# TENSILE PROPERTIES CHARACTERIZATION OF DRY HIGH-MOLECULAR-WEIGHT POLYETHYLENE 3D WARP INTERLOCK FABRICS FOR COMPOSITE REINFORCEMENTS

**Mengru Li, Peng Wang, François Boussu, Damien Soulat**
*University of Lille, Ensait, Gemtex, F-59000 Roubaix, France*
E-mail: mengru.li@ensait.fr

**ABSTRACT**

In the present work, five 3D warp interlock fabrics (3DWIFs) with stuffer warp yarns were made from 135Tex linear density Spectra® 900, high-molecular-weight polyethylene (HMWPE) yarns, with the same warp density (10 ends/cm) and weft density (40 picks/cm) and manufactured on the same dobby loom. After production, several mechanical and physical measurements are done and especially tensile tests to understand their final behaviour with respect to process and product parameters. The effects of fabric density and yarn density on tensile properties of the fabrics, in the warp and weft directions respectively, have been investigated. Besides, other influent factors as yarn crimps are also discussed in this paper.

**Key Words:** High-molecular-weight polyethylene (HMWPE) ; 3D warp interlock fabrics (3DWIFs); Tensile properties characterization; Composite reinforcements.

## 1. INTRODUCTION

In recent years, the research interest of 3DWIFs as reinforcement in composites is warranted and obtained popularity due to their advantages over two-dimensional (2D) laminated fabrics. Generally, 3DWIFs are comprised of continuous high-strength filament yarns or tows, made from materials that are inseparable from the performance of the 3D woven fabrics. According to the related literature, the 3DWIFs can be woven in the monolithic or hybrid form using almost any type of fibre tows/ filaments/yarns. The HMWPE yarns have favourable properties such as high impact resistance, cutting resistance, low dielectric constant, high heat conductivity, high sonic modulus, and low stretch. These properties are important for applications such as ballistic (bulletproof vests), helmets (impact), gloves (cutting resistance), hybrid composites (impact), loudspeaker cones (sonic modulus), and radomes/sonar domes (dielectric properties) [1,2]. Using all these high-performance yarns into 3D warp interlock woven fabrics seems to be difficult during the weaving process, especially in the management of warp tensions, compared to more classical yarns as cotton or polyester [3].

Although uniaxial quasi-static tensile tests have been done to evaluate their tensile behaviour of 3DIWFs, rarely biaxial tensile tests are performed. In the previous study, the effects of tensile mechanical parameters on tensile mechanical properties were also studied from the following aspects: the materials used [4,5], the structures [6], the weaving parameters [7-10], and test conditions [11]. Huang et al. [12] reported that the tensile properties of a woven structure were mainly determined by the waviness of the fibre in the loading direction. Besides, the 3D orthogonal structure with the lowest yarn crimp in the loading direction exhibited the highest tensile strength [12]. Bandaru et al. [4] reported that all the 3D-warp-angle interlock fabrics exhibited typical tensile response (two peaks) in the warp direction, which was similar to those presented by Boussu et al. [7].

In the current work, in order to explore the properties of dry 3DWIFs, 5 different structures 3DWIFs are designed, which includes four main categories of 3DWIFs: Angle interlock/Through-the-thickness binding (A/T), Angle interlock/Layer-to-layer binding (A/L), Orthogonal interlock/Through-the-thickness binding (O/T), Orthogonal interlock/Layer-to-layer binding (O/L). Five 3DWIFs with stuffer warp yarns were made from 135Tex linear density Spectra® 900, HMWPE yarns, with the same warp density (10 ends/cm) and weft density (40 picks/cm) and manufactured on the same dobby loom. In order to better understand and compare their mechanical behavior according to their different structures, quasi-static tensile tests in the warp and weft directions respectively are performed.

## 2. EXPERIMENTAL

### 2.1 Materials

The Spectra® (S-900), HMWPE filaments which were supplied by Honeywell Company, USA, of 1350dTex were used both in the warp direction and weft direction to weave 3D warp interlock fabrics using the same dobby loom. Product parameters are mentioned in Table 1.

