Force Plate and Witness Material Measurement of Behind Armour Impact Forces for Different Armour Classes

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Abstract. Initial results from experimental and analytical methods for assessing ballistic performance of three classes of armour (i.e. aramid shootpacks, ultra-high molecular weight polyethylene (UHMWPE) plates, and a multi-layered ceramic plate system) showed different forces and pressure distributions behind the armour when challenged with a matched threat. Experimental methods using a force plate and witness materials provide different perspectives of the behind armour forces than residual clay deformation alone provides. Impact plate measurements behind armour showed differences in force-time response between the different armour classes and pad thicknesses. Testing with aluminium honeycomb and tin witness materials show that residual deformations behind a shootpack were deeper and narrower than those observed behind UHMWPE and ceramic plates. These results suggest that different experimental methods and metrics used to assess armour performance may result in different criteria depending on the armour class. These results have application to developing new metrics for measuring behind armour forces that predict the potential for injury.

1. INTRODUCTION/BACKGROUND

Behind Armour Blunt Trauma (BABT) test standards have used a clay standard for decades to evaluate the potential for injury behind armour from non-penetrating projectile impacts. Initially established [1],[2],[3] for relatively low velocity (243-400 m/s), .22-.45 calibre projectiles against 7- to 12- layer woven fibre fabric armour, the clay test method has been applied to a range of projectiles ranging from 9 x 19mm NATO FMJ at 434 m/s against 22-layer Kevlar woven fibre fabric armour to NIJ Level IV projectiles at 878 m/s against a 3-layer armour system of ceramic plates, ultra-high molecular weight polyethylene (UHMWPE) fibre composite plates and Kevlar woven fabric armour.

Analysis of test results show that clay results do not necessarily parallel results gathered using other armour test methods, such as force plates or other witness materials. The development of new behind armour acceptance criteria for armour requires an understanding of how the impact force and energy are related to injury so that criteria can be developed that span numerous armour and threat combinations. Force plate and witness material responses for different classes of armour (with matching threat) are compared with previously collected clay and pressure-sensitive Fujifilm Prescale® results [4],[5]. In PASS 2014 [4], Fujifilm Prescale® was placed between armour and the clay block and the resulting pressure pattern on the Fujifilm was measured. In PASS 2018[5], the energy needed to deform clay was measured using air-cannon launched impact cones. The force plate yields information on the forces behind armour, which may be compared to the Fujifilm Prescale®, while the witness plate provides insight into the impact energy and its distribution that may be compared to clay deformation.

Different methods of behind armour impact force measurement have varying advantages and disadvantages. A force plate may have traceability of its measurement back to international standards [6], but lacks the mechanical impedance and deformation characteristics of the human body. By combining the measurement of deformation depth with the known material deformation response to impact, witness materials offer a direct measurement of the impact energy and its absorption distribution behind armour. However, while some materials have less strain hardening than others, no highly deformable, elastic/plastic materials were identified whose yielding behaviour is insensitive to strain rate. Clay has elastic/plastic/viscous behaviour and its deformation has been shown to be velocity dependent and its mechanical properties vary over time [7]. Fujifilm Prescale® is easy to use and measure, but has been shown to stretch and tear behind armour and to be strain-rate dependent [4].

2. EXPERIMENTAL METHODS

2.1 Threat-Armour Combinations Tested

Testing was conducted used three threat-armour combinations: 1) 9x19 mm FMJ NATO against an aramid Kevlar shootpack with an areal density of 5.3 kg/m^2, 2) 7.62x39 mm lead core against an

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UHMWPE panel with an areal density of 9.8 kg/m^2, and 3) .30 calibre APM2 against a combination of Silicon Carbide (SiC) faced and UHMWPE-backed hard armour plate and aramid shootpack (SiC/shootpack) with a combined areal density of 29 kg/m^2. Each configuration was tested at two different velocity levels, the first being close to the estimated perforation velocity for that configuration, and the second being 65-80% of the V0 velocity, which corresponded to 46-65% of the perforation velocity kinetic energy.

