ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

STUDY OF RESISTANCE TO SHARP OBJECT PENETRATION AND SPREAD OF THE RESULTING RUPTURE IN WOVEN FABRICS

AMIRSHIRZAD Forough[1], MOUSAZADEGAN Fatemeh[2], EZAZSHAHABI Nazanin[3]

[1, 2,3] Amirkabir University of Technology, Textile Engineering Faculty, 424 Hafez Ave, 15875-4413, Tehran, Iran

E-Mail: amirshirzad@aut.ac.ir, f_mousazadegan@aut.ac.ir, ezazshahabi@aut.ac.ir

Corresponding author: Amirshirzad, Forough, E-mail: amirshirzad@aut.ac.ir

Abstract: *Textiles designed to protect the wearer against damages caused by sharp objects have various applications in the workplace and sports. In this study, the resistance of woven fabrics against sharp object penetration was assessed. In this regard, three different fabric samples, including the Twill 2/2, Satin 1/7 weft, and Hopsack 4/4 weave patterns were prepared. Force and energy of penetration by a sharp object were measured in mentioned fabric structures. It was observed that weft density and yarn interlacement are prominent factors that determine the woven fabric resistance against sharp object penetration. Higher weft density leads to greater penetration force and energy since a higher number of yarns resist the sharp object penetration. Moreover, the weave pattern with more firmness restricts the yarn displacement in the fabric structure and consequently provides greater penetration resistance. In this regard, the Hopsack weave pattern, which has higher weft density than Twill fabric, and shorter yarn floats compared to Satin fabric, showed the best resistance among tested samples. In addition to the penetration test, the cut spread test was also performed to evaluate the fabric resistance against the expansion of the cut created in the fabric by sharp object penetration. According to the results, in the cut spread test, the Hopsack fabric provided the greatest resistance. The force and energy of spreading the cut region are much more than creating the cut in the fabric structure since the sharp object should cut the bunched yarn instead of the single yarn.*

Key words: *Woven Fabric, Weave Pattern, Weft Density, Penetration Force, Sharp Object*

1. INTRODUCTION

Resistance to penetration is one of the fundamental properties of fabrics utilized for protection against various types of mechanical impact [1]. Several 2D and 3D textile structures can be used in designing protective textiles. Among them, two-dimensional woven fabric is the most commonly used material for various mechanical impact threats [2]. A study by Nolan et al. [3] revealed that wearing multiple layers of clothing increases the penetration force relative to each clothing layer separately. However, no direct relationship was observed between the penetration force in multi-layer and single-layer clothing. Amirshirzad et al. [4] analyzed the penetration resistance of a three-layer textile structure and its constituted layers. Based on their observation, the penetration force diagram by sharp object displacement of the studied three-layer structure was divided into two regions representing resistance of top layer and both middle and bottom layers. In another study, Amirshirzad et al. [5], studied bending and resistance to sharp object penetration in metal-reinforced fabrics. According to their results, in addition to providing greater penetration resistance, achieving lower stiffness and lower weight of fabric is desired by inserting higher number of metal threads, instead of using coarser metal threads. Cooper et al. investigated the damage morphology caused by kitchen knives, taking into account the effect of fabric extension. Their results showed that the length of the injury is affected by the assailant gender, the fabric structure, and knife properties. In contrast, the fabric extension (0%, 10%) has no significant effect on the injury's length [6].

2.1 Materials

Woven fabrics in three weave structures, including weft-backed Twill $\frac{2}{2}$ Z, Satin $\frac{1}{7}$ weft, and Hopsack $\frac{4}{4}$, were used to study woven fabric's resistance to sharp object penetration and spread the caused cut region. Plain, Twill, and Hopsack are appropriate weave patterns for soft vest applications because of their high in-plane properties. The crimp in the fabric structure acts as an impact absorbing mechanism due to the friction between the yarns and the fibers' slippage. On the other hand, the Satin weave structure is commonly preferred for rigid armor applications due to its low crimp degree. These fabrics were woven through a weft-backed weaving system with a weave ratio of 3:1 using a handloom machine. In this weaving method, the weft density is increased, but the fabric handle properties are not changed. The schematic view of these weave structures is illustrated in Fig. 1. Acrylic yarn with a count of 15/4 Nm was utilized to weave the fabric samples. The physical properties of prepared fabrics are reported in Table 1. The applied sharp object's characteristic is also presented in Table 2.

