Title: Performance Evaluation of Multi-threat Body Armour Systems

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The emergence of stab/puncture resistant, flexible body armour material technologies has resulted in a variety of comfortable and functional multi-threat 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) handgun bullets, knife blades, or anti-personnel flechettes, new systems are offering increased protection without requiring ceramic plates or other rigid materials. An evaluation of novel technologies comprising advanced unidirectional fibres, coated fabrics, and non-metallic materials was conducted. Ballistic (i.e. bullets and fragments) and stab performances were evaluated under standard test protocols. For flechette testing, a novel approach using a drop mass was developed to overcome targeting and flight stability difficulties associated with the traditional ballistic method. The results of the body armour evaluations and their potential impact on future designs and requirements are presented.

INTRODUCTION

With the development of new technologies for flexible stab/puncture resistant materials, there now exists the possibility of having non-rigid armour solutions with multi-threat protection capabilities. Combining various types of soft armour layers can create a light-weight, flexible protection system capable of defeating multiple threats.

In 2003, DRDC-Valcartier initiated a research project to identify the most promising flexible protection systems [1] for potential use by soldiers. The performance requirements were based on specifications from common standards and correspond to anticipated threats (TABLE 1).

Test samples were acquired from different manufacturers following a survey aiming to identify the most suitable materials commercially available. The samples were tested for stab, ballistic and flechette resistance. The best solutions will be considered for further development.

TABLE 1: THREAT DESCRIPTION AND REQUIRED PERFORMANCE LEVEL

Threat	Stab S1, P1	Spike	Flechette Artillery	FSP	Sphere	Handgun A	Handgun B
Calibre	NA	NA	2.34 mm	5.45 mm	2.5 mm	9x19 mm	9x19 mm
Type	NIJ 0115.00	NIJ 0115.00	STANAG 2920	MIL-P-46593	---	FMJ	Bofors HP
Mass (grain)	NA	NA	21.5	17	1	124	104
Performance Requirement (necessary)	Protection Level 1 E1 24 J E2 36 J	Protection Level 1 E1 24 J E2 36 J	250 m/s or equivalent	600 m/s	850 m/s	V_{proof} 367±9 m/s NIJ II	V_{50} 367 m/s (6 shots)
Performance Requirement (desired)	Protection Level 2 E1 33 J E2 50 J	Protection Level 2 E1 33 J E2 50 J	400 m/s or equivalent	750 m/s	1000 m/s	V_{proof} 436±9 m/s NIJ IIIA	V_{proof} 420 m/s (6 shots)
Impact Angle	0° & 45°	0° & 45°	0	0	0	0	0
No. Impacts per Sample	3@S1, 3@P1	3	6	TBD	TBD	TBD	TBD
Min. Distance Between Impacts	TBD	TBD	25 mm	50 mm	25 mm	75 mm	75 mm
Backing Material	Foam	Foam	Foam	Foam	Foam	Clay	Clay
Max. Back Face Deformation or Blade Penetration	7 mm at E1 20 mm at E2	7 mm at E1 20 mm at E2	NA	NA	NA	44 mm	NA

TABLE 2. ARMOUR SAMPLES

Armour Sample	**Description**	**Protection**	**Areal Density (kg/m^2)**
1	Steel sheets and woven fabric, 15 layers total	PSDB Level KR1	6.0
2	Coated woven aramid, 30 layers	NIJ Stab Level 2	10.2
3	Coated woven aramid, 30 layers	NIJ Stab Level 2	9.9
4	Coated woven polyethylene, 27 layers	NIJ Stab Level 2	9.9
5	2 types of woven aramid, 32 layers total	Custom	9.9
6	2 types of woven aramid, 31 layers total	Custom	8.4
7*	Multi-layers of dense woven aramid, 18 layers	NIJ Spike Level 2	2.2
8	Woven aramid and laminated polyethylene, 26 layers total	NIJ Ballistic Class II NIJ Stab Level 2	6.3
9	Woven PBO and aramid, laminated polyethylene, 50 layers total	NIJ Ballistic Class IIIA NIJ Spike Level 2	6.6
10**	Woven PBO, 20 layers	Custom	2.7
11**	Coated woven aramid, woven aramid, laminated polyethylene, 41 layers total	Custom	11.9
12**	Coated woven aramid, woven PBO, laminated polyethylene, 51 layers total	Custom	12.3
13**	Woven PBO, unidirectional aramid, 38 layers total	Custom	6.3

