Effect of Backing on Residual Armour Deformation

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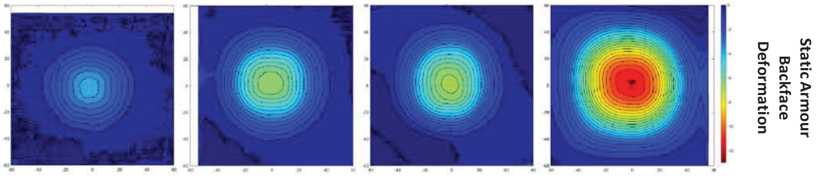
Abstract. A key challenge in transitioning from a clay to force-based measurement of armour backface forces is identifying a suitable pad material to place between the armour and rigid force plate that allows for meaningful force measurements and for armour to deform as it would when coupled with a clay backing. This study focuses on comparing the residual deformation of ceramic armour when tested with a clay versus pad backing material, and on the effects of pad material and thickness on spatial distribution of forces. APM2 (.30 calibre) projectiles impacted both flat and curved ceramic armour plates backed with soft armour. The armour was tested on clay, as a baseline, and on a custom force plate fixture that measured the impact forces in two zones: at the centre (< 30 mm diameter) and outer (approximately 30-150 mm ring) regions. A polymeric pad was placed between the armour and force plate to dampen the force and allow the armour to deform. A wide variety of pad materials and thicknesses were evaluated. The mechanical properties of the pads were characterized using Dynamic Mechanical Analysis, allowing estimation of the strain rate effects on the material's storage modulus using time-temperature superposition. The depth, diameter and volume of residual armour deformation was measured for each impact. Test results showed that pad material and thickness has a significant effect on the residual armour deformation and peak forces measured. The pad material and thickness also affected the force distribution between the centre and outer regions. The flat tiles and curved ceramic plates produced different force and back face deformation measurements.

1. INTRODUCTION/BACKGROUND

Body armour ballistic test standards have been using clay to measure backface deformation as way to estimate the potential for Behind Armour Blunt Trauma (BABT) injury [1]. First established for testing soft armour against lower-velocity, handgun projectiles, the test method and acceptance criteria have been applied to thicker woven fibre, composite and ceramic armour impacted with heavier, higher-velocity projectiles, as well as armour piercing projectiles [2]. Variation of clay properties over the decades and the inherent instability of clay's mechanical properties [3] are a couple of factors motivating a consideration of transition from a clay standard to one that measures forces.

The focus of this study is identifying a suitable pad material to place in between ceramic armour system (including multilayer fabric backing, i.e. shootpack) and the force plate that allows armour to deform as it does on clay while also allowing for meaningful force measurements. For this series of tests, armour deformation was characterized by the maximum residual deformation depth, diameter and volume. Testing armour with different backing materials, including pads and clay, can produce a range of armour deformations (Figure 1). The goal of this project was to identify a pad material mounted on a force plate that permits the armour deformation, i.e. the depth, diameter and general shape, to match that for a ceramic tile/shootpack armour backed with clay when impacted with a .30 calibre APM2 at the rated velocity. If a similar armour deformation is achieved when backed with either clay or a pad, the force transmission is likely to be more similar than if the armour deformation is different.



(a) (b) (c) (d)

Figure 1. Contour plot of armour deformation after ballistic impact with different backing materials: (a) high durometer neoprene, (b) Roma Plastilina Clay No. 1, (c) 30A durometer neoprene, (d) soft HD60 foam

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2. EXPERIMENTAL METHOD

Ballistic testing was conducted on flat tile plates and curved, torso plates. Test series 1-3 assessed the behaviour of flat tile plates, while test series 4-6 evaluated the curved plates. For each series of tests, armour was first tested with a clay backing in accordance with NIJ test protocols to provide reference armour curvature to compare with the pad results [2]. The armour was then tested with various pad backing materials using a custom force plate test system, described below. The armour was impacted with .30 calibre APM2 projectiles at 853 (-0, +15) m/s in the centre of the flat tile and on the plate crown for the curved armour. Lessons learned from prior test series informed the materials selection and test matrix for each subsequent test series. In general, earlier test series had a lower sample size as the goal was to screen a large number of material combinations in order to choose the best performing pads for later test series. Details of the armour, impact measurement and pad materials follow.

