High-Speed Video Analysis of Ballistic Trials to Investigate Simulation Methods for Fiber-Reinforced Plastics Under Impact Loading

Using the Example of Ultra-High Molecular Weight Polyethylene

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***Abstract*—In the security sector, the partly insufficient safety of people and equipment due to failure of industrial components are ongoing problems that cause great concern. Since computers and software have spread into all fields of industry, extensive efforts are currently made in order to improve the safety by applying certain numerical solutions. This work presents a set of numerical simulations of ballistic tests which analyze the effects of composite armor plates. The focus lies on high-speed videos and modern investigation methods. The goal is to improve fiber-reinforced plastics in order to be able to cope with current challenges. Of course, the maximization of security is the primary goal, but keeping down the costs is becoming increasingly important. This is why numerical simulations are more frequently applied than experimental tests which are thus being replaced gradually.**

Keywords-solver technologies; simulation models; fiber-reinforced plastics; optimization; armor systems; ballistic trials.

I. Introduction

This work will focus on 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. The goal is to evaluate the ballistic efficiency of UHMW-PE composite with numerical simulations, promoting an effective development process. First approaches are discussed in detail in [1].

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 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. Modeling will also help to understand how the fiber-reinforced plastic 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.

After a brief introduction and description of the different methods of space discretization in Section III, there is a short section on ballistic trials where the experimental set-up is depicted, followed by Section V describing the analysis with numerical simulations. The paper ends with a concluding paragraph in Section VI.

II. State-of-the-art

The numerical modeling of composite materials under impact can be performed at a constituent level (i.e., explicit modeling of fibre and matrix elements, e.g., [2]), a meso-mechanical level (i.e., consolidated plies or fibre bundles, e.g., [3]), or macromechanically in which the composite laminate is represented as a continuum.

In [4–7] 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 fibre 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 [8].

Lässig et al. [9] 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. The target geometry is homogenized. The projectile is an aluminum ball in simplified terms. However, homogenized target geometries with orthotropic material models are not able to reproduce different modes of failure. The results are valid for aluminum spherical-shaped projectiles in hypervelocity range only.

Nguyen et al. [10] evaluated and refined the modeling approach and material model parameter set developed in [9] 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. Here, the target geometry is divided into sub-laminates joined by bonded contacts breakable through a combined tensile and shear stress failure criterion.

The models mentioned above are valid for blunt FSP´s from a velocity range of 400 to 6600 m/s. They show considerable shortcomings in simulating pointed projectiles and thick HB26-composites.

This paper will present an optimal 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 the current military threats.

III. Methods of Space Discretization

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 [11]. They apply an explicit method and use very small time steps for stable results.

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.

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.

Fig. 1 gives a short overview of the solver technologies mentioned above. The crucial factor is the grid that causes different outcomes.

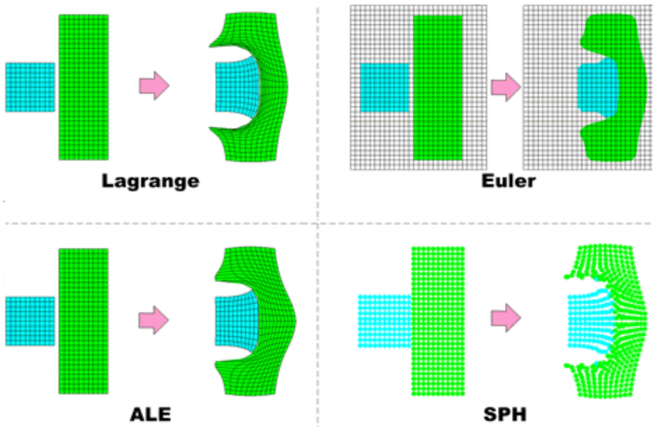

Figure 1. Examples of Lagrange, Euler, ALE, and SPH simulations on an impact problem [14].

The behavior (deflection) of the simple elements is well-known and may be calculated and analyzed using simple equations called shape functions. 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 [15].

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 modeling the behavior of continuous media. In its purest sense, a hydrocode is a computer code for modeling fluid flow at all speeds [11]. For that reason a structure will be split into a number of small elements. The elements are connected through their nodes (see Fig. 2).

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Using a CAD-neutral environment that supports bidirectional, direct, and associative interfaces with CAD systems, the geometry can be optimized successively [17].

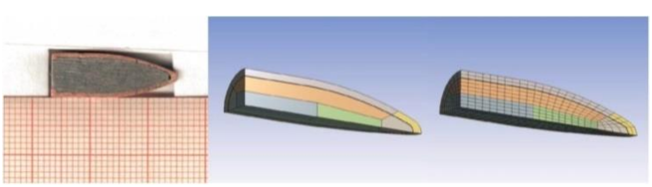


Figure 2. Example grid.

