Threat Assessment and Performance Evaluation of Multi-threat Body Armour Systems

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1. Abstract

With the development of new technologies for flexible stab/puncture resistant materials, and flexible ceramic body armour, there now exists the possibility of having non-rigid armour solutions with protection against emerging ballistic threats (such as hard core/jacket handgun bullets), knife blades, and anti-personnel flechettes, with body coverage similar to fragment resistant vests currently in use. Under the assumption that the required protection performance and weight criteria could be met, such a multi-threat body armour system would eventually be included as a complement to the individual protective equipment of the Canadian Army. An evaluation of novel technologies comprising advanced unidirectional fibres, coated fabrics, and non-metallic materials was conducted. Ballistic (i.e. bullets and fragments) performance was evaluated under the test protocols of NIJ 0101.04 and STANAG 2920 for small calibre handgun and fragments while stab resistance performance was evaluated under the methods described in NIJ 0115.00. Testing approaches are also presented for flechette resistance. The results of the body armour evaluations and their potential impact on future designs and requirements are presented.

2. Introduction

The emergence of stab resistant, flexible body armour material technologies has resulted in a variety of comfortable (i.e. wearable) and functional protective solutions for police, military and correctional personnel. While previous soft body armour was shown to provide limited protection against high performance (hard core/jacket) bullets or knives, new systems are offering increased protection without requiring ceramic plates or other rigid materials. Combining various types of soft armour layers can create a light-weight, flexible protection system capable of defeating multiple threats including hard core bullets, knife blades, spikes and flechette weapons.

To benefit from the development of such technologies, a research project was initiated by DRDC-Valcartier with the objective of identifying the best overall flexible protection system for potential use by soldiers. The performance requirements defined initially were based on specifications from common standards and correspond to anticipated threats (Table 1). Additional body armour requirements were also identified and are presented in Table 2.

Several protection system samples were acquired from different manufacturers following a survey aiming to identify the most suitable materials commercially available. The samples were tested for stab and ballistic resistance using the procedures outlined in Table 1. The samples were also evaluated for flechette resistance using a drop-mass test method simulating ballistic flechette testing. The experimental results allow for the selection of the most promising solutions to be considered for further development of a complete lightweight flexible protection system.

Table 1: Threat description and required performance level.

Threat	Stab S1, P1	Spike	Flechette Artillery	Flechette Rifle	FSP	Sphere	Handgun A	Handgun B
Calibre	NA	NA	2.34 mm	1.75 mm	5.45 mm	2.5 mm	9x19 mm	9x19 mm
Type	NIJ 0115.00	NIJ 0115.00	STANAG 2920	STANAG 2920	MIL-P-46593	---	FMJ	Bofors HP
Mass (grain)	NA	NA	21.5	10.0	17	1	124	104
V50 (m/s)	Protection Level 2 E1 33 J E2 50 J	Protection Level 2 E1 33 J E2 50 J	400 or equivalent	400 or equivalent	750	1000	Vproof 436±9 NIJ IIIA	Vproof 420 (6 shots)
Impact Angle	0° & 45°	0° & 45°	0	0	0	0	0	0
No. Impacts per Sample	3@S1, 3@P1	3	6	6	TBD	TBD	TBD	TBD
Min. Distance Between Impacts (mm)	TBD	TBD	25	25	50	25	75	75
Backing Material	Foam	Foam	Foam	Foam	Foam	Foam	Clay	Clay
Max. Back Face Deformation or Blade Penetration (mm)	7 at E1 20 at E2	7 at E1 20 at E2	NA	NA	NA	NA	44	NA

Table 2: General requirements for body armour.

Criteria	Requirements
Minimum vest coverage	70% of current Canadian Army fragment resistant vest
Maximum areal density	10 kg/m^2
User wearable rating	Should be rated using ISO body armour comfort protocol [1].
Other	Thickness, weight, and heat stress should be minimized

3. Threat Assessment

3.1 Stab

The stab threats used were those defined in the NIJ 0115.00 test standard [2] and are identified as P1, S1, and Spike (Figure 1). P1 corresponds to a thin blade with one cutting edge while S1 is a thick blade with two cutting edges. The spike is a pointed weapon similar to an ice pick.

For each stab threat, the NIJ 0115.00 test standard [2] defines a standard strike (E1) energy and an over-strike energy (E2) requirement.

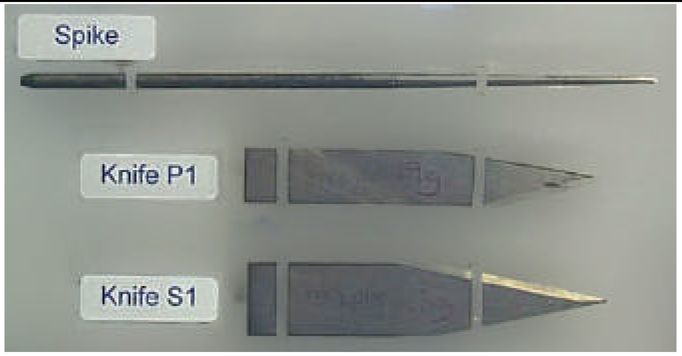

Figure 1: NIJ stab threat.

