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An investigation into ballistic performance and energy absorption capabilities of woven aramid fabrics

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Abstract

This paper presents an investigation regarding the ballistic performance of protection panels of different fabric ply numbers used in body armours. Twaron CT 710 type fabric layers of differing numbers are joined by using three stitch types to form the panels and then the panels are subjected to ballistic tests according to NIJ standards. Ballistic performance of the panels is determined by measuring trauma depth and trauma diameter. The energy absorbed by the fabric layers and the energy transmitted to the back of the fabric layers are determined from the trauma depth and trauma diameter values using a different approach. It is shown that the fabric ply number and stitching type have significant effects on ballistic properties and the effect of conditioning is limited.

Keywords: Ballistic performance; Aramid woven fabric; Energy absorption

1. Introduction

Woven and nonwoven fabrics produced from high-tenacity fibres are used in ballistic protection due to their high energy absorption ability and low tenacity/weight ratio. Ballistic behaviour of textile fibres and fabrics has been investigated experimentally and ballistic behaviour of textile fabric systems has been estimated by using mathematical models [1–7]. As bullet–fabric interaction is a very complex phenomenon, the estimation of ballistic behaviour of fabrics from fibre properties has not been made possible especially when the bullet dimensions are small. Basically, it is known that bullet mass and speed determine its kinetic energy and that higher kinetic energy causes more deformation. When a woven fabric is subjected to ballistic impact, it is deformed in vertical and horizontal directions. Deformation formed on the fabric spreads outwards when the bullet speed remains within the limits. As the bullet speed exceeds a certain limit, the bullet passes through the fabric. Fabric layers have a limited energy absorption capacity. It is necessary to develop different designs to stop the bullet if the bullet kinetic energy exceeds fabric energy absorption limits.

Propagation speed of shock wave formed on the ballistic plane during ballistic impact is related to energy absorption ability of fabric layers and is important from ballistic view point. Energy absorption and propagation ability of fabric layers are dependent on tensile modulus of fibres and yarns forming the fabrics. The tensile modulus along with tensile strength of yarns is the main parameter affecting ballistic performance. For this reason, high tenacity and high elastic modulus fibres are used in the production of ballistic fabrics. Aramids (Kevlar and Twaron), very high molecular weight polyethylene fibres (Spectra, Dyneema) and PBO fibres (Zylon) are the examples of fibres used widely in ballistic fabrics. Apart from yarn tensile properties, fabric construction is also important for ballistic performance. Low-twist yarns are used and the same yarns and densities are used in the warp and weft directions to obtain the same fabric properties in all directions. The absorbed energy of a bullet is propagated on the fabric and the part of energy that cannot be absorbed causes trauma at a certain depth in vertical direction to the fabric plane. Both the energy

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propagating on the fabric plane and formation of trauma are very complex phenomena and dependent on yarn properties and fabric construction. Explanation of ballistic impact phenomenon has not been complete yet. Different parameters affect ballistic resistance, such as fibre and yarn properties, fabric construction, fabric unit area weight and fabric ply number used in protective structures. Apart from these parameters, bullet speed, shooting angle, bullet geometry and boundary conditions are other parameters affecting impact behaviour. Cheeseman and Bogetti [8] carried out studies on important parameters of ballistic protective fabrics.

In some studies, the effect of boundary conditions (type of fixing sample to test frame) on ballistic properties was investigated. Shockey et al. [9] found interesting results on this topic. He investigated and compared the ballistic performance of fabrics fixed to test frame from two sides and four sides. He found that fabric samples fixed to the test frame from two sides had energy absorption capacity 25–60% more than those fabric samples fixed to the test frame from four sides. In a similar study, Zeng et al. [10] fixed fabric samples to the test frame from two and four sides in straight angle and in 45° as bias. They reached the conclusion that the energy was propagated on the fabric surface better with the fabric sample fixed in 45° position. Cunnif [11] investigated the effect of fabric sample dimensions on ballistic properties using Kevlar and Spectra fabric samples. He concluded that higher energy absorption values were obtained with smaller-dimension fabric samples.

Ballistic fabrics have different warp and weft crimp values due to weaving processes. Weft crimp is lower than warp crimp in general. During ballistic impact, weft yarns get broken before warp yarns. Chitrangad [12] suggested the use of hybrid panels which increase the resistance of fabrics and delay the deformation of fabrics by using higher-tenacity weft yarns in ballistic fabrics. Today, new-generation fabrics to be used in ballistic applications are preferred to be woven with the same type and number of yarns at the same densities in warp and weft directions. This produces equal warp and weft crimps and causes the same amount of deformation in warp and weft directions during ballistic impact. This fabric construction brings the energy absorption to a higher level. Tan et al. [13] investigated the effect of crimp on ballistic properties of fabrics by developing a method of computer modelling.

Another parameter affecting ballistic properties is the friction between yarns. Slip between the yarns becomes more difficult as the friction force increases between them. When the bullet penetrates the fabric structure, it breaks the yarns and tries to pass through the fabric. While breaking the high-tenacity yarns, the bullet loses most of its energy and its effect decreases significantly. But in the case of lower frictional force between the yarns, the bullet pushes yarns to the left and right and opens a way for itself. This causes less bullet energy loss and therefore the bullet passes through more fabric layer. This point was investigated by researchers [14–16]. Briscoe and Motamedi [14] subjected fabrics at three different levels of oiling and then performed ballistic tests. They showed that the ballistic performance increased with a decrease in oiling level. They also showed that a moderate change in friction force between the yarns caused a significant change in ballistic performance and bringing the friction force between the yarns to the highest level caused more energy-propagating ability in the fabrics. Cunnif [11] found that ballistic performance decreased in loose fabric structures (i.e., lower weft and warp densities) as well as with lower friction force between the yarns. Bazhenov [17] pointed out that ballistic performance was related to slip between the yarns and therefore wetting the fabrics decreased ballistic properties because it increased slip between the yarns in the fabric. In another study, Duan et al. [18] pointed out that the frictional forces help to protect fabric structure during ballistic impact. Tan et al. [19] treated yarn surfaces by silica colloidal to increase frictional forces between the yarns. They increased ballistic performance of fabrics woven by using these yarns.