2.1 Armour Tested

The flat tile plates were fabricated using St. Gobain SiC tiles (8.9 mm x 102 mm x 102 mm) mounted on 152 mm x 152 mm Dyneema HB80 ultrahigh molecular weight polyethylene (UHMWPE) panels. Flat tile plate armour areal density (without cover) was 41.5 kg/m^2. The shootpack tested was Kevlar KM2, 600 denier plain weave, 86 cm x 86 cm (end/picks), 28 plies with an areal density of 5.3 kg/m^2. The curved torso plates were previously fielded ceramic-faced armour provided by the US Army.

2.2 Pad Materials

Many combinations of materials and thicknesses were tested. The pad materials tested were selected for their mechanical properties and availability. For some tests, different thicknesses and layered combinations of pads were evaluated. Twenty-nine combinations were tested on flat plates, 11 combinations for curved plates. Each pad was impacted only once to ensure that the potential effect of damage was eliminated. Table 1 lists the armour and pad materials and thickness combinations tested in each test series.

2.3 Dynamic Mechanical Analyser Characterization

Since the pad mechanical properties were critical, the pads were tested using a dynamic mechanical analyser (DMA), TA instruments RSA G2, to measure the storage modulus, a measure of the elastic modulus. By making these measurements across a range of test frequencies and temperatures, the elastic properties at high strain rates, similar to those seen in ballistic testing, can be determined using time-temperature superposition. This measurement is important because the elastic properties of polymers measured at low strain rates may be considerably different if measured at high strain rates [4]. DMA measurements are made using small displacements and do not reflect the large amplitude behaviour seen in ballistic testing.

2.4 Clay Ballistic Testing

Clay ballistic testing was conducted following current NIJ-0101.06 methods to provide reference armour curvature to compare with the pad results [2]. The clay was preconditioned and drop-tested to insure its properties were within the range and mean limits. The armour was impacted with .30 calibre APM2 projectiles at 853 (-0, +15) m/s in the centre of the flat tile and on the plate crown for the curved armour. Each armour plate was impacted only once. For the flat tiles, the tiles and shootpack backing were placed against the flat surface. For the curved armour, a clay preform was used to assure contact of the clay and armour during testing. The clay was laser scanned before and after impact so that the depth, diameter and volume of the displaced clay could be measured.

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Pad Material and Thickness	Durometer (Shore #)	Part Number and Supplier	Number of Flat Plate Tests			Number of Curved Plate Tests		
			Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Evazote: 25 mm	50 (OO)	Evazote VA-35		2				
Evazote: 51 mm	50 (OO)	Evazote VA-35		2				1
Sil. Rub./Neop. layers: 6.3 mm/38 mm	60(A)/30 (A)	Home Depot/Warco Biltrite	1					
Sil. Rub./Neop. layers: 13 mm/38 mm	30 (A)	Home Depot/Warco Biltrite	1					
HD30: 51 mm	72 (OO)	Plastazote HD-30		1				
HD60: 32 mm	78 (OO)	Plastazote HD-60		1				
HD60: 48 mm	78 (OO)	Plastazote HD-60		2				
Neoprene (Hard): 13 mm	70 (A)	Warco Biltrite Black 70A	1					
Neoprene (Hard): 25 mm	70 (A)	Warco Biltrite Black 70A	1					
Neoprene (Hard): 38 mm	70 (A)	Warco Biltrite Black 70A	1					
Neoprene (Hard): 51 mm	70 (A)	Warco Biltrite Black 70A	1					
Neoprene (Medium): 13 mm	50 (A)	Warco Biltrite Black 50A	1					
Neoprene (Medium): 25 mm	50 (A)	Warco Biltrite Black 50A	2					
Neoprene (Medium): 38 mm	50 (A)	Warco Biltrite Black 50A	2					
Neoprene (Medium): 51 mm	50 (A)	Warco Biltrite Black 50A	1					
Neoprene (Soft): 25 mm	30 (A)	Warco Biltrite Black 30A	1	2	5	6		
Neoprene (Soft): 38 mm	30 (A)	Warco Biltrite Black 30A	1		6	6	7	
Neoprene (Soft): 44 mm	30 (A)	Warco Biltrite Black 30A	1					
Neoprene (Soft): 51 mm	30 (A)	Warco Biltrite Black 30A	1	2	6		9	5
Neoprene (Soft): 76 mm	30 (A)	Warco Biltrite Black 30A	1					
Neoprene (Ultra-Soft): 51 mm	20 (A)	Warco Biltrite						4
Plastazote: 25 mm	61 (OO)	Pastazote LD-45		2				
Plastazote: 51 mm	61 (OO)	Pastazote LD-45		2				
Poron (XRD-20): 51 mm	N/A	Rogers Corp.						6
Poron (XRD-25): 51 mm	N/A	Rogers Corp.						2
Roma Plastilina No. 1: 140 mm	N/A	Roma Plastilina	5	4	5	6	7	4
Silicone: 25 mm	40 (A)	Sponsor Provided		2				
Silicone: 51 mm	40 (A)	Sponsor Provided		2			7	
Silicone – Soft: 51 mm	10 (A)	Stockwell SSP4749-10D						3
Soft/Firm Neoprene layers: 13 mm ea.	30 (A)/70 (A)	Warco Biltrite		2	5	6		
Soft/Firm Neo. Comp.: 25 mm ea.	30 (A)/70 (A)	Warco Biltrite		2	5	6	7	
Sorbothane: 25 mm	70 (OO)	Sorbothane 0266100-70-10		2				
Sorbothane: 51 mm	70 (OO)	Sorbothane 0266100-70-10		2	6			
VN600: 41 mm	N/A	Der-Tex VN600		2				

