ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

STUDY OF BENDING AND RESISTANCE TO SHARP OBJECT PENETRATION IN METAL-REINFORCED FABRICS

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

[1,2, 3] Amirkabir University of Technology, Textile Engineering Faculty, 424 Hafez Ave, 15875-4413, Tehran, Iran
E-Mail: amirshirzad@aut.ac.ir, ezazshahabi@aut.ac.ir, F_mousazadegan@aut.ac.ir

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

Abstract: *In various working conditions and some hazardous situations, people may be subjected to assaults by sharp objects. Therefore, protective clothing is utilized to defend the human body against dangers and damages caused by these threats. In this study several metal-reinforced fabrics were designed and prepared through a weft-backed weaving system and their protection performance was assessed. To prepare the fabric samples, different metal threads having various diameters and weave ratios were used. The designed fabric's resistance to bending and penetration of sharp objects was measured and the outcomes showed that using metal threads in fabric structure increased the fabric resistance against bending and penetration of sharp objects in general. The impact of metal threads diameter and weave ratio was also investigated. Thicker metal threads resulted in further increasing of the fabric resistance to penetration and bending. In fabrics reinforced with metal thread that have similar diameters, the samples with lower weave ratio need considerably greater force and energy for penetration. It was also observed that the impact of weave ratio is more significant than the impact of diameter of metal threads on fabric resistance to penetration. However, in terms of fabric resistance to bending, the impact of diameter of metal threads was higher compared to number of metal threads.*

Key words: *Bending Resistance, Penetration Force, Weave Structure, Metallic Thread, Protective Clothing*

1. INTRODUCTION

There are many occupations that may be at the risk of sharp object assaults. Protective clothing is used to protect the human body against various threats such as damages caused by sharp objects. Aramid multi-layer fabrics are widely used in the production of bullet-proof and stab resistant vests [1]. In addition to high strength multi-layer fabrics, using ceramic or metallic components can improve protection performance of protective clothing [2]. Tien et al. (2011) found that the stab resistance of the woven fabrics changed considerably with the variation of fabric's density [3]. Reiner et al. (2015) studied the effect of inserting wool layers instead of aramid fabrics as top and bottom layers in a multilayer panel, on stab resistance of panel. It was pointed out that application of wool fabrics provides acceptable penetration depth value with fewer layers, as well as reducing weight and improving comfort for the wearer [4]. Hejazi et al. (2016) investigated the effect of coating a woven textile with a series of metallic particles on the stab resistance of the textile. According to their findings, adding metallic particles to the surface of the fabric increased fabric's elastic modulus, and reduced the depth of knife penetration [5]. Aliverdipur et al. (2020) analyzed the relation between the tensile modulus and the penetration depth of woven fabrics. In this research it was observed that when the tensile modulus of the fabric is small, it extends more before the penetration, and due to this reason, the passage of sharp object through the fabric is delayed. Besides, it was declared that there was a direct relation between the sharp object's geometry and fabrics' destruction [6].

2. EXPERIMENTS

2.1 Materials

The metal-reinforced fabric was woven through a weft-backed system with the Twill $\frac{2}{2}$ Z weave pattern using a handloom weaving machine. The acrylic yarn with the count of $33_{/2}$ Nm was used as both warp and weft yarns for weaving the samples. In order to raise the fabric's resistance against penetration of sharp object, stainless steel metal threads were used as the backing weft yarns, which only appear on the back of the fabric. This provides no contact of metals with the skin surface. To avoid fabrics heaviness and improvement of the flexibility, a combination of acrylic and metal threads with a woven ratio of 5: 1 and 3:1 was applied as weft threads in weaving process. In other words, as it is shown in Figure 1, after each five or three acrylic yarns, one metal thread is inserted as weft yarn in the fabric structure. Three metal thread diameters including 0.2, 0.3, and 0.4 mm were used to prepare different samples. To examine the influence of metal thread's presence on the fabric's resistance against penetration of sharp object, fabrics were also woven without metal threads to be used as the control specimens. The warp and weft density of samples were 12 and 11 (cm^{-1}), respectively. Physical properties of woven fabrics are reported in Table 1.

