Thermal Softening Effects on Simulation Models of Fiber-Reinforced Plastics Under High-Velocity Impact

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***Abstract*—In the security sector, the partly insufficient safety of people and equipment due to failure of industrial components is an ongoing problem that causes great concern. Since computers and software have spread into all fields of industry, extensive efforts are currently made to improve the safety by applying certain numerical solutions. A fibre-reinforced composite is a promising material for ballistic protection due to its high strength, stiffness and low density. Para-aramid fibre was introduced into the market in the 1970s. These fibres are five times stronger than steel. In more recent years, Ultra-High Molecular Weight Polyethylene (UHMW-PE) fibre has been used in ballistic application owing to certain property advantages. UHMW-PE composites as part of the personal armour system have the potential to provide significant weight savings or improved protection levels over traditional metallic materials. Although already used in different applications, both as spall liners and within complex multi-element/multi-material packages, there is a limited understanding of the mechanisms driving ballistic performance. Existing analysis tools do not allow a good approximation of performance, while existing numerical models are either incapable of accurately capturing the response of thick UHMW-PE composite to ballistic impact or are unsuited to model thick targets. In response, this paper aims to identify the key penetration and failure mechanisms of thick UHMW-PE composites under ballistic impact and develop numerical models that capture these mechanisms and allow accurate prediction of ballistic performance to optimize modern armour systems. An important aspect of impact loading of polyethylene-based composites is their propensity to thermally soften or even melt during a collision due to shock heating. Consequently, this needs to be taken into account in both analytical and computational models. The motivation of this work was to develop a thermal softening model and investigate the effects on existing simulation models.**

Keywords-hydrocode analysis; thermal softening; fiber-reinforced plastics; optimization; armor systems; ballistic trials.

I. INTRODUCTION

The object behind combining different materials to form a composite with enhanced properties and synergetic effects is par for the course in nature. A section through a paracortical cell in merino wool or through a bamboo stems exhibits structures similar to the micrograph of a unidirectional Carbon-Fibre-Reinforced Epoxy Resin (CF-EP). Not only in the microstructure can nature be seen as the progenitor of fibre-reinforced plastics, but also in the application of lightweight design principles.

Why material scientists integrate fibers in materials to such advantage can be answered by the following four paradoxes of engineering materials:

- The paradox of the solid material: The actual strength of a solid material is very much lower than the calculated theoretical value.
- The paradox of the fiber form: The strength of a material in fiber form is many times higher than that of the same material in another form, and the thinner the fiber, the greater the strength.
- The paradox of the free clamped length: The shorter the length between the clamps, the greater the strength measured on the test piece.
- The paradox of composites: When taken as a whole, a composite can withstand stresses that would fracture the weaker component, whereas the composite's stronger component can exhibit a greater percentage of its theoretical strength than when loaded singly.

So, the principle of combining different materials to form a composite with enhanced properties is just as common in nature as it is in lightweight engineering. This design method based on nature's example has virtually revolutionized many fields of technology, with the result that they can now utilize the superior properties of high-tensile, lightweight materials for the first time.

This work will focus on fiber-reinforced plastics, more precisely composite armor structures consisting of several layers of UHMW-PE, a promising ballistic armor material due to its high specific strength and stiffness. First numerical approaches are discussed in [1].

UHMW-PE is a thermoplastic polymer made from very long molecular chains of polyethylene. Thermoplastics soften when subjected to heat and so can be repeatedly remoulded. Cut-offs can be remelted and introduced back into the production process. Many thermoplastics are soluble in organic solvents. Thermoplastics can be joined by welding under the application of heat or by the action of solvents [2].

Figure 1 shows the chemical structure of polyethylene, where in UHMW-PE the number of repeated chains (n) is in the order of 10^5, giving rise to molecular weights in the order of 10^6 [3]. As a non-polar molecule, interaction between polyethylene molecules is given by very weak Van der Waals forces.

However, due to the ultra-long polymer chain, significant strength can be derived through a gel spinning process that produces highly oriented and crystalline molecular structures aligned in the spinning direction. The gel spinning process firstly involves dissolving UHMW-PE in a solvent at high temperature. The solution is then pushed through a spinneret to form liquid filament that is then quenched in water to form gel-fibers. These fibers are then drawn in hot air at high strain rates of the order of 1 s^{-1} forming fibers with smooth circular cross-sections approximately 17 µm in diameter [4] with a molecular orientation greater than 95% and a crystallinity of up to 85% [3], see Figure 2.

These fibers are composed of smaller macro-fibrils approximately 0.5 mm to 2 mm in diameter, which in turn are made of micro-fibrils, 20 nm in diameter. Commercial UHMW-PE fiber is manufactured by, amongst others, Dutch State Mines (DSM) and Honeywell under the trade names Dyneema® and Spectra®, respectively. The fibers are used in a variety of applications requiring high specific strength and low weight. This includes high strength ropes and nets, cut-resistant gloves, as well as blast and ballistic protection.

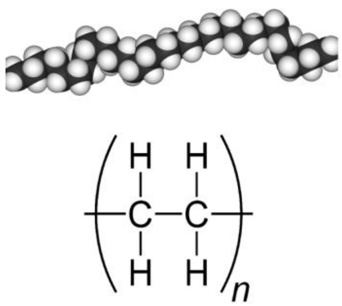

Figure 1. Skeletal formula and spacefill model of a polyethylene.

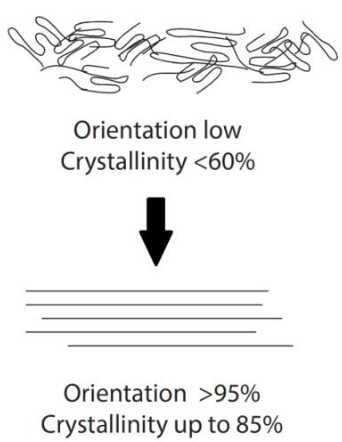

Figure 2. Increase in molecular orientation and crystallinity through gel spinning of UHMW-PE [5].

For ballistic protection applications, the fibers can be woven into fabrics to provide a soft and flexible material or coated in a matrix and aligned to form uni-directional plies, which are then stacked and pressed under temperature and pressure to form rigid laminates.

UHMW-PE composites and fabrics have been shown to be extremely effective against ballistic threats, particularly in weight-critical applications, e.g., personal protection vests and helmets for protection against small calibre threats [6]. The goal is to evaluate the ballistic efficiency of UHMW-PE composite with numerical simulations, promoting an effective development process. Additionally, a thermal softening model is implemented and analyzed.