This paper presents an experimental research regarding ballistic performance of fabrics at certain ply numbers used in finished-body armour. The fabric ply number, stitch type and conditioning are three parameters whose effects on ballistic performance are investigated. These parameters are important in designing body armours. Fabric ply number is important to determine minimum weight for optimum ballistic performance as well as cost of body armour or protective panels. Stitch type affects the stitch density and may affect ballistic resistance in this way because the bullet has to break sewing yarns as well. Tests are conducted with dry panels as well as wet panels. Only front fabric layers of a panel were wetted to simulate the wetting of body armour in a rainy weather. NIJ standard also proposes this by wetting. For this purpose, Twaron CT 710 type fabrics were plied at different ply numbers and stitched in three different ways. Ballistic performance tests were conducted using these fabrics according to NIJ standards. After the tests, ballistic performance of test samples was obtained by measuring trauma depth and diameter. The amount of absorbed energy and the energy transmitted to the back side were determined using a different approach from the measured trauma depth and trauma diameter.

2. Materials and methods

2.1. Materials

2.1.1. Balistic fabrics

Twaron CT 710 type of fabric is used in this research and parameters of this fabric are given in Table 1.

Fabrics were plied at different ply numbers and joined using different stitch types. Panel dimensions are $31\times31\,\mathrm{cm}^2$. Plain-stitch and high-twist para-aramide sewing yarn were used in joining fabrics. Stitch types of fabrics

Table 1
Parameters of Twaron CT 710 type of fabric used in this research

Fabric type	Count (dtex) warp/weft	Material type warp/weft	Weave	Densities (ends and picks/10 cm)	Fabric weight (g/m^2)	Treatment	Strength (kN) dry/wet
Twaron CT 710	930/930	2040/2000	Plain	117/117	220	Scouring/water repellent treatment	(4.45 ± 0.15)/(3.97 ± 0.24)

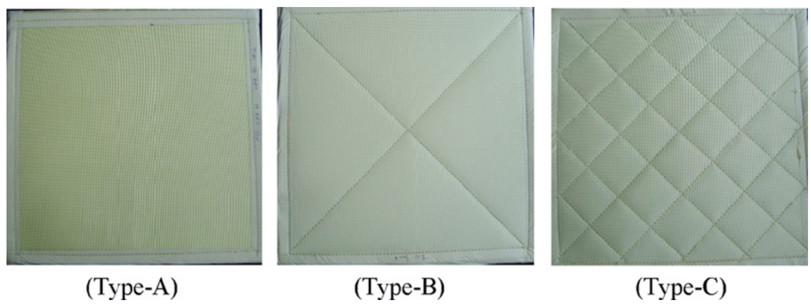

Fig. 1. Stitching types used in Twaron panels. Type A: sewn only 2.5 cm inside from the edges; type B: sewn 2.5 cm inside from the edges and in diamond shape; type C: sewn 2.5 cm inside from the edges and then with 5 cm intervals in bias type.

Table 2
Panel types used in the tests

Ply number	Stitch type	Panel weight (kg/m^2)
20	Type a Type b Type c	4.40
22	Type a Type b Type c	4.84
24	Type a Type b Type c	5.28
26	Type a Type b Type c	5.72
28	Type a Type b Type c	6.16
30	Type a Type b Type c	6.60
32	Type a Type b Type c	7.04

are shown in Fig. 1. Panels used in the tests are given according to fabric ply numbers in Table 2.

2.1.2. Test apparatus

Test apparatus adapted to NIJ 0101.03 Level-II standards [20] (Fig. 2) is used in this research. In this apparatus, there is 5 m distance between the exit of the bullet from the gun barrel and the target. The midpoint of the speed measuring unit is positioned at the midpoint of the distance which is 2.5 m from the target.

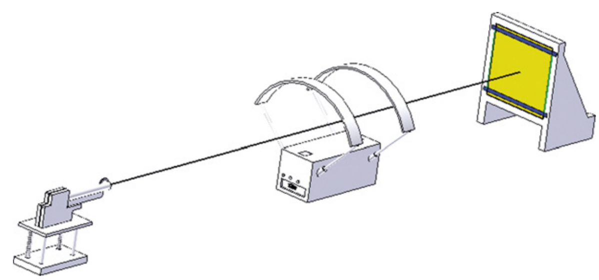

Fig. 2. Test apparatus used in the experiments.

2.1.2.1. Shooting barrel and bullets. MP5 gun was used in the shootings. The bullets used in the shootings have 8 g core weight and 9 mm diameter. Amount of gun powder of bullets was determined based on speed measurements in the preliminary tests. Total bullet weight including core, gun powder and cartridge is 12 g. All the bullets were provided by Machine and Chemistry Industry Company of Turkey.

2.1.2.2. Cronograph. In the tests, Prochrono model cronograph provided from Competition Electronic Inc. was used in the speed measurement of bullets. Cronograph had photoelectric principle and bullet speed was read from its digital display after every shooting.

2.1.2.3. Backing material. No. 1 Type Roma Plastilina (clay) given in NIJ standards was used as backing material in this research. Clay was filled in a box as pointed out in the standard. Targets were determined by putting bands on the front side of panels. Hardness of backing material can show variability depending on temperature and environmental conditions. For this reason, it is important to do the calibration. An iron weight with half sphere front tip and having 1 kg weight and 45 mm diameter was used in the calibration.

2.2. Method

2.2.1. Shooting tests

Shooting tests were carried out according to NIJ 0101.03 standard. Tests were conducted in two ways as dry and wet. In wet tests, both front and back sides of panels were subjected to water spray during 3 min as proposed by the standard. The tests were conducted 30 min after water spraying. Before actual tests, the preliminary tests were conducted to adjust the shooting precision. Targets were marked with elastic tape on the front side of backing material. Six bullets were shot to each sample as proposed in the standard (Fig. 3). After shootings, the depth and diameter of trauma formed on the backing material were measured. All the tests were conducted in Bursa Police College Shooting Polygon.

