IN-PLANE SHEAR PROPERTIES OF FIBER-REINFORCED AND TAPE-REINFORCED UHMWPE LAMINATES: EXPERIMENTAL STUDY

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ABSTRACT

Tape-reinforced Ultra-High Molecular Weight Polyethylene (UHMWPE) composites have the potential to enhance the ballistic performance of lightweight protection systems. These UHMWPE tapes are developed using highly oriented solid-state extruded polyethylene (SSE-PE) films. In-plane shear modulus of tape-reinforced composites is generally higher than gel-spun based polyethylene fiber-reinforced composites. The shear behavior of UHMWPE composite laminates influences the ballistic performance of the material. This motivates the current study to evaluate the in-plane properties of commercially available Dyneema HB26 and Tensylon HSBD 40A. Tensile tests with [±45°] layups were performed according to ASTM D3518 standard, with nearly equal areal density and four plies in a single lamina. This study was extended to Dyneema HB210 and Dyneema HB212 to investigate the influence of fiber thickness and matrix material on the shear response of UHMWPE composites. The experimental results showed that Tensylon in-plane shear modulus is nineteen times greater than the Dyneema HB26.

1 INTRODUCTION

The development of protective systems for defense personnel is continuing to progress in order to counter new threats in the combat zone. Although providing ballistic protection is of the utmost importance, lightweight and comfort are also crucial design considerations that must be considered. Ballistic helmets, bulletproof vests, and other personal protection equipment are continuously evolving. From 1980 to the beginning of the 2000s, the US Army employed the Personnel Armor System for Ground Troops (PASGT). In 2003, the PASGT was subsequently phased out by the Advanced Combat Helmet (ACH) [1]–[3]. These two helmets are fabricated from different grades of Kevlar composite. Kevlar is the commercial name of aramid fiber developed by Dupont, which is a ballistic-resistant material. This design trend is followed by Ultra-High Molecular Weight Polyethylene (UHMWPE) composite-made Enhanced Combat Helmets (ECH) [4]. Compared to aramid fibers, UHMWPE composites provide superior protection while being lighter.

Highly oriented Solid-State Extruded Polyethylene (SSE-PE) films have begun to take the place of these gel-spun based polyethylene fiber-reinforced composites in several applications due to their reduced cost. UHMWPE tapes are currently the second choice for ballistic protection after UHMWPE fiber-reinforced composites[5]. Both materials respond differently to in-plane shear loading [5], [6]. This motivates the current study to evaluate the in-plane properties of commercially available UHMWPE composites and UHMWPE tapes. In this study, UHMWPE composites made of Dyneema HB26, HB210, and HB212 were used for [±45°] layup tensile testing, while UHMWPE tape made of Tensylon HSBD 40A was utilized. Effects of the manufacturing process were investigated for UHMWPE composites produced by the gel spin method and for tapes produced by solid-state extrusion. The influence of matrix material and fiber thickness on the in-plane behavior of composite panels was also studied.

2 METHOD AND FRAMEWORK

2.1 Materials

In this work, four types of UHMWPE composite materials were used. Details about those materials are given in Table 1. These materials came in prepreg form. In all four systems, approximately 80 % was fiber/tape content, and 20% was resin/glue [7]. Dyneema HB210 was composed of Dyneema SK99 and Polyetherdiol-Aliphatic Diisocyanate Polyurethane (PADP) resin. Dyneema HB26 is made from Dyneema SK76 and PADP resin. Dyneema HB210 and Dyneema HB26 have the same resin but different fibers. This will allow us to study the effect of fiber thickness on the in-plane response of composite. Similarly, Dyneema HB210 and Dyneema HB212 have the same fiber (Dyneema SK99) but different resins, PADP and styrene–isoprene–styrene triblock copolymer (SISTC), respectively, which were used to study the effect of resin on shear properties. The efficacy of these fiber composite systems was compared with the tape-reinforced composite Tensylon HSBD 40A, which is a product of Dupont. Details about the orientation and lamina thickness using Scanning Electron Microscope (SEM) images are shown in Figure 1.

