COMPRESSIVE AND BENDING STRENGTH OF UHMWPE LAMINATES

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ABSTRACT

This paper presents an experimental investigation of compressive and bending strengths of ultra-high molecular weight polyethylene (UHMWPE) fibre composites. The combined loading compression and four-point bending approaches based on the ASTM standards were successfully employed to determine the compressive and bending strengths of a cross-ply UHMWPE laminate and to quantify the influence of laboratory seawater immersion on the strength. For the laminate configuration investigated, very low compressive and bending strengths are measured and the results are consistent with results reported in literature for various grades of UHMWPE composites. Moreover, it was found that a 24-hour seawater immersion has a significant influence on the compressive and bending strengths. A reduction of approximately 40% in strength was observed for both tests, although failure modes were not affected. Finally, failure modes for the two types of loading were identified with the aid of optical and scanning electron microscopy. Distinct modes of local layer buckling are clearly demonstrated.

1 INTRODUCTION

Ultra-high molecular weight polyethylene (UHMWPE) fibre composites are gradually being employed as light armours in more and more defence applications [1-3]. In many of these applications, composite armour is required to act simultaneously as ballistic protection and as load-carrying structure [4]. For instance, in addition to meet the ballistic requirement, a combat helmet should also withstand various mechanical loads such as compressive load to the helmet shell, load induced by helmet attachments, and low-speed impact load. In particular, as described in Reference [5], under repeated compressive loads applied to the helmet shell side by side or from top to bottom, the helmet shell should have adequate stiffness so that the resulted permanent deformation is less than a certain extent and no visible damage induced. On the other hand, for applications in military vehicles such as armoured personnel carriers, composite armour is usually an integral part of the structure and thus needs to withstand service loading not associated with ballistic impact [6]. Obviously, testing and understanding of the mechanical properties of these orthotropic materials at low strain-rate are critical to design and analysis of structural composite armours considering the tradeoff between the ballistic and mechanical performance. However, as indicated in References [4, 6-7], testing of UHMWPE and aramid fibre composites usually carries some special challenges compared with carbon and glass fibre composites. For instance, the high strength in fibre direction but very low shear strength and coefficient of friction of UHMWPE composites preclude the use of a standard test specimen for tensile test since it would result in shear/pull-out failure at the grips [8]. Consequently, tensile tests of cross-ply UHMWPE fibre composites were usually performed using special specimens with large gripping areas and bolts in order to prevent slippage of the specimen [6, 8-10]. On the other hand, compression and shear failures are generally noncatastrophic with yield occurring early in the stress-strain curve. Careful observation of failure modes is important for interpretation of test results [4, 11]. Experimental work to estimate the behaviour of UHMWPE fibre composites at low strain-rate included tension, compression, shear, bending and delamination tests. A review summarized in [6] and the references cited therein provide recent investigations of the mechanical performance of UHMWPE composites as well as dynamic ballistic impact behaviour. In the following a brief review on the compression and bending responses of UHMWPE composites is provided.

Knowledge of compression and flexural responses of UHMWPE composites is imperative for the analysis of armour composites under quasi-static loads or for non-armour applications in light-weight structures. Attwood et al. [12] studied the in-plane compressive response of UHMWPE composites using notched specimens. Two grades of composites with inter-laminar 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. They concluded that, 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. In Reference [13], both the in-plane and out-of-plane compression behaviours of HB80 composites were investigated based on the ASTM D695 standard for rigid plastics [14]. The prism specimen cut from HB80 composite panels was placed between two compressive plates and was then compressed at a uniform rate. The results were employed to establish constitutive models for the prediction of ballistic performance [13]. Compressive and bending properties were determined for a UHMWPE composite with SK75 fibre and DSM Turane resin using ASTM standard approaches, in an investigation to develop hybrid composites made with high strength carbon fibres and UHMWPE fibres [15]. Bending test results of UHMWPE composites were also reported in References [9, 15-17] employing three-point or cantilever beam bending schemes. As demonstrated by these investigations, the bending response includes a yield point and the specimen can have a very large deflection without breaking. Therefore bending strength is usually determined by the yield point of the load versus deflection curve. Furthermore, it is noticed that numerical simulations [16-17] were frequently employed to study the bending response focusing on the noncatastrophic failure involving local buckling. In summary, there is a lack of comprehensive data on the mechanical properties of UHMWPE composites. The reviewed experimental work include diverse testing approaches and various grades of UHMWPE composites. It is difficult to directly compare these results. In addition, to the authors' best knowledge, there are little or no studies on the influence of seawater immersion on the compression and bending responses of UHMWPE composites which is an important consideration for military applications [5].