2.2 Force Plate Design

To provide a measurement of spatial distribution of forces, the force plate design has a two-part configuration with a circular centre impact cap surrounded by a ring impact cap with an outer diameter of 152 mm. Centre impact cap diameters of 7.6 mm, 15 mm, 30 mm, and 61 mm were selected for testing. The force on the centre impact cap was measured by a single load cell while the outer ring impact cap force was measured by summing the four load cells that supported it. The five PCB 200C20 piezoelectric load cells were mounted onto a 19 mm thick stainless steel plate, and arranged as depicted in Figure 1. Data from the load cells was collected at 1 x 10^6 samples/s during impact and filtered to 50 kHz based on frequency content of signal and noise using a digital, 20-pole low pass filter. This configuration allowed measurement of the force-time distribution behind an impact as well as the force distribution.

(a) (b) (c)

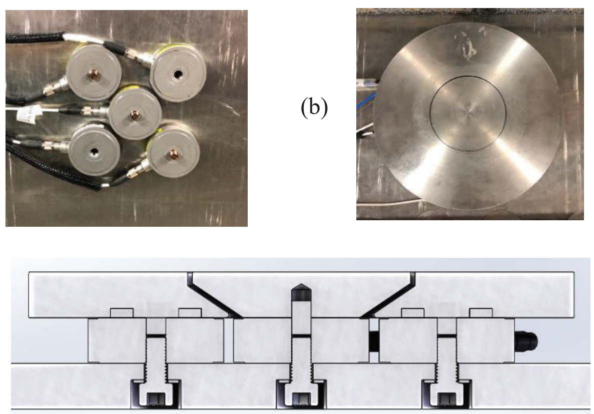

Figure 1. Force plate configuration: (a) with 5 load cells, (b) ring cap with 61 mm centre cap, (c) section view of force plate. Other impact cap diameters tested were: 7.6 mm, 15 mm, and 30 mm

Located between the back face of the armour and force plate impact caps was a sheet of neoprene (Shore-A 40 durometer), either 6 or 12.7 mm thick. The intent of adding the neoprene layer is to allow the armour to deform and to reduce the peak impact forces of the bullet.

Testing was conducted using the 3 bullet armour combinations at two impact velocities against the 4 centre caps. For the higher velocity tests, two pad thicknesses were tested.

2.3 Witness Material and Deformation Testing

An ideal witness material would have neither strain rate sensitivity nor strain hardening. Two witness materials, pure tin and an aluminium honeycomb, were selected for evaluation and testing because published data ([8] and [9]) suggested both materials exhibited elastic-plastic behaviour with little strain hardening.

2.3.1 Aluminium Honeycomb

TrussGrid (Gill Corporation) is a honeycomb-type material that was identified as a potentially suitable material for ballistic impact testing. TrussGrid is a three-dimensional aluminium honeycomb made of cross-laminated aluminium foil corrugations. Its deformation force is isotropic and uniform for 75% of the deformation range. Blocks (15x15x10 cm) with a density of 86 kg/m^3 and a crush resistance of 2.76 MPa were used for characterization and testing.

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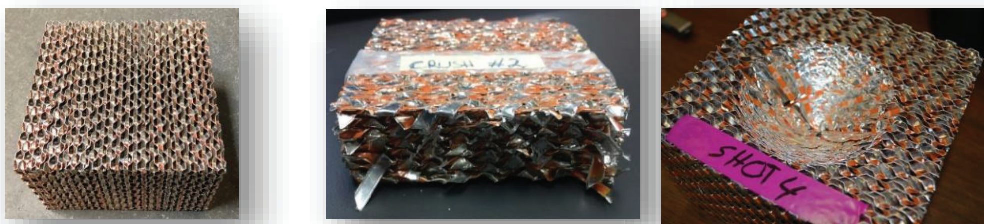
Three sets of tests were conducted to characterize the deformation resistance of TrussGrid. (1) compression between two flat plates on a mechanical test machine (at 2.5 mm/s) that measured deformation force and energy, (2) driving a wedge-shaped cone with either a 0.3, 0.6 or 0.9 aspect ratio into the TrussGrid at a cross-head speed of 2.5 mm/s on a mechanical test machine that measured deformation force and energy, (3) launching the same cones into the TrussGrid using an air cannon at 19-45 m/s, where a high speed camera and accelerometer measured dynamic displacement and kinematics, while later a 3 dimensional laser scanner measured residual deformation. In this fashion, the amount of force and energy needed to deform the TrussGrid could be measured across a range of velocities and indenter shapes.

The blocks used in ballistic testing were mounted on the force plate (30 mm impact cap) with double-stick tape so that the forces behind the blocks could be measured. The 3 different types of armour were mounted in front and impacted with a matching threat round at two velocities. With 3 tests at each velocity, 18 tests were conducted.



