi-fidelity modeling (tiers of models) vs. analysis time and uncertainty – both the blast and ballistics survivability tools had low tier models that ran extremely fast, and high-tier models that had very high fidelity.

Specifically, the ballistics multi-fidelity model tiers are

Tier 1: Empirical data fits extended through dissimilar material modeling approaches,

Tiers 2: Fast-running physics-based analysis models [2],

Tier 3: Full-scale finite-volume hydrocode computations (using CTH).

The blast solver multi-fidelity model tiers are

Tier 1: Nondeforming vehicle (Fig. 3),
Tier 2: Predefined-connections-only finite element solver on a PC (Fig. 3),
Tier 3: Contact surfaces finite element solver (using LS-DYNA)
Tier 4: Higher resolution of Tier 3 (again, using LS-DYNA)
Tier 5: Tier 4 but also including pre-meshed blast seats and anthropomorphic test devices (ATDs) (using LS-DYNA).

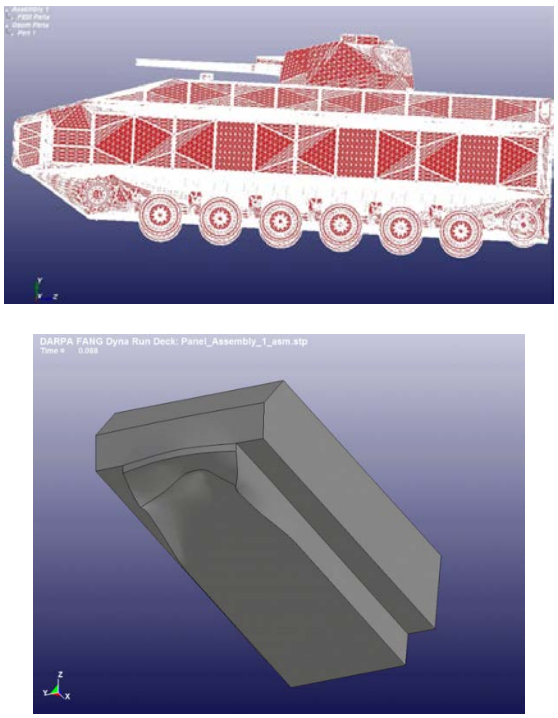

Figure 3: Motion from a Tier 1 blast under a front tread of a detailed design (upper) and a Tier 2/3 blast near the front of the conceptual hull (lower). The analysis of the first takes seconds and of the second is on the order of an hour.

INNOVATION #2: AUTOMATED MESHING AND CONNECTING OF PARTS FOR COMPLEX VEHICLE STRUCTURE

One of the most tedious and time consuming steps in survivability analysis is transforming the CAD geometry to a format that is amenable to the analysis tools. To make the survivability tools useful to the designer and to head towards the goal of "press one button in CAD to get your analysis," tools were developed to automatically mesh and then connect parts for the blast analysis. Tools were developed for the automatic meshing of the various structural parts with a focus on producing quad shell meshes, the types of meshes that have been shown to give the most accurate results in structural blast computations. Structural parts include plates, panels, skins, and various-cross-section beams such as I-beam, C sections, and brackets. The various parts are then automatically assembled to produce the vehicle. Many different types of parts with various meshing schemes can be assembled this way. The emphasis was on robustness in automatically producing a good mesh for blast loading. Figure 4 shows the development of a mesh for an armored ground vehicle; upon transfer of the STEP files and assembly files the development of this mesh took 4 to 5 minutes on a PC [3].

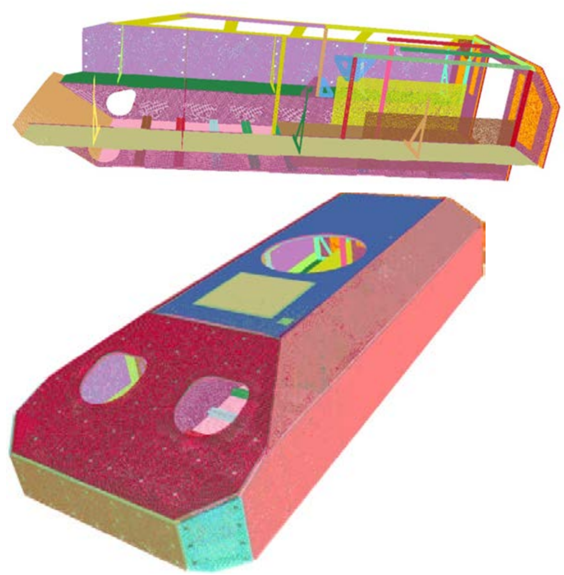

Figure 4: Images during the automatic production of a mesh for a ground vehicle; the meshing of this vehicle including interior structural members took 4 to 5 minutes on a PC.

