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The out-of-plane compressive response of Dyneema® composites

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Out-of-plane compression tests were conducted on six grades of ultra high molecular weight polyethylene fibre composites (Dyneema®) with varying grades of fibre and matrix, ply thickness, and ply stacking sequence. The composites with a [0°/90°] lay-up had an out-of-plane compressive strength that was dictated by in-plane tensile fibre fracture. By contrast, the out-of-plane compressive strength of the uni-directional composites was significantly lower and was not associated with fibre fracture. The peak strength of the [0°/90°] composites increased with increasing in-plane specimen dimensions and was dependent on the matrix and fibre strength as well as on the ply thickness. A combination of micro X-ray tomography and local pressure measurements revealed the existence of a shear-lag zone at the periphery of the specimens. Finite element (FE) and analytical micromechanical models predict the compressive composite response and reveal that the out-of-plane compression generates tensile stresses along the fibres due to shear-lag loading between the alternating 0° and 90° plies. Moreover, the compressive strength data suggests that the shear strength of Dyneema® is pressure sensitive, and this pressure sensitivity is quantified by comparing predictions with experimental measurements of the out-of-plane compressive strength. Both the FE and analytical models accurately predict the sensitivity of the compressive response of Dyneema® to material and geometric parameters: matrix strength, fibre strength and ply thickness.

1. Introduction

Low density fibre composites are increasingly used in lightweight structures where ballistic resistance is a requirement. Kevlar, other aramid composites, and more recently composites made from ultra high molecular weight polyethylene (UHMWPE) fibres embedded in thermoplastic matrices are exploited for their superior impact resistance.

Ultra high molecular weight polyethylene 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 name Spectra®. A number of studies have been conducted to measure the static stress–strain response (Liu et al., 2014; Wilding and Ward, 1978; Govaert and Lenstra, 1992) and dynamic stress–strain response (Russell et al., 2013; O'Masta et al., 2014b; Koh et al., 2010; 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

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GPa but shear strengths of only a few MPa. Moreover, they found that the tensile strength of UHMWPE fibres displays nearly no strain rate dependence for strain rates up to $10^3\ s^{-1}$. Such measurements have been utilized for the development of continuum models (Grujicic et al., 2009; Iannucci and Pope, 2011) with the goal of predicting the penetration resistance of UHMWPE composites. However, penetration calculations performed using such constitutive models (Grujicic et al., 2009; Iannucci and Pope, 2011) are typically unable to predict the ballistic performance of UHMWPE composites unless unrealistic material parameters are employed (for example, a tensile strength of approximately 2 GPa is used in these numerical models rather than the measured value of approximately 800 MPa for the [0°/90°] laminate (Russell et al., 2013)).

An alternative approach to predicting the ballistic performance of UHMWPE composites is based on the scaling relation of Cunniff (1999). He argued that the ballistic limit of fibre composites scales linearly with the so-called Cunniff parameter

$$c^* = \left(\frac{s_f e_f}{2\rho_f}\sqrt{\frac{Y_f}{\rho_f}}\right)^{1/3} \quad (1)$$

where s_f and e_f are the tensile failure strength and failure strain of the fibres, respectively, and Y_f is the tensile modulus of the fibres of density ρ_f. In an elegant analytical study, Phoenix and Porwal (2003) demonstrated that the ballistic limit of composite plates scales with c* when an impacted plate undergoes membrane stretching deformation and failure. However, there is growing experimental evidence that the matrix shear strength (which governs the inter-laminar shear strength) has a significant influence on the ballistic performance of UHMWPE composites. For example, Karthikeyan et al. (2013b) have reported ballistic measurements where the composite shear strength was systematically varied, while keeping the tensile strength in the fibre directions fixed. Their measurements show a clear trend whereby the ballistic resistance increases with decreasing shear strength; such an effect is neither captured by the scaling relation (1) nor predictable from a membrane stretching analysis. Further, Greenhalgh et al. (2013) have reported a detailed fractography study and argued qualitatively that the matrix shear strength influences energy absorption and failure mechanisms such as delamination and splitting.

UHMWPE composites are often loaded in out-of-plane compression. For example, the normal impact of projectiles against UHMWPE composites during ballistic events generates out-of-plane compressive loading beneath the projectile. Similarly, the clamping pressure to grip a composite plate results in out-of-plane compressive loading with rather surprising consequences to the structural response, as detailed below.

1.1. *Effect of clamping on the failure of* Dyneema® *beams*

Our interest in the out-of-plane compressive response of composites originated during experiments by Karthikeyan et al. (2013a), on the stretch-bend response of clamped Dyneema® beams (grade HB50) using the apparatus, sketched in Fig. 1. Beams of length 400 mm, width 35 mm and thickness 6 mm were clamped by 5 M6 bolts and a 10 mm thick steel cover plate at each end, as sketched in Fig. 1a(i). The free-span of the beams was 200 mm and the bolts were tightened to a torque of 9 Nm. The measured load F versus central roller displacement δ from the study of Karthikeyan et al. (2013a) is given in Fig. 1b, and a photograph of the observed failure mode of the HB50 beams is shown in Fig. 1c. In-plane failure of the Dyneema® occurred between the bolt-holes within the clamped region; fibre fracture occurred with minimal deformation of the bolt-holes. The measured load versus displacement curve exhibited a dramatic load drop at the point of fibre failure.

Here we repeated the stretch-bend test of Karthikeyan et al. (2013a) with one small modification. A spacer was introduced into the clamping set-up such that the steel cover no longer applied a clamping pressure, see Fig. 1a(ii). The measured load versus displacement curve for the case with no clamping pressure has been added to Fig. 1b and a photograph of the section of the beam within the clamping zone at a displacement $\delta = 115$ mm is included in Fig. 1c. There is a dramatic change in failure mode, due to relaxation of the clamping constraint. Extensive in-plane shear deformation now occurs and this results in elongation of the bolt-holes, with no fibre fracture. Consequently, the load versus displacement curve shows no dramatic load drop.

These observations suggest that the shear strength of the HB50 Dyneema® composite is *pressure sensitive*. This is consistent with a large body of data on polymers including polyethylene, see for example Ward (1971) and Spitzig and Richmond (1979). When clamping pressure is applied the shear strength is enhanced such that it allows the net-section stress within the beam to build up to the fibre failure stress. In contrast, when no clamping pressure is applied the low shear strength of the HB50 composite resulted in shear deformation at the sides of the bolts, and the net section stress does not attain the level required to cause fibre fracture. We conclude that constraint has a major effect on the observed failure mechanism.

A literature search reveals that little is known about the out-of-plane response of fibre composites. Henriksson (1990) presented an elastic laminate plate theory analysis to calculate the out-of-plane modulus of cross-ply CFRP composites but no analysis of the plastic response and associated failure was given. To-date there have been no investigations of the out-of-plane compressive behaviour of Dyneema® composites and any associated pressure sensitivity of the shear strength. This is the focus of the present study.

The outline of the paper is as follows. First, we summarise the manufacturing process of DSM Dyneema, NL, followed by a description of the microstructure and composition for several grades of Dyneema®. Second, the in-plane tensile response and inter-laminar shear response of these composites are reported. The sensitivity of the out-of-plane compressive response of Dyneema® composites to the inter-laminar shear strength, the fibre strength, ply stacking sequence and ply thickness are determined. Finally, we describe analytical and finite element (FE) models for the out-of-plane compressive response and validate the predictions by the measurements.