After a brief introduction and an overview of all state-of-the-art models of fiber-reinforced plastics, the principles of simulation are discussed in Section III, followed by the penetration and perforation principles of composites in Section IV. There is a short section on ballistic trials where the experimental set-up is depicted, followed by Section VI describing the model validation. Section VII presents the analysis with numerical simulations and the results of this work. The paper ends with a concluding paragraph in Section VIII.

II. State-of-the-art

The numerical modelling of composite materials under impact can be performed at a constituent level (i.e., explicit modelling of fiber and matrix elements, e.g., [7]), a meso-mechanical level (i.e., consolidated plies or fiber bundles, e.g., [8]), or macromechanically in which the composite laminate is represented as a continuum.

In [9–12], a non-linear orthotropic continuum material model was developed and implemented in a commercial hydrocode (i.e., ANSYS® AUTODYN®) for application with aramid and carbon fiber composites under hypervelocity impact. The non-linear orthotropic material model includes orthotropic coupling of the material volumetric and deviatoric responses, a non-linear Equation of State (EoS), orthotropic hardening, combined stress failure criteria and orthotropic energy-based softening. For more detail refer to [13].

Lässig et al. [14] conducted extensive experimental characterization of Dyneema® HB26 UHMW-PE composite for application in the continuum non-linear orthotropic material model, and validated the derived material parameters through simulation of spherical projectile impacts at hypervelocity.

A number of researchers have applied the non-linear orthotropic model for UHMW-PE composites with varying levels of success (Hayhurst et al. [15], Herlaar et al. [16], Ong et al. [17], Heisserer and Van der Werff [18] and Lässig et al. [14]). Ong et al. [17] assumed material properties of UHMW-PE composite based on those of Kevlar® with some data from literature, which resulted in poor predictions of the penetration behaviour. Hayhurst et al. [15], Herlaar et al. [16], Heisserer and Van der Werff

[18] used material input parameters derived from a range of experiments, and reported better prediction, although the results cannot be independently verified because the material parameters are not provided. Nguyen et al. [19] evaluated and refined the modelling approach and material model parameter set developed in [14] for the simulation of impact events from 400 m/s to 6600 m/s. Across this velocity range, the sensitivity of the numerical output is driven by different aspects of the material model, e.g., the strength model in the ballistic regime and the EoS in the hypervelocity regime.

This paper will present an optimized solution of this problem with an enhanced model for ultra-high molecular weight polyethylene under impact loading. The composite armor structures consisting of several layers of fiber-reinforced plastics are simulated for all current military threats. Following this, a user-defined subroutine was written to incorporate the effects of thermal heating into the material data. This subroutine was then tested iteratively until an appropriate level of thermal softening was accounted for to accurately predict the deformation, damage and residual velocity of a range of target thicknesses and impact velocities.

III. PRINCIPLES OF SIMULATION

To deal with problems involving the release of a large amount of energy over a very short period of time, e.g., explosions and impacts, there are three approaches: as the problems are highly non-linear and require information regarding material behavior at ultra-high loading rates which is generally not available, most of the work is *experimental* and thus may cause tremendous expenses. *Analytical* approaches are possible if the geometries involved are relatively simple and if the loading can be described through boundary conditions, initial conditions or a combination of the two. *Numerical* solutions are far more general in scope and remove any difficulties associated with geometry [20]. They apply an explicit method and use very small time steps for stable results.

For problems of dynamic fluid-structure interaction and impact, there typically is no single best numerical method which is applicable to all parts of a problem. Techniques to couple types of numerical solvers in a single simulation can allow the use of the most appropriate solver for each domain of the problem.

The goal of this paper is to evaluate a hydrocode, a computational tool for modelling the behavior of continuous media. In its purest sense, a hydrocode is a computer code for modelling fluid flow at all speeds. In essence, the code considers the effect of external and internal forces on a predefined "mesh" of cells [21]. For that reason, a structure will be split into a number of small elements. The elements are connected through their nodes (see Figure 3). The behavior (deflection) of the simple elements is well-known and may be calculated and analyzed using simple equations called shape functions [22].

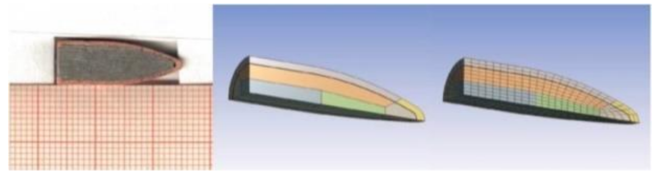

Figure 3. Example grid.

By applying coupling conditions between the elements at their nodes, the overall stiffness of the structure may be built up and the deflection/distortion of any node – and subsequently of the whole structure – can be calculated approximately [23].

A repeatedly used term in this context will be discretization. Its meaning is that equations, formulated to continuously describe a function or functional in space and time, is solved only at certain discrete locations and instants of time [24]. The most commonly used spatial discretization methods are Lagrange, Euler, ALE (a mixture of Lagrange and Euler), and mesh-free methods, such as Smooth Particles Hydrodynamics (SPH) [25].

A. Lagrange

The Lagrange method of space discretization uses a mesh that moves and distorts with the material it models as a result of forces from neighboring elements (meshes are imbedded in material). There is no grid required for the external space, as the conservation of mass is automatically satisfied and material boundaries are clearly defined. This is the most efficient solution methodology with an accurate pressure history definition.

The Lagrange method is most appropriate for representing solids, such as structures and projectiles. If however, there is too much deformation of any element, it results in a very slowly advancing solution and is usually terminated because the smallest dimension of an element results in a time step that is below the threshold level.

B. Euler

The Euler (multi-material) solver utilizes a fixed mesh, allowing materials to flow (advect) from one element to the next (meshes are fixed in space). Therefore, an external space needs to be modeled. Due to the fixed grid, the Euler method avoids problems of mesh distortion and tangling that are prevalent in Lagrange simulations with large flows. The Euler solver is very well-suited for problems involving extreme material movement, such as fluids and gases. To describe solid behavior, additional calculations are required to transport the solid stress tensor and the history of the material through the grid. Euler is generally more computationally intensive than Lagrange and requires a higher resolution (smaller elements) to accurately capture sharp pressure peaks that often occur with shock waves.