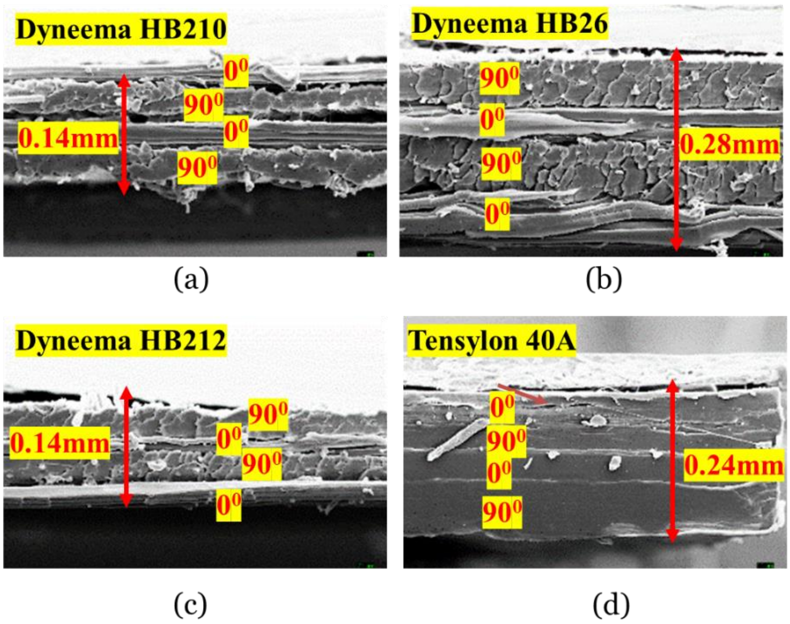


Figure 1: SEM images of (a) Dyneema HB210 (b) Dyneema HB26 (c) Dyneema HB212, and (d) Tensylon 40A

Table 1: Laminate prepreg material details

	Dyneema HB26	Dyneema HB210	Dyneema HB212	Tensylon HSBD 40A
Manufacturer	DSM	DSM	DSM	Dupont
Fiber Type	Dyneema SK76	Dyneema SK99	Dyneema SK99	N/A
Resin/Glue	PADP	PADP	SISTC	LDPE*
Ply Thickness (mm)	0.24	0.14	0.14	0.28
Number of Ply	$[0/90]_2$	$[0/90]_2$	$[0/90]_2$	$[0/90]_2$

* LDPE = Low-Density Polyethylene

2.2 Sample Preparation

All the materials were available in a prepreg form with four piles that have a $[0/90]_2$ configuration. First, prepregs were cut into 300x300 mm^2 pieces using marking at a 45-degree angle. These prepreg sheets were arranged into a sequence of $[\pm45^o]_4$. Special caution is needed during the stacking sequence arrangement. After that, pressure and temperature were applied simultaneously using the hot compression molding machine. Samples were placed between the metallic plates with non-sticking sheets. Pressure and temperature were applied as per the supplier's suggestions [8]. In this case, 125 bar pressure and 135-degree centigrade temperature were applied for 20 minutes. Once the laminates were consolidated, pressure was released, and cooling was applied to the laminates. Samples were cooled using liquid cooling for five minutes to room temperature. Steps for preparation are shown in the schematic diagram (see Figure 2). After this, fabricated composite sheets were subjected to waterjet cutting. Samples were cut as per ASTM D3039 standard for tensile testing. The same methodology was followed for the UHMWPE tape.

