# Building Simulation Tools for Next Generation Soft Body Armour Testing Standards

S.P. Mates<sup>1</sup>, A.L. Forster<sup>1</sup>, M. Riley<sup>1</sup>, K. Rice<sup>1</sup>, and J. Ivancik<sup>2</sup>

<sup>1</sup>National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Md., USA, 20899-8553 <sup>2</sup>US Army Research Laboratory, 4502 Darlington Rd., Aberdeen Proving Ground, 21005, Md., USA smates@nist.gov

**Abstract.** Accurate simulation tools for soft body armour testing would vastly improve a test designer's ability to optimize and refine standards by supplying quantitative information about the influence of test variables on test outcomes. Such tools would also facilitate the development of future armour testing standards that will leverage the improved understanding of impact injury mechanics by providing meaningful comparisons between actual human injury conditions and ballistic testing conditions. These potential benefits are real and well recognized. So, too, is the difficulty of developing such tools, which involve material systems ranging from the metal projectile to the woven polymer composite armour to the synthetic clay body surrogate. However, the emergence of the Digital Image Correlation (DIC) experimental method has greatly enhanced our ability to understand dynamic material behavior, making this difficult problem more tractable. This paper outlines our current vision for developing finite element simulation tools for soft body armour testing, including the types of measurement data and validation techniques being used, and describes preliminary simulation results of an idealized ballistic impact involving a rigid projectile striking clay-backed steel armour.

## **1. INTRODUCTION**

The current National Institute of Justice (NIJ) Standard 0101.06 [1] for soft body armour testing continues to provide assurance to law enforcement departments across the United States that the body armour they acquire will protect officers on duty against the threats they were designed to defeat. An opportunity exists to provide even better assurances by leveraging considerable recent efforts to understand blunt impact injury. These efforts include the development of accurate, instrumented physical models designed to mimic human anatomy [2] as well as post-mortem human subjects (PMHS) [3] used to measure response to full-scale blunt impact and blast waves, detailed numerical models to investigate material-level effects and possible injury mechanics [4,5], and methods to quantify human injury using battlefield data [6]. Combined, these different elements promise to help us better understand and ultimately predict human injury under impact loads in a way that will allow engineers to better optimize body armour designs for law enforcement officers and soldiers alike.

Body armour testing standards can potentially leverage this new knowledge to provide more detailed assessments of armour protection level against ballistic impact than are afforded currently. A first step in this direction is to develop simulation tools that can reliably predict the ballistic standard test in its current form, so that the physics of current armour testing can be better quantified and compared to injury metrics and models developed under real field conditions. Accurate simulation tools are not easily developed due to the complex interplay between the wide variety of materials and interfaces involved in the ballistic impact problem. True predictive capability will likely remain elusive in the near future, given the complexity level and resource limitations. Mindful of this, in the present paper we outline our approach to developing simulation tools to better understand ballistic testing. In our favor is the fact that impact conditions are more tightly controlled compared to real field conditions. Projectile velocity is measured accurately, impact angle and mechanical constraints on the armour are controlled, and the backing material is pre-conditioned to provide a consistent response. Thus many sources of potential variability are already eliminated, improving chances that simulation tools might provide useful quantitative information.

Finally, in addition to the potential of providing insight into how current ballistic testing might compare to actual human injury response, simulation tools will allow test designers to investigate ways to improve body armour testing. Simulation tools will allow them to explore many important, practical test performance issues, such as the effects of inter-shot spacing, thermal or strength changes within the clay, bullet characteristics, and so on. Simulation tools could also help test designers transition testing to new clay formulations, other deformable backing materials, or to instrumented witness devices developed in the future. This paper outlines our current vision for developing finite element

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simulation tools for soft body armour testing, describes the kinds of measurement data and validation techniques that are being incorporated into the model, and provides preliminary simulations of idealized ballistic impacts involving a rigid projectile striking a clay-backed steel armour using commercial finite element software.