N/A: Not Available or Not Applicable

2.5 Force Plate Test Systems

The pad materials were tested on two test fixtures (Figure 2), one flat and the other curved. Both systems shared a common impact plate geometry of a centre 30 mm diameter impact cap, surrounded by a 152 mm diameter force ring whose shape matched that of the flat or curved armour. These two test fixtures were used to assess the effect of the pad on force distribution. The centre plate force measurement was collected by a single load cell while the outer ring was supported by four load cells whose measurements were summed. Data from the five (5) load cells (PCB Model 200C20) was collected at 1 x10^6 samples/s during impact and filtered to 50-kHz using a digital, 20-pole low pass filter.

2.6 Armour Deformation Analysis Methods

After ballistic impact testing, the armour was scanned using a 3D laser scanner (ROMER Absolute Laser Scanning Arm) to create a point cloud of the back surface of the armour. The point cloud was manually analysed using Geomagic Wrap & Geomagic Control software where the point clouds from an undamaged armour plate and impacted armour plate were compared. Measurements were made of the maximum residual deformation of the armour, average diameter of the deformation (an average of 3 diameter measurements) and volume displaced from undamaged armour.

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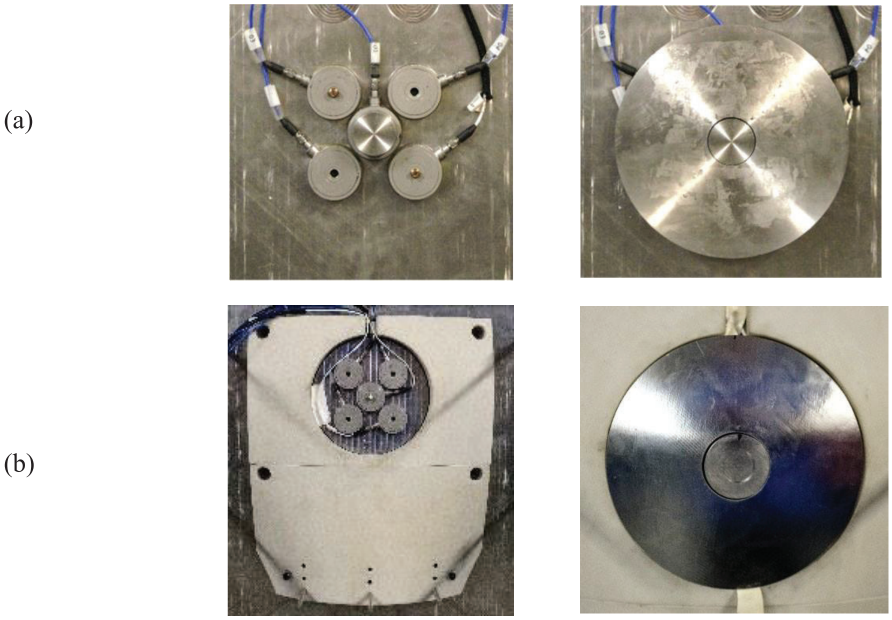

Figure 2. Views of (a) flat and (b) curved plate test systems

3. RESULTS

3.1 DMA Results

DMA testing was conducted to characterize the strain rate sensitivity of the elastic modulus of the pads (Figure 3). In comparing the curves, the storage modulus of the different durometer neoprene materials at low strain rates were different, but becomes similar above $1\text{x}10^3$ strain/s. For reference, a 50 mm thick pad that is compressed at a velocity of 100 m/s is $2 \text{ x } 10^3$ strain/s. While Sorbothane and neoprene both become significantly stiffer above 1 strain/s, the Evazote and Plastazote foams did not exhibit the similar changes. Silicones dramatically change stiffness with strain rate and over a narrower range of strain rates than seen in neoprene and Sorbothane. Poron becomes stiffer at much lower strain rates than neoprene and Sorbothane.

