FUNCTION-ORIENTED MATERIAL DESIGN FOR INNOVATIVE COMPOSITE STRUCTURES AGAINST LAND EXPLOSIVES

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ABASTRACT

The objective of this research is to develop an advanced design methodology for innovative composite structure concepts which can be used in the Army's future ground vehicle systems (FCS, FTTS, LTV) to protect vehicle and occupants against various explosives, including landmines. A multi-level and multi-scenario blast simulation and design system is being developed, which integrates three major technologies: a newly developed landmine-soil-composite interaction model; an advanced design methodology called Function-Oriented Material Design (FOMD); and a novel patent-pending composite material concept called BTR (Biomimetic Tendon-Reinforced) material. A novel blast-protective composite structure (BTR-*Bl*) is being developed with the new design tool, which can be fabricated and tested against land explosives for use in military vehicles.

1. INTRODUCTION

Existent numerical models used for blast simulation can be roughly divided into two categories: the empirical model for blast pressure prediction, and the model based on the Lagrange/Euler method used for fluid and structure coupling problems. The design of composite structures for blast mitigation has been focused on two fields: structural shape design to deflect the blast energy, and composite material design for blast energy absorption. The fundamentals of blast simulation and composite structure design are briefed here.

1.1 Blast Prediction Model

For the empirical blast pressure model, the CONWEP air blast function was developed (Kingery and Bulmash 1984) for blast overpressure determination under certain conditions. The CONWEP blast functions can be used for two cases, the free air detonation of a spherical charge and the surface detonation of a hemispherical charge. While the surface detonation approaches the conditions of a mine blast, anti-vehicular mines are most commonly buried anywhere from 5 to 20 cm below the surface of the soil (sometimes more if a road is resurfaced for example). The depth of burial, among other things, has a significant effect on the energy directed on the target by funneling the force of the blast upwards. Other variables such as soil moisture content and soil type have equally important effects on the mine. But none of these effects are included in the CONWEP blast model. The CONWEP method is computationally less expensive than the coupled fluid/structure method at the cost of accuracy.

In a numerical model of a continuum, the material is discretized into finite sections, over which the conservation and constitutive equations are solved. The scheme of spatial discretization leads to different numerical methods. For blast impact simulation, the complexity of the problem lies in the following difficulties: the high speed wave front propagation, the flow of various materials, and the large structural deformation. To our knowledge, the most appropriate numerical method might be the Arbitrary Lagrangian-Eulerian (ALE) method. The ALE solver allows for a type of "automatic remapping" in simulation. The edge nodes of a finite section can be completely Lagrangian (the nodes move with the material motion), while the inner nodes can be remapped so that the mesh is more smooth than the one in the single Lagrangian method. The ALE solver is well suited for a variety of fluid-structure interaction problems. Multiple material ALE

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can be formulated in a fashion which allows material to flow from cell to cell.

The concept of ALE has been integrated into commercial code such as LS-DYNA and CTH. In the Army Research Laboratory, Kerley (2001) and Gupta (2001) have used the CTH to simulated the buried mine explosion on a receptor (steel plate) with the consideration of soil effect. The CTH code is tuned to minimize the dispersion present in conventional Eulerian methods. Since the mine blast is a hypervelocity impact, the initial momentum determination on receptors can be assumed independent of the elastic/plastic deformation of the composite/metal receptor (Hanssen *et al*. 2002 found that soft panel can amplify the blast result, though the amplification is small for rigid panels.).

One drawback for the CTH model in blast simulation is that the soil model must be assumed continuous to carry out the simulation. Some of the results reported in the Army reports by Kerley (2001) and Gupta (2001) show that the soil model is inhomogeneous, the CTH code is not appropriate for the numerical simulation. Furthermore, the CTH code is time consuming in simulation, which makes the statistical analysis of blast impact effect formidable due to various soil models.

1.2 Structure Design for Blast Wave Deflection

The blast energy is release within a very short period of time (the duration of blast can be less than 1.0 ms), making it hard for protection material to absorb majority of blast energy. In order to protect the crew members inside the vehicle and the integrity of the main structure, protection panels are inserted in military vehicles to deflect the blast wave (Pytleski and Catherine 1993). Numerical simulations have been carried out (Dillion *et al*. 1998) to determine the dynamic loads produced by the mine detonation on the cargo bed and other structural elements of the truck. A series of calculations are designed to simulate the corresponding field tests in which explosive charges of various sizes were detonated beneath instrumented vehicles. Using numerical analysis, a wedge/wing deflector structure was designed which is placed under the truck's cab.