Table 1: *Physical properties of woven fabrics*

Sample Code	Metal Diameter (mm)	Weave Ratio	Thickness (mm)	Mass per unit area (g/m^2)
S0W5	- (control sample)	5:1	1.29	201.76
S2W5	0.2	5:1	1.33	268.24
S3W5	0.3	5:1	1.36	294.39
S4W5	0.4	5:1	1.45	381.29
S3W3	0.3	3:1	1.42	299.98

Fig. 1 *The weave pattern and front and back images of sample S3W3*

According to Table 1, there is no significant difference between thickness of S2W5 and S0W5; however, application of metal threads has increased mass of S2W5 sample. S4W5 and S3W3 have the most thickness and mass. In other words, using thicker metal threads or more number of them has increased thickness and mass of fabric samples. Characteristic of the applied knife is also presented in Table 2.

Table 2: *Characteristic of the applied knife*

Knife's Shape	Length (mm)	Thickness (mm)	Tip Angle (°)	Application
	78	1.96	127	Toggle Knife

2.1 Test Method

Evaluating the fabric stiffness was carried out on Instron 5566 universal testing machine based on the standard test method for stiffness of fabric by the circular bend procedure (ASTM D 4032). In this test method, a plunger forces the fabric through an orifice in a platform. The maximum force required to push the fabric through the orifice is an indication of the fabric stiffness (resistance to bending). The test was carried out; using 24×24 cm^2 samples and the speed of the test was set on 100 mm/min.

Penetration test was also performed on Instron machine, according to the method presented by San et al (2011) [7]. The fabric holding system was substituted with the bottom jaw of the testing machine, and the knife was positioned in the machine's upper jaw. At the initiation of the test, the knife tip is in contact with the surface of the fabric. As the test starts, the knife moves down and penetrates the fabric sample. The penetration speed of knife was 100 mm/min and the penetration process was executed to the depth of 50 mm. For each fabric, three specimens were tested, and the average of the obtained outcomes was reported. Setup of penetration and stiffness tests on Instron machine are illustrated in Figure 2. To investigate the effect of inserting metal threads in fabric structure on fabric resistance, penetration test was conducted in the weft direction.

a *b*

Fig. 2*: Setup of a) penetration, and b) stiffness tests*

3. RESULT AND DISCUSSION

3.1. Resistance to bending

The bending force-displacement diagram obtained from stiffness tests are illustrated in Figure 3. As the test starts, the plunger tries to push the fabric sample out of the orifice. In respect to the fabric stiffness, the force reaches its maximum value and then decreases to zero, which means that the fabric is fully passed through the orifice. The maximum bending force (maximum force in the chart) and bending energy (area under the chart) of each fabric sample are reported in Table 3.

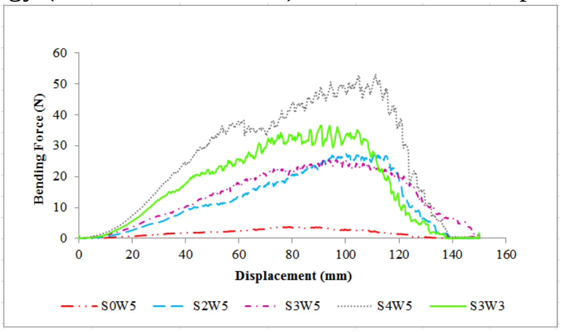


Fig. 3*: Bending force by displacement diagram of fabric samples*

Table 3: Bending force and energy of fabric samples

Sample Code	S0W5	S2W5	S3W5	S4W5	S3W3
Bending Force (N)	3.79	27.65	25.66	53.03	36.69
Bending Energy (J)	0.258	1.800	2.050	3.890	2.566