3.2 Clay Backface Deformation Results

Testing was conducted with a clay (Roma Plastilina No. 1) backing to collect reference armour deformation measurements for comparison. Table 3 summarizes the measurements of flat tile and curved plate armour against clay. The flat tile clay BFD data for Series 2 testing were statistically significantly different ($p<0.017$) than data collected for Series 1 and 3. Despite the difference in clay BFD, the residual armour deformation for the three flat tile test series showed no statistically significant differences. This suggests that the difference in clay BFD had no effect on the armour deformation.

The clay deformation results are summarized in Table 4. There was no statistically significant difference in the clay BFD behind the curved plates and the flat tile test series 1 and 3. However, there was a statistically significant difference between the flat tile and curved plate armour deformation values ($p<0.0001$ for all armour values) for the three armour deformation parameters measured, with the difference in volume being the greatest, an increase of 180%.

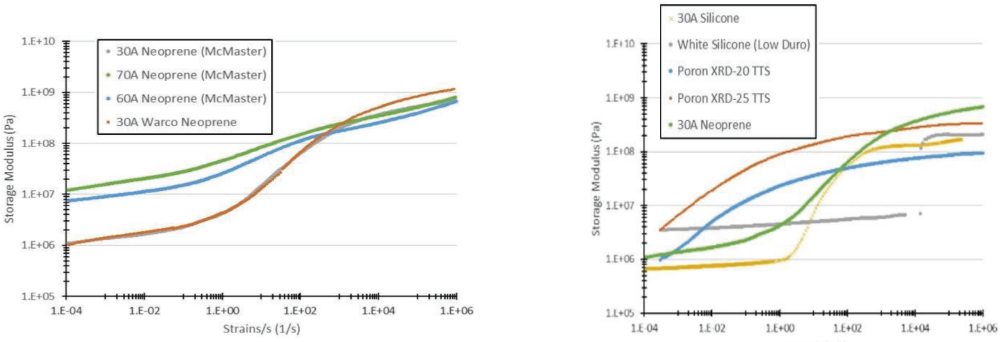

Figure 3. DMA measurements for a selection of materials

Table 3. Results of testing flat tiles and curved plate armour against clay

Characteristic	Flat Tile			Curved Plates		
	Series 1	**Series 2**	**Series 3**	**Series 4**	**Series 5**	**Series 6**
Avg. Clay BFD (mm)	31.8	26.7	33.6	32.1	33.0	31.4
Avg. Residual Armour Deformation (mm)	5.2	6.0	6.1	9.6	10.0	8.5
Armour Avg. Dia. (mm)	88.8	87.0	88.1	120.1	117.5	121.3
Avg. Armour Volume (mm^3)	10628	12416	12664	33396	31069	36711

Table 4. Summary of flat tile and curved plate armour results on clay

Measurement	Flat Avg.	Curved Avg.	Increase	p-Value
Clay BFD (mm)	31.0	32.3	4%	0.26
Residual Armour Deformation (mm)	5.73	9.49	66%	<0.0001
Average Diameter (mm)	88	119	35%	<0.0001
Volume (mm^3)	11866	33207	180%	<0.0001

3.3 Residual Armour Deformation Results

3.3.1 Flat Tile Armour - Clay and Pad Results

Figure 4 compares the residual armour deformation collected from flat plate testing on clay and force plate. A number of pad combinations showed results similar to those measured against clay. The similarity between clay and the different pad materials and thicknesses was calculated using Dunnett's method [5] to quantify the difference in armour deformation between the clay and pads. A value of 1 shows the two test conditions are similar and a value of 0 shows very poor similarity. Table 5 summarizes the average values measured and the similarity between clay and pad measurements.

The pads that best matched the flat tile armour deformation seen in clay were:

- Soft (30A) neoprene at 25 mm, 38 mm, 44 mm, and 76 mm thicknesses
- Soft/Firm layered neoprene, 25 mm thick
- Sorbothane, 51 mm thick