C. ALE

The ALE method of space discretization is a hybrid of the Lagrange and Euler methods. It allows redefining the grid continuously in arbitrary and predefined ways as the calculation proceeds, which effectively provides a

 ISBN: 978-1-61208-672-9

continuous rezoning facility. Various predefined grid motions can be specified, such as free (Lagrange), fixed (Euler), equipotential, equal spacing, and others. The ALE method can model solids as well as liquids. The advantage of ALE is the ability to reduce and sometimes eliminate difficulties caused by severe mesh distortions encountered by the Lagrange method, thus allowing a calculation to continue efficiently. However, compared to Lagrange, an additional computational step of rezoning is employed to move the grid and remap the solution onto a new grid [26].

D. SPH

The mesh-free Lagrangian method of space discretization (or SPH method) is a particle-based solver and was initially used in astrophysics. The particles are imbedded in material and they are not only interacting mass points but also interpolation points used to calculate the value of physical variables based on the data from neighboring SPH particles, scaled by a weighting function. Because there is no grid defined, distortion and tangling problems are avoided as well. Compared to the Euler method, material boundaries and interfaces in the SPH are rather well defined and material separation is naturally handled. Therefore, the SPH solver is ideally suited for certain types of problems with extensive material damage and separation, such as cracking. This type of response often occurs with brittle materials and hypervelocity impacts. However, mesh-free methods, such as Smooth Particles Hydrodynamics, can be less efficient than mesh-based Lagrangian methods with comparable resolution.

ANSYS Autodyn lets you select from these different solver technologies so he most effective solver can be used for a given part of the model. Figure 4 gives a short overview of the solver technologies mentioned above. The crucial factor is the grid that causes different outcomes.

Using a CAD-neutral environment that supports bidirectional, direct, and associative interfaces with CAD systems, the geometry can be optimized successively [28]. Therefore, several runs are necessary: from modelling to calculation to the evaluation and subsequent improvement of the model.

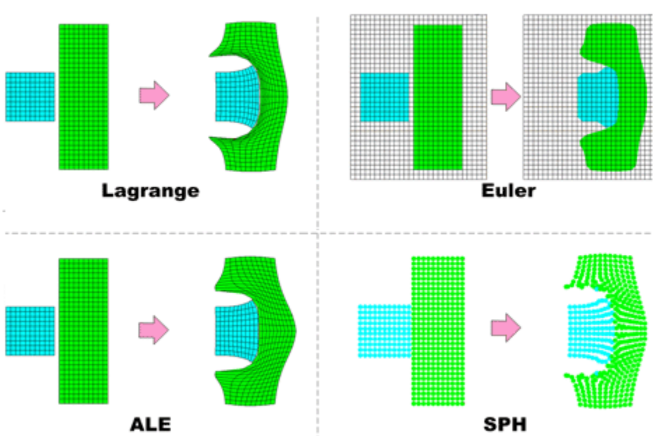

Figure 4. Examples of Lagrange, Euler, ALE, and SPH simulations on an impact problem [27].

AUTODYN's interaction logic enables automatic communication between the various solvers coexisting within the same model. Lagrange-Lagrange, SPH-Lagrange and Euler-Lagrange interactions can all be created within the model in a simple and intuitive manner. This allows fluid structure interactions to be simulated. Furthermore, it can be combined with AUTODYN's extensive remapping and dezoning capabilities between the different solvers and a wide range of erosion settings. It is also possible to retain inertia of eroded material. In this case, the mass and momentum of the free node is retained and can be involved in subsequent impact events to transfer momentum in the system.

IV. Penetration and Perforation of Composites

Composites have arguably been used as armor materials since the middle ages. Advantages of using composite materials are their relatively low density, their tailorable properties, and fair to high strength. The disadvantages of composites are the inconsistency of hand lay-up, the dependency of strength on manufacturing process, and the somewhat expensive nature of their manufacture. Additionally, composites pose a problem to the designers because they are difficult to model.

Composites resist penetration primarily by dissipating energy. Because of the complex structure of the material, this energy dissipation manifests itself in the failure of portions of the laminate, fiber breakage, matrix cracking, and delamination. Since composite properties can vary from isotropic to a complicated anisotropic, the behavior will depend upon the configuration.

In chopped fiber composites, the material properties are usually isotropic. A notable exception to this is in injection moldings where the fibers tend to align with the flow directions near mold gate areas or areas of higher velocity flow. An isotropic composite is usually treated as we do a metal and those formulas should work well.

Continuous fiber composites behave differently from metallic plates. A typical load-displacement curve is shown in Figure 5. In this figure, after an initial delamination point, where the load carrying capability is degraded, we see increases and decreases in load carrying ability based on successive delaminations of material followed by a final plug shear out. This delamination actually promotes energy dissipation by forcing the fibers to elongate. In many composites, shear failure of the fibers, as well as tensile failures dominate during an impact [29].

It is extremely difficult to obtain an analytical model for the penetration of continuous fiber composites. This is due to the change of energy dissipation as the composite is damaged. Finite element methods have been utilized to determine limit velocities, but there are nuances to each analysis that must be explained. Section II presents a general view of all state-of-the-art models of fiber-reinforced plastics.

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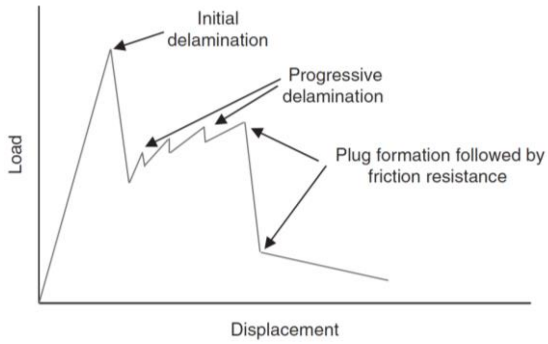

Figure 5. Load–displacement curve for a typical continuous fiber reinforced composite.

The first issue that must be dealt with is how to handle the damage and its effect on the remaining strength of the composite. Some researchers have actually modeled each lamina with its correct directional properties and assumed a failure criterion based on interlaminar shear strength [30]. When the interlaminar shear strength is exceeded, the layer no longer supports shear and the overall bending stiffness is reduced. This can be accounted for explicitly having the model change internal constraints between layers or implicitly by tracking the overall smeared bending stiffness of the composite and reducing it based on the lamina that failed. Another means of handling the behavior of the composite is to average the stiffness change because of the progressive failure of lamina as shown in Figure 6. The issue with this approach is that test data from some sort of penetration event is required.