(a) (b) (c)

Figure 2. TrussGrid as-received (a), after deforming between two flat platens (b), and after air-cannon testing (c)

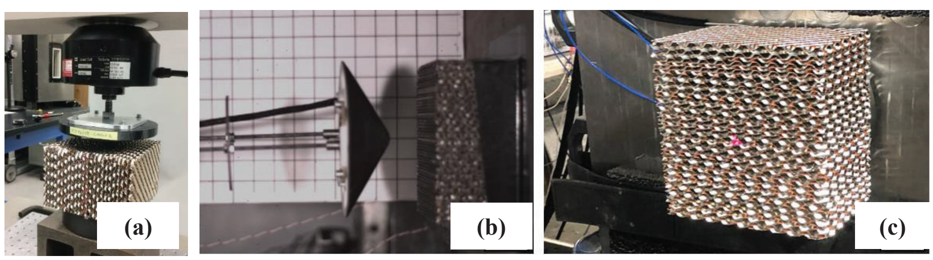


Figure 3. TrussGrid testing configurations during mechanical (a) and air cannon (b) testing and before ballistic (c) testing

2.3.2 Tin Ingot

The tin ingots used were fabricated by melting and casting pure tin pellets (99.9% pure, Rotometals inc.) into slowly cooled ingots approximately 25x76x230 mm in size. Mechancial testing was conducted using spherical indentors (32 mm and 38 mm diameter hardened steel balls) that were pressed into its surface using a mechanical test machine. The tin was loaded in a step-wise manner, measuring the increase in deformation diameter with each increase in load after the indenter was removed for each measurement.

Ballistic testing was conducted on 4 tin blocks. The tin was machined from the cast ingots into 75x75x19 mm blocks and mounted on the force plate with only the 30 mm impact cap. The three bullet-armour combinations were tested at the higher velocity and the 9 mm/shootpack combination was tested at both velocities.

2.4 Range Methods

The ballistic test velocity varied depending on the bullet and armour with the maximum velocity selected to prevent complete perforation of the armour. The bullet velocity was varied by adjusting the powder

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loaded in the cartridge. Each shootpack received up to 9 shots while the composite panels received up to 5 shots each. Each ceramic plate was shot only once. The impact velocity was calculated based on velocity measurements made by two sets of velocity screens placed between the barrel and the armour and the distance to the target.

2.5 Post-Processing of Witness Plate Materials

The witness materials were scanned after each air cannon and ballistic test using a ROMER Absolute Laser Scanning Arm 3-D scanner. The scanner creates an array of 3-D coordinates of the surface under investigation which forms a point cloud. The point cloud was transformed into a surface using Geomagic Wrap & Geomagic Control software so that the deformation depth, diameter and displaced volume could be measured.

3.0 RESULTS

3.1 Force Plate Testing

Force-time measurements were recorded during the impact from the 5 load cells to determine the centre and outer ring forces. Example forces are shown below for the 9 mm threat impacting the shootpack at 434 m/s with 13 mm neoprene backing material (Figure 4).

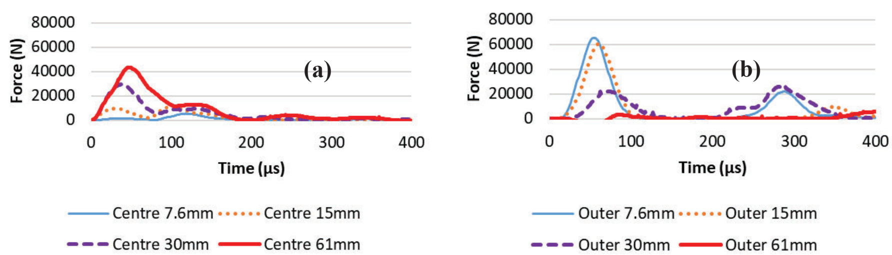

Figure 4. Centre (a) and outer (b) ring forces measured for 9 mm bullet at 434 m/s into a shootpack backed with a 13 mm neoprene pad

Impact forces were measured with time on the centre and outer rings. The outer ring force response occurs later than the centre ring response (Figure 5). Because the peak force in the centre occurred at a different time than outer peak force, the sum of peak forces (i.e. the sum of the 5 load cell measurements at the same time) is not equal to the sum of the centre and outer peak forces. Nearly all of the impact forces fall within the 61 mm cap. Unexpectedly, for many of the tests, the second peak force for the centre cap was greater than the first peak – in 8 out of 9 test conditions with the 7.6 mm cap and in 2 out of 9 conditions for the 15 mm cap. The only test condition where the first peak force was greater than the second for all tests was for the 9 mm bullet at 434 m/s (nominal) into a shootpack backed with a 6.4 mm neoprene pad.