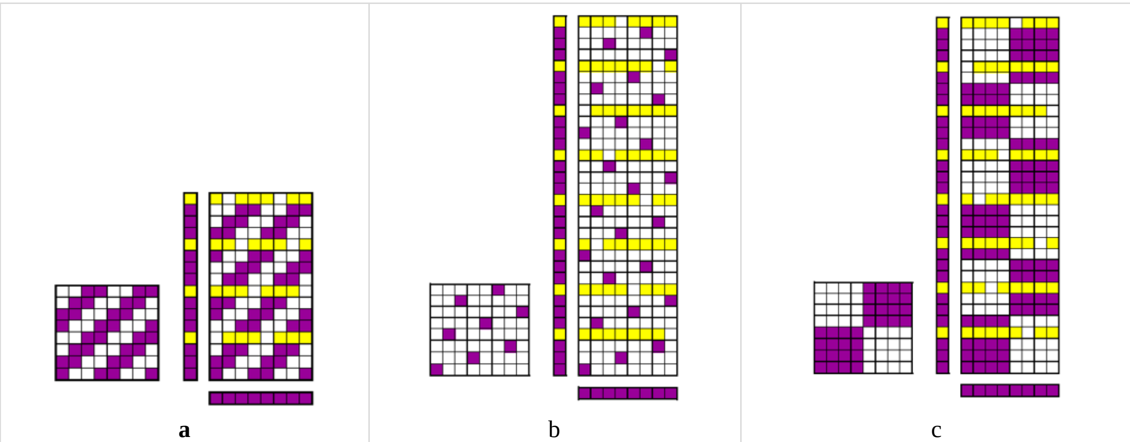


Fig. 1*. The Weave Pattern Design of a) Twill 2/2, b) Satin 1/7, and c) Hopsack 4/4 fabrics*

Table 1. *Physical Properties of Woven Fabrics*

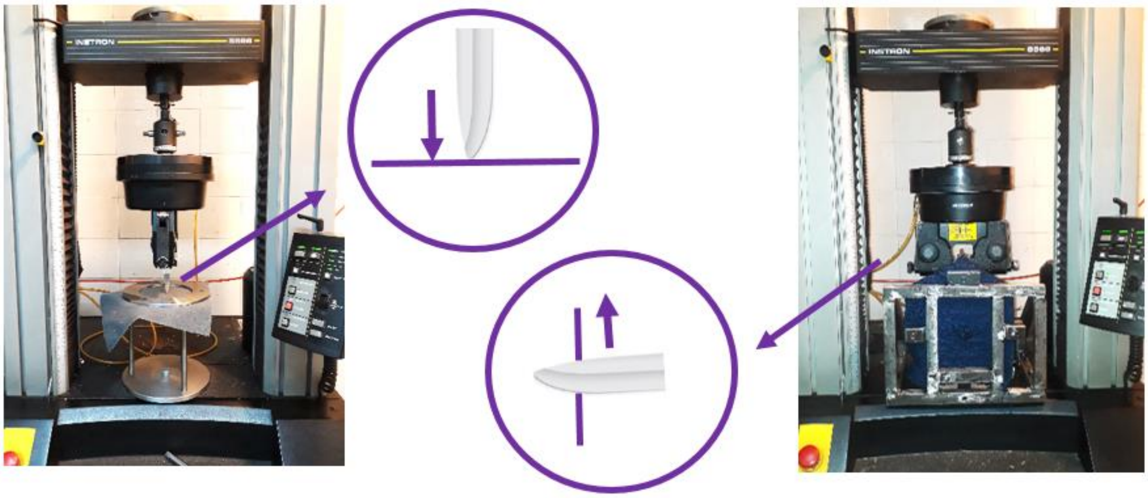
Weave Pattern	Warp Density (1/cm)	Weft Density (1/cm)	Thickness (mm)	Mass per unit area (g/m^2)
Twill 2/2	11	10	2.45	612.75
Satin 1/7	11	16	3.50	940.76
Hopsack 4/4	11	17	2.98	876.36

