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Experimental Investigation on the Stab Resistance of Warp Knitted Fabrics

Abstract
The stab resistance of two guide bar warp knitted fabric made from ultra-high molecular weight polyethylene was characterised by a maximum load, and energy at the maximum load and load versus displacement curves under quasi-static test conditions are presented. Penetration angles and side were designed. Samples with different lapping, densities and layers were tested, with a woven fabric used as the original reference. The results showed that warp knitted fabric with a moderate density and longer underlaps on the front guide bar performed better. The penetration angle and side have no observable influence on warp knitted fabrics' stab resistance. Furthermore the performance of warp knitted fabrics during a knife penetration shows the difference from woven fabric in the damage process.

Key words: *stab resistance, warp knitted fabric, penetration, ultra-high molecular weight polyethylene (UHMWP).*

Introduction

Due to the tight restriction on gun ownership rules prevailing in many countries, the proportion of assaults which are committed with knives has increased alarmingly, necessitating the development of protective, flexible armour systems with additional stab-resistant capabilities. Armor made from textile materials giving flexibility, light-weight, comfort and invisibility has become the key development aspect in the field of protective armour in recent years.

There have been some research and development related trials to apply textile material as body protection against stabbing. Mayo et al. [1] found that the cut resistance of woven aramid fabric was increased by integrating thermoplastic. Decker and Leonowicz [2, 3] integrated shearing thickening fluid into textile to enhance the stab resistance, respectively. Olszewska [4] investigated the application possibility of magnetorheological fluids in textile multilayered systems for multi-threat protections. Wang [5] and Decker [6] focused on the modeling or simulation of a knife stab in textile armors. Commonly stab-resistant textile structures theoretically studied or commonly used are based on woven fabrics [7], nonwoven fabric [8] and their hybrids. Only Flambard and Polo [9] used weft knits as a basic stab resistance textile structure. No studies published focus on warp knitted fabrics. In the past, researches on woven fabric, knitted fabric and nonwoven fabric indicated that different textile structures exhibited different stab resistant behavior, with each structure having both advantages and disadvantages. With poor resistance to sharpened instruments such as a spike, knitted fabrics are seldom recommended as stab resistant textile materials.

Warp knitted fabric is a kind of knit whose warps form interlocked loops along the length i.e. in the direction of warp. The behavior of warp knits is almost between that of weft knits and woven fabrics. For the purpose of studying the characteristic of warp knitted structure with respect to stab resistance, samples are subject to quasi-static loadings from a standard knife. The comparative performance and behaviour of the various warp knitted structures give a reference for the design and optimisation of stab resistant body armour.

***Table 1.** Structure parameters of samples; *The course density of fabric is determined by the speed of take-up which is set by the density of take-up on the machine. **Areal density is the grams of a fabric per square meter,before test the samples were cut into circles with diameter of 10 cm, then the gram of each sample were tested three times with a sensitive electronic scale, finally changed the resaults into garms per square meter through unit conversion.*

Sample	Structure of fabric		Take-up*, courses cm^{-1}	Wales density, wales cm^{-1}	Courses density, courses cm^{-1}	Areal density**, g·m^{-2}
	front bar	back bar				
1	1-0/1-2//	1-2/1-0//	9	9.1 ± 0.1	11.5 ± 0.2	315 ± 3
2	1-0/1-2//	2-3/1-0//		9.6 ± 0.2	10.6 ± 0.2	339 ± 2
3	2-3/1-0//	1-0/1-2//		10.2 ± 0.2	11.0 ± 0.1	364 ± 1
4	1-2/1-0//	1-0/3-4//		9.1 ± 0.1	11.2 ± 0.2	398 ± 2
5	1-0/3-4//	1-2/1-0//		9.7 ± 0.1	11.3 ± 0.1	418 ± 3
6	1-0/1-2//	1-2/1-0//	7	8.7 ± 0.2	10.7 ± 0.2	307 ± 2
7	1-0/1-2//	1-2/1-0//	11	9.0 ± 0.1	12.2 ± 0.2	320 ± 3
8	Plain woven fabric		—	9.53 ± 0.2, warps cm^{-1}	9.00 ± 0.5, ends cm^{-1}	440 ± 1

