THE MICROBUCKLING FAILURE OF DYNEEMA® COMPOSITES UNDER COMPRESSION

Guangyan Liu¹(†), Wei Zhu², Guangyan Huang²
¹School of Aerospace Engineering, Beijing Institute of Technology, Beijing, China
²School of Mechatronical Engineering, Beijing Institute of Technology, Beijing, China
(†)Email: gliu@bit.edu.cn

ABSTRACT
Two grades of Dyneema® composite laminates with the commercial designations HB26 and HB50 were cut into blocks with or without an edge crack and subjected to compression in the longitudinal fiber direction. The cracked and uncracked specimens show similar compressive responses including failure pattern and failure load. The two grades of Dyneema® composites exhibits different failure modes: a diffuse, sinusoidal buckling pattern for Dyneema® HB50 due to its weak matrix constituent and a kink band for Dyneema® HB26 due to its relatively stronger matrix constituent. An effective finite element model is used to simulate the collapse of Dyneema® composites and the sensitivity of the predicted microbuckling responses to the overall effective shear modulus and interlaminar shear strength are investigated. The change of failure mode from kink band to sinusoidal buckling pattern by decreasing the interlaminar shear strength is validated by the finite element analyses.

Keywords: Ultra high molecular-weight polyethylene, Microbuckling, Cohesive, Finite Element Analysis, Compression.

INTRODUCTION
Ultra High Molecular-weight Polyethylene (UHMWPE) fibres are the third generation of high-performance fibres after carbon fibres and Kevlar fibres. They possess strengths several times higher than that of steel and densities less than water, making them popular in lightweight armour systems. The UHMWPE fibres have been commercialised in the late 1970s by DSM Dyneema, NL under the trade name Dyneema®. To enhance the bullet-proof and blast-resistant capability, Dyneema® composites are usually hot-pressed to a laminate with a 0/90 cross-ply configuration. A detailed description on the processing steps in manufacturing of Dyneema® composite laminates can be found in Russell (2013). Although Dyneema® composites are finding increasing applications in armour protection industries, the mechanisms by which they outperform other composites in ballistic and blast resistance still remain poorly understood. So far extensive research has focused on the ballistic performance of Dyneema® composites (Tan, 2003; Tan, 2005; Greenhalgh, 2013). By testing two grades of Dyneema® composites with different matrix constituents, Karthikeyan (2013) argued that the load carrying capacity of composites can be enhanced by reducing the interlaminar shear strength.

Some finite element models have been proposed in literature for Dyneema® composites. For example, Iannucci (2011) studied the ballistic impact behaviour of Dyneema® composites by continuum damage-mechanics approaches. Utomo (2008) embedded rod elements in continuum elements to model fibre bundles discretisation in Dyneema® composites. Although some damage features can be predicted by these models, most of them are based on empirical
approaches. To know better of the failure mechanisms of Dyneema® composites, there is an urgent need for basic material property tests. Russell (2013) measured the strain rate responses of Dyneema® fibres, yarns and laminates. It is observed that the tensile strength of the yarns is insensitive to strain rate in the range of $10^{-2}/s$ to $10^3/s$. Attwood (2014) investigated the out-of-plane compressive response of six grade of Dyneema® composites and found that the out-of-plane compression generates tensile stresses along the fibres due to shear-lag loading between the alternating 0° and 90° plies. Liu (2014, 2015) studied the collapse mechanisms of Dyneema® HB26 cantilever beams. The measured shear modulus and strength are about three orders lower than the Young’s modulus and tensile strength in fiber direction. Due to this high anisotropy, long beams show a collapse mode of two wedge-shaped kink bands. This new type of microbuckling involves both elastic bending and shearing of the plies, and plastic shear of the interface between adjacent plies. Inspired by this work, the microbuckling response of Dyneema® composites in compression will be studied in this paper to understand further on the collapse mode of composite laminates.

The paper is organized as follows. In Section 2, the compressive responses of two grades of Dyneema® composites, HB26 and HB50, are reported. Section 3 describes a finite element model used to simulate the microbuckling failure of Dyneema® composites. In Section 4, a sensitivity study of the predicted microbuckling responses to the laminate effective shear modulus and interlaminar shear strength is performed. Section 5 gives some concluding remarks.

