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NUMERICAL MODELING AND ANALYSIS OF DYNAMIC BEHAVIOR OF GRADIENT DESIGN COMPOSITES

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ABSTRACT: The paper gives some numerical results of ballistic resistance studied for a developed plain woven and orthogonal (0°/90°) composite plate models, with and without ceramic facing (Gradient Design Composite). The difference in performance between a full ceramic facing versus a set of ceramic spheres embedded in light epoxy is evaluated. Materials properties and geometry effects are explored. Possible applications include body armors, helmets, and protection against projectile threats in structures such as helicopters, tanks and aircrafts.

KEYWORDS: Textile Composites, Gradient Design, Numerical Modeling.

INTRODUCTION

The main objective of this work is to address the computational modeling of the impact performance of textile based composite and Gradient Design Composite (GDC) materials. Possible applications of these kind of materials, would be the development of the light armor materials systems: body armors, helmets, and protection against projectile threats in structures such as helicopters, tanks and aircrafts, which would have a significant improvement in penetration resistance, impact energy dissipation, and damage containment. Due to their high impact resistance and low density, fabric composite armors are usually employed for personal protection, and considerable research has been directed to the study of the ballistic behavior of laminated, woven, and braided fabrics [1,5].

It is evident that the complexity of the modern light armor construction has increased many fold and so did its structural analysis. To complement and perhaps guide the necessary experimental evaluation of such system, it is essential to develop a computational methodology that may lead us to an improved understanding of the relative significance of the various design parameters. The associated computational complexity in terms of both geometry and material models is the key difficulty of this approach.

This work explores the ability to analyze the ballistic impact on complex structures, such as plane woven and orthogonal composites, with and without ceramic facing layer. Additional goal was to evaluate the difference in performance between a full ceramic facing versus a set of ceramic spheres embedded in light epoxy.

The characteristic of presented approach is that it considers each material separately. From the computer simulation point of view, the introduction of discrete models for the study of textile composites offers the advantage of using different and more detailed description of material properties for both matrix and fibers, with a more accurate description of the geometry. In this way, more elaborate (and more realistic) failure criteria can be introduced and the effects of fiber architecture on the dynamic properties of these composites can be explored.

BACKGROUND AND OBJECTIVES

The unique advantage of composite material is their ability to tailor their properties to the structural or materials system of which they are intended. On the other hand, many structural components have to meet service conditions and, hence, required materials performance, which vary with location within the component. This consideration founds basics for development of a special class of composite materials, that are functionally graded-*Gradient Design Composites* (GDC). Rather than developing new materials with higher stiffness, it might be more advantageous to create structures using the optimal placement of components.

The performance of a fiber-matrix composite depends on orientation, length, shape, and composition of the fibers; mechanical properties of the matrix; and integrity of the bond between fibers and matrix. In order to achieve higher penetration resistance, both experimental results [5], and numerical simulations [1], show necessity for harder, facing layer, which would first shatter or blunt armor piercing projectile, and than spread the load over a larger area. The composite backing would, in that case deforms to absorb the remaining kinetic energy of the projectile.

In order to defeat higher velocity threats and address the need for lighter weight and more complex shape structures, the concept of introducing a harden phase in the spherical form or Gradient Design Composite (GDC) was developed [5]. The system consists of a harden component with ceramic spheres for destroying the projectile tip and creating a greater surface area to contact between the facing layer and the backing composite plate which is for maximizing strength and energy absorption, (Fig.1).

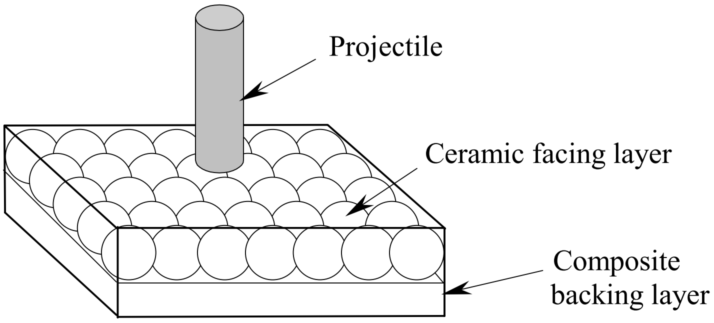


Fig.1 Gradient Design Composite material concept.