#### 2. MODEL ELEMENTS

## 2.1 Ballistic Clay

Ballistic clay has been investigated in compression over a range of temperatures and strain rates to determine its plastic response in our laboratory. Results have been fit to a Johnson-Cook viscoplastic material model developed originally for metals [7], given by Equation 1. The model was then compared to experimental results from the NIJ ball drop test [1] and the Prather impact test [8]. In the former, high-speed Digital Image Correlation (DIC) was used to track the ball impact on a standard clay box fixture (square box with inside dimensions measuring 610 mm on a side and 140 mm deep). In this test, a steel sphere measuring 6.35 cm in diameter impacts the clay box at a velocity of 6.26 m/s and with a kinetic energy of 20.44 J. The experiments were conducted at an average clay block temperature of 37 °C. An axisymmetric finite element model was constructed of the ball and clay block, which in the simulation measures 140 mm deep and has a radius of 305 mm, as shown in Figure 1(a). The block position was fixed along the side but not on the back surface, to mimic the experimental conditions. The ball was modeled as a rigid object, and the clay was modeled using the Johnson-Cook parameters found from the compression testing study, which are given in Table 1. The elastic response of the clay was linear with a Young's modulus of 2 GPa based on confined compression test results [9].

Results showed that while the final indentation depth was captured correctly, the model did not capture the elastic rebound of the clay, which was almost 25 % of the final indentation depth, as shown in Figure 1b. We concluded that a viscoelastic treatment of the clay elasticity was needed to capture the observed behavior, but that it was beyond the capability of the finite element software at hand. Regardless, the ball drop test demonstrated that the plastic response of the clay during this blunt, dynamic indentation test was captured well using the model derived from compression tests. The results are described in our previous PASS publication [9].

$$\sigma = \left(A + B\varepsilon^n \left(1 + c \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right)$$
(1)

Table 1. Johnson-Cook constants derived from quasi-static and dynamic compression tests.

Material	A [MPa]	B [MPa]	n	$c^1$	$m^2$
Roma Plastilina	0.00001	0.238	0.290	0.25	0.502
Pafaranca strain rate is 0.118 strain per second					

<sup>1</sup>Reference strain rate is 0.118 strain per second  ${}^{2}T_{m} = 100 \text{ °C}, T_{0} = 23 \text{ °C}$ 

Next, we used the model to predict a higher velocity impact test, called the Prather test [8]. In this test, a hemispherical projectile with a mass of 200 g is fired horizontally at a clay block that rests on a table. In the modeled test, the impact speed is 55 m/s, giving an impact kinetic energy of 315 J, much higher than the ball drop discussed earlier but only about half that of soft body armor ballistic tests, an idealized simulation of which is described next. The projectile penetration depth is determined in the experiment as a function of time using a high-speed camera. We note that the experiments were performed in an external laboratory (Experimental Facility 20, US Army Research Laboratory) with a different batch of Roma Plastilina #1 than the batch used in the experimental program at the National Institute of Standards and Technology (NIST) from which we derived our clay model. Figure 2 compares the axisymmetric model prediction of the projectile penetration history against the experimental results for an average block temperature of 37.4 °C  $\pm$  1 °C. The model captures the deceleration of the projectile qualitatively quite well, but shows a somewhat softer response (deeper penetration) compared with the experiment. The maximum penetration depth obtained from the simulation was approximately 1.2 cm deeper than the average value obtained from the experiments  $(9.0 \text{ cm} \pm 0.4 \text{ cm})$ . Of note in the simulation is the importance of the friction coefficient between the impactor and the clay, which was taken to be rather high given the nature of the clay. Friction has a

significant effect on the penetration depth, and bears further attention going forward. We also note that the experiment showed no sign of elastic springback as was observed in the ball drop test. Despite the imperfect agreement with the experiment, the similarity was encouraging, given the fact that the clay used to derive the model was different in age and batch identification from the clay used in the Prather test.



**Figure 1**. (a) Computation domain for ball drop test simulation. (b) Comparison of simulated and measured ball position and velocity history during the test.



Figure 2. Final frame of a finite element simulation of Prather test (left) and a comparison of the simulated impactor tail position history with experimental results (right) for an average impact speed of 56.4 m/s  $\pm$  1 m/s and an average clay temperature of 37.4 °C  $\pm$  1 °C for a total of 19 experiments.