EXPERIMENTAL INVESTIGATION OF DYNEEMA® COMPOSITES IN COMPRESSION

Dyneema® laminate plates were obtained from Henan Yongwei Security Co. LTD, China. The company bought Dyneema® composites in a [0/90/0/90] stack from DSM and then cut, laid-up and hot pressed them to laminate plates. Two grades of Dyneema® composites with the commercial designations HB26 and HB50 were tested in this study. Each was composed of a compliant thermoplastic resin reinforced with a high volume fraction (>80%) of UHMWPE fiber, and provided us with cross-ply laminates in the form of [0/90]_{3x}. Dyneema® HB26 utilizes SK76 for the fiber and a polyetherdiol-aliphatic diisocyanate polyurethane (PADP) resin for the matrix. Dyneema® HB50 uses the same type of fiber, but a much more compliant styrene–isoprene–styrene triblock copolymer (SISTC) resin for the matrix. Therefore, both grades have the same ply tensile strength (about 1.6GPa (Russell, 2013; Attwood, 2014)) but different interlaminar shear strength. Double-notch shear tests have been conducted to measure the interlaminar shear strength (Liu, 2014; Attwood, 2014; O’Masta, 2015). The reported values for Dyneema® HB50 range from 0.2 to 0.35MPa, which are about 5 to 9 times lower than those of the HB26 grade.

The compressive behaviors of the Dyneema® composites were studied by experiments using the geometry shown in Fig. 1(a), with a sharp edge crack being used to initiate the formation of a kink band. In this figure, the x- and y-axis correspond to the 0° and 90° fiber directions, respectively, and z-axis corresponds to the thickness direction. The tests were conducted on a screw-driven testing machine with a cross-head speed of 0.1 mm/min. The axial force on the specimen and the compressive displacement were measured directly with the load cell of the test machine. The deformation of the specimen during the loading history was recorded using a digital camera. The maximum nominal compressive stress acting on the ligament was equated to the compressive strength, and the average compressive strength for Dyneema® HB26 was determined to be 34.3MPa with a coefficient of variation of 10.2% from a series of
nine tests. It has been shown by Liu (2015) that the longitudinal splitting along the fiber direction due to matrix yielding or debonding will alleviate the stress concentration at notch tips. For Dyneema® composites, the matrix constituent is extremely weaker than the fiber. The yielding of the matrix at the crack tip will blunt the crack and make the stress concentration very small. For this reason, the nominal compressive stress is calculated by averaging the applied load over the ligament area. To confirm this, three compressive tests on uncracked blocks with geometry shown in Fig. 1(b) were also conducted. The width of the uncracked specimen is equal to the ligament length (25mm) of the cracked specimen, and other dimensions are the same as those of the cracked specimen. It was found both the average compressive strength and final failure pattern are quite similar between the uncracked and cracked specimens.

![Fig. 1 - Schematic illustration of the geometry of Dyneema® specimens in compression.](image)

Fig. 1 shows a representative plot of the nominal compressive stress versus compressive displacement curve with occasional unloading and reloading for a cracked Dyneema® HB26 specimen. The inset images on this plot show the evolution of the kink band at various stages

![Fig. 2 - Plot of nominal compressive stress versus compressive displacement for a cracked Dyneema® HB26 specimen. Inset images show the evolution of the kink band during the loading history.](image)
during the loading history. It can be observed that microbuckling starts from the crack tip and propagates in a direction perpendicular to the loading. With the increasing of the compressive displacement, an inclined kink band is formed. Fig. 3 shows the kink band of a failed specimen as viewed on a plane perpendicular to the direction of the kink-band propagation. Images in Fig. 3(b) and 3(c) were taken by a Keyence laser scanning microscope, which scans the specimen square by square and the square patterns can be seen in these figures. The specimen failed by out-of-plane plastic microbuckling mainly due to the plastic shear of the interfaces between plies. The formation of the kink band is sketched in Fig. 4, where the plastic kinking of a band of width $w$ inclined at an angle $\beta$ to the remote fiber direction, and the fibers within the kink band rotated by an angle $\alpha$ to the initial fiber direction. For comparison, the images of a failed specimen without initial crack are shown in Fig. 5. The same failure mode, i.e., an inclined kink band is also observed for this uncracked specimen. However, the location of the kink band might not be in the middle of the specimen. It depends on the position and magnitude of the initial imperfection, such as fiber misalignment or ply waviness in the laminate.