A second issue with analyzing fiber reinforced composites is the actual failure of the fibers themselves. The fibers can themselves delaminate from the matrix. They can also fail in tension and are usually very sensitive to fracture. These issues of necessity complicate the analysis.

After extensive work in the area of composite materials under impact loads, the following observations regarding their behavior were made: First, delaminations tend to prefer moving along the fiber direction. Additionally, compression of the composite material (e.g., at clamped locations) tends to suppress delamination, as one would expect. The extent of delamination increases linearly as the distal surface is approached if perforation occurs.

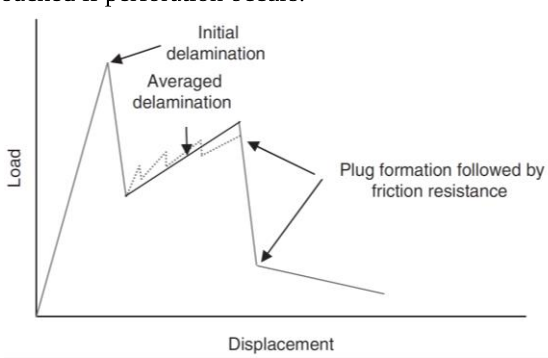

Figure 6. Load–displacement curve for a typical fiber reinforced composite modeled with averaged properties after initial delamination.

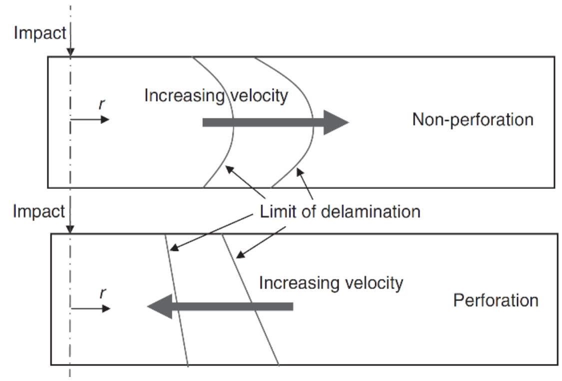

Figure 7. Extent of delamination in a composite with respect to increasing velocity during both perforating and nonperforating impacts.

However, the delamination increases then decreases if no penetration occurred. As the impact velocity increases, the delamination decreases indicating that the bending of the target becomes less significant. This is shown in Figure 7.

V. BALLISTIC TRIALS

Ballistics is an essential component for the evaluation of our results. Here, terminal ballistics is the most important sub-field. It describes the interaction of a projectile with its target. Terminal ballistics is relevant for both small and large caliber projectiles. The task is to analyze and evaluate the impact and its various modes of action. This will provide information on the effect of the projectile and the extinction risk.

The science and engineering of impacting bodies have a large range of applications depending on their type and their impact velocities. At very low velocities, these impacts can be limited to the elastic range of response, with practically no damage to the impacted bodies. In contrast, at very high impact velocities these bodies experience gross deformation, local melting, and even total disintegration upon impact. Various scientific and engineering disciplines are devoted to specific areas in this field such as: vehicle impacts, rain erosion, armor and anti-armor design, spacecraft protection against meteorites and the impact of planets by large meteors at extremely high velocities.

Given that a projectile strikes a target, compressive waves propagate into both the projectile and the target. Relief waves propagate inward from the lateral free surfaces of the penetrator, cross at the centerline, and generate a high tensile stress. If the impact was normal, we would have a two-dimensional stress state. If the impact was oblique, bending stresses will be generated in the penetrator. When the compressive wave reached the free surface of the target, it would rebound as a tensile wave. The target may fracture at this point. The projectile may change direction if it perforates (usually towards the normal of the target surface).

Because of the differences in target behavior based on the proximity of the distal surface, we must categorize targets into four broad groups. A semi-infinite target is one where there is no influence of distal boundary on

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penetration. A thick target is one in which the boundary influences penetration after the projectile is some distance into the target. An intermediate thickness target is a target where the boundaries exert influence throughout the impact. Finally, a thin target is one in which stress or deformation gradients are negligible throughout the thickness.

There are several methods by which a target will fail when subjected to an impact. The major variables are the target and penetrator material properties, the impact velocity, the projectile shape (especially the ogive), the geometry of the target supporting structure, and the dimensions of the projectile and target.

In order to develop a numerical model, a ballistic test program is necessary. The ballistic trials are thoroughly documented and analyzed – even fragments must be collected. They provide information about the used armor and the projectile behavior after fire, which must be consistent with the simulation results (see Figure 8).

Several experiments have to be performed to create a data set for the numerical simulations. Ballistic tests are recorded with high-speed videos and analyzed afterwards. The experimental set-up is shown in Figure 9.

The camera system is a PHANTOM v1611 that enables fast image rates up to 646,000 frames per second (fps) at full resolution of 1280 x 800 pixels. The use of a polarizer and a neutral density filter is advisable, so that waves of some polarizations can be blocked while the light of a specific polarization can be passed.

Several targets of different laminate configurations were tested to assess the ballistic limit (V_{50}). The ballistic limit is considered the velocity required for a particular projectile to reliably (at least 50% of the time) penetrate a particular piece of material [30]. After the impact, the projectile is examined regarding any kind of change it might have undergone.

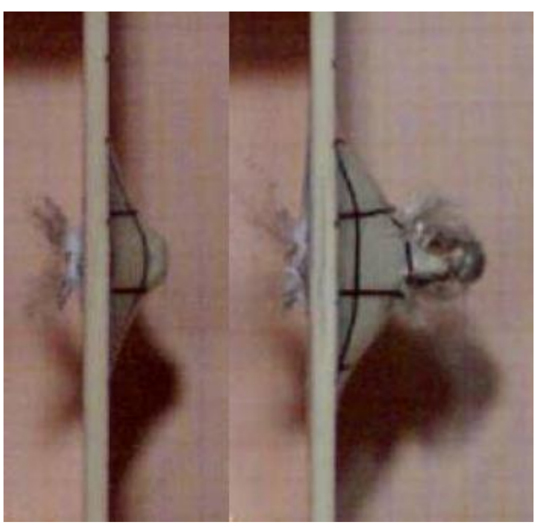

Figure 8. Ballistic tests and the analysis of fragments after 47 µs (left) and 88 µs (right).