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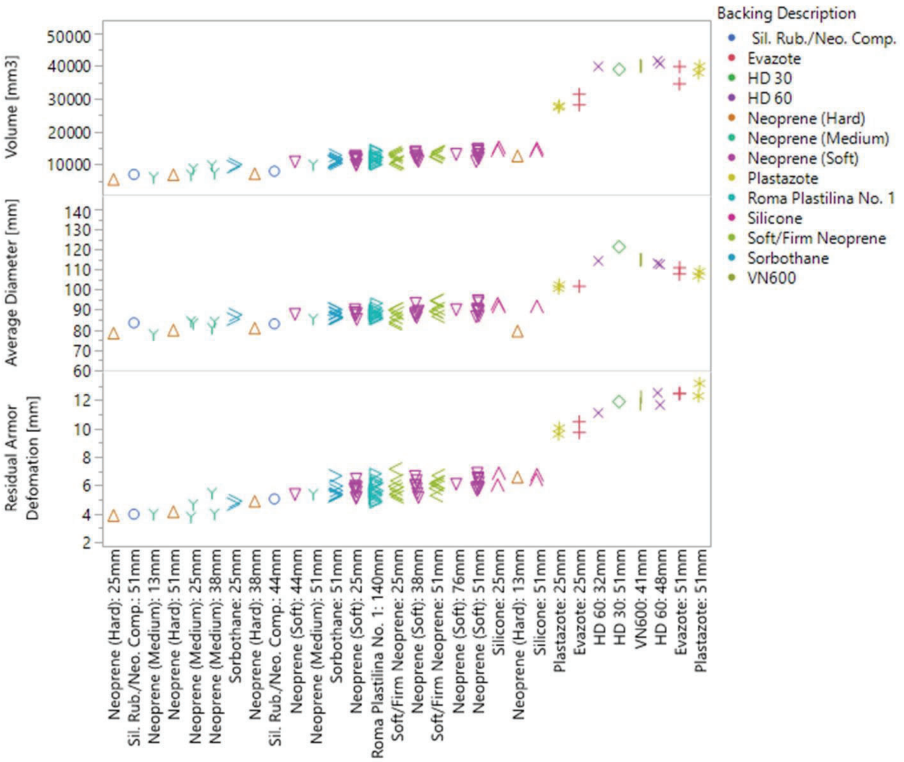

Figure 4. Residual depth of deformation, average deformation diameter and deformed volume results for flat tile armour, rank ordered by residual armour deformation

3.3.1 Curved Plate Armour - Clay and Pad Results

In Test Series 4-6, with curved plate armour, 86 tests were conducted against clay and 12 pad material and thickness combinations. The best pads identified in Series 1-3 were tested in Series 4 to determine how well they repeated the armour deformation behaviour seen over clay. The results differed significantly between Series 1-3 and 4. In Series 5 and 6, additional pads not tested in Series 1-3 were evaluated to improve the similarity in armour deformation between clay and pads.

Overall, the armour deformation seen on the curved plates over pads was greater than that seen on flat plates for clay and similar pads. However, Series 4 results showed that the pads that best matched armour deformation on the flat tiles produced much less deformation on the curved plate. The materials that produced too much deformation in the flat tile tested produced results that better matched clay results on the curved plate (Table 6). The results of the curved plate armour testing are summarized in Table 6 and Figure 5.

The armour deformation for the 51 mm Poron XRD-25 pad was the best match for the curved plate armour deformation seen when tested over clay. However, the conclusion is based on 2 tests, and additional tests may show that the Poron XRD-20 may perform similarly.

3.4 Force Plate Measurement Results

Force measurements were made during each ballistic impact. These measurements showed a wide range of force-time behaviours, examples of which are shown in Figure 6. From these measurements, peak centre force and peak total forces were extracted for analysis (Figure 7).

In examination of the plots, a number of observations may be made:

- The peak centre force was always greater for the curved armour plate than the flat tile.
- The peak total force was generally, but not always, less for the curved armour plate than the flat tile.

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- Foam material generally had smaller centre and total forces.
- The peak total and centre force generally decreased with increasing pad thickness. There were a couple of exceptions that were probably due to test variability and the limited number of tests conducted at a given thickness.
- The ratio of centre to total force was greater for the curved plate.

Table 5. Comparison of armour deformation of flat tiles (Series 1-3) backed by clay and pads. Value of 1 is very similar; value of 0 is very poor similarity. Highlighted lines were the best match with clay results

