The Development of the f-BTTR and its use for Hard Armour Testing

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Abstract. The development and use of the BTTR (Blunt Trauma Thoracic Rig) has been presented during previous PASS conferences. There were two key issues with its use: a) the membrane deformation was measured only at one point which limits the capacity of the system to measure the transient peak behind armour deformation, and; b) the cylindrical shape of the BTTR prevented the correct support of rigid armour. In order to solve these two issues, the f-BTTR (Flat - Blunt Trauma Thoracic Rig) was developed. The f-BTTR system now enables 3D transient deformation measurement of the backface deformation. Because it is flat, behind armour boundary conditions are easier to control. This paper describes the design and features of the f-BTTR along with its response to generic impacts. Its 3D LDT (Laser Displacement Transducer) based instrumentation is also described and insights into its spatial and temporal resolutions are provided. The development of a test method for the assessment of BABT for hard armour is also presented and includes an analysis of the f-BTTR membrane response for different boundary conditions. The f-BTTR membrane response is finally compared to ballistic clay deformation data for the same armour/projectile/boundary condition combinations. Advantages of the f-BTTR having 3D transient deformation measurement capability include the ability to assess additional response metrics that may be indicative of injury risk including the loading area, volume of deformation and shape of the deformation profile. Initial results of these capabilities are discussed in relation to their accuracy and implications for injury assessment.

1. INTRODUCTION

Early assessments of thoracic behind armour blunt trauma (BABT) for non-penetrating armour impacts have been based on the measurement of the residual deformation in ballistic clay used to support the armour system. While this method is still widely used for assessing armour penetration resistance and blunt impact performance, the limited biofidelity and ability to assess injury risk has been questioned over the past few decades [1]. More recent efforts to further employ ballistic clay for armour performance studies have been made associating the deformation characteristics of clay, e.g. depth, width, volume) with energy/momentum transfer as an indicator of blunt trauma potential [2, 3]. A further study of clay deformation under ballistic re-enactments involving law enforcement survivor cases indicated poorer correlation of clay deformation and volume with injury classifications in comparison to energy-based methods [4]. It is recognized that while static measurements of clay deformation may be indicative on injury potential, they are not necessarily complete nor do they represent the dynamic loading mechanisms that have been related to blunt injury outcome such as the Viscous Criterion (VC) [5]. Alternative approaches using deformable backing systems having biofidelic responses and the ability to measure the dynamic response are perhaps better suited to assessing thoracic blunt trauma such as the Dstl/DLO BABT rig [6] and the 3-RCS [7]. These surrogates are capable of measuring some of the dynamic deformation characteristics to better represent the biomechanics of injury.

The Blunt Trauma Torso Rig (BTTR) was developed to predict the risk of blunt trauma for defeated ballistic impacts onto armour systems and for direct impacts from kinetic energy non-lethal weapons (KENLW) [8. 9. 10]. The design was based on the average human male chest anthropometry with the ability to measure the inner dynamic chest wall deformation at the mid-sternal level to match post-mortem human subject (PMHS) and animal studies conducted at that time. Its biofidelity originally conformed to the PMHS force-deflection data for behind armour impact conditions approximated by a rigid baton impacts [11], and to the animal surrogate (porcine) responses from baton impacts [12, 13]. Injury assessments with the BTTR were based on a review of multiple dynamic metrics for the anticipated loading regime with the Viscous Criterion (VC) being proposed as the most applicable [14].

While the BTTR demonstrated excellent repeatability (SD <7%), better biofidelity and required less testing time than ballistic clay [15], improvements were desired to better characterize the dynamic deformation (e.g. depth, area, volume) for use with energy based injury criteria and to further improve its applicability in assessing armour performance. Specifically, improvements were desired to; a) overcome the single point for dynamic deformation measurements which limited the ability of the system to assess behind armour blunt trauma as deformation shape and volume were not available, and; b) to simplify the cylindrical shape of the BTTR to better support rigid armour plates and provide more realistic and repeatable performance evaluations. The BTTR test setup in Figure 1 depicts the armour system supported by the curved membrane, and when struck by a defeated projectile, the back-face deformation is measured at the interior surface of the membrane by a single point laser deflection sensor that is coaxial with the projectile point of impact. Membrane impact locations are not constrained to the centre but must account for edge constraints that may affect response. Rotation of the membrane is also possible to achieve obliquity or for changing the armour impact location. Rotation also permits quick repositioning of the armour on the membrane in case of perforation or damage.