An important part of the assembly of a mesh is the connections. A bolter/welder tool was developed, which includes the ability to operate the tool both when connections are specified and in an automatic mode when they are not. This automatic welding feature is incredibly powerful, and combined with the automatic generation of meshes, greatly reduces the amount of time to perform analysis. To highlight features of the bolter/welder tool, Figure 5 shows examples of automatic weld insertion. Welds are automatically inserted when free edges are near other components. As to bolts, bolts are automatically inserted when holes are found aligned and a bolt for the region has been specified. In particular, the tool will bolt multiple plates together (three or more) if the bolt holes line up.

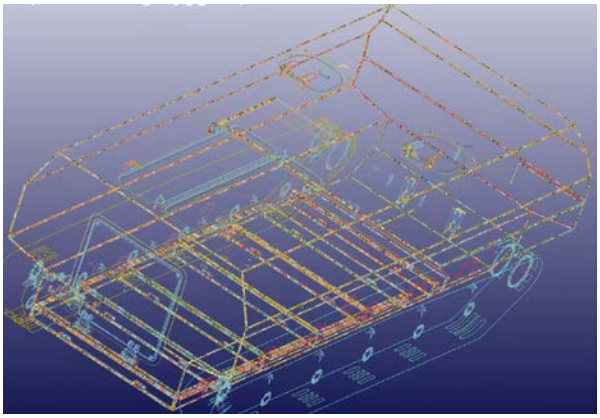

Figure 5: Image of automatically produced welds for a vehicle mesh.

An important part of our weld-connection mesh-production capability is the inclusion of a heat affected zone (HAZ). Not including the HAZ leads to unrealistic strength near joints. The automeshing tool, after connections are complete, passes through the mesh and produces a HAZ near all welds. The material strength and damage properties are adjusted in the HAZ. Figures 6 and 7 show images of an automatically meshed conceptual vehicle hull and then computations without and with the HAZ. It is seen there is considerably more damage when the HAZ is included. It is important to include the HAZ in a mesh when performing blast computations, and our tools do it automatically. During the connections step, a corrosion analysis is performed

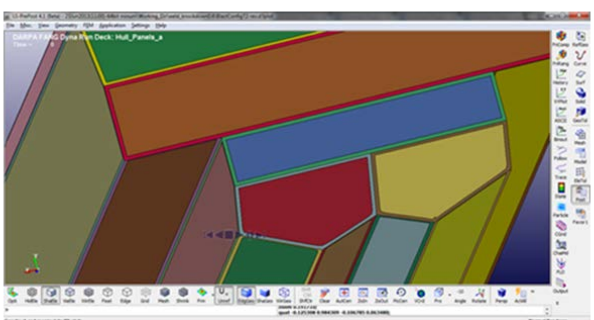

Figure 6: Images of a meshed conceptual hull showing the automatically produced heat affected zones (HAZs) surrounding all the automatically produced welds.

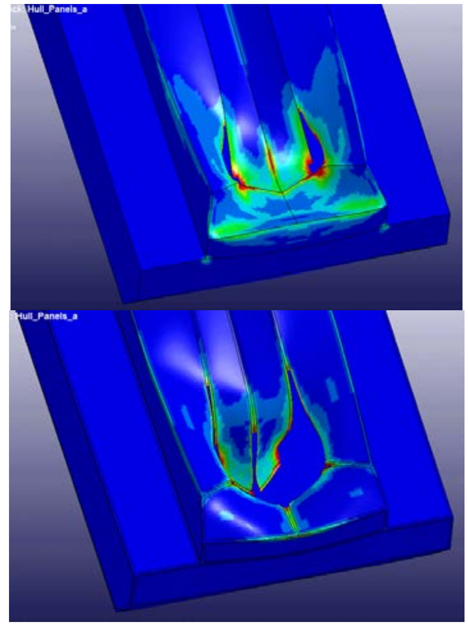

Figure 7: Images of a blast computation on a conceptual hull without an HAZ (above) and with an HAZ (below), showing the importance of including the HAZ. The HAZs and the welds in these examples were automatically produced by the tools developed for this program.