3.2 *Flechette*

The flechette is a small spike-style projectile that is typically fired at high velocity in a cluster from a variety of warhead munitions. Flechette ammunition have the ability to penetrate dense vegetation very rapidly and can strike a relatively large number of targets simultaneously. Recent progress in the development of anti-personnel weapon have demonstrated the potential lethality of this threat [4, 3].

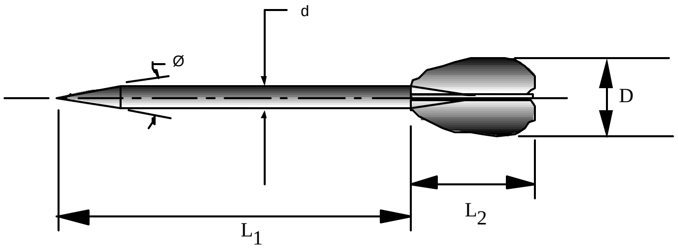

Figure 2: Flechette geometry [3].

Table 3 presents some of the main flechette types and their characteristics. Two types of flechette simulator were defined in STANAG 2920 [5] for evaluation testing purposes. The small arms flechette simulator was selected initially to conduct the proposed armour evaluation since it is considered to be the most severe threat. Further tests are also planned with artillery flechette simulator to compare the severity of the two flechette simulator types.

Table 3: Anti-Personnel Flechette Comparison [6].

	Small Arms (Rifle)	**Shotgun (12-Gauge)**	**Rocket**	**Artillery**	**Rifle Grenade**	**Artillery / Shotgun Flechette Simulator**	**Small Arms Flechette Simulator**
Mass (g)	0.52 – 0.65	1.30 – 1.42	3.89	1.30 – 1.42	0.84	1.40	0.65
Mass (gr)	8 - 10	20 – 22	60	20 – 22	13	21.5	10.0
d (mm)	1.6 – 1.8	2.26	3.96	2.26	2.1	2.34	1.75
D (mm)	5	5.53	9.3	5.53	4.8	2.34	1.75
L1 (mm)	33	26.5	37	26.5	29	43.1	39.5
L2 (mm)	8	15.2	13	15.2	10.5	0 (no fins)	0 (no fins)
q	10	20 – 30	20 – 30	20 – 30		30	10
Nose Shape	Conical	Nail type	Nail type	Nail type	Nail type	Conical	Conical
No. of flechette	1	20	700	1000 - 8000	160	---	---
Material	Steel	Steel	Steel	Steel	Steel	Steel	Steel
Hardness (Rc)	38 – 44	38 – 44	38 – 44	38 – 44	38 – 44	40	40
Striking Velocity (m/s)	1100 – 1300	400-500	750-850	300-400	50-70	---	---
Striking Energy (J)	315 – 550	105 – 180	1100 - 1405	60 – 115	1 - 2	---	---

3.3 *Ballistic*

Fragment Simulating Projectile (FSP) / Small Sphere

The detonation of a fragmentation warhead can generate up to tens of thousand of fragments weighing between 1 to hundreds of grains. Smaller fragments are typically more abundant over larger ones by a ratio of approximately 1000:1 as described by the relationship between the number of fragments and their weight given by the Mott curves [7]. Clearly, the risk of being hit by smaller fragment is relatively high which suggests that individual protection systems must be designed to defeat this threat. Effective body armour should also consider the widest spectrum of fragment characteristics. For these reasons, the standard 1.1 g FSP as described in MIL-P-46593 [8] with an obturator and the 1 gr steel sphere (2.5 mm dia.) were selected as representative small fragment threats. The 1.1 g FSP, which consists in a chisel-nose steel cylinder, is the most common shrapnel surrogate specified for fragment resistant jacket and helmet. The small sphere was selected because its shape makes it easier to launch and also because it offers higher penetration performance than Right Circular Cylinders (RCC) for the same weight. Furthermore, spheres are often used as fragments in pre-fragmented munitions such as many modern hand grenades. The basic characteristics of the selected fragment threats are presented in Table 1.