2.2.2. Determination of trauma depth and diameter

If the bullets cannot pass through the panels after shootings, a trauma is formed in the backing material at certain diameter and depth. The depth of this trauma shows the effect of the bullet transmitted to the back side of a panel. After the shootings, both the depth and the diameter of each trauma were measured with ± 0.02 mm precision. Later, a mold of trauma was prepared to obtain trauma geometry.

2.2.3. Determination of energy absorption of samples

2.2.3.1. Formation of trauma geometry using molds. Energy absorption capacities of panels were determined depending on trauma depth and diameter in the tests. For this purpose, the trauma depth and diameter were measured after the tests. Volume of trauma geometry was taken as a basis to find energy absorption capacity of panels. Exact mold of trauma geometry was obtained for each test result using mold clay. Millimetrical divisions were formed on the mold by showing diameter axis by 'x' and depth by 'z'. With the help of these millimetrical divisions, the depth value was obtained for each value of the diameter. Then, curves were fitted to 'x' and 'z' data using Maple 10 software [21,22]. Among polynom, rational polynom and Spline curve fitting techniques, Spline curve

Fig. 3. Shooting points on the sample

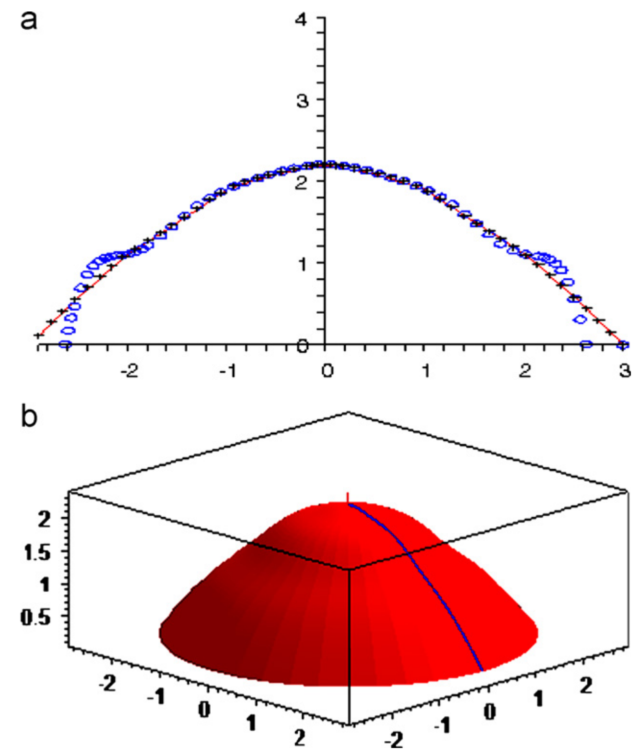

Fig. 4. (a) Comparison of measured and fitted curves: (–) measured curve; (○) polynomial curve; (+) b-spline curve. (b) View of 3-D model of trauma obtained by a curve fitted using Spline curve fitting method.

fitting technique was found to be the most suitable for the purpose of this research [23,24] as shown in Fig. 4a.

Fig. 4b shows 3-D trauma shape obtained by turning Spline curve around 'y'-axis. Data obtained from the fitted curves were transferred to Inventor 10 CAD software, which is the solid modelling software, and the volume of the trauma was calculated for each sample.

2.2.3.2. Calibration of backing material and determination of the absorbed and transmitted energies. Calibration test was conducted to determine the trauma on the backing material created by the energy. After the tests, energy required for unit volume of trauma on the backing material was found in J/mm^3. In the tests, a cylindrical iron bar of 1 kg weight and 45 mm diameter was dropped on the backing material from 0.5, 1.5 and 2 m heights respectively from inside a hollow tube. The tip of the iron bar had semi-sphere shape. Trauma depth and diameter were measured for each case. The shape of trauma was taken as the semi-sphere shape of the tip of the iron bar. Trauma volumes were calculated using Inventor CAD software with the depth and diameter values obtained in this way. Unit trauma energies were calculated for 0.5, 1.5 and 2 m heights. Results of the tests were found to be within the interval of the results recommended by NIJ 0101.03 standard of 2 m height. Tests were repeated five times for each height. Potential energy of the weight dropped is calculated using the following formula and

Table 3
Dropping test results (average values)

H (m)	Trauma depth (mm)	V_{cal} (mm^3)	EP_{cal} (J)	E_{unit} (J/mm^3)	Eav_{unit} (J/mm^3)
2	22.5	23,860	19.62	8.22×10^{-4}	
1.5	17.6	16,020	14.72	9.18×10^{-4}	8.72×10^{-4}
0.5	12.8	11,360	8	8.8×10^{-4}	

results are given in Table 3:

$$EP_{cal} = mgh, \tag{1}$$

where EP_{cal} is the potential energy of the iron weight dropped (J), m the weight of the iron bar having semi-sphere tip (kg), g the gravitational acceleration (m/s^2) and h the dropping height (m).

According to NIJ standards, dropping test with 2 m dropping height is sufficient for calibration. But the dropping tests with different heights were also conducted in this work to approve the agreement of the test results with the results recommended by NIJ standards. With the test results, the calibration of backing material was carried out and energy for unit volume (E_{unit}) was calculated. Average unit volume energy was found to be 8.72×10^{-4} J/mm^3. The unit volume energy was calculated using the following formula:

$$E_{unit} = \frac{EP_{cal}}{V_{cal}}, \tag{2}$$

where V_{cal} is the volume of the trauma formed by weight dropped on backing material (mm^3) and E_{unit} the energy absorbed by unit volume of trauma (J/mm^3).

By establishing a relation between the trauma volume after shooting tests (V_{test}) and trauma volume (V_{cal}) created by a known potential energy (EP_{cal}) on the backing material, the energy absorbed and the energy transmitted by the fabric are determined.

In the calculation of V_{test}, the following relationship was obtained using fitted curve. The volume of the body formed by turning the curve by 360° around y-axis is found using the following formula:

$$V_{test} = 2\pi \int_0^x x f(x)\,\mathrm{d}x, \tag{3}$$

where V_{test} is the volume of the trauma formed on backing material due to shooting tests (mm^3), $f(x)$ the equation of the curve fitted by using Spline curve fitting method and x the radius of the trauma formed on backing material (mm).

