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The compressive response of ultra-high molecular weight polyethylene fibres and composites

J.P. Attwood [a], N.A. Fleck [a], H.N.G. Wadley [b], V.S. Deshpande [a,*]

[a] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, UK
[b] Department of Material Science and Engineering, School of Engineering and Applied Science, University of Virginia, Charlottesville, VA 22904, USA

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ABSTRACT

Measurements are reported for the compressive response of ultra-high molecular weight polyethylene (UHMWPE) fibres and laminated composites loaded along the fibre direction. The compressive strength of the fibres was measured by both recoil tests and knot (or bend) tests. The strength of the fibres is governed by micro-kinking of the fibrils within the fibres. The recoil tests suggest that this kinking occurs at a compressive stress of approximately 340 MPa. Consistent with observations of other fibres such as Kevlar and carbon fibres, the compressive strength inferred from bending tests is approximately a factor of two higher than that from a direct compression test, such as the recoil test. The in-plane compressive response of laminated UHMWPE composites was measured using notched specimens. Two grades of composites with shear strengths of about 1.5 and 0.5 MPa were investigated and found to have compressive strengths of about 12 MPa and 3 MPa, respectively. Thus, unlike Kevlar composites, the composite compressive strength is not governed by the compressive strength of the fibres but by the micro-buckling of the composite plies. Detailed experimental measurements are reported for the kink-band width, fibre rotation within the band and its subsequent broadening after lock-up due to fibre rotation. These are shown to be adequately modelled by traditional kinking theory while a net section stress analysis models the propagation of the micro-buckle with sufficient fidelity.

1. Introduction

Composites comprising ultra-high molecular weight polyethylene (UHMWPE) fibres in a polyurethane matrix were originally developed for personnel and vehicle armours because of their exceptionally high tensile strength to density ratio, but are now being evaluated for air cargo containers, as backing materials for solar panels, and radomes, due to their microwave transparency. In most of these applications the composites are laminates comprising of unidirectional plies stacked in alternating 0° and 90° orientations.

Ultra-high molecular weight polyethylene fibres were commercialised in the late 1970s by DSM® under the trade name Dyneema®, and more recently by Honeywell in the USA under the name Spectra®. The fibres are composed of many sub-μm diameter filaments each consisting of densely packed, extended chain polyethylene molecules with molecular weights exceeding 10^6 Da. The fibres are highly anisotropic with properties in the fibre's longitudinal direction governed by the very strong sp^3 C—C bond while those in the radial direction are governed by weak van der Waals interactions. The fibres can be combined with thermoplastic polymers to make composite materials that can be shaped and consolidated by hot pressing below the melting point of the fibres (~135 °C). A number of studies have been conducted to measure the static stress–strain response (Wilding and Ward, 1978; Govaert and Lenstra, 1992) and dynamic stress–strain response (Russell et al., 2013; O'Masta et al., 2014; Koh et al., 2010; Chocron Benloulo et al., 1997) of UHMWPE fibres and their composites. For example, Russell et al. (2013) have observed that UHMWPE composites have tensile strengths of a few GPa but shear strengths of only a few MPa. Moreover, they found that the tensile strength of UHMWPE fibres exhibits nearly no strain rate dependence for strain rates between 10^{-1} and 10^3 s^{-1} Such measurements can provide the required inputs for continuum models (Grujicic et al., 2009; Iannucci and Pope, 2011) with the eventual goal of predicting the penetration resistance of UHMWPE composites.

These studies all focused on the tensile and shear properties of UHMWPE composites. To respond to the emerging structural

* Corresponding author.
E-mail address: vsd@eng.cam.ac.uk (V.S. Deshpande).

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applications of these materials, knowledge of the compressive response of both the fibres and laminates is imperative. However, there is a paucity of measurements and models for the compressive response of UHMWPE in the literature. Notable exceptions are: (i) the work of Liu et al. (2013) who investigated the bending response of Dyneema® composite beams and observed the formation of a compressive kink-band on the compressive face of the beam and (ii) the studies by Attwood et al. (2014) and O'Masta et al. (2015) who investigated the out-of-plane compressive response of Dyneema® composites. However, there are no reported studies on the direct compressive response of Dyneema® fibres and composites along the fibre direction.

The main competing mechanisms governing the compressive strength of long fibre composites are: (i) elastic micro-buckling, which is an elastic instability involving matrix shear; (ii) plastic micro-buckling in which the matrix deforms plastically; (iii) fibre crushing due to compressive fibre failure; (iv) splitting by matrix cracking parallel to the main fibre direction; (v) buckle delamination and (vi) shear band formation at 45° to the main axis of loading due to matrix yielding, as reviewed by Fleck (1997). In composites with high toughness matrices, the micro-buckling and fibre crushing modes are most commonly encountered. For example, the compressive strength of glass and carbon fibre polymer reinforced composites (GFRP and CFRP, respectively) is usually governed by elastic or plastic micro-buckling. While the micro-buckling strength is typically set by matrix properties, Kyriakides and Ruff (1997) showed that the wavelength, amplitude, distribution of imperfections and fibre waviness also strongly influences the strength of long-fibre composites. Moreover, Vogler and Kyriakides (1997) demonstrated that CFRP and GFRP composites can continue to carry (a reduced) load after the onset of micro-buckling by the broadening of the kink band. On the other hand, aramid fibre composites such as Kevlar typically fail by fibre crushing under compressive loading. In fact, Kevlar fibres themselves are micro-composites comprising wavy fibrils in a soft matrix and hence kink/crush by micro-buckling within the fibres, as shown by Greenwood and Rose (1974).

