Investigating Different Ballistic Threats to Validate the Simulation Model of Fiber-Reinforced Plastics

Experimental Model Validation of Fiber Composites Under Ballistic 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. The use of ultra-high molecular weight polyethylene (UHMW-PE) composite as part of the personal armour system has 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 analytical and numerical models that capture these mechanisms and allow accurate prediction of ballistic performance to optimize modern armour systems. An analysis methodology is proposed to model the behaviour of thick UHMW-PE composite panels under ballistic impact using inhomogeneities on the macroscale. A sub-laminate approach for discretisation of the target is proposed to overcome the problems of premature through-thickness failure in the material model. The methodology was extensively validated against existing experimental ballistic impact data and results for UHMW-PE targets. Finally, a numerical modelling methodology was developed for the analysis of thick UHMW-PE composite under ballistic impact.**

Keywords-generally valid simulation models; hydrocode analysis; fiber-reinforced plastics; optimization; armor systems; ballistic trials.

I. INTRODUCTION

For thousands of years, natural materials had formed the basis of human existence: clothing, tools, and articles of consumption, all were made from leather, metal, stone, clay, or other substances obtained directly from nature. In contrast, most of the manmade materials such as porcelain, glass, and metal alloys were discovered more or less by accident. At the beginning of the twentieth century, dwindling deposits of important resources and their escalating prices triggered off an intensive search for synthetic, or manmade, substitute materials. The demand from the fast-growing industries was increasing in line with fundamental technical changes and could no longer be satisfied with natural materials alone. In time, countless compounds, including a high number of plastics, were synthesized from naturally occurring raw materials such as coal, coal tar, crude oil, and natural gas.

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 ultra-high molecular weight polyethylene (UHMW-PE), a promising ballistic armor material due to its high specific strength and stiffness. First approaches are discussed in detail 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 mm in diameter [4] with a molecular orientation greater than 95% and a crystallinity of up to 85% [3], see Figure 2.

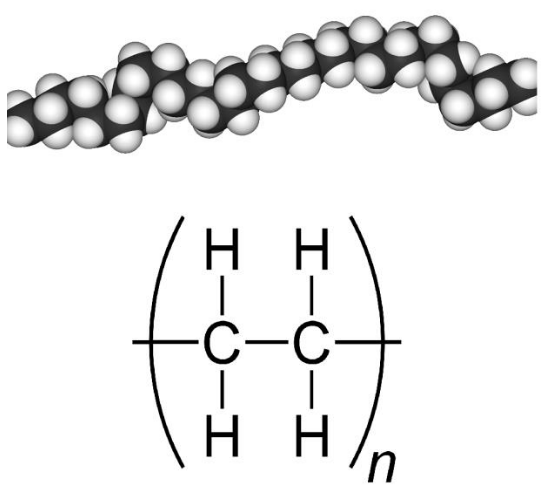


Figure 1. Skeletal formula and spacefill model of a polyethylene.

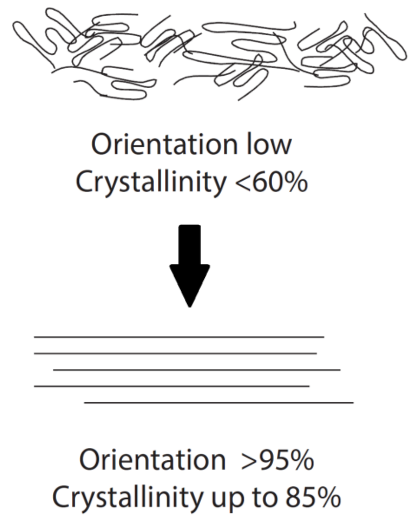


Figure 2. Increase in molecular orientation and crystallinity through gel spinning of UHMW-PE [5].

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.

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.

Due to the fact that all engineering simulation is based on geometry to represent the design, the target and all its components are simulated as computer-aided design (CAD) models. The work will also provide a brief overview of ballistic tests to offer some basic knowledge of the subject, serving as a basis for the comparison of the simulation results. Details of ballistic trials on composite armor systems are presented. Instead of running expensive trials, numerical simulations should identify vulnerabilities of structures. Contrary to the experimental result, numerical methods allow easy and comprehensive studying of all mechanical parameters. Modelling will also help to understand how the armor schemes behave during impact and how the failure processes can be controlled to our advantage. By progressively changing the composition of several layers and the material thickness, the composite armor will be optimized.

There is every reason to expect possible weight savings and a significant increase in protection, through the use of numerical techniques combined with a small number of physical experiments.