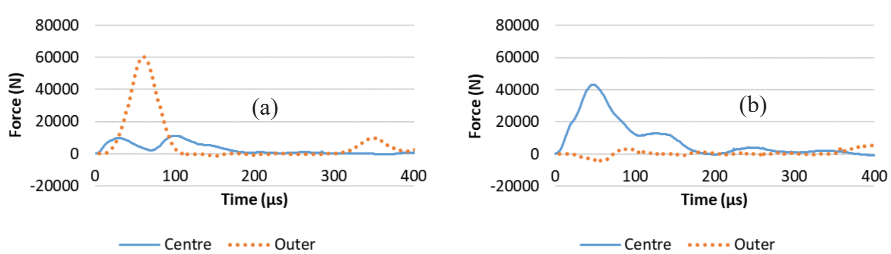

Figure 5. Centre and outer ring forces measured for 9 mm bullet at 434 m/s (nominal) into a shootpack backed with a 13 mm neoprene pad for (a) 15 mm and (b) 61 mm cap results

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For the 9 mm threat impacting a shootpack, impact forces range from 4-13 kN for the smallest cap and 30-70 kN for the largest cap (Figure 6). The diameter where the forces are 50% of the maximum forces is estimated to be 19-23 mm. The scatter of data at the smallest cap size for the 9 mm threat may be expected since the cap is smaller than the bullet diameter and the nominal range tolerance on impact location is +/- 5 mm.

Reducing the pad thickness had a much greater effect on the impact forces than a decrease in impact kinetic energy. The double peak phenomena observed for the 7.6 and 15 mm caps nearly disappears for the thinner neoprene pad. This suggests that the thickness of the pad affects the double peak.

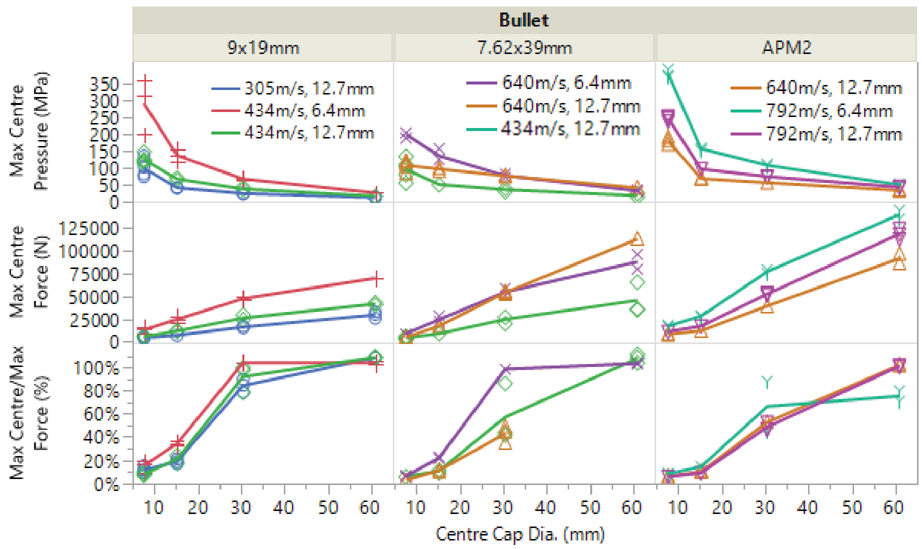

Figure 6. Force measurements for the armours and matched threats tested with various impact velocities and backing material thicknesses

The effect of the centre cap size is shown in Figure 6. While the forces on the 7.6 mm cap are relatively small, the maximum pressure (peak force divided by area of impact cap) is quite high, ranging from 106-245 MPa. Pressure drops off by about half with each doubling of diameter. The sample sizes at each test condition were limited - 1 to 3 shots.

3.2 Witness Material Testing Results

3.2.1 Aluminium Honeycomb Witness Material Results

Flat plate compression testing of three 7.5x7.5x10 cm aluminium honeycomb blocks on the square face at 2.5 mm/s showed the material, on average, deformed at 3.01 MPa, about 10% above the 2.75 MPa specified by the manufacturer. An average deforming energy of 3.01 J/cm^3 was measured in flat compression.

