Low Velocity Puncture Response on Multi-Angle Layered Woven Fabric Subjected to Different Puncture Load

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Abstract. A low cost high-tenacity polyester fibre material is one of the best candidates for use in puncture-resistant fabric products. In this study, a high-tenacity polyester plain woven fabric was manufactured and tested against different low-velocity puncture loads of 10 and 50 kN. The woven fabric samples were arranged in one and two layers. The multilayered woven fabric samples were organized at different angles (0°, 45°, 90°, and 135°). The findings revealed that multi-layered woven fabric arranged with a variation of 90°, 90° yielded the maximum puncture force for both 10 and 50 kN loads, at 1323.41 and 1129.14 N, respectively.

Keywords: Low-velocity Puncture Load, Multi-angle Layered Fabric, Plain Fabric, Polyester.

1.0 Introduction

Personal protective equipment is a vital component of workplace safety, essential in preventing injuries. The application of personal protective equipment includes a range of clothing and equipment designed to shield workers from harm while on the job. For example, protective textile equipment is highly effective in safeguarding the human body against dangerous and hazardous weapons or materials [1]. It is the responsibility of employees to wear the personal protective equipment appropriately and utilize the proper protection for their tasks. Body armor is a common example of protective equipment widely used to safeguard against injuries. In addition to protecting against bullets, it also offers protection against sharp knives and spikes [2]. Moreover, workers in the security industry are at a high risk of encountering ballistic and sharp objects, making it mandatory for them to use protective equipment for their safety and protection.

Protective textile equipment is generally constructed from either composites or textile materials, with the selection of material depending on the specific application. For instance, helmets, shields, battle dress uniforms, and body armor may utilize composites due to their exceptional strength and rigidity [3-4]. Conversely, for ballistic protection vests

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and gloves, a flexible and soft texture is required, hence the use of soft armor protective equipment. This equipment can be produced using two distinct fabric technologies, including weaving and knitting processes. There are various types of textile fabrics that can be employed in protective textiles, such as knitted, braided, non-woven, and woven fabrics. Among these, woven fabrics are known to offer superior impact performance when subjected to high-speed impact. In fact, several studies have examined the influence of the woven fabric structure on impact performance by considering factors such as weaving architecture, energy absorption, yarn crimp and fabric dissipation [5-9].

Plain weave structures are commonly utilized in woven fabrics, particularly for ballistic applications, due to their elevated strength and decreased air permeability compared to twill and satin structures. Trans et al. [10] noted that plain weave structures possess the highest strength, but their compact structure results in lower air permeability. This is because plain fabrics decrease slippage, making them suitable for puncture resistance [2] [11]. However, a challenge arises due to the stress concentration caused by the 90° angle between the warp and weft yarns. The US National Institute of Justice Body Armor stated that an increased thickness of body armor provides greater protection to the wearer. The stresses will be transferred at 0°, 90°, 180°, and 270° angles when the layers are placed on top of each other. Nevertheless, this results in low stress distribution, especially at 45°, 135°, 225°, and 315° angles. The direction of the angles is shown in Figure 1 for improved visualization.

Aramid or KevlarTM, is a type of fiber commonly utilized for body armor. It is widely employed in military applications and by civilians for personal protective clothing and defense systems, as well as in weapons. Kevlar fiber is engineered to withstand bullet and blade penetration, and increasing its thickness provides greater protection to the wearer. Additionally, Kevlar has a tensile strength five times higher than steel, making it one of the strongest materials on earth. However, its bulky and inflexible nature renders it less desirable for certain users. Despite its high demand, Kevlar is not cost effective for civilian use in developing countries. Researchers have conducted extensive studies on the use of soft body armor, encompassing fabric production [2, 11, 16, 17], analytical model and FEM [18-22], as well as the shear fluid thickening (STF) behavior [23-29]. These investigations have underscored the importance of high modulus fibers, such as carbon, glass, and the ultra-high molecular weight polyethylene (UHMWPE) fibers, which are relatively expensive and employed in fields with lower protection requirements. Consequently, there exists a need to manufacture a protective body armor with more economical materials, such as high tenacity polyester.

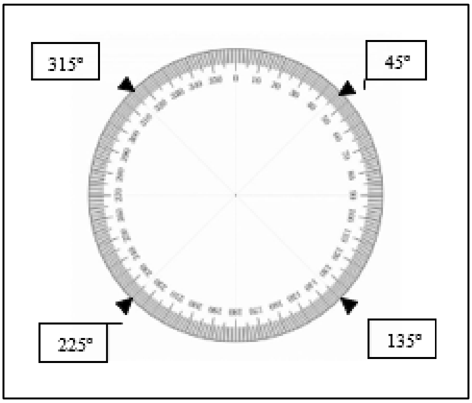

Fig. 1. Stress distribution angle.

