Development and simulation of Protective Systems for Energy Absorption under Ballistic Loading Conditions

Lennart Alkemade[1], Jan Bohlen

1TSS International BV Zuideinde 2991 LK Barendrecht Nederland
lennart.alkemade@tssh.com
+31 (0) 180618922

Abstract.
This work presents an experimental and simulative investigation of the protective capabilities of SKYDEX® material solutions subjected to ballistic loading. In this work, the application of a new DYNEEMA® / SKYDEX® material approach to reduce BABT (behind armour blunt trauma) when used in bulletproof vests is simulated, tested and evaluated. For direct comparison, a reference set-up is used, which equally fulfils the VPAM 6 protection level (7.62 x 39 FeC projectile). The assessment criteria for the evaluation of the corresponding human injuries, the 44mm indentation criterion in ballistic clay, is part of different current test standards like the VPAM BSW 2006. For the simulation-based development and iterative evolution of this novel approach to ballistic protective vests, IMPETUS Afea® is used for the numerical simulation of the interactions of the projectile with the protective structure and to visualise causal relationships for further structural optimisations with the objective to further minimize BABT effects. For this purpose, a numerical representation study of fibre composites or fabric materials is presented to determine a suitable modelling type for this kind of materials. Additionally, the ballistic clay material model, which is adapted to the requirements of the VPAM for determining the BFS (Back-Face-Signature) is also presented. This is followed by the comparison and evaluation of the two protective vest configurations regarding the existing impact mechanism, penetration depth, impulse transfer and trauma severity by simulation and ballistic testing. This proves that the new DYNEEMA® / SKYDEX® approach offers a significant improvement in terms of penetration depth, general BFS and BABT and therefore lower injury severity risk and higher probability of unharmed survivability compared to the reference protective vest.

1. MOTIVATION FOR SOPHISTICATED DEVELOPMENTS IN BALLISTIC PROTECTION

As with all certifications and test specifications, these are limited to a specific range of load cases, which are intended to represent as many real scenarios as possible but are far from being able to capture all potential threats, which means that the protective effect for certain areas of application or attack situations is already reduced. Even in the case of scenarios that are covered by the certification and are therefore averted by the vest, this does not mean that human injury is ruled out. The certifications allow certain puncture or trauma depths during the test, which certainly cause injuries to people.

The "BABT", which stands for "Behind Armor Blunt Trauma", is decisive in terms of ballistics. This describes the trauma that the body experiences behind the body armour. If the case required by the certification occurs that the projectile does not penetrate the protective layer, its energy is partially absorbed by the protective layer in the form of failure modes and deformation while deaccelerating the projectile. However, according to [1] the rest is conducted to the body and occurs there as BABT. It thus describes, according to [2], a "non-penetrating injury due to the rapid deformation of the body armour", caused by the impact of a bullet or other projectile. According to [3], if the residual energy is sufficiently high, this can cause not inconsiderable injuries to the body such as lesions in the lungs, bone and tissue damage in the chest or even ruptures of the heart. In extreme circumstances, the BABT can even result in death. Therefore, it is critical to reduce the Back Face Signature (BFS) of the trauma plate, as reducing the BFS will reduce BABT and thus increase the chance of survivability.

1.1 Development of a New Type of Ballistic Trauma Plate to Reduce the BABT

Due to the already existing cooperation between EDAG Engineering GmbH & TSS International BV in the field of shock mitigation for armoured vehicles, it has been examined whether a variant of the SKYDEX® panels can make a positive contribution to reducing the BABT, since it has outstanding energy absorbing properties. Since it does not provide ballistic protection DYNEEMA® plates can be used to stops the projectile threats. Combined these materials complement each in terms of ballistic protection and energy absorption. Therefore, the composite of DYNEEMA® & SKYDEX® is the most optimum protection composite for both soldier personal protection systems and armoured vehicles with mine protection flooring. The aim of this simulation-driven development, using IMPETUS AFEA

 https://doi.org/10.52202/080042-0003

Solver® Simulation Software, is to demonstrate how the different materials react when combined and thus further reduce the risk of BABT-related injuries.

