Development and use of an instrumented alternative to the clay box

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Abstract. Roma Clay #1 is frequently used in ballistic testing of body armour systems. It allows the residual depth of the clay indent to be measured, which standards limit for system approval. TNO is developing experimental methods that get more data from these tests. This data can be used to improve the correlation to injury and lethality. An instrumented clay box was developed that allows real time measurement of local pressure, local accelerations, as well as the indent depth using an ultrasound system. The positioning of the sensors in the box was aided by the use of finite element simulation of several bullet to armour systems with a clay backing. Using ultrasound pulses from the rear of the clay box, the formation of the bullet impact induced clay indent could be measured real time as well. This system also provides the maximal dynamic indent in the clay and its elastic recovery.

Experiments with the instrumented clay box on hard and soft body armour systems using various ballistic threats has given insight on the repeatability of the measurements. The use of RP1 required a special repair routine for the clay between each shot to maintain the sensitivity of the ultrasound measurement system. This significantly reduced the cycle time between shots. A second concept was developed where a transparent synthetic gelatin backing material was used which does not require repairs between shots and allows for high speed videos to verify the ultrasound measurements. The signals of the embedded sensors and the indent formation process can be used to compare and validate computer simulation results. The instrumented box allows parameters like pressure, acceleration and velocity of the clay to be measured to assess their possible correlation with injury levels.

1. INTRODUCTION

Measurements of indent depth in Roma plastilina #1 clay boxes have formed the backbone of body armour testing since the 1970s. The 44 mm behind-armour blunt trauma (BABT) standard was selected as threshold as it corresponds to a 6% probability of lethality [1]. TNO believes that the future of body armour lies in scalability of protection to correspond to the level of risk acceptance. This scalability requires that body armour testing should be able to identify different levels of injury consequences (where TNO has chosen to adopt the Abbreviated Injury Scale (AIS)).

The clay box used in ballistic testing of body armour systems only measures the residual backface deformation. TNO is developing experimental methods that get more data from these tests. Such data can be used to improve the correlation with injury and lethality. An instrumented clay box was developed that allows real time measurement of local pressure and accelerations, as well as the indent depth formation using an ultrasound system. The positioning of the sensors in the box was aided by the use of finite element simulation of several bullet to armour interactions with a clay backing. Using ultrasound pulses from the rear of the clay box, the formation of the clay indent could be measured real time as well.

This paper describes the parameter selection, experimental method and future plans for ballistic instrumented backings and TNO's vision on their function in body armour testing.

2. MEASUREMENT PARAMETER SELECTION

An instrumented backing requires selection of measurement parameters. For the instrumented backing, this choice is based on blunt injuries that may arise from non-penetrating impacts. Prediction of blunt injuries can be done using the blunt criterion [2, 3, 4] or the viscous criterion [5, 6].

$$BC = \ln\left(\frac{\frac{1}{2}MV^2}{W^{\frac{1}{3}}TD}\right) \quad (1)$$

$$VC_{max} = \left(\frac{dy(t)}{dt}\frac{y(t)}{D}\right)_{max} \quad (2)$$

The Blunt Criterion (1) correlates impact conditions (projectile mass M, velocity V and diameter D) and the human body (mss W, body wall thickness T) in order to predict injury. The Viscous Criterion

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(2) directly correlates torso deformation and velocity ($y(t)$, $\frac{dy(t)}{dt}$, scaled by the torso diameter D) to injury. Sturdivan [2] notes the similarity of both, energy based, approaches. This is reflected in the similarity of the outcomes. Sturdivan also suggests that the VC may be better suited for assessing blunt injury in experimental situations. The added benefit is that the VC is independent of any potentially applied armour. It should be noted that the VC was originally developed for automotive purposes. The application to ballistic impacts is researched and shows chest wall mechanics that are similar [7, 8] for sternum impacts.

However, to apply the VC the torso deformation (or a well correlating parameter) should be measured over time. The current claybox test method prescribes measurement of indent depth [9] and indent velocity [10], but the method does not allow for velocity measurements. This inspired the search of measurement parameters that can be used in future BABT testing equipment and the development of a measurement system with equipment that could measure or correlate to deformation velocity. Additional measurement parameters are also introduced (pressures and accelerations in the backing), so that future correlations to injury could be made based on multiple measured parameters.