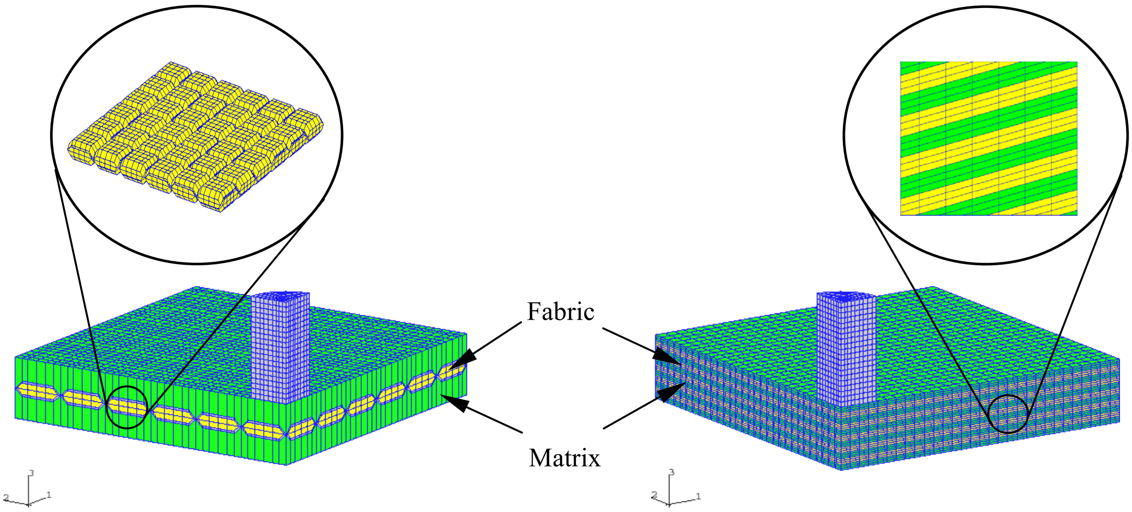
Changing the direction of a projectile, by its deflection on the particulate ceramic facing, gives the additional effect to the energy absorption increase.

Main objectives of this work are: to evaluate an ability to simulate complex material systems such as the Gradient Design Composites using finite element analysis; to attribute significance to the various design parameters such as material property, textile and overall composite architecture, and to evaluate the difference in performance between a full ceramic facing versus a set of ceramic spheres embedded in light epoxy.

It is important to note, that the results presented below may be influenced by the level of discretization, which is often coarse in order to limit the CPU time of the simulations to bellow one hour, on a modern (733MHz) personal computer. An effort to understand the effect of mesh density on the results is underway.

IMPACT MODELING

A set of 3D FE simulations (using ABAQUS-Explicit computer code) were carried out to evaluate the impact resistance for a developed plain woven and orthogonal (0°/90°) composite plates (Fig.2), vith the same volume fraction of 50%, with and without ceramic facing layer. Models of a plain woven fabric and orthogonal composite structure are shown in details.



Plane woven composite model.

Orthogonal (0°/90°) composite model.

Fig.2 FE models of different fabric architecture.

In order to explore effect of different ceramic facing geometries on the ballistic resistance of armor model, monolithic ceramic tile versus layer of spheres embedded in epoxy, were considered. Figure 3 represents GDC model with spherical ceramic facing.

ABAQUS-Explicit utilizes an explicit time integration scheme designed specifically to model nonlinear dynamic problems. It also has the ability to reduce the stiffness of elements that reach user defined, failure criterion.

Due to symmetry, only one quarter of the model is considered with appropriate boundary conditions. The model consisted of 38962 eight-node hexahedral, reduced integration elements and 42548 nodes. Specifically, the projectile, the ceramic facing and the backing plate used 262, 9000 and 29700 elements, respectively. A cylindrical projectile with a diameter of 7.62mm, was modeled as a deformable, elastic plastic steel material. The dimension of a model is 28mm x 28mm and backing plate is assumed to have thickness of 6mm, and ceramic facing thickness of 8mm.