9 mm FMJ and 9 mm Bofors HP bullets
The 9 x 19 mm FMJ Ball round was selected in this study since it is widely used throughout the world for military pistols and sub-machine guns. It is also used in the NIJ 0101.04 standard [9] to define protection levels for soft body armour against handgun projectiles. The evaluation of the armour samples with this threat will therefore allows direct comparison with current protection systems. Recently, 9 mm armour piercing rounds have appeared on the market. Bofors (HP) as well as Conjay (CBAP Mark 3), among others, manufacture these types of bullets. They can be used in standard NATO Parabellum 9 x 19 mm chambered weapons. The muzzle velocity of this bullet is approximately 420 m/s. The 9 x 19 mm Bofors HP bullet selected for this test series has a lead core and a gilding metal clad steel jacket that is much thicker at the bullet nose, thus providing high penetration capability (Figure 4). It is claimed that the 9 mm HP Bofors round can go through 50 layers of para-aramid fabric at 50 m. Basic characteristics of these two bullets are presented in Table 1. Other types of high penetration handgun bullets were considered for this study but not included in the experimental evaluation. They were the .357 KTW (monolithic brass round) and other hard core bullets for the Personal Defence Weapon (PDW) family (4.6 mm and 5.7 mm cal.). The PDW military rounds are designed to defeat the NATO CRISAT body armour (aramid-titanium with areal density of about 11 kg/m^2).


Figure 3: 9 mm FMJ cartridge and bullet.

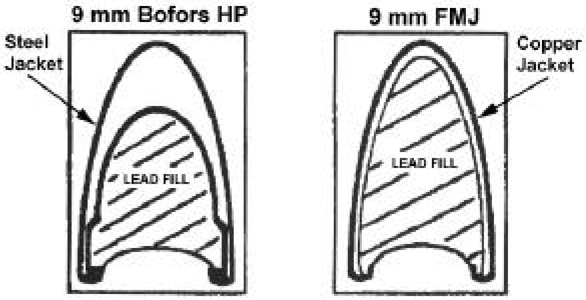

Figure 4: Comparison between the 9 mm Bofors HP and the 9 mm FMJ bullets.

4. Armour Material and Test Methods

4.1 Armour samples

Initially, available technologies for spike and knife threats were evaluated [10]. Manufacturers of body armour materials and vests were sought and contacted to identify candidate materials that, when combined with sufficient conventional ballistic resistant fabrics, could provide stab protection in a so-called hybrid protection system. Several samples of these materials were acquired from companies in Canada, Europe and the United States for evaluation of the performance against the stab and ballistic threat described in Table 1. Each manufacturer was supplied with the same performance requirements that included NIJ Stab Level 2, flechette and ballistic resistance. While some were able to provide a combination of materials to cover the multi-threat requirements, other manufactures simply addressed the stab resistant requirement as it was identified as the first priority. A total of nine different protection systems were acquired and are summarized in Table 4. The proposed solutions consisted essentially of multiple layers of woven or laminated fabric using various fiber materials such as para-aramid (Kevlar®, Twaron®), UHMW polyethylene (Spectra®, Dyneema®), and PBO (Zylon®).

Table 4: Armour samples.

Armour Sample	**Description**	**Protection**	**Areal Density (kg/m^2)**
1	Steel sheets and woven fabric layers	PSDB Level KR1	6.0
2	Multi-layers of coated woven fabric	NIJ Stab Level 2	10.2
3	Multi-layers of coated woven fabric	NIJ Stab Level 2	9.9
4	Multi-layers of coated woven fabric	NIJ Stab Level 2	9.9
5	Multi-layers of 2 woven fabric types	Custom	9.9
6	Multi-layers of 2 woven fabric types	Custom	8.4
7	Multi-layers of dense woven fabric	NIJ Spike Level 2	2.2
8	Multi-layers of woven and laminated fabrics	NIJ Ballistic Class II NIJ Stab Level 2	6.3
9	Multi-layers of woven and laminated fabrics	NIJ Ballistic Class IIIA NIJ Spike Level 2	6.6

4.2 Stab Resistance

All tests were conducted according to the procedures outlined in the NIJ 0115.00 test standard [11]. However, some deviation was required to reduce the number of samples. The NIJ 0115.00 test standard [2] requires that a total of four samples must be tested at the specified threat level to receive the corresponding NIJ certification. For this testing series, each sample was used repeatedly, providing a fair strike could be achieved. In most cases, all tests for both the two edged threats and the spike were completed on one armour sample.

Figure 5: Stab apparatus.

The stab resistant testing was conducted on a drop tower apparatus similar to that described in the NIJ 0115.00. This apparatus, see Figure 5, consisted basically of a vertically mounted tube through which a drop mass can travel. The drop mass has a compliant plunger to provide a multi-peaked force profile similar to that delivered by hand-held weapons [12]. The drop mass has inter-changeable tips to allow each different threat to be secured into place. The total mass of the stab drop assembly, including threats, was 1.906 kg.