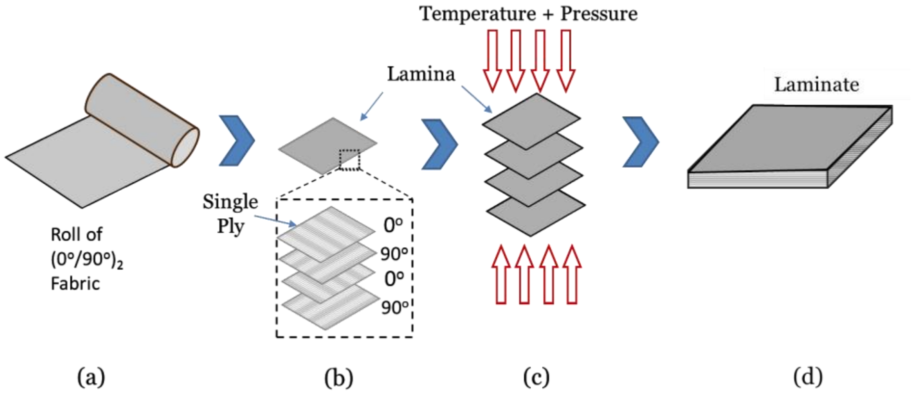


Figure 2: Steps for preparation of UHMWPE laminate

2.3 Experimental setup

Tensile testing was performed on the Shimadzu universal testing machine with a capacity of 10kN load cell, as shown in Figure 3. Tensile tests on rectangular samples were performed in accordance with ASTM D3518 guidelines [9]. ASTM D3518 follows the ASTM D3039 standards for sample preparation. For the current study, wedge action grippers were used. Initial testing was conducted using 20 x 250mm^2 (Width x Length) at a recommended feed rate of 0.001 m/sec [5]. The specimen had a 50mm grip length at both ends. All the specimens had the 8-ply composite system. The thickness of the composite panel varied as per the thickness of a single lamina. Test were conducted using two different width cases. In the first case, a sample with a width of 20 mm was examined; in the second case, the sample width was 10 mm. For specimens with a 10mm width, the exposed area for tensile testing was 80 x 10 mm^2.

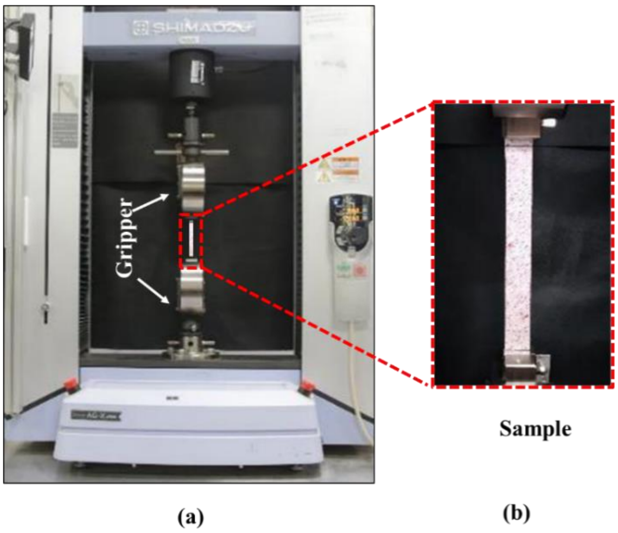


Figure 3: (a) Experimental setup, and (b) Sample clamped between grippers

2.4 Calculation for $[\pm 45]_n$ tensile testing

Testing was done using $[\pm 45°]_4$ layup as per ASTM D3518 standards. In this case, output was available in the form of axial force (P) and displacement. This axial force was converted into axial stress (σ_x) by dividing cross-section area (A) and then into shear stress (τ_{12}) (See equation 1-2). In-plane shear strain is calculated using Equation 3. Figure 4 depicts a schematic illustration of the sample and stress state. Carlsson et al.[10] had discussed all types of shear testing methods for composites. Shear modulus (G_{12}) is determined by plotting $\sigma_x/2$ verses ($\varepsilon_x - \varepsilon_y$).

$$\sigma_x = \frac{P}{A} \tag{1}$$

$$\tau_{12} = \frac{\sigma_x}{2} \tag{2}$$

$$\gamma_{12} = \varepsilon_x - \varepsilon_y \tag{3}$$

Where τ_{12} in-plane shear stress, σ_x is the axial stress (P/A). ε_x and ε_y are the axial and transverse strains, respectively.

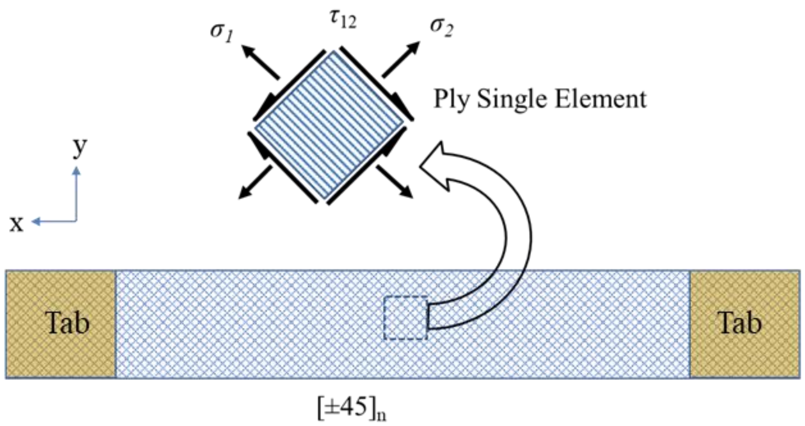


Figure 4: Schematic representation of tensile test sample with orientation and stress state