Therefore, several runs are necessary: from modeling to calculation to the evaluation and subsequent improvement of the model (see Fig. 3).

Bullet-resistant materials are usually tested by using a gun to fire a projectile from a set distance into the material in a set pattern. Levels of protection (see Fig. 4) are based on the ability of the target to stop a specific type of projectile traveling at a specific speed.

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.

Terminal ballistics is the general name for a large number of processes which take place during the high velocity impact of various projectiles/target combinations. There are two related disciplines which deal with launching these projectiles. Interior ballistics concerns their acceleration to the desired velocity, and exterior ballistics deals with their flight dynamics from the launcher to the target.

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.

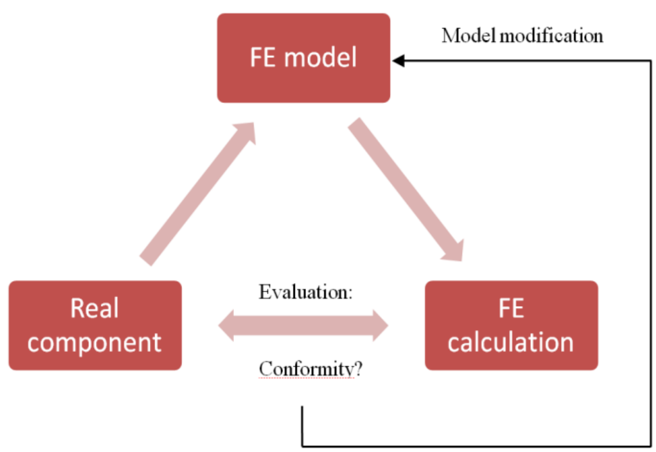


Figure 3. Basically iterative procedure of a FE analysis [15].

In order to follow these different events the researcher has to be acquainted with diverse scientific fields which include: elasticity and plasticity of solids, fracture mechanics and the physics of materials at high pressures and temperatures.

Terminal ballistics is the generic name for the science and engineering of impacts which are of interest to armor and anti-armor engineers. The relevant impact velocities usually range between 0.5 and 2.0 km/s, the so-called ordnance velocity range. These are the velocities at which projectiles are launched against personnel, armored vehicles and buildings, by rifles and guns. The impact velocities of shaped charge jets are within the hypervelocity range of 2.0–8.0 km/s, and their interaction with armor is also of major interest to both armor and anti-armor engineers.

The science of terminal ballistics started with the works of the great mathematician Leonard Euler (1745) and the British engineer Benjamin Robins (1742), who analyzed data for the penetration of steel cannonballs in soil as a function of their impact velocities. In the following two centuries, until the Second World War, the field of terminal ballistics was based on empirically derived relations between the penetration depth and the impact velocity of various projectiles into different targets. The reviews of Hermann and Jones (1961) and Backman and Goldsmith (1978), summarize many of these empirical formulas which were suggested over this period.

During the years of WW-II, scientists in the US and UK have analyzed the penetration process of shaped charge jets and rigid steel projectiles into armor plates, through analytical models which were based on physical considerations. These models identify the main force exerted on the projectile during penetration, which is then inserted in its equation of motion. The aim of these models is to reduce the mathematical description of a complicated three dimensional problem to a simple form which retains the essential physics of the penetration process. This simplification results in either a low dimensional system of ordinary differential equations or a few one-dimensional partial differential equations, which can be easily solved. The models can be tested by controlled experiments, in which the parameters are varied in a systematic way, in order to establish the non-dimensional parameters of the process. With these analytical models data correlation is made easy and extrapolations, to areas beyond the ability of experimental facilities, are possible. On the other hand, these analytical models require some compromise to be made, limiting their use to ideal cases where only a single mechanism is at work. Still, these models have been used successfully in order to account for the data and to reduce the number of the necessary experiments in terminal ballistics. Since the advancements in numerical simulations, the role of analytical models seems to decline as the codes are getting better and more efficient. However, these numerical simulations are often used just to account for experimental data, offering little physical insight for the process. Our strong belief is that analytical modeling is crucial for the field of terminal ballistics in order to understand the physics involved, and to highlight the important parameters which influence these processes.