More recently, Laffan et al. (2012) following on from Sivashanker et al. (1996) investigated the compressive toughness and strength of notched unidirectional (UD) carbon fibre composites. Unlike Sivashanker et al. (1996), they observed that calculations based on an effective stress intensity factor were unable to predict the measurements with sufficient fidelity and attributed this discrepancy to failure modes such as crushing, band broadening and delamination, that were not appropriately accounted for in the toughness model. Finite element (FE) calculations reported by Laffan et al. (2012) reproduced these mechanisms with sufficient fidelity and agreed with the measured failure stresses to a high level of accuracy. These findings were further reinforced by Pinho et al. (2012) who emphasized the role of matrix splitting in governing the micro-buckling stresses and Wind et al. (2015) who showed that a FE model in which the fibres and matrix were explicitly modelled, captured the 4-point bend response of a notched CFRP specimen with a high degree of fidelity.

The difficulties in determining the exact sequence of events during the micro-buckling of CFRP cross-ply composites prompted Gutkin et al. (2010) to investigate the compressive failure of CFRP in-situ within an SEM. Their experiments revealed that fibre rotation and matrix splitting occurs simultaneously and the bending associated with rotations results in fibre fracture within the kink band. Prabhakar and Waas (2013) used a finite element model to study this interaction between kinking and splitting in fibre composites. They proposed that the mismatch in properties between the fibres and matrix results in large shear stresses being developed at the interfaces, leading to local misalignments and instabilities that cause the kink band to develop. Their parametric study demonstrated that the fibre/matrix sliding/splitting mechanism is critical in setting the compressive failure of fibre composites.

Kinking/micro-buckling theory as developed for fibre composites has also been shown to be applicable for other materials with a fibrous structure such as balsa wood which has a significantly lower shear to compressive strength ratio compared to conventional CFRP and GFRP composites; see for example Da Silva and Kyriakides (2007). Dyneema® composites are similar in this respect to balsa wood and here we investigate some fundamental aspects of the in-plane compressive failure of these composites. In particular we investigate the so-called micro-buckling phenomenon (which results in the formation of kink bands) as defined by Fleck (1997) in Dyneema® fibre composites. The outline of the paper is as follows. First, we report measurements of the compressive strength of Dyneema® fibres via both recoil and knot (bend) tests. Next, the compressive response of two grades of Dyneema® composites (with different polymer matrices but the same fibre) is investigated using an edge notched compression specimen. Measurements are reported for the propagation as well as the structure of the kink-band. Compressive strength predictions based on kinking theory are finally compared with the observations.

2. Compressive strength of fibres

When the matrix of a composite is sufficiently stiff and strong the usual elastic and plastic micro-buckling compressive failure mechanisms are not operative, and alternative failure modes such as fibre crushing intervene. Fibre crushing occurs when the uniaxial strain in the composite is equal to the intrinsic crushing strain ε_f^c of the fibres. A variety of mechanisms may be associated with fibre crushing including: (i) local crushing due to plastic yielding (e.g. in steel fibres) (Piggott and Wilde, 1980; Fleck, 1997); (ii) longitudinal splitting of glass fibres, and (iii) microscopic micro-buckling or kinking within each Kevlar or carbon fibre wherein the micro-fibrils within the fibres kink due to the deformation of the intervening matrix. Typical fibre crushing strains are $\varepsilon_f^c = 0.5$ and 2.5% for Kevlar and PAN-based carbon fibres, respectively. There are no reported fibre compressive strength measurements for ultra-high molecular weight polyethylene fibres and here we report compressive strength measurements for single SK76[1] fibres using two techniques. Measurements of its other mechanical properties can be found in Russell et al. (2013).

2.1. Recoil tests

Allen (1987) developed a recoil technique to measure fibre compressive strengths. Here we summarise salient aspects of this technique, and refer readers to Allen (1987) for further details. A single filament/fibre is rigidly clamped at one end and a known weight W hung vertically from the other (Fig. 1a). Under static conditions this generates a tensile stress

$$\sigma_0 = \frac{W}{\pi a^2} \tag{2.1}$$

within the fibre, where a is the radius of the circular fibre. This fibre is then suddenly cut at a length L_0 from the rigid support at time $t = 0$. The spatio-temporal evolution of the stress within the fibre, assuming that the fibre remains linear elastic, is sketched in Fig. 1b with $x = 0$ and $x = L_0$ corresponding to the clamped and cut edges of the fibre. At time $t = 0^-$, the stress $\sigma = \sigma_0$ throughout the fibre and reduces to zero at $x = L_0$ at $t = 0$. This zero stress front then moves from $x = L_0$ towards the clamped end as the initial

[1] SK76 is a grade of the Dyneema® UHMWPE fibre manufactured by DSM.