During testing, the armour samples were positioned on a pack of backing material which had been constructed in accordance to that specified in NIJ 0115.00. The pack consists of several layers of materials including neoprene sponge, polyethylene foam and rubber. Figure 6 illustrates the assembly of these materials that makes up one pack, where the neoprene sponge is the top or impact face. The packs were tested in accordance with NIJ 0115.00 to ensure dynamic compliance by measuring the restitution of a steel ball dropped onto the top surface.

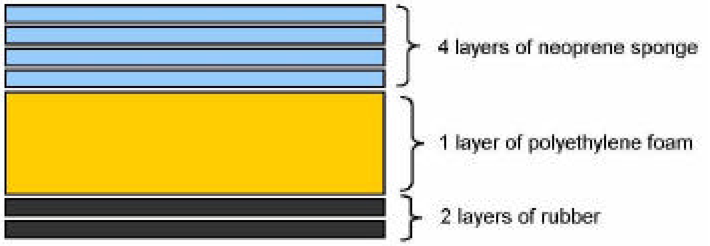

Figure 6: Composite backing material.

Figure 7: Direct measurement.

Two methods are available from the standard to measure the level of penetration during the stab testing. One method is to use witness paper (Polyart^{TM}) placed between the armour sample and the backing material and the other is to measure the protruding threat directly. For the knife blades, the level of penetration can be determined by first measuring the length of the cut in the witness paper and correlating that length to a penetration depth. This method is not suitable for the spike testing as the shaft diameter is constant for the most part of its length. Direct measurement, as shown in Figure 7, is not always possible as the threats may sometimes recede after penetrating the material and partially or completely pull out of the armour sample. For this test series, both measurement methods were employed and the most appropriate for each test scenario was used in reporting the results.

Table 5 describes the minimum number of strikes that were performed on each armour sample. Tests were only repeated if the first attempt did not produce a fair hit. An example of a fair hit would be one that falls within the specified velocity range and strikes no closer than 50 mm away from a previous hit.

Table 5: Test Matrix for Stab Resistance at NIJ 0115.00 Level 2.

Test #	Threat Type	Energy Level	Angle of Incidence
1	P1	E1	0 °
2	P1	E2	0 °
3	P1	E1	45 °
4	S1	E1	0 °
5	S1	E2	0 °
6	S1	E1	45 °
7	Spike	E1	0 °
8	Spike	E2	0 °
9	Spike	E1	45 °

4.3 Flechette Resistance

The purpose of this test series [11] was to determine whether the sample armour materials would meet the performance requirements for flechette resistance as well as to develop a replacement drop mass test method.

Traditionally, flechette testing used ballistic means to deliver the flechette to the sample but there are many difficulties with this method including targeting and flight stability. Using drop mass testing could provide a more repeatable method for testing materials against flechette threats. In a future study, the results of this testing will be correlated with ballistic flechette test results of similar materials to validate the drop mass method.

The flechette resistance testing was conducted in a manner similar to that described in the NIJ 0115.00 stab standard in as far as a mass was being dropped to impact a test sample. While the measure of NIJ testing pertains to the level of penetration, the STANAG 2920 test standard for flechette simulators uses V50 as a means to evaluate performance. The resulting method for this testing was to use a NIJ-style drop mass with the test method described in the STANAG 2920 standard [5].

The flechette simulator used in this testing, pictured in Figure 8, is similar to the rifle flechette simulator from STANAG 2920 [5]. The flechette was constructed with the same profile for the impact point but the overall length was increased to 65 mm. The additionally length was necessary for the flechette to be secured inside the drop mass assembly. When installed into the flechette holder, the protruding length of the flechette was 38.1 mm, which is very similar to the STANAG specified length of 39.5 mm.

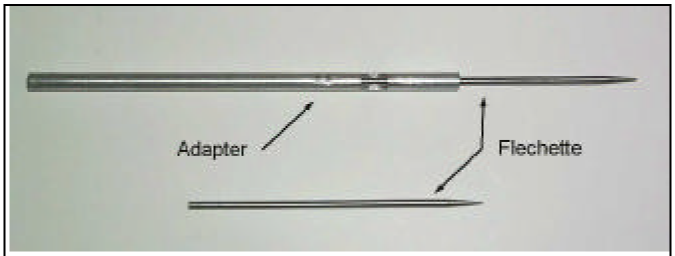

Figure 8: Flechette and Adapter.

The flechette testing was conducted using the same drop tower apparatus used in the stab testing. A cylindrical adapter was constructed to allow a flechette to be secured into the holder used for the spike threat (see Figure 8). The bottom mass and housing of the drop mass assembly is normally separated by two foam discs to simulate a stab strike by a person. For the flechette testing, these foam discs were replaced by a wooden dowel that rigidly coupled the bottom mass and the housing. This arrangement was to better represent the impact strike of a ballistic fired flechette. The total mass of the flechette drop assembly, including a flechette, was 1.918 kg.

During testing, the armour samples were positioned on the same backing material as that used in the stab testing. The Polyart^{TM} witness paper was also used to indicate any perforation.