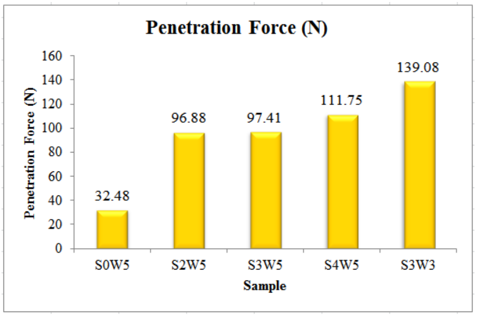
As it was expected, the control sample without metal (S0W5) has the lowest bending force and energy, and adding metals to fabric structure has increased the fabric stiffness. In samples woven with the same weave ratio and different metal thread diameters of 0.2 and 0.3 mm (S2W5 and S3W5), there was not much difference between the bending forces. Whereas, the use of metal threads with a diameter of 0.4 mm (S4W5) considerably increased the bending force and reduced the flexibility of the fabric, due to the higher bending rigidity of coarser metallic threads. Both S3W5 and S3W3 specimens were woven with a metal thread diameter of 0.3 mm and different weave ratios of 5:1 and 3:1, respectively. According to Table 3, the bending force of S3W3 sample is higher than the S3W5, and this means that increment in the number of metals in fabric structure has increased the fabric stiffness.

3.2. Resistance against penetration of sharp object

The diagram of the penetration force versus knife displacement is illustrated in Figure 4. As displayed in Figure 4, at the beginning of the diagrams, a slight increase in force is observed by increasing displacement. Initially, the knife blade is not able to penetrate the fabric and displace the yarns; in fact, this part is the knife indentation step into the fabric. As the knife displacement continues, the slope of the diagram increases; this part of the diagram can be attributed to the knife's involvement with the yarns and metals. The blade encounters threads and metals over its path of movement and tries to push them apart and pass through them. The rise of force by increasing the knife's displacement, eventually results in the fabric being extended, destructed, and abraded by the knife blade, resulting in the cutting of threads. As a result, the force reaches the maximum value, and then diminishes as seen in the chart. In Figure 5, the penetration force and energy of various fabric samples are compared.

***Fig. 4**: Penetration force by knife displacement of fabric samples*

As can be seen in Figure 5, the greatest penetration force and energy was related to the S3W3, S4W5, S3W5, S2W5, and S0W5 samples, respectively. S0W5 fabric which is the control specimen and is woven without metal threads has the lowest penetration force, while using metal threads in fabric structure has considerably increased the penetration force and energy. S3W3 sample which is woven by application of metal threads with the diameter of 0.3 mm and weave ratio of 3:1 has the greatest penetration force and energy. S2W5 and S3W5 samples have similar penetration force, and then S4W5 fabric has more penetration force compared to S2W5 and S3W5 samples. When using thicker metal threads, the knife blade needs further force to push the metals aside and penetrate through the fabric, which causes the higher penetration force and energy of S4W5 fabric compared to S2W5 and S3W5 samples. S3W3 sample has more penetration force and energy than S3W3 one. In weave ratio of 3:1, after insertion of three acrylic yarns, a metal thread is inserted as the weft yarn in the fabric; consequently, the number of metal threads in the fabric structure is more than weave ratio of 5:1. In this regard, higher number of metal threads resulted in greater penetration force and energy in S3W3 fabric. From Figure 4, it is visible that after the 20-30 mm displacement of the knife, the differences between the sample's penetration forces became more distinct. In the process of penetration into the fabric, the knife tries to push yarns aside in the fabric structure and pass through them. When the knife moves further into the fabric, it pushes more yarns sideways and a concentration of acrylic and metal threads are formed around the knife. When using a higher number of metal threads, the role of mentioned concentration is more critical, and this results in greater penetration force and energy. The mentioned phenomenon and the deformation of the fabric in the penetration region are shown in Figure 6.



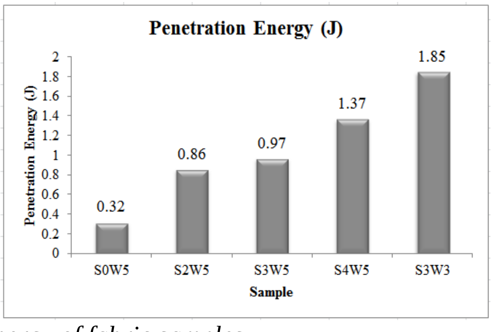


Fig. 5*: Penetration force and energy of fabric samples*

According to the obtained data for stiffness and penetration tests, it was observed that generally the samples with more bending force also have more penetration force. During the knife penetration into the fabric, because of fabric's extension, fabric is pulled down with the downward movement of the knife in the penetration zone. It seems that, this phenomenon can be affected by the fabric flexibility or in other words the fabric's bending behavior.