INNOVATION #3: UNCERTAINTY QUANTIFICATION AND BOUNDING MODELS

Given the complexity of the computations and the multi-fidelity nature of the tools, uncertainty quantification and the development of bounding models were performed. In particular, both the ballistic and the blast models return 95% bounding results. The approach utilized off-line computations to develop an understanding of the domain for the models, thus allowing development of the bounding models. The bounding model is based on historical knowledge of variations in inputs into the models, for example, a standard deviation is assigned to the armor plate strength and a standard deviation is assigned to the armor plate thickness. Using these statistical variations, many off-line executions of the physics-based survivability models were run a priori for certain situations to allow the development of inputs to these same models that would return the 95% bounding results. As examples, Fig. 8 shows the results and 95% bounds returned by the Walker-Anderson penetration model [4], which is the principle Tier 2 ballistic model. For this case of a tungsten projectile striking a steel armor panel, the residual velocity and its 95% bounds were computed with many computations. Then, the most probable point (MPP is a technical term) was found.

Comparing the most probable point domain values to the initial input nominal domain values to the model led to a procedure to adjust the nominal inputs to the model to produce a set of inputs to the model that produces the 95% bound. These adjustments were generalized into an algorithm: in all cases a second set of inputs to the model was produced from the nominal values, and a second execution of the model produced the 95% bounding result. Figure 9 (upper) shows the computation of the nominal model compared with data, as well as the extensive suite of computations performed to develop the 95% bounding model (dashed line) compared to points returned by a second iteration of the model using the most probable point (MPP) adjustment (open circles). This graph shows the developed approach to quickly finding the bounding result works. Figure 9 (lower) shows related results for our blast models, where the spinal injury metric Dynamic Response Index DRIz has been used and a seat model with shock mitigating mechanisms to reduce the injury is used. More details on the uncertainty modeling are in Ref. [5].

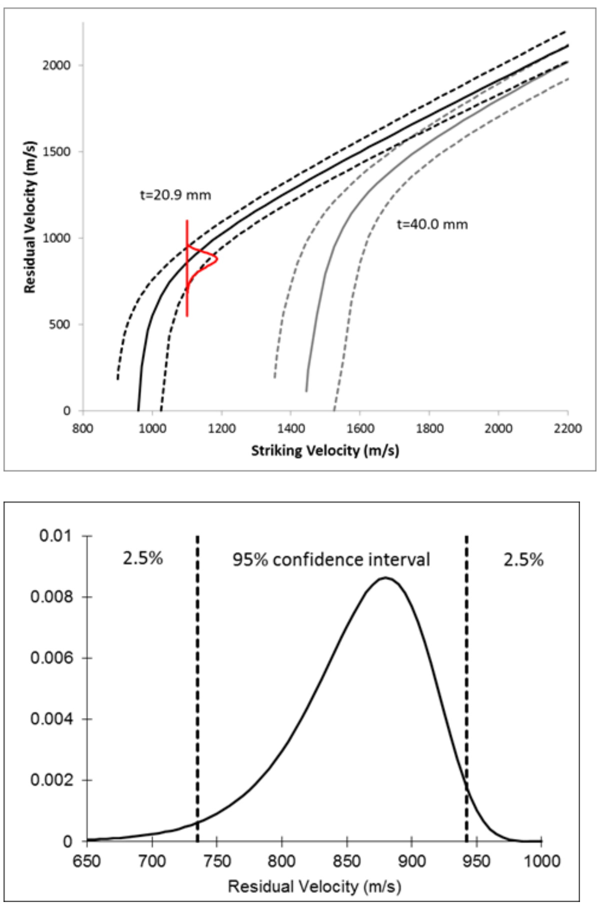

Figure 8: Computation of 95% bounds for the residual velocity from the Walker-Anderson model based on historical known variations in inputs to material properties and geometry.