* Armour No. 7 was included in the test matrix even if it did not address all the established performance requirements.
** Armour samples No. 10, 11, 12, and 13 were tested for flechette resistance only.

ARMOUR MATERIALS AND TEST METHODS

Armour samples

A total of thirteen different protection systems were acquired from companies in Canada, Europe and the United States (TABLE 2). The proposed solutions consisted essentially of multiple layers of woven, unidirectional or coated fabric using various fiber materials such as para-aramid (Kevlar®, Twaron®), UHMW polyethylene (Spectra®, Dyneema®), and PBO (Zylon®).

Stab Resistance

Stab resistant testing was conducted on a drop tower apparatus according to the procedures outlined in the NIJ 0115.00 test standard [2] using the stab threats identified as P1, S1, and Spike. 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 level, the NIJ 0115.00 test standard [3] defines a standard strike (E1) energy and an over-strike energy (E2) requirement. In this test series, samples were evaluated at protection level 2 (TABLE 1). The weight of the drop mass was 1.9 kg.

Flechette Resistance

Flechettes are small spike-style projectiles fired in a cluster from a variety of warhead munitions. Recent studies have demonstrated the potential lethality of this threat against rigid composite armours, e.g. combat helmet [4, 5]. For testing purposes, the artillery flechette simulator defined in STANAG 2920 [6, 7] was selected to conduct the proposed armour performance assessment. This flechettte simulator does not have the typical fins used for flight stabilization since the target is positioned close to the launcher.

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. Although, it is understood that it will not be possible to match both kinetic energy and momentum of the original threat with this approach. A first test series was conducted using the traditional ballistic test method described in the STANAG 2920 standard [7] but with using the foam backing material of the stab test procedure. A second test series 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. The resulting method for this testing was to use an NIJ-style drop mass with the test method described in the STANAG 2920 standard [7].

Armour samples were positioned on the same backing material as that used in the stab testing. The Polyart™ witness paper was used to indicate any perforation. The test sequence for the drop mass method was based on the V_{50} procedure described in STANAG 2920 [7]. However, for testing with a drop apparatus it was found to be more appropriate to use the height, or H_{50}, to define the outcome of each test. The H_{50} 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. The velocity V_{50} corresponding to the drop height H_{50} can be calculated using the work-energy relationship ($v = \sqrt{2gh}$).

Ballistic Resistance

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 fragment threats as they cover the range of mass and shape from modern ammunition. The basic characteristics of the selected fragment threats are presented in TABLE 1.

Two 9 x 19 mm projectiles were chosen to represent both typical and emergent handgun threats, i.e. the FMJ Ball round [9] and the HP Bofors. The later has a lead core and a gilding metal clad steel jacket that is much thicker at the bullet nose, thus providing high penetration capability. The muzzle velocity of this bullet corresponds to 420 m/s.

Ballistic limits for the FSP and the sphere were determined using the V_{50} procedure described in STANAG 2920 [7] under dry conditions with composite foam backing. 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.

Nine mm bullets were tested according to the NIJ 0101.04 Standard [9]. 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).

RESULTS

Stab Resistance

Figure 1 summarizes the results of the stab testing with the samples ranked according to the areal density. Four of the armour samples passed the performance requirement of NIJ Level 2 stab testing. Armour sample No. 1 and 8 failed completely while armour No. 7 passed only the spike requirement. Armour sample 9 passed the S1 knife and spike requirements at NIJ Level 2 but failed with the P1 knife.