3 RESULTS AND DISCUSSION

Testing was performed on the $[\pm 45^o]_4$ tensile samples with different UHMWPE composites. Dyneema HB210 samples at different times are shown in Figure 5. Load was applied in the y-direction Figure 5(a). Sample went under significant deformation and necking before failure (see Figure 5(b)). It was observed that failure occurred at around $\pm 45^o$ angle, which indicated the shear-dominant failure (see Figure 5(c)). Engineering stresses with respect to the initial area are plotted for all the UHMWPE composites in Figure 6.

Highly non-linear behavior was observed in all the fiber-reinforced composites, as shown in Figure 6(a)- 6(c). These commercially available UHMWPE fiber-reinforced polymers come with PADP and SISTC polymer resins. As shear is a matrix-dominant phenomenon and both the matrix material is thermoplastic polymers, this material behavior like hyperplastic material with reinforcement. In contrast, Tensylon behavior was completely different as it behaved like bilinear elastic-plastic material in shear. Tensylon followed a linear stress and strain relationship initially. After that, the slope dropped at a yield point, but a relation between stress-strain showed linear behavior, following strain hardening before failure, see Figure 6(d). Stress-strain plots of all four composites (Dyneema HB210, Dyneema HB212, Tensylon HSBD 40A, and Dyneema HB26) are shown in Figure 6.

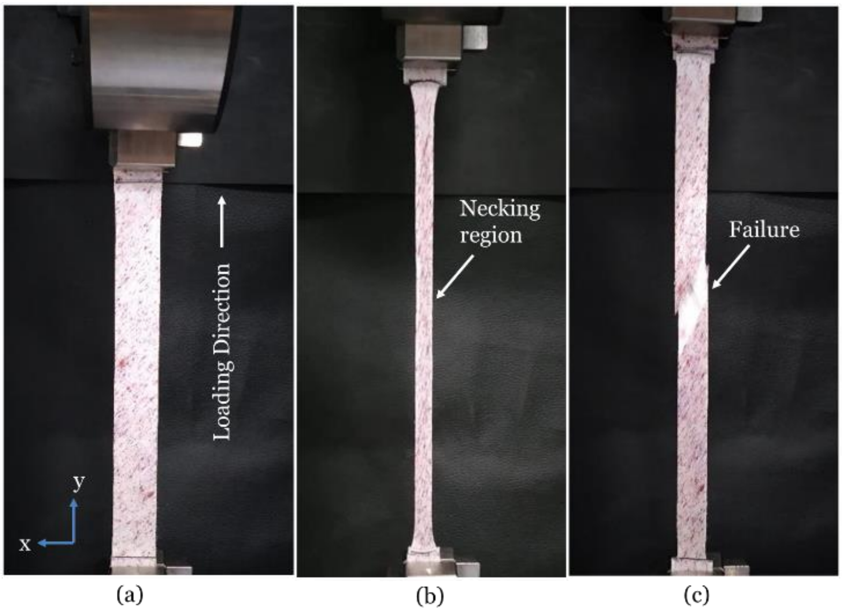


Figure 5: Dyneema HB210 specimen with eight plies (a) before load application, (b) just before failure, and (c) after the failure