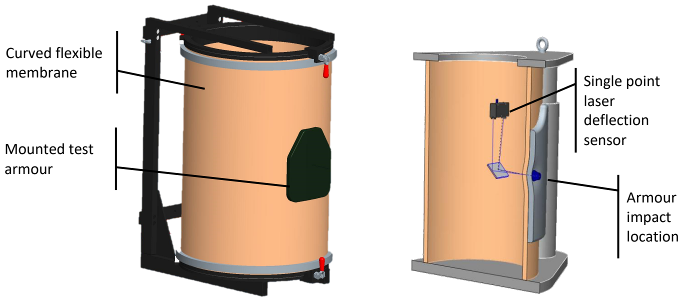

Figure 1. The first generation BTTR.

The cylindrical shape of the BTTR was based on averaged chest breadth and approximated curvature to allow for correct armour fit. However, the use of hard armour plates on the BTTR introduced an air gap between the armour back-face and membrane surface in contrast to the fully supported condition seen with typical ballistic clay infills. This motivated further investigation of the BTTR's response and injury assessment capabilities.

2. STUDY OF ARMOUR SUPPORT

A numerical assessment of hard armour fit on six human subjects was conducted for a variety of configurations including the curved Canadian Forces BRP (Ballistic Resistant Plate) and a flat plate of equal size. Three degrees of plate penetration into the thorax (2 mm, 5 mm, 10 mm) were investigated to approximate the plate support conditions with underlying soft armour systems. It was observed that there was greater contact area for the flat plate, regardless of penetration, with supported areas of 26 cm^2 to 319 cm^2 for compressed penetrations of 2 mm to 10 mm respectively across subjects. The plates were typically supported at three contact points, as depicted in Figure 2. The greater contact area for the flat plate suggested that a better fit would be obtained with a flatter supporting surface.

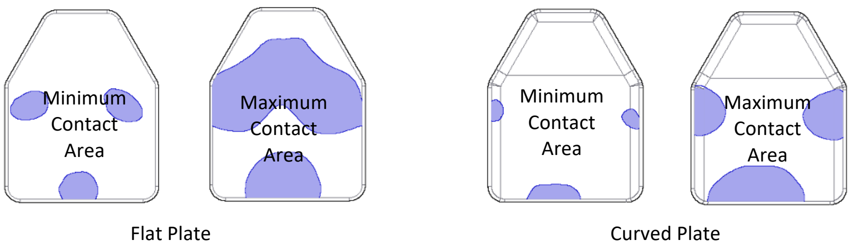

Figure 2: Typical ballistic plate support areas (shaded) for a single subject.

3. F-BTTR DEVELOPMENT

The design of a new flat torso surrogate, the flat-BTTR (f-BTTR), would overcome limitations of single point deflection measurements while providing more realistic ballistic plate support conditions and increased ease of testing. The flat design would also overcome sensitivity of the computed injury metrics due to armour and/or shot misplacement relative to target. For example, the cylindrical shape of the BTTR was noted to require a positioning accuracy better than 3 mm horizontally and 4.5 mm vertically to keep VC errors below 5% for direct impacts thereby requiring close muzzle-to-target distances [16].

The f-BTTR design consists of a flat membrane having inner test surface dimensions of 686 mm wide by 686 mm tall (27" x 27"), comparable to the standard ballistic clay backing configuration of armour performance standards, Figure 3(a). Rear-face support conditions of the mounted ballistic plates could encompass air backed, partially and fully infilled conditions with membrane add-ons. An integrated backfill was also implemented by moulding the shape of the armour plate into the membrane to further facilitate testing. Two horizontal rails were installed in front of the f-BTTR to facilitate positioning and support of the backing filler and armour system. Support clamps on the rails allowed for straps to be used to suspend the infill and soft armour as well as providing adjustable feet to support the hard armour plate along the bottom edge. Finally, two horizontal straps straddle the hard armour at the test site and foam blocks were sandwiched between the strap and armour plate to keep it secured.