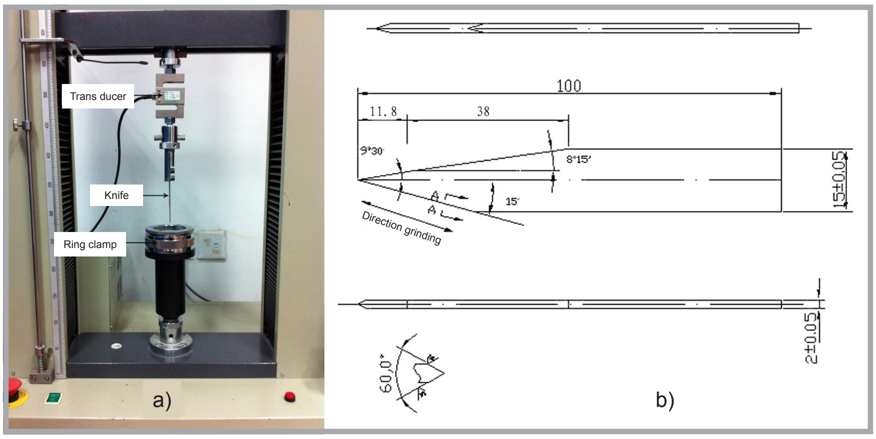

***Figure1.** a) Quasi-static stab tester and (b) size of knife.*

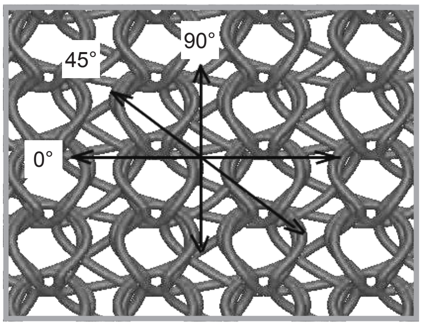

Figure 2. Penetration angles of technical face.

Experiment

Sample preparation

Flexible stab resistant armour uses high performance Fibre such as aramid and ultra-high molecular weight polyethylene (UHMWPE). Single faced warp knitted fabric with two fully threaded guide bars were produced from UHMWPE (Beijing Tong Yingzhong Specialty Fibre Dechnology & Development Co. LTD, China) filament yarns with a count of 27.8 tex (250 den). Considering an appropriate needle gauge, Karl Mayer's E22 Rachel double needle bar machine was used to knit five single face structures of samples with only one needle bar. The same structure with different taken-up densities was also knitted. Subsequently the warp knitted fabrics were washed at 90 degrees Celsius for 20 minutes under fresh water and heat set at 110 degrees Celsius at a speed of 19 meters per minute through 8 drying ovens. ***Table 1*** (see page 65) shows the parameters of samples.

Testing

Quasi-static stab testing of the samples was carried out. An electronic fabric strength tester was modified to act as a quasi-static stab resistant tester (***Figure 1.a,*** see page 65) by changing the bursting head to an asymmetric knife with a single-edged blade. The size and shape of the knife is shown in ***Figure 1.b***. A transducer was placed on top of the knife to record the penetration load. The samples were cut into circles with an 8 cm diameter and put in a ring clamp under the knife. The knife was then driven into the ring clamped sample at a constant rate of 20 mm/min and stopped when the attenuation of the load was 90%.

Warp knitted fabric has loop interlocked wales along the lengthwise which are connected by the angled underlaps. The technical face shows the loops with the legs almost oriented lengthwise. However, the technical back shows the underlaps. Thus warp knitted fabric not only depicts anisotropy, but also has different structures between the two sides. For these reasons, testing was carried out at different penetration angles (0°, 45° and 90°) and on both sides, i.e. technical face and technical back. ***Figure 2*** shows three penetration angles on the technical face. Each sample with a defined penetration side and angle was tested five times. The maximum load, displacement and energy of penetration were measured and averaged. A load versus displacement curve was established and destruction of the textile structure observed.

Results and discussion

General behaviour

Stab threats can be classified into two categories: puncture and cut [7]. The penetration process can be defined as windowing, cut or damaged. The results were analysed according to the NIJ Standard [10].

In the initial windowing, the peaked head of the knife punctured the warp knitted fabric easily because the loop structure was fairly loose. Fibres and yarns were extended and slipped rather than broken, forming a penetrating window (***Figure 3.a***). The load was gradually increased at the same time.

In the second stage, i.e. cutting, the knitted loop structure was deformed by the knife's penetration (***Figure 3.b***). When the windowing reached the limit, with the gathering yarns compacted and no more space present to extend further, the penetration force reached the maximum threshold and the knife was almost locked up (***Figure 3.c***). It was observed that yarns faced the cut from the blade and fibres were gradually broken.

The third is the so-called 'damaged' phase (***Figure 3.d***) where yarns started to break. The knife penetrated through the fabric when a number of yarns were broken and caused the whole structure to be destroyed. The load started to drop until the knife had completely penetrated the sample.