Flechette Resistance

Flechette testing was not conducted with armour samples No. 1 and 8 because of their poor performance in stab testing. Four additional soft body armour materials (sample No. 10, 11, 12, and 13) were tested to provide more data points for characterizing the relationship between both methods. For the ballistic method, flechette resistance limit of all armour samples was found to be significantly lower than the minimum requirement (250 m/s). A relatively good correlation (R^2=0.86) was found between ballistic and drop mass test results (Figure 2), suggesting that flechette resistance could potentially be predicted using a drop mass system. However, it was not possible to defeat armour sample No. 7 and 9 with flechette simulators mounted on the drop mass. For armour sample No. 9, the flechette simulator bent and no penetration occurred. For armour sample No. 7, the backing material was compressed and the armour never showed any sign of penetration. Interestingly, these two armour samples include materials specifically designed to defeat spike threats. This may indicate that different penetration mechanisms exist between an impact at ballistic rate with a flechette (low mass, high velocity) and a drop mass impact (high mass, low velocity) for these types of materials.

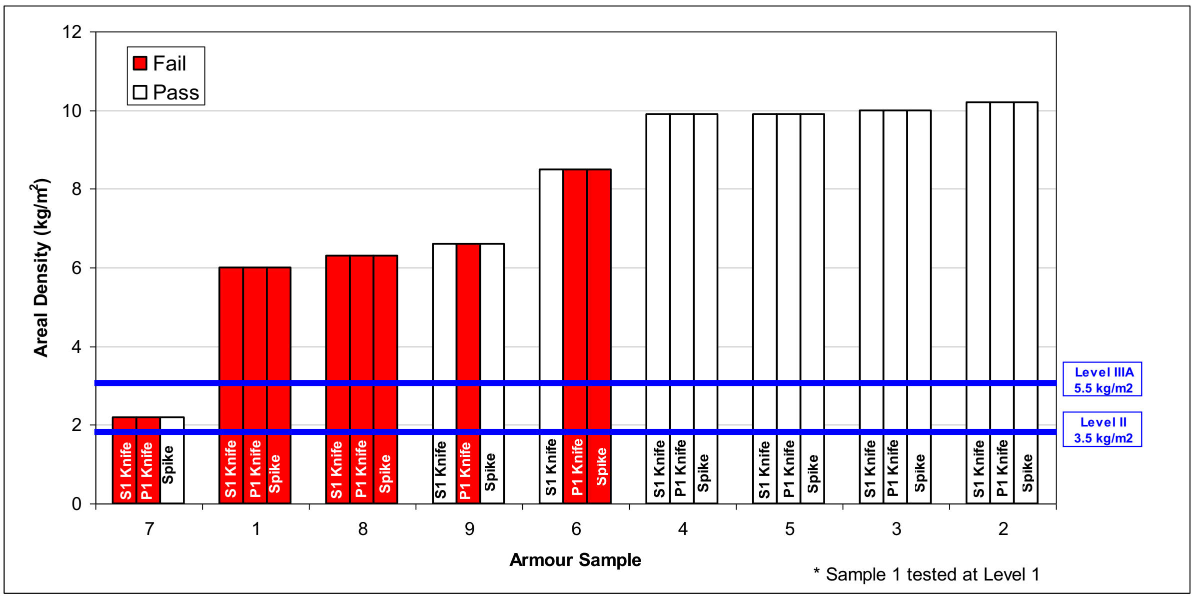

Figure 1. Results of stab testing (level 2).

