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Evidence of optimal interfaces in bio-inspired ceramic-composite panels for superior ballistic protection

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Abstract

Ceramic-composite panels are acknowledged to provide effective impact protection even against small fragments and armour piercing projectiles. Nature shows similar solutions, coupling an hard face and soft backing layers, in dermal animal armours for protection against predators. Finite element simulations of impact on ceramic-composite panels, to evaluate their energy absorption capability, are presented. The influence of key parameters, like interface strength and friction, on ballistic limit is studied. We find that a proper set of interface parameters is able to maximize the specific energy absorption of the panel: although this optimum is variable case by case depending on projectile penetrability and target configuration, general guidelines are provided. Oblique impact results in a higher ballistic limit also thanks to projectile change in trajectory, providing interesting spots for future developments. Numerical results are compared with experimental data from literature and forecasts of analytical models.

Keywords: Impact; Ceramic-composite panels; Energy absorption; Oblique impact; Finite element simulations

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1. Introduction

Laminated composite materials are widely employed in protective armours, automotive and aerospace applications: these homogeneous panels have their weak point in small and high penetrating fragments and armour piercing (AP) projectiles. Hard faced ceramics with a multilayered composite backing are widely used in order to solve these problems, for example, in protective body armours. On these heterogeneous plates, impactors are first blunted and weared down by the exterior hard ceramic which also spreads the load over a larger area; then the composite tough backing[1–5] deforms and absorbs the residual kinetic energy of the decelerated and damaged fragment; the backing also delays and mitigates the initiation of tensile failure in the ceramic and it is capable to catch both ceramic and impactor fragments, preventing them to constitute further injury. This solution can be found also in nature, for example in *Arapaima gigas* dermal armour, whose scales are made up of an external hard mineral layer on a multilayered collagen backing.[6]

The optimum balance between lightness, thickness, performance, and economic requirements is a challenging engineering task. Ceramics are lighter with respect to traditional monolithic hard-steel panels, while comparable in stiffness, hardness and compressive strength. However, they are characterized by a higher density (about a factor of two) with respect to composite materials. Thus, their use has to be carefully balanced and limited in lightweight applications like, for instance, spacecraft or human body protection from micrometeorites and space debris.

Alumina (Al_2O_3), Boron Carbide (B_4C) and Silicon Carbide (SiC) are some of the most widely employed ceramics in the sector. For the backing, polyetilene- and aramid-based tough fibres are arranged in woven or unidirectional (UD) textiles within a polymer thermoplastic or thermoset matrix (epoxy or vinylester resins): they can range from traditional ones, like Kevlar® (aramid), and more recent like Dyneema® (UHMWPE)[7] or Twaron® (aramid).[8] The main advantage of composites is that that their properties can be tailored on the requirements for a specific application. High specific strength, specific stiffness

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and toughness make them an obvious choice for aerospace vehicles; the resistance against unkind environments (e.g. corrosive, UV, extreme temperatures, etc.), enhances the robustness of the structure. A measure of the fibres performance against ballistic impact was provided by Cunniff[9] for flat targets hit by cylindrical projectiles, and was defined as the product of the fibres specific toughness by the strain wave velocity.

The design and the performance evaluation of composite panels undergoing ballistic impact require the understanding of material properties under high-velocity impact conditions. Recht and Ipson[10] proposed a relatively simple analytical model, based on energy conservation laws, able to determine ballistic curves to fit experimental results. In this model the final velocity V_f of the impactor is given, as a function of its initial velocity V_0, by:

$$V_\mathrm{f} = q\left(V_0^p - V_B^p\right)^{1/p} \tag{1}$$

where V_B is the target ballistic limit, p a fitting parameter, usually equal to 2 in case of rigid projectiles and target resistance independent to impactor velocity, and q a coefficient depending on model assumption (e.g.: $q = 1$ if assuming that dissipation is only due to target deformation, and no projectile damage is considered). A comparison between experimental ballistic curves and Eq. (1) can be found in Ref. 11 showing that this model can apply with a good level of approximation for the estimation of the final velocity, both for isotropic and heterogeneous composite material.