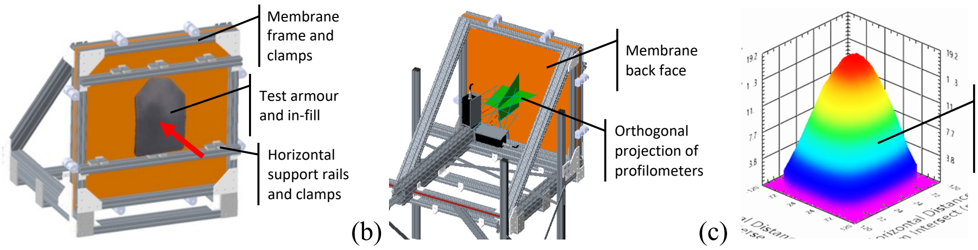

Figure 3: The f-BTTR system; (a) membrane setup, (b) backface measurement system, and; (c) estimated deformed 3D surface.

Measurement of the membrane backface deformation for BABT assessment was approximated in three dimensions (3D) with a Laser Displacement Transducer (LDT) comprising two laser profilometers (Keyence LJ-V7300, ±0.3 mm at 8 kHz, 290 mm depth range, 110-240 mm measurement width) placed orthogonally to each other and offset from the line-of-fire in case of perforation, shown in Figure 3(b). The deformation profiles are captured synchronously for each timestep and are used to create 3D surfaces from the control profiles through scaling of the first profile when propagated along the second profile, Figure 3(c). Custom software was developed to compute metrics associated with injury assessment methods including peak bulge deflection, velocity, volume, and width in two directions. All profile data was transformed to the membrane's coordinate system prior to computation of the metrics. The displacements were smoothed with a cubic spline to remove background noise and velocities were computed employing a two-point central method to remove noise from the differentiation process. Depiction of a typical f-BTTR ballistic impact on a hard and soft armour system can be seen in Figure 4: f-BTTR time histories for; a) peak deflection, b) computed velocity, c) bulge width, and; d) bulge volume..

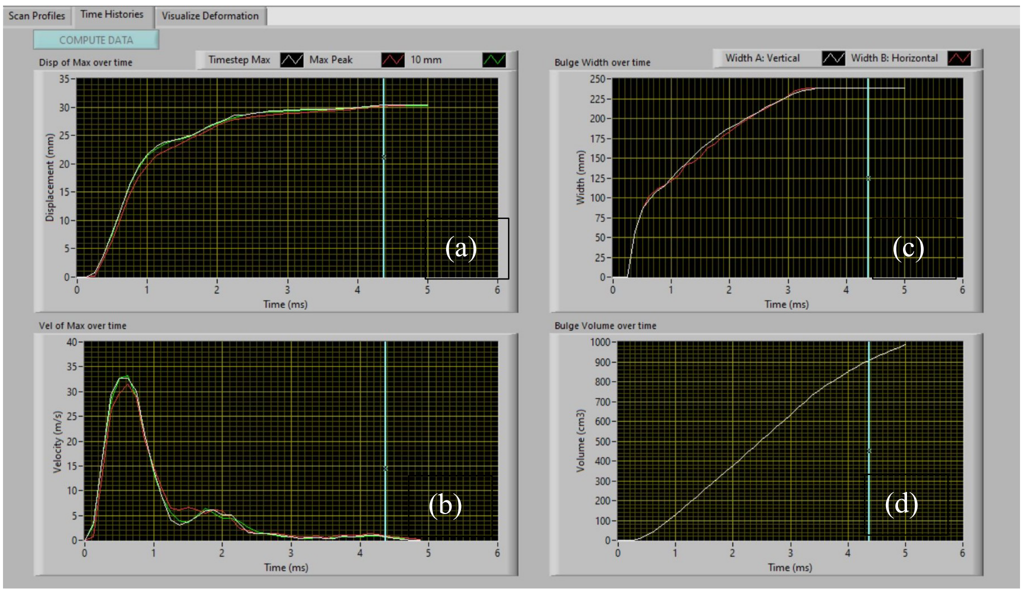

Figure 4: f-BTTR time histories for; a) peak deflection, b) computed velocity, c) bulge width, and; d) bulge volume.