This work deals with numerical simulations of impact problems on fiber-based composite armor using the commercial finite-element-code ANSYS AUTODYN. Having presented some basic knowledge on the theory of numerical simulation in AUTODYN, two recently published approaches for modelling impact on the selected composite (Dyneema® HB26) are explained. While both of them make use of a nonlinear-orthotropic material model implemented in the AUTODYN-code, they differ in the way how the highly inhomogeneous microstructure of HB26 is represented geometrically. The first approach chooses a fully homogeneous description, whereas the other approach discretizes the composite into sublaminates, which are kinematically joined at the surfaces and breakable when a certain contact-stress is reached. They will be discussed in detail in Section III. In order to validate the two approaches, the response of HB26-samples impacted by handgun-projectiles was determined experimentally and compared to the corresponding numerical results. Unfortunately, a poor agreement between experimental and numerical results was found, which gave rise to the development of an alternative modelling approach. In doing so, the composite was subdivided into alternating layers of two different types. While the first type of layers was modeled with open-literature properties of UHMW-PE-fibers, polymer-matrix-behavior was assigned to the second type. Having adjusted some of the parameters, good agreement between experiment and simulation was found with respect to residual velocity and depth of penetration for the considered impact situations.

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

II. 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 [7]. 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 [8]. 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 [9].

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 [10].

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 [11]. 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) [12].

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.

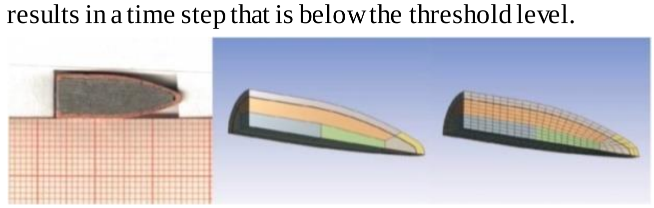


Figure 3. Example grid.

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 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 [13].

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.

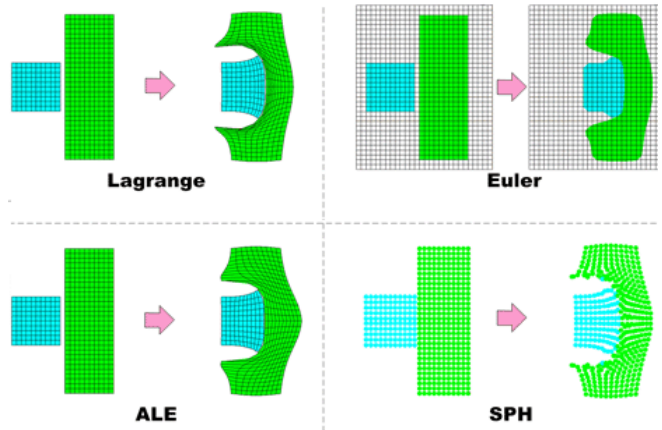


Figure 4. Examples of Lagrange, Euler, ALE, and SPH simulations on an impact problem [14].

Using a CAD-neutral environment that supports bidirectional, direct, and associative interfaces with CAD systems, the geometry can be optimized successively [17]. Therefore, several runs are necessary: from modelling to calculation to the evaluation and subsequent improvement of the model (see Figure 5).

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.

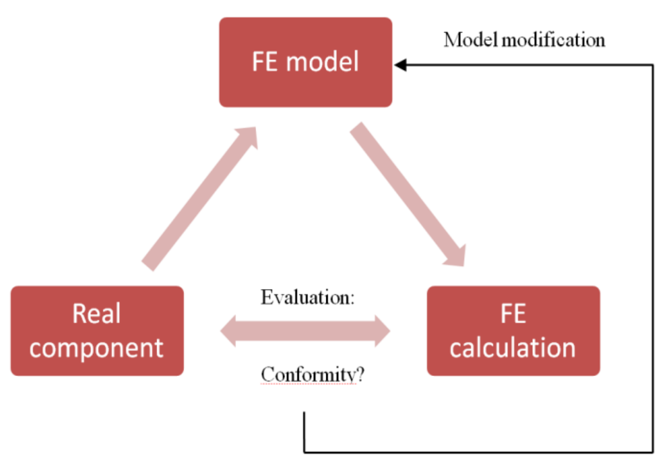


Figure 5. Basically iterative procedure of a FE analysis [15].

III. 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., [9]), a meso-mechanical level (i.e., consolidated plies or fiber bundles, e.g., [10]), or macromechanically in which the composite laminate is represented as a continuum.

In [11–14] 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 [15]. Lässig et al. [16] 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. [17], Herlaar et al. [18], Ong et al. [19], Heisserer and Van der Werff [20] and Lässig et al. [16]). Ong et al. [19] 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. [17], Herlaar et al. [18] and Heisserer and Van der Werff [20] 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. [21] evaluated and refined the modelling approach and material model parameter set developed in [16] 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 equation of state (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. For the first time, composite armor structures consisting of several layers of fiber-reinforced plastics are simulated for all current military threats.