An experimental study of the compressive and bending strengths of a cross-ply UHMWPE fibre composite is reported in this paper. The combined loading compression (CLC) [18] and four-point bending [19] approaches described in the ASTM standards were employed in the investigation. The compressive and bending strengths of the UHMWPE laminates were determined and compared with a number of published results in literature. The influence of laboratory seawater immersion on the strength was demonstrated and quantified. Specimen failure modes for the two types of loading were identified with the aid of optical and scanning electron microscopy.

2 EXPERIMENTAL

2.1 Test Method

Combined Loading Compression Test

The ASTM D6641 standard establishes a procedure for determining the compressive strength and stiffness properties of polymer composite materials using a combined loading compression test fixture [18]. In this method, the compressive force is introduced into the specimen by combined end- and shear-loading, see a schematic illustration shown in Figure 1(a). The fixture, which subjects the specimen to combined loading, is itself loaded in compression between flat platens in a universal testing machine. The load at the end can be diminished therefore eliminate the end crush of the specimen. Furthermore, the compression specimen has a relatively short gauge length of 12.7 mm to prevent premature buckling and allow for more surface areas being used for load transfer.

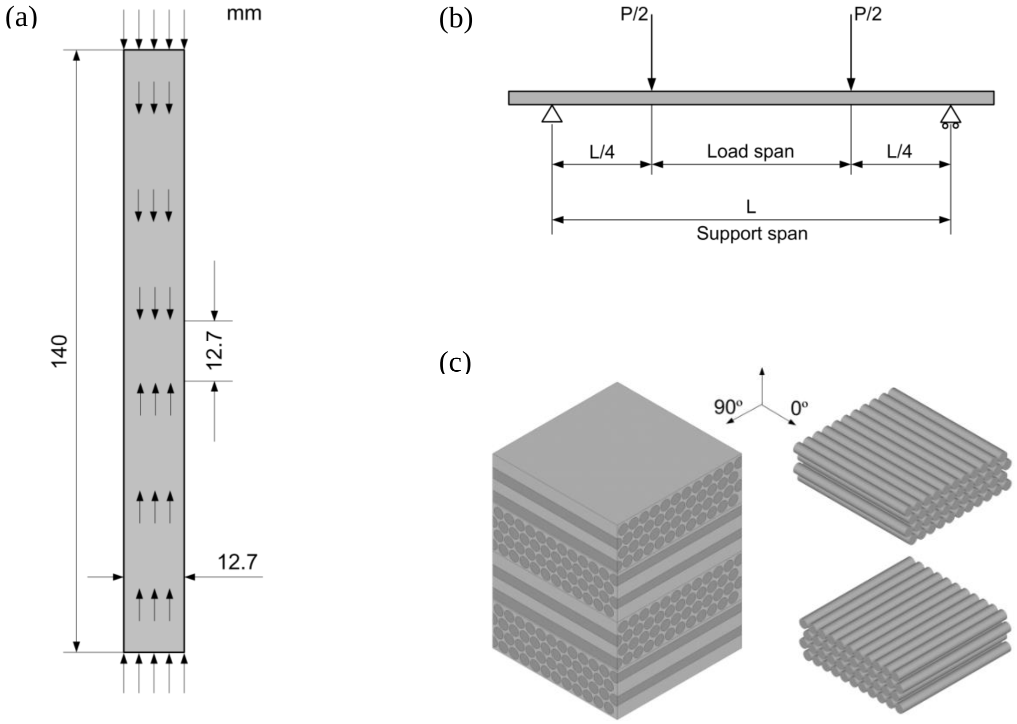


Figure 1. Schematic test setup. (a) Compression; (2) Bending; (c) Laminate configuration

Four-point Bending Test

Figure 1(b) schematically shows the four-point bending test setup based on the ASTM D7264 standard [19]. It is noticed that in this setup the load span is half of the support span (L). In the present investigation, a fixed support span of L= 160 mm was employed and a span ratio (L/t) of 32 was maintained for all specimens used which had a nominal thickness of 5 mm. A large span ratio provides the advantage of reducing the inter-laminar shear stress and the contact (compressive) stress in the loading and support zones. Large support and loading rollers with a diameter of 12.7 mm were also adopted in the bending test fixture to further diminish the contact stress.

