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Computational Polyethylene-Ceramic Composite Plate Design and Optimization

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INTRODUCTION

A composite designed Ultra High Molecular Weight Polyethylene (UHMWPE) reinforced by a material with a failure mode that will strengthen the system may significantly improve on modern armor designs. UHMWPE is considerably less dense than steel or high density ceramics. It is reasonable to consider making improvements to the weight-performance of armor by using the lower density UHMWPE and combining it with inserts of a high-density ceramic. A cellular ceramic encapsulated by rubber may significantly increase the amount of kinetic energy a composite will absorb through a phase transition.

It is theorized that a series of ceramic inserts distributed in a polymer matrix will result in an increased impact resistance. Shock propagation in the ceramic will be minimal, and the elastomeric properties of the polymer will provide maximum tensile support. The ceramic inserts will act as a stress concentrator and physical resistor to the impacting object. When the ceramic inserts are shattered by the impactor they will impart a resistive force by forcing additional deformation in the polymer matrix.

Study of design variations by examination of multiple geometries for the ceramic inserts will maximize the impact resistance of the structure. The resistance of the structure is enhanced by providing a multi-dimensional failure mode. The ceramic, once shattered, will still occupy space, forcing additional plastic deformation, and additional deformation in the impactor.

COMPUTATIONAL DESIGN

The computational analysis was performed using ANSYS/AUTODYNE explicit dynamics software. Multiple models with variations in geometry and distribution were analyzed. The inserts were of varied in geometry, size, and distribution density, while the polyethylene was consistent in every model. A baseline polyethylene model was also created to serve as an analogue for commercial UHMWPE products, and against which the capacity of the composite model could be tested.

- An in-depth description of the computational model provides a sufficient background for both iteration and replication of the process. The UHMWPE was model was based on data from an article published in 2014 on the tensile properties of polyethylene Dyneema SK76 fiber . A linear orthotropic model was used to represent the UHMWPE fiber. The model could afford to be linear due to the fact that the behavior of the fiber under high strain rate is very similar to a simple linear model without a significant plastic region prior to failure (Figure 1).
- Tungsten Carbide inserts were modeled utilizing a Johnson-Cook fracture/failure model consistent with experimental results that have been used in other computational experimentation . Constants in the Johnson-Cook model describe the erosion criteria and fracture criteria for materials with high strength and low ductility. Additionally, a Johnson-Cook failure model is relatively easy to utilize in a computational simulation of materials failure.
- The impactor is modeled as a 7.62x39mm NATO round with a solid ogive tip. The impactor has a simulated mass of 3.3 grams. The ogive models are due to convergence errors that occur when Ansys attempts to solve models with sharp points. The impactor was simulated with plastic stress failure criteria. The plastic stress failure was set to a high value, 5.0, in order to maximize the models deformation in impact and accurately observe the metals ductile deformation and failure.
- The tungsten carbide inserts were designed in the form of a number of different geometric shapes. Each model was subjected to an identical impact at 609 m/s to determine the composites general impact resistance. As higher velocity impacts are more prone to convergence errors, high velocity simulations were performed on only the two most effective models. The composite that showed the most resistance were then subjected to an impact at 900 m/s, in excess of the National Institute of Justice testing standards.

COMPUTATIONAL RESULTS

The following geometries and distributions of material were tested. They are listed in Table 1. 5mmx2.5mm consist of plates with a width of 5mm and a depth of 2.5mm spaced 5mm apart from edge to edge. The plates were placed at three levels offset from one another in the composite such that an impactor in any location would encounter at least one plate. Tetrahedral inserts with a side-length of 8.5mm spaced 5mm apart and oriented so that a point of the tetrahedron faced towards the oncoming impactor. The ceramic sheet was a single 2.5mm thick layer of tungsten carbide placed 2.5mm below the surface of the composite that was uninterrupted from one side of the composite to the other. The 2.5mm cubic were cubes with a length of 2.5 mm separated by a distance of 2.5mm in four vertical layers, offset from one another. The 5mm cubic were cubes with a length of 5mm separated by a distance of 5mm in 2 vertical layers offset from one another.