IV. 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.

Historically, impact events are classified according to the impact velocity. One such approach was proposed by Zukas et al. [22] who categorised impact problems based on impact velocity, where the material response and established strain rate characterised the impact problem. Figure 6 depicts the strain rate, the impact velocity required to achieve the strain rate and the material effects as proposed by Zukas et al. [22].

Under this classical approach, the ballistic regime could be considered to be within the strain rate range of 10^2 s^{-1} to 10^4 s^{-1}, which corresponds to an impact velocity of between 50 m/s to 3000 m/s. Beyond 4000 m/s (depending on the materials), an impact will lead to a complete break-up and melting of the projectile. According to Zukas et al. [22], within this region the material strength is important in resisting penetration, and there is an onset of hydrodynamic effects. This approach to define the impact regime using the strain rate is insufficient when considering the impact behaviour for a diverse range of materials with different properties. For example, very low velocity impact of a hard object into a fluid can be described entirely using hydrodynamic theory, which under Figure 6 would be classified as both a low strain rate (low velocity) and high strain rate (hydrodynamic effects) problem.

On the other hand, Wilbeck (in [23]) proposed classification by the ratio of the impact pressure (P) to the material strength (S).

$$P/S_p \text{ and } P/S_t \tag{1}$$

where subscripts p is the projectile and t is the target. The pressure, P, according to hydrodynamic theory is given by:

$$P \cong \rho V^2 \tag{2}$$

where ρ is material density and V is the impact velocity. From this, impact events can be classified in nine different regimes, depicted in matrix form in Figure 7.

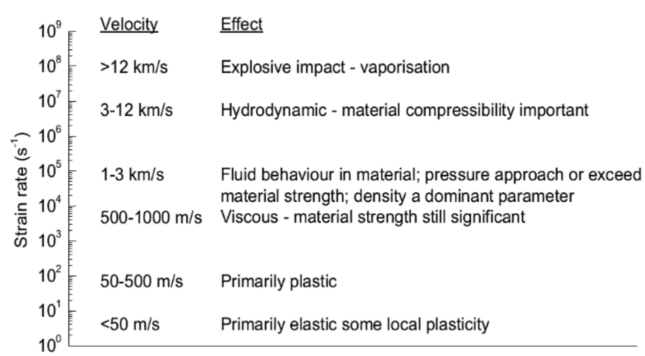


Figure 6. Impact response of high strength materials [22].

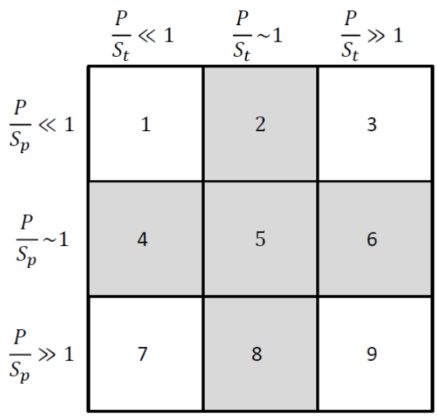


Figure 7. Matrix of impact regime [23]. The ballistic regimes are shaded.

The ballistic regime is considered to reside in regime 2, 4, 5, 6, and 8 according to Figure 7, where the impact pressure is close to the material strength of the target, projectile or both. For this paper, regime 5, 6 and 8 are of interest because at impact velocities typical of FSPs and projectiles, the impact pressures are considered to be on the order of, or greater than the strength of UHMW-PE composite.

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 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.

In order to create a data set for the numerical simulations, several experiments have to be performed. Ballistic tests are recorded with high-speed videos and analyzed afterwards. Testing was undertaken at an indoor ballistic testing facility. The target stand provides support behind the target on all four sides. Every ballistic test program includes several trials with different composites. The set-up has to remain unchanged.

The camera system is a PHANTOM v1611 that provides the versatility and flexibility needed in a variety of applications. With the proprietary widescreen CMOS sensor, the v1611 can acquire and save up to 16 gigapixels-per-second of data. That means at its full megapixel resolution of 1280×800, it can achieve 16,000 frames-per-second (fps). At reduced resolutions, the v1611 offers frame rates of 646,000 fps. With an internal mechanical shutter, the black frame can be obtained by simply closing the shutter. No physical access to the camera is needed. Ease-of-Use features include common signal connections which are conveniently located on its back panel, and include connections for timecode, dual power inputs, HD-SDI, a GPS input, frame synchronization, and trigger.

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 [24]. After the impact, the projectile is examined regarding any kind of change it might have undergone.