2.2 Material and Specimens

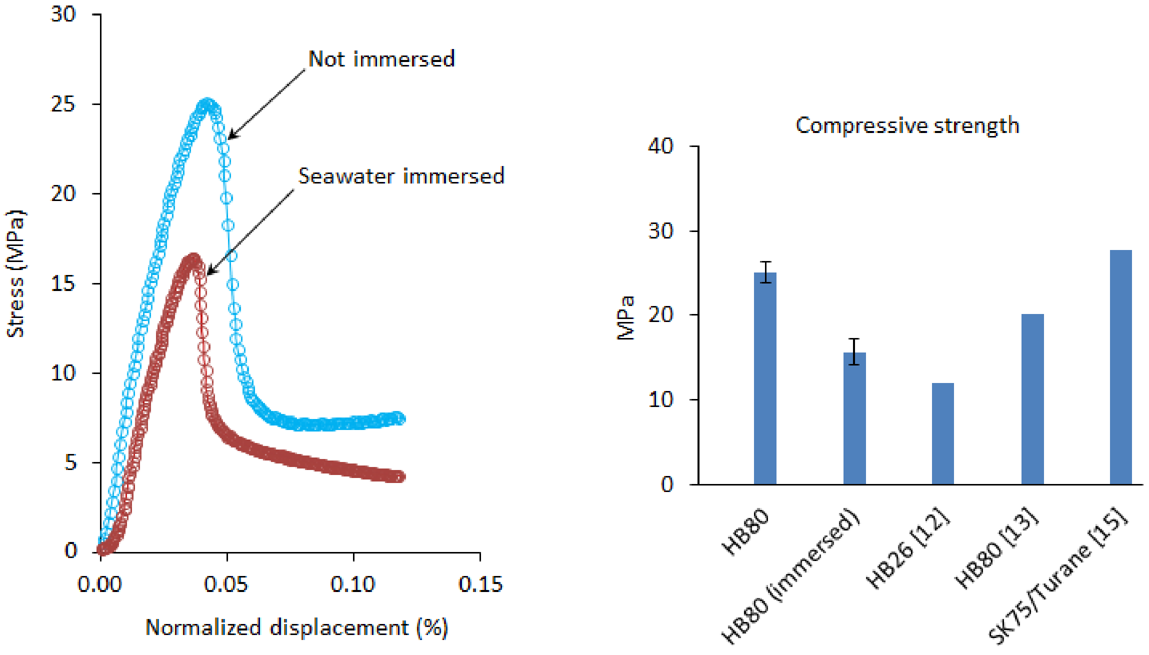
The composite material studied in this effort is an UHMWPE fibre based composite laminate (Dyneema® HB80) from DSM [20]. Panels of laminates consist of layers of unidirectional sheet cross plied at 90 degrees to each other and consolidated with a polyurethane based matrix [20]. Rectangular specimens were machined from the composite panels with a thickness of 5 mm. A computer numerical controlled (CNC) milling machine and tools were employed to produce a smooth finish along the specimen edges, especially along the end of the compression specimens. The in-plane dimensions of the compression and bending specimens are 12.7 mm by 140 mm, and 19 mm by 254 mm, respectively. Figure 1(c) is a three-dimensional sketch showing the ply configuration of the [0°/90°] UHMWPE composite.

To investigate the influence of seawater immersion on the strength behaviour, some of the compression and bending specimens are immersed in a laboratory seawater solution containing 3 percent sodium chloride and 0.5 percent magnesium chloride [5] at standard ambient conditions for 24 hours. Before and after seawater immersion, specimens were weighed.