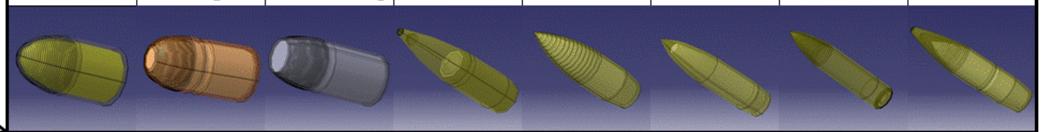
Predictive numerical simulation of any structural deformation process requires objective constitutive equations including parameters that are derived objectively for the material. Objective, in this context, means that the parameters are valid for the whole spectrum of loading conditions covered by the material model. This includes its applicability to arbitrary domains or geometries without restriction to specific structures. Experimental parameter derivation providing that kind of data can be called material test. The objectivity criterion to the parameters distinguishes the material test from a structural test used for verification or validation purposes.

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 (see Fig. 5).



Protection Level		9 x 19 mm	.357 Magnum	.44 Rem. Mag.	5,56x45 mm	7,62x39 mm	7,62x51 mm	7,62x54 mm R	.50 BMG
1	PM 1 / VR 1								
2	PM 2 / VR 2	$v = 360 \pm 10 \frac{m}{s}$ $E = 518\,J$							
3	PM 3 / VR 3	$v = 415 \pm 10 \frac{m}{s}$ $E = 689\,J$							
4	PM 4 / VR 4		$v = 430 \pm 10 \frac{m}{s}$ $E = 943\,J$	$v = 440 \pm 10 \frac{m}{s}$ $E = 1510\,J$					
5	PM 5 / VR 5		$v = 580 \pm 10 \frac{m}{s}$ $E = 1194\,J$						
6	PM 6 / VR 6					$v = 720 \pm 10 \frac{m}{s}$ $E = 2074\,J$			
7	PM 7 / VR 7 *STANAG Level 1*				$v = 950 \pm 10 \frac{m}{s}$ $E = 1805\,J$		$v = 830 \pm 10 \frac{m}{s}$ $E = 3289\,J$		
8	PM 8 / VR 8 *STANAG Level 2*					$v = 740 \pm 10 \frac{m}{s}$ $E = 2108\,J$			
9	PM 9 / VR 9						$v = 820 \pm 10 \frac{m}{s}$ $E = 3261\,J$		
10	PM 10 / VR 10 *STANAG Level 3*							$v = 860 \pm 10 \frac{m}{s}$ $E = 3846\,J$	
11	PM 11 *STANAG Level 3*						$v = 930 \pm 10 \frac{m}{s}$ $E = 3633\,J$		
12	PM 12						$v = 810 \pm 10 \frac{m}{s}$ $E = 4166\,J$		
13	PM 13								$v = 930 \pm 10 \frac{m}{s}$ $E = 18595\,J$

Figure 4. The APR 2006 resistance classification and related CAD models [19].

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. The experimental set-up is shown in Fig. 6.

Testing was undertaken at an indoor ballistic testing facility (see Fig. 7). 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 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 [20]. After the impact, the projectile is examined regarding any kind of change it might have undergone.

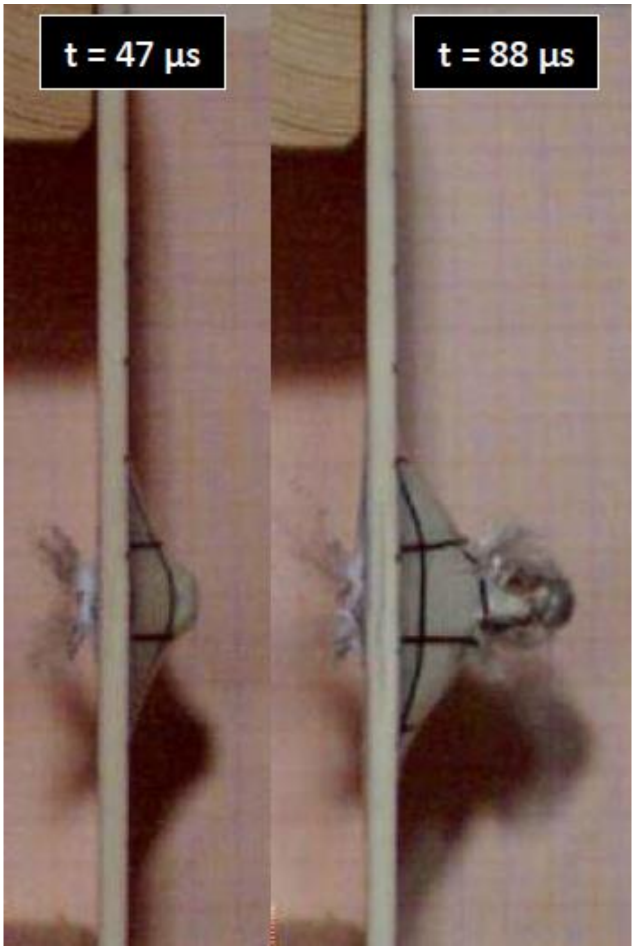


Figure 5. Ballistic tests and the analysis of fragments.