## 3.2 Deformable Projectiles

A potentially significant issue in ballistic testing is the deformation behavior of the test bullets. Experience shows that nominally similar bullets, in terms of mass and caliber, can perform differently in ballistic testing. While the most prominent projectile effects can be attributed to the sometimes large differences in the strength of the component materials (steel versus lead), there may exist more subtle differences among nominally similar bullets that can affect ballistic test results. We examined methods to develop accurate simulations of several different projectiles used in the current NIJ Standard. Model predictions of dynamic compression in whole bullets were explored using direct-impact Kolsky bar experiments, where the bullet is held fixed at the impact end of a Kolsky bar where it is struck by a massive striker moving at moderate velocity. In the example described in [10], a .40 caliber Smith and Wesson (S&W) Full Metal Jacket (FMJ) projectile is struck at 15.3 m/s with a kinetic energy of 62.5 J, which is about 10 % of the energy of an NIJ standard soft body armour shoot test for this bullet type

(reference velocity of 325 m/s, bullet weight of 11.66 g, kinetic energy of 617 J). The impact produces a total axial engineering strain of 0.35 in the bullet. The bullet deformation history was captured using three-dimensional, high-speed digital image correlation (3D DIC) [11], and the measurements were compared to an axisymmetric finite element model of the test.

A multitude of simulations were performed where design-of-experiments techniques were used to investigate the sensitivity of the material parameters and to find the best match between the simulation and the measured deformation and impact load history. Using in-house developed material parameters for the lead core, we found that the improved constitutive constants for the jacket material were much stronger than the literature values for cartridge brass, the material though to most closely mimic the copper alloy jacket for which constitutive data are available [12]. The comparison between the baseline and optimized simulations of the bullet deformation history and the experiments, repeated from [10], is shown in Figure 3. Overall, despite the smaller impact velocities and lower deformation levels present in the Kolsky bar experiment, this method helps improve the accuracy of whole bullet models for simulating ballistic testing. Full details on the .40 S&W and the .357 Jacketed Soft Point (JSP) projectile impact tests are given in [10] and [13], respectively.



Figure 3. Comparison of baseline and improved simulation results derived from design-of-experiments methods that explore the effect of model parameter variations for the jacket material on the shape history and force history measurements.

# **3.3 Preliminary Ballistic Test Simulations**

To explore the performance of the clay model under real ballistic test conditions, we simulated an idealized ballistic test using simplified armour and projectile models. The clay model was identical to the one used previously to model the ball drop test and the Prather impact test. For the armor, we used a simple steel plate placed in front of the clay block. The intent of this simulation was to observe the behavior of the clay model under real ballistic impact velocities and not, at this time, to explore the effect of armor or bullet behavior, which is obviously more complex. The armour plate was made of 4340 steel and was 5 mm thick and 300 mm in diameter. The steel has a Young's modulus of 200 GPa and Johnson-Cook (Equation 1) plasticity parameters of A = 792 MPa, B = 510 MPa, n = 0.26 and C = 0.015 obtained from [14]. We used a rigid, spherical projectile with a diameter of 20 mm impacting at 322 m/s and having a mass of 11.7 g, equivalent to a Type IIA armour test shot. The diameter of the rigid projectile was chosen to mimic the mushrooming impact behavior of a lead-cored projectile against soft body armour. At this time we have yet to incorporate our deformable bullet model into the ballistic test simulation, which requires special adaptive meshing techniques to handle the extreme deformations expected in the bullet.

The finite element solution is shown in Figure 4 at three times during the impact process, while Figure 5 plots the positions of the projectile, the rear surface of the armour, and the top surface of the clay on the axis of symmetry throughout the impact simulation. As the plots show, soon after impact the simulation predicts a separation between the clay surface and the back face of the armour, which grows in time to substantial proportions. The permanent indentation left in the clay was 30 mm deep,

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whereas the maximum indentation in the armour plate was less than 7 mm. This separation phenomenon has been shown experimentally by high-speed X-ray photography in a previous PASS conference [15]. Their work also pointed out significant elastic rebound in the clay during ballistic impact, which was also observed in our own ball drop experiments using DIC measurements of the ball impact. Elastic rebound is not captured in the present model for reasons discussed earlier. Overall, the simulated plastic impact behavior of the clay seems consistent with experimental observation.

We are currently investigating how to better validate the simulations quantitatively, which remains challenging due to the extremely short timescales and large deformations involved. Examples of high-speed DIC measurements of armour panels during ballistic impact are prevalent in the literature [16], and we believe that this kind of experiment is a useful approach. We plan to report on progress in this area, as well as on incorporating deformable bullet models developed in-house and woven armour models from the literature, in future PASS conferences.



**Figure 4.** Simulation of a 20 mm rigid sphere impacting at 322 m/s on a 5 mm thick steel armour plate backed by a standard ballistic clay fixture at 37 °C. Results are shown at three time points: prior to impact (top left), just after armour-clay separation (top right), and well after armour-clay separation (bottom). Step time units are seconds. PEEQ stands for equivalent plastic strain.