The test matrix was based on the V50 procedure described in STANAG 2920 [5] (see Section 4.4). However, for testing with a drop apparatus it was found to be more appropriate to use the height, or H50, to define the input condition of each test. The H50 is defined as the arithmetic mean of the height from which an even number of at least six drops are made, half of which perforate the target material, half of which do not. From those drops used in the calculation, the highest must not be more than 50 mm than the lowest. A perforation includes any penetration through the last layer of sample material, and which was indicated by a tear in the witness paper.

4.4 Ballistic Resistance

The ballistic tests were conducted under the general test methods outlined in Draft STANAG 2920 [5] and NIJ 0101.04 [9] as described in Table 1. However, some deviation was required to simplify the preliminary evaluation process of the samples. As a result, all tests were conducted in the dry condition and the samples were evaluated with the composite foam backing for the FSP and small sphere threats. In addition, specific procedures were required for each ballistic threat as described below.

FSP / Sphere

Ballistic limits for the FSP and the sphere were determined using the V50 procedure described in STANAG 2920 [5]. This procedure defines the V50 as the arithmetic mean of 3 partial and 3 complete penetrations of the armour within a spread of 40 m/s. Both projectiles were fired using 0.22 cal branch barrel of 560 mm length with a twist of 1/16. A 10 GHz Doppler radar and a set of light screens (for redundancy) were used to measure the impact velocity of the projectiles. Test samples were tied with rubber straps to a rigid aluminum box fixture that contained the backing material described in Figure 6. For the 1.1 g FSP trials, the target was positioned at 5 m from the gun muzzle while a distance of 3 m was used for the tests with the small spheres.

Two repetitions were performed for the tests conducted with the FSP. For the trials conducted with the sphere, only the tests with armour samples that were close to the targeted performance requirements were repeated.

9 mm FMJ bullet

Ballistic performances of armour samples were tested according to the procedures described in the NIJ 0101.04 Standard [9]. The projectiles were fired using a universal receiver equipped with a 9 mm cal. Mann barrel of 152 mm length. A 10 GHz Doppler radar and a set of light screens (for redundancy) were used to measure the impact velocity of the bullets. Test samples were tied with rubber straps to a rigid aluminum box fixture that contained standard clay backing. As a part of the test routine, the clay was calibrated before and after each test series, i.e. after 3 shots. For each solution, the first test was done to verify if the test sample would meet the NIJ level IIIA requirement. In case of failure, the sample was tested at the next lower level (i.e. NIJ level II). The backface deformation, i.e. the maximum depression depth in the clay, was measured from the plane defined by the front edge of the clay box fixture.

9 mm Bofors HP

This test series was conducted with the same equipment as for the 9 mm FMJ bullet trials. Since the expected performances against 9 mm Bofors HP round at 420 m/s were unknown, pre-tests were conducted initially on all test samples using the standard clay backing to determine if penetration will occur. All samples failed radically which indicated a much lower ballistic limit for these materials.

Additional ballistic testing was conducted to determined V50 using the same procedure as described for FSP and sphere testing but with clay backing. However, due to the limited number of available test samples, only armour sample No. 9 was evaluated.

5. Results

5.1 *Stab Resistance*

Table 6 summarizes the results of the stab testing with the samples ranked according to the areal density. Many of the armour samples easily passed the performance requirement of NIJ Level 2 stab testing. In fact, there was zero penetration observed in many cases, well below the maximum allowable penetration.

Table 6: Results of Stab Testing.

Armour Sample		**7**	**1**	**8**	**9**	**6**	**4**	**5**	**3**	**2**
Areal Density (kg/m^2)		**2.2**	**6.0**	**6.3**	**6.6**	**8.5**	**9.9**	**9.9**	**10.0**	**10.2**
Threat	S1 Knife	Fail	Fail	Fail	Pass	Pass	Pass	Pass	Pass	Pass
	P1 Knife	Fail	Fail	Fail	Fail	Fail	Pass	Pass	Pass	Pass
	Spike	Pass	Fail	Fail	Pass	Fail	Pass	Pass	Pass	Pass

5.2 *Flechette Resistance*

The height from which half of the strikes would penetrate the material was determined and the velocity was recorded. Based on this drop height and the mass of the drop mass assembly, the corresponding energy at this height was also determined. Table 7 summarizes the results of this testing.

Armour Sample 8 was not included in the flechette testing because of its poor performance in the stab testing. Flechette testing was begun on Armour Sample 7 but the required drop height was too low to be accurately measured and therefore removed from the series. All other samples from the stab testing were tested for flechette resistance. Further flechette testing using flechette simulators and high velocity gas gun will be conducted at DRDC-Valcartier to establish a correlation with the drop tower test method.