3 RESULTS AND DISCUSSION

3.1 Compressive Strength

To account for possible variations in material property, ten specimens were tested to determine the in-plane compressive strength of the composites. Another ten specimens were immersed in laboratory seawater for 24 hours and then tested for the compressive strength after immersion. Figure 2(a) depicts the compressive stress (plotted in absolute values) versus the normalized displacement curves. Note that the displacement is normalized to the gauge length shown in Figure 1(a). For the sake of clarity, only the curves of two representative specimens are displayed in the figure. Figure 2(b) shows the compressive strengths of the present study along with the results of two similar composites reported in References [12-13, 15].

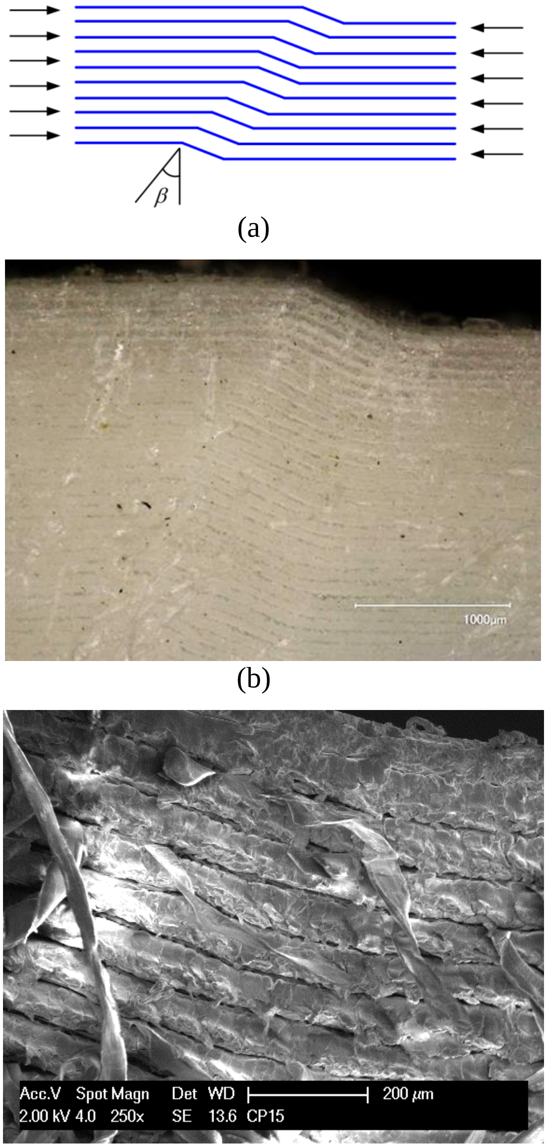


(a) (b)

Figure 2. (a) Compressive stress versus displacement curve; (2) Comparison of compressive strength

As shown in Figure 2(a), the compressive response of the UHMWPE composites is almost linear before reaching the maximum stress, indicating that there is apparently no yielding involved. It is seen from Figure 2(a) that the seawater immersion has a significant influence on the compressive modulus and strength. The compressive strength of the UHMWPE composites determined in the present study is 25.1 MPa (mean value of 10 specimens). The compressive strength after seawater immersion is 15.7 MPa (mean value of 10 specimens), showing a reduction of 37%. Figure 2(b) compares the present results with the results in References [12-13,15] which include data of different UHMWPE composites and by different test methods. It is observed that the in-plane compressive strength of UNMWPE composites is very low compared with their tensile strength of about 1400 MPa [15]. The low compressive strength is primarily due to the low interlaminar shear strength of the material system [12-13,15].

Tested specimens were examined by optical and scanning electron microscopes to understand the failure behaviour and the influence of the seawater immersion. Figure 3 shows the images of the damage zone observed by an optical microscope (OM) and scanning electron microscope (SEM) for representative specimens.