The successfully developed crew/vehicle protection panel can increase crew survivability of tactical wheeled vehicles subject to mine blast. However, these protection kits are based on conventional steel/aluminum construction, and are close to 0.5 ton in weight. A sandwich structure has been proposed and tested for alternative design (Condon *et al*. 1995). Experiments have been carried out to test the composite panel under blast. It is found the panel cannot restrain the maximum deflection as the original alloy panel (Condon *et al*. 1995). Due to the deficiency in inter-laminar strength of the sandwich panel's faces and the subsequent consequence from dynamic blast loading, the dynamic deflection of the panel is not satisfactory compared to the past monolithic panel test results.

Due to the complexity of the progressive failure mode of composite panel, a new material model has been developed (Yen and Jones 1996) and integrated into the commercial FEM code, LS-DYNA. The guidelines for composite panel design for blast protection have been summarized (Yen and Jones 1996). These guidelines make a composite structure design difficult for successful mine blast protection.

1.3 Composite Material Design for Blast Energy Absorption

Aluminum foam is a lightweight material with excellent plastic energy absorbing capability. The characteristics of aluminum foam in close-range blast loading have been investigated (Hassen *et al*. 2002), including field tests and simple analytical simulations. The use of foam material as blast energy absorption has the following advantages: i) increase the captured energy to receptors; ii) reduce the force/stress transmitted to main structure; iii) achieve protection of main structure.

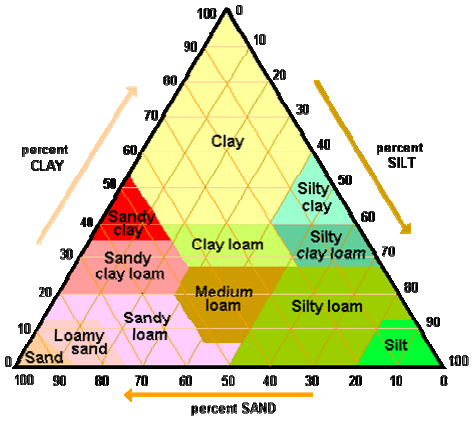
Fiber-reinforced composites can also be tailored towards high energy absorption (Jensen *et al*. 2006). Impact-damaged composite panels that are constructed using glass fibers that adhere poorly to the polymer matrix display large damage areas due to extensive fiber-matrix debonding, pullout, and delamination mechanism. The major difficulty in energy-absorption fiber-reinforce composite design is in obtaining reasonable structural properties as the tradition (well bonded) composite. Some achievements have been made (Jensen *et al*. 2006) through unique chemistry processes between the fiber-matrix interface. The achievement of excellent structural properties has been obtained with concurrent superior impact energy absorption characteristics. The study shows strong rate dependence before, during, and after fiber-matrix debonding; and the post-debonding frictional mechanism is found to absorb a great amount of energy.

Protecting buildings from explosives is a closely related topic of blast protection. Extensive research has been conducted in this field for advanced protective building structure designs. Innovative concepts developed for protecting the buildings can be learned from new structural concepts for protecting vehicle and crew. Crawford (2001) summarizes some interesting ideas developed in civil engineering for building protection, including i) a cable-reinforced window concept, where the glass fragmentation under a blast attack has been prevented by installing reinforcing cables in the window; ii) a bi-plate concept of a building structure, which can be used to make, for example, a roof, for better protection; iii) a multi-layered composite

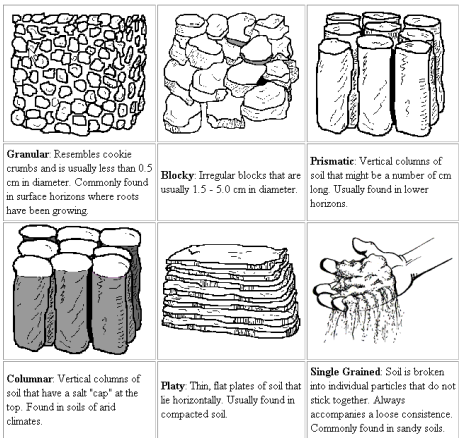
concept for a wall design against blast, which includes three different layers, from outside to inside: 1) bricks, 2) polyurethane foam core bonded to bricks with adhesive, and 3) metal or FRP (Fiber Reinforced Polymer) skin used to catch wall debris. These innovative ideas can be useful when considering a blast-protective composite structure design for vehicle systems.