Fig. 4 - Schematic illustration of the kink band in failed Dyneema® HB26 specimen.
To explore the effect of interlaminar shear strength on the microbuckling response, compressive tests on Dyneema® HB50 were also conducted. The average compressive strength for Dyneema® HB50 was determined to be 7.6MPa with a coefficient of variation of 16.7% from a series of nine tests. Fig. 6 shows a representative plot of the nominal compressive stress versus compressive displacement curve for a cracked Dyneema® HB50 specimen. The inset images on this plot show the deformation at various stages during the loading history. Since no much useful information could be extracted from the images for the face of the specimen ($x-y$ plane), the deformed shapes are shown in the $x-z$ plane. It can be seen that out-of-plane microbuckling initiates from a location near the top end instead of the crack tip in the middle of the specimen. With the increasing of the compressive displacement, a diffuse and sinusoidal buckling pattern is formed and no inclined kink band is observed. Due to the extremely weak matrix constituent, the stress concentration is negligibly small at the crack tip. In this case, the fiber misalignment or ply waviness will become to the dominant factor to initiate the microbuckling. Because the plies are weakly bonded at the interfaces, it seems that the $0^\circ$ plies undergo elastic buckling individually.

![Fig. 6 - Plot of nominal compressive stress versus compressive displacement for a cracked Dyneema® HB50 specimen. Inset images show the deformation during the loading history.](image-url)
FINITE ELEMENT SIMULATIONS OF DYNEEMA® COMPOSITES IN COMPRESSION

Since the cracked and uncracked Dyneema® specimens presented very similar compressive responses and both were failed by out-of-plane microbuckling, only the uncracked specimens are modelled in this section. For simplicity, a two dimensional finite element analysis was performed using the explicit version of the commercial finite element software ABAQUS. In this manner, the size of the degree of freedom in the finite element model is significantly decreased and an enormous amount of computational time can be saved. Due to the lack of material properties for the Dyneema® composites tested in this paper, material properties reported by Liu (2014) for Dyneema® HB26 laminates from DSM are used in the finite element simulations. It should be noted that the material properties, mainly the shear modulus and interlaminar shear strength, could be very different due to the different manufacturing processes, which are confidential for both DSM and Henan Yongwei Security Co. LTD. Therefore, the comparison of compressive strength between tests and simulation is not made, and our focus is on the sensitivity of failure patterns on composite shear modulus and interlaminar shear strength.

In microbuckling failure analysis of composite laminates, an initial ply misalignment with a geometric imperfection is usually introduced in the finite element model to trigger the observed microbuckling. In this study, a portion of length $\lambda$ in the middle of the Dyneema® composite laminate is rotated through an imperfection angle $\phi$, see Fig. 7. A parametric study is performed in order to determine the sensitivity of the collapse response on $(\phi, \lambda)$.

![Finite element model of Dyneema® laminates in compression.](image)

Table 1 - Material properties of solid elements in the two dimensional finite element analyses

<table>
<thead>
<tr>
<th></th>
<th>$E_1$</th>
<th>$E_2$</th>
<th>$v_{12}$</th>
<th>$G_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° ply</td>
<td>68GPa</td>
<td>150Mpa</td>
<td>0.3</td>
<td>100Mpa</td>
</tr>
<tr>
<td>90° ply</td>
<td>150Mpa</td>
<td>150Mpa</td>
<td>0.3</td>
<td>100Mpa</td>
</tr>
</tbody>
</table>

Each ply has been modelled by four-noded plane strain elements with reduced integration (CPE4R in ABAQUS notation). A mesh dependent study revealed that two elements per ply in the thickness direction are adequate. Orthotropic properties were assigned to the elements, as shown in Table 1. Here the 1- and 2-directions lie along the longitudinal and thickness directions, respectively. Four-noded zero-thickness cohesive elements (COH2D4 in ABAQUS notation) were placed between adjacent plies to allow for delamination. Consequently, the final mesh was comprised of 95 layers of cohesive elements connecting 96
plies for a cross-ply laminate [0/90]_{48}. In the simulations, the laminate was subjected to an increasing uniform displacement at its end. The displacement rate was chosen to be sufficiently small for inertial effects to be negligible.

