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The soft impact response of composite laminate beams

K. Karthikeyan [a,*], B.P. Russell [a], N.A. Fleck [a], M. O'Masta [b], H.N.G. Wadley [b], V.S. Deshpande [a]

[a] *Cambridge University Engineering Department, Trumpington Street, Cambridge CB2 1PZ, UK*
[b] *Department of Material Science & Engineering, School of Engineering and Applied Science, University of Virginia, Charlottesville, VA 22903, USA*

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A B S T R A C T

The quasi-static and dynamic responses of laminated beams of equal areal mass, made from monolithic CFRP and Ultra high molecular weight Polyethylene (UHMWPE), have been measured. The end-clamped beams were impacted at mid-span by metal foam projectiles to simulate localised blast loading. The effect of clamping geometry on the response was investigated by comparing the response of beams bolted into the supports with the response of beams whose ends were wrapped around the supports. The effect of laminate shear strength upon the static and dynamic responses was investigated by testing two grades of each of the CFRP and UHMWPE beams: (i) CFRP beams with a cured matrix and uncured matrix, and (ii) UHMWPE laminates with matrices of two different shear strengths. Quasi-static stretch-bend tests indicated that the load carrying capacity of the UHWMPE beams exceeds that of the CFRP beams, increases with diminishing shear strength of matrix, and increases when the ends are wrapped rather than through-bolted. The dynamic deformation mode of the beams is qualitatively different from that observed in the quasi-static stretch-bend tests. In the dynamic case, travelling hinges emanate from the impact location and propagate towards the supports; the beams finally fail by tensile fibre fracture at the supports. The UHMWPE beams outperform the CFRP beams in terms of a lower mid-span deflection for a given impulse, and a higher failure impulse. Also, the maximum attainable impulse increases with decreasing shear strength for both the UHMWPE and CFRP beams. The ranking of the beams for load carrying capacity in the quasi-static stretch-bend tests is identical to that for failure impulse in the impact tests. Thus, the static tests can be used to gauge the relative dynamic performances of the beams.

1. Introduction

Ultra High Molecular Weight Polyethylene (UHMWPE) fibres were commercialised in the late 1970s by DSM Dyneema, NL under the trade name *Dyneema*® and more recently by Honeywell in the USA under the trade name *Spectra*. Both materials have densities of $\rho_f = 970$ kgm^{-3} below that of water and tensile strengths in excess of 3 GPa [1]. The very high specific strength of these fibres has led to many applications in high performance sails, fishing lines, marine mooring cables; in laminate form they are used for ballistic protection [2,3] and in woven-fabric form for protective gloves.

A number of studies have been conducted to measure the static [4–12] and dynamic response [13–17] of UHMWPE fibres and composites. For example, Russell et al. [18] have explored the highly anisotropic nature of UHMWPE composites: they measured tensile strengths of a few GPa along the fibre direction, and an in-plane shear strength of less than 10 MPa. Moreover, they observed that UHMWPE fibres display nearly no strain rate sensitivity for strain rates up to about 10^3 s^{-1}. Such measurements are used to develop continuum models (Grujicic et al. [19,20], Iannucci and Pope [21]) and are implemented within finite element codes in order to model the penetration resistance of UHMWPE composites.

Recently, there has been considerable interest in the application of multi-layered UHMWPE laminated composites to enhance the ballistic resistance of light weight vehicles. This interest arises from a commonly held view that the ballistic limit of fibre composites scales linearly with the so-called Cunniff velocity c^* of the fibre as given by

$$c^* = \left(\frac{\sigma_f \varepsilon_f}{2\rho_f}\sqrt{\frac{E_f}{\rho_f}}\right)^{1/3} \tag{1}$$

where σ_f and ε_f are tensile failure strength and strain of the fibres, respectively, while E_f is the tensile modulus of the fibres. The ballistic

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* Corresponding author. Tel.: +44 01223748525.
E-mail address: kk412@cam.ac.uk (K. Karthikeyan).

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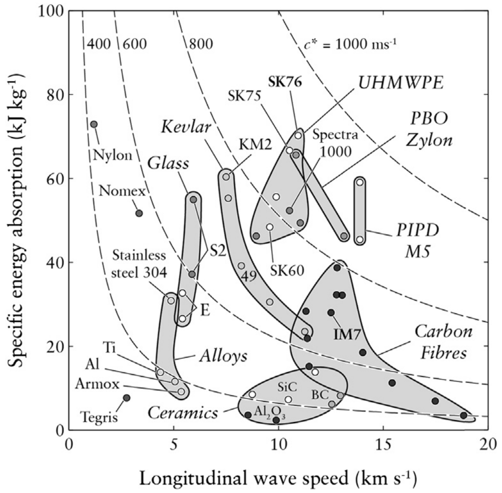

Fig. 1. Materials typically used for ballistic protection applications plotted in longitudinal wave speed versus specific energy absorption space. Contours of constant Cunniff velocity c^* are included to indicate the best ballistic materials.

performance of a large number of fibre composite systems scale with c^*, see Cunniff [2]. Subsequently, Phoenix and Porwal [3] rationalised this theoretically via a dynamic membrane stretching model. Candidate ballistic materials are plotted in Fig. 1 using axes of specific energy absorption and longitudinal wave speed. Contours of constant Cunniff velocity c^* are included in this plot. It is clear by this metric that the various grades *Dyneema*® fibre (SK60, SK76 etc.) and *Spectra* considerably outperform most other fibres and also surpass armour steels, supporting their use in ballistic applications. In contrast to the use of UHMWPE laminated composites for ballistic application, little data have been published on the ability of these composites to withstand air blast or landmine blast.