Trauma energy (E_{test}) is found depending on the trauma volume for each test as follows:

$$E_{test} = Eav_{unit} V_{test}. \tag{4}$$

Kinetic energy of the bullet just before it touches the fabric is as follows:

$$EK_p = \frac{mv^2}{2}, \tag{5}$$

where EK_p is the kinetic energy of the bullet just before it touches the fabric (J), m the mass of the bullet (kg) and v the speed of the bullet (m/s).

When the fabric layers prevent the bullet to pass through the panel, the majority of the energy is absorbed by fabric layers and the smaller part passes to the back side. The energy absorbed by the fabric (EA_{fabric}) is calculated using the following formula:

$$EA_{fabric} = EK_p - E_{test}. \tag{6}$$

The energy creating the trauma is calculated by multiplying the unit volume energy obtained during calibration tests (8.72×10^{-4} J/mm^3) by the trauma volume for each shooting. Energy absorbed by the fabric is calculated by subtracting this energy from kinetic energy of the bullet.

3. Results and discussion

3.1. Effect of number of shooting on ballistic properties

As was mentioned above, each panel was shot successively at six different points. Figs. 5a and b show the effect of number of shooting on trauma depth and trauma diameter for 24-ply fabric panel. Although a monotonic increase is observed in trauma depth and trauma diameter with increasing number of shooting in a few cases, this change is not observed in all cases and cannot be generalised. A similar relation was observed between the absorbed and transmitted energies and number of shootings. In Table 4, average of six values of trauma depth and trauma diameter are given together with standard deviations to analyse the effect of fabric ply number, stitch type and conditioning on trauma depth and trauma diameter.

The damage caused by the bullet in the fabric is shown in Fig. 6 as two examples. It was observed from these examples and the other samples that warp and weft yarns were subjected to the stresses due to the impact of the bullet. The yarn stresses can be seen on the fabric as horizontal and vertical lines because of the straightening of weft and warp yarns, which damages the fabric structures.

3.2. Trauma depth and diameter results

Shooting tests were conducted in two ways as dry and wet as was mentioned before. Tests were cancelled when the bullet speed remained out of the values given in NIJ standards. Trauma diameter and trauma depth were measured for the cases in which panel stopped the bullet. Average values of trauma depth and diameter are given in Table 4 together with the bullet speeds.

ANOVA statistical test results obtained with 95% confidence interval showed that conditioning, stitch type and number of fabric ply affected trauma depth. The most significant parameter affecting the trauma depth was found to be the number of fabric ply. The stitch type and conditioning followed it. Fabric ply number was also found to be the most significant parameter affecting trauma

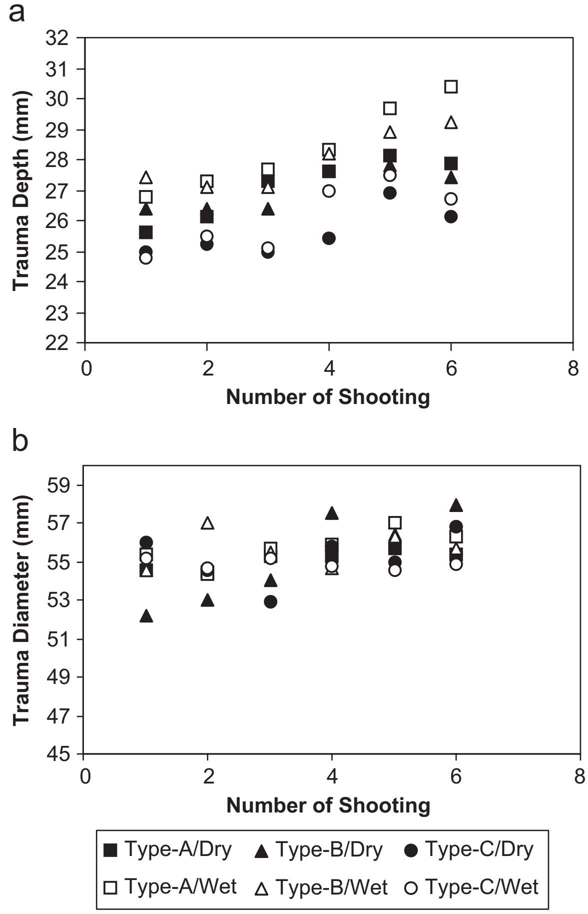

Fig. 5. (a) Change in trauma depth with respect to number of shooting in 24-ply fabric panels. (b) Change in trauma diameter with respect to number of shooting in 24-ply fabric panel.

diameter. Stitch type had the second significant effect and conditioning showed no significant effect on trauma diameter. Change in the trauma depth and diameter is shown in Figs. 7–9 for fabric ply number, stitch type and conditioning, respectively. The data used in figures are average values obtained by Student–Newman–Keuls (SNK) tests and least significant difference (LSD) values are given in the figures for 95% confidence interval.

Depth and diameter of a trauma formed on the backing material give information about the energy absorbed by fabric layers and ballistic strength of panels. The depth of a trauma shows the effect of a bullet energy transmitted to the back of a panel. If panels propagate the energy to a larger area, the volume of a trauma will be lower. If the energy cannot be propagated to a large area, a deeper trauma with a larger diameter is formed because the same amount of energy affects a smaller area. As the energy absorbed by fabric layers increases, the trauma depth and volume decrease. Number of fabric ply has the most significant effect on trauma depth and an increase in the number of fabric ply decreases the trauma depth. But, increasing number of fabric ply also increases panel weight (Table 2). Average trauma depth was found to be 30.40 mm with 20-ply fabric. It became 19.64 mm by a decrease of 35.4% in the case of 32-ply fabric (Fig. 7). In ballistic protection, panel weight should be taken into consideration as much as ballistic performance. Panel flexibility decreases and panel rigidity increases with an increase in the number of fabric ply. In ballistic protection of body armours, both wearing and carrying of this type of panels are difficult. Also, these kind of panels limit the movement ability of the user. Because of this, trauma depth and other parameters should be optimised by considering body armour rigidity and weight.