Therefore, an organized experimental study was undertaken to investigate the feasibility of identifying cost-effective materials for body armor by (i) characterizing single and multi-angle layered plain woven fabrics, (ii) analyzing multi-angle layered woven fabrics for low puncture resistance, and (iii) assessing the puncture performance at various force magnitudes.

2.0 Materials and Method

2.1 Materials

The research utilized high tenacity polyester yarns with a yarn linear density of 455 Tex. The yarns were manufactured by plying 8 individual yarns into a single yarn using a hollow spindle ring spinning machine (YCHN-303) at a speed setting of 250 revolutions per minute. The single yarn strength was determined using an SDL Testometric Strength Tester in accordance with the guidelines of ASTM D2256 [30]. The resulting yarn tenacity and elongation at break were 293.64 N and 55.95 mm, respectively.

The production of the woven fabrics was accomplished through the utilization of a Donier PTS-8/JC rapier weaving machine, which was operated at a machine setting parameter of 300 revolutions per minute. High tenacity polyester yarns were utilized for the weft yarn, while polyester yarns were employed for the warp. The polyester yarns were recorded to have a yarn linear density of 150 Tex. The woven fabrics were constructed using a plain weave design, with a warp and weft woven fabric density of 32 ends per cm and 8 picks per cm. A close-up image of a woven fabric sample is displayed in Figure 2. Additionally, Table 1 presents the physical properties of the plain-woven fabric.

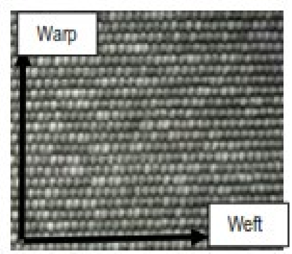

Fig. 2. Plain woven fabric sample.

Table 1. Physical properties of plain-woven fabric.

Fabric Type	Number of Layer	Angle Arrangement (°)	Fabric Thickness (mm)
Plain weave fabric	1	90	0.81
	2	90, 90	1.65
		90, 0	1.63
		90, 45	1.64
		90, 135	1.65

2.2 Quasi Static Puncture

The quasi-static puncture test was carried out utilizing a conical impactor attached to an SDL Tensolab 3000 Mesdan machine, in strict adherence to the protocol outlined in ASTM D5628 [31]. A total of five individual samples were required to establish an average performance of quasi-static puncture. The setup and probe used for the quasi-static puncture test are depicted in Figures 3 and 4. The impactor probe possessed a 25 mm diameter, a 60° conical angle, and a 50 mm probe length. The diameter of the circular woven fabric samples was 130 mm, and they were positioned in the center between two circular plates with a diameter of 75 mm, as shown in Figure 5. The quasi-static puncture load versus multi-angle layered fabric was recorded and employed for comparing the performance of multi-angle layered fabric.

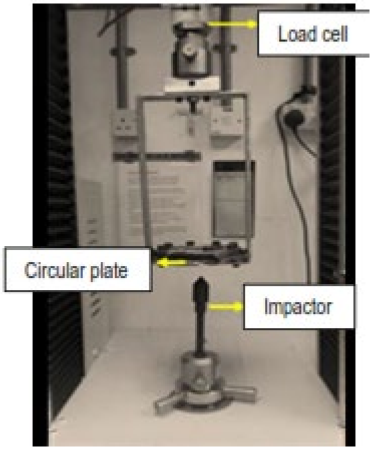

Fig. 3. Quasi static puncture test setup on SDL Tensolab 3000 Mesdan.

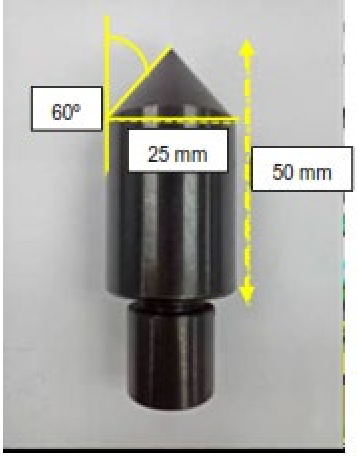

Fig. 4. Conical impactor probe used.

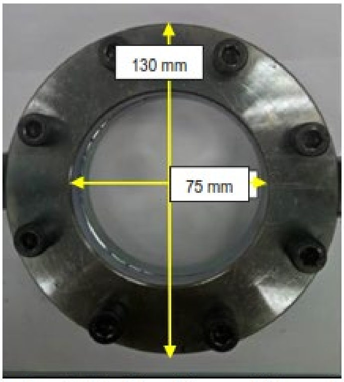

Fig. 5. Circular plate to hold the plain-woven fabric sample.