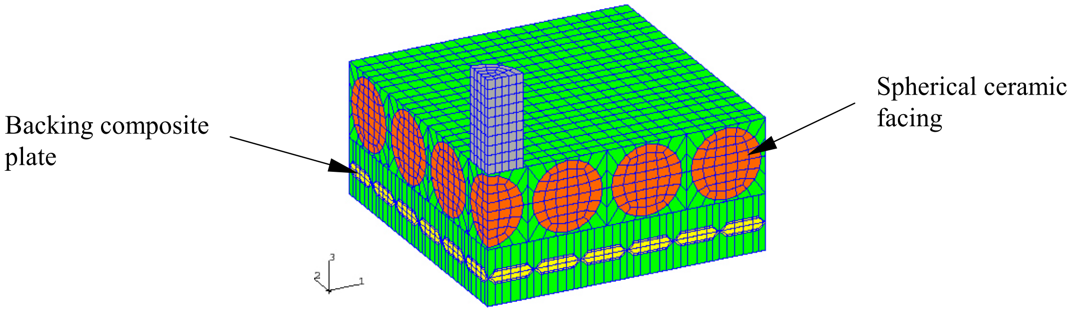


Fig.3 GDC model with spherical ceramic facing.

The impact velocities are assumed to be in the range of 250m/s to 1000m/s. An initial velocity was imparted on all nodes of the projectile to simulate the incident velocity. Contact was defined between the outer surface of the projectile and the nodes in the target. The termination time, for the FE runs of GDC models, was set at 100μs. This particular value is arived at after several iterations and after analysing the maximum displacement and kinetic energy distributions of the projectile, which were leveled off at around 80μs.

MATERIAL MODELS

Contrary to the analysis of a high velocity impact on materials such as steel or aluminum, the simulation of high velocity impact and penetration processes into non-isotropic fiber reinforced material is a more challenging research task. However, such analysis is needed in order to understand the complex dynamic interactions between structural components undergoing large deformations and nonlinear material behavior including failure, delamination, erosion, etc.

In order to simulate the dynamic behavior of composite materials, the constitutive equations must cover the elastic regime, the material failure, and the behavior of the partially or completely failed material.

From the computer simulation point of view, the introduction of simple discrete models for the study of textile composites offers the advantage of introduction of different material properties for both matrix and fibers, as far as possibility of more accurate description of the geometry. Further, more elaborate (and more realistic) failure criteria can be introduced.

Using the higher-order discretization it is possible to explore the effects of fiber architecture on the properties of these composites. In addition using separate models for the fiber and matrix will allow for more complex models for both materials that can include rate dependence in the modulus of the fiber and matrix behavior.

The absorption of energy under both low and high velocity impacts depends strongly on the evolution of damage in the target and the resulting progressive degradation of its properties during its interaction with the projectile. For this reason, any computational simulation of impact phenomena must integrate in a rational way the dominant damage mechanisms in the target (and occasionally in the projectile).

T1. Material properties used in impact models

	Steel	Alumina	Epoxy	Spectra
Density (kg/m^3)	7800	3900	1200	970
Modulus (GPa)	210	350	4.5	268
Poisson's ratio	0.3	0.22	0.35	0.4
Plasticity σ(MPa), ε_{pl}	1500, 0.00 1800, 0.10	2400,0.00	50	3000,0.00
Tensile strength (MPa)	/	360	/	/
Strain to failure	1.0	/	0.4	0.07

Material properties used for steel, alumina and polymer matrix composite, consisted of spectra fabric embedded in epoxy matrix, are shown in Table 1.

Alumina was modeled to fail at a tensile stress of 360MPa. At this value of stress, the material underwent brittle failure.

The ductile failure model, used for both fabric and matrix phase of polymer matrix composite, provides simple failure criteria, which are designed to allow the stable removal of elements from the mesh as a result of tearing or opening of the structure. The failure model is based upon the value of the equivalent plastic strain. When the equivalent plastic strain at a material point reaches the value defined as the plastic failure strain, $\varepsilon^{pl}{}_{f}$, the material point is failed. If all of the material points in the element fail, the element loses its ability to resist any further load and, hence, it is removed from the mesh.

The ductile failure model is based on a damaged Von Mises plasticity theory with isotropic hardening. The damage manifests itself in two forms: degradation of the yield stress with damage and damaged elasticity. In the case of epoxy, it was assumed that fracture occurred when the material is in plastic state, i.e. ductile fracture. Brittle fracture of spectra fibers, on that way, was considered as a limiting case of ductile fracture where fracture occurs after very little plastic flow.