Espinosa et al.[12] investigated the response of multilayered ceramic–steel targets under high-velocity impact through finite element simulations. A multiple-plane microcracking model to describe the inelastic constitutive behaviour of ceramics under severe damage was implemented into a finite element code. Their analyses showed that the penetration process is highly dependent on the multilayered configuration (stacking sequence) and the target structural design (geometry and boundary conditions), rather than on the type and properties of the ceramic material. In addition the erosion parameter in simulations, to which the residual damage strength is related, plays a key role in predicting the interaction of the penetrator in the target: thus, a coupled experimental and numerical study is found to be necessary in a meaningful ceramic-composite armour design.

Hetherington et al.[13,14] developed an analytical model for the analysis of two-component composite armours subjected to normal and oblique impact. They observed that, circular contours of constant deformation which occur in backing plates under normal impact, tends to be elliptical for oblique strike. They assumed that the projectile tip deforms into an ellipse as it impacts the front face of the ceramic under the oblique impact. It was found that an inclined ceramic composite armour plate is more effective, on a thickness basis, than one arranged perpendicular to the line of impact; parallel the ballistic limit velocity increases with obliquity. This model is reported in Ref. 15.

Considering the cost related to the ceramic and composite materials used in ballistic experiments, the need for developing accurate predictive simulation tools becomes more important. Large simulation sensitivity campaigns would let the understanding of the influence of each considered parameter, leading into the design of the optimal solution that couples toughness maximization and weigh reduction. Analytical modelling for the evaluation of impact behaviour of composite targets[16,22] generally assumes the laminate resistance σ as a quadratic function of the impactor istantaneous velocity V, taking into account strain rate effects, $\sigma = \sigma(V, V^2)$. Since the backing layers, due to impactor deceleration, progressively face a lower velocity, the specific absorbed energy E_abs for each ply is expected to decrease as the number of layers N, i.e. the areal density of the plate, increases:

$$\frac{E_\mathrm{abs}}{N} \propto N^\alpha \tag{2}$$

with $\alpha < 0$. However, this is usually in contrast with experimental tests which show that generally the exponent α can be positive. Jacobs and Van Dingenen[23] showed how the scaling of Eq. (2) can invert from soft to hard (pressed) panel: however, in the study it is not provided a formal explanation of the trend. The observation of scalings of energy absorption and the understanding of related mechanisms could lead into optimized panels against high-strain and strain-rate loads.

Our study focuses on these trends in order to find if and how the failure mechanism of ceramic-composite panels could be enhanced in order to maximize dissipation. The outcomes would be extensible in general to other typologies of multilayered structures. The effect of oblique impact on the ballistic limit is also studied. These scopes require advanced finite element models with proper material constitutive laws in order to catch the real dynamics of impactor–armour interaction and to find effective ways of developing optimized solutions. This work presents a numerical model for ballistic impact simulations in hybrid ceramic-fibre reinforced composite armours. The explicit non-linear finite element solver LS-DYNA®[24,25] was used.

2. Modelling of impact

Basing on an energetic approach for modelling impacts, as widely used in literature,[16–23] the variation of projectile kinetic energy in penetrating the plate must balance the amount of dissipated energy (E_{abs}) in the damaged volume of the target, which is assumed to be cylindrical and, defined by the projectile radius R and the plate thickness t. Thus, the following relation can be written:

$$\tfrac{1}{2}mV_0^2 - \tfrac{1}{2}mV_f^2 = \sigma\pi R^2 t \tag{3}$$

where m is the mass of the projectile, V_0 and V_f the initial and final velocity of the impactor respectively and σ the ultimate compressive strength of the material. Assuming a rigid projectile, Eq. (3) yields Eq. (1) for $q = 1$ and $p = 2$. A more realistic approach consists in considering the velocity as a quadratic function of the istantaneous impact velocity V; for each layer it can be assumed:

$$\sigma = \sigma_0\left(a_0 + a_1 kV + a_2 k^2 V^2\right) \tag{4}$$

where a_0, a_1, a_2 are parameters depending on material behaviour and impactor geometry according to Ref. 21, σ_0 is the material