Backing & Thickness	Deformation Depth (mm)		Avg. Diameter (mm)		Volume (mm^3)		Mean Similarity
	Mean	Similarity	Mean	Similarity	Mean	Similarity	
Roma Plastilina No. 1: 140 mm	5.7	1.00	88	1.00	11866	1.00	1.00
Neoprene (Soft): 25 mm	5.7	1.00	88	1.00	11433	1.00	1.00
Neoprene (Soft): 38 mm	5.9	1.00	89	1.00	12410	1.00	1.00
Neoprene (Soft): 44 mm	5.4	1.00	88	1.00	10857	1.00	1.00
Soft/Firm Neoprene: 25 mm	5.9	1.00	87	1.00	11862	1.00	1.00
Neoprene (Soft): 76 mm	6.1	1.00	90	1.00	13112	1.00	1.00
Sorbothane: 51 mm	5.6	1.00	88	1.00	11282	1.00	1.00
Neoprene (Medium): 51 mm	5.4	1.00	86	1.00	10000	0.975	0.99
Soft/Firm Neoprene: 51 mm	6.1	0.989	91	0.354	12992	0.716	0.69
Neoprene (Hard): 13 mm	6.6	0.962	79	0.007	12450	1.000	0.66
Sorbothane: 25 mm	4.8	0.441	86	1.000	9606	0.355	0.60
Sil. Rub. / Neo. Comp.: 44 mm	5.1	0.998	83	0.522	7928	0.073	0.53
Neoprene (Soft): 51 mm	6.2	0.543	90	0.484	13212	0.272	0.43
Silicone: 51 mm	6.6	0.566	92	0.572	14526	0.135	0.42
Silicone: 25 mm	6.4	0.848	92	0.283	14723	0.077	0.40
Neoprene (Hard): 38 mm	4.9	0.944	81	0.045	7012	0.008	0.33
Sil. Rub. / Neo. Comp.: 51 mm	4.0	0.056	84	0.703	6925	0.007	0.26
Neoprene (Medium): 38 mm	4.8	0.362	83	0.044	8571	0.019	0.14
Neoprene (Medium): 25 mm	4.2	0.011	84	0.296	7838	0.001	0.10
Neoprene (Hard): 51 mm	4.1	0.116	80	0.012	6706	0.004	0.04
Neoprene (Medium): 13 mm	4.0	0.064	78	0.001	6108	0.001	0.02
Neoprene (Hard): 25 mm	3.9	0.031	78	0.001	5282	<.0001	0.01
Evazote: 25 mm	10.1	<.0001	102	<.0001	29927	<.0001	0.00
Evazote: 51 mm	12.5	<.0001	110	<.0001	37356	<.0001	0.00
HD30: 51 mm	11.9	<.0001	121	<.0001	38963	<.0001	0.00
HD60: 1.25 in	11.1	<.0001	114	<.0001	39835	<.0001	0.00
HD60: 1.875 in	12.1	<.0001	113	<.0001	41102	<.0001	0.00
Plastazote: 25 mm	9.8	<.0001	102	<.0001	27632	<.0001	0.00
Plastazote: 51 mm	12.7	<.0001	108	<.0001	38928	<.0001	0.00
VN600: 1.626 in	12.0	<.0001	115	<.0001	40191	<.0001	0.00

Table 6. Results of Series 4-6 testing on curved plates. Poron XRD-25 was the best match with clay results. Boxes highlight how poorly the curved plate results matched the flat plate results

Backing & Thickness	Deformation Depth (mm)		Average Diameter (mm)		Volume (mm^3)		Series 1-3 Similarity Mean	Series 4-6 Similarity Mean
	Mean	Similarity	Mean	Similarity	Mean	Similarity		
Roma Plastilina No. 1: 140mm	9.5	1.00	119	1.00	33207	1.00	1.00	1.00
Poron (XRD-25): 51 mm	9.1	1.00	123	0.986	28158	1.00	Not Tested	1.00
Poron (XRD-20): 51 mm	10.2	0.952	113	0.435	39951	0.97	Not Tested	0.79
Silicone (White): 51 mm	8.3	0.851	108	0.238	22824	0.79	Not Tested	0.63
Evazote: 51 mm	12.2	0.468	120	0.115	52694	1.00	0	0.53
Neoprene (Ultra-Soft): 51 mm	7.4	0.101	106	0.114	22633	0.48	Not Tested	0.23
Soft/Firm Neoprene: 51 mm	7.6	0.009	110	0.007	23400	0.44	0.69	0.15
Neoprene (Soft): 51 mm	8.2	0.195	101	0.017	23999	0.003	1.00	0.072
Neoprene (Soft): 38 mm	7.9	0.060	105	0.005	22681	0.065	1.00	0.043
Neoprene (Soft): 25 mm	7.2	0.014	97	0.001	18581	0.005	1.00	0.006
Silicone: 51 mm	7.0	0.005	97	0.0002	17219	0.007	0.42	0.004
Soft/Firm Neoprene: 25 mm	6.2	0.0003	93	0.0001	13578	0.005	1.00	0.002