Due to very limited experimental results available in (at least, open) literature, for this simulations, viscoelasticity of spectra polymer fabric is introduced in stepwise manner. Static Young's moduli are used but elevated according to specific strain rate. Table 2 shows Spectra modulus for different rates of strain [2].

T2. Spectra fiber modulus strain rate dependency.

Strain rate (min^{-1})	10	500	1,000	5,000	10,000
E [GPa]	101	130	145	221	268

Based on some experimental results [3,4], during the impact, alumina below the projectile crushed and consolidate. To model this behavior, as it is suggested in [3], a limited number of alumina elements diretly below projectile were not allowed to fail in tension, (Fig.4). The addition of this "fail-free" zone, greately improved the stability of solution and has solved convergence problems, due to mesh distortion.

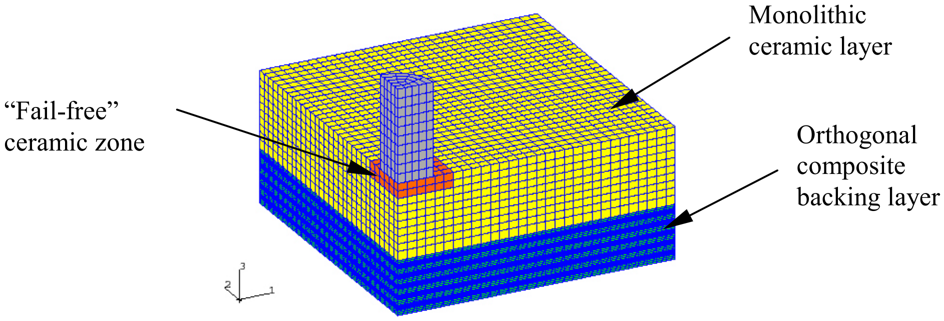


Fig.4 Fail-free zone in ceramic layer under the projectile.

The displacement of the projectile tip and center point of the back plate surface, as a measure of the penetration depth and blunt trauma effect, respectively, were tracked throughout the solution. The velocity of the projectile as well as time history of the energy, for the model constituents, is also recorded.

RESULTS AND DISCUSSION

In order to explore effects of textile architecture on the armor impact performance, first set of simulations was performed on both plain woven and orthogonal (0°/90°) polymer matrix composite models, for the impact velocity of 250m/s.

From Fig. 5, that shows velocity time history for different textile architectures, it is clear that fabric geometry plays important role in the textile composite impact resistance. While woven composite model is completely perforated for a given impact velocity, projectile was stopped by the orthogonal composite.

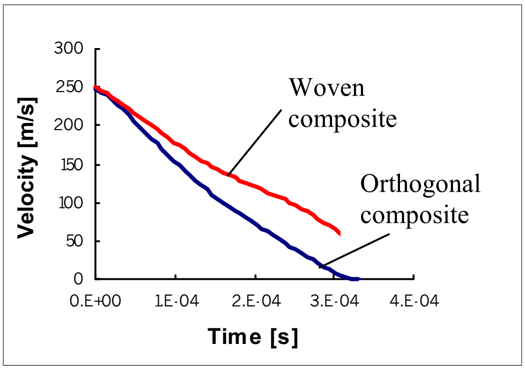


Fig.5 Effect of composite fabric architecture on velocity time history.

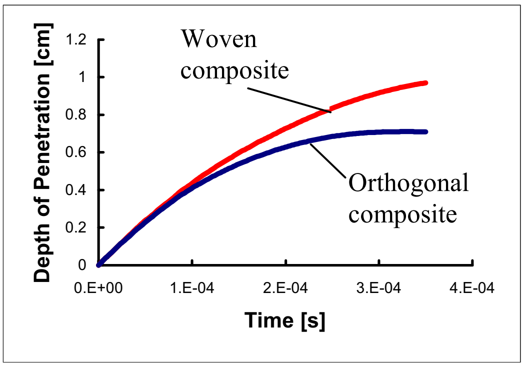


Fig.6 Depth of penetration as a function of composite fabric architecture.

The similar effect of the textile architecture on the ballistic efectivness is shown on Fig.6, were penetration depth is given as a function of time.

Described behavior is shown on Fig.7 and Fig.8 for initial and final stage of simulation.