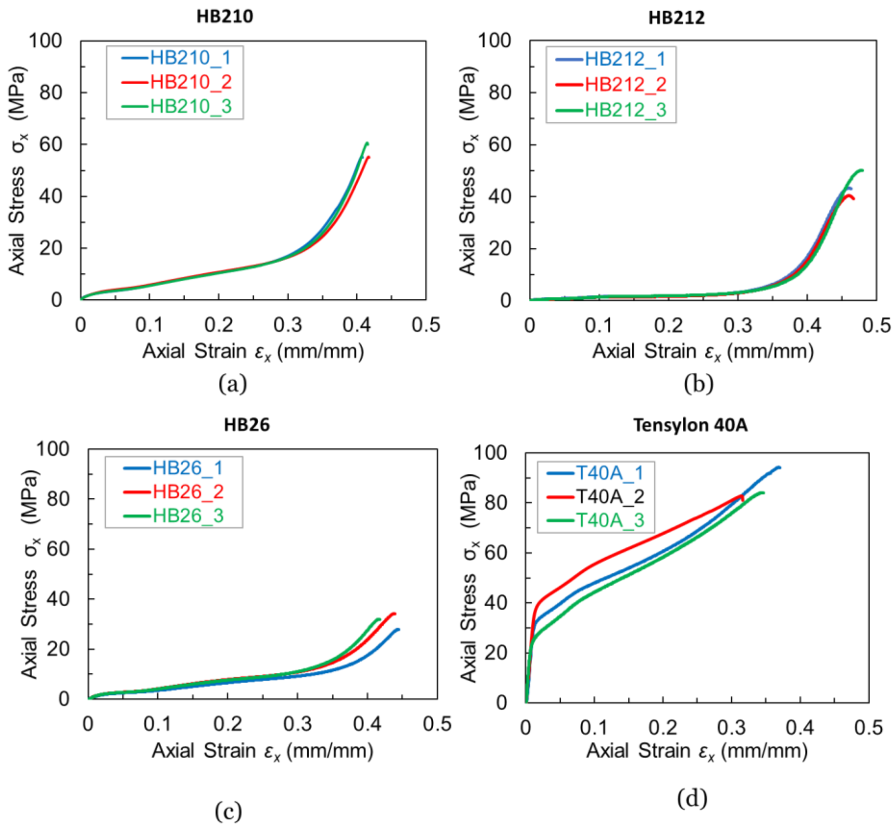
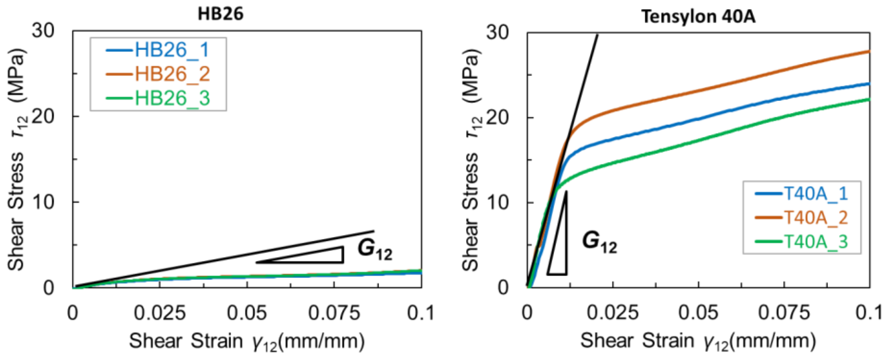


Figure 6: Axial engineering stress (σ_x) with respect to axial engineering strain (ε_x) for (a) Dyneema HB210, (b) Dyneema HB212, (c) Tensylon HSBD 40A, and (d) Dyneema HB26

The shear stress (τ_{12}) and shear strain (γ_{12}) were calculated using the equation 1-3. As per ASTM standard 3518, it assumes that laminate orientation would be unchanged throughout the test. ASTM standard 3518 recommended that shear modulus ($G_{12)}$ should be calculated within 5% engineering strain. Data should be used up to this point only for the shear modulus calculation. Shear stress as a function of shear strain for Tensylon 40A and Dyneema HB26 is shown in Figure 7. Modulus was calculated within the recommended range (0.5% and 1.0% strain) [5], [9]. Shear modulus was calculated in the linear range of the curve. Shear modulus of all four UHMWPE composites is given in Table 2.