3. EXPERIMENTAL METHOD

3.1 Sensor positioning

For the multiple use and repeatability of the instrumented clay box, the sensors should be sufficiently away from the impact and indent zone in order to prevent permanent displacement in the clay as a result of the impact. In order to determine this safe distance both experiments and FEM simulations have been performed. In the experimental set-up the clay consisted of a stack of Roma #1 clay disks with a thickness of about 2 cm and aluminum foil between the layers. Figure 1 shows images of both the FEM model and the stack of clay disks (laminate) after impact of a .44 Magnum bullet (at 400 m/s) with an Aramid surrogate vest as body armour (here protecting the clay stack). From both the FEM and the cross-section of the clay stack, the dent as well as the permanently (plastically) deformed zone can be observed. This allows the safe-distance from the impact point for the sensors in the clay to be determined (150 mm). A cylindrical area in the clay should be free of sensors in order not to damage them for the unwanted situation of a perforation of the armour. Figure 2 shows the position used for the embedded sensors in the clay block. The embedded sensors need a direct line of sight to the impact point of the projectile. Also, their alignment is important as it influences the measurements. For the pressure sensors, the alignment should be such that they are approximately perpendicular to the travel direction of the pressure wave. On the other hand, the acceleration sensors should be approximately aligned with the expected local deformation direction of the clay (which is approximately the travel direction of the pressure wave). The embedded pressure and acceleration sensors measure the pressure wave and local acceleration over time inside the clay.

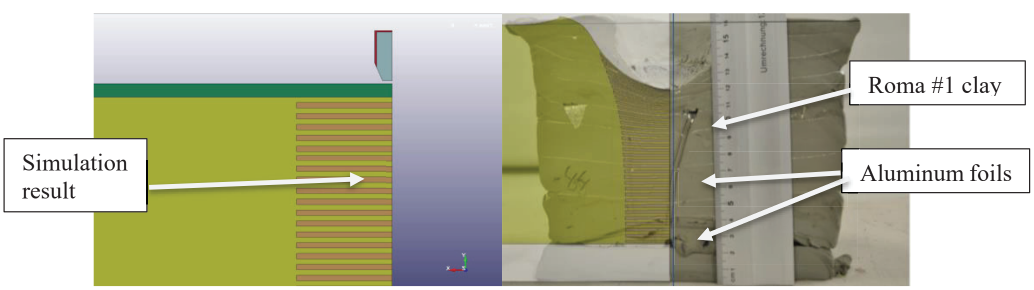

Figure 1. Simulation (left) and experimental result (right) of an indent (top) in Roma #1 clay (with aluminum foil interlayers) after impact of a .44 Magnum on an Aramid simulant vest

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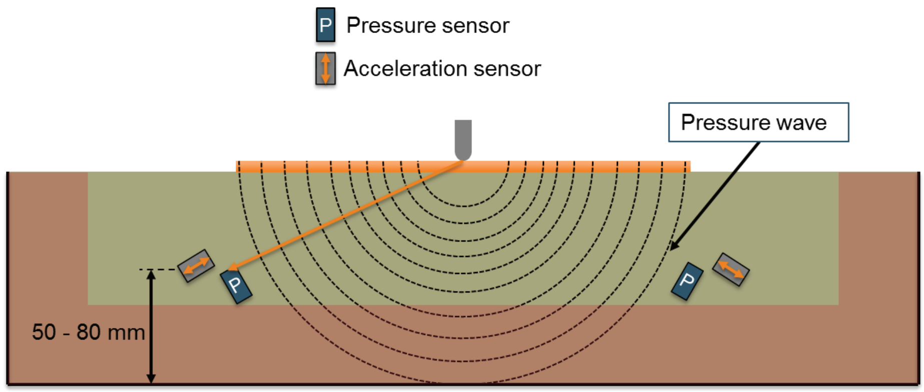

Figure 2. Cross-section of the clay box showing the position of the pressure and acceleration sensors

3.2 Back-face deformation

The back-face deformation is measured dynamically by transmitting ultrasonic pulses rapidly after each other, see figure 3. The two wedges are filled with Roma #1 plastilina clay. The wedge angle is 30 degrees. On each wedge a 250 kHz transducer is mounted. The distance between the two wedges can be varied to change the depth of the beam intersection point (focal point) in the clay. When the clay starts deforming the arrival time between the pulses will change. The time difference can be translated to the indentation depth during the development of the dent.

For the ballistic experiments a pulse repletion time of 100 µs is used. A typical display of a measurement is shown in Figure 4. The horizontal axis is the time scale at which the indentation occurs. The vertical axis is ultrasonic travel time. At 7 ms the pressure wave arrives and the clay starts to deform, a dent is formed which reduces the distance, hence travel time to the reflecting free clay surface. The pressure wave is very strong and overloads the ultrasonic measurement initially for a short time. Just in time the ultrasonic signal is obtained again to determine the maximal indent size and its reduction due to elastic recovery of the clay. The constant value corresponds to the indent depth that is normally measured (many seconds) after an experiment.