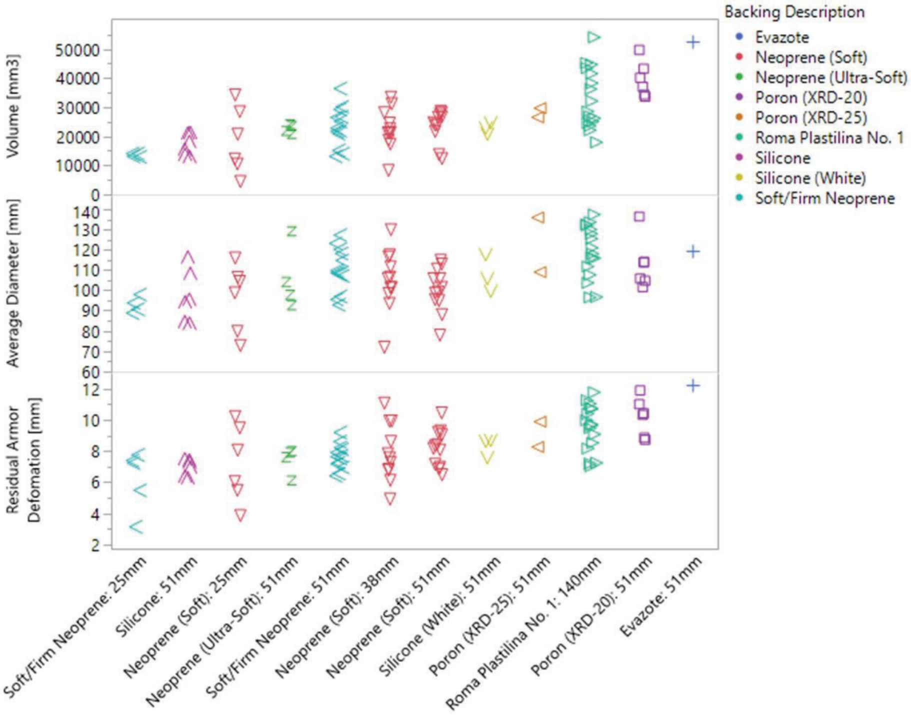

Figure 5. Comparison of curved plate armour deformation on clay and pads

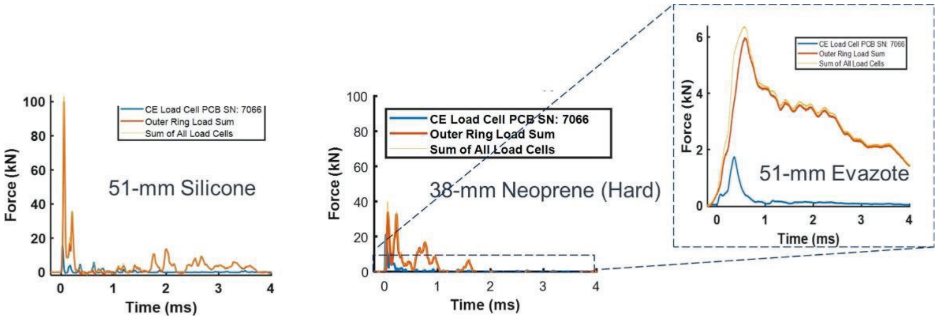

Figure 6. Examples of force-time plots measured behind different pad materials

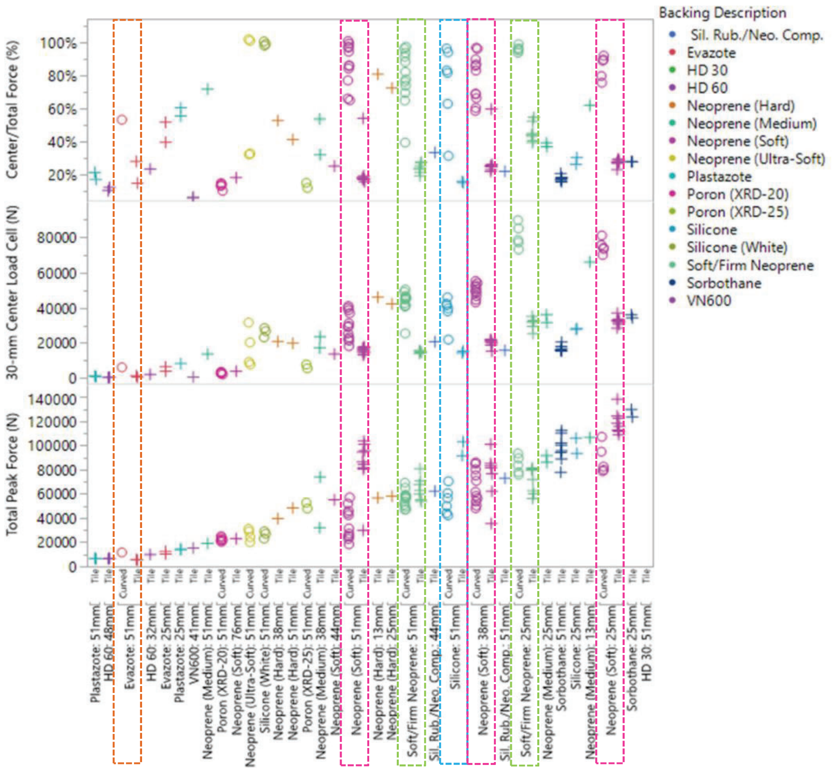

Figure 7. Centre, total and ratio of centre to total force measurements behind flat tiles and curved plates. Pad material/thickness combinations tested under both flat and curved armour are enclosed in a box

4. DISCUSSION AND FUTURE WORK

Comparison of the clay results in Table 4 shows that the clay BFD values measured were similar between flat and curved armour plates. However the data showed the magnitude and scatter of the residual armour deformation, deformation diameter and deformation volume was greater for the curved plates than the flat tiles. This suggests that there were fundamental differences between plates and/or test methods. Given the lack of cross-over tests, the differences are difficult to attribute to one source. The statistically significant differences in clay BFD results between Series 2 versus Series 1 and 3 may indicate poor reproducibility in the clay test protocol despite all clay blocks passing the clay calibration drop test.

Differences between flat tiles and curve armour plates performance were also observed when testing was conducted on force plates. The pads needed to match the deformation over clay for the flat tiles were much firmer than pads needed behind curved plates. There were also differences in the distribution of forces behind the flat tiles and curved armour plates. The curved armour plates had much greater centre loads than flat tiles across the range of pads tested in both conditions.

There are a number of potential explanations for the differences in pad and clay performance against the flat tiles and curved armour plates. They include:

- Differences in the mechanical response of the ceramic and UHMWPE properties and material thicknesses between the flat tiles and curved ceramic plates.
- Effect of plate curvature on the material performance.
- Effect of moulded clay curvature on the clay test. Mechanical properties of the clay may be different due to moulding into a curved insert and geometric differences in flow.
- Effect of curvature on the pad properties. When the flat pad is curved, one side is in tension and the other is in compression.
- Effect of curved impact caps, which presents a convex shape facing the impact
- Differences in measuring force behind flat and curved plates.