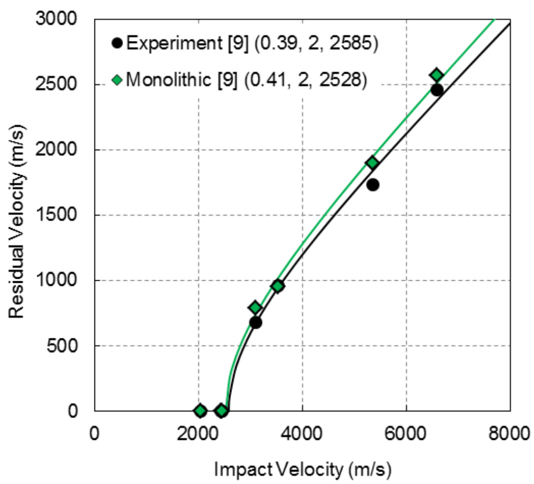
V. Model Validation

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 [16], 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 8. The modelling approach and material parameter set from [16] 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 8, 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.



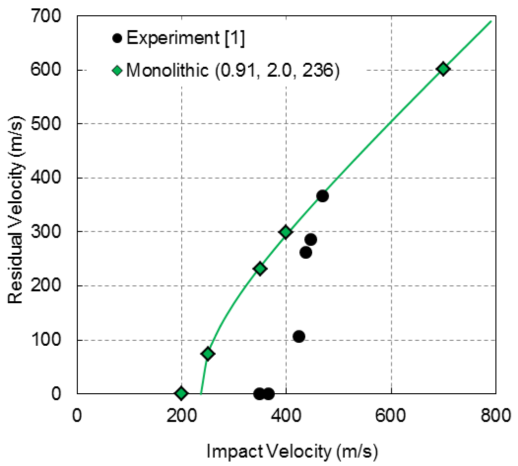


Figure 8. Experimental and numerical impact residual velocity results for impact of 6 mm diameter aluminum spheres against 15 kg/m^2 Dyneema® HB26 at normal incidence (left) and impact of 20 mm FSP against 10 mm thick HB26 at normal incidence (right).

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 [25]. The aluminum sphere was modelled using AL1100-O from the AUTODYN library that uses a shock EoS and the Steinburg Guinan strength model [26]. The master-slave contact algorithm was used to detect contact between the target and projectile.

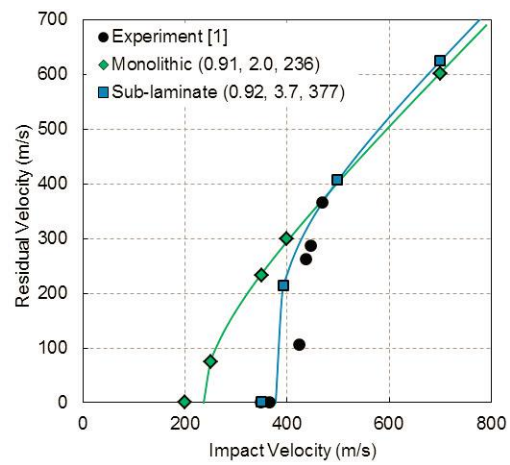
The sub-laminate model with shock EoS was applied to the aluminum sphere hypervelocity impact series and 20 mm FSP ballistic impact series presented in Figure 8, the results of which are shown in Figure 9.

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 10, 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. But in both models, material fails and the projectile penetrates the plate.



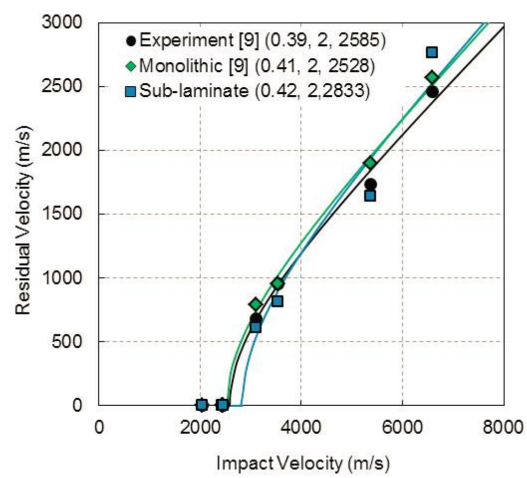


Figure 9. Comparison of the experimental results with the two numerical models for impact of 20 mm FSP against 10 mm thick Dyneema HB26® at normal incidence (left) , and impact of 6 mm diameter aluminium spheres against 15 kg/m^2 HB26 at normal incidence (right).