Trauma diameter did not change in parallel with trauma depth with increasing fabric ply numbers. No significant change occurred in trauma diameter with 20-, 22- and 24-ply fabric panels. But trauma diameter decreased like trauma depth with fabric ply numbers over 24. Trauma diameter was 54.89 mm with 20-ply fabric whereas it was 47.89 mm with 32-ply fabric (12.7% decrease). Trauma diameter decreased less than trauma depth with increasing fabric ply number as shown in Fig. 7. Decrease in trauma depth and diameter with increasing fabric ply number is due to the propagation of the energy on the panel more. This decreases the impact affecting to the back of the panel.

Analysis of test results with respect to three stitching types shows that the stitching type has some effect on trauma depth. An increase in stitch density decreased trauma depth. There is a significant difference between the trauma depth values of especially type a and type c. Type c is more advantageous than type a. An average of 25.32 mm trauma depth was obtained with type b panels. It is 25.63 mm with type a panels. In type c panels, trauma depth became 23.90 mm with a decrease of 6.7% compared to type a (Fig. 8). The reduction in trauma depth without increasing panel weight is important. Stitchs holding fabric layers provide an additional resistance to bullets and increase the panel strength. Using high-twist para-aramid yarn prevents stitch points to be as weak places. Despite these advantages, higher stitch density increases the rigidity of the panel and makes it difficult to use this type of panels in protective body armours. Therefore, these type of panels are more suitable for vehicle protection. Stitch type has also some effect on trauma diameter. Trauma diameter and trauma depth change in parallel to each other (Fig. 8). Trauma diameter was found to be 53.08, 52.80 and 52.39 mm for type a, type b and type c panels, respectively.

Conditioning showed a limited effect on trauma depth as shown in Fig. 9. Average trauma depth was 24.49 mm for dry panels whereas it was 25.41 mm in the case of wet panels (only 3.6% increase). The strength of fabric is affected adversely by wetting as given in Table 2. As water repellent finish was applied to the fabrics used in the panels, water was not absorbed by the fabrics during water spraying. Despite this, the trauma depth increased a small amount in wet panels. Wetting did not show any significant effect on trauma diameter. As a result, conditioning was found to have only a limited effect on ballistic properties.

Table 4
Trauma depth and diameter values and bullet speeds

Fabric ply number	Joining type	Conditioning	Bullet velocity (m/s)	Standard deviation	%CV	Trauma depth (mm)	Standard deviation	Trauma diameter (mm)	Standard deviation
20	Type a	Dry	372.17	3.06	0.82	30.52	0.77	55.45	1.96
		Wet	372.83	3.87	1.04	31.43	0.47	54.98	1.95
	Type b	Dry	372.33	2.16	0.58	30.20	0.59	55.47	2.25
		Wet	370.33	5.09	1.37	31.10	0.55	54.67	1.57
	Type c	Dry	368.83	5.60	1.52	29.05	0.44	54.33	2.54
		Wet	373.50	7.40	1.98	30.12	0.18	54.43	2.43
22	Type a	Dry	367.17	5.49	1.50	28.47	0.71	56.62	0.38
		Wet	370.67	5.20	1.40	29.70	0.52	55.33	0.63
	Type b	Dry	368.67	5.75	1.56	28.20	0.67	55.27	0.80
		Wet	372.50	4.37	1.17	29.50	0.63	55.16	0.68
	Type c	Dry	367.50	6.25	1.70	27.10	0.40	55.28	1.00
		Wet	368.33	5.28	1.43	27.90	0.60	54.95	0.39
24	Type a	Dry	365.67	5.72	1.56	27.10	1.02	55.13	0.48
		Wet	370.50	4.85	1.31	28.37	1.42	55.78	0.88
	Type b	Dry	371.67	3.08	0.83	27.00	0.67	55.17	2.41
		Wet	370.33	3.50	0.95	27.98	0.93	55.63	0.90
	Type c	Dry	368.17	6.34	1.72	25.60	0.78	55.18	1.37
		Wet	367.50	5.79	1.57	26.10	1.11	54.92	0.25
26	Type a	Dry	369.00	5.33	1.44	24.90	1.02	54.00	0.38
		Wet	369.33	7.12	1.93	25.50	1.18	54.42	0.61
	Type b	Dry	369.83	3.97	1.07	24.58	0.38	54.36	0.69
		Wet	369.00	4.60	1.25	25.43	0.84	54.45	0.61
	Type c	Dry	368.50	5.96	1.62	23.27	0.79	54.10	0.58
		Wet	368.00	5.40	1.47	24.12	0.82	53.75	0.52
28	Type a	Dry	367.67	6.22	1.69	23.08	0.60	52.15	1.33
		Wet	371.67	2.73	0.74	24.17	0.31	52.45	0.58
	Type b	Dry	370.17	6.37	1.72	22.85	0.72	52.37	0.58
		Wet	371.33	3.56	0.96	23.40	0.52	51.75	0.52
	Type c	Dry	369.17	4.12	1.12	21.47	0.50	51.30	0.41
		Wet	366.17	6.62	1.81	22.25	0.43	51.47	0.77
30	Type a	Dry	370.67	6.95	1.87	21.90	0.85	50.50	0.41
		Wet	370.50	5.75	1.55	23.10	0.74	50.27	0.58
	Type b	Dry	371.33	4.18	1.13	21.55	0.64	49.43	0.41
		Wet	369.33	3.01	0.82	22.80	0.66	50.08	0.71
	Type c	Dry	368.33	5.89	1.60	19.78	0.57	49.15	0.61
		Wet	367.33	5.61	1.53	20.55	0.85	49.70	0.75
32	Type a	Dry	370.83	6.40	1.73	19.85	0.30	48.25	1.03
		Wet	369.67	5.32	1.44	20.78	0.62	48.76	1.16
	Type b	Dry	370.00	4.20	1.13	19.70	0.51	48.23	2.04
		Wet	368.00	4.69	1.27	20.20	0.34	47.16	0.94
	Type c	Dry	369.00	3.52	0.95	18.21	0.96	47.75	0.75
		Wet	371.33	2.50	0.67	19.10	0.53	47.20	0.52

3.3. *Ballistic and absorbed energies*

During ballistic impact, a shock wave is created on ballistic plane due to kinetic energy of the bullet. A part of this energy is absorbed by the fabric layers and the rest is transmitted to the back of the panel and forms a trauma. More energy is absorbed and less is transmitted to the back side in the panels propagating energy wave at a higher speed. Trauma depth is important because a higher trauma depth causes bone breaks and inner organ bleeding. Propagating shock energy wave on the fabric causes yarn and fibre breaks and fabric deformation (Fig. 6). Therefore, when a panel stops a bullet, it is deformed and its strength decreases. In shooting tests, it was observed that trauma depth increased from the first to sixth shot.