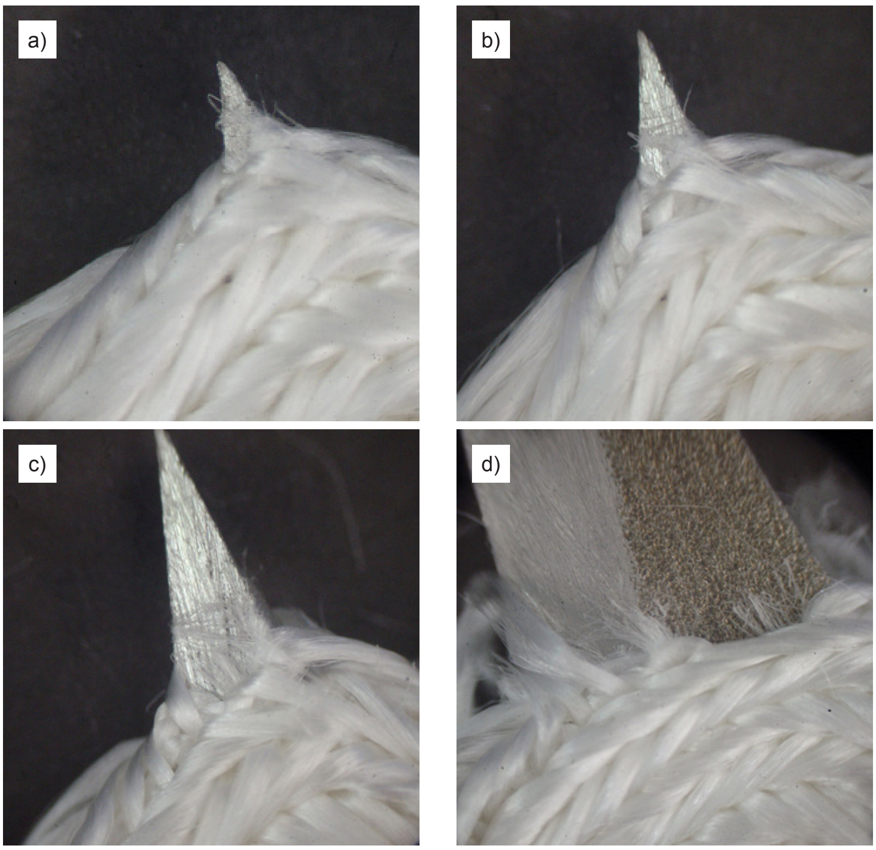

Figure 3. *Penetration process of warp knitted fabric; a) process of initial windowing, b) further windowing, c) process of cut, d) sample damaged.*

The load-penetration depth curves of various structures shown in ***Figure 4*** also

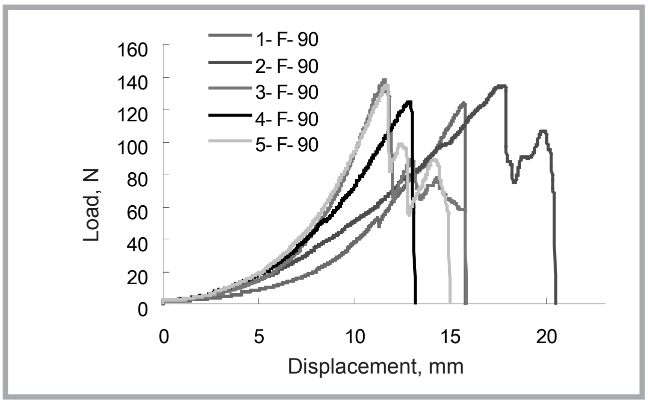

Figure 4. Load versus displacement of warp knitted fabric.

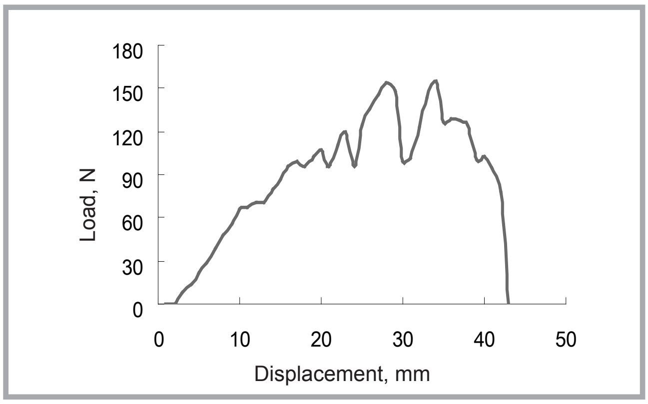

Figure 5. Load versus displacement of woven fabric.

reflect the above three stages of penetration. In the windowing stage, the initial load increases slowly with the penetration depth. Following the cutting stage, the curves gradually become steeper and steeper until the load reached the maximum yield. Corresponding to the damage stage, the curves have waves representing yarns breaks, and stop when the knitted structure fell apart and the load slumped.