2. DEVELOPMENT OF A NEW LANDMINE-SOIL-COMPOSITE INTERACTION MODEL

Prediction of blast load on the composite structure will be the first and critical step for designing an advanced blast-protective composite structure. Many blast models and computational methods have been developed in the past with a focus on predicting blast overpressure on the structure surface. Some prediction methods employ empirical models, and others employ hydro models. In hydro codes (*i.e.*, CTH code), the soil is modeled as various time-dependent elasto-(visco) plastic materials, in which details of soil behaviors are ignored and only average behavior is considered. However, the detailed texture and composition of soils may have significant influence on the simulation fidelity of the explosion process as well as on the damage prediction of the composite structure. As mentioned by Gupta (2001), soil models need to be improved, particularly to include the granularity and realistic soil fragmentation (see Fig. 1) as well as ejecta formation. At this stage, there is no efficient method that can predict both blast overpressure and the fragments that penetrate the composite structure, even though fragments may cause more serious damages to the vehicle structures and crew members. Accurate predictions for blast effects after the first interaction are critically important for designing a multi-layered composite structure. However, existing prediction methods usually become invalid when the blast wave passes through the first layer of the composite structure.



(a) Textural triangle



(b) Structures of soil

Figure 1. Textures and structures of soil: a) textural triangle, showing the percentages of clay (below 0.002mm), silt (0.002-0.05mm), and sand (0.05-2.0mm) in the basic soil textural classes, (US Department of Agriculture), b) structures of soil (Courtesy of NASA, Soil Science Education Home Page http://ltpwww.gsfc.nasa.gov/globe/pvg/prop1.htm)

2.1 New Blast Load Model

A unique numerical simulation model is developed to more accurately predict landmine-soil-composite interactions. In this model, the soil is discretized into small segments with detailed consideration of soil structure and texture (e.g., density, porosity, and failure criteria). As shown in the example in Fig. 2, a buried mine is represented by JWL equation of state. The top soil is then discretized using a statistical scheme that can represent soil structure and texture in a statistical way based on experimental data. The base soil is still assumed to be a continuum and is modeled as the conventional soil model (e.g., using Hugoniot curve). An air blast model is further developed to model the blast air, which interacts with the debris and contribute to the overall pressure/impact force on the composite structure. Using this discretization scheme, the inhomogeneous property of soil, and interactions between the blast wave and soil debris; the true loading condition of the composite structure can be accounted for in the blast load prediction.

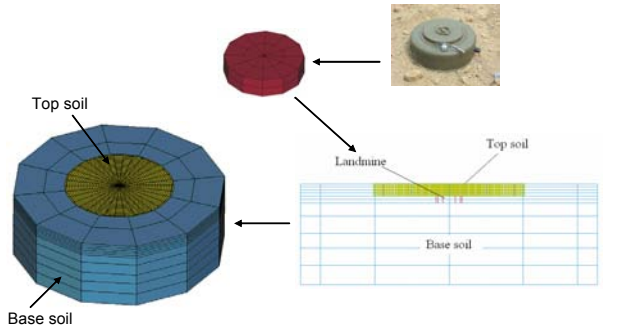
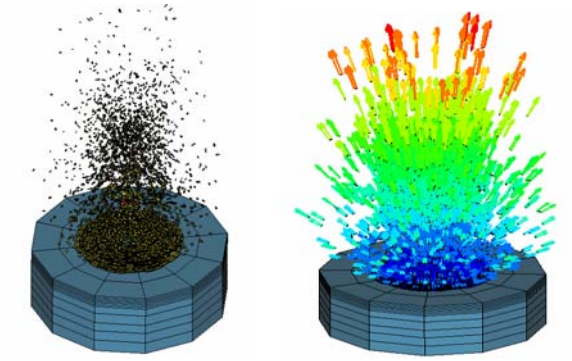