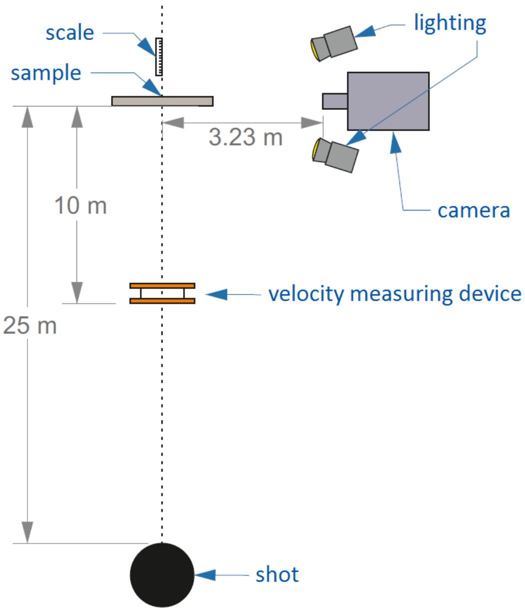

Figure 9. Experimental set-up.

The damage propagation is analyzed using the software called COMEF [31], image processing software for highly accurate measuring functions. The measurement takes place via setting measuring points manually on the monitor. Area measurement is made by the free choice of grey tones (0…255). Optionally the object with the largest surface area can be recognized automatically as object. Smaller particles within the same grey tone range as the sample under test are automatically ignored by this filter.

VI. Model Validation

Experimental characterisation of the ballistic performance of UHMW-PE composite can be prohibitively expensive, so it is highly desirable to establish computationally efficient numerical models that accurately predict the ballistic response of the material. First, existing models should be validated.

A. *Resources*

In [19], numerical simulations of 15 kg/m^2 Dyneema® HB26 panels impacted by 6 mm diameter aluminum spheres between 2052 m/s to 6591 m/s were shown to provide very good agreement with experimental measurements of the panel ballistic limit and residual velocities, see Figure 10. The modelling approach and material parameter set from [14] were applied to simulate impact experiments at velocities in the ballistic regime (here considered as < 1000 m/s). Lambert-Jonas parameters (a, p, V_{bl}) are provided in the legend.

In Figure 11, the results of modelling impact of 20 mm fragment simulating projectiles (FSPs) against 10 mm thick Dyneema® HB26 are shown. The model shows a significant under prediction of the ballistic limit, 236 m/s compared to 394 m/s.

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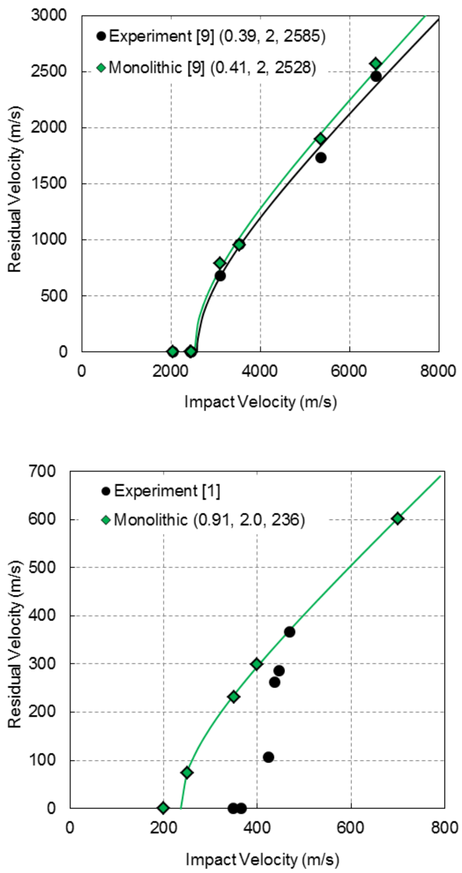

Figure 10. Experimental and numerical impact residual velocity results for impact of 6 mm diameter aluminum spheres (above) and 20 mm FSP (below) against 10 mm thick HB26 at normal incidence.

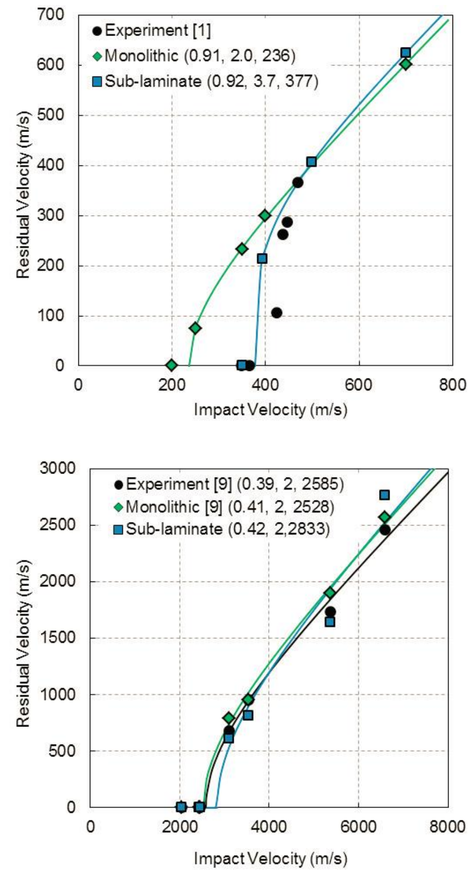

Figure 11. Experimental and numerical results with the two numerical models for 20 mm FSP against 10 mm thick HB26 (above), and 6 mm diameter aluminium spheres against HB26 (below) at normal incidence.

B. *Method*

The FSP material was modelled as Steel S-7 from the AUTODYN library using a linear EoS and the Johnson-Cook strength model [32]. The aluminum sphere was modelled using AL1100-O from the AUTODYN library that uses a shock EoS and the Steinburg Guinan strength model [33]. The master-slave contact algorithm was used to detect contact between the target and projectile.

The sub-laminate model with shock EoS was applied to the aluminum sphere hypervelocity impact series and 20 mm FSP ballistic impact series presented in Figure 10, the results of which are shown in Figure 11.

The sub-laminate model is shown to provide a significant improvement in predicting the experimental V_{50} of 394 m/s for the FSP ballistic impacts (377 m/s) compared to the monolithic model (236 m/s).

The ballistic limit and residual velocity predicted with the sub-laminate model for the hypervelocity impact case are shown to be comparable with the original monolithic model. For conditions closer to the ballistic limit, the sub-laminate model is shown to predict increased target resistance (i.e., lower residual velocity). For higher overmatch conditions, there is some small variance between the two approaches.