(a) (b)

Figure 7: (a) Dyneema HB26 and (b) Tensylon HSBD 40A shear stress (τ_{12}) as a function of shear strain (γ_{12})

3.1 Effect of fiber thickness, matrix material on in-plane shear response

Shear modulus was calculated for the Dyneema HB26, HB210, and HB212 grades in fiber-based systems. Dyneema HB26 and Dyneema HB210 had the same matrix with different fibers (Dyneema SK76 and Dyneema SK99). Dyneema SK99 was thinner than Dyneema SK76. Dyneema HB26 and Dyneema HB210 had an average shear modulus of 68.7 MPa ± 2.5MPa and 71.0 MPa ± 2.9MPa, respectively. The coefficient of variation was 3.6% and 4.1% for Dyneema HB26 and Dyneema HB210, respectively. It indicated that the fiber thickness does not affect the shear modulus significantly, as shear modulus is a matrix-dominant phenomenon.

Table 2: Shear modulus of different UHMWPE composites with 20mm width specimens

Material	Tensylon 40	HB212	HB26	HB210
Average Shear Modulus (MPa)	1323.8	33.6	68.7	71.0
Standard Deviation (MPa)	31.6	2.5	2.5	2.9

Dyneema HB210 was compared with Dyneema HB212 to see the effect of the matrix material, as both have the same fiber (Dyneema SK99) but different matrix materials (PADP and SISTC). Where the average shear modulus for Dyneema HB210 and Dyneema HB212 was 71.0 MPa ± 2.9MPa and 33.6 MPa ± 2.5 MPa, respectively. This indicated that Dyneema HB210 is stiffer than Dyneema HB212. The shear modulus of Dyneema HB210 is 211% of Dyneema HB212.

3.2 Comparison of fiber-reinforced and tape-reinforced composites

Dyneema HB26, HB210, and HB212 have been manufactured using the gel-spun method [6]. Tensylon HSBD 40A is a highly oriented tape manufactured by the solid-state extrusion (SSE) technique [6]. Tensylon had an average shear modulus of 1323.8 MPa ± 31.6 MPa with a coefficient of variation of 2.4%. Tensylon shear modulus was almost nineteen times of Dyneema HB210 and Dyneema HB26. It is almost 38 times compared to Dyneema HB212. This showed that the tape-reinforced system is highly stiff compared to fiber-reinforced systems.

3.3 Effect of geometry on the material properties

The shear test was performed with two different widths while maintaining the aspect ratio of Length and width as per ASTM standard 3518. Dyneema HB26 and Dyneema HB210 had an average shear modulus of 64.5 MPa ± 3.1MPa and 65.5 MPa ± 1.5MPa, respectively, with 10mm width specimens. Here shear modulus was 6.1% and 7.7% lower for Dyneema HB26 and Dyneema HB210, respectively, compared to the 20 mm width specimen. A similar type of behavior was observed with the Tensylon HSBD 40A and Dyneema HB212, as mentioned in Table 3. Details about the influence of geometrical parameters on shear modulus are shown in Figure 8. In this figure, T40 represents the Tensylon HSBD 40A, whereas HB26 represents the Dyneema HB26. This clearly indicated that wider width sample showed a higher modulus. A potential reason behind this is the defects caused by the machining forces at the edges. As these samples were prepared using waterjet machining, the fiber got damaged at the edges. For the wider sample, the effect of these was minimal. So, testing with wider specimens while maintaining the aspect ratio of width and Length is recommended.

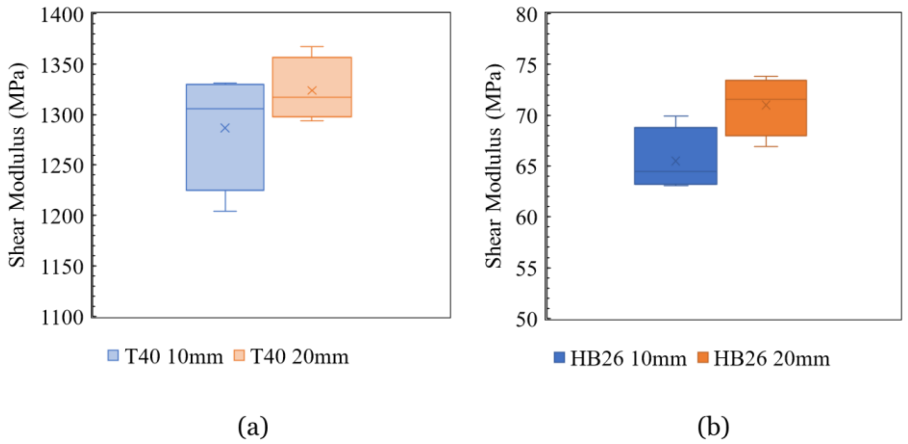


Figure 8: Tensylon HSBD 40A and Dyneema HB26 shear modulus (G_{12}) with (a) 20mm and (b) 10mm width specimen