Figure 2. The simulation scheme for mine-soil problem

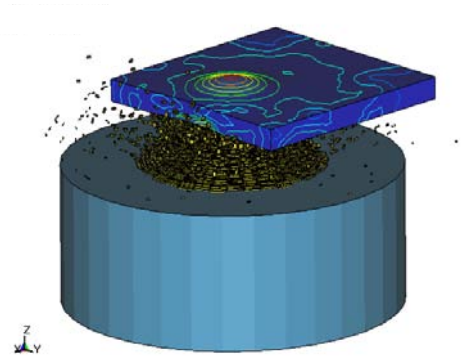
The example in Fig. 3 illustrates preliminary simulation results obtained using the proposed landmine-soil-composite interaction model. As shown in Fig. 3-a, a real soil blowup process under a landmine explosion can be simulated using the proposed simulation model, where velocity (and therefore momentum) of individual soil debris can also be predicted as shown in Fig. 3-b.



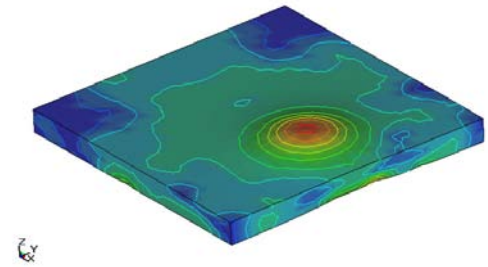
(a) Top soil explosion (b) Explosion velocity

Figure 3. Landmine-soil blast simulation using the proposed simulation model

Figure 4 illustrates the soil debris-structure interaction, when a steel plate is placed to capture the soil debris as well as the blast wave. It is seen that the whole landmine-soil-structure interaction process can be simulated with both effects of blast wave and soil debris. This simulation capability will be further benchmarked to compare with available experimental results and other valid simulation models.



(a) Soil debris-structure interaction

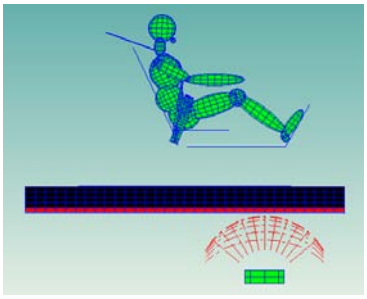


(b) Resultant stress inside the plate

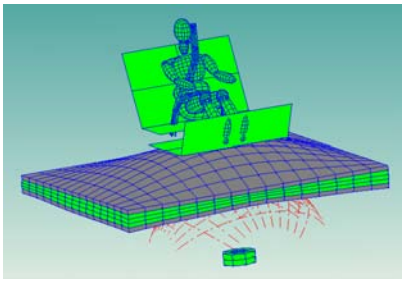
Figure 4. Landmine-soil-structure blast simulation using the proposed simulation model

2.2 Integrated Landmine-Soil-Composite Interaction Model

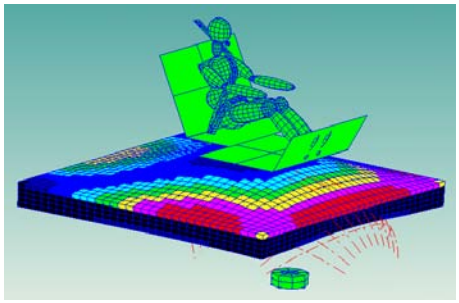
Figure 5 illustrates the capabilities that have been developed in our in-house blast software, FOMD-Blast, for pressure prediction due to the blast wave on a composite plate.



(a) plate configuration before blast wave reached



(b) plate deformation due to blast wave



(c) stress in the plate

Figure 5. Blast wave pressure modeling in FOMD-Blast *software* (*The belted dummy model is provided by LS-DYNA.*)

In addition to blast wave, the proposed mine-soil-composite interaction mechanism will be fully developed and implemented into the FOMD-Blast software system as a major module for the advanced blast-protective composite design. The inhomogeneous property of soil and the interactions between blast wave and soil debris will be accounted for in the blast load prediction so that the composite structure can be optimized with more realistic loading conditions.