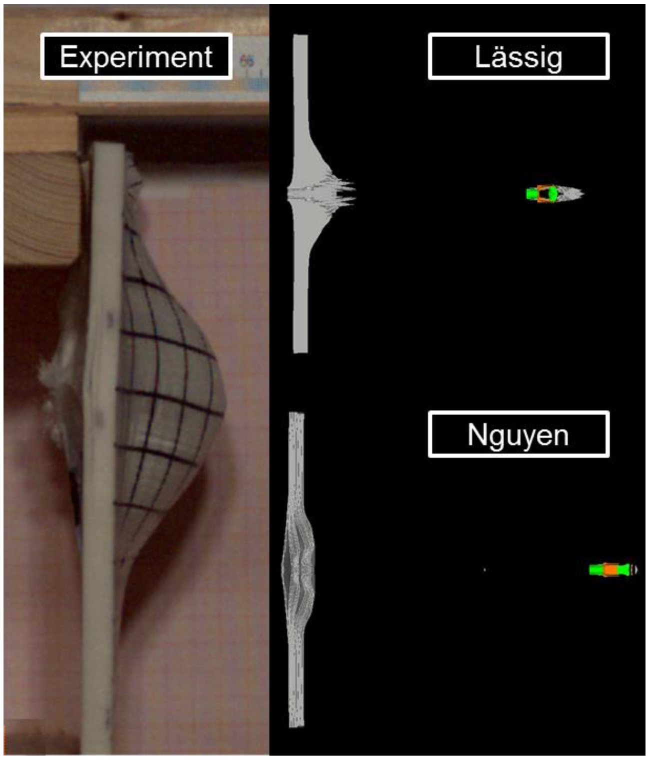


Figure 10. Bulge of a 11 mm target impact by a 7.62×39 mm FMJ projectile at 689 m/s (experiment) and the simulation results using both “state-of-the-art” models of Lässig and Nguyen 700 m/s.

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. These disadvantages are addressed in a very new and more representative model.

VI. 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. Figure 3 shows a cross-section of the projectile and a CAD model. 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.

The projectile 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).

Modelling of fiber-reinforced composites under impact is challenging because of the complexity of the material composition and the many failure modes it exhibits at different scales (fibrillation, intra- and inter-laminar failure, etc.) and impact regimes. For this reason, numerical simulation of impact using hydrocodes was exclusively performed for isotropic materials up until the late 1990’s. Since then, there have been many advances in modelling composites brought about by the introduction of more accurate constitutive models and modelling techniques. In general, fiber-reinforced composites can be modelled at three different scales, as shown in Figure 11:

- Micro-scale, where the individual fiber, matrix and (in some cases) the fiber-matrix interface is explicitly modelled;
- Meso-scale, where the properties of the individual plies that are homogenised in the principal directions are modelled and stacked together to produce a laminate; and
- Macro-scale, where the laminate is modelled as a continuum and the properties of the laminate are homogenised in the principal directions.

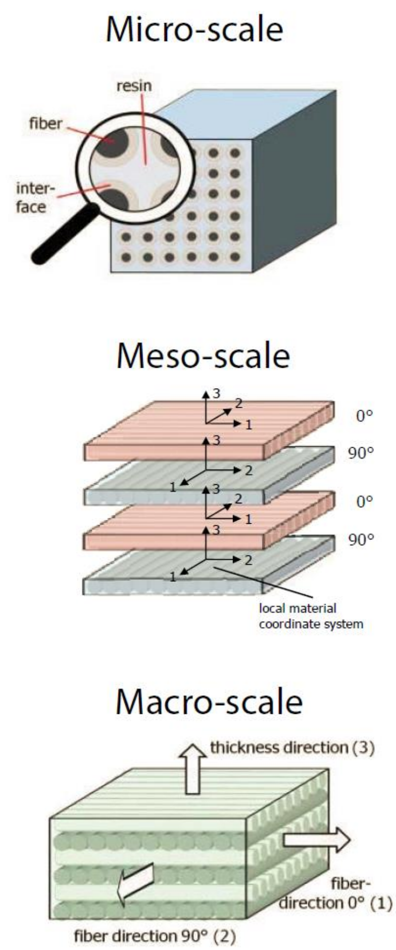


Figure 11. Micro, meso and macro mechanical model of fiber reinforced composites [27].

Modelling of fiber-reinforced composites at the micro-scale has several important advantages. This includes increased model fidelity, relatively simpler constitutive equations to describe the fiber, matrix and the interface, and characterisation tests that are relatively easy to perform. However, models at this scale require explicit modelling of every single fiber, matrix and the contact interface, which is extremely computationally expensive and not practical currently for typical engineering problems (see Figure 12).

While the meso-scale approach is far more computationally tractable compared to the micro-scale, models at this scale are still not practical for thick targets.

A. *Modelling*

Because of the discrepancies discussed in Section V, 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 layers are bonded and have different material models (see 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.