Sample 8 was a dense plain woven fabric which had been commercially used in the manufacturing of stab resistance armour. It was used as a reference for the warp knitted samples. The knife met with more resistance at the beginning of puncturing sample 8. However, once the knife pierced in, the warp or weft yarn at the edge of knife was cut directly because dense interlaced points restricted the slippage of yarns. The force of cutting a yarn applied was relatively smaller and specific yarn breakage did not cause the disassembly of the woven structure. Other unbroken yarns kept on restricting the penetration until a number of yarns had broken, with the knife penetrating through the target completely. ***Figure 5*** shows the load-displacement curve of sample 8. The load increased with the displacement quickly as the knife was driven into the fabric. Load waves starting from the first broken yarn and its displacement were found to be usually bigger than for warp knitted fabric.

It is observed that the tightness of the textile structure is a key factor influencing the puncture and cut. A dense structure is beneficial in resisting the puncture of the knife head, but made against yarn gathering to resist the cut of a knife blade.

Table 2 summarises the quasi-static stab data at a confidence level of 95%. "F" and "B" in the middle of the label rep-

Table 2. *Data collection of quasi-static stab testing; # The first character represents sample number, the alphabet "F" and "B" in the middle of label represent technical face and technical back respectively, The numbers at the end of label represent the penetration angle. For example, "5-B-90" means no. 5 fabric's structure, penetrated on technical back at an angle of 90°. This kind of label applied to the whole paper.*

Label of sample#	Max. load, N	Displacement at max. load, mm	Energy at max.load, J
1-F-0	113.3 ± 26.59	13.30 ± 2.43	0.50 ± 0.20
1-F-90	116.3 ± 42.16	12.94 ± 4.37	0.43 ± 0.32
1-F-45	113.0 ± 13.26	11.31 ± 0.32	0.35 ± 0.03
1-B-0	115.7 ± 26.47	11.93 ± 1.58	0.39 ± 0.11
1-B-90	106.3 ± 13.50	10.74 ± 1.09	0.32 ± 0.09
1-B-45	96.0 ± 5.58	10.43 ± 0.86	0.28 ± 0.07
2-F-0	107.3 ± 8.45	13.69 ± 1.04	0.51 ± 0.05
2-F-90	127.0 ± 12.12	11.98 ± 1.87	0.48 ± 0.04
2-F-45	139.3 ± 48.34	13.25 ± 2.02	0.58 ± 0.26
2-B-0	126.7 ± 32.59	14.26 ± 6.43	0.71 ± 0.68
2-B-90	125.8 ± 23.99	12.24 ± 0.52	0.42 ± 0.09
2-B-45	112.0 ± 17.69	11.77 ± 0.70	0.35 ± 0.10
3-F-0	114.0 ± 32.91	11.41 ± 0.99	0.42 ± 0.14
3-F-90	136.3 ± 4.93	13.42 ± 2.70	0.61 ± 0.25
3-F-45	114.7 ± 9.61	11.22 ± 0.31	0.35 ± 0.03
3-B-0	134.7 ± 8.50	13.51 ± 2.28	0.56 ± 0.23
3-B-90	124.0 ± 25.03	11.80 ± 0.21	0.41 ± 0.07
3-B-45	127.0 ± 13.11	12.70 ± 1.51	0.45 ± 0.14
4-F-0	122.3 ± 21.02	15.63 ± 3.89	0.71 ± 0.22
4-F-90	121.7 ± 9.73	12.16 ± 1.89	0.52 ± 0.13
4-F-45	131.0 ± 8.66	12.45 ± 1.28	0.45 ± 0. 05
4-B-0	129.7 ± 28.75	12.00 ± 0.68	0.43 ± 0.08
4-B-90	117.8 ± 8.44	11.64 ± 0.95	0.40 ± 0.09
4-B-45	137.7 ± 36.47	12.06 ± 0.77	0.51 ± 0.09
5-F-0	150.7 ± 4.82	16.90 ± 7.97	0.89 ± 0.64
5-F-90	138.6 ± 7.02	11.64 ± 0.76	0.47 ± 0.11
5-F-45	122.7 ± 10.26	13.19 ± 0.75	0.52 ± 0.18
5-B-0	159.0 ± 21.07	13.46 ± 0.23	0.60 ± 0.14
5-B-90	144.7 ± 19.09	12.77 ± 0.52	0.51 ± 0.08
5-B-45	146.0 ± 5.00	12.59 ± 0.17	0.47 ± 0.03
6-F-0	137.3 ± 32.96	13.46 ± 0.98	0.54 ± 0.08
6-F-90	108.7 ± 16.07	10.79 ± 1.09	0.31 ± 0.06
6-F-45	124.0 ± 31.76	19.86 ± 13.45	1.23 ± 1.39
7-F-0	129.0 ± 17.06	11.49 ± 0.60	0.45 ± 0.10
7-F-90	99.3 ± 38.69	11.01 ± 2.76	0.39 ± 0.27
7-F-45	118.3 ± 35.73	11.73 ± 1.96	0.45 ± 0.21
8-0*	125.0 ± 34.51	22.63 ± 11.15	1.59 ± 1.20
8-90*	114.6 ± 27.08	20.76 ± 10.87	1.43 ± 0.96
8-45*	117.7 ± 25.72	32.80 ± 11.42	2.22 ± 0.72