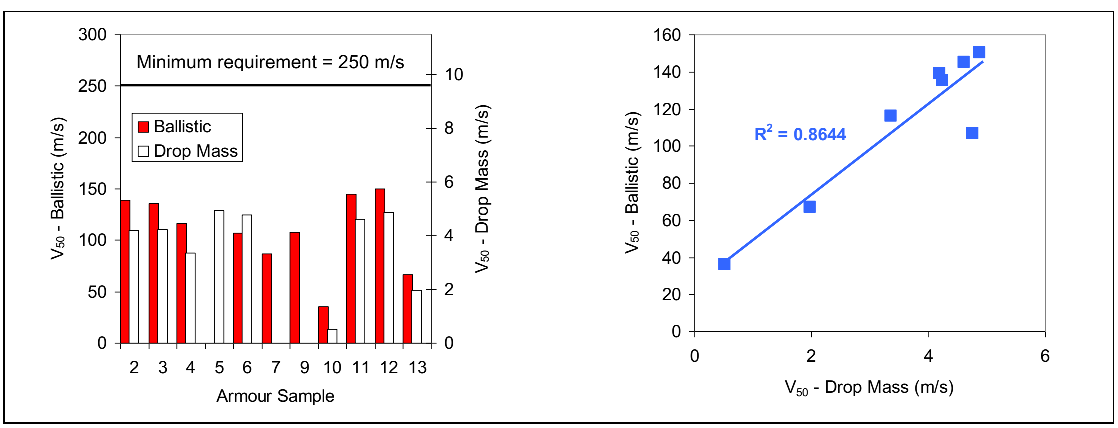

Figure 2. Flechette resistance values for ballistic and drop mass methods.

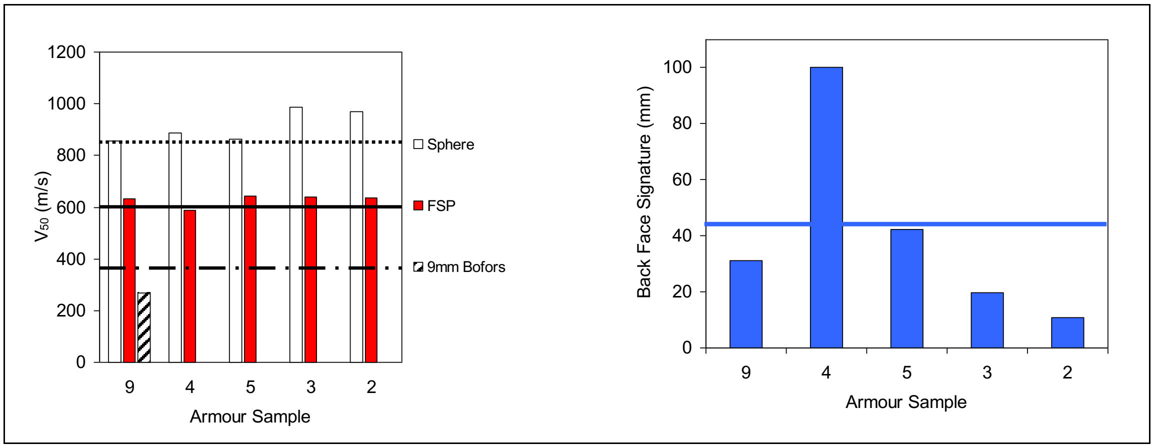

Figure 3. Ballistic test results.

Ballistic Resistance

To reduce the number of trials, only the armour samples that passed the stab tests for S1 and the spike threats were submitted for ballistic resistance testing. Figure 3 (right) summarizes the results of ballistic resistance testing.

The V_{50} values obtained with FSP were higher than the minimum requirements (i.e. 550 m/s) but lower than the desired performance (i.e. 750 m/s). Armour samples No. 9, 5, 3, and 2 showed similar performances (V_{50} = 626.6-650.7 m/s) whereas the ballistic limit of armour sample No. 4 was significantly lower (587.4-589.7 m/s).

Armour samples No. 2 and 3 presented sphere ballistic limits close to the desired 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.

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 V_{50} 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. If the results obtained with the FSP and the 9 mm FMJ are any guide, it is expected that the other armour samples will perform similarly against the 9 mm Bofors HP round. Thus, it is not expected that any test sample will meet the desired or the minimum performance requirement established initially for this threat, i.e. V_{proof} = 420 and 367 m/s, respectively.