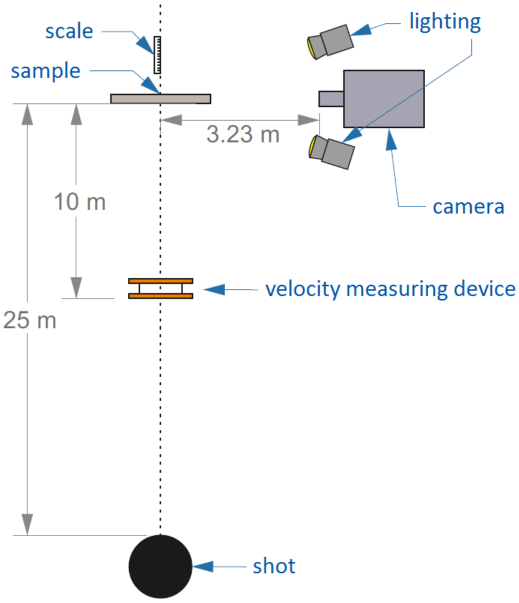


Figure 6. Experimental set-up.

Figure 7. Indoor ballistic testing facility.

The damage propagation is analyzed using the software called COMEF [21], 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.

Fig. 8 shows an example of measuring and analyzing damages after impact.

V. Numerical Simulation

The ballistic tests are followed by computational modeling of the experimental set-up. Then, the experiment is reproduced using numerical simulations. Fig. 1 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).

A. Modelling

In [9], 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 Fig. 9.

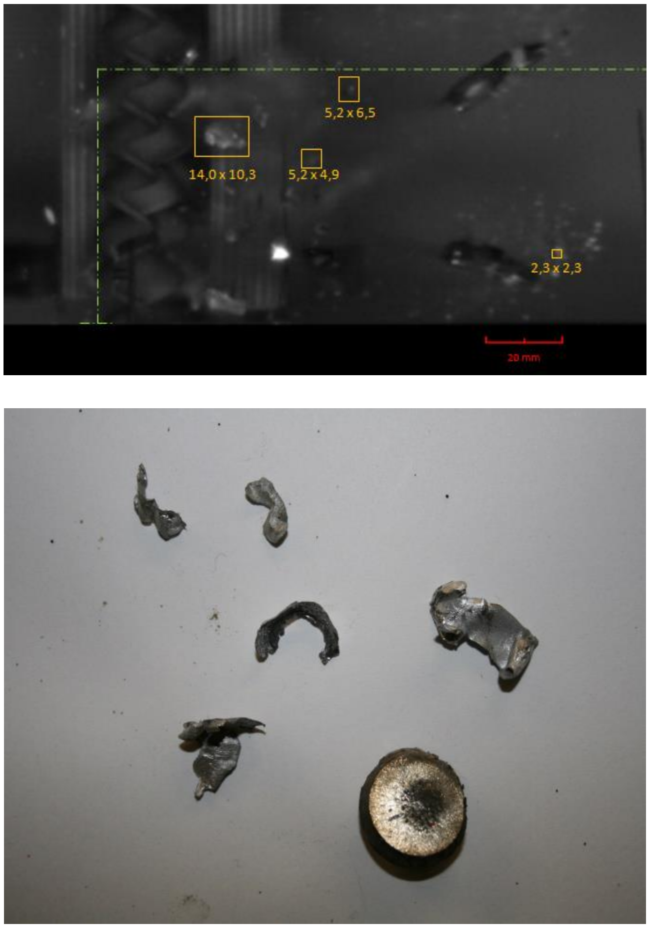


Figure 8. Ballistic tests and the analysis of fragments.

The modelling approach and material parameter set from [8] were applied to simulate impact experiments at velocities in the ballistic regime (here considered as < 1000 m/s). In Fig. 9 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.

B. *Simulation Results*

Relatively newer numerical discretization methods, such as Smoothed Particle Hydrodynamics (SPH), have been proposed that rectifies the issue of grid entanglement. The SPH method has shown good agreement with high velocity impact of metallic targets, better predictions of crack propagation in ceramics and fragmentation of composites under hypervelocity impact (HVI) compared to grid-based Lagrange and Euler methods. Although promising, SPH suffers from consistency and stability issues that lead to lower accuracy and instabilities under tensile perturbation. The latter makes it unsuitable for use with UHMW-PE composite under ballistic impact, because this material derives most of its resistance to penetration when it is loaded in tension. For these types of problems, the grid-based Lagrangian formulation still remains the most feasible for modeling UHMW-PE composite.