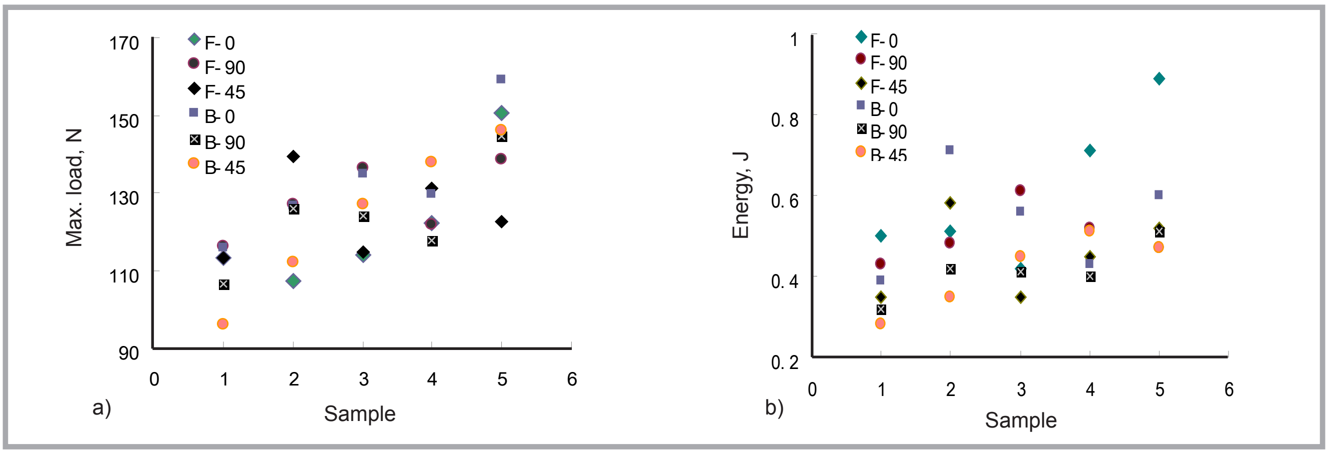

Figure 6. a) Max. load and b) energy comparison in different penetration angle.

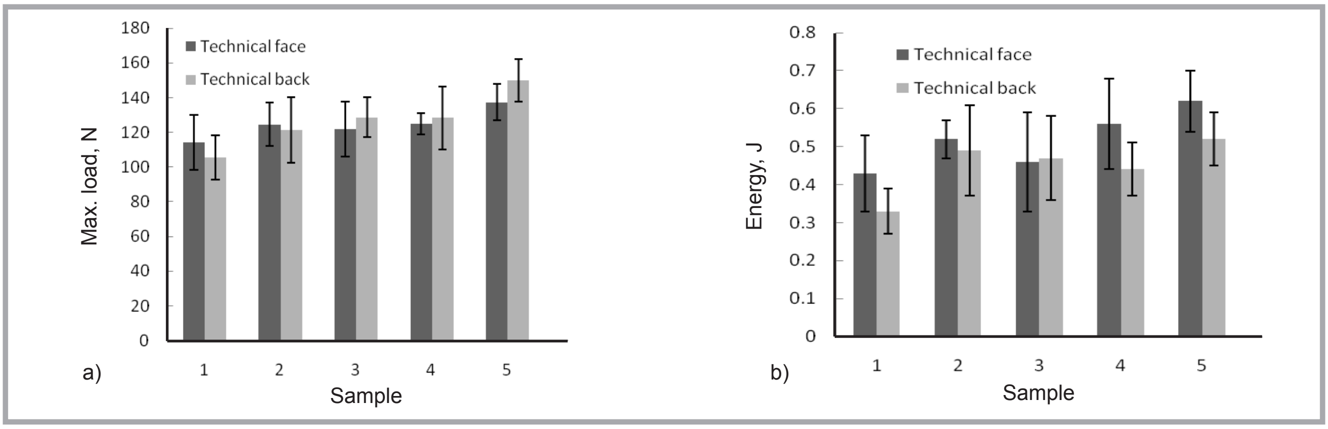

Figure 7. a) Max. load and b) energy comparison of technical face and technical back.