Table 7: Results of Flechette Testing

Armour Sample	**1**	**9**	**6**	**4**	**5**	**3**	**2**
Areal Density (kg/m^2)	**6.0**	**6.6**	**8.5**	**9.9**	**9.9**	**10.0**	**10.2**
H50 (m)	0.17	0.58	0.38	0.30	0.49	0.38	0.49
Energy (kJ)	3.2	10.9	7.1	5.6	9.1	7.1	9.2
Velocity (m/s)	1.50	3.20	2.54	2.21	2.94	2.52	2.94

5.3 *Ballistic Resistance*

To reduce the number of trials, only the armour samples that passed the stab tests for P1 and the spike threats were submitted for ballistic resistance testing.

FSP

Table 8 summarizes the results of the FSP testing. Overall, the V50 values obtained were significantly lower than the targeted performance (i.e. 750 m/s). Armour samples No. 9, 5, 3,and 2 showed similar performances

(V50 = 626.6-650.7 m/s) whereas the ballistic limit of armour sample No. 4 was significantly lower (587.4-589.7 m/s). Larger variability for the ballistic limit values and the lowest complete penetration velocities were observed for armour samples No. 3, 5 and 9 (10-15 m/s).

Table 8: Ballistic limit evaluation for FSP.

Armour Sample	9		4		5		3		2	
Areal Density (kg/m^2)	**6.6**		**9.9**		**9.9**		**10.0**		**10.2**	
Test series no.	1	2	1	2	1	2	1	2	1	2
V50 (m/s)	626.6	636.1	589.7	587.4	636.6	650.7	643.5	632.6	634.0	635.3
ZMR*	7.1	0.0	0.0	0.0	1.5	2.5	0.0	0.0	0.0	0.0
Lowest complete (m/s)	617.6	633.8	590.5	588.1	636.4	648.7	647.6	633.8	635.6	637.0
Highest partial (m/s)	624.7	627.2	586.1	585.3	637.9	651.2	647.4	630.3	630.5	629.4
Spread (m/s)	37.9	37.9	35.6	16.3	33.1	25.5	39.0	16.9	20.4	39.4

*ZMR: Zone of Mixed Results. It is defined by the difference between the highest velocity measured for a partial penetration and the lowest velocity measured for a complete penetration.

Sphere

Results of sphere trials are presented in Table 9. Armour samples No. 2 and 3 presented ballistic limits close to the performance requirement of 1000 m/s and were superior to the other materials by approximately 100 m/s. Results obtained for armour sample No. 3 appeared to be slightly better, however.

Table 9: Ballistic limit evaluation for sphere.

Armour Sample	9	4	5	3		2	
Areal Density (kg/m^2)	**6.6**	**9.9**	**9.9**	**10.0**		**10.2**	
Test series no.	1	1	1	1	2	1	2
V50 (m/s)	856.6	886.7	861.5	996.6	979.2	978.5	963.6
ZMR	2.1	20.3	4.6	10.7	0.0	0.0	0.0
Lowest complete (m/s)	858.3	872.3	858.9	991.8	982.7	986.1	968.1
Highest partial (m/s)	860.4	892.6	863.5	1002.5	972.8	974.6	962.5
Spread (m/s)	35.8	28.0	24.5	29.8	35.9	35.3	34.5

9 mm FMJ bullet

Table 10 summarizes the results obtained with the 9 mm FMJ bullet against clay backing. Impact velocity and the corresponding backface deformation for each of the 3 shots are presented. NIJ threat levels to which the samples were tested are also identified. Only armour sample No. 4 failed at NIJ level III A. It passed, however, at NIJ level II. Marginal results were obtain for armour sample No. 5 since the backface deformation measured corresponded to the 44 mm pass/fail for two of the three shots.

Table 10: Ballistic resistance for 9 mm FMJ bullet.

Armour sample	Areal Density (kg/m^2)	Test Level	Impact velocity (m/s)			Backface deformation (mm)			Result
			Shot 1	Shot 2	Shot 3	Shot 1	Shot 2	Shot 3	
9	6.6	NIJ IIIA	442.7*	443.6	445.0	39*	26	28	Pass
4	9.9	NIJ IIIA	434.6	434.4	441.7	12	18	C	Failed
		NIJ II	371.6	366.3	363.8	4	2	3	Pass
5	9.9	NIJ IIIA	424.9	436.0	428.8	39	44	44	Pass
3	10.0	NIJ IIIA	435.5	438.6	430.4	24	21	14	Pass
2	10.2	NIJ IIIA	436.8	439.3	428.6	7	9	16	Pass

*Impact located close to the edge of the test sample.