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Additional ballistic and air cannon testing, as well as analytical modelling, is needed to determine the source of the differences observed. Additional testing can be conducted on the current curved plates to provide greater statistical confidence in the results, particularly for the Poron pad material where limited testing was conducted.

The current testing using ceramic plates and .30 calibre APM2 projectiles at one velocity shows that the pads had a range of effects on the forces and their distribution. The differences between the flat tiles and curved armour plates was sufficient that different patterns of behaviour were observed. Testing with different armour plates, armour plate materials and projectiles may produce a similar diversity in results. The current testing focused on armour and test conditions for the 44 mm clay BFD criteria; additional work can be done to assess armour pad suitability for a 58 mm clay BFD criteria.

5. SUMMARY

The goal of the project was to identify pad materials that can be placed in between ceramic armour and a rigid load cell impact plate that allows armour to deform similarly as when tested on clay. The project developed flat and curved test fixtures and analytical methods to assess armour response for different backing materials and established a database of impact pad configurations and armour response. It measured the peak centre and peak total forces associated with the pad material and thickness. This effort lays a groundwork of initial test results that can be leveraged by future efforts to develop force- based ballistic test devices.

The findings of this project include: discovering that pads and plates respond as a system; and the best pad materials for flat tiles was different than curved plates. For flat tiles, the pad materials most similar to clay were: soft (30A durometer) neoprene at 25 mm, 38 mm, 44 mm and 76 mm thicknesses, soft/firm layered neoprene at 25 mm thick, and Sorbothane at 51 mm thick. For curved plates, only one pad produced similar residual armour deformation to clay, Poron XRD-25. Additional testing is required to confirm this result since only two Poron samples were tested.

Differences in the clay test block response was observed for the test series, but it did not affect the armour residual deformation depth, diameter and volume deformation measurements of the flat tiles. These results reflect testing with .30 calibre APM2 bullets against ceramic plates back with a shootpack. Other armour and bullet combinations may result different results.

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