Table 2. *Characteristic of the applied knife*

Knife's Shape	Length (mm)	Thickness (mm)	Tip Angle ($^\circ$)	Application
	88	1.78	141	Slicing Knife

2.2 Test Method

Fabric resistance against sharp object penetration in the vertical and horizontal directions was assessed by modifying Tensile Tester Machine, Instron model 5566. Distinct sample holders replaced the machine's bottom jaw to perform penetration and cut spread tests, and a sharp object was inserted in the machine's upper jaw. Set up of penetration and cut spread tests, the knife, and fabric position at the beginning of the test, and the knife movement direction is depicted in Fig. 2.



a b

Fig. 2*. Set up of a) Penetration, and b) Cut-spread tests*

The penetration test was conducted as a test method proposed by Sun et al. [7]. According to Fig. 2a, the knife is in contact with the fabric surface at the beginning of the test. As the test starts, the knife moves downward, and penetration force and knife displacement are recorded. The penetration test was conducted at the speed of 100 mm/min, and the penetration process was executed to a depth of 45 mm.

The purpose of performing the cut spread test is to obtain the force required to expand the cut caused by sharp object penetration. As shown in Fig. 2b, the knife is placed in the rupture area caused by vertical knife penetration in the penetration test at the beginning of the test. As the test starts, the blade moves upward at the speed of 100 mm/min. The knife movement along the fabric is set to 30 mm. Three fabric samples' reputations were tested for both penetration and cut spread experiments, and the average of obtained data is reported.

3. RESULTS AND DISCUSSION

3.1. Evaluation of penetration force in fabric samples

Penetration force by knife displacement diagrams of three fabric samples with different weave patterns are shown in Fig. 3. Three stages of indentation, penetration, and perforation can be defined in the knife penetration process into the fabric. In all weave structures, at the beginning of the diagrams, a slight increase in the penetration force is observed with increasing displacement. At first, the knife is not able to penetrate the fabric and move the threads. In fact, this is the indentation step. Gradually, as the knife moves downward, the slope of the graph increases, this area of the diagram can be attributed to the knife involvement with the fabric yarns. Growing the force by increasing the knife displacement eventually leads to the fabric stretching and cutting of the threads.

In this way, the penetration force reaches the maximum value in the diagram and then decreases.

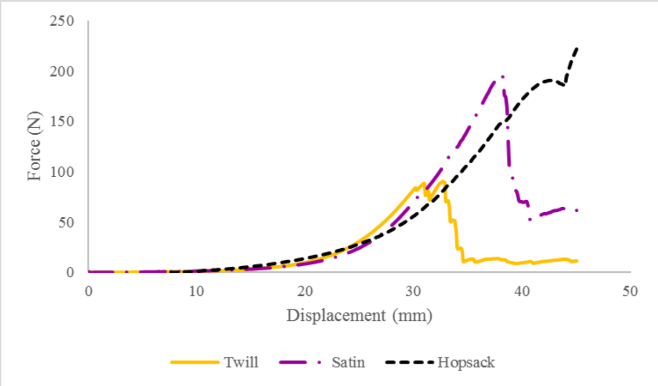


Fig. 3. *Force by knife displacement of fabric samples in penetration test*

Differences in the penetration force of the Twill, Satin and Hopsack weave patterns; can be elucidated by differences in the yarn interlacing and weft density. The Twill weave pattern has the lowest resistance against knife penetration. In the Twill weave pattern, which has the lowest weft density, fewer yarns resist knife penetration than Satin and Hopsack fabrics, resulting in less penetration force in Twill fabric. On the other hand, Satin and Hopsack weave patterns, with nearly same weft densities were more resistant to the knife penetration.