There is considerable current interest in the development of an understanding for the response of UHMWPE composite structures subjected to landmine blast loading; this is the focus of the present paper. Detailed dynamic measurements and observations of the deformations via high-speed photography are difficult in experiments involving the detonation of explosives (the gaseous explosive products often engulf the test structure and obscure visualisation via standard high-speed photography). Thus, alternative methods to simulate landmine blast loading within a laboratory setting have been proposed.

Park et al. [22] have developed an apparatus to launch high-speed sand slugs against structures to simulate the localised loading of structures by ejecta from a landmine explosion. They have demonstrated that the loading due to the sand is primarily inertial in nature. While such experiments conducted with sand slugs provide significant information on the mechanisms of the interaction of structure with sand ejecta, they are very difficult to perform and it is not practical to use this method for a wide ranging experimental study. More recently, Liu et al. [23] have used coupled discrete-continuum calculations to show that a metal foam projectile is able to simulate the loading of a sand slug to a remarkable degree of accuracy. The dynamic loading of structures via foam projectiles was first introduced by Radford et al. [24] as a method to simulate the soft impact of structures. Subsequently, this method has been widely used to quantify the dynamic performance of range of monolithic metal and sandwich structures [25–28] and was recently employed by Russell et al. [29] to study the dynamic response of Carbon Fibre Reinforced Plastic (CFRP) monolithic and sandwich beams.

The present study investigates the dynamic response of UHMWPE beams subject to sand ejecta loading as simulated via a metal foam projectile impact, and compares the response of UHMWPE and CFRP composite beams. Attention is restricted to UHMWPE laminates with an equal number of 0° and 90° plies: such laminates are the most commonly used layup of UHMWPE laminates for ballistic application. The focus is on understanding the effect of the matrix properties and of end clamping geometry on the blast performance of these structures.

The outline of our study is as follows. First are reported the manufacture of two grades of UHMWPE and CFRP composites and their quasi-static material properties. Second, discussion is made on the quasi-static stretch-bend response of beams made from these composites. Finally, the dynamic response of these beams subject to a metal foam impact is reported and the dynamic and quasi-static deformation and failure mechanisms contrasted. These observations are used to rationalise a method to rank the relative dynamic performance of the different beams using only quasi-static measurements.

2. Materials and properties

Two types of fibre laminates were investigated: (i) UHMWPE laminates manufactured by DSM Dyneema[1] and (ii) CFRP laminates manufactured by Hexcel Composites.[2] Two variants of each of these composites were employed in this study and their designations, fibre and matrix types, lay-ups and volume fraction V_f of fibres are listed in Table 1. All composite plates had an areal mass of approximately 5.89 kg m^{-2} with plate thicknesses as indicated in Table 1. A brief description of the manufacturing route for each of these composites is given below.

2.1. Composite fabrication

DSM Dyneema composites. Two grades of laminate, with commercial designations HB26 and HB50, were employed. The two laminates contained different matrices, and had slightly different number of plies in order to give the same areal mass, as detailed in Table 1. Both laminates are manufactured in 3 steps:

Step I: Fibres are produced through a gel-spinning/hot drawing process [30,31]. The UHMWPE is dissolved in a solvent at a temperature of 150 °C and the solution is pumped through a spinneret comprising a few hundred capillaries to form liquid filaments. These liquid filaments are then quenched in water to form a gel-fibre. The gel-fibre is drawn at a strain rate on the order of 1 s^{-1} in hot air (at 120 °C), resulting in a highly orientated and highly crystalline fibre of diameter 17 μm.

Step II: Fibres are coated in matrix resin solution and are then formed into a [0°/90°/0°/90°] stack. The stack is then dried to remove the matrix solvent.

Step III: The [0°/90°/0°/90°] stack is cut, laid-up to the required thickness and hot pressed (using a pressure of 20 MPa at 120 °C). Bonding of the layers is achieved through partial melting of the matrix.

CFRP laminates. Hexply® 8552/33%/134/IM7 (12 K) pre-preg, comprising unidirectional IM7 carbon fibres in an epoxy resin (fiberite 934), was obtained from Hexcel composites. Two composites were manufactured, with identical lay-ups as detailed in Table 1. The so-called cured composite was generated using the standard cure cycle for this resin system (2 h at 120 °C, held under a pressure of 0.6 MPa) and shall be subsequently referred to as 'CFRP-C'. The uncured composite was used in its pre-preg state and stored

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[1] DSM Dyneema, NL.

[2] Hexcel Composites, Duxford, UK.