(a)

(b)

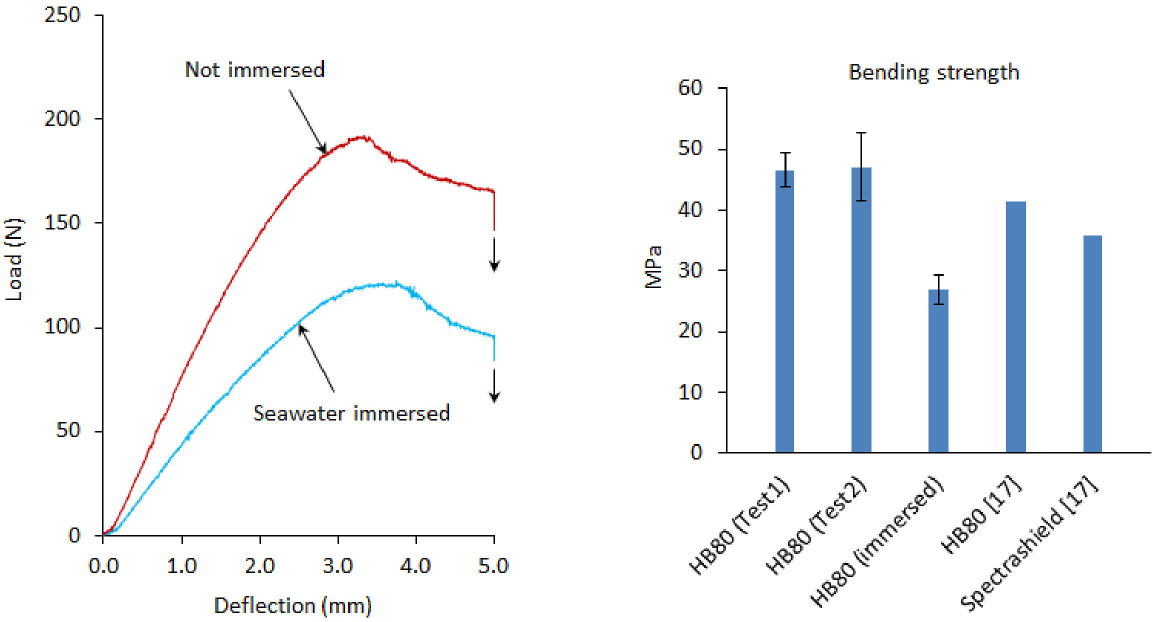
(c)

Figure 3. Compressive failure: (a) Kinking of layers; (2) OM image; (c) SEM image.

Careful examination of all the tested specimens indicates that they failed in local kinking of layers across the specimen width, as shown schematically in Figure 3(a). Figure 3(b) shows an OM image of the local layer buckling of a typical specimen. Figure 3(c) shows an SEM image of the local buckling at a higher magnification. It is noted that images in Figures 3(b) and 3(c) are both from immersed specimens. For specimens without seawater immersion, the same failure mode was observed with the inclination angle of the kinking bands, β (see Figure 3a), is smaller than that of the immersed specimens. Analysis of compressive kicking bands can be found in Reference [12] for UHMWPE composites and in [21] for general laminates.

3.2 *Four-point Bending*

The bending strength of the UHMWPE composites was measured in two rounds of test. Test round 1 employed 10 specimens and test round 2 included 8 specimens. Moreover, in test round 2, additional 8 specimens were immersed in a laboratory seawater solution for 24 hours and then tested for the bending strength after immersion. Figure 4(a) represents curves of the bending load versus the deflection at the loading point (the crosshead displacement). Again, for brevity, only the curves of two representative specimens are displayed. Figure 4(b) shows the bending strengths of the present study along with the data form Reference [17].