4. BIOFIDELITY TARGETS

The biomechanical response of the f-BTTR was based on PMHS studies [17, 18, 19] to establish the biofidelity of the membrane under impact conditions representative of behind armour loading and direct impacts from kinetic non-lethal projectiles. A range of target response deflections was defined for each case as detailed in Table 1.

Table 1: Biofidelity response targets for the f-BTTR.

Body Region [Ref.]	Impactor	Mass (g)	Vel (±2 m/s)	Target Deflection (mm)
Thorax [17]	Baton 37 mm dia.	140	40	45-65
Abdomen [18]	Baton 37 mm dia.	45	60	26-34
Thorax [19]	Lacrosse Ball 65 mm dia.	215	27	30-42

A study of different f-BTTR membrane materials and thicknesses was carried out under the various impact conditions to determine the best configuration that would satisfy the biofidelity targets. Furthermore, the peak deflection response variation across the test surface from centre to periphery (100 mm or 4 in from the edge) was assessed with observed differences of up to 17% relative to the centre location when tested. Typical deflection time histories across impact conditions are presented in Figure 5. The average peak membrane deflections were below the lower bound target for the 140 g - 40 m/s baton impacts by 11% and generally met the remaining deflection targets for the 45 g – 60 m/s baton and the 215 g – 27 m/s Lacrosse ball impacts (a 48 g baton was used in place of the 45 g specification for the abdominal corridor). Figure 5 also shows that the membrane's deformation velocity during the first few milliseconds generally meet the requirements for the 3 response targets.

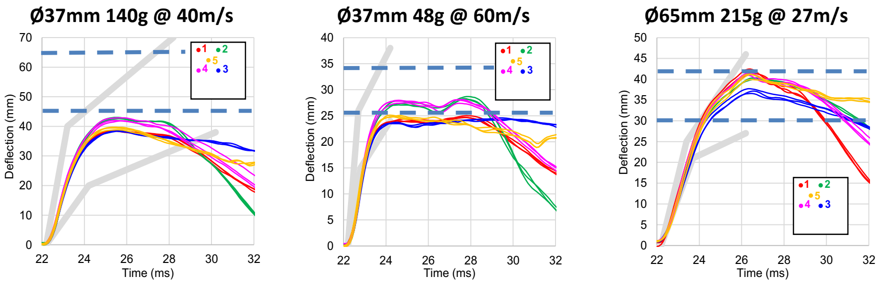

Figure 5: Deflections of the f-BTTR plotted against biofidelity corridors.

5. ACCURACY ASSESSMENT

Initial evaluation of the f-BTTR's accuracy was assessed under a variety of conditions listed in Table 2 with three repeats each. A single high-speed video camera was use for comparative purposes and was skewed from the line-of-fire due to obstructions from the membrane support frame with introduced errors of <1%. Data was collected at 8 kHz for the f-BTTR profilometers and at 3 kHz for the video without any smoothing operations applied. All impacts with the batons implemented a single layer of Kevlar® to prevent surface abrasions.

Table 2: Test conditions for evaluating the accuracy of the f-BTTR.

Loading Condition	Strike Velocity (m/s)	Deflection Error
Ø37 mm, 140 g rigid baton	20	5%
Ø37 mm, 140 g rigid baton	40	-2%
9 mm FMJ bullet, NIJ Level IIA soft armour	373	7%
7.62 mm C21 bullet, NIJ Level III hard armour	847	19%

The ballistic tests with the 9 mm FMJ bullet were carried out with the soft armour supported on the f-BTTR membrane, whereas the combined soft and hard armour were tested without infill for the 7.62 mm C21 bullet. Bullet strike was centred with the membrane and ballistic plate. The error estimates for the averaged peak data is presented in Table 2 where the results for the 9 mm bullet compared well but less so for the 7.62 mm bullet due to the low sampling rate of the video. Further difficulty in assessing the bulge deflection from video persisted due to the low spatial resolution compared to the profilometers, 1.4 mm vs. 0.6 mm.