Mechanical testing pressing cone-shaped indenters into the square face of 15x15x10 cm aluminium honeycomb blocks at 2.5 mm/s resulted in deformation at 3.37, 3.50 and 2.90 MPa for the 0.3, 0.6, and 0.9 pitch cones respectively. Because of the elastic springback of the TrussGrid, the final pitch differed from the pitch of the cone indenter. For the 0.3 cone the final pitch was 0.29. For the 0.6 cone the final pitch was 0.55. For the 0.9 cone the final pitch was 0.79.

Overall, the deformation pressure of the cones was 3.31MPa (and a corresponding 3.31 J/cm^3 deformation energy), about 10% higher than seen in flat platen compression testing.

Air cannon testing results using cones are shown below in Table 1. The calculated deformation pressure (using the filtered peak force divided by the deformation area) was similar to that found on the mechanical test machine, with an average of 3.23 MPa. However, the energy density of the deformed area is greater than that measured in the mechanical test, potentially due to alternative damage mechanisms such as splitting of the block. Visual observation of the honeycomb blocks after testing revealed that the blocks had split along bonded layers of the honeycomb structure during impact testing.

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This potentially created an alternative elastic deformation mechanism for storing energy in the block which could have increased the apparent energy storage density.

Ballistic testing of armour backed by the TrussGrid aluminium honeycomb was conducted, and the results are shown in the Table 2. Ballistic testing revealed similar splitting of the aluminium honeycomb observed in air-cannon testing. Both the shootpack and the UHMWPE had a conical deformation shape, while the ceramic plate/shootpack armour had a more semi-hemispherical deformation shape (Figure 7). The deformation pressure tended to increase with increasing pitch and was approximately twice the quasi-static and air cannon values. Assuming that the deformation pressure (calculated from the peak load cell force divided by deformation area) is equal to the volumetric deformation energy (in J/cm^3), it allows a lower threshold estimation of the energy to deform the aluminium honeycomb material.

Table 1. TrussGrid aluminium honeycomb data collected during air cannon testing

Test ID	Cone Pitch	Impact Velocity (m/s)	Impact Kinetic Energy (J)	Peak Force (N)	Dent Diameter (mm)	Dent Depth (mm)	Dent Pitch	Total Volume Displaced (mm^3)	Deformation Pressure (MPa)	Energy Density (J/cm^3)
AC2_053	0.6	18.6	96.5	8202.7	56.7	13.8	0.49	11057	3.25	8.73
AC2_054	0.6	27.8	216	14249	77.2	19.0	0.49	32712	3.04	6.59
AC2_055	0.6	39.2	429	22496	91.7	23.7	0.52	45295	3.41	9.47

Table 2. Data from ballistic testing against TrussGrid aluminium honeycomb

Target Material	Threat	N	Avg. Velocity (m/s)	Avg. Depth (mm)	Avg. Diameter (mm)	Avg. Pitch	Avg. Volume Displaced (mm^3)	Avg. Impact Peak Force (N)	Avg. Deformation Pressure (MPa)	Avg. Total Deformation Energy (J)
Shootpack	9mm	3	309	21.6	60.2	0.72	21549	18969	6.84	146
Shootpack	9mm	3	437	33.6	64	1.05	35327	26041	8.20	288
UHMWPE	7.62x39	3	431	11.6	94.2	0.25	29421	35907	5.15	152
UHMWPE	7.62x39	3	642	21	97.2	0.43	59402	46616	5.23	321
SiC/ Shootpack	APM2	3	642	20.3	86.1	0.47	48066	32680	5.66	271
SiC/ Shootpack	APM2	3	806	29	88.8	0.65	79019	41198	6.67	527

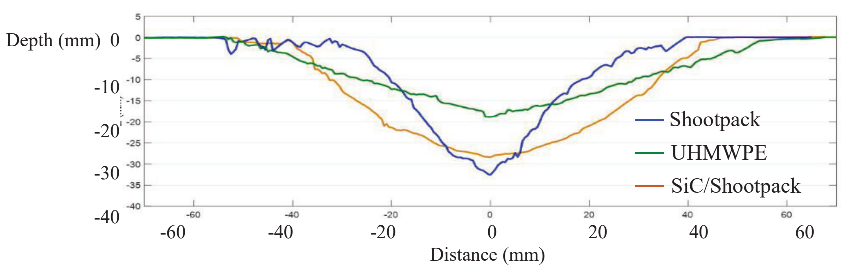

Figure 7. Comparison of TrussGrid cross-section profiles from ballistic testing at the higher velocity

3.2.2 Tin Ingot Witness Material Results

Mechanical compression testing with a 32 mm and 38 mm diameter ball was conducted on tin. The yield strength was measured to be about 42 MPa for both indentors, and the energy density of deformation was 42 J/cm^3.