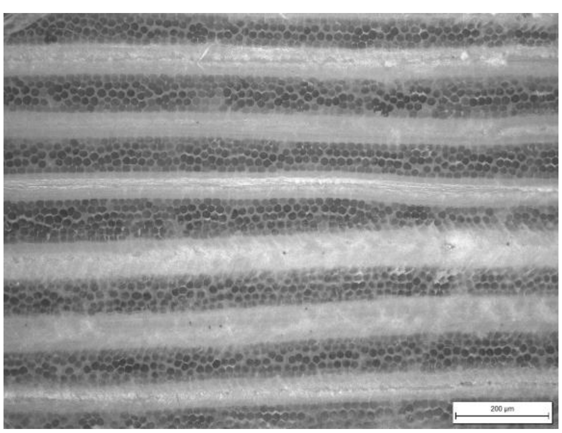


Figure 12. Cross section of a Dyneema® HB26 panel.

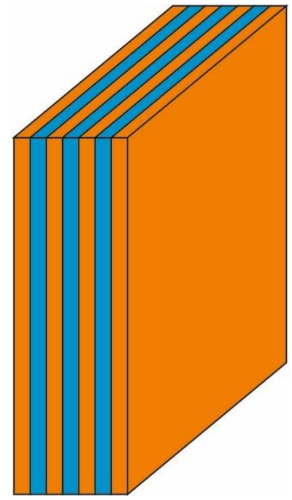


Figure 13. Geometry of a target plate: alternating layers of fibers and matrix are used in the computer model.

B. *Simulation Results*

The model developed in [16] 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. The simulation results with the modified model and a 7.62×39 mm bullet are shown in Figures 14, 15, and 16.

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 I.

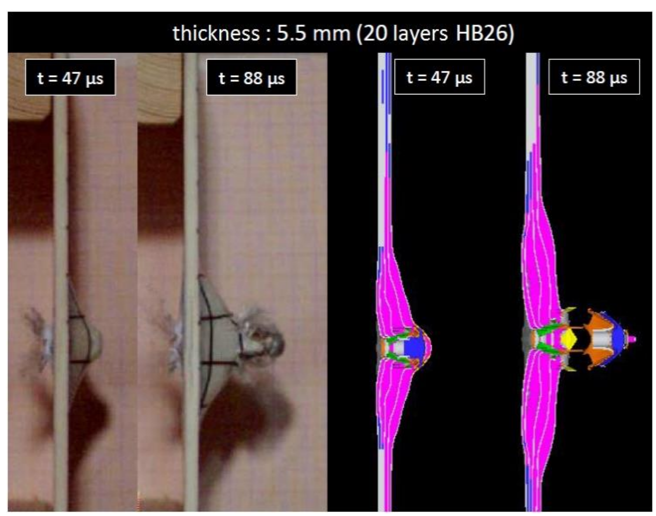


Figure 14. Effect of a 5.5 mm target impact by a 7.62×39 mm bullet at 686 m/s, 47 µs and 88 µs after the initial impact.

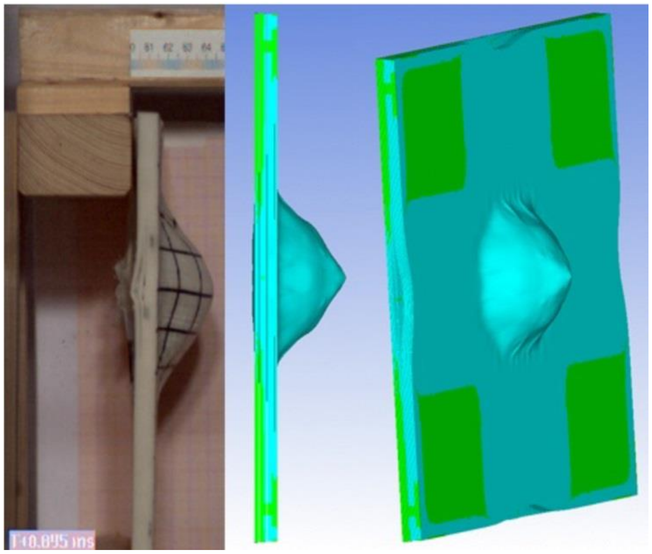


Figure 15. Effect of a 11.0 mm target impact by a 7.62×39 mm bullet at 682 m/s.