Table 3: Shear modulus of different UHMWPE composites with 10mm width specimens

Material	**Tensylon 40**	**HB212**	**HB26**	**HB210**
Average Shear Modulus (MPa)	1286.9	30.1	64.5	65.5
Standard Deviation (MPa)	58.3	2.8	3.1	1.5

3.4 Fiber angle changes with applied load

When the test was performed with $[\pm 45°]_4$ fiber orientation in the specimens, it was observed that the fiber angle changed with the applied load. This change of angle varied with the material. Details about this were discussed by Cline and Love [5]. The initial angle for the specimen was 45°, about the symmetry plane for all the specimens. For the unit element, X and Y were the initial dimensions, as shown in Figure 9. At the initial stage, the angle was 45°, and X =Y. As the load was applied in the y-direction, the unit element had an elongation of ΔY in the y-direction and contraction of ΔX in the transverse direction (x-direction). After applying the load, the angle between the fiber was changed to θ°.

$$\theta = \frac{1}{2}\tan^{-1}\frac{(X-\Delta X)}{(Y+\Delta Y)} = \frac{1}{2}\tan^{-1}\frac{(1-\varepsilon_x)}{(1+\varepsilon_y)} \qquad (4)$$

Angular orientation was measured for all the composites just before the failure using Equation 4. For the Dyneema HB212, HB210 and HB26, this angle was reduced from 45° to 9.5°, 10.4° and 11.05°, respectively. On the other hand, the angle was 15.3° for the Tensylon HSBD 40A. These materials were prepared by high-strength fibers, which indicated that fiber orientation, not fiber elongation, was the dominant phenomenon in the fiber systems under shear. This should be considered during material modelling to capture the accurate behavior of the material.

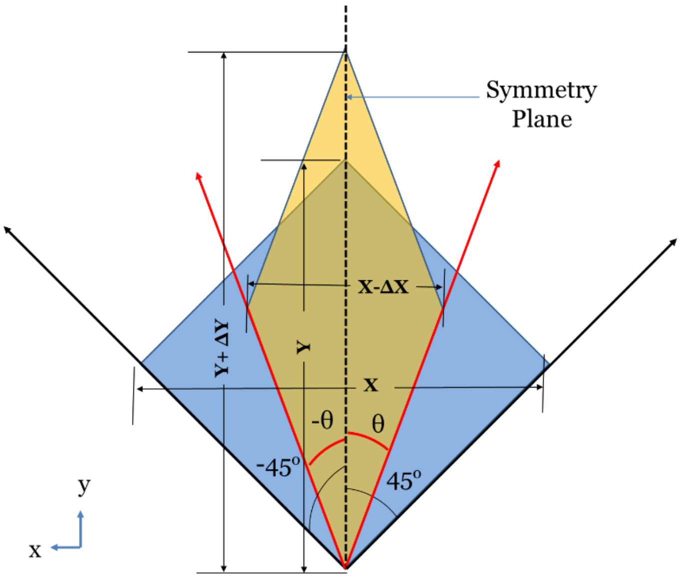


Figure 9: Fiber angle changes with applied load in the y-direction

4 CONCLUSIONS

In the presented work, shear test was performed with four different UHMWPE composite materials as per ASTM D3518 standard. Based on the test results, it was observed that the shear modulus of tape-reinforced composite (Tensylon HSBD 40A) was almost nineteen times of fiber-reinforced composites with PADP matrix (Dyneema HB210 and HB26). Fiber thickness is not affecting the shear modulus of composites (Dyneema HB26 and HB210) with the same matrix and fiber volume fraction. SISTC polymer-based composite (Dyneema HB212) is less stiff than PADP polymer-based composite (Dyneema HB210). Shear modulus of Dyneema HB212 is almost half of Dyneema HB212. Experiments were performed with the two different width specimens. Wider specimens are recommended to predict the shear modulus accurately. It is also observed that fiber orientation is the dominant phenomenon during deformation in the shear for fiber-based systems.

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