The ultrasonic waves reflect from inhomogeneities in a material, for the clay box this means that any voids, foreign objects and residual air pockets resulting from indentation repairs may cause reflections. These unwanted reflections interfere with the indentation echo. A special repair method for the indent of the clay was developed which has to be applied between each shot. Also the temperature sensitivity of the clay provides an issue as its velocity of sound is a function of temperature. In order to keep the clay box at one temperature (39 °C), it was decided to heat the clay box during its operation in the shooting range using two infra-red heaters; one at the back and one in front of the clay box. Figure 5 only shows the infra-red heater in front of the instrumented clay box, which was positioned away from the strike-face in order to allow personnel access for sample manipulation and indent repairs.

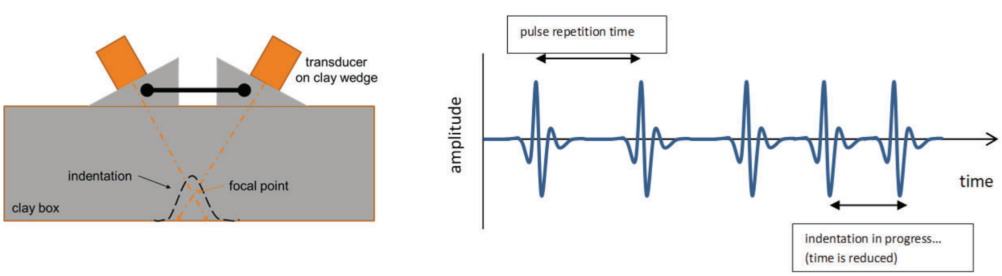

Figure 3. Working principle of the time-resolved ultrasonic clay deformation measurement

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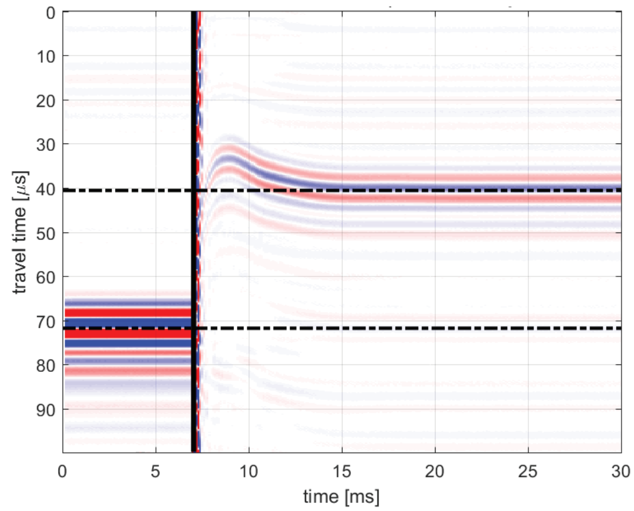

Figure 4. Ultrasonic result of indent formation in clay due to projectile impact. Dashed lines indicate the initial (70 µs) and final position (40 µs) of the dent in the clay

Figure 5. Infra-red heater (lower-right) in front of the instrumented clay box allowed the temperature to be constant and provided access for personnel.

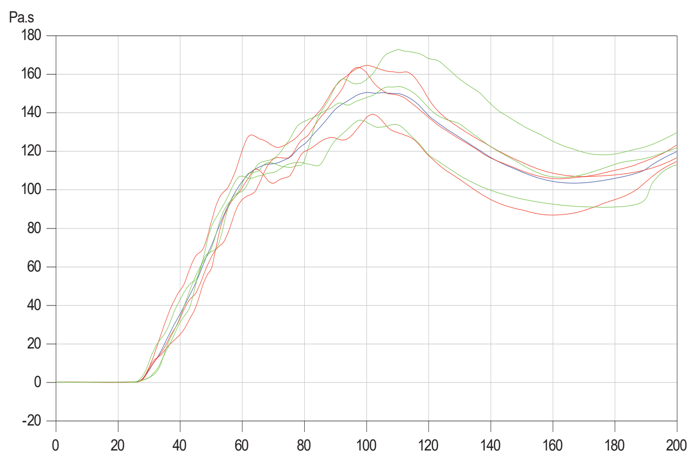

Figure 6. Impulse from pressure signal in clay (P2) of several identical 7.62 Ball shots (at 830 m/s) on a Dyneema® plate in conjunction with a surrogate vest.

