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Optimal fibre architecture of soft-matrix ballistic laminates

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ABSTRACT

Soft-matrix ballistic laminates (such as those composed of fibres of Ultra High Molecular-Weight Polyethylene, e.g. Dyneema® HB26 and Spectra Shield) find extensive use as catching type armour systems. The relationship between the lay-up of these laminates with respect to the observed failure mechanisms has not been empirically investigated in the open literature, and is the subject of this work. Lay-ups are characterised by two parameters: (i) sequencing (or interply lay-up angle) $\bar{\theta}$ and (ii) in-plane anisotropy β, and can be mapped on to $\bar{\theta} - \beta$ space. Four geometries that lie at the extrema of this parameter space are designed, built and tested. Testing is through ball bearing impact on circular clamped plates. The anisotropy (β) is coupled to the macroscopic response of the plates, while sequencing ($\bar{\theta}$) is coupled to the microscopic response. Penetration velocity is strongly affected by pull-out at the boundary, and in the present study this is shown to account for two-thirds of the ballistic resistance. The results have implications for validation testing on scaled samples, predictive modelling and simulation, and armour design.

1. Introduction

Light-weight ballistic armours are of key interest as protective systems against high velocity fragments, both for military application (protective vests) and civil use (turbine engine nacelles). At present, the best mass-efficient armours are polymer fibre based laminates. Ultra High Molecular-weight Polyethylene (UHMWPE) fibre laminates are one such armour system. They are of a class of composite materials that differ from more traditional structural composite systems (like carbon-fibre reinforced epoxies) in that they are significantly weaker in shear [1]. The combination of high fibre strength and low matrix shear strength results in a suite of complex mechanisms that give rise to their unrivalled performance, and consequently, they see extensive use in military and civil protection. It is only recently that much of the underlying physics has been understood. Low shear strength enables large interlaminar and intralaminar shear strains [1,2], increasing the structural compliance to allow out-of-plane displacement, and in so doing, reducing the peak pressures exerted by the projectile. The nature of the local failure of the fibres under the projectile has been the subject of some debate, but recent publications [3,4] provide evidence for the so-called *indirect-tension* mechanism, whereby fibres fail in tension through the constraint imposed on lateral expansion by the orthogonal arrangement of plies. An important component of this mechanism is the pressure-dependent shear stress which has been demonstrated in these laminates [5].

The fibre architecture within a plate has a first-order effect on its ballistic limit; yet there is very little literature that explores this aspect. The ballistic capability of laminates with an orthogonal lay-up was recognised by inventors in the late 1940s [6,7], and is still the architecture chosen for the latest fibrous armours [8]. Vargas-Gonzalez et al. [9], Vargas-Gonzalez and Gurganus [10], and Zhang et al. [11] investigate a large number of lay-ups (orthogonal lay-ups, isotropic, and hybrids) and fibre types to assess both ballistic limit and back face deflection in relation to helmet design. Both parameters must be balanced to achieve acceptable survivability. Wang et al. [12] looked at the effect of multi-angled plies with woven fabrics, and report that multi-angled plies absorb more energy. Some studies using carbon fibre/epoxy composites have been performed on so-called helicoid lay-ups (e.g. [13,14]). These showed an improvement in impact strength over more traditional quasi-isotropic lay-ups.

The gap in understanding is how fibre architecture relates to these assessment criteria (i.e. ballistic limit, back face deflection) with respect to the underlying mechanics; and consequently, what tools are required for the engineer to design configurations that maximise penetration resistance, back face deflection, or some combination of the two.

Presently, it shall be demonstrated how the lay-up architecture relates to a number of different deformation mechanisms that operate in polyethylene fibre laminates systems. In particular, the essential characterisation parameters of the laminate are defined that relate to the main mechanistic groups. Configurations are tested