The surfacing algorithm which combined the two profiles into a continuous surface was also identified as a possible source of error for off-target impacts. The algorithm's susceptibility to error was assessed by numerically shifting the measured profiles obtained from baton impacts laterally up to 48 mm (1.9 in). Errors of 1%-3% were observed from the peak reference deflection. Differences in backface shape could result in different observations, such as in the case of pencilling with soft body armour, but this affect has not been investigated.

Additionally, the sampling rate of the profilometers was investigated to determine its effect on sampling resolution, accuracy and measurement width. The Keyence LJ-V7300 profilometers are capable of sampling at 8 kHz, 16 kHz and 32 kHz but the higher sampling rates are only made possible by downgrading the measurement width (240 mm to 120 mm) and deactivating the integrated noise reduction features. As a result, the higher rates experienced interference from the intersecting profilometer not seen at the lower sampling rate. The final recommendation was to use an 8 kHz sampling rate to provide reliable scan data while preserving the maximum measurement width.

6. HARD ARMOUR BOUNDARY CONDITIONS

An initial study of armour support conditions was carried out with the f-BTTR to determine the effects of having a soft and hard armour system supported by; a) an air gap between the hard and soft armour, b) an add-on polyurethane (PU) infill to fully support the soft/hard armour system, and; c) an add-on polyurethane infill partially supporting the soft/hard armour system. A typical setup is presented in Figure 7. The partial support was provided at three points with the uppermost corners supported by 50 mm diameter pucks and the lower centre portion by a 120 mm diameter puck similar to that shown in Figure 2 for the curved plate. Impacts were conducted with 7.62 mm NATO Ball rounds (147 grain) striking the target at a nominal velocity of 847±9.1 m/s at the centre of the armour plate. The deformations were sampled at 8 kHz with the profilometers and the peak values extracted without smoothing. The results of the limited test series are presented in Table 3: Test results of hard and soft body armour systems on the f-BTTR and ballistic clay for different support conditions. where larger peak deformations, lower peak velocity and greater deformed volume are observed for the polyurethane infill conditions compared to the air gap condition. The response of the membrane for the fully supported versus partially supported ballistic plate is similar.

Comparison of the air gap and fully supported conditions of the f-BTTR was also conducted with ROMA Plastilina® clay backing and infill. The same 7.62 mm NATO Ball round ballistic impact conditions were used and the clay met the pass-fail criteria for the ball (steel, 50.8 mm diameter, 1.043 kg) drop indentation depth of 19 ±2 mm with no individual value greater than 21 mm or less than 17 mm. The maximum clay indentation depth, volume and surface area of the indentation was obtained from a 3D surface scan acquired with a structured white light scanner (DAVID Pro 3D, ±0.3 mm) and post processed using PTC Creo software for surfacing and volume estimates. The deformed surface was compared to a baseline surface scan of the clay taken prior to each test. Scanned images of the backface deformation from the clay block and extracted volume are shown in Figure 6.

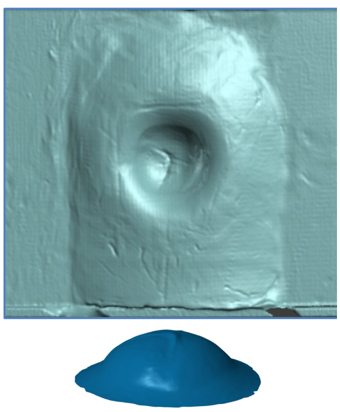

Figure 6: Scanned images of the behind armour indentation in situ and extracted.

Results of the ballistic clay tests are presented in Table 3: Test results of hard and soft body armour systems on the f-BTTR and ballistic clay for different support conditions. which shows that the peak deformation and volume of the indentation are larger for the tests with the clay infill versus the edge supported condition with air gap. The results also indicate that the indentation is less in clay than for the f-BTTR with air gap but greater for the fully supported clay infill condition. It can also be noted that volumes between the clay backing and f-BTTR are very different due to translation of the f-BTTR membrane that occurs for impacts to the hard armour plates. This contrasts with the clay backing which has a higher stiffness and is fully supported by the containment frame. Furthermore, the f-BTTR measures the interior membrane wall deflection and not the back-face of the armour when using clay so through-thickness compression of the membrane is not accounted for.