3. OPTIMAL COMPOSITE STRUCTURE DESIGN FOR BLAST PROTECTION

Current composite armor design processes rely heavily on testing, which can be expensive and time-consuming. To expedite the development of composite armor design, a combined design process is proposed and applied in the design process with a core design methodology developed at MKP Inc. This design methodology is called *Functional-Oriented Material Design* (FOMD), which was developed under two US Army and US Air Force SBIR Phase II programs, and has proven to be an effective tool for innovative structural and material designs for needed light-weight and high-performances (Ma *et al*. 2003). It will be used to design materials and structural components for the specific tasks demanded of structures in current and future ground and air vehicle systems. In order to carry out the FOMD process, first the functions of a structure in the vehicle system need to be explicitly defined in a systematic way. Then these functions must be quantified, so as to define the objective and constraint functions in the optimization process. Finally, an advanced optimization process needs to be carried out, and the material layout has to be finalized by the design engineer. Typically a number of constraints, such as manufacturing and cost constraints, need to be considered in the optimal design process. Note that the term "material design" used here can take two different meanings, namely, micro-structural design and macro-structural design.

3.1 FOMD-Blast for Composite Design

Figure 6 illustrates the proposed simulation and design process for developing the advanced composite concept for blast protection. This design process includes: 1) explosive modeling, 2) soil modeling, 3) geometry modeling of vehicle structure and occupants, 4) blast prediction, which will predict both blast pressure and fragment penetrations on the composite, 5) composite layout, which includes raw material selection and material configuration, and 6) optimal design based on the FOMD. A post-process will also be conducted for finalizing the design for prototype manufacturing.

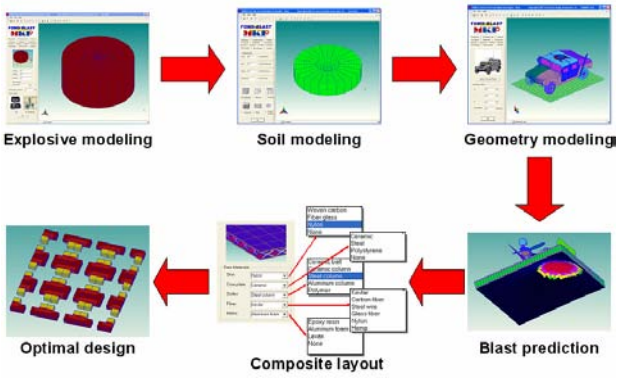


Figure 6. Proposed simulation and design process

Figure 7 illustrates a preliminary study using the current FOMD-Blast for a special sandwich composite design under a landmine explosion. Only blast pressure is considered in this design case. Effects of the blast-soil interaction and fragmentation are ignored. The composite plate is assumed to have dimension of 2.44 m x 2.44 m, and the landmine is detonated at 0.61 m beneath the composite plate with a specified charge. The sandwich is assumed to have three layers: the top layer is made of aluminum and the bottom layer is made of steel. The design problem is to lay out the optimum reinforcing material distribution in between the aluminum and steel plates with a given amount (mass) of material so that the strain energy stored in the sandwich due to the blast can be minimized. As an initial study, the optimum design is considered with respect to the blast loads at different moments of the explosion, which are 0.03 ms, 0.15 ms, and 0.3 ms. Because the blast load distribution varies with time, as shown in the top row of Fig. 7, different optimum reinforcement designs are obtained, which are shown in the middle row of Fig. 7. The bottom row of Fig. 7 further illustrates the Von Mises stress distribution in the optimum composite structures under the corresponding blast loads. Note that the final design

should be obtained in consideration of either the most critical loading case or multiple loading conditions, which can represent the overall blast damaging process. This will be studied in the future.

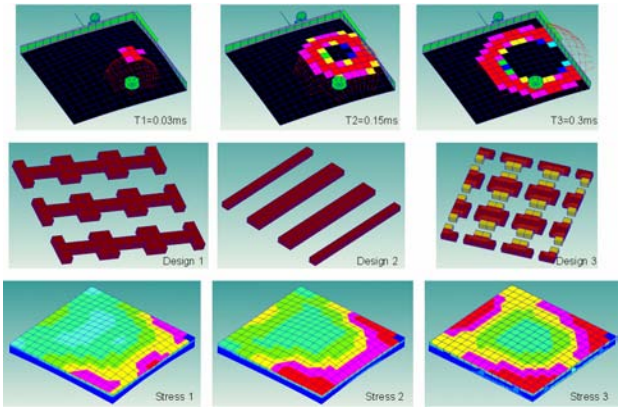


Figure 7. Proposed simulation and design process example results for reinforcing stuffer design under blast loads at different time (The optimum design will consider all possible worst cases.)