Now, regarding common handgun projectiles, the results look sobering. As the most widespread weapon in the world, the Kalashnikov rifle (AK-47) is a good example to compare ballistic trials and simulation results. A 7.62×39 mm full metal jacket (FMJ) projectile with a velocity of 700 m/s is used and the model is shown in Figure 3.

In Figure 12, a qualitative assessment of the bulge formation is made for the 11 mm panel. Prediction of bulge development is important as it is characteristic of the material wave speed and is also a key measure in defence applications, particularly in personal armour systems (i.e., vests and helmets). In the ballistic experiments, the 11 mm target panel resists the 7.62×39 mm FMJ projectile. On the left, the “state-of-the-art” models of Lässig and Nguyen are shown. But in both models, material fails, and the projectile penetrates the plate.

There is no accurate reproduction of the bulge. The problem is a neglect of micro-structures. Fraction and fragmentation between the laminate layers cannot be described by homogeneous continuum models.

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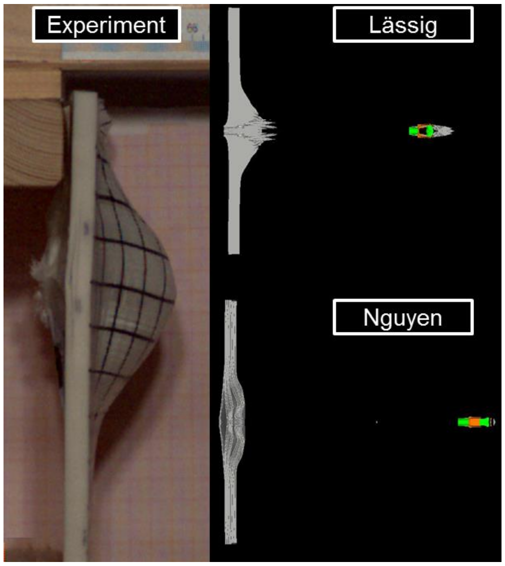

Figure 12. Bulge of a 11 mm target impact by a 7.62×39 mm FMJ projectile at 689 m/s (experiment, left) and the simulation results.

The significant decrease in accuracy of the numerical prediction may be due to an insufficient in-plane tensile strength defined in the material data set, a critical material property in the ballistic performance of fiber reinforced composites. Numerous researchers have investigated the tension properties of UHMW-PE composite (e.g. [6] and [34]). These tests showed that due the low friction coefficient and poor fibre/matrix adhesion in UHMW-PE composites, specimen griping is problematic, often leading to delamination rather than tension failure [8]. These disadvantages are addressed in a very new and more representative model.

VII. Numerical Simulation

As mentioned before, the ballistic tests are followed by computational modelling of the experimental set-up. Then, the experiment is reproduced using numerical simulations. The geometry and observed response of the laminate to ballistic impact is approximately symmetric to the axis through the bullet impact point.

Numerical simulation of modern armor structures requires the selection of appropriate material models for the constituent materials and the derivation of suitable material model input data. The laminate system studied here is an ultra-high molecular weight polyethylene composite. Lead and copper are also required for the projectiles.

A. Geometry

The projectile is a 7.62×39 mm round, a rimless bottlenecked intermediate cartridge of Soviet origin that was designed during World War II. It was divided into different parts - the jacket and the base - which have different properties and even different meshes. These elements have quadratic shape functions and nodes between the element edges. In this way, the computational accuracy, as well as the quality of curved model shapes increases. Using the same mesh density, the application of parabolic elements leads to a higher accuracy compared to linear elements (1st order elements). The standard model geometry was replicated from previous works with targets sized 250×250 mm at thicknesses of 5.5 mm, 11 mm and 16.2 mm.

B. Modelling

Because of the discrepancies discussed in Section VI, a new model was developed – a concept for the numerical simulation of fiber-reinforced plastics under impact loading. Here, the homogeneous continuum model is replaced. Alternating layers of fibers and matrix are used for the geometry. The mesh applied used a central bias to ensure the elements in vicinity of the point of impact were cubic whilst decreasing the overall computational complexity and hence run-time of the simulations. A 0.1 mm gap was placed between each layer for the use of an external gap contact algorithm. It was established in previous works that gapless contacts resulted in overpenetration of elements leading to poorer predictions [1]. An example of the standard model geometry and mesh can be seen in Figure 13.

The fiber layers apply anisotropic elasticity, no plasticity and anisotropic material failure (stress-dependent). The matrix layers use isotropic elasticity, von Mises plasticity and isotropic material failure (stress-dependent). To simulate the effect of delamination, principal stress failure is applied.

3D numerical simulations were performed of the full target and projectile, where both were meshed using 8-node hexahedral elements. The projectile was meshed with 9 elements across the diameter.

The target is composed of sub-laminates that are one element thick, separated by a small gap to satisfy the master-slave contact algorithm (external gap in AUTODYN) and bonded together as previously discussed. The mesh size of the target is approximately equal to the projectile at the impact site. The mesh was then graded towards the edge, increasing in coarseness to reduce the computational load of the model. Since UHMW-PE composite has a very low coefficient of friction, force fit clamping provides little restraint. High speed video of ballistic impact tests typical showed clamp slippage upon impact. As such no boundary conditions were imposed on the target.

C. Thermal Softening

In order to create automatic thermal softening in the UHMW-PE model, a custom subroutine was required that could update the material parameters of each cell based on the local element temperature. The software packages Microsoft Visual Studio 2010 and Intel Professional Fortran Compiler 2013 were used to create the custom subroutines and compile them into AUTODYN® executables. These software packages enabled the implementation of the existing erosion model along with the creation of a new subroutine for the application of thermal softening. The initial standard model was modified as to ensure each sub-laminate layer was defined as a unique material. By this method the subroutine could be called at the end of each cycle to iterate through each sub-laminate layer and modify the material parameters based on the maximum temperature within each layer.

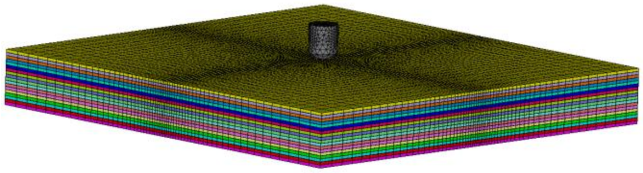

Figure 13. Geometry of a target plate: alternating layers of fibers and matrix are used in the computer model.