Table 3: Test results of hard and soft body armour systems on the f-BTTR and ballistic clay for different support conditions.

Test Device	Armour Support Condition	Test #	Test Sample	Impact Velocity m/s	Max. Indentation mm	Max. Velocity m/s	Max. Volume cm^3
f-BTTR	Air Gap / Edge Supported	1	Soft + Hard Armour	846	18.6	23.0	396
f-BTTR	Fully Supported PU Infill	2	Soft + Hard Armour	851	24.1	20.0	610
f-BTTR	Partially Supported PU Infill	3	Soft + Hard Armour	849	22.8	17.6	542
		4	Soft + Hard Armour	841	23.3	18.7	598
		5	Soft + Hard Armour	839	23.9	20.2	672
Clay Block	Air Gap / Edge Supported	6	Soft + Hard Armour	841	15.1	N/A	40
Clay Block	Fully Supported Clay Infill	7	Soft + Hard Armour	848	31.3	N/A	113

A second investigation of the f-BTTR membrane response with different armour infill conditions was carried out and compared to ROMA Plastilina® clay, Figure 7. The tests described in Table 4 were conducted with 7.62 mm NATO Ball rounds (147 grain) striking the target at a nominal velocity of 847±9.1 m/s with minimum shot distances of 60 mm to the edge or 120 mm from adjacent shots. As in the previous study, all tests were conducted at the recommended sampling rate of 8 kHz for the profilometers but enhanced with the data smoothing techniques for deflection and velocity noted earlier. The use of a light block-out curtain also eliminated any external influence from ambient illumination that could contribute to data fluctuations and drop-out by the profilometers. Furthermore, similar controls on ballistic clay consistency were met between shots for meaningful comparisons with the f-BTTR.

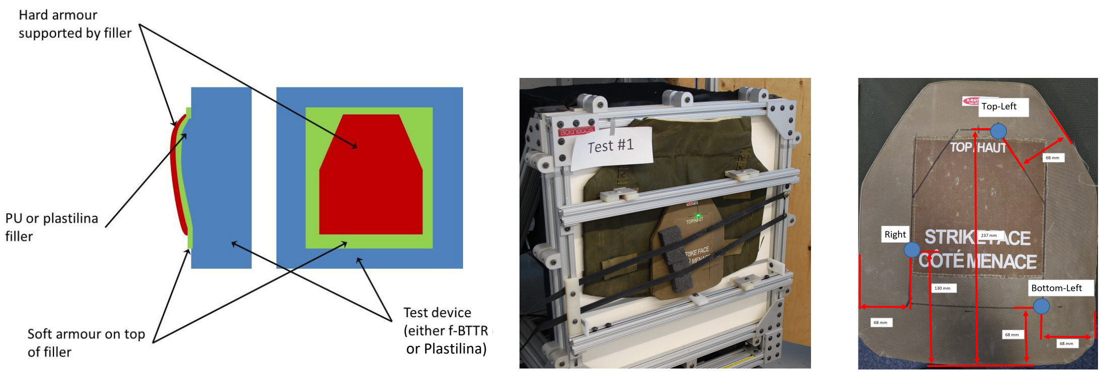

Figure 7: Hard and soft armour layup on top of the backing filler and shot locations.

Table 4: f-BTTR test matrix for different armour support conditions.

Test Device	Soft and Hard Armour Support Condition	No. Samples	Shot Locations
f-BTTR	separate polyurethane infill	5	upper left, right side, bottom left
f-BTTR	integrated polyurethane infill	5	upper left, right side, bottom left
Ballistic Clay	ROMA Plastilina® infill	5	upper left, right side, bottom left

The maximum clay indentation depth, volume and surface area of the indentation was again obtained with a structured white light scanner (DAVID Pro 3D) and post processed using PTC Creo software. The deformed surface was compared to a baseline surface scan of the clay taken prior to each test.