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.

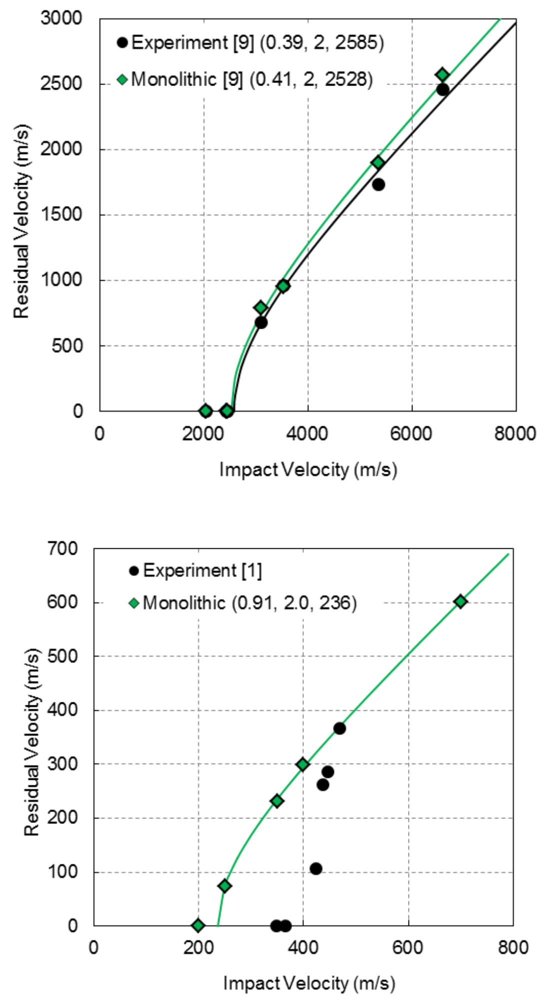


Figure 9. Experimental and numerical impact residual velocity results for impact of 6 mm diameter aluminum spheres against 15 kg/m2 Dyneema® HB26 at normal incidence (left) and impact of 20 mm fragment simulating projectiles against 10 mm thick Dyneema® HB26 at normal incidence (right). Lambert-Jonas parameters (a, p, V_{bl}) are provided in the legend.

High speed video of ballistic impact tests typical showed the action of loosening and moving clamps upon impact. As such no boundary conditions were imposed on the target. The FSP material was modelled as Steel S-7 from the AUTODYN® library described using a linear EoS and the Johnson-Cook strength model [22]. The aluminum sphere was modelled using AL1100-O from the AUTODYN® library that uses a shock EoS and the Steinburg Guinan strength model [23]. 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 Fig. 9, the results of which are shown in Fig. 10. 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).

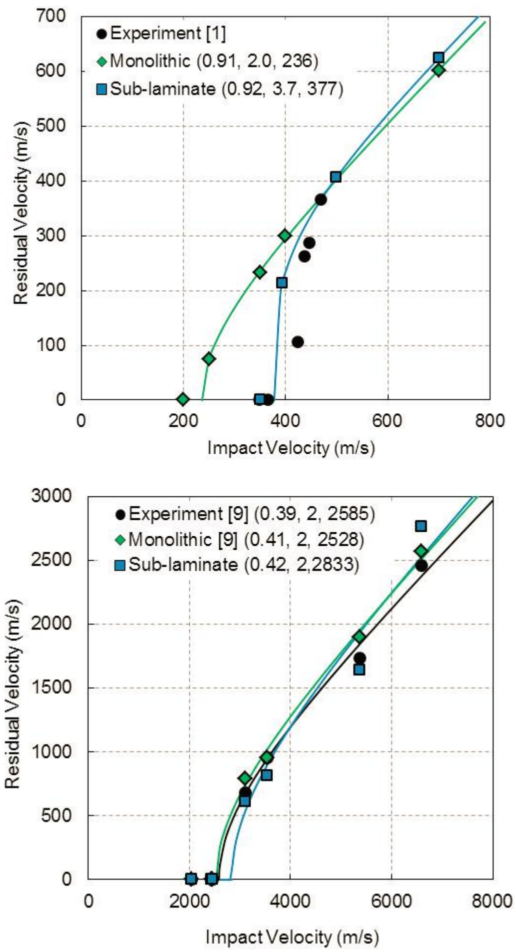


Figure 10. Comparison of the experimental results with the two numerical models for impact of 20 mm fragment simulating projectiles against 10 mm thick Dyneema HB26® at normal incidence (left) , and impact of 6 mm diameter aluminium spheres against 15 kg/m2 Dyneema® HB26 at normal incidence (right). Lambert-Jonas parameters (a, p, Vbl) are provided in the legend.

