MECHANICAL CHARACTERIZATION OF NEAT AND CHEMICALLY CROSSLINKED UHMWPE FABRICS SUBJECTED TO QUASI-STATIC LOADINGS

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ABSTRACT

This study aims to characterize the in-plane and out-of-plane mechanical behaviour of a covalently crosslinked ultra-high molecular weight polyethylene (UHMWPE) fabric. The experimental analysis included tensile, shear, bending, and puncture tests. The results showed that, by adding a diazirine-based crosslinker to UHMWPE fabric, there is a considerable increase in the shear force and the engaged bending length observed during the Pierce bending test, without a substantial effect on the in-plane tensile properties of the fabric. Additionally, the puncture resistance of the material was significantly improved (by 72%) through the addition of the crosslinker. Finally, the study examined rate dependencies of the tensile and shear properties of the crosslinked UHMWPE fabric at three strain rates ranging from 10^{-4} to 10^{-2} s^{-1}, revealing that the material's response is only marginally strain rate-dependent at lower strain rates within this range.

1 INTRODUCTION

In recent decades, lightweight woven fabrics have become increasingly important in a variety of industrial fields, including aerospace, automotive, and marine applications. One material that has garnered significant attention in such industries is ultra-high molecular weight polyethylene (UHMWPE) fabric. UHMWPE fabrics are known for their exceptional strengths and high moduli, making them an ideal choice for structural applications that require high-impact resistance. Additionally, UHMWPE fabrics have been used extensively in engineering products due to their low density, high toughness, minimal moisture absorption, chemical resistance, and excellent wear resistance [1]–[3].

In certain applications such as armour panels, the adaptation of a UHMWPE fabric can require the use of numerous layers to achieve the desired ballistic strength, occasionally leading to issues of high weight and bulkiness [4]. Consequently, in such cases, it is deemed necessary to modify UHMWPE fabric material to optimize its mechanical properties, and hence possibly use a smaller number of layers. Researchers have explored various factors to improve the impact performance of UHMWPE fabric plies, with inter-yarn friction being a critical factor affecting the mechanical performance of the fabric. Previous studies have shown that increasing the friction between the warp and weft yarns can decrease the slippage between yarns during loading, leading to enhanced energy absorption and improved impact resistance of the ply [5]–[8]. To improve the inter-yarn friction, researchers have investigated the use of chemical treatments, as well as using additives such as shear-thickening fluids [9]–[12].

In this study, a novel diazirine-based crosslinker is added to a typical UHMWPE fabric, and the mechanical properties of the new material are compared with the neat (control) fabric. Tensile and shear loading tests were performed under different strain rates over the range of 10^{-3} to 10^{-2} s^{-1}. A puncture test was carried out to assess the performance of the fabrics in both in-plane and out-of-plane deformation modes. The results indicated that with the addition of a diazirine-based crosslinker, the mechanical performance of the UHMWPE fabric was improved by as much as 72% when compared to the untreated fabric under specific deformation modes.

2 MATERIAL AND METHODS

2.1 Preparation of crosslinked UHMWPE fabrics

The neat fabric used for the following tests is a 200 denier UHMWPE woven fabric with an areal density of 75 g/m². The fabric was impregnated with a bis-trifluoromethyl aryl diazirine crosslinker, previously reported in [13]. The diazirine-based crosslinker was designed to improve the mechanical properties of the parent material by engaging in rapid C–H insertions along the polymer chain upon thermal- or photo-activation. The efficiency of insertion into C–H bonds was enhanced by an electronic optimization of the aryl diazirine warhead. Further details about the synthesis and optimization of the crosslinker can be found in [13] and references therein.

To impregnate the fabric with the crosslinker, the neat fabric sample was first placed in a close-fitting aluminium pan, filled with the crosslinker solution in pentane at the appropriate concentration. In this study, we aimed to obtain 1 wt% crosslinker loading on the fabric. However, to account for losses of mass deposited on the sides of the pan, 1.25 wt% of crosslinker was used in order to achieve a nominal mass of 1 wt%. The pan was covered with aluminium foil and left at room temperature for 30 minutes. Next, the foil was removed to allow the pentane to evaporate in a well-ventilated fume hood for 20 minutes. After evaporation, the impregnated fabric sheets were wrapped in aluminium foil and placed in an oven at 110°C for 4 hours to activate the crosslinker. The samples were then weighed to determine the total mass of reacted crosslinker with the fabric. Each piece was washed three times for 5 minutes at room temperature with pentane to remove unreacted crosslinkers and possible side products that were not attached to the fabric. Finally, the treated fabrics were dried, and each sample was weighed again to determine the mass of reaction products lost during solvent washing.