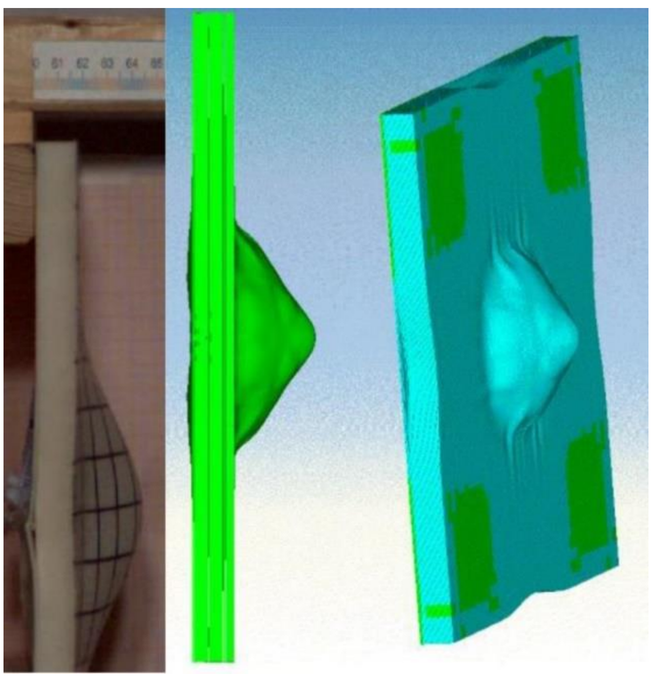


Figure 16. Effect of a 16.2 mm target impact by a 7.62×39 mm bullet at 679 m/s.

TABLE I. 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

Even the simulation results with other calibers provide very good results. A common projectile is the 9×19 mm Parabellum. Under STANAG 4090, it is a standard cartridge for NATO forces as well as many non-NATO countries. According to the 2014 edition of Cartridges of the World, the 9×19 mm Parabellum is "the world's most popular and widely used military handgun and submachinegun cartridge." In addition to being used by over 60% of police in the U.S., the 9×19 mm pistols are more popular than revolvers. The simulation results with the modified model and a 9×19 mm bullet are shown in Figures 17, 18, and 19.

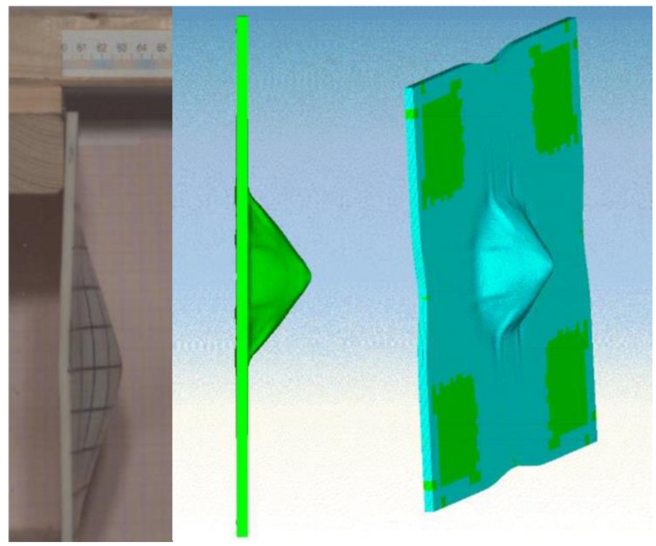


Figure 17. Effect of a 5.5 mm target impact by a 9×19 mm Parabellum bullet at 348 m/s.

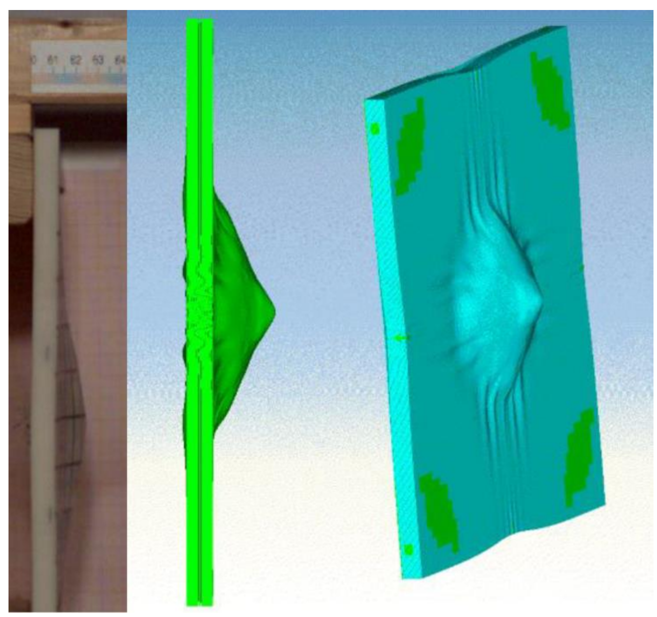


Figure 18. Effect of a 11.0 mm target impact by a 9×19 mm Parabellum bullet at 343 m/s.