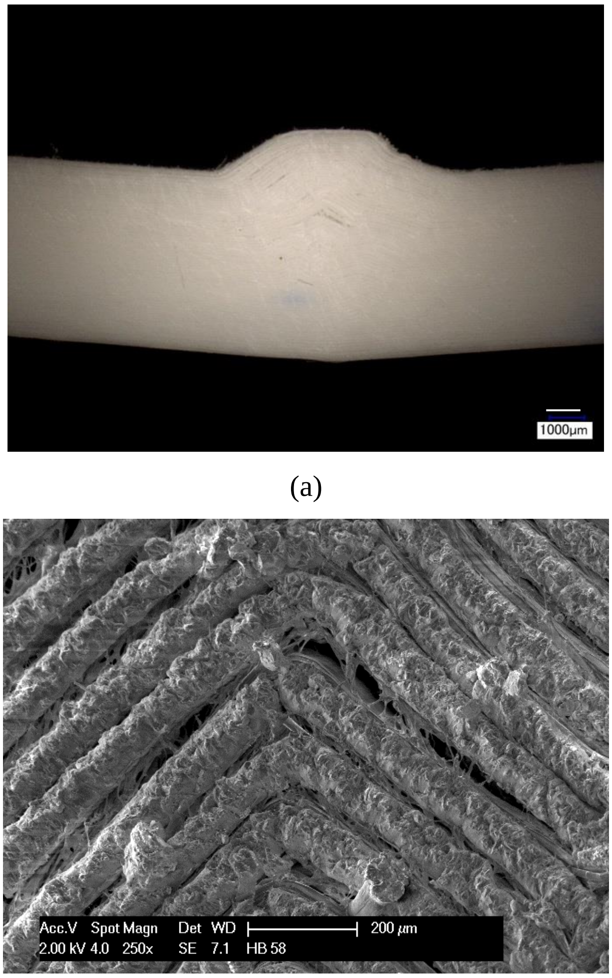


(a) (b)

Figure 4. (a) Bending load versus deflection curve; (2) Comparison of compressive strength

As shown in Figure 4(a), the bending response of the UHMWPE composites is nonlinear before the maximum load at which the bending strength is determined. After the maximum load, the specimen can still hold load up to a very large defection (over 30 mm at the loading point) without breaking. In this study, about half of the bending specimens were unloaded at a limited deflection (indicated by the downward arrows in Figure 4a) to avoid extra specimen damage induced by possible interference with the fixture; and these specimens were used for failure analysis. It is seen from Figure 4(a) that the seawater immersion has a significant influence on the bending modulus and strength. The bending strength of the UHMWPE composites determined in the present study is 46.9 MPa (mean value of 18 specimens). The bending strength after seawater immersion is 26.9 MPa (mean value of 8 specimens), showing a reduction of 42%. Figure 4(b) compares the present results with the results reported in Reference [17] for two types of UHMWPE composites using 3-ponit bending. It is observed that the bending strength of UNMWPE composites is very low compared to their tensile strength of approximately 1400 MPa [15] but higher than their compressive strength. The difference in compressive and bending strengths is probably related to the distinct local buckling patterns in the compression and bending tests, which is discussed as follows.

Figures 5 (a) and (b) show OM and SEM images of the damage zone of bent specimens. Examination of the tested specimens indicates that they failed in local buckling of layers in compression, as shown in Figure 5(a). Figure 5(b) shows an SEM image of the local buckling at a higher magnification. It is noted that images in Figures 5(a) and 5(b) are from different specimens and both were not immersed. For specimens with seawater immersion, the same failure mode was observed. Compared with the kinking band in compression test shown in Figure 3, it is seen that the patterns of local layer buckling are different for the two tests. In bending, the damage band consists of layers bent in different orientations forming a severely bent portion.



(a)

(b)

Figure 5. Damage band in bending test: (a) OM image; (b) SEM image

4 CONCLUSIONS

An experimental study was carried out to investigate the compressive and bending strength behaviour of a cross-ply UHMWPE composite laminate (Dyneema$^{®}$ HB80) and to quantify the influence of laboratory seawater immersion on the strength. The major results and findings are summarized in the following:

- The compressive and bending strengths were determined using the approaches based on the ASTM standard. Very low compressive and bending strengths were measured and the results are consistent with the results reported in literature for various grades of UHMWPE composites.
- It was demonstrated that seawater immersion has a significant influence on the compressive and bending strengths. For a 24-hour immersion, a reduction of approximately 40% in strength was observed for both tests, although failure modes were not affected.
- Compression specimens failed in kinking bands induced by local buckling of all layers across the specimen width. Bending specimens failed in local buckling of layers in compression (induced by bending) and in a different pattern.

5 REFERENCES

[1] S.G. Kulkarni, X.-L. Gao, S.E. Horner, J.Q. Zheng, N.V. David. Ballistic helmets – Their design, materials, and performance against traumatic brain injury. *Composite Structures.* Vol.101, pp.313-331, 2013.

[2] S.M. Walsh, D.M. Spagnuolo, B.R. Scott. The potential advantages of thermoplastic and hybridized ballistic materials and processes for U.S. Army helmet development, *SAMPE Proceedings*, Long Beach, CA. 2006.