To better isolate and understand the direct effect of the crosslinker on the mechanical performance of the fabric material, three groups of samples were fabricated: untreated (neat) samples, vehicle control samples, and crosslinked samples. The process used in preparing the vehicle control samples was the same as that used for the crosslinked samples, but without adding the crosslinker. Meanwhile, the untreated samples were 200 denier UHMWPE woven fabrics without any further chemical processing. The results of the respective tests were then compared.

2.2. Experimental tests

The in-plane and out-of-plane mechanical behavior of the fabric groups were characterized by performing quasi-static tensile, bias-extension (shear), and bending tests. For the tensile and shear tests, an Instron 5969 dual column load frame was employed, with a crosshead speed of 5 mm/min. The sample dimensions were 75 mm × 250 mm (following ASTM D5035). It should be noted that 50 mm of each side of the samples was placed between the grips. Consequently, the distance between the grips was 150 mm. Three samples of each group of fabrics were tested to ensure consistent results. In order to study the effect of strain rate on the crosslinked fabric, three loading rates of 5, 100, and 300 mm/min (corresponding to strain rates of 0.00056, 0.011, and 0.033 s^{-1}) were chosen.

In order to characterize the out-of-plane bending behavior of the fabrics, the Pierce bending test was employed (Figure 1). In the first step of the test, the specimen of size 25 mm × 200 mm was placed on the horizontal platform with the length of the specimen parallel to the platform edge. Then the clamped specimen was moved gradually by hand until the edge of the sample touched the 41.5° indicator. Finally, the bending length of the specimen was read. The flexural rigidity in this test was determined based on Eq. (1) [14].

$$G = 9.81 \times 10^{-12} \times w \times c^3. \quad (1)$$

Assuming the bending length, c, is in mm and the areal weight, w, is in g/m^2, then the flexural rigidity, G, has the units of N·m.

In addition, a puncture test was performed to evaluate the puncture resistance of the fabrics. The same 5969 dual column load frame was employed in this test. Samples of size 70 mm × 70 mm and a conical penetrator were used. According to ASTM F1342/F1342M, the loading rate was set at 500 mm/min [15]. All tests were repeated 3 times and average values are reported.

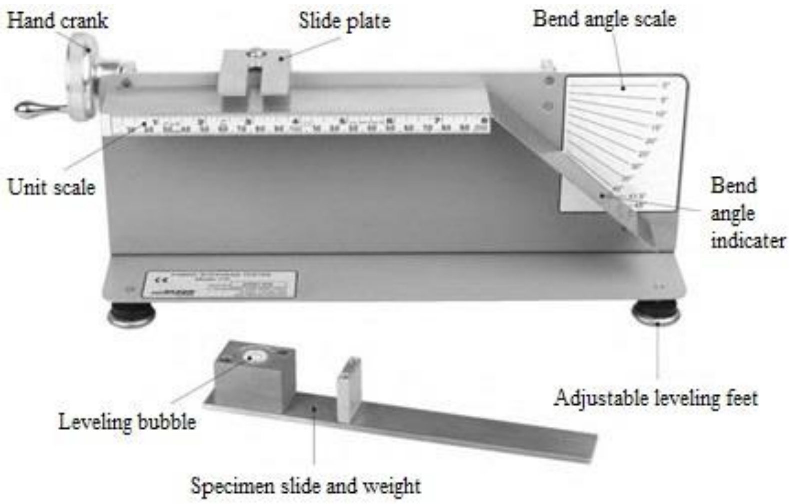


Figure 1: Test setup for performing Pierce bending test on fabrics.