resent the technical face and technical back, respectively. The numbers at the end of the label represent the penetration angle, for example, "5-B-90" means no. 5 fabric's structure, penetrated on the technical back at an angle of 90°. The warp and weft yarn count and density of the plain woven fabric tested were the same, and the difference between either the back and front side or penetration angles 0° and 90° can be neglect. Thus only penetration angles 0° and 45° were selected for the testing of sample 8. The table includes the averaged maximum load, displacement at the maximum load, and the energy at the maximum load along with the standard deviation for each case. The maximum load is the highest value of force that is reached during quasi-static stab testing while the energy at the maximum load is the penetration energy required to reach it. The energy at the maximum load is determined by the displacement and maximum load.

By check the windows of the samples tested, it was found that the initial puncture point may be on the yarn or between yarns. If the initial puncture was on the yarn, knife slippage could have happened during the penetration. This led to bigger standard deviation in some test groups, especially relatively loose structures, such as sample 1.

Penetration angle

With the penetration angle changed, the knife's stab met with different parts of

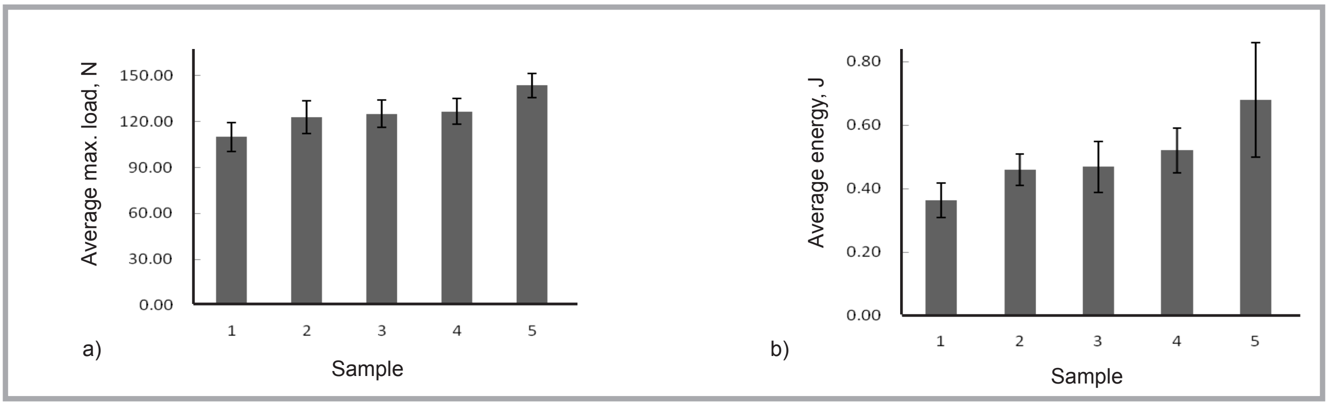

Figure 8. a) Maximum load and b) energy comparison of different Lapping.

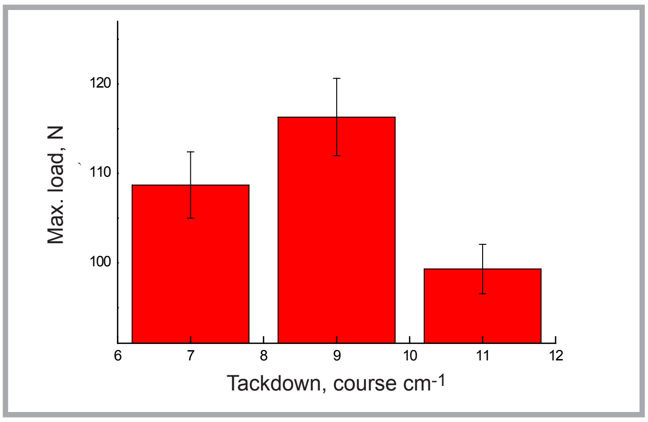

Figure 9. Relation between the max. load and tackdown.