1.2 Approaches to cover the 7,62 x 39 FeC Threat

Two main designs of protective vests have prevailed, the soft ballistic protective vest and the hard ballistic plate carrier:

- The soft ballistic protective vest: Mainly composed of many layers of ballistic textiles and fibre fabrics. These can have different interweaving structures at the layer level and different connection techniques between the layers. This type of body armour is used for both ballistic and stab protection applications, as modern fabrics, usually made of aramid or polyethylene, offer very high mobility and low weight on the one hand, but also have a high potential for energy absorption on the other.
- Hard ballistic armour: Consists of one or more rigid plates attached to a flexible fabric panel called plate carrier. These plates usually consist of steel, ceramic, or pressed fibre composites such as "DYNEEMA® HB212" UHMWPE plates from AVIENT. They are typically used for higher ballistic threats, such as rifle attacks, and offer good protection in terms of both penetration and trauma depth minimization. In combination with cushioning layers, however, these are often heavy and limit mobility.

The project partners have set themselves the goal of developing effective protection to cover the VPAM 6 threat (7,62 × 39mm FeC) and have pursued three approaches as part of the simulative design:

- Monolithic Steel approach (Domex Protect 500): To be able to classify the development progress better and to make the differences more visible, the classic monolithic steel plate is taken into account as a slide-in solution for a plate carrier in the context of the simulative design and reference. With this approach, the kinetic energy of the projectile is converted into the plastic deformation of the protection plate, which destroys/deforms the projectile core with its hardness.
- UHMWPE-Plate approach (DYNEEMA® HB212): The second approach pursued as part of the simulative design aims to stop the projectile by deformation and catching it inside the different layers of the DYNEEMA® HB212 trauma plate UHMWPE material. The advantage is a lighter and therefore more comfortable to wear trauma plate, but it comes with the disadvantage of a larger BABT than heavier monolithic steel solutions.
- Stacked approach (DYNEEMA® HB212 / SKYDEX® Trauma Reduction Layer): In order to compensate for the described disadvantages of the UHMWPE-Plate compared to the monolithic steel plate, the third pursued approach of the simulative design is to combine strong stopping power and the enhanced weight benefit of the bare UHMWPE-DYNEEMA-Plate with a highly reduced BABT by using SKYDEX**®** as trauma reduction layer on the inner side of the trauma plate. As shown in Figure 1.

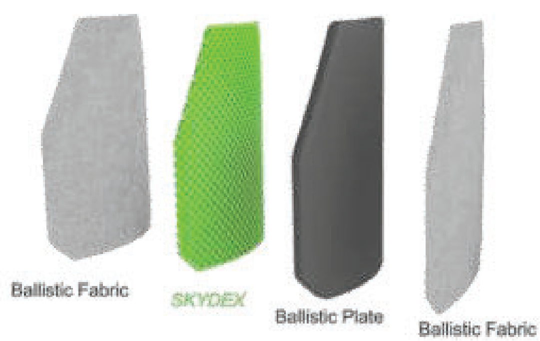

Figure 93 Example of DYNEEMA® HB212 & SKYDEX®

The IMPETUS Afea Solver®, specially developed by IMPETUS Afea AS for highly non-linear and highly dynamic tasks, is used to develop an effective layering of the selected material combination. This explicit FE solver, with Lagrangian discretization, is particularly suitable for the simulative depiction of stresses and ballistic effects on structures and thus for the numerical depiction of large structural dynamic deformations under extreme load conditions. Only volume elements are used since shell elements would lead to inaccurate results under these loading conditions according to [4].

2. MODELLING APPROACH OF THE PROTECTION AND EVALUATION MATERIALS

In this paragraph we like to present the different modelling approaches of the protective and evaluation materials and their corresponding constitutive material formulations when necessary. For the reference setup Domex Protect 500® of „SSAB AB" is used in the MAT-METAL material formulation of IMPETUS [5]. Like the chosen projectile materials (mild steel core, brass jacket and lead filler) this materials were calibrated internally prior to this project and are therefore not part of this technical report.

2.1 DYNEEMA® HB212 UHMWPE of „AVIENT Corporation"

First of all, there are different ways of mapping a fibre composite on a geometric level, independently of the material model. The volume elements specified by IMPETUS as an element type are very well suited for modelling the fabric materials. The distinction to be considered much more closely is the choice between "macro", "meso" and "micro" level according to [6]. These three types of modelling describe how exactly the fibre strands and the matrix are discretized by elements.

- Macro Level: Modelling of the entire network as a single continuum. Failure of fibre strands, the matrix or delamination of individual layers can or must be calculated and mapped solely by the material model. An intralaminar failure cannot be represented.
- Meso Level: Modelling of single or multiple layers as a continuum layer. Failure of fibre strands and matrix must be represented by the material model. Delamination of individual layers or stacks of layers can be realized through contacts and MPC conditions.
- Micro Level: Discretization of the individual fibres and the matrix with elements. Both failure of fibre strands and matrix as well as delamination of individual layers and fibre strands can be imaged.