3 RESULTS AND DISCUSSION

3.1 In-plane tensile and shear behavior

Figure 2 depicts the stress-strain curves obtained from the tensile testing of the fabrics. The results demonstrate a significant increase in maximum tensile stress, with the crosslinked UHMWPE sample (prepared using 1 wt% crosslinker); exhibiting a 25% and 32% increase compared to the untreated and vehicle control samples, respectively. However, the initial slope of the stress-strain curve for all groups is similar. As a result, the addition of covalent crosslinkers did not have a significant effect on the elastic modulus of the UHMWPE fabric.

Figure 3 indicates the normalized shear force versus the shear angle of the three groups of fabrics. The formula provided in [16] was used to derive the normalized shear force. As illustrated in Figure 3, there is a considerable increase in the normalized shear force of the crosslinked UHMWPE fabric when compared to the untreated and vehicle control samples.

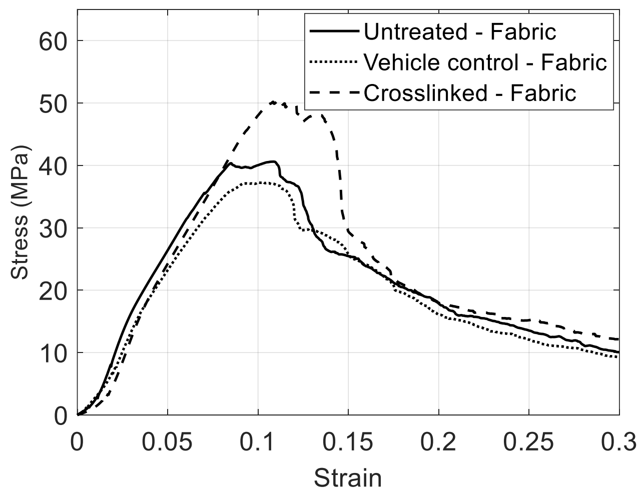


Figure 2: Comparison between stress-strain responses of the crosslinked, neat and vehicle control UHMWPE fabric samples, under tensile testing at the strain rate of 0.00056 s^{-1}.

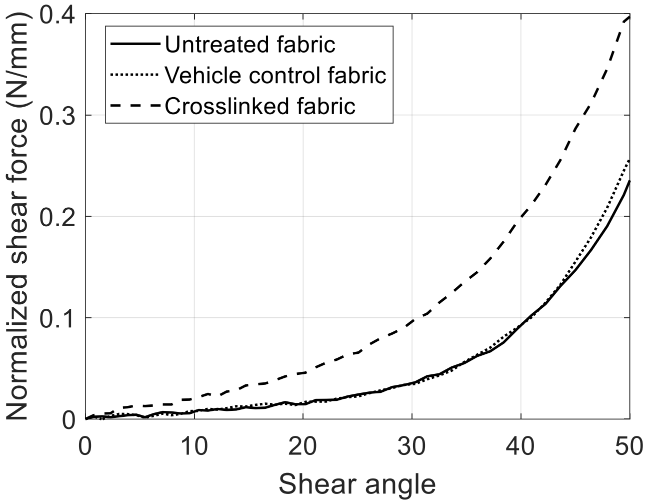


Figure 3: Comparison between normalized shear force –shear angle of crosslinked, neat and vehicle control UHMWPE fabric samples, under bias-extension testing at the strain rate of 0.00056 s^{-1}.