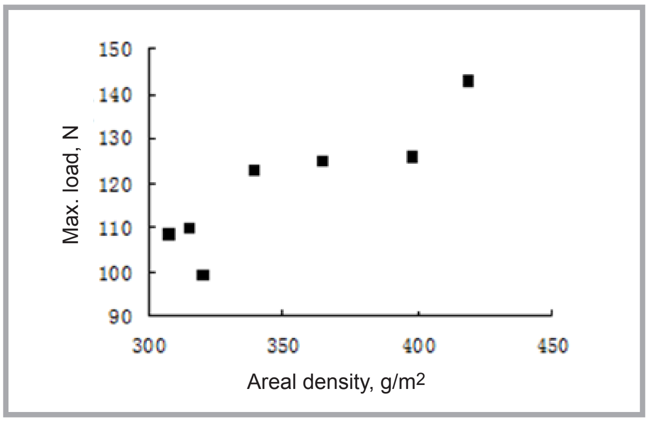

***Figure 10.** Relation between max. load and areal density*

stitches, some of which were stretched and cut directly, playing an important role in resisting the penetration. Other parts produced corresponding deformation and decided the yarns' slippage ability.

When the knife penetrated at an angle of 0°, the slit extended along the length. Mostly underlaps between the wales came into contact with the edge of the knife, stretched and suffered a direct cut. The loops shrank at the same time. When the knife stabbed at an angle of 90°, the slit extended transversally. The legs of the loops became the main part to bear the force, becoming displaced and cut directly. When the penetration angle was changed to 45°, the underlaps of one bar may be parallel to the knife and have little effect on the stab resistance. In contrast the underlaps of the counter lapping guide bar played an important role in resisting the penetration.

Figures 6.a and ***6.b*** show the distribution of the penetration load tested and energy at different angles of Samples 1 to 5. Although the knife penetrated and cut different parts of stitches at different angles, the distribution of the value at different angles has no corresponding relationship in these two figures, and six values of every sample vary without any trend. No evidence shows that some of the five warp knitted structures performed better or worse when they were penetrated at some angle. Thus the penetration angle has no evident influence on the stab resistance of warp knitted fabric.

Penetration side

The penetration side determines which parts of stitches withstand the knife's action first. The penetrating knife meets the loops on the technical face first, while it meets the underlaps on the technical back. In order to observe whether the penetration side plays a role in stab resistance, the values of the maximum force and energy of three penetration angles on each side were averaged. ***Figure 7*** compares the stab resistance of the technical face with technical back of samples 1 to 5. The length of underlaps determines how many yarns resist the cut on the technical back. ***Figure 7.a*** indicates that with the increasing length of the underlaps, the knife met with more resistance on the technical back than on the technical face. But longer underlaps contribute little to the loops on the technical face in resisting the cut. ***Figure 7.b*** shows that penetration on the technical face mostly consumes more energy than that on the technical back. By comparing the displacement at a maximum load in ***Table 2***, it is found that the technical face mostly exhibits more penetration depth than that of the technical back. Thus it is most likely that the greater deformation taking place on the technical face absorbed the energy.

Lapping

By averaging all values of specimens 1 to 5 for different penetration angles and sides, five structures with the same take down density are compared in ***Figure 8***.

Both ***Figures 8.a*** and ***8.b*** basically show that the samples exhibit a higher maximum force and energy with the increasing length of GB2's underlap (sample 1, 2 and 4) or GB1's underlap (samples 1, 3 and 5), which may be explained by the fact that more underlaps gathering on the blade increased the penetration resistance. Furthermore the knife has to cut more yarns of fabric which has longer underlaps to disassemble the structure. For example, sample 1 has two underlaps linking neighbouring wales in one course, whereas both samples 2 and 3 have three underlaps, and samples 4 and 5 have four underlaps.

Figures 8.a and ***8.b*** also show that the stab resistance of the fabrics with a longer underlap on the front guide bar is superior to those with the same length of underlap in the back guide bar (2 < 3, 4 < 5). This phenomenon could be attributed to yarn slippage, i.e. yarn movement on back guide bar is restricted by yarns on the front guide bars, thus it is difficult for longer underlaps to avoid the direct cut of the knife edge effectively. Hence longer underlaps arranged on the back guide bar have less influence on the stab resistance than on the front guide bar.

Density of fabric

Density is a key factor which determined the tightness of the fabric. Samples 1, 6 and 7 have the same lapping but different densities of take down. ***Figure 9*** shows the maximum load as a function of the density of the take down. Sample 1, with moderate density, has the best stab resistance. Although a tight structure with higher density is helpful to resist puncture, the little slippage space may be a disadvantage for yarns are easily cut directly by the blade of a knife.