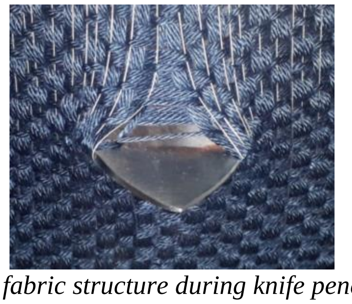


Fig. 6*: Deformation of fabric structure during knife penetration into the fabric*

As discussed earlier, S4W5 and S3W3 samples had the highest penetration force and energy among the tested samples. However, the increment in penetration force and energy of the S3W3 sample is much more considerable than the S4W5 sample. Besides to the greater protective performance of the S3W3 sample, it also has lower weight and stiffness. Hence, S3W3 seems to be the most suitable sample to use in protective clothing.

4. CONCLUSIONS

Fabrics in either soft or rigid forms are used for personal protection against sharp objects' threats. In this study, a metal-reinforced fabric is designed and prepared through a weft-backed system. Different diameters of metal threads including 0.2, 0.3, and 0.4 mm, with weave ratio of 5:1 and 3:1 were used to weave the fabric samples. Bending resistance and resistance against penetration of sharp object were measured for each fabric sample. Test results revealed that adding metals to fabric structure increased the fabric stiffness. Samples constituted of the thickest metal threads had the highest bending force and energy among the tested samples. Furthermore, with the same metal thread diameter, fabric samples with lower weave ratio and higher number of metal threads in a specified area of the fabric had greater bending force and energy.

Using metal threads in fabric structure had significantly increased the penetration force and energy of the fabric samples. Using thicker metals or a higher number of metal threads had resulted in greater resistance against penetration of sharp object. It has to be considered that the impact of the number of metal threads was considerably greater than the influence of metal threads' diameter. However, the impact of metal threads diameter on the fabric resistance against bending was higher than the number of metal threads. In general, the same trend is perceived in bending resistance and resistance against penetration of sharp object. Fabrics with more bending force also had more penetration force.

Based on the obtained results, in addition to providing better protective performance, achieving lower weight and lower stiffness of fabric is also desired by incorporating higher number of metal threads, instead of using coarser metal threads.

REFERENCES

[1] G. Nolan, S.V. Hainsworth, G.N. Rutty, *"Forces Generated in Stabbing Attacks: An Evaluation of the Utility of the Mild, Moderate and Severe Scale,"* International Journal of Legal Medicine, vol. 132(1), p.p. 229–236, 2018.

[2] R. Nayek, 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), p.p. 812-832, 2018.

[3] D.T. Tien, J.S. Kim, Y. Huh, *"Stab-Resistant Property of the Fabrics Woven with the Aramid/Cotton Core-Spun Yarns,"* Fibers and Polymers, vol.11(3), p.p. 500-506, 2010.

[4] P. Reiners, Y. Kyosev, L. Schacher, D. Adolphe, K. Ku¨ster, *"Experimental Investigation of the Influence of Wool Structures on the Stab Resistance of Woven Body Armor Panels,"* Textile Research Journal, vol. 86(7), p.p. 685-695, 2015.

[5] S.M. Hejazi, N. Kadivar, A. Sajjadi, *"Analytical Assessment of woven fabrics under vertical stabbing – The role of protective clothing,"* Forensic Science International, vol. 259, p.p. 224-233, 2016.

[6] N. Aliverdipour, N. Ezazshahabi, F. Mousazadegan, *"Characterization of the effect of fabric's tensile behavior and sharp object properties on the resistance against penetration,"* Forensic science international, vol. 306, 2020.

[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), p.p. 992-1007, 2011.