Taking into account the weave patterns of Satin and Hopsack fabrics shown in Fig. 1, both fabric samples have one interlacing point between warp and weft yarns. It means that, for each weft thread, only at one point the position of weft yarns are changed in relation to warp yarns. For instance, in Hopsack weave pattern, weft yarns are positioned over four adjacent warp yarns, and in the next four warp yarns, weft threads are located under the warp yarns. On the other hand, in Satin weave pattern, in seven adjacent warp yarns, weft thread is placed over warp yarns, and in the eighth warp yarn, weft thread is below the warp yarn. Therefore, Satin and Hopsack fabrics are similar in terms of weft density and yarn interlacement. However, in Satin fabric, weft yarn floats are longer than Hopsack fabric, which allows the threads to move more easily, leading to lower resistance in Satin weave pattern.

In previous studies, it is reported that expanding the cut created in the fabric by sharp object penetration requires less force than penetrating the fabric and creating the cut in the first place [8]. The graphs in Fig. 3 are also a compelling example of this. As illustrated in Fig. 3, as the knife penetrates the fabric and punctures it, the force reaches the maximum value, and after creating the cut in the fabric structure, the force decreases. However, the force needed to expand the cut region in a perpendicular knife movement direction is not explored. In this regard, the cut spread test is performed in the next step, and fabric behavior is assessed.

3.2. Evaluation of cut spread force in fabric samples

Force diagrams by knife displacement of fabric samples are illustrated in Fig. 4. As can be seen from Fig 4, Twill weave pattern has the least resistance to cut spread. In Twill weave pattern, weft density and, consequently, the number of yarns resistant to the cut spreading force is fewer. Therefore, as anticipated, this weave pattern has the lowest resistance to cut spread compared to Satin and Hopsack fabrics. The longer yarn floats in the Satin fabric compared to the Hopsack fabric makes yarns easier to move against the knife, resulting in less force in the cut spread test. Therefore, as the penetration test, maximum force in cut spread test is related to

Hopsack, Satin, and Twill fabrics, respectively. Force and energy of fabric samples in penetration and cut spread tests are reported in Table 3.

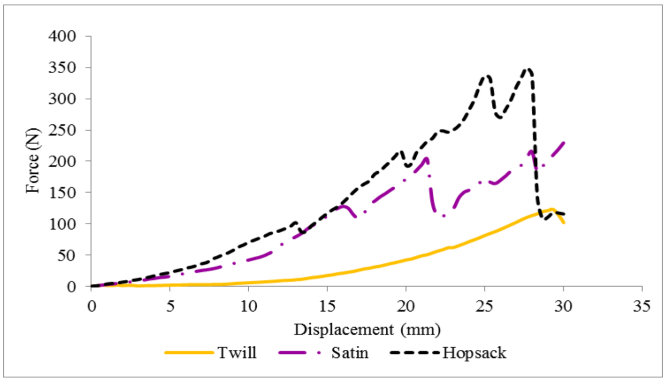


Fig. 4. *Force by knife displacement of fabric samples in cut spread test*

Table 3. *Force and energy of fabric samples in penetration and cut spread tests*

		Twill	**Satin**	**Hopsack**
Penetration Test	**Maximum Force (N)**	90.54	196.64	221.93
	Energy (J)	0.84	1.90	2.42
Cut Spread Test	**Maximum Force (N)**	123.24	229.53	349.74
	Energy (J)	1.04	2.94	4.02

In the cut spread test, the fabrics are in contact with the knife blade and cut by it. The knife blade is much blunter than the knife tip, and it is more difficult to cut the threads with it. Due to this, during the cut spread test, the knife can not easily cut the yarns, and as it moves upward in the fabric, it causes the fabric to shrink. In this case, the knife blade is faced with a bunch of threads instead of a single thread in the fabric structure. As a result, both force and energy values are greater in the cut spread test for all weave patterns than the penetration test.