3.2 Out-of-plane bending behavior

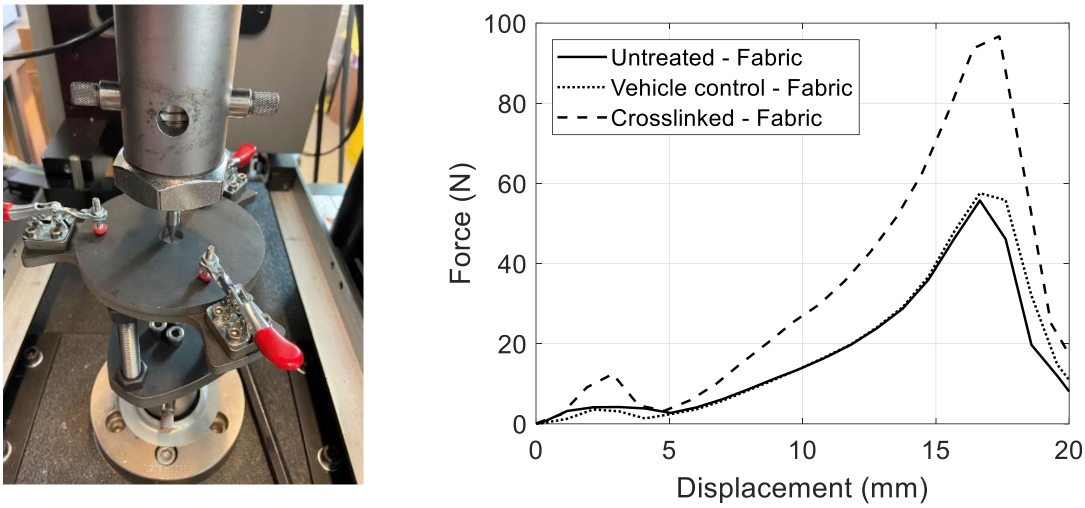
The bending length of the specimens was measured, and the results are presented in Table 1. As shown, the crosslinked samples exhibit higher bending lengths than the vehicle control and untreated samples, indicating that the treatment has increased the bending stiffness of the fabric. The crosslinked samples, in particular, show the maximum bending length; with an increase of approximately 34% compared to the untreated UHMWPE fabric. Moreover, the flexural rigidities of the samples are compared in Table 1. As indicated, the flexural rigidity has been substantially enhanced in the crosslinked fabric, with an increase of 283% and 140% compared to the untreated and vehicle control samples, respectively.

	Bending length, *c* (mm)			Flexural rigidity, *G* (N·m × 10^{-4})		
	Untreated	Vehicle control	Crosslinked	Untreated	Vehicle control	Crosslinked
Average	38.5 ± 1.22	44.75 ± 3.82	59.9 ± 4.83	0.42 ± 0.04	0.67 ± 0.17	1.61 ± 0.36

Table 1: Comparison between bending lengths and flexural rigidities of crosslinked, neat, and vehicle control UHMWPE fabric samples.

3.3 Puncture test

Figure 4 shows the force-displacement response obtained from the puncture tests of the fabrics. The results indicate a significant improvement offered by using the crosslinker on the puncture resistance of the UHMWPE fabric (once again prepared using 1 wt% of the covalent crosslinker). As illustrated in Figure 4, the maximum puncture force in the crosslinked fabric has increased by approximately 72% compared to the untreated and vehicle control samples.



(a) **(b)**

Figure 4: (a) Test setup of puncture test, (b) Comparison between force-displacement results of the crosslinked, neat, and vehicle control UHMWPE fabrics subjected to puncture test.

3.4 Strain rate effect

The effect of different strain rates on the tensile and shear behavior of the crosslinked UHMWPE fabrics is illustrated in Figure 5 and Figure 6, respectively. As observed, below the strain rate of 0.011 s^{-1}, the tensile and shear response of the fabric is significantly affected by the strain rate level. At higher strain rates (> 0.011 s^{-1}) within the limited range of strain rates considered in this study, the tensile and shear responses of the material become nearly independent of the strain rate, as was also reported in previous studies on UHMWPE fabrics [17].

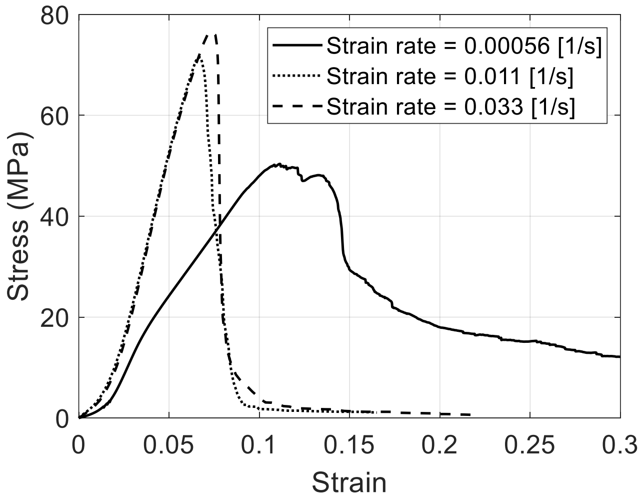


Figure 5: Comparison between the stress-strain response of the crosslinked UHMWPE fabric under tensile test at different strain rates.