2.3 Analysis of magnitude orders (kilonewton)

There are various forces of magnitude that can be exerted upon the woven fabric, with the specific magnitude being designed to evaluate the fabric's resistance to puncture. However, due to constraints in the experimental parameters, only a limited number of forces can be applied. To provide a more practical description of the process, the method is proposed based on the change in magnitude of puncture force. Table 2 presents the order of magnitude force in kilonewton. In this study, two load cell forces at 10 and 50 kN were employed.

Table 2. Magnitude force [32-33].

Magnitude Force (kN)	Description
8	The maximum force generated by weight lifters during the "clean and jerk" maneuver
9	The bite force of adult American alligator
16.5	The bite force of a 5.2 m saltwater crocodile
18	The estimated bite force of 6.1 m adult great white shark
25.5 – 34.5	The estimated bite force of a large 6.7 m adult saltwater crocodile
45	The force applied by the engine of a small car during peak acceleration
100	The average force applied by seatbelt and airbag to a restrained passenger in a car which hits a stationary barrier at 100 km/h
890	Maximum pulling force (tractive effort) of single large diesel-electric locomotive

3.0 Results and Discussions

3.1 Quasi-static puncture performance

Figure 6 exhibits the quasi-static performance of high tenacity plain woven fabric against different number of fabric layer and set of angle arrangements parameters. In general, the puncture performance yielded higher puncture force as the number of fabric layer increased from single to double layers. However, the puncture force shows a downward trend as the angle arrangement were set from 90º to 135º. In this study, two different set of load cell were used, 10 and 50 kN. For the 10 kN load cell setup, the maximum and minimum puncture force produced are 1323.41 and 488.51 N, respectively. On the other hand, for the 50 kN load cell setup, the highest and lowest puncture force recorded are 1129.14 and 420.17 N, respectively.

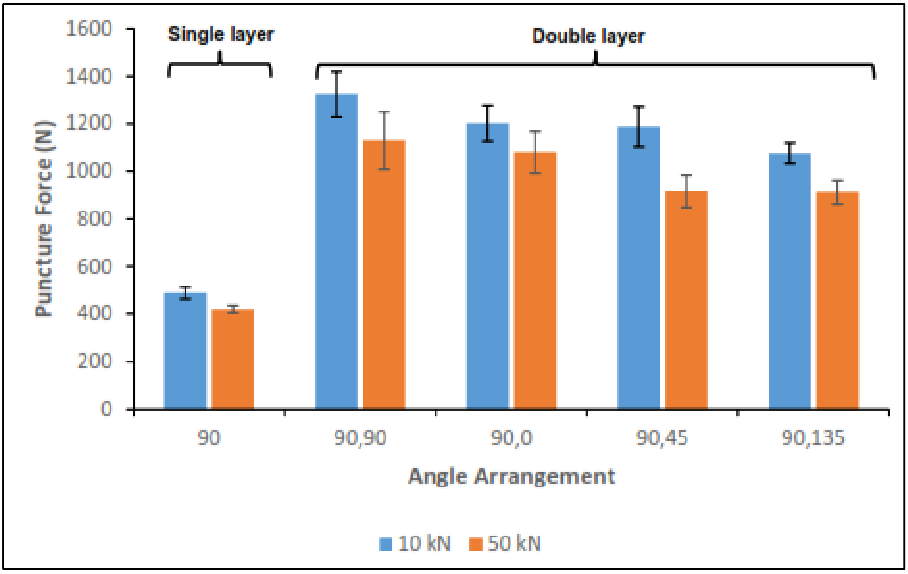

Fig. 6. Quasi-static puncture force performance of plain-woven fabrics.

As depicted in Figure 6, there is a positive correlation between the maximum puncture force and the number of layers across all angle arrangements. The puncture resistance of two layers of fabric is significantly better than that of a single layer. Specifically, when the number of layers reaches two, the maximum puncture force for 50 kN and 10 kN increases by 60% and 62%, respectively.

High-density fabrics, such as plain weave, are expected to have lower absorption and therefore benefit from being layered with multilayer fabrics. There is a linear relationship between the puncture force and the number of layers. However, when comparing the angle arrangements of two layers of fabrics, it was found that the [90º, 90º] arrangement had the highest value of puncture force, indicating that this arrangement performs better when layering the fabric.