Table 5 shows ballistic energy, energy absorbed by the fabric layers and the energy transmitted to the back of a panel. Kinetic energy of a bullet is the energy affecting the panels. As the mass of the bullet is constant, the energy affecting the panels is proportional to the bullet speed. As

Fig. 6. Damage of the bullet on the fabric surface in successive shooting.

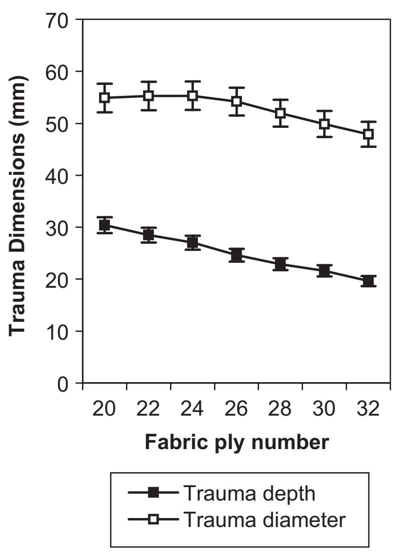

Fig. 7. Change in trauma depth and diameter with respect to fabric ply number ($LSD_{0.05}$ for trauma depth: 0.45; $LSD_{0.05}$ for trauma diameter: 0.82).

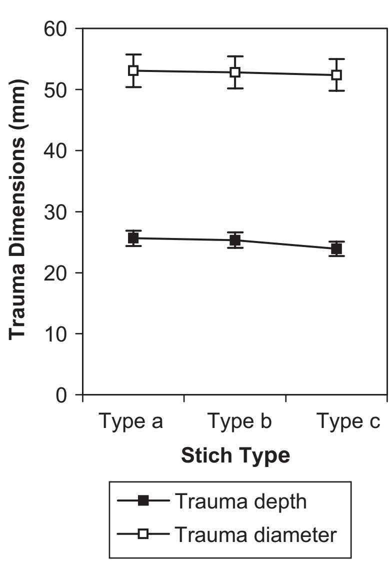

Fig. 8. Trauma depth and diameter for different stitching types ($LSD_{0.05}$ for trauma depth: 0.29; $LSD_{0.05}$ for trauma diameter: 0.54).

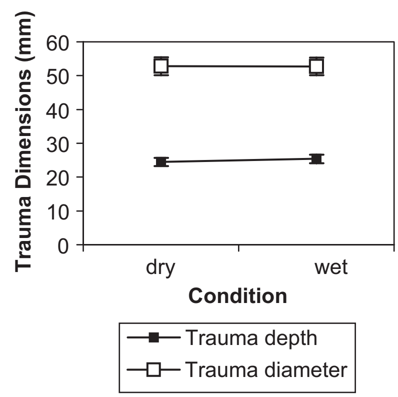

Fig. 9. Trauma depth and diameter for wet and dry conditions ($LSD_{0.05}$ for trauma depth: 0.24; $LSD_{0.05}$ for trauma diameter: 0.44).

the bullet speed can show variability within tolerances between shootings, the energy affecting the panel differs from shot to shot as shown in Table 5.

ANOVA tests applied to the data in Table 5 at 95% confidence interval show that the order of importance of parameters affecting the energy transmitted to the back of panels (E_{test}) is fabric ply number, stitch type and conditioning. In the case of energy absorbed by panels (EA_{fabric}), the fabric ply number had a significant effect and stitch type and conditioning did not show any significant effect. LSD values are given (Figs. 10, 12 and 14) for fabric ply number, stitch type and conditioning, respectively.

Energy absorbed by panels increases and energy transmitted to the back of panels decreases with increasing fabric ply number. Fig. 10 shows the amount of absorbed and transmitted energies. As seen from the figure, energy absorption capacity of panels increases significantly and similarly energy transmitted to the back of a panel decreases after 24-ply fabric. Energy transmitted to the back of the panel is 48.24 J with 20-ply fabric whereas it is 19.40 J with 32-ply fabric which corresponds 59.8% decrease. Energy absorbed by 20-ply fabric panel is 504.31 J whereas it increases to 527.65 J by 4.4% in 32-ply fabric panel. Increasing fabric ply number from 20 to 32 causes only 28.84 J increase in the amount of energy absorbed or 28.84 J decrease in the amount of energy transmitted to the back of the panel. This can be seen as a

Table 5
Bullet speed, ballistic energy, energy absorbed by the fabric layers and energy transmitted to the back of the panels