4. CONCLUSIONS

In the current research work, resistance to sharp object penetration and spread of the resulting rupture in woven fabrics was examined. In this regard, the penetration and cut spread tests were performed on woven fabrics in different weave patterns, including weft-backed Twill $\frac{2}{2}$ Z, Satin $\frac{1}{7}$ weft, and Hopsack $\frac{4}{4}$. The effect of fabric constructional parameters, such as weft density and weave pattern, on fabric resistance to sharp object penetration and spread of the cut caused by sharp object was investigated. In the knife penetration test, the fabric resistance against vertical knife penetration relative to the fabric surface is obtained. In contrast, in the cut spread test, fabric resistance against horizontal knife movement relative to the fabric surface is measured. The results revealed that weft density and weave pattern considerably affect the fabric resistance against creating and spreading the cut caused by a sharp object. The higher the weft density, the higher the penetration resistance and cut expansion resistance since more threads resist the penetration of a sharp object or expand its resulting rupture in higher weft densities.

Furthermore, weave structure of the woven fabrics significantly affect its protective performance against assaults by sharp objects. Woven fabrics with weave structures having more firmness resist better against sharp object penetration. They also have greater resistance to the cut-spread caused by penetration of sharp objects. Hopsack fabric has the highest force in penetration and cut spread tests due to its higher weft density than Twill fabric and shorter yarn floats compared to Satin fabric. In all fabric samples, the force and energy recorded in the cut-spread test are greater than the penetration test because in the cut spread test, the blunter part of the sharp object cut the fabric that requires more energy. Besides, in the cut spread test, the blade encounters a bunch of yarns since it pulls fabric as it moves downward.

REFERENCES

[1] M. El Messiry, E. Eltahan, "*Stab Resistance of Triaxial Woven Fabrics for Soft Body Armor*", Journal of Industrial Textiles, vol. 45(5), pp.1062-1082, 2016.

[2] K. Bilisik, "*Two-Dimensional (2D) Fabrics and Three-Dimensional (3D) Preforms for Ballistic and Stabbing Protection: A Review*", Textile Research Journal, vol. 87(18), pp. 2275-2304, 2017.

[3] G. Nolan, S. Hainsworth, G. Rutty, "*Forces Required for a Knife to Penetrate a Variety of Clothing Types*", Journal of Forensic Sciences, vol. 58(2), pp. 372-379, 2013.

[4] F. Amirshirzad, F. Mousazadegan, N. Ezazshahabi, "*Evaluating the Resistance of Metal Reinforced Multi-layer Textile Structure against Penetration of Sharp Objects*", International Journal of Protective Structures, 2020.

[5] F. Amirshirzad, N. Ezazshahabi, F. Mousazadegan, "*Study of Bending and Resistance to Sharp Object Penetration in Metal-Reinforced Fabrics*", presented at the 21th Int. Conf. FASCICLE OF TEXTILES, LEATHERWORK, Oradea, Romania, 2020.

[6] E.J. Cowper, D.J. Carr, I. Horsfall, S.M, Fergusson, "*The Effect of Fabric and Stabbing Variables on Severance Appearance*", Forensic Science International, vol. 249, pp. 214–224, 2015.

[7] B. Sun, Y. Wang, P. Wang, H. Hu, B. Gu, "*Investigation of Puncture Behaviors of Woven Fabrics from Finite Element Analyses and Experimental Tests*", Textile Research Journal, vol. 81(10), pp. 992-1007, 2011.

[8] R. Nayak, I. Crouch, S. Kanesalingam, J. Ding, P. Tan, B. Lee, M. Miao, D. Ganga, L. Wang, "*Body Armor for Stab and Spike Protection, Part 1: Scientific Literature Review*", Textile Research Journal, vol. 88(7) , pp. 812-832, 2018.