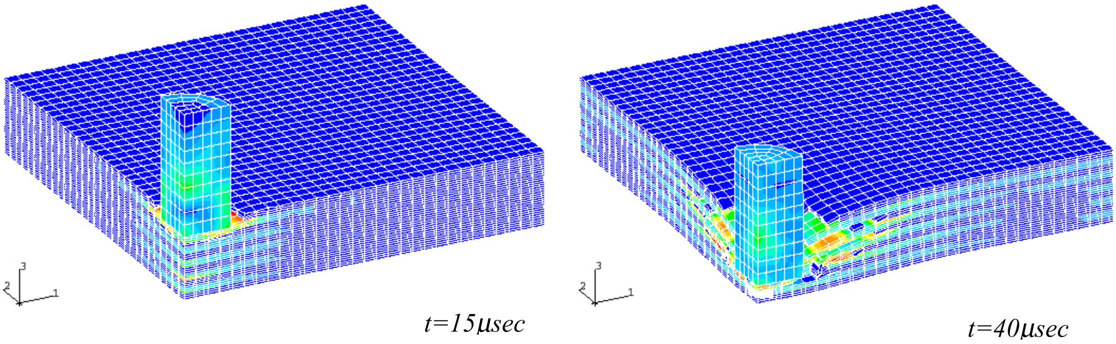


Fig.7 Von Mises stress distribution in the orthogonal composite model during the impact.

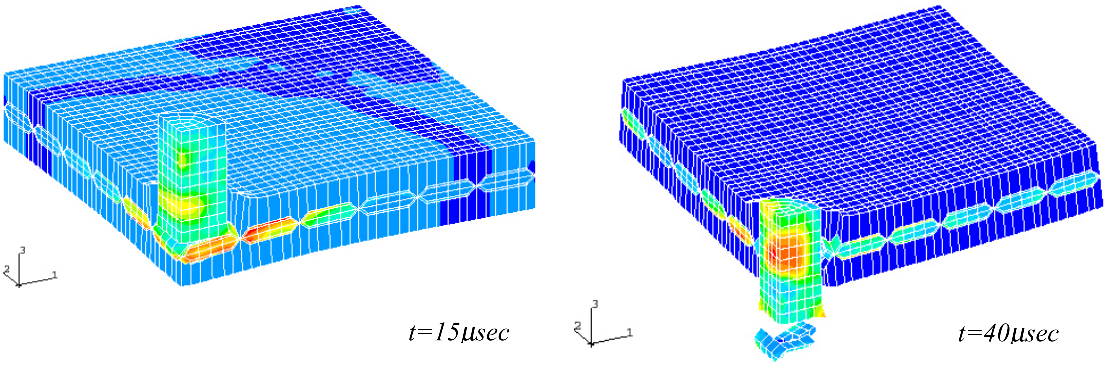


Fig. 8 Von Mises stress distribution in the plane woven composite model during the impact.

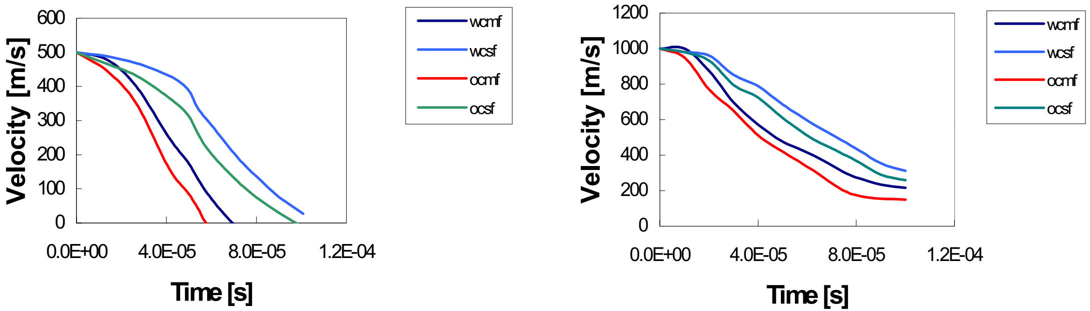
Sice the target is composed of various material systems, stress pulses incident to an interface will have components transmitted and reflected waves depending on the mechanical impendance, areal density and speed of wave [6]. At the moment of impact (within 10µsec), a very high stress develops at the impact point. As a result, fiber breakage is expected. As time passes, the highest stress moves away from the impact site. Impact simulations have showed potential of layered, orthogonal fabric structure to absorb and transfer impact energy faster than woven textile composite, lowering on that way stresses and deformations at the impact site.