Fabric ply number	Joining type	Conditioning	Average bullet velocity (m/s)	Kinetic energy of the bullet (J)	Trauma volume (mm^3)	Energy transmitted to the back of the panel (E_{test}) (J)	Energy absorbed by the panel (EA_{fabric}) (J)
20	Type a	Dry	372.17	554.03	56670	49.42	504.62
		Wet	372.83	556.02	58490	51.00	505.02
	Type b	Dry	372.33	554.53	55760	48.62	505.91
		Wet	370.33	548.59	56910	49.63	498.96
	Type c	Dry	368.83	544.15	50480	44.02	500.13
		Wet	373.50	558.01	53630	46.77	511.24
22	Type a	Dry	367.17	539.25	51130	44.59	494.66
		Wet	370.67	549.58	54060	47.14	502.43
	Type b	Dry	368.67	543.66	49790	43.42	500.24
		Wet	372.50	555.03	53190	46.38	508.64
	Type c	Dry	367.50	540.23	46890	40.89	499.34
		Wet	368.33	542.68	48440	42.24	500.44
24	Type a	Dry	365.67	534.85	46650	40.68	494.17
		Wet	370.50	549.08	51130	44.59	504.50
	Type b	Dry	371.67	552.54	46450	40.50	512.04
		Wet	370.33	548.59	49810	43.43	505.15
	Type c	Dry	368.17	542.19	42950	37.45	504.73
		Wet	367.50	540.23	43780	38.18	502.05
26	Type a	Dry	369.00	544.64	39530	34.47	510.17
		Wet	369.33	545.63	41560	36.24	509.39
	Type b	Dry	369.83	547.11	39310	34.28	512.83
		Wet	369.00	544.64	41430	36.13	508.52
	Type c	Dry	368.50	543.17	36010	31.40	511.77
		Wet	368.00	541.70	37410	32.62	509.07
28	Type a	Dry	367.67	540.72	33070	28.84	511.88
		Wet	371.67	552.54	35740	31.17	521.38
	Type b	Dry	370.17	548.09	32880	28.67	519.42
		Wet	371.33	551.55	33210	28.96	522.59
	Type c	Dry	369.17	545.14	28900	25.20	519.94
		Wet	366.17	536.31	30580	26.67	509.65
30	Type a	Dry	370.67	549.58	28780	25.10	524.48
		Wet	370.50	549.08	30780	26.84	522.24
	Type b	Dry	371.33	551.55	26950	23.50	528.05
		Wet	369.33	545.63	29980	26.14	519.49
	Type c	Dry	368.33	542.68	23650	20.62	522.05
		Wet	367.33	539.74	25500	22.24	517.50
32	Type a	Dry	370.83	550.07	22890	19.96	530.11
		Wet	369.67	546.61	24910	21.72	524.89
	Type b	Dry	370.00	547.60	22630	19.73	527.87
		Wet	368.00	541.70	22390	19.52	522.17
	Type c	Dry	369.00	544.64	19940	17.39	527.26
		Wet	371.33	551.55	20760	18.10	533.45

small amount but it can save life. Therefore it is important. Fig. 11 shows the absorbed and transmitted energy values in percentage. The panel with 20-ply fabric absorbs an average of 91.26% of bullet kinetic energy (i.e., ballistic energy) whereas 32-ply fabric panel absorbs an average of 96.45% of bullet kinetic energy.

Fig. 12 shows the absorbed and transmitted energies for three different stitching types. Significant difference was found in the energy transmitted to the back of the panel between type a, type b and type c. The transmitted energies are 35.84, 34.92 and 31.69 J for type a, type b and type c, respectively. There is 11.5% difference in the transmitted energy between type a and type c. This difference is only 2.56% between type a and type b and 9.2% between type b and type c stitching. By stitching fabrics, material properties of panels do not change. But, the panel rigidity increases with stitch density and this increases panel strength and affects the energy transmitted to the back of the panel. Fig. 12 also shows the energy absorbed by the panels. Type b stitching has the highest amount of energy

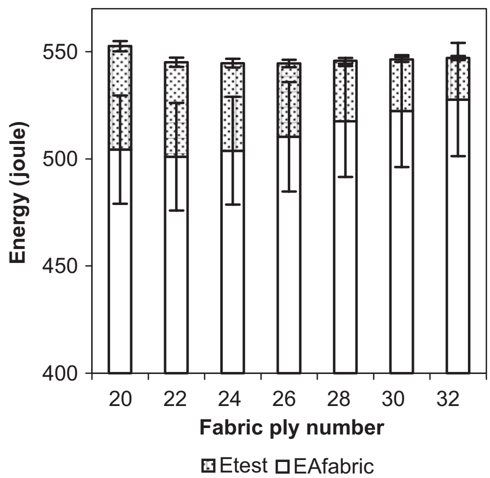

Fig. 10. Amount of absorbed energy (E_{test}) and transmitted energy (EA_{fabric}) for different fabric ply numbers ($LSD_{0.05}$ for E_{test}: 0.94; $LSD_{0.05}$ for EA_{fabric}: 9.04).

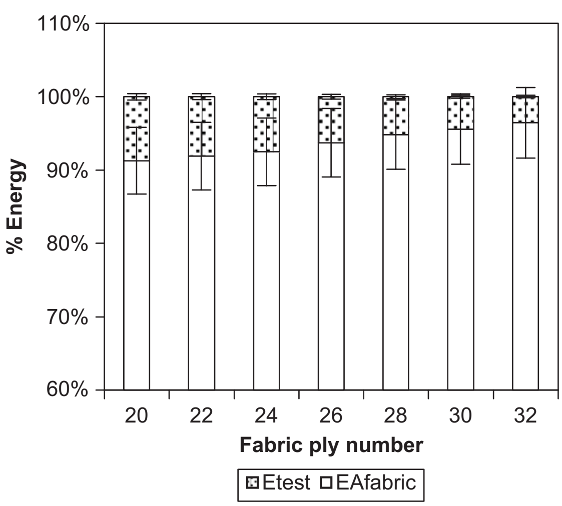

Fig. 11. Absorbed and transmitted energies in percentage for different fabric ply numbers.

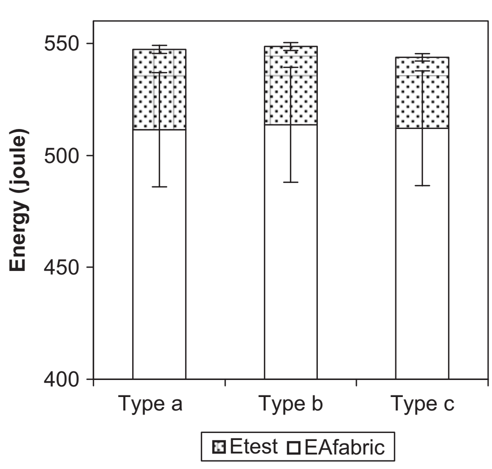

Fig. 12. Absorbed and transmitted energies for three different stitching types ($LSD_{0.05}$ for E_{test}: 0.62; $LSD_{0.05}$ for EA_{fabric}: 5.91).