An elastic-plastic traction-separation law was used for the cohesive elements. The same or similar methods have also been used in Liu (2014, 2015) and Guo (2014). The total separation rates can be written as the sum of an elastic part and a plastic part,

\[
\begin{align*}
\dot{U}_n &= \dot{U}^{el}_n + \dot{U}^{pl}_n \\
\dot{U}_s &= \dot{U}^{el}_s + \dot{U}^{pl}_s
\end{align*}
\]  

(1)

where \( \dot{U}_n \) and \( \dot{U}_s \) are separation rates in normal and shear directions, respectively. The elastic separation rates are related to the traction rates by:

\[
\begin{align*}
\dot{U}^{el}_n &= \frac{\dot{T}_n}{k_n} \\
\dot{U}^{el}_s &= \frac{\dot{T}_s}{k_n}
\end{align*}
\]  

(2)

where \( k_n \) is the initial stiffness of the cohesive law. The value of \( k_n \) is adjusted to ensure that the effective elastic shear modulus of the composite equals to the measured one. \( \dot{T}_n \) and \( \dot{T}_s \) are traction rates in normal and shear directions, respectively. A power law is used to describe the plastic separation rates:

\[
\begin{align*}
\dot{U}^{pl}_n &= U_0 \left( \frac{\dot{T}_n}{T_0} \right)^{n-1} \frac{\dot{T}_n}{T_n} \\
\dot{U}^{pl}_s &= U_0 \left( \frac{\dot{T}_s}{T_0} \right)^{n-1} \frac{\dot{T}_s}{T_s}
\end{align*}
\]  

(3)

where \( T_0 \) is the effective traction defined as \( T_0 = \sqrt{(T_n)^2 + (T_s)^2} \), \( T_0(U_0^{pl}) \) is the flow traction at an equivalent plastic separation \( U_0^{pl} \) defined by \( U_0^{pl} = \sqrt{(U_n^{pl})^2 + (U_s^{pl})^2} \), \( U_0 \) and \( n \) are the reference separation rate and separation rate sensitivity exponent, respectively. In order to simulate the quasi-static response, a small value of reference separation rate \( \dot{U}_0 = 0.001 m/s \) and a big value of separation rate sensitivity exponent \( (n = 10) \) were used in all of the FE analyses. The Macaulay bracket \( \{ \) implies that compressive tractions are omitted (i.e. given a value of zero). The elastic-softening plastic cohesive law (Fig. 8) was implemented for the cohesive elements. The traction-separation curve was determined by modelling Dyneema® double-notch shear test specimens (Liu, 2014). Inspired by experimental results, some residual strength (0.2 MPa) remains instead of decreasing to zero for the flow traction.

\[
\begin{align*}
T_0 \text{ (MPa)} & \\
\hline
\text{U}_0^{pl} \text{ (mm)} & \\
0 & 0.2 \quad 2.0 \quad 20 \quad 0.1 \quad 0
\end{align*}
\]  

Fig. 8 - The softening cohesive zone law used to model the interlaminar failure of the Dyneema® composites.
The predicted compressive response of a Dyneema® composite is given in Fig. 9a for an imperfection length of $\lambda = 40t$, where $t = 60\mu$m is the ply thickness, and selected values of imperfection angle $\phi = 0^\circ$, 2.5°, 5° and 7.5°. Similarly, the response is given in Fig. 9b for $\phi = 5^\circ$ and for selected values of $\lambda (= 0, 20t, 40t$ and $60t)$. In all cases the predicted response is almost linear elastic followed by a peak load and then an abrupt load drop to a nearly constant stress with ensuing displacement. This stress level is in the magnitude of about 10MPa, which is in good agreement with the derived microbuckling stress of Dyneema® HB26 from cantilever beam bending analysis (Liu, 2014). It is clear that the predicted peak stress is quite sensitive to the imperfection angle $\phi$. The peak stress decreases with the increasing of the imperfection angle $\phi$. In contrast to the imperfection angle, the compressive response is only mildly sensitive to the imperfection length $\lambda$. The peak stress decreases gracefully with the increasing of the imperfection length $\lambda$. The deformed shapes of the laminates at a compressive displacement of 0.3mm are given in Fig. 10 for the values of imperfection reported in Fig. 9. It is evident that all models show similar kink band features, regardless of the choice of initial imperfection.