9 mm Bofors HP

Ballistic limit results obtained for armour sample No. 9 against the 9 mm Bofors HP are presented in Table 11. Only an approximate ballistic limit value could be obtained since the velocity distribution was too large to validate the results. Nevertheless, the lowest complete and the highest partial penetrations were relatively close to the approximate ballistic value. If the results obtained with the FSP and the 9 mm FMJ are any guide, it is expected that the other armour samples will performed similarly against the 9 mm Bofors HP round. Thus, it is not expected that any test sample will meet the performance requirement established initially for this threat (Vproof = 420 m/s).

Table 11: Ballistic resistance for 9 mm Bofors HP.

Armour Sample	**9**
Areal Density (kg/m^2)	**6.6**
V50 approx. (m/s)	268.2
ZMR	0.0
Lowest complete (m/s)	270.4
Highest partial (m/s)	266.0
Spread (m/s)	136

6. Discussion

As expected, the stab resistance performance generally increases with the areal density of the sample, Figure 9. (for reference, typical areal densities required for NIJ 0101.04 levels II, IIIA, and III are also indicated in this figure). Materials with areal density equal or greater than 9.9 kg/m^2 were found to meet the 3 stab threat requirements. The same trend between performance and areal density was also observed when considering flechette and ballistic threats. Although, due to the rather large discrepancies between the different threat characteristics, the best resistance performances did not always corresponded to heavier materials. For example, it is possible to defeat the spike threat with a very light armour solution, i.e. 2.2 kg/m^2 (Table 6, Figure 9). To facilitate comparison between test samples, flechette, ballistic limit, and backface deformation results were normalized as illustrated in Figure 10 where a value of one corresponds to the best results obtained. From this figure, armour sample No. 2 appears to be the most promising solution against all the threats considered. Armour sample No. 4 does not meet the requirement for the 9 mm FMJ round and ranks below average for the other threats. While results for armour sample No. 5 seem acceptable, marginal performance was obtained in terms of backface deformation for the 9 mm FMJ round. Interestingly, the lightest solution of those tested under ballistic conditions, armour sample No. 9, offers the best resistance against flechette and has an average performance against ballistic threats. It should be noted, however that this sample did not pass the requirement for the knife P1 stab threat.

Increased ballistic protection would be necessary for all armour samples to meet the requirements established initially (Table 1). Resistance against FSP has to be improved since the best V50 results were under the target value by approximately 100 m/s. A more challenging problem is posed by the 9 mm Bofors HP round. To be able to defeat this projectile at a muzzle velocity of 420 m/s, further armour development will be required. This may be solved by adding more layers of woven material or considering semi-rigid solutions such as the addition of thin metallic or ceramic tiles to a flexible membrane. This latest solution will have the advantage of providing added protection against the most severe ballistic threats in combination with better performance against spike, flechettes and knife blades. Although, the addition of semi-rigid components will reduce the flexibility of the armour and the increased weight would likely necessitate to limit its application to the more vulnerable areas of the body. It is expected, however, that the resultant protection coverage will be greater than current bullet resistant plates (i.e. 25 x 30 cm).