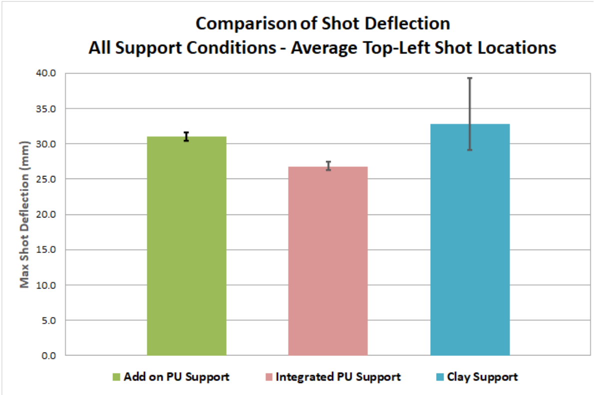

Figure 8: Comparison of f-BTTR deflections.

A comparison of the add-on and integrated polyurethane back-fill elements showed lower deflections and peak velocities for the integrated back-fill condition due to the higher flexural stiffness. Comparisons were not possible across shot locations due to varying armour geometry and differences in response, but similar trends were noted. Additionally, permanent back-face deformation of the armour plates prevented intimate contact with the f-BTTR membrane for subsequent shots, unlike ballistic clay which maintains better contact. Deflections for the top left shot location of the armour plate are shown in Figure 8 with error bars representing the minimum and maximum values. The standard deviations for all test locations across the five hard-soft armour samples were 4% for the f-BTTR with the add-on infill, 6% with the integrated infill and 13% for the ballistic clay infill. An ANOVA on the membrane response with add-on polyurethane back-fill showed that except for the top-left (first) and the right (second) shot deflection and volume, all other values are statistically different. In contrast, similar analysis for clay showed no statistical difference between the 3 shot responses. This is due to the very large standard deviation values associated with the clay results. This also indicates that the f-BTTR is more sensitive to variations in armour support.

Comparison of the shot deformation volume and area could not be made at this time due to bulge width exceeding the measurement width capacity of the current profilometers. While strikes onto soft armour alone would normally be within the capacity of the f-BTTR's measurement system, the hard armour plates resulted in larger width deformations due to a combination of local deformation and plate translation/rotation into the supporting membrane.

7. DISCUSSION

7.1 Biofidelity

The f-BTTR was shown to generally comply with the deflection targets and response corridors with some improvement required to meet the 140 g - 40 m/s baton data [Bir 2000] having peak deflections 11% below target. While this can be realized with a thinner membrane or material change, the current f-BTTR possesses the correct trends to match the biomechanical responses without significant discontinuities and, as a result, it should be possible to develop suitable transfer functions for proper assessment of injury risks across BABT and KENLW loading conditions. It is recommended to limit impacts to the central area for better consistency relative to edge or peripheral impacts. Increasing the lateral extents of the membrane may reduce the edge constraint effects.

It will be important to validate the biofidelity of the f-BTTR against a larger scope of biomechanical studies with PMHS and animal studies as identified by Bourget [14] to increase the relevance and sensitivity of the injury assessments to varying loading conditions. Additionally, compliance of the f-BTTR with the surrogate validation requirements for biofidelity and Viscous Criterion (VC) injury assessment targets presented in NATO STANREC 4744 AEP 99 [20] would be required for use with non-lethal projectiles.

7.2 Accuracy

A preliminary study on the f-BTTR sensor accuracy was conducted for baton and bullet strikes. General agreement for peak deflections was obtained for the batons and 9 mm bullet but not for the 7.62 mm NATO Ball rounds. This is not necessarily a limitation of the f-BTTR sensing system but more a result of the low sampling rate and low spatial resolution of the high-speed video system used. A more complete assessment could be carried out with a Digital Image Correlation system employing two higher speed cameras with better resolution. Such systems would provide independent validation of the peak deflections, bulge widths and volumes along with computed membrane wall velocities. Any comparisons would have to be conducted through separate tests due to light interference and will require several tests to achieve statistical significance.