**Table 1.** Parameters of HMWPE.

| Product Family | Spectra® fiber | Linear density (Tex) | Ultimate Tensile Strength (Gpa) | Elongation (%) | Breaking Strength (N) | Density ($g/cm^3$) | Filament Tow | Heat resistance (°C) |
|---|---|---|---|---|---|---|---|---|
| S-900 | 1200 | 135 | 2.57 | 3.9 | 351 | 0.97 | 120 | 150 |

### 2.2 Sample preparation

2.2.1 HMWPE yarns

Different twist per meter values were chosen as followed: 0, 25, 50, 75, 100, 125, 150, 175, 200. Experimental TWISTEC TECHNOLOGY® machine at the speed of 40m/min and “z” twist was used. Afterward, the tensile properties of the different twisted HMWPE yarns were tested according to the ISO 2062 (1993) standard at 21°C (±1°C) and 65% (±2%) relative humidity standard conditions. Banc de traction MTS Criterion (10N-10KN) test machine was used to test the tensile properties of different twisted HMWPE yarns.

2.2.2 Fabrics manufacturing

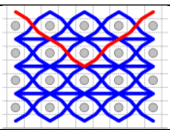
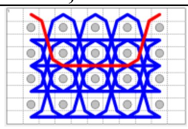
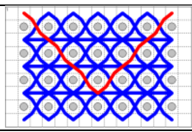
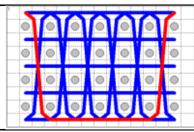
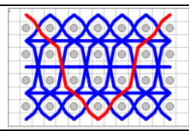
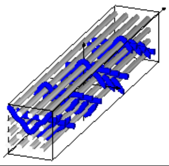
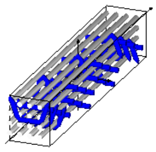
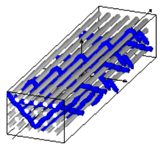
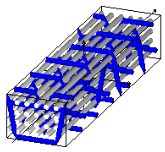
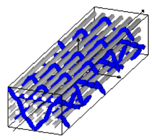
Same warp density (10 ends/cm) and weft density (40 picks/cm) were used to manufacture the five different structures 3DWIFs on the same dobby loom. The structure definition and their results, weft cross-section and 3D views are shown in Table 2. The weft cross-section view helps to highlight the binding warp yarn evolution inside the woven structure.

### 2.3 Characterization

2.3.1 Preparation of test samples

Rectangular sample size in bending and tensile tests are 300mm×50mm. In order to avoid errors in load-cell reading of displacements and strains due to the possibility of slippage of the different specimens in the grip, adhesive bonding on both ends with an extension of 50mm have been added.

**Table 2.** The weft cross-section and 3D views of 5 structures fabrics

| No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Structure name | A-L 3-2 4 Binding {Twill 4 effect left}-Stuffer | O-L 3-2 4 Binding {Twill 4 effect left}-Stuffer | A-L 5-3 4 Binding {Twill 6 effect left}-Stuffer | O-T 5-4 4 Binding {Twill 6 effect left}-Stuffer | A-T 5-4 4 Binding {Twill 6 effect left}-Stuffer |
| Weft cross-section |  |  |  |  |  |
| 3D views |  |  |  |  |  |

2.3.2 Tensile properties characterization

Tests were done in INSTRON 5900 with a 250 KN load cell according to the EN ISO 13 934-1 standard.