3.2 New Blast-Protective Composite Concept (BTR-*Bl*)

The present armor concept to defeat light to medium threats typically consists of a hard-strong frontal surface and a relatively softer backing structure with specified toughness and strength. In addition to ballistic and blast protection, other major requirements for advanced vehicle armor are lightweight, flexibility, maintainability and reduced life-cycle cost. Lightweight is crucial to maintaining excellent road and cross-country mobility, which is directly related to military deployability and survivability. Lightweight is also crucial to the transportability and sustainability as well as to structural integrity and durability. Flexibility means the armor structure can be shaped or formed to fit various vehicle contours. Maintainability implies two things: 1) the integrated armor system can be easily installed and removed from the vehicle with minimal time and manpower, and 2) the armor can be easily repaired during war time without replacing the whole armor structure. Life-cycle cost is directly related to affordability by the US military and the wide application of the armor system.

MKP's blast-protective Biomimic Tendon Reinforced (BTR-*Bl*) material concept is used to build an under-body deflector. Figure 8 illustrates a preliminary concept of the blast-protective BTR-*Bl* material, including the following five modules: 1) a thin skin layer; 2) a protective layer with energy absorption material; 3) a ceramic plate; 4) a fiber-reinforced composite plate made of cable tendons, stuffers, and foam matrix; and 5) woven fiber laminates for inner surface(s).

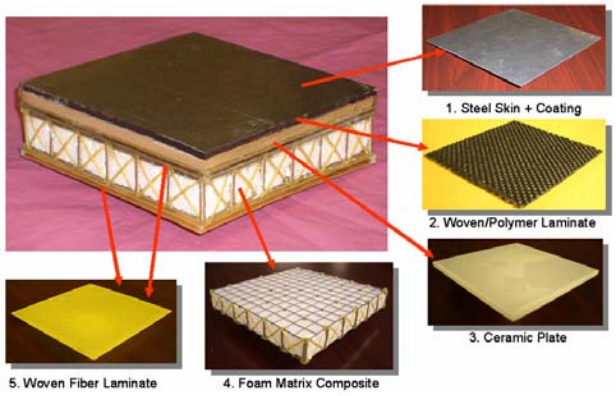


Figure 8. Example configuration of proposed blast-protective composite (BTR-Bl) material

Also note that the use of cable in the composite structure has the following advantages:

- Cables can quickly transfer the blast energy to a far-reaching area, thus reducing the localized damage;
- Cables can sustain large-amplitude deformation to capture more blast energy;
- There is a wide ranging selection of high blast toughness materials for cables, such as Kevlar and Nylon, which can be used to develop super-tough composite for blast protection.

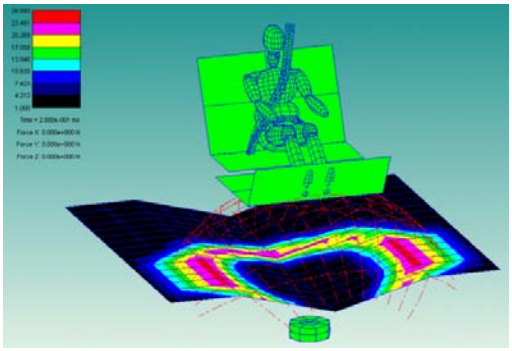
Cable reinforcements will work well with other materials in the system, such as with foam matrix as a tough energy absorption material.