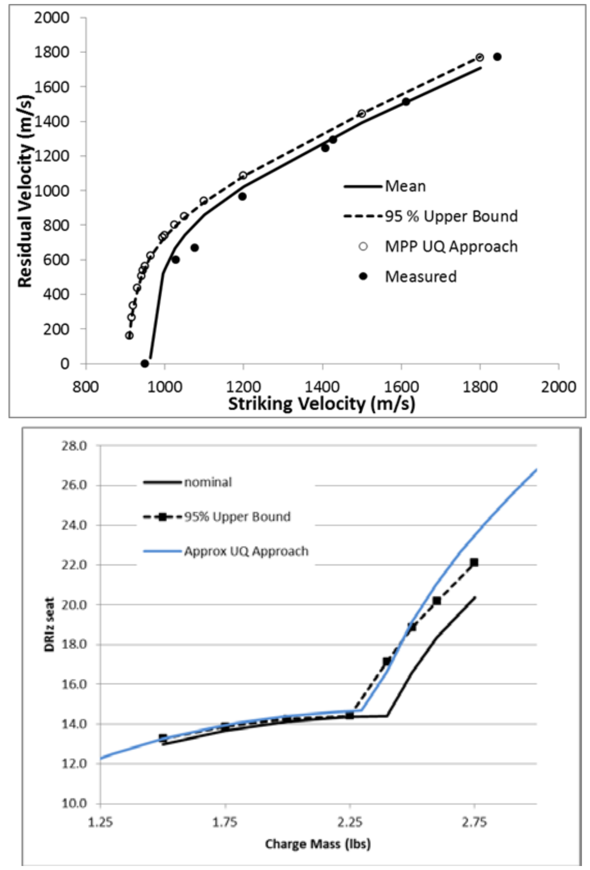

Figure 9: Computations with the Walker-Anderson model (upper, solid line) showing comparison to test data and then a second set of computations using adjusted input values (broken line) to produce a 95% bounding model; similar bounding results for spinal injury during blast (lower).

INNOVATION #4: SOPHISTICATED LARGE DEFORMATION AND MATERIAL FAILURE MODEL LIBRARY AND BETTER BLAST LOADS

Survivability systems are used once, and the materials are used all the way through failure. Hence, it is necessary to know the large deformation and failure properties of the materials. As part of this program, a database of survivability materials was compiled with constitutive properties that described the large deformation plastic deformation and flow as well as the damage and failure properties. The database contained constants for the constitutive models of these materials; e.g., for metals the database primarily contained the Johnson-Cook flow-stress model constants and the Johnson-Cook damage model constants [6]. These coefficients were taken from published journal articles, conference proceedings, and government reports.

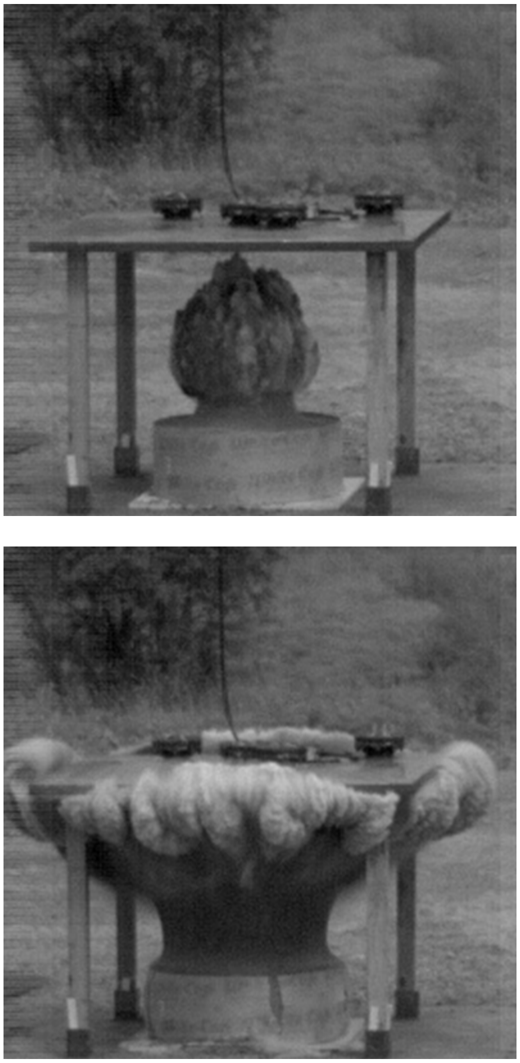

Figure 10: Stills from high speed video of an experiment to measure the loads produced by a buried charge.