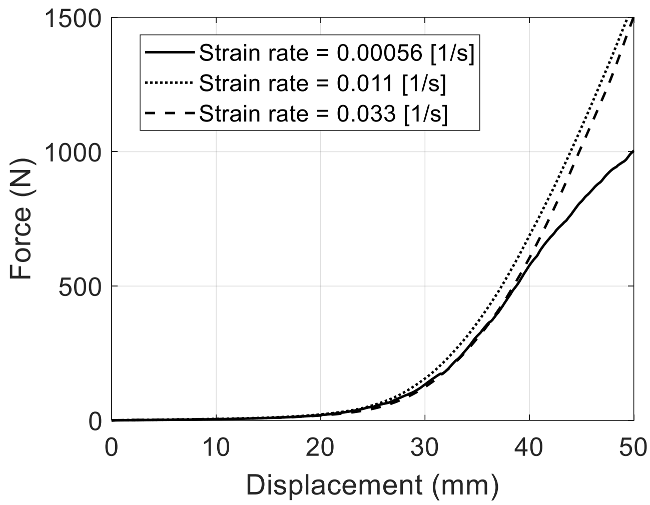


Figure 6: Comparison between the force-displacement response of the crosslinked UHMWPE fabric subjected to puncture test at different strain rates.

4 CONCLUSIONS

This work investigated the mechanical properties of a novel, covalently crosslinked UHMWPE fabric through in-plane and out-of-plane experiments including tensile, shear, bending, and puncture tests. Two additional material groups, untreated and vehicle control samples, were included for comparison purposes. The experimental results revealed the following:

- The addition of crosslinkers to the UHMWPE fabric did not significantly affect the neat fabric's elastic modulus in the tensile test. However, the crosslinked fabric exhibited an increase in maximum tensile stress by 25% and 32% compared to the untreated and vehicle control samples, respectively.
- The results of the bias extension test indicated that the normalized shear force was increased considerably (by approximately 60% at a shear angle of ~50°) in the crosslinked UHMWPE fabric compared to untreated and vehicle control samples.
- The Pierce bending test results showed a significant increase in the out-of-plane bending stiffness of the crosslinked UHMWPE fabric compared to the untreated and crosslinked fabrics. In particular, the crosslinked sample exhibited the maximum bending length, representing an increase of approximately 34% compared to the untreated UHMWPE fabric and a corresponding approximate 4-fold increase in bending stiffness.
- The puncture test results demonstrated a sizable increase (by 72%) in the puncture resistance of the UHMWPE fabric by adding the chemical crosslinker.
- The tensile and shear behavior of the crosslinked UHMWPE fabric tested at three different strain rates was found to exhibit weak strain rate-dependency at strain rates above 0.011 s^{-1}. However, the rate dependency of the tensile and shear responses was more pronounced over the range of 10^{-4} to 10^{-2} s^{-1}. Other fabric shear test methods [18] may also be employed in future work to confirm the rate-dependency results reported here.

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REFERENCES

[1] A. Bhatnagar and D. Lang, “Military and law enforcement applications of lightweight ballistic materials,” *Lightweight Ballistic Composites*, pp. 364–397, 2006.

[2] S. Gürgen, O. N. Çelik, and M. C. Kuşhan, “Tribological behavior of UHMWPE matrix composites reinforced with PTFE particles and aramid fibers,” *Compos. Part B Eng.*, vol. 173, p. 106949, 2019.

[3] Y. Yang and X. Chen, “Investigation of failure modes and influence on ballistic performance of Ultra-High Molecular Weight Polyethylene (UHMWPE) uni-directional laminate for hybrid design,” *Compos. Struct.*, vol. 174, pp. 233–243, 2017.

[4] M. P. Ribeiro, P. H. P. M. da Silveira, F. de Oliveira Braga, and S. N. Monteiro, “Fabric Impregnation with Shear Thickening Fluid for Ballistic Armor Polymer Composites: An Updated Overview,” *Polymers (Basel).*, vol. 14, no. 20, p. 4357, 2022.

[5] Y. Chu, S. Min, and X. Chen, “Numerical study of inter-yarn friction on the failure of fabrics upon ballistic impacts,” *Mater. Des.*, vol. 115, pp. 299–316, 2017.