The results from ballistic testing on tin are shown in Table 3. The peak force per unit area is far greater than the quasi-static results. The deformation energy is far less than measured using TrussGrid. A cross-sectional view of the tin deformation is shown in Figure 8. While the sample size was one test in each condition, the results show differences in responses.

Table 3. Ballistic test results on tin

Target Material	Threat	Velocity (m/s)	Depth (mm)	Diameter (mm)	Pitch	Volume Displaced (mm^3)	Impact Peak Force (N)	Peak Force/Area (MPa)	Total Deformation Energy (J)
Shootpack	9mm	306	2.41	19.5	0.25	364	34402	115.2	41.9

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Shootpack	9mm	425	5.10	22.0	0.46	954	42066	110.7	105.6
UHMWPE	7.62x39	641	4.73	37.8	0.25	1739	81580	72.9	126.8
SiC/Shootpack	APM2	800	3.31	39.25	0.17	1907	107870	89.1	170.0

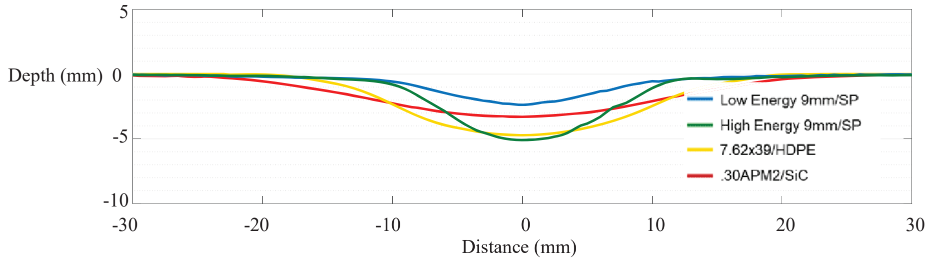

Figure 8. Cross-section of tin deformation from ballistic testing of armour

4.0 DISCUSSION

4.1 Peak Forces Behind Armour

The dynamic peak forces measured behind armour in ballistic testing using the force plate had a number of interesting trends. The centre and outer forces frequently had double and triple peaks visible in the trace. For the smallest impact caps, the second peak in time usually had a greater force than the initial peak. The outer first peak occurred noticeably later than the centre. The thicker pad produced peak forces that were less than the thinner pad. The small sample sizes show a number of trends, but limit the ability to quantify the measurement error.

For the three armour classes, at least 50% of the force falls less than 32 mm diameter centre area, with the remainder falling usually within a 61 mm diameter area. This distribution of forces may have implications in the development of force-based criteria for evaluating armour performance and predicting behind armour injury.

Three measurements, peak force, total force and deformation energy can be compared with data collected and presented at PASS 2014 [4] and PASS 2018 [5]. A model was created using the PASS 2018 data and applied to the clay deformations measured in the PASS 2014 results.

The same bullet and armour configurations for the shootpack (5.3 kg/m^2 Areal Density (AD)) and SiC/Shootpack (29 kg/m^2 AD) were used in these studies, while the UHMWPE was thicker (13.6-16.6 kg/m^2 vs. 9.8 kg/m^2 AD) in the PASS 2014 testing (Table 4). The nominal impact velocities and data fits were used to determine the Fujifilm Prescale® measurements, as well as estimates of the clay deformation. The clay energy calculations developed in PASS 2018 are compared with the TrussGrid and tin energy estimates.