Figure 3 (right) presents the results obtained with the 9 mm FMJ bullet against clay backing. Only armour sample No. 4 failed at NIJ level III A. It passed, however, at NIJ level II. Marginal results were obtained for armour sample No. 5 since the backface deformation measured corresponded to the 44 mm pass/fail for two of the three shots.

DISCUSSION

As expected, the stab resistance performance generally increases with the areal density of the sample, Figure 1. That trend was also observed when considering flechette and ballistic threats. Materials with areal density equal or greater than 9.9 kg/m^2 were found to meet the 3 stab threat requirements. Samples who failed at NIJ Level 2 should be retested to assess if they will meet the necessary requirements (Level 1). While flechette resistance was found to be much lower than targeted performance, results of experimental trials were used to establish a correlation between the typical ballistic method and a proposed drop mass procedure. Data analysis suggests that a preliminary assessment of performance can be achieved with the simpler drop mass approach. Thus, materials with poor flechette resistance characteristics can be discarded initially before conducting the final assessment with the ballistic method. Further work should consider reducing the weight of the drop mass and increasing the velocity. Modifications to the flechette simulator (e.g. high strength steel, larger diameter at the base) can also be explored to reduce the risk of buckling.

To facilitate comparison between test samples, flechette and ballistic limit results were normalized to the areal density of the samples as illustrated in Figure 4. Interestingly, armour sample No. 9 (AD=6.6 kg/m^2) offers better flechette and ballistic performance per unit of weight in comparison with the other options. It should be noted, however that this sample did not meet the desired requirement for the knife P1 stab threat.

Increased ballistic protection would be necessary for all armour samples to meet the desired performance requirements established initially (TABLE 1). 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.

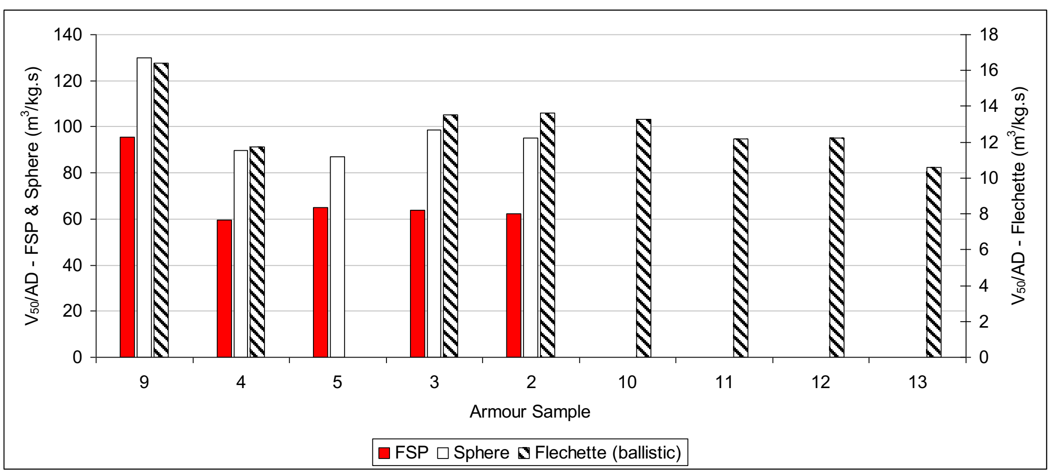

Figure 4: Performance rating of armour samples for flechette and ballistic threats.

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 and the flechette, it is not expected that a non-rigid solution weighing less than 10 kg/m^2 can be achieved. Complete body armour made with such material will have a mass of approximately 10 kg which is considered excessive. In addition, the lack of flexibility will reduce significantly its practicability. Further investigation shall be conducted to consider zones with different protection levels (e.g. front, back, sides) for maintaining the total weight within 20% of a typical armour rated NIJ Level IIIA while meeting all the necessary protection requirements defined earlier.

Analysis of flechette test results indicates that a correlation exists between the ballistic and the drop mass test methods. The latter may be used initially as a ranking tool to identify materials with better performance characteristics to defeat flechettes.

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