Of the designs evaluated to date, viewable in Table 1, it was found that small cubic inserts seem to have the highest efficacy when it comes to increasing the total impact resistance of the composite material. The polyethylene matrix showed a marked increase of overall resistance with the addition of four alternating layers of 2.5mm by 2.5mm cubes of tungsten carbide.

A great deal of stress concentration took place in tungsten carbide cubic inserts. The cubic inserts were stressed to the point of simulated erosion up to 2 centimeters from the original impact point (Figure 2). The stress concentrates in the corners of the cubes leading to erosion of the structure from the outside in.

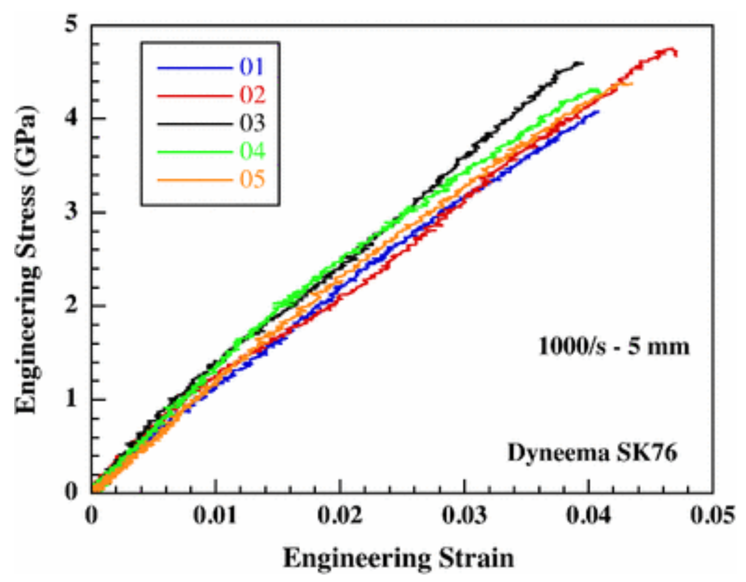

Figure 1: Stress-Strain curve of Dyneema SK76 UHMWPE fibers as tested by Sanborn, Brett,(2014) . Used to determine computational values.