**Figure 5.** Position histories along the axis of symmetry of the impacting sphere, the back surface of the armour, and the top surface of the clay during a ballistic impact simulation at 322 m/s.

## 4. CONCLUSIONS

We have outlined our vision of and progress toward creating finite element simulation tools for soft body armour testing. If successful, these tools can be employed by the testing community to improve and refine ballistic testing, making standard test methods even more robust and helping to draw more substantial links between testing conditions and actual blunt human injury.

Our current state of model development is as follows:

1) Material models for ballistic clay have been developed that show good quantitative agreement with the ball drop test and good qualitative agreement under actual ballistic impact conditions in terms of plasticity. Efforts are needed to better characterize the viscoelastic portion of the material response to fully capture the impact behavior of the clay.

2) A method for establishing models to predict dynamic deformation of the types of projectiles used in NIJ armour testing standards has been developed based on simulating dynamic, large strain axial impact tests on such bullets. Ballistic test simulations will be attempted using deformable bullet models run within commercial finite element codes that can be made to account for the extreme plastic strains that develop during ballistic impact, most likely via adaptive re-meshing techniques.

3) Accurate models of woven soft body armour are complex, and their continuing development remains at the forefront of ballistics research. As such, for the short term we will include idealized armour models that provide acceptable macro-scale response.

4) We are working to develop experiments that can provide time-resolved data during actual ballistic testing experiments. These data can be used to assess the accuracy of our ballistic test simulations, which bring together the data and model elements thus far developed that have been outlined in this paper.

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#### References

- [1] NIJ Standard-0101.06. Ballistic Resistance of Body Armour. Washington, DC (USA): U.S. Department of Justice, 2008.
- [2] Biermann PJ, Ward EE, Cain RP, Carkhuff BG, Merkle AC and Roberts JC, J. Adv. Mater., 38 (2006), 3-12.
- [3] Wilhelm M, and Bir C, Forensic Sci. Int., 174 (2008), 6-11.
- [4] Roberts JC, Ward EE, Merkle AC and O'Connor JV, J Trauma, 62 (2007), 1127-1133.
- [5] Shen X, Niu Y, Bykanova L, Laurence P and Link N, "Characterizing the Interaction Among Bullet, Body Armor, and Human and Surrogate Targets," J. Biomech, Eng.-T. ASME, 132 (2010).
- [6] Champion HR, Holcomb JB, Lawnick MM, et al., J Trauma, 68 (2010), 1139-1150.
- [7] Johnson GR and Cook WH, Proc. 7<sup>th</sup> Int. Symp. Ballistics, 1983.
- [8] Prather RN, Swann CL and Hawkins CE, Army Technical Report ARCSL-TR-77055, 1977.
- [9] Mates SP, Riley M, Forster A and Rice K, "Mechanical Behavior of Ballistic Clay as a Function of Temperature, Pressure and Strain Rate," Personal Armour Systems Symposium 2014, Cambridge, UK, Sept. 2014.
- [10] Mates SP, Rhorer RR, "Dynamic Deformation of Copper-Jacketed Lead Bullets: Experiments and Modeling," Personal Armour Systems Symposium 2010, Quebec City, Canada, Sept. 2010.
- [11] Sutton MA, Orteu JJ and Schreier HW, Image Correlation for Shape, Motion and Deformation Measurements, (Springer, New York, 2009).
- [12] Johnson GR, Hoegfeldt JM, Lindholm US and Nagy A, ASME J. Eng. Mat. and Tech., 105 (1983) 42-47.

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- [13] Mates SP, Rhorer RR, "Dynamic Deformation of Copper-Jacketed Lead Bullets Captured by High Speed Digital Image Correlation," Society for Experimental Mechanics 2010 Annual Meeting, Indianapolis, IN, June 7-10, 2010.
- [14] Meyers MA, The Dynamic Behavior of Materials, (Wiley-Interscience, New York, 1994), p.328.
- [15] Broos JPF, van der Jagt-Deutekom M, Halls VA, Zheng JQ, "Separation Between Armour and Clay Backing during Projectile Impact," Personal Armour Systems Symposium 2012, Nuremburg, Germany, Sept.17-21, 2012.
- [16] O'Masta MR, Compton BG, Gamble EA, Zok FW, Deshpande VS and Wadley HNG, Int. J. Impact Eng., 86 (2015), 131-144.