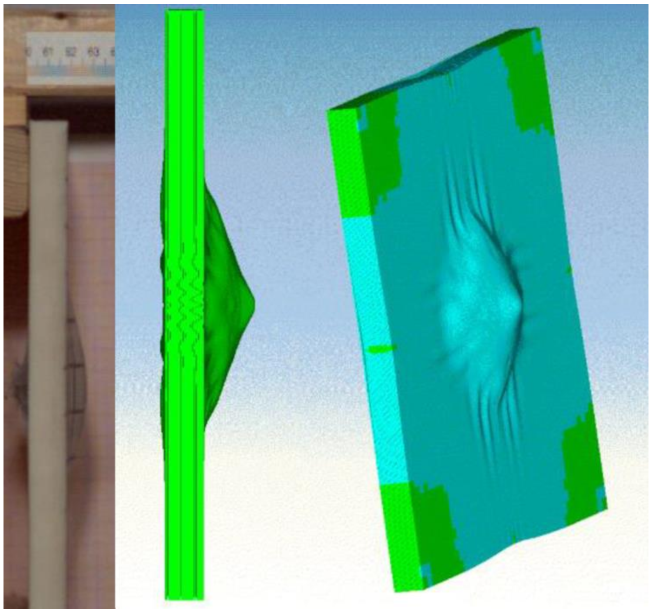


Figure 19. Effect of a 16.2 mm target impact by a 9×19 mm Parabellum bullet at 346 m/s.

The next step is to test the influence of meshing, based on Ramezani and Rothe [28]. The accuracy that can be obtained from any FEA model is directly related to the finite element mesh that is used. The finite element mesh is used to subdivide the CAD model into smaller domains called elements, over which a set of equations are solved. These equations approximately represent the governing equation of interest via a set of polynomial functions defined over each element. As these elements are made smaller and smaller, as the mesh is refined, the computed solution will approach the true solution. This process of mesh refinement is a key step in validating any finite element model and gaining confidence in the software, the model, and the results.

Early in the analysis process, it makes sense to start with a mesh that is as coarse as possible – a mesh with very large elements. A coarse mesh will require less computational resources to solve and, while it may give a very inaccurate solution, it can still be used as a rough verification and as a check on the applied loads and constraints.

After computing the solution on the coarse mesh, the process of mesh refinement begins. In its simplest form, mesh refinement is the process of resolving the model with successively finer and finer meshes, comparing the results between these different meshes. This comparison can be done by analyzing the fields at one or more points in the model or by evaluating the integral of a field over some domains or boundaries. Table II summarizes the four different mesh sizes. A Hewlett-Packard (HP) ProLiant DL380p G8 Server is used for all calculations. By comparing these scalar quantities, it is possible to judge the convergence of the solution with respect to mesh refinement. The results are shown in Figure 20. It should be noted that an explicit modelling of the individual fibers is not an option, since the computational effort would go beyond the scope of modern server systems.

TABLE II. COMPARISON OF THE CALCULATION TIME

Mesh Size	Number of Elements over Edge Length	Calculation Time [h]
Coarse	25	0.5
Medium	50	4
Fine	75	25
Very Fine	100	268

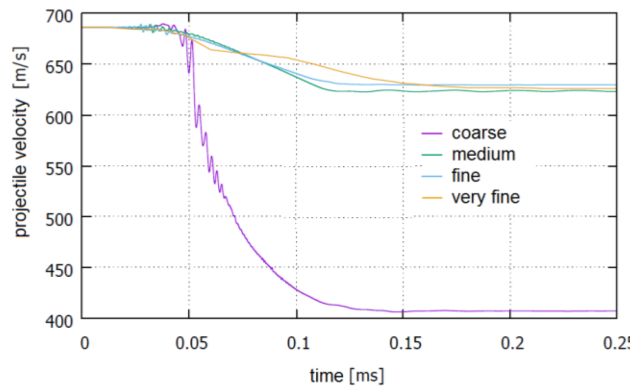


Figure 20. Convergence analysis: comparison of the projectile velocity (7.62×39 mm bullet) at different mesh sizes.

VII. CONCLUSIONS

The material model developed in [16] 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.

A major difficulty in the numerical simulation of fiber composites under impact is the detection of failure processes between fiber and matrix elements as well as between the individual laminate layers (delamination). One promising approach is the use of "artificial" inhomogeneities on the macroscale.

This paper is based on Ramezani and Rothe [29]. 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. Such approach is known to be mesh-dependent and has been replaced by fracture energy based failure (mode I, II, and III) [30]. Most finite element models of fibre-reinforced composite today capture interlaminar failure through zero thickness cohesive elements which accounts for both damage and fracture mechanics (using tractionseparation laws), though this is not available in the hydrocode used in this work.

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.

VIII. Future Work

Generally, the field of ballistic and penetration mechanics is extensive due to the unlimited combination of targets and threats. The response of targets is different depending on the projectile size, geometry, material and impact velocity. The scope of this work was restricted to the most common threats (where FSPs are used as a representative surrogate), however, understanding the penetration and failure mechanisms of the material impacted by different projectiles (spherical and ogive) can also be valuable. This work also only considered normal impacts (the worst-case scenario), but attacks experienced on the front line are almost always at an oblique angle (large or small). Understanding how UHMW-PE composite responds to obliquity is important and deserves attention.

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