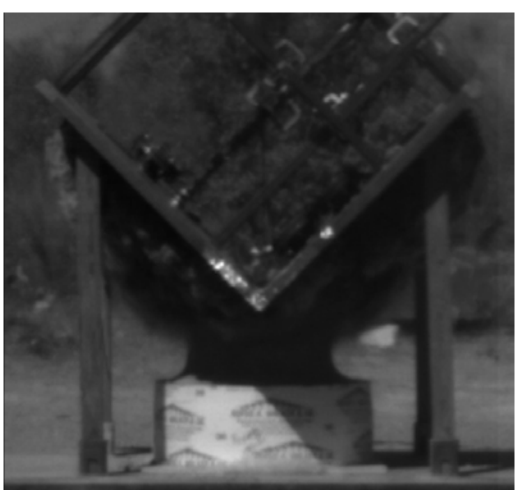

Figure 11: Blast experiments measuring loads on a V hull.

Another important fact for survivability is that blast loads for buried charges are still a research topic. Experiments were performed to further characterize the blast loads on simple structures. Figures 10 and 11 show frames from high speed video of buried charges loading a simple plate and V hull for impulse estimation. New formulations of blast loading were developed to apply loads to the structures [7].

Tests were also performed with structural members to test out the loads and to validate the computational pipeline. Structural members were held in the Land Mine Test Fixture at the SwRI Range and blast loaded with buried charges. These same structures were blast loaded using the computational pipeline. Through this work, as well as extensive use of historical data, the blast survivability tools are validated and showing good results.

INNOVATION #5: CONNECTING THE WHOLE COMPUTATIONAL PIPELINE TOGETHER SO IT EXECUTES AUTOMATICALLY

Historically, performing all the steps in survivability analysis has been quite tedious, manual, and time consuming. There was a concerted effort to automate the whole process, and this effort paid off in greatly reducing the amount of time required to perform an analysis. One of the design exercise teams said that use of the survivability software allowed them to perform detailed conceptual design iterations in 30 minutes per iteration, something that previously may have taken on the order of two weeks per iteration. There was an extensive verification and validation exercise performed on all the models to confirm their implementation and to confirm the implementation of the pipelines.

Figure 12 shows an image of an infantry fighting vehicle analysis performed by the pipeline. All the steps in the process were automated and required no designer involvement except for requesting the blast analysis be performed. From CAD, the vehicle was meshed with mostly quad shell elements. Then it was welded and connected. The HAZ was inserted around all welds. Blast loads were then computed and applied to the vehicle. The resulting deformation was computed with LS-DYNA using material properties from the large strain/material failure model database. A movie was produced and returned to the designer to convey the effect of the blast on the vehicle. In addition, DRIz values were computed to assess potential spinal injury to the occupants, and bounding DRIz results were also returned. These quantitative measures can be compared to requirements as well as used in design optimization studies.

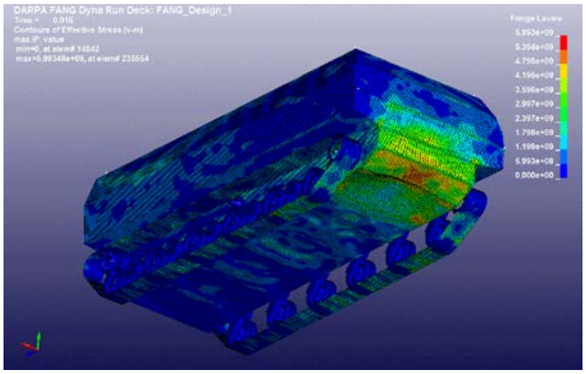

Figure 12: Blast loading by a buried explosive of a tracked infantry fighting vehicle, where the analysis and frame from a movie were automatically produced using the new software tools.

CONCLUSION

The survivability tools are an important and successful part of the DARPA AVM portfolio of programs. They perform as designed, fully automating complex steps that typically take man-weeks to perform in total, and also providing estimates and bounds on the goodness of the answers. The automation of steps required in ballistic and blast survivability analysis including meshing and connecting the geometry and providing uncertainty quantification (UQ) analysis was successfully demonstrated in the DARPA-run design exercises and is a great capability for blast and impact resistant vehicle design. In the design exercises, design teams that included commercial engineering design and manufacturing firms that produce defense systems, confirmed that the survivability tools allowed speedups in design time and reductions in analysis time. Thus, the objective of providing survivability tools that the designer could use to assist in the design process was realized.

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