In the case of Gradient Design Composite, balistic resistance of four different models were evaluated, under two different impact velocities, 500m/s and 1000m/s, namely:

- *wcmf*-woven composite backing with monolithic ceramic facing,
- *wcsf*-woven composite backing with spherical ceramic facing,
- *ocmf*-orthogonal composite backing with monolithic ceramic facing, and
- *ocsf*-orthogonal composite backing with spherical ceramic facing.

The most important characteristic of protective ballistic system is its ability to slow down and stop the projectile. The best way to estimate armor penetration resistance is to measure residual velocity of a projectile. Another consideration for system integration is back face deformation, or the deflection of the armor material on the back surface. Even though the armor may defeat a threat projectile, the back face deformation can cause other damage, for example, blunt force trauma to a person wearing an armored west or a helmet.

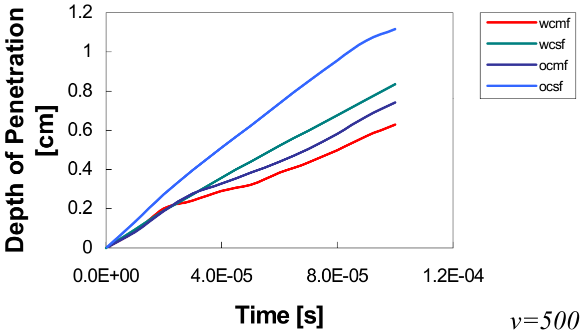
Figure 9 shows effects of both fabric architecture (woven vs. orthogonal), and ceramic facing (monolithic vs. the set of discrete spheres), on velocity time history for two impact velocities.



v=500m/s *v=1000m/s*

Fig. 9 Effect of composite fabric architecture and ceramic facing on velocity time history.

Better penetration resistance is predicted for orthogonal composite backing, which is able to absorb and disperse ballistic energy immediately, compared to woven fabric which crossover points probably serve as barriers to fast and efficient energy transfer. In the same time, the spherical ceramic facing seems to be good alternative to traditional monolithic ceramic plates, since simulations show comparable ballistic resistance.

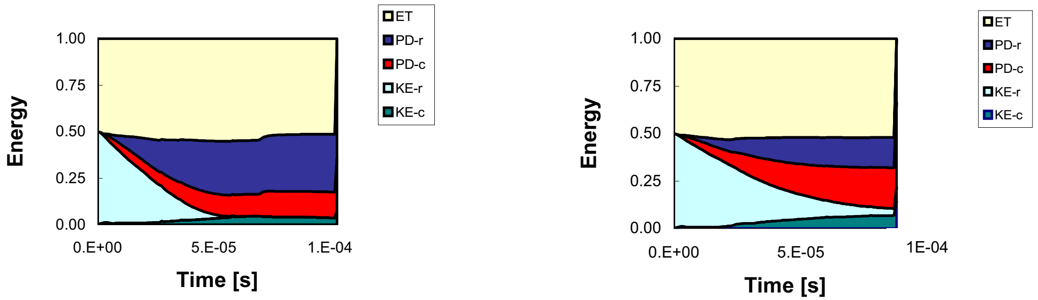


v=500m/s

Fig. 10 Depth of penetration as a function of time for different models.

After impact, the kinetic energy of the projectile is imparted to the armor, and as the projectile penetrates the target, the kinetic energy will be reduced while the internal energy of the system will increase. Distributions of these energies (KE-kinetic energy; SE-recoverable strain energy; PD-energy dissipated by rate-independent and rate-dependent plastic deformation), for different parts of a system (c-ceramic facing; r-rod-like projectile), and two impact velocities, with respect to time, are shown in Fig. 11. Kinetic energy dissipation is an indication that the velocity of the projectile is being slowed down as it ploughs through the armor.

The total energy balance for the model (ET) is seen to remain almost constant during the analysis, as it should.



v=500m/s

v=1000m/s

Fig. 11 Energy time history for orthogonal composite with monolithic ceramic facing.

Absorbed projetile impact energy is mainly transformed into kinetic (KE) and plastic energy dissipated in the target (PD) and deformation of rod-like projectile (PD-r), as it is shown on Fig.12. Due to crimped structure, woven preform absorbs more recoverable strain energy (SE), than orthogonal one.