3.2 Fabric structure and angle arrangement

The present study employed plain woven fabric, albeit with an alternate angle setting for the weft density. This modification affected the results of the puncture force, as a weft density of 8 picks per cm displayed a maximum force value of 50 kN at 452.44 N and 10 kN at 505.14 N, respectively, when subjected to a force of 45 kN. As depicted in Figure 6, the puncture force has decreased. Previous research by Wang et al. [2] has established that plain fabric possesses superior puncture resistance properties compared to structures such as twill and satin. Therefore, the maximum force value of 50 kN is associated with an angle arrangement of [90°, 90°]. The plain structure exhibits a tighter arrangement of yarns compared to the twill and satin structures. The interlacing density of yarns in the plain structure is higher than in the latter structures [7]. As a result, the slippage of plain fabric is significantly less than that of the twill and satin structures, thereby conferring upon the plain structure a superior quasi-static puncture resistance property compared to the twill and satin structures [2] [11].

3.3 Relationship between different load cell and puncture performance

Figure 7 presents the relationship between different load cell and puncture performance trend based on different load cell setup, 10 and 50 kN. Generally, both 10 and 50 kN trend lines showed a curvature trend from single to double layers of woven fabric. 10 and 50 kN produced r-square value at 0.7764 and 0.7268, respectively. It can be seen that both trend line depicts a significant puncture force improvement between angle arrangement of [90°, 90°] and [90°, 0°]. However, the puncture performance substantially decreased as the angle arrangement were organized at [90°, 45°] and [90°, 135°].

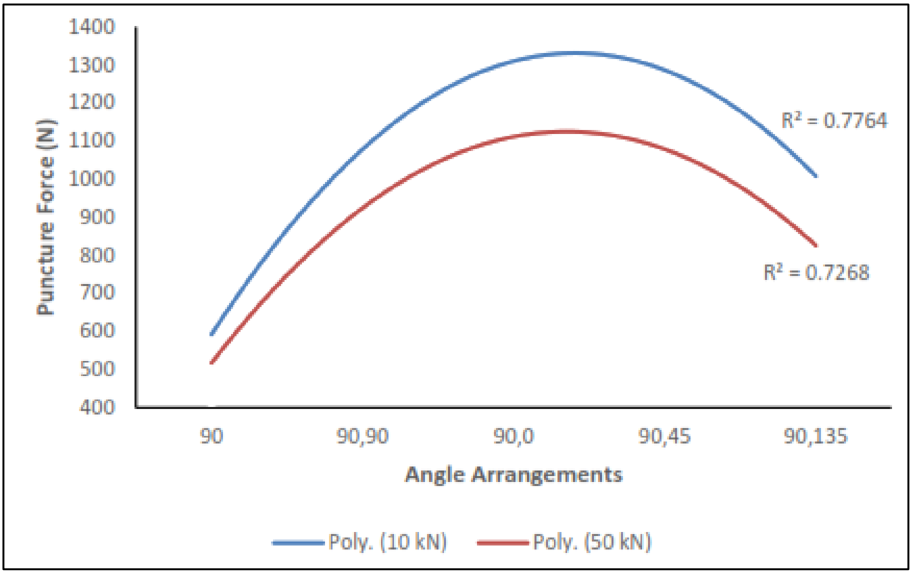

Fig. 7. Relationship between different load cell and puncture performance.

The results of the experiment clearly indicate that the quasi-static puncture with a force of 10kN was the appropriate load to apply to the plain-woven fabrics, as compared to the 50kN setup. The highest puncture force of 10kN increased approximately 194.27 N from 1129.14 N (50kN). Therefore, it can be concluded that a force of 10kN was the suitable load to be applied to the experimental fabric, as compared to 50kN.

As noted in Table 3, the force of 45 kN is identical to the force of engine peak acceleration. However, due to the availability of a load cell of 50 kN, it was adopted in the study. Furthermore, the force magnitude of 10 kN is approximately equal to the bite force of an alligator. This impact magnitude is considered suitable for the study since the woven fabric will be impacted with a sharp impactor. The woven fabric designed for this work is expected to be used as hand gloves.

4.0 Conclusion

In previous studies, the utilization of costly high-performance fibers such as carbon, glass, and ultra-high molecular weight polyethylene (UHMWPE) has been prevalent in the manufacturing of materials with improved puncture resistance. This study has contributed to the development of high tenacity polyester weft direction double layer fabrics with enhanced puncture performance, offering a more cost-effective alternative to aramid and glass fibers. The results obtained showed that the optimal angle arrangement of the multilayered woven fabric resulted in improved puncture force values, with a value of [90°, 90°] on a two-layered fabric made of polyester. The use of a 10kN load cell provided suitable force for testing the puncture resistance of the fabric. In conclusion, this study has demonstrated that high tenacity polyester possesses not only economic advantages but also superior puncture resistance properties as a multilayer fabric, making it a suitable material for various technical and engineering applications. Further potential research work can be explored to investigate the influence of high numbers of fabric layers, different angle arrangements, and fibre type material parameters.

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