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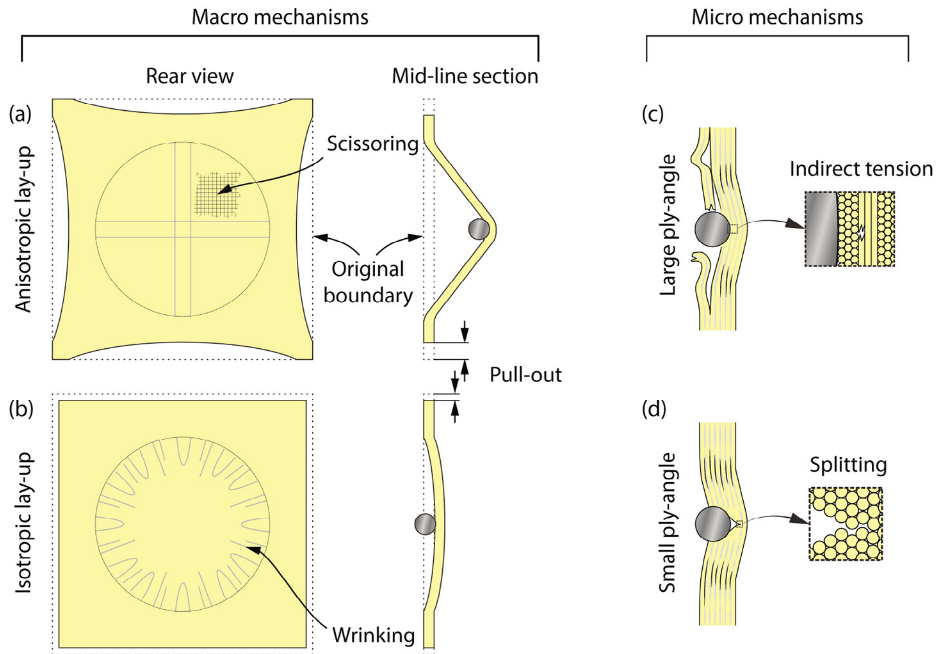

Fig. 1. Overview of the deformation mechanisms of UHMWPE laminates. Macro mechanisms differ between (a) anisotropic and (b) isotropic lay-ups. In the first case, pull-out is large and scissoring occurs; in the latter, pull-out is small and wrinkling is seen. Micro mechanisms operating under the projectile are either (c) fibre-failure through indirect-tension, which is associated with large ply off-set angles, and (d) splitting, occurring at small angle off-sets.

that explore the extremes of lay-up design. We then proceed to demonstrate where optimal lay-ups exist with respect to ballistic limit.

1.1. Macro and micro mechanism groups

The failure of UHMWPE laminates is complex, involving a range of interrelated mechanisms. The approach taken here is to categorise deformations into what shall be termed *macro mechanisms*: deformations that occur over the whole geometry, and *micro mechanisms*: deformations in the immediate vicinity of the projectile impact site (Fig. 1). The former encompass a group of interacting mechanisms: pull-out, interlaminar shear, intralaminar shear (or scissoring), and the latter: indirect tension and splitting. These two umbrella categories shall be considered throughout this paper.

We shall presently show how the laminate architecture influences both the macro and micro mechanisms, and how the overall ballistic performance arises from the contribution that each of these categories brings in the retardation of the projectile.

For clarity, splitting and indirect tension are defined at this point, since these terms are used to mean specific things throughout this study.

Splitting

This is the transverse failure of a ply (or stack of plies) with respect to the fibre direction (Fig. 1d). The strength is governed by the matrix tensile strength and the interfacial strength between fibre and matrix. Fibres themselves are not fractured, rather they are pushed laterally with respect to the projectile trajectory to allow passage of the projectile.

Indirect tension

Fibre-failure within a 0°/90° lay-up under the projectile has been extensively investigated and modelled [3,4,15]. Failure of fibres is through tension, which arises from the mutual constraint imposed on the Poisson's expansion from the alternating 0° and 90° plies. An important component is the pressure-dependent shear strength that prevents splitting. Note here that the deformation around the region of indirect-tension is complex and involves transverse ply failure, see detailed micro XCT of O'Masta et al. [4]. However, the term 'splitting' is reserved to indicate situations where transverse ply failure is the primary mechanism by which penetration is achieved.

1.2. Characterisation of architectures

Limiting the scope of architectures to 2D, non-woven systems, fibre lay-ups can be quantified in terms of their *anisotropic ratio* and *sequencing*. These quantities can be defined as follows:

Anisotropic ratio

The range of different ply angles in a lay-up will have a bearing on the variation of the in-plane stiffness (Fig. 2). Extreme anisotropy is seen in unidirectional long-fibre composites, where the longitudinal stiffness is often orders of magnitude greater than the transverse stiffness. The anisotropic ratio, β is defined thus:

$$\beta = \frac{E_{max} - E_{min}}{E_{max}} \tag{1}$$

where E_{max} and E_{min} are the maximum and minimum stiffnesses in the plane of the laminate. In the case of a UD lay-up: $\beta \sim 1$, and an isotropic lay-up would give: $\beta = 0$.

Sequencing

The angle between fibres of adjacent plies, θ, influences how plies interact with each other. The average of θ through the composite needs to take into account the ordering of plies through the whole laminate. Given that θ is not necessarily constant through the laminate, it is convenient to define an averaged quantity, $\bar{\theta}$:

$$\bar{\theta} = \frac{1}{k\,(n-1)} \sum_{i=1}^{n-1} |\theta_{i+1} - \theta_i| \tag{2}$$