In this work, the Young's modulus was not softened since in AUTODYN® it is intimately linked to the equation-of-state and was unlikely to affect the ballistic performance of the laminate. Instead, the master effective stress, plastic strain curve was softened according to the data given by Dessain et al. [35] where a linear decrease in strength was interpolated. Given that softening occurred over the whole individual layer in the laminates as opposed to local cells, it was necessary to introduce a thermal-softening limit. In this work, this limit was set to 50%. The variables that were thermally softened in the model are shown in Table I.

D. Simulation Results

The model developed in [19] was adjusted and the concept has been extended to different calibers and projectile velocities. Composite armor plates between 5.5 and 16.2 mm were tested in several ballistic trials and high-speed videos were used to analyze the characteristics of the projectile – before and after the impact. An example of the simulation results with the modified model and a 7.62×39 mm bullet is shown in Figure 14.

The deformation of the projectile is in good agreement with the experimental observation. Both delamination and fragmentation can be seen in the numerical simulation. Compared to the homogeneous continuum model, fractures can be detected easily. Subsequently, the results of experiment and simulation in the case of perforation were compared with reference to the projectile residual velocity. Here, only minor differences were observed. The results are summarized in Table II.

TABLE I. PARAMETERS THAT WERE CHANGED IN EACH INDIVIDUAL LAYER DUE TO THERMAL SOFTENING

Parameter	Description	Initial value
k	Master effective stress – effective plastic strain curve	-
A22	Plasticity constant, 22	6×10^{-4}
A33	Plasticity constant, 33	6×10^{-4}
S22	Tensile failure stress, 22	1.15 GPa
S33	Tensile failure stress, 33	1.15 GPa

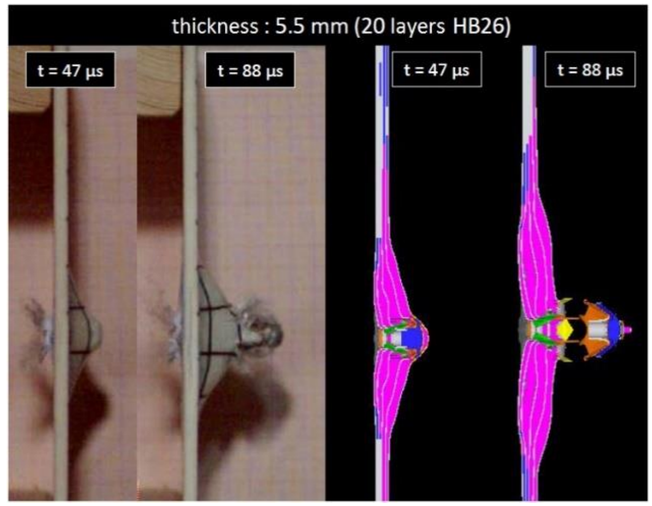

Figure 14. Effect of a 5.5 mm target impact by a 7.62×39 mm bullet at 686 m/s, 47 µs and 88 µs after the initial impact; comparing experimantal (left) and simulation (right) results.

TABLE II. SUMMARY OF RESULTS FOR A 7.62×39 MM BULLET

Target Thickness	5.5 mm Residual Velocity	11.0 mm Residual Thickness	16.2 mm Residual Thickness
Experiment	604 m/s	6 mm	11 mm
Simulation	587 m/s	4 mm	10 mm

It was found that the ballistic limit was satisfactorily reproduced in all cases. The tests showed that the projectile was stopped using thick target panels. Here, the residual thickness was correctly predicted by the FE-simulation.

VIII. CONCLUSION

The material model developed in [19] has some shortcomings regarding the simulation of handgun projectiles (e.g., 7.62×39 mm). Although previously found to provide accurate results for hypervelocity impact of aluminum spheres, the existing model and dataset was found to significantly underestimate the composite performance under impact conditions driven by through-thickness shear performance (ballistic impact of fragment simulating projectiles). The model was found to exhibit premature through thickness shear failure as a result of directional coupling in the modified Hashin-Tsai failure criterion and the large discrepancy between through-thickness tensile and shear strength of UHME-PE composite. As a result, premature damage and failure was initiated in the through-thickness shear direction leading to decreased ballistic performance. By de-coupling through-thickness tensile failure from the failure criteria and discretizing the laminate into a nominal number of kinematically joined sub-laminates through the thickness, progresses in modelling the ballistic response of the panels was improved.

Thermal softening and melting effects have been shown in previous work to account for a large degree of error in the prediction of thick UHMW-PE composite ballistic limit velocities. Through the modification of a custom subroutine the thermal softening effects of UHMW-PE have been adequately modelled in a manner that both saves computational processing time and increases predictive capability through softening whole individual discrete layers of the laminate.

New approaches make it possible to increase the accuracy of the simulation results. The previous concept was not valid for all projectiles/calibers. An alternative model has been developed to overcome these difficulties. Using sub-laminates and inhomogeneities on the macroscale, the model does not match the real microstructure, but allow a more realistic description of the failure processes mentioned above. The numerical model proposed a sub-laminate discretisation of the laminate in order to better model delamination failure. For this to occur, the sub-laminates are joined together using bonded contacts where failure is initiated based on a combined normal and shear stress criterion.

This work also demonstrated how a small number of well-defined experiments can be used to develop, calibrate, and validate solver technologies used for simulating the impact of projectiles on complex armor systems and composite laminate structures. Ballistic trials can be used as the basis of an iterative optimization process. Numerical simulations are a valuable adjunct to the study of the behavior of metals subjected to high-velocity impact or intense impulsive loading. The combined use of computations, experiments and high-strain-rate material characterization has, in many cases, supplemented the data achievable by experiments alone at considerable savings in both cost and engineering man-hours.

References

[1] A. Ramezani and H. Rothe, "A New Approach to Modelling Fiber-Reinforced Plastics for Hydrocode Analysis - Experimental Model Validation of Composite Materials Under Ballistic Impact," The Ninth International Conference on Advances in System Simulation (SIMUL 2017) IARIA, Oct. 2017, pp. 41-50, ISBN 978-1-61208-594-4.

[2] R&G Composite Technology, Manual of Fibre Reinforcements. D-71111 Waldenbuch, 2009.

[3] J. Van Dingenen, "Gel-spun high-performance polyethylene fibres," in High Performance Fibres, pp. 62–92, 2001.