[6] M. P. Rao, Y. Duan, M. Keefe, B. M. Powers, and T. A. Bogetti, “Modeling the effects of yarn material properties and friction on the ballistic impact of a plain-weave fabric,” *Compos. Struct.*, vol. 89, no. 4, pp. 556–566, 2009.

[7] C. Ha-Minh, F. Boussu, T. Kanit, D. Crépin, and A. Imad, “Effect of frictions on the ballistic performance of a 3D warp interlock fabric: numerical analysis,” *Appl. Compos. Mater.*, vol. 19, pp. 333–347, 2012.

[8] B. J. Briscoe and F. Motamedi, “The ballistic impact characteristics of aramid fabrics: the influence of interface friction,” *Wear*, vol. 158, no. 1–2, pp. 229–247, 1992.

[9] M. L. Lepage, M. Takaffoli, C. Simhadri, R. Mandau, M. Parvinzadeh Gashti, R. Nazir, M. Mohseni, W. Li, C. Liu, L. Bi, G. Falck, P. Berrang, K. Golovin, A. S. Milani, G. A. DiLabio and J. E. Wulff, “Influence of Topical Cross-Linking on Mechanical and Ballistic Performance of a Woven Ultra-High-Molecular-Weight Polyethylene Fabric Used in Soft Body Armor,” *ACS Appl. Polym. Mater.*, vol. 3, no. 11, pp. 6008–6018, 2021.

[10] S. Arora, A. Majumdar, and B. S. Butola, “Structure induced effectiveness of shear thickening fluid for modulating impact resistance of UHMWPE fabrics,” *Compos. Struct.*, vol. 210, pp. 41–48, 2019.

[11] J. Gu, X. Huang, Y. Li, X. Wang, M. Shi, and Z. Zheng, “Improving the stab-resistance performance of ultra high molecular weight polyethylene fabric intercalated with nano-silica-fluid,” *J. Shanghai Jiaotong Univ.*, vol. 19, pp. 102–109, 2014.

[12] Y. Chu, X. Chen, and L. Tian, “Modifying friction between ultra-high molecular weight polyethylene (UHMWPE) yarns with plasma enhanced chemical vapour deposition (PCVD),” *Appl. Surf. Sci.*, vol. 406, pp. 77–83, 2017.

[13] S. F. Musolino, M. Mahbod, R. Nazir, L. Bi, H. Graham, A. Milani and J. Wulff, “Electronically optimized diazirine-based polymer crosslinkers,” *Polym. Chem.*, vol. 13, no. 25, pp. 3833–3839, 2022.

[14] N. Lammens, M. Kersemans, G. Luyckx, W. Van Paepegem, and J. Degrieck, “Improved accuracy in the determination of flexural rigidity of textile fabrics by the Peirce cantilever test (ASTM D1388),” *Text. Res. J.*, vol. 84, no. 12, pp. 1307–1314, 2014.

[15] “Standard test method for protective clothing material resistance to puncture.” ASTM International West Conshohocken, PA, USA, 2005.

[16] J. Cao, R Akkerman, P. Boisse, J. Chen, H. S. Cheng, E. F. de Graaf, J. L. Gotczyca, P. Harrison, G. Hivet, J. Launay, W. Lee, L. Liu, S. V. Lomov, A. Long, E. de Luycker, F. Morestin, J. Padvoiskis, X. Q. Peng, J. Sherwood, Tz. Stoilova, X. M. Tao, I. Verpoest, A. Willems, J. Wiggers. T. X. Yu and B. Zhu, “Characterization of mechanical behavior of woven fabrics: experimental methods and benchmark results,” *Compos. Part A Appl. Sci. Manuf.*, vol. 39, no. 6, pp. 1037–1053, 2008.

[17] H. Wang, D. Weerasinghe, D. Mohotti, P. J. Hazell, V. P. W. Shim, K. Shankar and E. V.

Morozov, “On the impact response of UHMWPE woven fabrics: Experiments and simulations,” *Int. J. Mech. Sci.*, vol. 204, p. 106574, 2021.

[18] A. S. Milani, J. A. Nemes, G. Lebrun, and M. N. Bureau, “A comparative analysis of a modified picture frame test for characterization of woven fabrics,” *Polym. Compos.*, vol. 31, no. 4, pp. 561–568, 2010.