The two profile scanners used in the f-BTTR were configured to operate at their upper limits for performance. For achieving sufficient temporal resolution when capturing ballistic events, compromises between spatial and temporal resolution were required. Sampling at rates higher than the recommended 8 kHz would result in half of the available measurement width and increased ambient light sensitivity which reduces measurement reliability and trigger certainty. A black-out curtain was also shown to improve reliability in all cases but prohibits the simultaneous use of external illumination sources such as those used with high-speed cameras. Further limits of the f-BTTR profilometers restricts data width and volume analysis to moderate deformation widths (< 240 mm) which may be exceeded for some cases. As new profilometer technologies emerge, these limitations will likely be overcome.

7.3 Surface Deformation Approximation

The use of two laser profilometer sensors in combination with the custom surfacing algorithm was shown to accurately assess the peak dynamic deformations. Sensitivity of peak dynamic deformation measurements to off-target impacts was small (<3%) for baton impacts with lateral deviations of 48 mm (1.9 in). The errors may increase with greater lateral deviations or decrease in curvature of the deformation profile but further investigation is required.

7.4 F-BTTR Comparison with Ballistic Clay

Greater consistency in the peak deflections measurements was observed for the f-BTTR across the five armour systems and three strike locations in comparison to clay with standard deviations of 6% and 13%, respectively. Similar observations were made in prior studies with soft armour (Level II - NIJ 0101.04, 9 mm 124 gr FMJ bullets 350±9 m/s) with a standard deviations of 3.0% (N=27) vs. 5.7% (N=26) for the BTTR and clay, respectively [15].

7.5 Surrogate Operation

The flat surface of the f-BTTR was selected to provide more representative support of hard armour plates while simplifying back-face deformation measurements. The use of horizontal support bars offset from the front surface worked well to suspend soft armour with straps as well as supporting hard armour plates.

Initial issues with membrane slippage and resulting sagging were overcome with the use of a robust edge lip and clamp. No residual deformation or degradation of the membrane was observed after 29 successive impacts with the baton (140 g, 40 m/s) on the bare membrane or after strikes with a 147 grain, 7.62 mm NATO Ball round at a nominal velocity of 847±9.1 m/s on a soft and hard armour combination, with either the add-on or integrated polyurethane back-fill. In the absence of bullet perforation, membrane durability is expected to be good and matches that of the BTTR which can be used for many years.

Operationally, pre/post test requirements for the f-BTTR are needed and are proposed to be similar to the built-in 2.2 kg 100 mm dia. pendulum impactor employed in the BTTR. Each pre and post test series consists of five consecutive impacts and are intended to be practical and reproducible but not necessarily representative of ballistic impact conditions. The tests are to confirm that the response of the surrogate is within tolerance before and after testing. Large discrepancies between the pre and post tests would indicate a deficiency with the equipment such as a damaged membrane or instrumentation error.

The operational efficiency of the f-BTTR is expected to be similar to the BTTR where the testing time was shown previously with soft body armour tests to be reduced by 44%, including the pre and post verification tests. This was primarily due to the lack of repairs, calibration tests and measurement time needed when using ballistic clay. With use of the integrated polyurethane infill option, further time reductions are expected due to the lack of effort required to create the infill in contrast to that for ballistic clay.

8. SUMMARY

Development of the f-BTTR was intended to provide enhancements over the BTTR by increasing the behind armour blunt trauma measurement capabilities and to provide more realistic armour support conditions known to affect performance.

Introduction of the f-BTTR 3D transient deformation measurement capability allows for the assessment of additional response metrics that may be indicative of injury risk including the loading velocity, area, volume of deformation and shape of the deformation profile. This should result in a more robust and representative system for assessing armour performance and injury risk. Furthermore, it is noteworthy that the initial results have leveraged the operational benefits of the BTTR in terms of repeatability and ease of use making for a more practical ballistic armour performance test methodology.

Future efforts will be focused on improvements and characterization of the f-BTTR response under varying ballistic and KENLW loading for validating injury risk across a wide range of conditions. The f-BTTR in combination with the operational procedures should result in the development of more relevant armour designs and protection.

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