![Fig. 9 - Sensitivity of Dyneema compressive response to initial imperfection. Nominal compressive stress versus compressive displacement response for (a) $\lambda = 40t$, and (b) $\phi = 5^\circ$.](image)

![a) Effect of imperfection angle ($\lambda = 40t$)](image)
SENSITIVITY OF PREDICTED MICROBUCKLING RESPONSES TO EFFECTIVE SHEAR MODULUS AND INTERLAMINAR STRENGTH

Dyneema® composites show high anisotropy with very high Young’s modulus and tensile strength in the fiber direction, and extremely low shear modulus and interlaminar shear strength. In the above finite element models of Dyneema® HB26, appropriate orthotropic elastic constants are ascribed to each ply, and appropriate interlaminar strength is ascribed to each interface. Since it has been observed from the experiments in Section 2 that Dyneema® HB50 shows different microbuckling response from Dyneema® HB26 by only changing the matrix constituent, it is instructive to investigate the sensitivity of the microbuckling responses of composite laminates to the shear modulus and interlaminar shear strength. For this purpose, finite element analyses are performed using the model described in Section 3 but varying the overall effective shear modulus \(G_{\text{eff}}\) and interlaminar shear strength \(\tau_{\text{max}}\). The dimensions of the model are the same as those shown in Fig. 7, in which an imperfection length of \(\lambda=40t\) and imperfection angle of \(\phi=5^\circ\) are used. Recall that the overall effective shear compliance of the model is the sum of the compliances of the solid elements and the cohesive elements, it is assumed that the solid elements and cohesive elements contribute equally to the overall effective shear compliance.

The predicted compressive stress against compressive displacement curves and the deformed shapes at a compressive displacement of 1.0mm are given in Fig. 11 for eight selected values of overall effective shear modulus \(G_{\text{eff}}\). The compressive responses are summarized as follows:

1) In the range of 5MPa \(\leq G_{\text{eff}} \leq 100\)MPa, the predicted compressive stress is very sensitive to the effective shear modulus. A drop in the effective shear modulus leads to a drop in the peak compressive stress. The failure of the laminate is dominated by a kink band as observed in Dyneema® HB26 compression test (Fig. 5). The kink band width decreases with reducing the effective shear modulus.

2) An increase in the effective shear modulus from 100MPa to 500MPa leads to a change in the deformation mode: the kink band switches to a diffuse, sinusoidal buckling pattern.
For $G_{\text{eff}} \geq 500\text{MPa}$, the peak compressive stress is mildly sensitive to the effective shear modulus and the responses after the peak are almost identical.

Fig. 11 - Finite element calculation to illustrate the sensitivity of the response of composite laminates to the effective shear modulus $G_{\text{eff}}$. (a) The compressive stress versus compressive displacement curves. (b) The predicted deformed shapes at a compressive displacement of 1.0mm.
The predicted compressive stress against compressive displacement curves and the deformed shapes at a compressive displacement of 1.0mm are given in Fig. 12 for eight selected values of interlaminar shear strength $\tau_{max}$. The compressive responses are observed as follows:

1) In the range of $0.5\text{MPa} \leq \tau_{max} \leq 10\text{MPa}$, the failure pattern of the laminate is governed by a kink band. An increase in the interlaminar shear strength leads to an increase in the compressive stress and a decrease in the kink band width.

2) However, if continuing to increase the interlaminar shear strength to $50\text{MPa}$, the kink band width gets bigger and the kink band inclination angle becomes negligible.

3) A decrease in the interlaminar shear strength from $0.5\text{MPa}$ to $0.1\text{MPa}$ leads to a change in the deformation mode: the kink band switches to a diffuse, sinusoidal buckling pattern, which resembles the observed failure pattern of Dynema® HB50 in compression test (Fig. 6).
CONCLUSION

The present study highlights the collapse responses of Dyneema® laminates in compression. It is observed that specimens with or without an edge crack show similar collapse modes and collapse loads. This can be explained by the negligible stress concentration at the crack tip due to the extremely weak matrix in this type of material. Dyneema® HB26 laminates collapse by kink bands, whereas the HB50 grade laminates collapse in a diffuse and sinusoidal buckling pattern. This is attributed to the much weaker interlaminar shear strength of Dyneema® HB50 compared with Dyneema® HB26.

Finite element analyses have been performed and the sensitivity of the predicted compressive responses to the effective shear modulus and the interlaminar shear strength of composite laminates are studied. It reveals that an increase in the effective shear modulus or a decrease in the interlaminar shear strength switches the failure pattern from a kink band to a diffuse and sinusoidal buckling pattern. This is in agreement with the experimental observation that Dyneema® HB26 and HB50 show different failure modes because of their different interlaminar shear strengths.

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