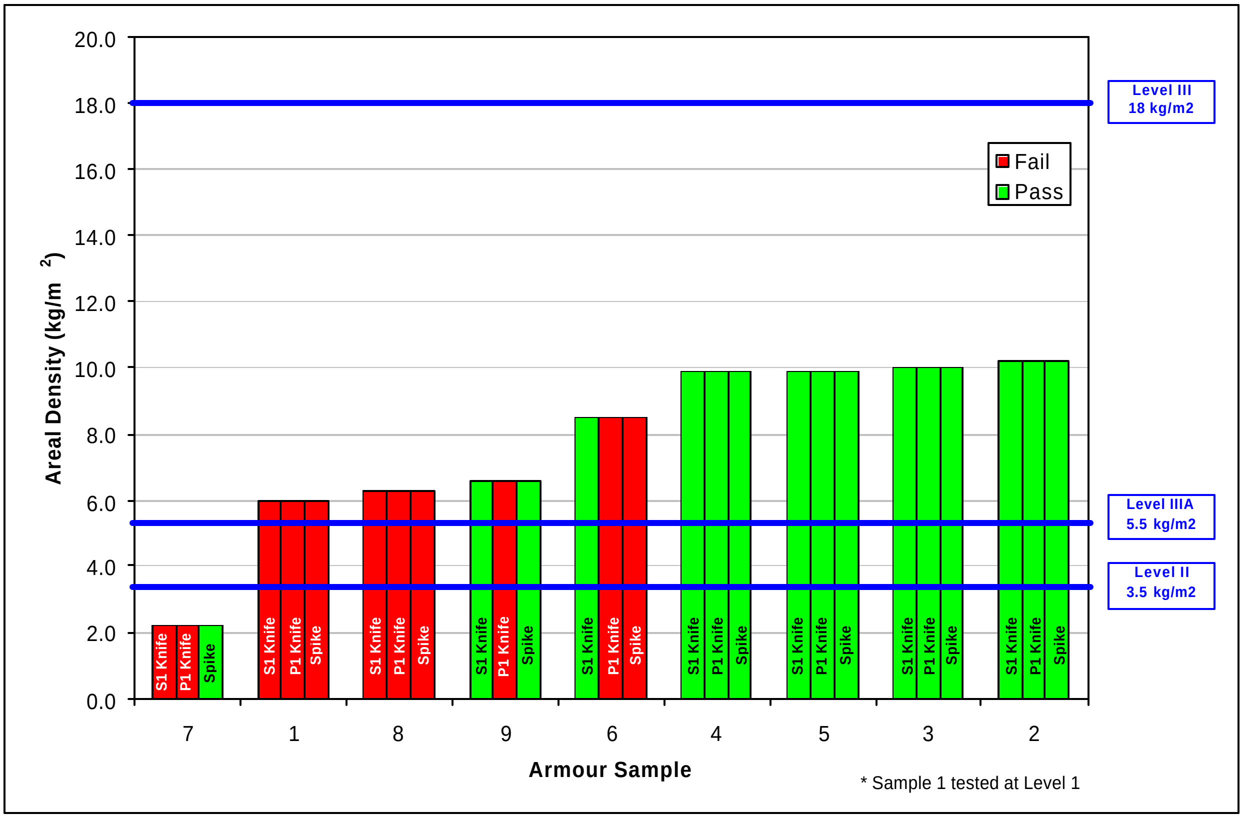

Figure 9: Results of stab testing.

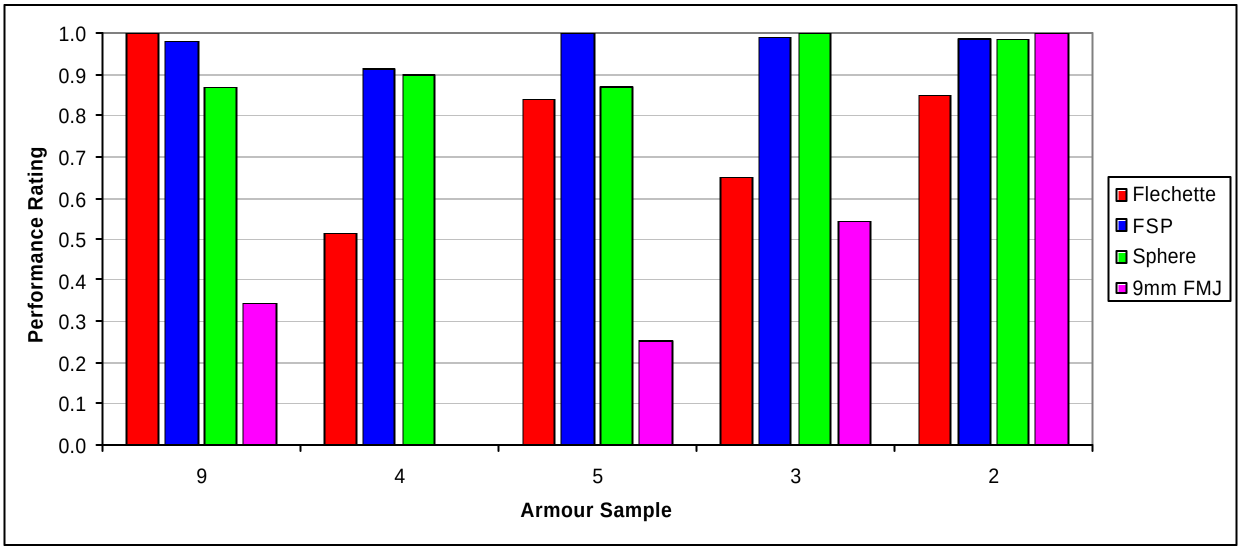

Figure 10: Performance rating of armour samples for flechette and ballistic threats.

7. Conclusion

The experimental results have shown that current technologies in soft body armour can provide protection against stab, flechette, and ballistic threats. These results also suggest that further optimization may be possible through changes in the number of layers and their relative sequence or efficient combinations with other materials. It is expected that an armour solution could be developed that would meet all the initial performance requirements. However, due to the severity of the 9 mm Bofors HP round, it is not expected that a solution weighing less than 10 kg/m^2 can be achieved. An objective of 12 kg/m^2 will be more realistic based on the current technologies, unless the threat level requirement is slightly reduced. Further testing with flechette simulators will also confirm the relative severity of this threat in comparison with the 9mm Bofors HP round.

While armour performance against flechette was presented, additional work will be required to assess the validity of the proposed drop test method. Several materials will have to be tested to correlate the drop mass testing with ballistic flechette testing. It is expected that equivalent V50 values could be derived from drop mass testing results if correlation between the two test methods can be established.

8. Acknowledgement

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