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3.3 Pressure and acceleration measurements

Figure 2 provides the position of the pressure and acceleration sensors within the clay. The pressure signals were rather noisy, yet after their integration over time, a reproduceable measurement of the impulse is obtained. Figure 6 provides the impulse from one of the embedded pressure sensor signals in clay for several repeated 7.62 Ball shots (at 830 m/s) on a Dyneema® plate in conjunction with a surrogate vest. After about 27 microseconds the pressure wave reaches the sensor and the impulse starts to rise. This behavior is quite repeatable. At about 60 microseconds the rise in impulse is interrupted, yet starts again at about 80 microseconds to reach its maximum of about 150 Pa s around 100 microseconds.

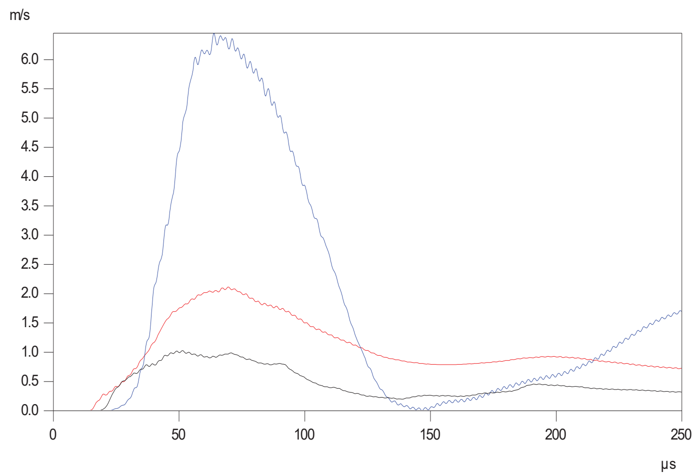

Figure 7. Velocity plots by integration of the embedded acceleration sensor (A1) signal impact of 9 mm FMJ at 400 m/s (black), .44 Magnum at 400 m/s (red) and 7.62 Ball at 830 m/s (blue).

Also the acceleration signals were very noisy, but again after their integration a reasonable smooth velocity history of the embedded sensor in the clay is obtained. Figure 7 compares velocity plots for the three projectiles used in this work: 9 mm FMJ (black), .44 magnum (red) and 7.62 Ball (blue). From figure 7 we see that for each projectile-target combination the maximal (local) clay velocity is reached at about 25 microseconds after the start of the signal. However, the maximal velocity reached is about 1 m/s for the 9 mm FMJ, 2 m/s for the .44 Magnum and 6.5 m/s for the 7.62 Ball. The decline of the (local) clay velocity is slower compared to its initial rise.

4. SYNTHETIC GELATIN BACKING

The instrumented ballistic clay box demonstrated the use of ultrasonic sensors for dynamic deformation measurements in clay. However, the inhomogeneity of clay, especially after multiple tests, causes a deterioration of the signal quality. To overcome this issue a search for a different backing material was initiated.

The second version of the instrumented backing uses Clear Ballistics (a commercial transparent synthetic elastomer). The choice for this material is based on;

- the homogeneity of the material for signal transmission
- the reduced need for repairs between shots due to the hyper elasticity
- the ease of repairability when needed (it can be casted)
- transparency to enable high speed imaging as a means to verify measurements

As this elastomeric material is hyper-elastic it will (self) recover directly after each impact, which prevents the shot-to-shot activity of indent repair and its chance on introduction of air gaps. This also saves a lot of time between shots allowing much more shots per hour.

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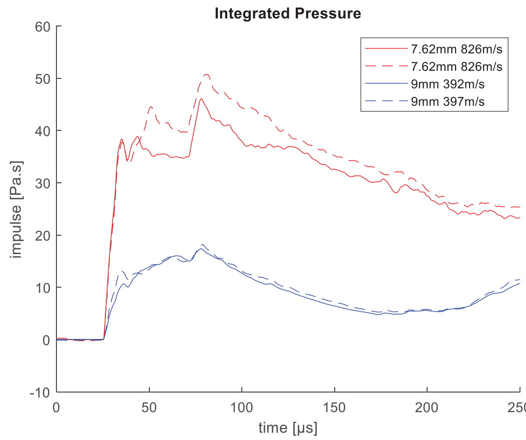

Figure 8. Impulse from pressure signal in clear ballistics (P1) of two 7.62 Ball shots on a Dyneema® plate in conjunction with a surrogate vest and two 9mm shots on a vest.