The areal density of the fabric definitely increases with the density of take down and the increasing length of the underlapping. ***Figure 10*** shows the maximum load as a function of the areal density for samples 1 to 5. The maximum load increases with the uneven increase in the areal density. The specific load is a key factor of the armour weight, thus it was calculated by dividing the maximum load by the areal density. In order to give more rational evaluation to different structures, the specific load of each sample is compared in ***Figure 11***. The woven fabric (sample 8) shows a lower value than all

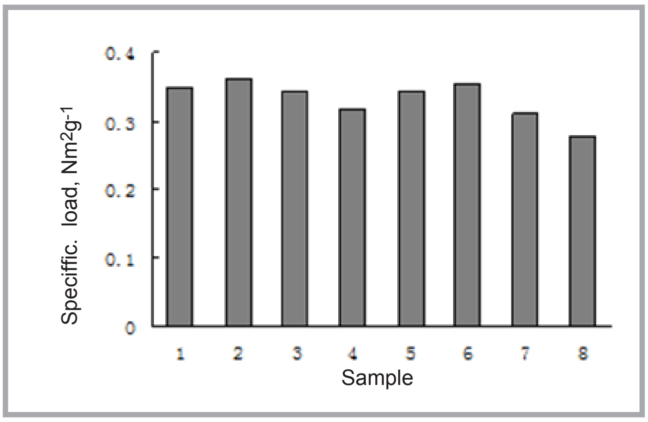

Figure 11. Specific load comparison of different structures.

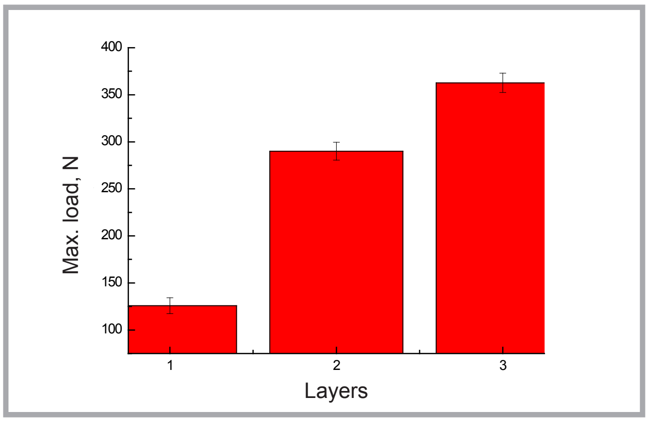

Figure 12. Relation between max. load and layers

warp knitted samples. It is interesting that the specific load of samples 1, 3 and 5, which have the same lapping on the back guide bar (GB2), are almost the same. However, when the lapping of GB1 is kept and GB2 is changed (sample 1, 2 and 4), the specific load obviously varies. Another fact is that the specific load decreases when the density of take down increases from 7 course/cm (sample 6) to 9 course/cm (sample 1) to 11 course/cm (sample 7). In this case, with the same structure of the same weight, a warp knitted fabric which has a lower density of take down may have more efficient resistance to stabbing.

Number of layers

Sample 4 was selected to test the relationship between the layers and the maximum load. ***Figure 12*** shows the relations between the layers and maximum load, where the stab resistance increases with more layers. But it also indicates that the maximum load of multilayer fabrics is not the accumulated value of every layer. The different layers acted variably during the punch of knife, hence the efficiency of every layer was different.

Conclusion

The results of the paper showed that warp knitted fabric was deformed, stretched and cut during knife penetration. The primary destruction of it was the breaking of yarns by cutting and following stitch disassembly.

It was proved that the lapping, density of the take down and the areal density were the factors which influenced the stab resistance of warp knitted fabric. The fabric with longer underlaps, regardless whether on front or back bar, had better performance in resisting the stab. The fabrics with longer underlaps on the front guide bar performed better than those with the same length of underlaps on the back guide bar. Although the tight structure was highly beneficial in resisting the knife's puncture, appropriate stitch deformation of moderate loop density led to the gathering of more yarns to resist the knife cut, thereby restricting further knife penetration. The specific maximum load and penetration energy of warp knitted fabrics with different structures were similar, and much better than those of woven fabric in the study. Hence warp knitted fabrics of varying structure may be a suitable hybrid in armour to meet the requirements of different layers.

Though the warp knitted structure is anisotropic, the test results showed that the penetration angle and side of the knife have no significant effect on stab resistance. When warp knitted fabric is used in stab resistant armour, the fabrics may be laid without considering the direction and side

For overall assessment and analysis of the stab resistance of warp knitted fabric, future work should be carried out on dynamic stab resistance testing. Further study on the quantitative relationship between the structure parameters of warp knitted fabrics and stab resistance is required.

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