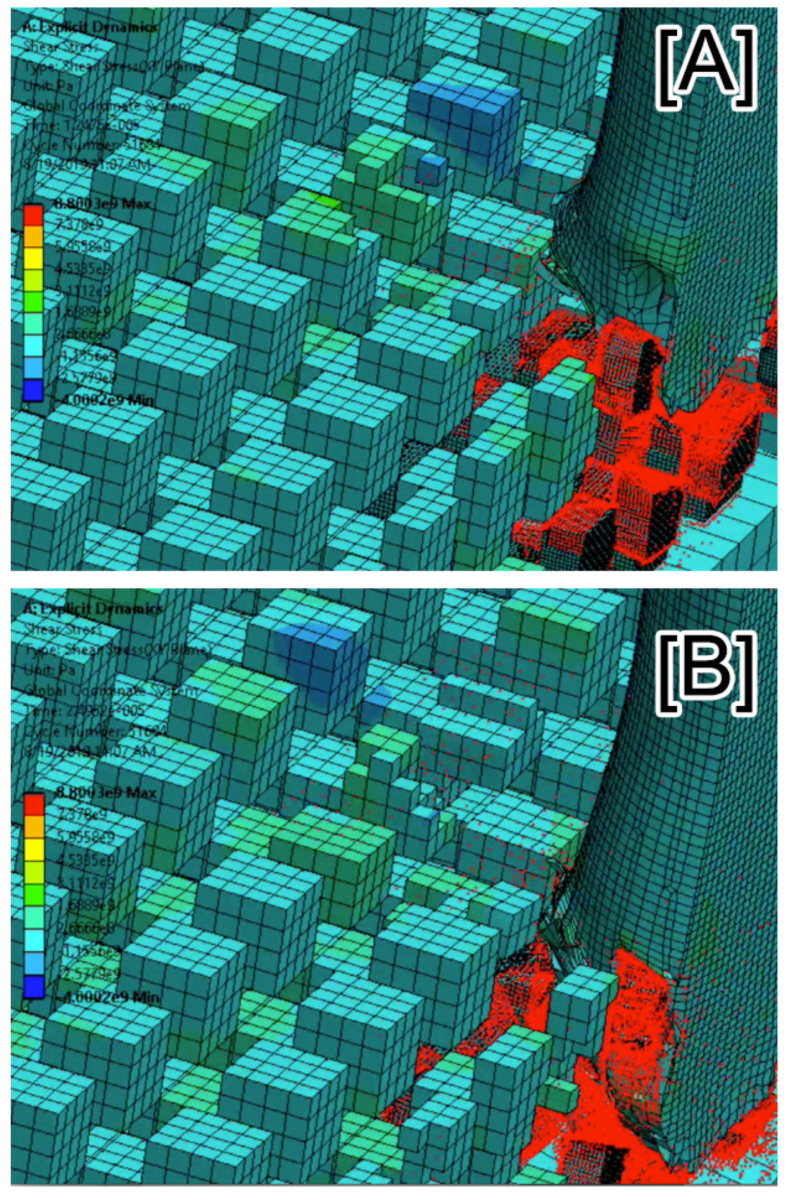

Figure 2 Shear stress in 2.5mm cubic inserts with intervening polymer layers transparent. 1.87e-5 seconds [A], 3.1e-5 seconds [B]

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CHARACTERIZATION DATA

The composite structures were characterized with respect to the penetration depth of the impactor and the time it took the impactor to decelerate. The data is visible in Table 1. The most effective composite structures simulated saw a penetration depth of 12.5mm and a deceleration time of less than 1e-4 seconds. Whereas a baseline composite structure saw a deceleration time of 1.8e-4 seconds and a penetration depth of over 20 mm.

Table 1. – Characterization data of computationally simulated composites

Ceramic Insert structure	Impactor Velocity (m/s)	Lead Penetration depth (mm)	Steel penetration depth (mm)	Lead deceleration time (s)	Steel deceleration time (s)
No Inserts	609	25	30 [full penetration]	1.8e-4	[Penetration]
No Inserts	900	30 [full penetration]	30 [full penetration]	-	[Penetration]
5mm x 2.5mm	609	22.5	20	1.2e-4	1e-4
Tetrahedral Inserts	609	-	27.5	-	1.4 e-4
Sheet of Ceramic	609	20	-	1.35 e-4	-
2.5mm Cubic	609	12.5	12.5	0.8e-4	0.75e-4
2.5mm Cubic	900	-	20	-	0.7e-4
5mm Cubic	609	20	12.5	1e-4	0.9e-4
5mm Cubic	900	27.5	25	0.82e-4	1.4e-4

CONCLUSIONS

A relatively small mass of high-density ceramic dispersed within a polyethylene matrix appears to cause a significant increase in the total impact-resistance of the composite compared to a pure polyethylene matrix. The different variations in the insert geometry similarly significantly alter the total impact resistance of the composite. High stress fields seem to concentrate around the ceramic inserts, particularly in the corners of cubic designs.

It appears to be the case inclusion of smaller inserts in the polymer matrix is more effective than the inclusion of larger inserts, at least down to some critical size. The stress fields around the tungsten carbide inserts are likely partially due to the high-density of the ceramic creating an inertial resistance to sudden motion that pins the polymer matrix into place.

FUTURE WORK

With additional computational modeling, and the plan to expand these studies into physical product testing, it may be possible to optimize these structures to markedly increase the impact-resistance to weight ratio of modern defensive personnel equipment. Should further study prove fruitful, it may become technically feasible to substantially reduce the weight of NIJ-4 compliant armored ballistic plates.

As a portion of an iterative study, it is reasonable to begin the development of physical models that may be tested in against high-velocity impactors. The model, as developed, indicates a significant degree of impact resistance with smaller particles. By performing real world tests it will be possible to refine the computational model. Once the computational model has been refined, in-depth testing of structural behavior around the ceramic inserts in highly accurate computational modeling will commence.