Figure 2 schematically shows the difference between the three types of modelling in IMPETUS.

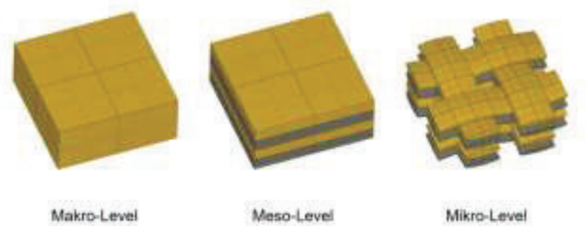

Figure 94 Differences between the three types of modelling

Modelling at the micro level is obviously the most accurate variant for mapping a fibre composite or fabric material. However, it must be noted that a very high number of elements is required for the networking of individual filament strands and the possibly complex, perforated matrix structure around the fibres, which increases the computing time and resource consumption. Nevertheless, the meso level modelling of multi-layered fabric material is also perfectly suited for the evaluation of ballistic impact scenarios and therefore used for the development of the new DYNEEMA® / SKYDEX® approach. In figure 3, the direct comparison between meso and micro level modelling is shown under ballistic impact loading of a soft ballistic layered aramid structure penetrated with a 9mm projectile.

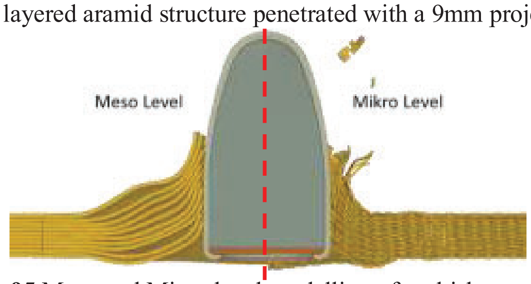

Figure 95 Meso and Micro level modelling of multi-layered fabric

The MAT_FABRIC material model implemented in IMPETUS according to [7] is used to simulate the HB212. This model is designed to simulate fabric materials as a continuum. It enables the input of matrix and fibre parameters, which are then converted into a common constitutive law. Figure 4 shows the characteristic of the stress-strain curve of this material model, whereby it should be noted that the fibre stress σ_i is dependent on the fibre strain ε_i in direction i.

https://doi.org/10.52202/080042-0003

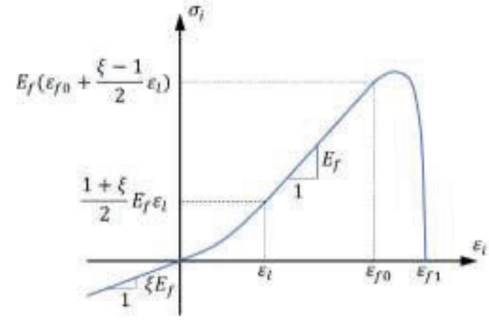

Figure 96 Characteristics of the stress-strain curve

The linear fibre modulus of elasticity E_f can be clearly seen here, although this does not start at the origin, but from the locking strain (fibre locking strain) ε_l. This locking strain describes the alignment of the fibres within the yarn or the strand and the alignment of the strands within the composite or fabric until the material is fully resilient. In addition to specifying the locking strain, it is also possible to enter an initial stiffness component ξ, which influences the reduced slope below the blocking strain, as well as the compression stiffness and the plasticization at the end of the linear law. The two parameters ε_{f0} and ε_{f1}, which represent the elongations at failure of the fibres, are also related to this. These can also be made dependent on the strain rate via the reference strain rate $\dot{\varepsilon}_0$ and a strain rate exponent c_ε. Two of these strains can thus be used to define the onset of failure and a point at which all fibres are torn, which significantly improves the characteristic of element failure. In addition, a matrix failure parameter and an erosion strain ε_e, can be configured. The total stress within the element is calculated according to Equation 1 by separating the hydrostatic, deviatoric and a damping part, which is set via the dynamic viscosity μ_{dyn}. In addition, the equation takes the previously calculated fibre stresses σ_i in the four principal directions into account.

$$\sigma = 2 \cdot G \cdot \varepsilon^e_{dev} - p \cdot I + \left(\sum_{i=1}^{4} f_{F,i} \cdot \sigma_i \cdot v_i \otimes v_i\right) + 2 \cdot \mu_{dyn} \cdot \dot{\varepsilon}_{dev} \quad 1$$

This material model is very well suited for modelling fabrics since it can numerically represent the volume fraction and the locking strain of a real fabric material. The HB212 used in this development project was initially derived from an existing material model for a comparable material and then validated based on ballistic tests.