[3] F. Folgar, B.R. Scott, S.M. Walsh, J. Wolbert. Thermoplastic matrix combat helmet with graphite-epoxy skin, *23rd International Symposium on Ballistics*, Tarragona, Spain, 2007.

[4] M.W. Wardle. Aramid fiber reinforced plastics-properties, in Vol. 2 of *Comprehensive Composite Materials*, A. Kelly and C. Zweben (editors-in-chief), Elsevier, Amsterdam, New York, 2000.

[5] Purchase Description of Advanced Combat Helmet (ACH). http://www.gentexcorp.com/assets/base/TechnicalPublications/CO-PD-05-041.pdf

[6] A. Levi-Sasson, I. Meshi, S. Mustacchi, I. Amarilio, D. Benes, V. Favorsky, R. Eliasy, J. Aboudi, R. Haj-Ali, Experimental determination of linear and nonlinear mechanical properties of laminated soft composite material system. *Composites: Part B*. Vol. 57, pp.96–104, 2014.

[7] P.G. Riewald, F. Folgar, H.H. Yang, W.F. Shaughnessy. Light weight helmet from a new aramid fiber, in *Proceedings of the 23rd International SAMPE Technical Conference*, R. L. Carri, L. M. Poveromo and J. Gavland (eds.), Kiamesha Lake, New York, 1991, pp. 684-695.

[8] B.P. Russell, K. Karthikeyan, V.S. Deshpande, N.A. Fleck. The high strain rate response of ultra high molecular-weight polyethylene: From fibre to laminate. *International Journal of Impact Engineering*. Vol. 60, pp.1-9, 2013.

[9] L. Czechowski, J. Jankowski, T. Kubiak. Experimental tests of a property of composite material assigned for ballistic products. *Fibers & Textiles in Eastern Europe*. Vol. 3(92), pp.61-66, 2102.

[10] L. Iannucci, D. Pope. High velocity impact and armour design. *Express Polymer Letters*. Vol. 5(3), pp.262-72, 2011.

[11] Y. Zhang. A Study of compression and shear behavior of two types of thermoplastic composites, in American Society for Composites 29th Technical Conference and 16th US-Japan Conference on Composite Materials. September 8-10, 2014. San Diego, USA.

[12] J.P. Attwood, N.A. Fleck, H.N.G. Wadley, V.S. Deshpande. The compressive response of ultra-high molecular weight polyethylene fibres and composites. *International Journal of Solids & Structures.* Vol. 71, pp.141-155, 2015.

[13] S. Chocron, A.E. Nicholls, A. Brill, A. Malka, T. Namir, D. Havazelet, H. Werff, U. Heisserer, J.D. Walker. Modeling unidirectional composites by bundling fibers into strips with experimental determination of shear and compression properties at high pressures. Composites Science and Technology, Vol. 101 (12), pp.32-40, 2014.

[14] ASTM D695. Standard test method for compressive properties of rigid plastics. ASTM International, 2008.

[15] J.G. H. Bouwmeester, R. Marissen, O.K. Bergsma. Carbon/Dyneema® interlaminar hybrids: New strategy to increase impact resistance or decrease mass of carbon fiber composites. *26th International Congress of the Aeronautical Sciences*. 14 -19 September 2008, Anchorage, Alaska, USA.

[16] G. Liu, M.D. Thouless, V.S. Deshpande, N.A. Fleck. Collapse of a composite beam made from ultra high molecular-weight polyethylene fibres, *Journal of the Mechanics and Physics of Solids.* Vol. 63, pp.320-335, 2013.

[17] J. Patel. *Mechanisms for Kink Band Evolution in Polymer Matrix Composites: A digital Image Correlation and Finite Element Study*. PhD Thesis, Arizona State University, USA, May 2016.

[18] ASTM D6641. Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture. ASTM International, 2008.

[19] ASTM D7264. Standard test method for flexural properties of polymer matrix composite materials. ASTM International, 2007.

[20] https://www.dsm.com/content/dam/dsm/dyneema/en_GB/Downloads/LP%20Product%20Grades/DSM_PSS_HB80.pdf.

[21] B. Budiansky. Micromechanics. *Computers & Structures.* Vol. 16 (1–4), pp.3–12, 1983.