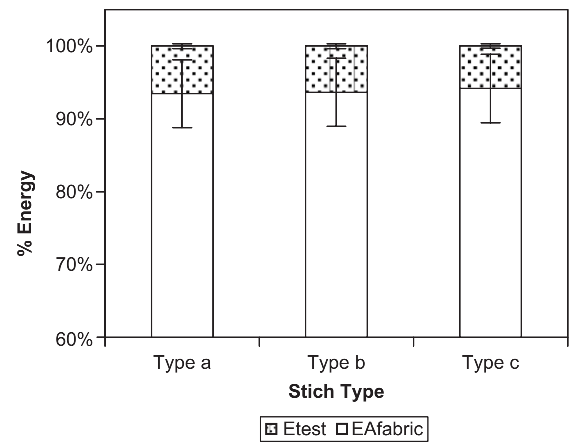

Fig. 13. Absorbed and transmitted energies in percentage for three different stitching types.

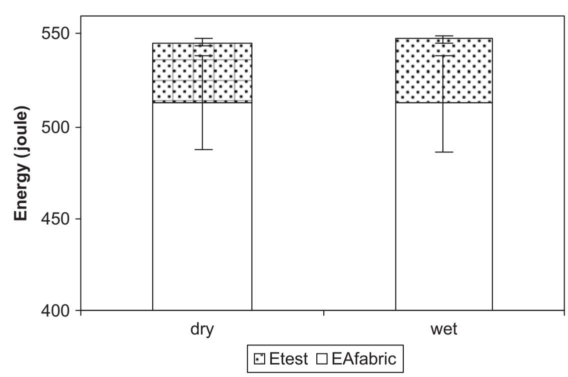

Fig. 14. Amount of absorbed and transmitted energies for dry and wet conditions ($LSD_{0.05}$ for E_{test}: 0.50; $LSD_{0.05}$ for EA_{fabric}: 4.83).

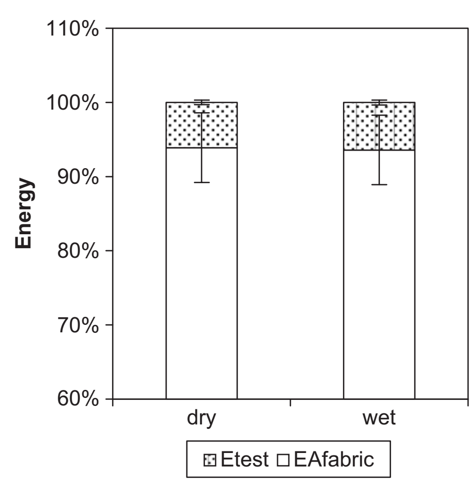

Fig. 15. Absorbed and transmitted energies in percentage for dry and wet conditions.

absorption and type c and type a stitch types follow it. But the differences in the absorbed energies are very small and remain lower than LSD value. In fact, the decrease in the transmitted energy almost corresponds to the increase in the absorbed energy. As the amount of absorbed energy is much higher than the transmitted energy, the effect of stitching type does not become statistically significant. Fig. 13 shows the absorbed and the transmitted energies in percentage for three stitching types. No significant difference is observed in percent absorbed energies between stitching types.

Conditioning was found to have only a limited effect on the energy transmitted to the back of panels and no significant effect on the absorbed energy by the panels. As the fabrics were subjected to water-repellent treatment and they have high weft and warp densities, no significant water penetration occurred during water spraying. For this reason, no significant difference was observed in energy absorption between dry and wet panels. The amount of absorbed and transmitted energies in dry and wet conditions is shown in Fig. 14. The amount of energy transmitted in dry state is 33.27 J whereas it becomes 35.03 J by 5.0% increase. This small difference does not show itself as a significant effect in the energy absorbed in the panels. Fig. 15 shows the absorbed and transmitted energies in percentage for dry and wet conditions.

4. Conclusions

Following conclusions were drawn from this research:

- In shooting tests, a trauma is formed in the backing material when the bullet is stopped by the panel. The depth and diameter of this trauma is dependent on ballistic properties of a panel. The trauma geometry is related to the energy transmitted to the back of the panel.
- Fabric ply number used in ballistic panels is the most important parameter affecting the trauma depth and diameter. An increase in fabric ply number caused a decrease in trauma depth and diameter. It was seen from the tests that increasing fabric ply number from 20 to 32 decreased trauma depth by 35.40% and trauma diameter by 12.7%.
- Stitching types used in the panels were found to have significant effect on ballistic properties. A reduction of 6.7% in trauma depth was found with type c stitching compared to the type a for the same fabric ply number. Reduction in trauma depth without increasing fabric weight is significant from practical point of view. High stitch density used in type b and type c panels brought the advantage of increasing panel strength. But high stitch density increases panel rigidity and this makes it difficult to use these panels in especially personal protective body armours. The change in trauma diameter depending on the stitch type was found to be limited.
- A limited effect of conditioning on trauma depth was observed. Only 3.6% difference in trauma depth was measured between the dry and wet panels. This result shows that no significant decrease will exist in ballistic performance of aramid fabrics due to wetting so long as a good water-repellent treatment is applied.
- Energy absorption capacity of panels increases and the amount of energy transmitted to the back of panels decreases with an increase in the number of fabric ply. Especially after 24-ply, the amount of energy absorbed by panels increased and the energy transmitted to the back side decreased significantly. Around 59.8% reduction in the transmitted energy and 4.4% increase in the absorbed energy occurred when the fabric ply number increased from 20 to 32.
- Significant differences were found in the energy transmitted to the back of the panel between stitching types. Biggest difference was observed between type a and type c as 11.5%. No significant difference was observed in the energy absorbed in the panels of type a, type b and type c stitching.
- Conditioning was found to have a limited effect on the energy transmitted to the back of the panel. Around 5.0% increase was observed in the energy transmitted to the back side in wet panels compared to dry panels. No significant effect of conditioning was found on the absorbed energy.

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