2.2 SKYDEX® Ballistic Trauma Reduction Layer (BTRL) of „SKYDEX Technologies"

In order to avoid unnecessary complexity in the simulation of the SKYDEX® ballistic trauma reduction layer (BTRL), a geometric representation of the specific, characteristic cell structure of the SKYDEX® -material was avoided. Instead, the BTRL was mapped to a closed continuum reflecting the mechanical stress-strain properties of the material itself. For this purpose, the *MAT_VISCOUS_FOAM material model [8] is used as part of this project, since it enables the characteristic properties by specifying the stress-strain curve under compression loads as shown schematically in figure 5.

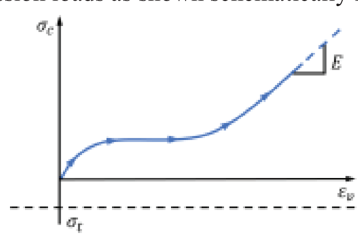

Figure 97 Characteristic stress-strain curve under compression loads

SKYDEX Technologies was able to provide the results of compression tests with speeds between 0.01m/s and 1m/s, which were extrapolated to the expected speed range of the back face of the strike face in the event of a projectile impact. The test procedure and evaluation were simulated and iteratively adjusted to the real results. Figure 6 shows the material test simulation set-up together with the extrapolated test curve for a punch speed of 200m/s and the associated stress-strain curve of the material.

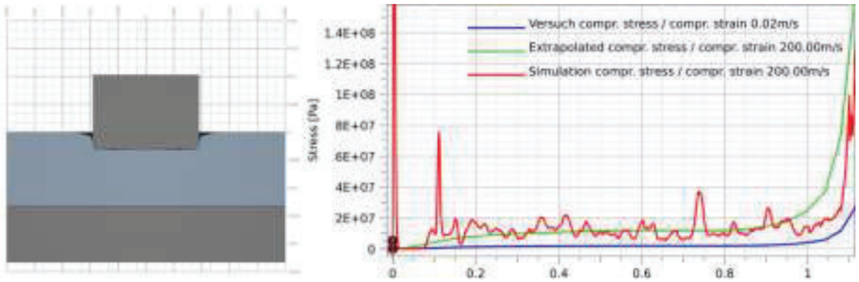

Figure 98 Punch-test simulation set-up & extrapolated test curve

2.3 Ballistic plasticine of „Carl Weible KG"

It should be noted in advance that the terms plasticine and ballistic clay are used synonymously in this report. The MAT-Metal is also used to represent the plasticine in this project, since, as described, it is a material model that can be used very flexibly for ductile materials. Due to the advantage of specifying the plastic flow directly as a stress-strain-curve and not having it calculated using predefined model parameters, this model makes it possible to numerically map the elastic-perfectly plastic behaviour of the ballistic clay directly. For this material model, it is also possible to convert the continuum discretized by finite elements into SPH particles with the same material properties, to receive reliable and numerically accurate results even with the expected very large deformations of the ballistic clay.
The plasticity test is carried out for all regulations by means of a ball drop test, whereby essentially only the drop heights, the associated expected intrusions and the number of tests differ. It can be seen that the plasticine from "Carl Weible KG" used in the VPAM test guidelines [9] and the " Roma Plastilina® No. 1" used in HOSDB, CAST and NIJ test standards behaved very similarly with regard to the required intrusions, which means that these measurements appear to be well comparable. As specified at the beginning, the VPAM test guidelines were used to validate the model of the ballistic clay.
In order to test the plasticity of the plasticine a sphere drop system with a steel sphere (diameter 63,50 ± 0,05 mm, mass 1.039 ± 5,00 g) is to be used [9]. The distance between the lower edge of the sphere and the surface of the plasticine is to be 2.000 ± 5,00 mm, which gives an impact velocity of 6,26m/s. The plasticine with its applied conditioning temperature is acceptable when the depth of each depression is 20,00 ± 2,00 mm [9]. In accordance with VPAM BSW 2006 a simulation model for the sphere drop test onto the plasticine was set up and the material parameter of the ballistic clay where iterative adjusted to provide the prescribed indentation depth, which is shown together with test results in figure 7.