3.3 Geometric Design of the BTR-*Bl* Structure

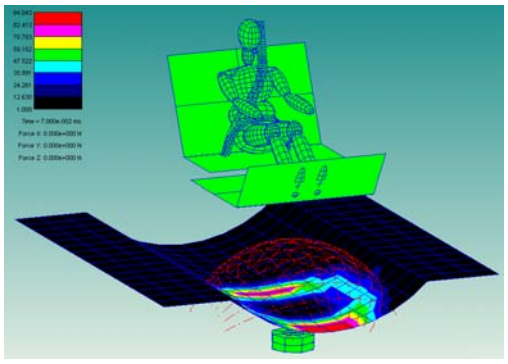
The above BTR material concept can be used to build a blast-protective composite (BTR-*Bl*) structure, for example, an under-body deflector shown in Fig. 9, for a specific vehicle. The geometric design of the structure will also be an important factor for the actual protection performance of the BTR-*Bl* structure. As an initial study, the geometry design of a wedge/wing deflector has been studied using a currently available blast model in FOMD-Blast. As shown in Fig. 9-a, the configuration of this deflector combines a sharp wedge for protection of the drive train, and a flat wing for deflection of blast energy to the sides, thus preventing exposure of the crew cab to the blast load. Figure 9-b illustrates that a more advanced deflector shape, namely Arc-deflector, can be designed using the capability developed in FOMD-Blast.

Figure 10 shows a preliminary performance comparison of these two deflector designs with respect to a design variable, the equivalent angle α. The angle α is first used to determine the V-shape of the Angle-

deflector when α=0, the deflector becomes a flat plate. The height of the V-shape at a given angle is then used to determine the radius of the arc in the Arc-deflector for achieving the same height. Figure 10-a shows the time history comparison of the total blast force for the two designs at the equivalent angle α=25 degrees, and Fig. 10-b shows the comparison of the impulses with respect to the design variable α. It is seen that the arc-shaped deflector may perform much better than the traditional angle-shaped design for given design conditions.

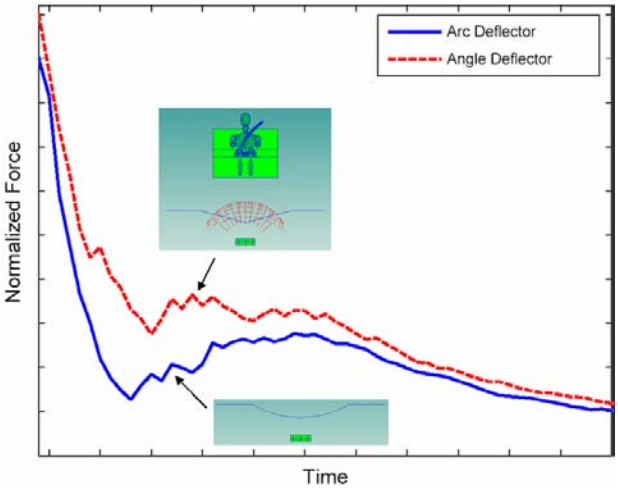


a) Angle-deflector design

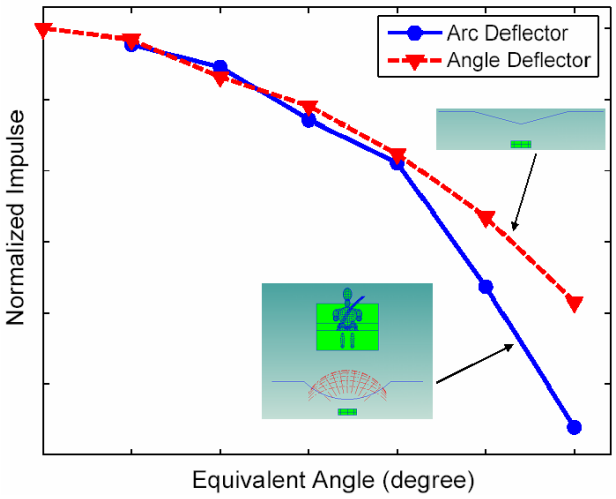


b) Arc-deflector design

Figure 9. Deflector design with different geometric shapes (*The belted dummy model is provided by LS-DYNA.*)



(a) Time history of total blast force for α=25°



(b) Impulse versus design variable α

Figure 10. Comparison of "Angle" and "Arc" deflector designs

CONCLUSIONS

The developed blast simulation and design system will enable the prediction, design, and prototyping of blast-protective composite structures for a wide range of damage scenarios in various blast events, ranging from vehicle damage, localized structural failure, blast fragment penetration, to crew injuries. The different levels of simulation and design capabilities will be implemented in an integrated software system called FOMD-Blast with a well-defined graphic user interface.

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