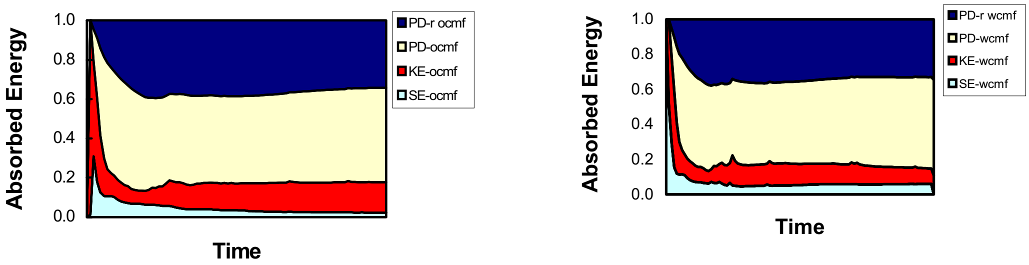


Fig. 12 The influence of textile architecture on energy time history (v=1000m/s).

Figure 13 represents relative distribution of the projectile kinetic energy in the different parts of target structure (Ec-total energy dissipated in ceramic facing; Et, Em-total energy absorbed by textile and matrix respectively), and the projectile (Er), as a function of ceramic facing.

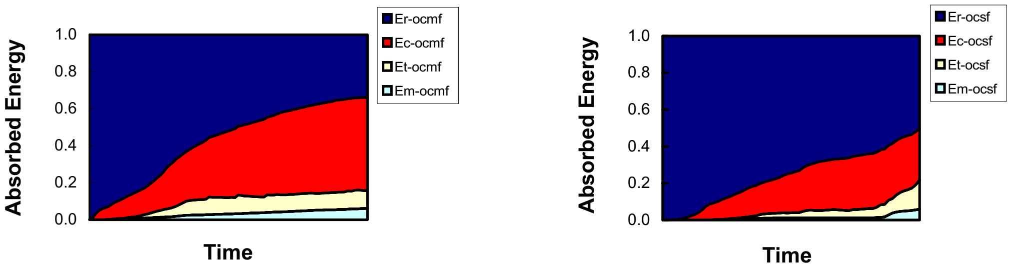


Fig. 13 The influence of ceramic facing on energy time history (v=1000m/s).

Considerably energy absorption capabilities of spherical ceramic facing are shown, comparable to that of solid ceramic tile.

One of the important effects in the ballistic event is the role of pojectile deformation. In the presented simulations is observed that the projectile deforms significantly during the first part of penetration within the ceramic layer.

The slowing down and the deformation of a projectile can be vizualized in Fig.14.

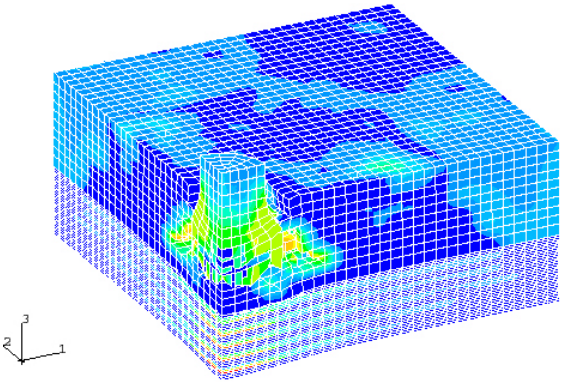


Fig.14 Von Mises stress distribution during the penetration of GDC.

CONCLUSION

The focus of the study is in the numerical assesment of energies, stresses and deformations and velocity histories of the different Gradien Design Composite systems in the event of an impact.
The developed FE tool shows to be capable to simulate structural behavior of textile composite, and to assess the effect of materials selection and fiber architecture.
Results are showing better penetration resistance of orthogonal (0°/90°) textile composites compared to woven composite.
It is shown that mutual contribution of both, textile architecture and ceramic facing layer influences ballistic performance of specific armor structure.
Ballistic resistance of GDC with facing layer of ceramic spheres embedded in epoxy is showed to be comparable to that of solid ceramic tile.
As a result of presented simulations, it can be said that ceramic spheres can be used effectively to replace the conventional ceramic tiles to reduce weight and cost without sacrificing its ballistic effectiveness.

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