The homogeneity of the elastomer ensures a much higher signal quality from all of the sensors and improves the repeatability of measurements (see figure 8). If one compares impulse measured for the 7.62 Ball shots on Clear Ballistics (figure 8) and Roma #1 clay (figure 6) there are quite some differences in signal shape and height. This is caused by the difference in both material (properties like density and stiffness) as well as the sensor position.

The transparent clear ballistics also allows a highspeed camera to record the deformation. Holes at the side of the box allow a side view on the impact area. The high speed video was calibrated using static indentations of known dimensions.

Though deformation of the transparent elastomer may result in image distortion due to refraction, the maximum deformation can be reliably extracted. This allows the high speed video to provide verification data of the ultrasonic measurements, see figure 9.

This elastomer based instrumented backing shows the potential benefits of a homogenous, elastic backing material. It provides improved results and reduces practical issues such as the need for repairs. Further investigation is required on the long-term ageing effects and temperature dependency on the performance of this alternative backing material as well as its differences compared to Roma #1 clay.

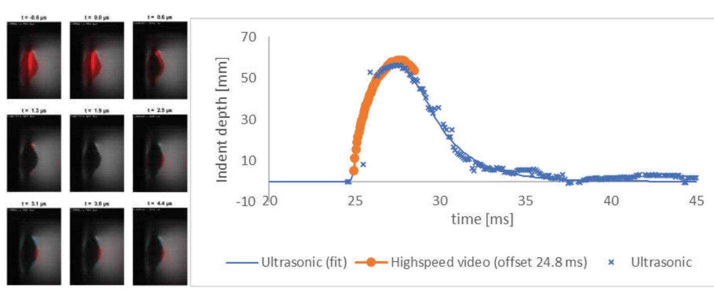

Figure 9. Clay deformation measurements using ultrasonic (blue) and highspeed video (orange) simultaneously.

5. INJURY LEVEL

The Blunt Criterion (1) correlates impact conditions (projectile mass M, velocity V and diameter D) and the those of the human body (mass W, body wall thickness T) to predict an injury level.

The kinetic energy of a 9 mm bullet at 353 m/s equals 500 Joules (E = ½ 0.00804 353^2 = 500 J). The mass of the clay box (body) used is 80 kg. The body (chest) wall thickness is estimated as $0.71*W^{1/3}$ = 2.3 cm. The effective diameter D is estimated to be 2 cm (includes diameter of the bullet and thickness of the body armour. Then, using equation 1 the blunt criterion is calculated as BC = ln [500/(4.3*2.3*2)] = 3.2, which can be estimated as AIS = 0.55 * BC = 1.75.

As the time-resolved ultrasonic measurement of the indent process allows the displacement (dy) and velocity of the clay to be determined (dy/dt), also the Viscous Criterion (equation 2) can be used for injury assessment.

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6 CONCLUSIONS

The clay backing system has its disadvantages, yet its application has helped to significantly reduce BABT related lethality. It remains the most widely used method to assess BABT. That does not prevent the continued development of new measurement systems. More data (besides just the residual indent depth) could provide a more refined appraisal of the PPE performance. Therefore, TNO is continuing research in this field. The presented clay box is a further development of the current setup, extended with pressure, acceleration and indent velocity measurements.

The safe positioning of ultrasonic transducers, as well as pressure and acceleration sensors has been determined both using FEM and experiments. The embedded sensors allow local pressure and acceleration histories to be recorded, while the ultrasonic set-up recorded the formation of the indent in the clay. The latter not only provides the terminal indent depth, but also the maximal dynamic indent depth, as well as the maximal clay velocity upon projectile impact on body armour. The measured parameters can be used to calculate injury levels using the viscous and blunt criteria.

The instrumented clay-box therefore provides a useful research tool for body armour and injury related research. It was shown to provide reproducible results using body armours impacted by 9 mm FMJ, .44 Magnum and 7.62 Ball projectiles.

A second system is assessed that evaluates a synthetic hyper-elastic material as a potential replacement for the clay backing. An elastomeric backing provides a more homogeneous medium, resulting in improved signals from the sensors, as well as a potential backing material that has no plastic deformation and hence does not need repair between tests.

The instrumented clay box with both backing materials are developed to improve current test methodologies. The instrumented system shows that more data can be obtained from a clay backing. It also provides a tool to assess the quality of the state of the clay. Some of the practical drawbacks of clay remain, and alternative backing materials should be explored to improve the quality of testing of body armours.

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