## 3. RESULTS AND DISCUSSIONS

3.1 Yarn twist

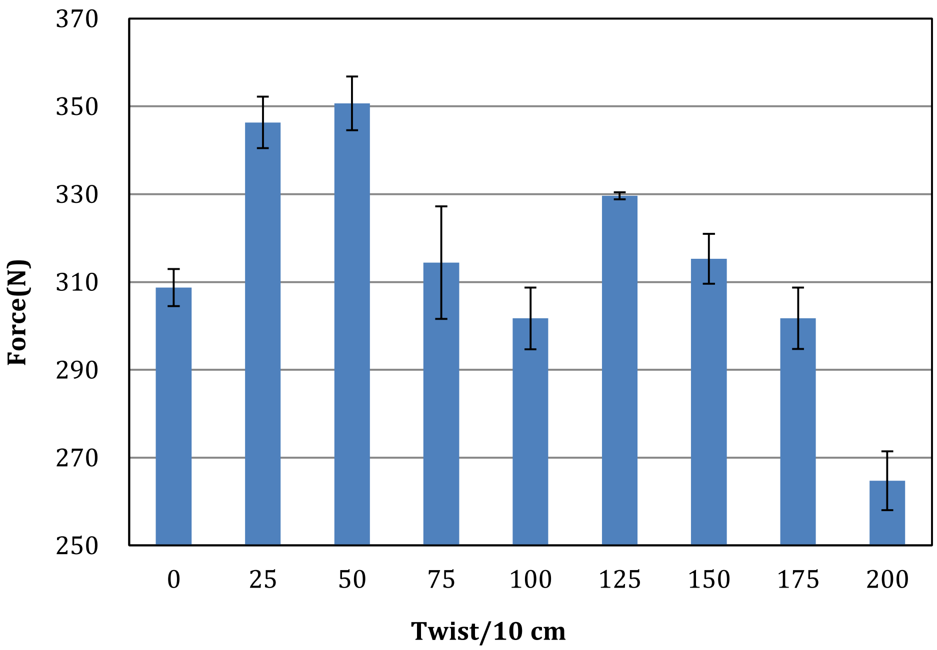



**Figure 1**. The breaking forces of different twists yarns

Rao et al. [13] showed that the strength of high-performance fibre yarns can be improved by a slight twist. A high degree of twist damages the fibres and reduces the tensile strength of the yarn. The elongation to break of the yarns monotonically increases with the degree of twist.

Therefore, the HMWPE filament should be twisted for increasing the strength of it. When the twist of the yarn is 50 twists per meter, the breaking force is the largest, as shown in Figure 1. Besides, the more the twist is, the less the maximum force by analysing the linear forecast trend is. Therefore, the value of 50 twists per meter and "z" twist were applied on the HMWPE yarns for the manufacturing of the 5 different fabrics structures.

3.2 Tensile properties

In this investigation, the tensile tests were performed both in the warp and weft directions for the different structures of 3D warp interlock fabrics until it reaches the maximum deformation states. Figure 2 and Figure 3 show the different samples at their deformed state both in the warp and weft direction. It demonstrated that the tensile resistance is greater in the weft direction than in the warp direction due to the main difference between ends and picks densities. Besides, it could be noticed for all the tested fabrics a higher value of elongation in the weft direction than in the warp direction. By contrast, the No.4 fabric(O-T 5-4 4 Binding {Twill 6}) has the larger displacement at the beginning of the warp direction tensile test, which due to the fact that the binding warp yarns in No.4 fabric(O-T 5-4 4 Binding {Twill 6}) have biggest bend degree. In other words, the binding warp yarns crimps of No.4 fabric(O-T 5-4 4 Binding {Twill 6}) are the largest and is about 6 times larger than other structures with stuffer warp yarns fabrics.