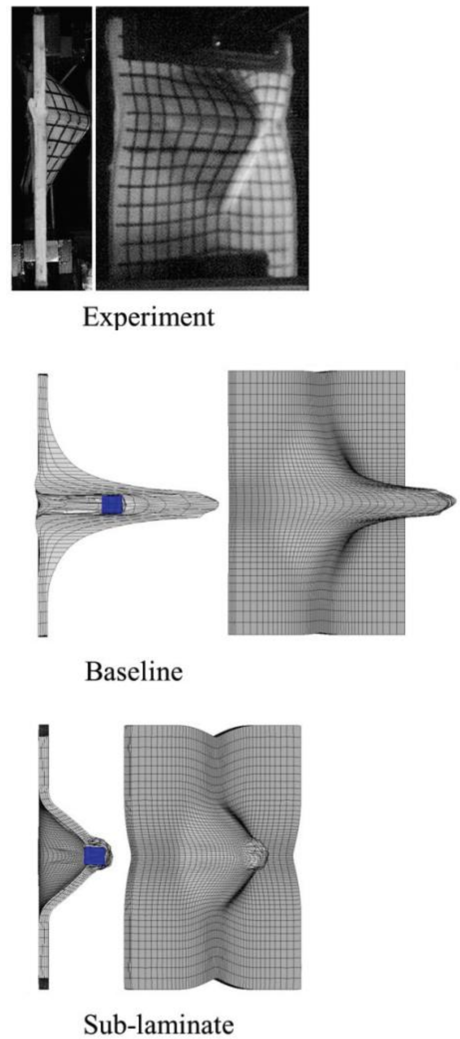


Figure 11. Bulge of a 10 mm target impact by a 20 mm FSP at 365 m/s (experiment) and 350 m/s (simulations), 400 μs after the initial impact.

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.

In Fig. 11, a qualitative assessment of the bulge formation is made for the 10 mm panel impacted at 365 m/s (i.e., below the V_{50}) by a 20 mm FSP. 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 personnel protection (i.e., vests and helmets). The sub-laminate model is shown to reproduce the characteristic pyramid bulge shape and drawing of material from the lateral edge. In comparison, the bulge prediction of the baseline model is poor, showing a conical shape with the projectile significantly behind the apex. In the baseline model penetration occurs through premature through-thickness shear failure around the projectile rather than in-plane tension (membrane) which would allow the formation of a pyramidal bulge as the composite is carried along with the projectile. Furthermore, in the baseline model the extremely small through thickness tensile strength (1.07 MPa) in the bulk material leads to early spallation/delamination of the back face. This allows the material on the target back face to fail and be accelerated ahead of the projectile. In the sub-laminate model, these two artifacts are addressed, and so a more representative bulge is formed.

C. Further Validations

The material model developed in [9] and [10] has some shortcomings regarding the simulation of handgun projectiles (see Fig. 12). The ballistic limit was significantly under predicted. Evaluation of the result suggests that the failure mechanisms, which drive performance in the rear section of the target panel (i.e., membrane tension) were not adequately reproduced, suggesting an under-estimate of the material in-plane tensile performance.