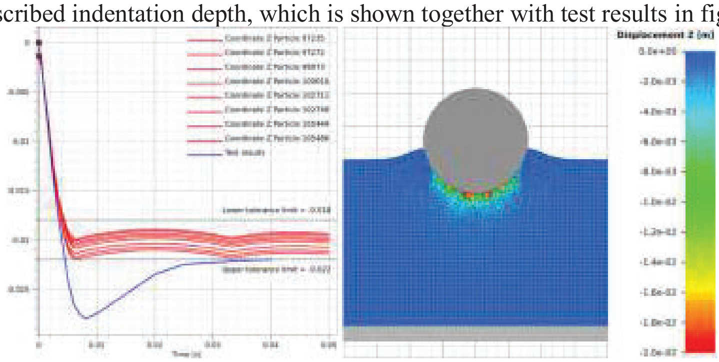

Figure 99 Impact test results of a sphere in ballistic clay

Since the behaviour of the ballistic clay is a critical factor for the subsequent evaluation of the BABT we additionally focussed on a correct behaviour of the displaced clay material, which forms a small circular hill on the edge of the impacting sphere which is also shown in figure 11. Hence the good correlation the chosen parameter set for the plasticine is suited for indicating the plastic deformation and the BABT with its corresponding maximum admissible indentation depth of 44,00mm [9].

3. CLASSICAL APPROACHES VS. THE DYNEEMA® / SKYDEX® STACKED APPROACH

The protective layer (steel or UHMWPE) and the ballistic trauma reduction layer (if used) form together the protective system. A sample size 300mm x 300mm sample is used to eliminate all edge and size effects. The protective system is located on top of the ballistic clay, which has a total thickness of

https://doi.org/10.52202/080042-0003

80,00mm supported by support surface, which is fixed in all translatory and rotatory directions. The protective system is refined in the impact area of the Projectile to achieve sophisticated material and failure behaviour. In total the simulation model, shown in figure 8 consists of ~ 1.000.000 SPH particles representing the ballistic clay and up to 79.000 quadratic elements representing the protective system.

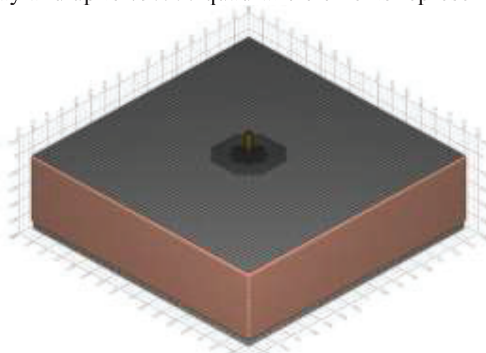

Figure 100 Simulation model with SPH particles and quadratic elements

The initial velocity of the 7,62 × 39mm FeC projectile is set to 720,00m/s according VPAM APR [10], which results in a kinetic muzzle energy of 2.074J, since it has a mass of 8,00g. The projectile itself is represented by around 2.000 cubic elements. The cross section of the real projectile in accordance with [11] and the discretized simulation model is shown in figure 9.

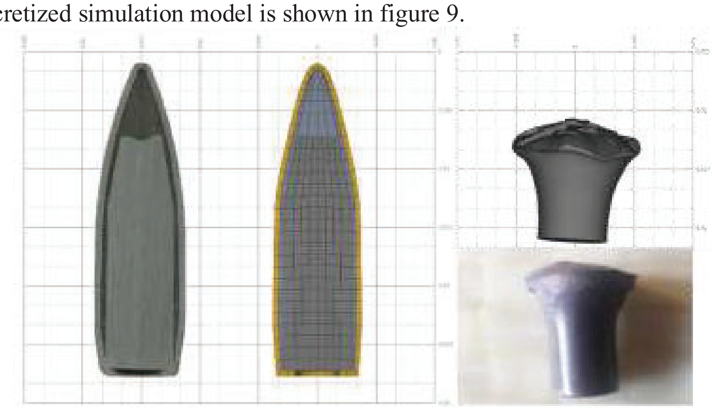

Figure 101 7,62 × 39mm FeC cross section acc. to [11] and core deformation in UHMWPE acc. to [12]

The AK47, one of the most widely used firearms in the world, is chambered for the 7,62 × 39mm cartridge. Therefore, it was the goal to recreate one of the most common threat scenarios below the entrance level for armour piercing projectiles with hardened steel cores. The chosen projectile consists of a mild steel core, a brass jacket and lead filler. The deformation behaviour of the mild steel core in UHMWPE layered material is also shown in figure 9 in comparison for reality according to [12] and the simulation model. As clearly visible the mild steel core is partly eroded and shows a small mushrooming effect by enlarging its diameter on the impacting side.