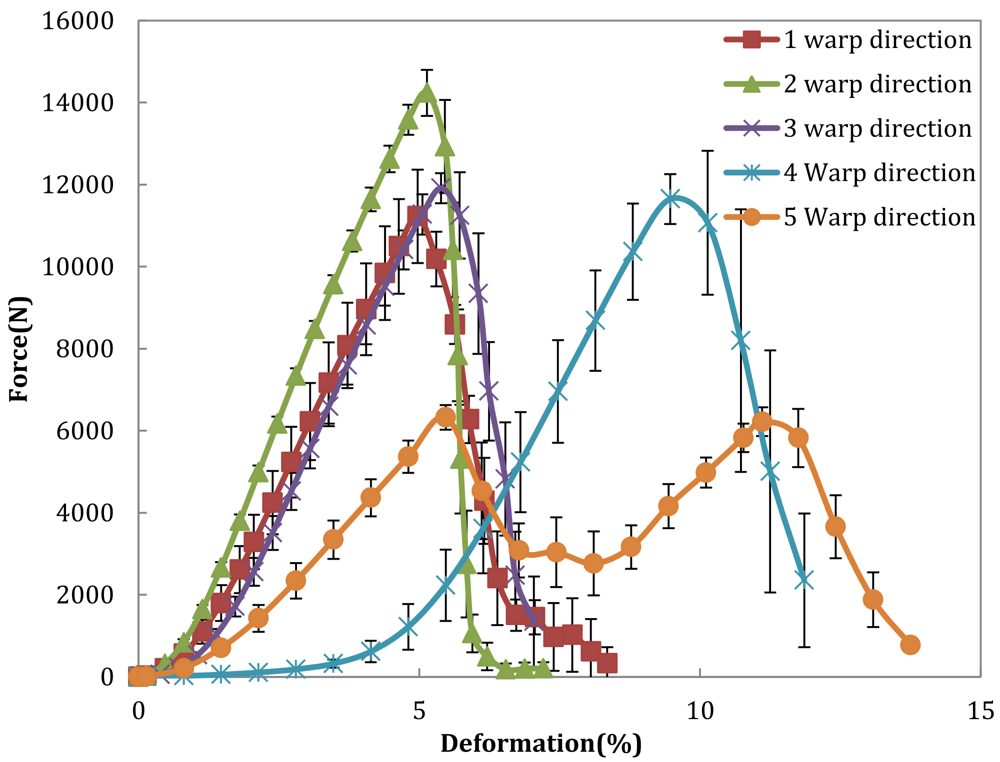



**Figure 2.** Warp direction tensile tests results of five structures

As for the two picks of No.5 fabric (A-T 5-4 4 Binding {Twill 6}) force-deformation curve, the main influence factor could be the manufacturing process. In fact, the first peak indicates the strength of the stuffer yarns and the second peak indicates the strength of the binding warp yarns where the second part of warp yarns can work after the break of the first yarns, as shown in Figure 3. The warp yarns tensions of the binding warp beam and stuffer warp beam may be different and uneven. The two picks of the force-deformation curve appeared in the tensile test of 3DWIFs without stuffer yarns. It may due to that the warp yarn tension could be better than before as the weaving goes on. In conclusion, there is no doubt that the manufacturing parameters also have a large influence on the tensile properties of 3D warp interlock fabrics.

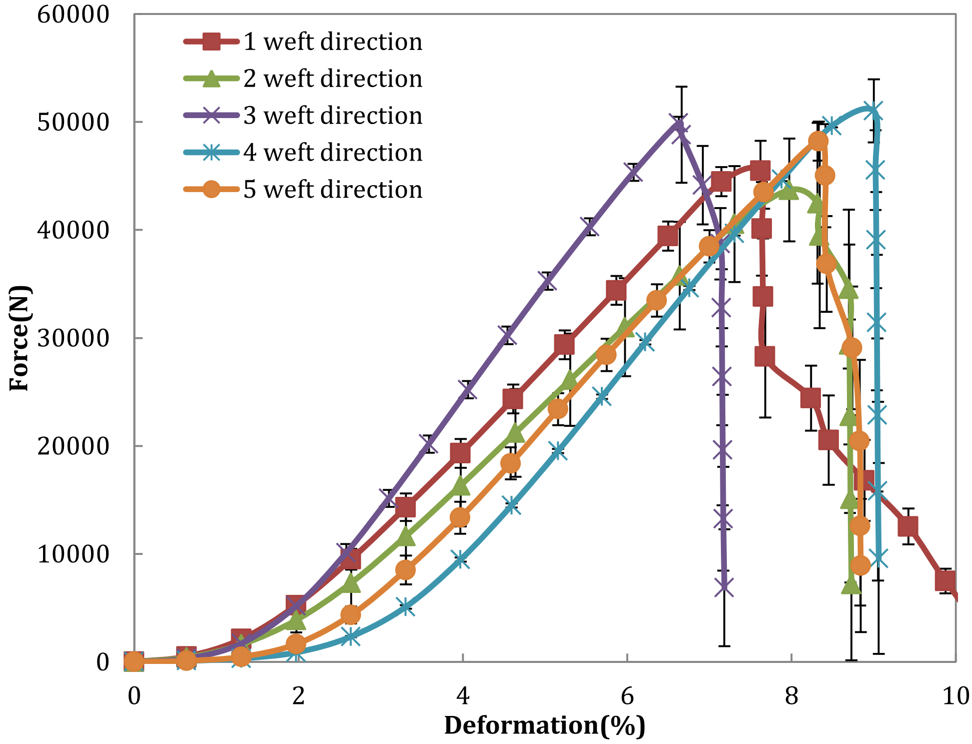



**Figure 3**. Weft direction tensile tests results of five structures.

Based on Figure 3, both curves have shown very similar progression in which the tensile force increases as the deformation become higher. Moreover, the curves can be generally divided into two parts, where the first part has the lower force with small deformation, and the second part shows higher force and deformation value. The first part of the non-linear curve revealed smaller load vs. strain values due to mainly the alignments of yarn within the fabric before real deformation occurs in the specific load direction [10]. Besides, in this particular part, the strain starts slowly increases with the small amounts of increasing tensile loads. Whereas, the next part of the curve revealed a linear progression where real straightening of yarn occurred with the rapid increase of tensile loads. The tensile load while deformation has been increased until the preform reaches its breaking point.