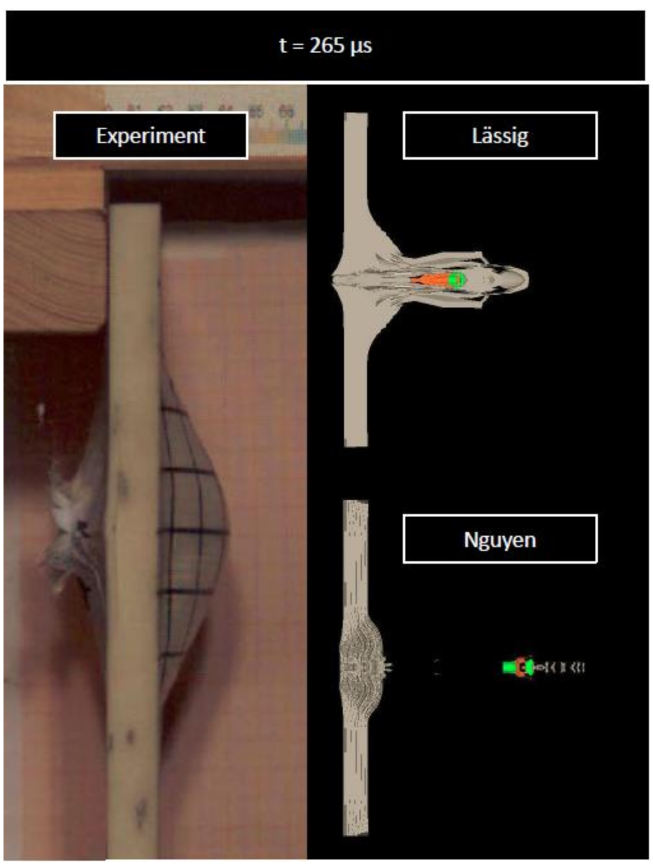


Figure 12. Comparing experimantal results with the previous simulation models of Lässig [8] and Nguyen [9], 265 µs after impact (grey = plastic deformation, green = elastic deformation, orange = material failure); projectile velocity: 674 m/s; target thickness: 16.2 mm (60 layers of HB26).

A major difficulty in the numerical simulation of fibre composites under impact is the detection of failure processes between fibre and matrix elements as well as between the individual laminate layers (delamination). One promising approach is the use of "artificial" inhomogeneities on the macroscale. Here, an alternative simulation 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 allows a more realistic description of the failure processes mentioned above.

Approaches based on the continuum or macroscale present a more practical alternative to solve typical engineering problems. However, the complexity of the constitutive equations and characterization tests necessary to describe an anisotropic material at a macro or continuum level increases significantly.

When considering the micromechanical properties of the orthotropic yield surface with a non-linear hardening description, a non-linear shock equation of state, and a three-dimensional failure criterion supplemented by a linear orthotropic softening description should be taken into account. It is important to consider all relevant mechanisms that occur during ballistic impact, as the quality of the numerical prediction capability strongly depends on a physically accurate description of contributing energy dissipation mechanisms. Therefore, a combination of ballistic experiments and numerical simulations is required. Predictive numerical tools can be extremely useful for enhancing our understanding of ballistic impact events. Models that are able to capture the key mechanical and thermodynamic processes can significantly improve our understanding of the phenomena by allowing time-resolved investigations of virtually every aspect of the impact event. Such high fidelity is immensely difficult, prohibitively expensive or near impossible to achieve with existing experimental measurement techniques.

The thermodynamic response of a material and its ability to carry tensile and shear loads (strength) is typically treated separately within hydrocodes such that the stress tensor can be decomposed into volumetric and deviatoric components. Since the mechanical properties of fibre-reinforced composites are anisotropic (at least at the meso- and macroscale level), the deviatoric and hydrostatic components are coupled. That is deviatoric strains will produce a volumetric dilation and hydrostatic pressure leads to non-uniform strains in the three principal directions.

The strength and failure model was investigated by modeling single elements under normal and shear stresses. It was found that under through-thickness shear stress, the element would fail prematurely below the specified through-thickness shear failure stress. It was found that if the through-thickness tensile strength was increased, failure in through-thickness shear was delayed. This evaluation study shows the importance of the strength, failure and erosion models for predicting performance in the ballistic regime.

Previous material models for fiber-reinforced plastics were 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 are shown in Fig. 13. The deformation of the projectile, e.g., 7.62×39 mm, 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.

It should be noted that an explicit modeling of the individual fibres is not an option, since the computational effort would go beyond the scope of modern server systems (see Fig. 14 and Fig. 15).

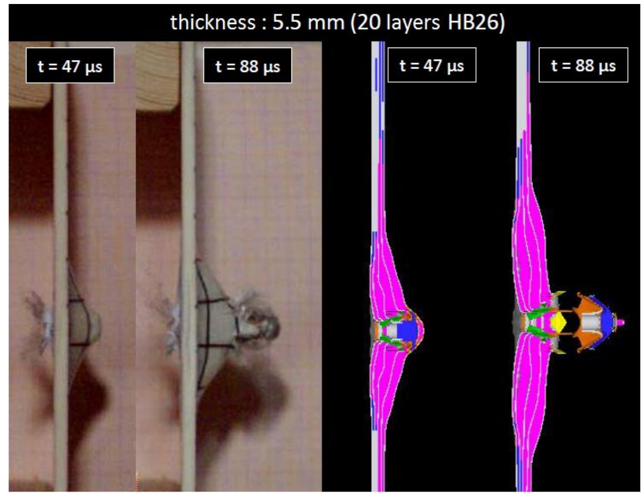


Figure 13. Effect of a 5.5 mm target impact by a 7.62×39 mm bullet at 686 m/s, 47 µs and 88 µs after the initial impact.