Table 4. Velocities used in analysis

Measurement Method	7.62x39mm		9x19mm		APM2	
	LTM Velocity (m/s)	Muzzle Velocity (m/s)	LTM Velocity (m/s)	Muzzle Velocity (m/s)	LTM Velocity (m/s)	Muzzle Velocity (m/s)
Force Plate - 7.6 Cap, 13 mm pad	426	642	307	438	640	791
Force Plate - 7.6 Cap, 6 mm pad	NT	644	NT	439	NT	800
TrussGrid Force Plate	431	642	309	437	642	806
Tin Force Plate	NT	641	306	425	NT	800
Fujifilm Prescale & Clay	434	640	305	434	640	805

LTM – Less than Muzzle, NT – Not Tested

Peak impact pressure can be compared between the Fujifilm Prescale® and the force plate with the 7.6 mm cap and the 6 and 13 mm pads (Figure 9). In comparing them, the peak pressures follow a consistent pattern with the thickest pad (13 mm) producing the lowest peak forces and pressures while the Fujifilm Prescale®, placed directly behind the armour, produced the highest peak pressures ranging from 645-592 MPa. It is important to note that the force plate pressure was based on the average pressure over the 7.6 mm cap, whereas the Fujifilm pressure was measured at a higher spatial resolution.

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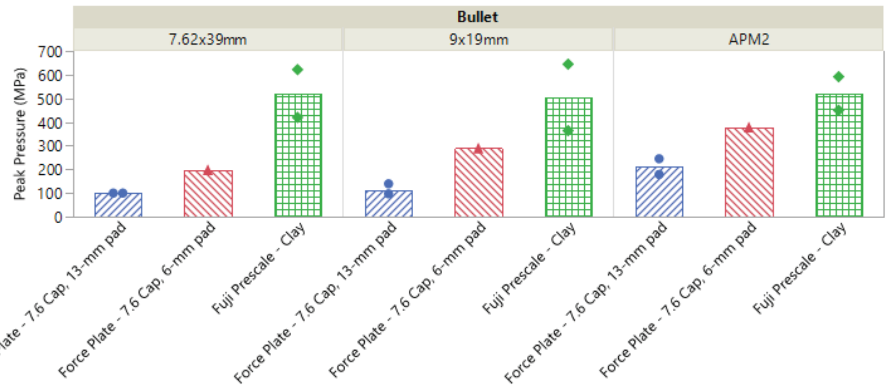

Figure 9. Peak pressure measurements from the force plate and Fujifilm Prescale® for muzzle velocity tests

The peak total force between the Fujifilm Prescale®, and force plate behind the pads and witness materials can also be compared (Figure 10). The Fujifilm Prescale®, tin and the TrussGrid underreports total force because they have a lower limit on the forces they measure. The lower limit on Fujifilm Prescale®, TrussGrid, and tin are 50 MPa [10], ~ 3 MPa and 42 MPa, respectively. The pads and witness materials are mounted on a rigid, heavy force plate that may affect the measurements, while the Fujifilm Prescale® measurements were made over clay that would resist the impacting force less. The force plate with the 6 and 13 mm pads measured the highest forces, much higher than the forces measured behind the witness plate materials and by the Fujifilm Prescale®.

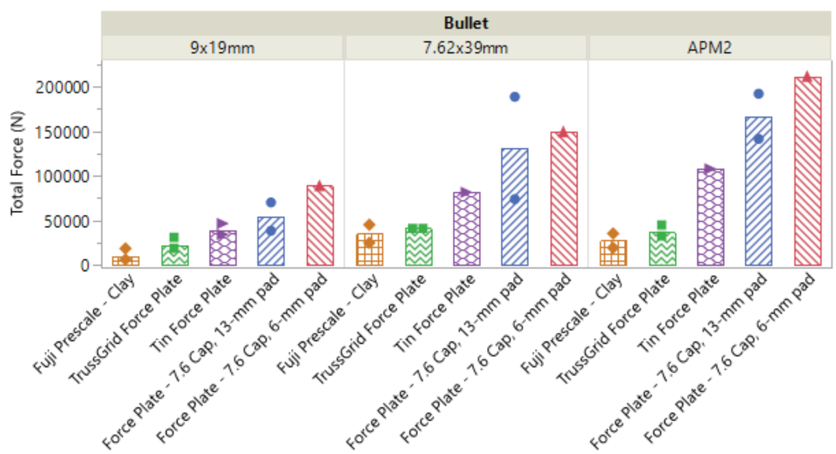

Figure 10. Peak total forces measured behind armour using a force plate, Fujifilm Prescale® and witness materials at muzzle velocity

4.2 Impact Energy

One advantage of witness materials are their ability to record the peak and distribution of energy behind the armour from the impact of the bullet. If the force displacement relationship is known, then the distribution of deformation is a direct mapping of the deformation energy distribution. However in testing armour, this deformation allows the armour to absorb more of the impact, changing the spatial-depth response of the witness plate material. The most realistic witness material response should be one that duplicates the response of human tissue at the location of impact. A stiffer material will support the armour more, result in less amour deformation and have higher forces at the interface.