## 4. CONCLUSIONS

For all of these fabrics, as shown in warp and weft directions, the tensile resistance is greater in the weft direction than in the warp direction due to the main difference between ends and picks densities. However, in the warp direction, it could be noticed for all the tested fabrics have a higher value of elongation in the warp direction than in the weft direction. O-L 3-2 4 Binding {Twill 4 effect left}-Stuffer has the largest tensile resistance in warp direction but relatively lower test resistance in weft direction in large part because of the structure and the friction between the yarns and machine during the weaving process. In a word, the methods for improving the tensile strength include a minimum waviness in the in-plane fibres which are affected by the weave architecture.

## 5. ACKNOWLEDGMENT

The first author wishes to express her gratitude to the China Scholarship Council (Project No. 201708420167) for financially supporting this work.

## 6. REFERENCES

1. M. Afshari, D. J. Sikkema, K. Lee, and M. Bogle, High performance fibers based on Rigid and Flexible Polymers, *Polym. Rev.*, 2008, Vol. 48, 230–274.
2. Y. Zhou, X. Chen, and G. Wells, Influence of yarn gripping on the ballistic performance of woven fabrics from ultra-high molecular weight polyethylene fibre, *Compos. Part B Eng.*, 2014, Vol. 62, 198–204.
3. Boussu F, Dufour C, Veyet F, Lefebvre M, *Advances in Composites Manufacturing and Process* Design, Woodhead Publishing, France, 2015, 55–78.
4. A. K. Bandaru, Y. Sachan, S. Ahmad, R. Alagirusamy, and N. Bhatnagar, On the mechanical response of 2D plain woven and 3D angle-interlock fabrics, *Compos. Part B Eng.*, 2017, Vol. 118, 135–148.
5. A. C. Corbin, A. Kececi, F. Boussu, M. Ferreira, and D. Soulat, Engineering Design and Mechanical Property Characterisation of 3D Warp Interlock Woven Fabrics, *Appl. Compos. Mater.*, 2018, Vol. 25, No. 4, 811–822.
6. A. K. Dash and B. K. Behera, Role of weave design on the mechanical properties of 3D woven fabrics as reinforcements for structural composites, J. Text. Inst., 2017, Vol. 109, No. 7, 952-960.
7. F. Boussu, S. Picard, and D. Soulat, *Narrow and Smart Textiles*, Springer, Cham, 2018, 21–31.
8. X. Chen and I. Zanini, An experimental investigation into the structure and mechanical properties of 3D woven orthogonal structures, *J. Text. Inst.*, 1997, Vol. 88, No. 4, 449–464.
9. F. M. Z. Nasrun, M. F. Yahya, S. A. Ghani, and M. R. Ahmad, Effect of weft density and yarn crimps towards tensile strength of 3D angle interlock woven fabric, *AIP Conf. Proc.*, 2016, Vol. 1774, No. 1.
10. M. A. Abtew et al., Influences of fabric density on mechanical and moulding behaviours of 3D warp interlock para-aramid fabrics for soft body armour application, *Compos. Struct.*, 2018, Vol. 204, No. 4, 402–418.
11. J E Rocher, S Allaoui, G Hivet, Experimental testing of two three-demensional (3D)-Non crimp fabrics of commingled yarns, Dresden, 2013, 13th AUTEX World Text. Conf..
12. H. Gu and Z. Zhili, Tensile behavior of 3D woven composites by using different fabric structures, *Mater. Des.*, 2002, Vol. 23, No. 7, 671–674.
13. Y. Rao and R. J. Farris, Modeling and experimental study of the influence of twist on the mechanical properties of high-performance fiber yarns, *J. Appl. Polym. Sci.*, 2000, Vol. 77, No. 9, 1938–1949.