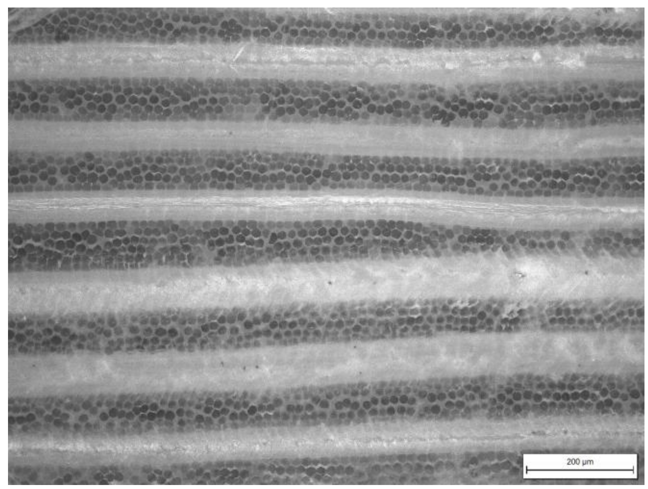


Figure 14. Cross section of a Dyneema® HB26 panel.

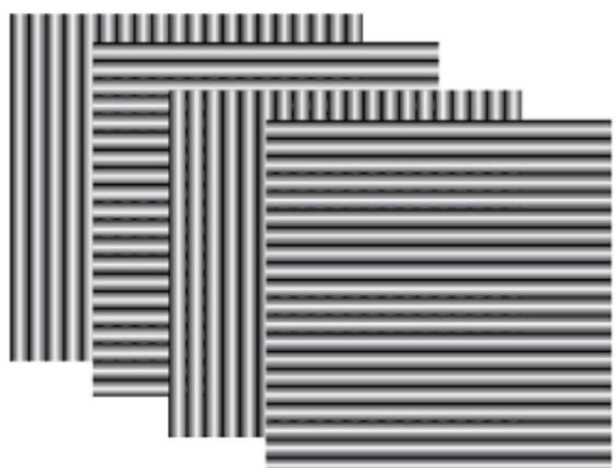


Figure 15. Setup / structure of a Dyneema® HB26 prepreg.

VI. CONCLUSIONS

Coming back to the task of designing structures for vehicles or buildings under dynamic loading conditions like crash, impact or blast, we realize that virtually all fields of application are nowadays supported if not driven by numerical simulation. Along with the rapid development of computer power, utilization of numerical methods as a tool to design structures for all kinds of loading conditions evolved. Simulation of the expected structural response to certain loadings is motivated by the wish

- to optimize the design
- and to better understand the physical processes.

For both intentions the predictive capability of the codes is an indispensable quality. In fact, the predictive capability separates numerical tools from graphical visualization. It means nothing less than the ability to calculate physical processes without experimental results at hand to a sufficient degree of precision.

This work 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.

Existing material models were optimized to reproduce ballistic tests. High-speed videos were used to analyze the characteristics of the projectile – before and after the impact. The simulation results demonstrate the successful use of the coupled multi-solver approach and new modeling techniques. The high level of correlation between the numerical results and the available experimental or observed data demonstrates that the coupled multi-solver approach is an accurate and effective analysis method.

A non-linear orthotropic continuum model was evaluated for UHMW-PE composite across a wide range of impact velocities. Although previously found to provide accurate results for hypervelocity impact of aluminum spheres, the existing model and dataset revealed a significant underestimation of 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.

New concepts and models can be developed and easily tested with the help of modern hydrocodes. The initial design approach of the units and systems has to be as safe and optimal as possible. Therefore, most design concepts are analyzed on the computer.

FEM-based simulations are well-suited for this purpose. Here, a numerical model has been developed, which is capable of predicting the ballistic performance of UHMW-PE armor systems. Thus, estimates based on experience are being more and more replaced by software.

The gained experience is of prime importance for the development of modern armor. By applying the numerical model a large number of potential armor schemes can be evaluated and the understanding of the interaction between laminate components under ballistic impact can be improved.

The most important steps during an FE analysis are the evaluation and interpretation of the outcomes followed by suitable modifications of the model. For that reason, ballistic trials are necessary to validate the simulation results. They are designed to obtain information about

- the velocity and trajectory of the projectile prior to impact,
- changes in configuration of projectile and target due to impact,
- masses, velocities, and trajectories of fragments generated by the impact process.

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.

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