The witness plate and clay measurement data provides insight into the amount and distribution of the impact energy. The maximum deformation reflects the region with the greatest energy dissipated, found in the centre of the impact. The total volume reflects the total energy while the volume/cross-

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sectional area ratio reflects the areal energy density or kinetic energy density. If the force-deformation response did not vary with depth and velocity, the correspondence of depth with impact energy would be a simple linear relationship, but any strain-rate, strain-hardening or flow effects affects this relationship.

In this preliminary study, the sample sizes were small, making measurement of the experimental errors difficult. Quantification of the witness plate deformation energy at relevant strain rates and shapes is difficult and introduces another source of error. The measurements presented show interesting trends and highlight the challenges of using witness materials in testing and quantification of the deformation energy.

The clay deformation data collected behind the Fujifilm Prescale [4] was processed using the energy estimation methods described in [5] to estimate the energy deposited into the clay. In Figure 11, the clay energy is compared with the energy estimates for tin and TrussGrid. The energy calculated from the clay deformation is much greater than estimated from the tin and TrussGrid. There are several potential causes of this difference including the difference between deforming behaviour of the clay, tin and TrussGrid. By dividing the deformation energy by the area of deforming contact, the kinetic energy density of the impact can be compared. This comparison shows that the kinetic energy density measured by the TrussGrid and the clay behind the Fujifilm were more similar than the kinetic energy density measured behind tin. Potential reasons for this difference include the differences in yielding and backing material (clay, tin and TrussGrid) between the tests.

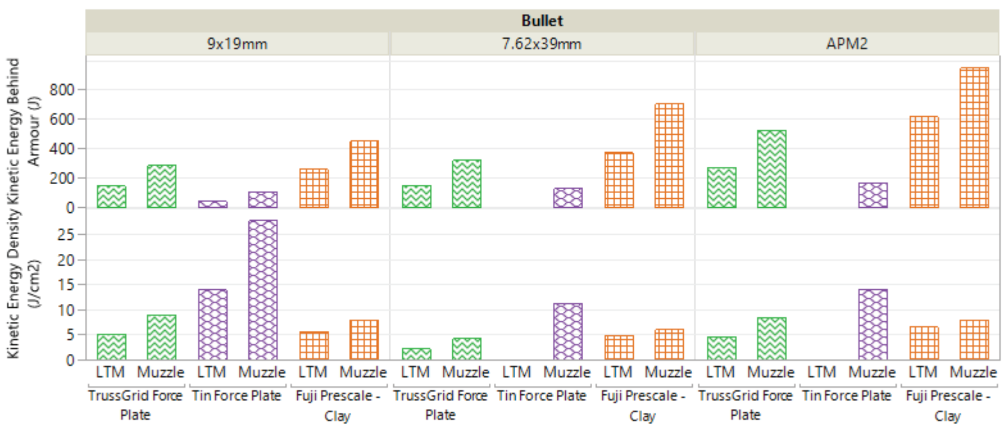

Figure 11. Behind armour total energy and kinetic energy density calculated from the clay deformation behind the Fujifilm and witness material deformation for muzzle and less-than-muzzle (LTM) impacts

5.0 SUMMARY AND FUTURE WORK

The residual impact forces, energies and their distribution behind armour were measured using force plates, Fujifilm Prescale®, and witness materials (clay, TrussGrid and tin). These measurements provide insight into the impact forces, force distribution and energy magnitudes, as well as the difficulty in quantifying these values. Because of the large deformation and complex interaction between the bullet, armour and backing material, these measurements reflect the experimental conditions tested and the limited sample sizes for each test condition. They do not provide a universal measurement of the event.

The peak pressure, total force, and total deformation energy results showed a wide range of measurements depending on the test method and bullet/armour/velocity combination. The peak pressures range from 100 MPa to 645 MPa which were measured on the shootpack while the composite and SiC/Shootpack armour combinations showed a smaller range of peak pressures. The total force measured ranged from 14.4 kN to 221 kN depending on the measurement method and bullet/armour tested. The total deformation energy ranged from 42 J to 952 J depending on the test conditions.

Future work needs to be conducted with post-mortem human tissue and matching force plate and Fujifilm testing so that these results can be grounded by understanding the potential for injury.

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