[4] B. Russell, K. Karthikeyan, V. Deshpande, and N. Fleck, "The high strain rate response of ultra-high molecular-weight polyethylene: From fibre to laminate," in International Journal of Impact Engineering (60), pp. 1–9, 2013.

[5] L. H. Nguyen, The Ballistic Performance of Thick Ultra High Molecular Weight Polyethylene Composite. RMIT University, 2015.

[6] P. M. Cunniff, "Dimensionless parameters for optimization of textile based body armor systems," in 18th International Symposium on Ballistics, pp. 1303–1310, 1999.

[7] D. B. Segala and P. V. Cavallaro, "Numerical investigation of energy absorption mechanisms in unidirectional composites subjected to dynamic loading events," in Computational Materials Science 81, pp. 303–312, 2014.

[8] S. Chocron et al., "Modeling unidirectional composites by bundling fibers into strips with experimental determination of shear and compression properties at high pressures," in Composites Science and Technology 101, pp. 32–40, 2014.

[9] C. J. Hayhurst, S. J. Hiermaier, R. A. Clegg, W. Riedel, and M. Lambert, "Development of material models for nextel and kevlar-expoxy for high pressures and strain rates," in International Journal of Impact Engineering 23, pp. 365–376, 1999.

[10] R. A. Clegg, D. M. White, W. Riedel, and W. Harwick, "Hypervelocity impact damage prediction in composites: Part I—material model and characterisation," in International Journal of Impact Engineering 33, pp. 190–200, 2006.

[11] W. Riedel, H. Nahme, D. M. White, and R. A. Clegg, "Hypervelocity impact damage prediction in composites: Part II—experimental investigations and simulations," in International Journal of Impact Engineering 33, pp. 670–80, 2006.

[12] M. Wicklein, S. Ryan, D. M. White, and R. A. Clegg, "Hypervelocity impact on CFRP: Testing, material modelling, and numerical simulation," in International Journal of Impact Engineering 35, pp.1861–1869, 2008.

[13] ANSYS. *AUTODYN Composite Modelling Release 15.0*. [Online]. Available from: http://ansys.com/ 2018.07.28.

[14] T. Lässig et al., "A non-linear orthotropic hydrocode model for ultra-high molecular weight polyethylene in impact simulations," in International Journal of Impact Engineering 75, pp. 110–122, 2015.

[15] C. J. Hayhurst, J. Leahy, J., M. van der Jagt-Deutekom, and P. Kelly, "Development of Material Models for Numerical Simulation of Ballistic Impact onto Polyethylene Fibrous Armour," in Personal Armour Systems Symposium, pp. 5–8, 2000.

[16] K. Herlaar, M. van der Jagt-Deutekom, and M. Jacobs, "Finite element simulations and experiments of ballistic impacts on high performance PE composite material," in 22nd International Symposium on Ballistics, pp. 1040–1047, 2005.

[17] C. Ong, C. Boey, R. S. Hixson, and J. O. Sinibaldi, "Advanced layered personnel armor," in International Journal of Impact Engineering 38(5), pp. 369–383, 2011.

[18] U. Heisserer and H. Van der Werff, "The relation between Dyneema fiber properties and ballistic protection performance of its fiber composites," in 15th International Conference on Deformation, Yield and Fracture of Polymers 3, pp. 242–246, 2012.

[19] L. H. Nguyen et al., "Numerical Modelling of Ultra-High Molecular Weight Polyethylene Composite Under Impact Loading," in Procedia Engineering 103, pp. 436–443, 2015.

[20] J. Zukas, Introduction to hydrocodes. Elsevier Science, 2004.

[21] G.-S. Collins, An Introduction to Hydrocode Modeling. Applied Modelling and Computation Group, Imperial College London, 2002.

[22] E. Madenci and I. Guven, "The Finite Element Method and Applications in Engineering Using ANSYS," Springer Verlag, February 2015.

[23] H.-B. Woyand, FEM with CATIA V5. J. Schlembach Fachverlag, 2007.

[24] S. J. Hiermaier, Structures Under Crash and Impact. Spinger Verlag, 2008.

[25] R. F. Stellingwerf and C. A. Wingate, "Impact Modeling with Smooth Particle Hydrodynamics," International Journal of Impact Engineering, vol. 14, pp. 707–718, Sep. 1993.

[26] X. Quan, N. K. Birnbaum, M. S. Cowler, and B. I. Gerber, "Numerical Simulations of Structural Deformation under

Shock and Impact Loads using a Coupled Multi-Solver Approach," 5th Asia-Pacific Conference on Shock and Impact Loads on Structures, Hunan, China, Nov. 2003, pp. 152-161.

[27] ANSYS Inc. Available Solution Methods. [Online]. Available from: http://www.ansys.com/Products/Simulation+Technology/Structural+Analysis/Explicit+Dynamics/Features/Available+Solution+Methods [retrieved: August, 2018]

[28] P. Fröhlich, FEM Application Basics. Vieweg Verlag, September 2005.

[29] J. Zukas, T. Nicholas, H.F. Swift, L. B. Greszczuk, and D. R. Curran, Impact Dynamics, Krieger Publishing, FL: Malabar, 1992.

[30] D. E. Carlucci and S. S. Jacobson, Ballistics: Theory and Design of Guns and Ammunition, CRC Press, FL: Boca Raton, 2007.

[31] OEG Optical Measuring and Test Equipment. [Online]. Available from: http://www.oeg-messtechnik.de/?p=5&l=1 [retrieved: August, 2018]

[32] G. Johnson and W. Cook, "A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures," in 7th International Symposium on Ballistics, pp. 541–547, 1983.

[33] D. Steinberg, Equation of state and strength properties of selected materials. California, 1996.

[34] A. Levi-Sasson, I. Meshi, S. Mustacchi, I. Amarilio, D. Benes, V. Favorsky, R. Eliasy, J. Aboudi, R. Haj-Ali, "Experimental determination of linear and nonlinear mechanical properties of laminated soft composite material system," Composites Part B: Engineering 57, pp. 96–104, 2014.

[35] B. Dessain, O. Moulaert, R. Keunings, and A. R. Bunsell, "Solid Phase Change Controlling the Tensile and Creep Behaviour of Gel- Spun High-Modulus Polyethylene Fibres," in Journal of Material Science, 27 (16), pp. 4515–4522, 1992.

 ISBN: 978-1-61208-672-9