To evaluate the results and the possibly occurring benefits several different evaluation criteria are chosen. With the areal density and thickness on the one hand side two values are chosen to assess the wearing comfort of the protective system based on design and manufacturing parameters. For the comparative evaluation of the protective capabilities on the other hand three ballistic performance parameters are chosen. First the maximum Force value between the protective system and the ballistic clay material, representing the human body. Secondly the BFS (back face signature) of the protective system is chosen to evaluate the plastic intrusion of the protective layer. It is estimated from the displacement plot of the backside of the protective layer without trauma reduction layer. Lastly the BABT (behind armour blunt trauma) of the protective system is chosen to evaluate the dynamic intrusion of the protective layer. It is determined from the displacement plot of the backside of the protective layer with trauma reduction layer thickness included if installed. The main goal by setting the evaluation criteria is to identify possibly occurring injury reduction potentials in the different approaches and to generate measurable values for the comparison.

For all validation tests of the DYNEEMA® HB 212 we rely on the worst-case scenario results regarding the number of penetrated layers. The results were obtained with the 7,62 × 39mm surrogate from “Sellier & Bellot” described within the CAST 2017 [13] to achieve the most aggressive test configuration. In the simulation the 92 plies are represented by eight layers. Each of the layers consists of two of finite elements in thickness direction, which means each element represents 5,75 plies of DYNEEMA HB 212. The simulation results with number of penetrated layers for validation purposes is shown in figure 10.

Figure 102 Simulation result of 92 plies DYNEEMA with number of penetrated layers

In the test setup a mean value of 54,28 penetrated layers occurred, which is equal to 59,0% of the pressed UHMWPE fibre structure. In the simulation the material model was therefore iteratively adapted to provide a mean value of 57,50 penetrated layers, which is equal to 62,5% for extra safety margin. The overall surface behaviour of the DYNEEMA® HB 212 panel is shown in figure 17 together with the damage behaviour of the SKYDEX® BTRL behind 92 plies of DYNEEMA® HB 212 after the impact of the 7,62 × 39mm projectile.

Figure 103 Surface behaviour of DYNEEMA® HB 212 and damage behaviour of SKYDEX® BTRL

On the strike-face of the DYNEEMA® HB 212 panel (left picture in figure 11) a change in the structure in the 0°/90° fibre orientation is noticeable. This elongation effect of the most heavily loaded fibres was also determined in the simulation regarding shape and size (second to left picture in figure 11). The SKYDEX® ballistic trauma reduction layer shows maximum plastic compression of the structural deformation chambers behind 92 plies of DYNEEMA® HB 212 after the impact of the 7,62 × 39mm projectile (second to right picture in figure 11). This amount of deformation and the affected elements size is not suited for explicit dynamic simulation, due to the inversely proportional behaviour of the element edge length to the possible time step size. Therefore, heavily compressed elements of the SKYDEX® BTRL will be eroded and deleted from the simulation (right picture in figure 11).

3.1 Monolithic Steel approach (Domex Protect 500)

The first classic approach numerically investigated is the monolithic steel approach, represented by Domex Protect 500 material in a thickness of 4,00mm, resulting in an areal density of 31,40kg/m². In figure 12 the general simulation setup is shown together with the mesh density in the impact region.

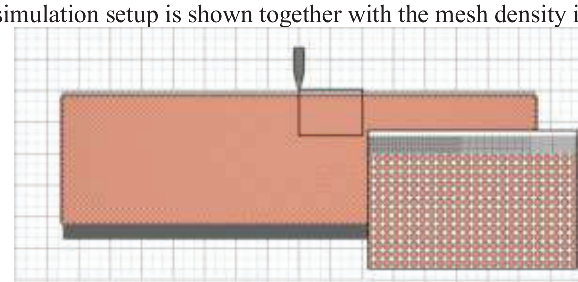

Figure 104 General simulation setup and mesh density in the impact region

In the impact area a mesh density of 0,67mm in thickness direction and 0,83mm in plane was chosen to achieve sophisticated material and failure behaviour of the armouring material. In figure 13 a row of six

https://doi.org/10.52202/080042-0003

pictures, representing six characteristic time frames within the simulation are shown, to give a better feeling of the course of the events.

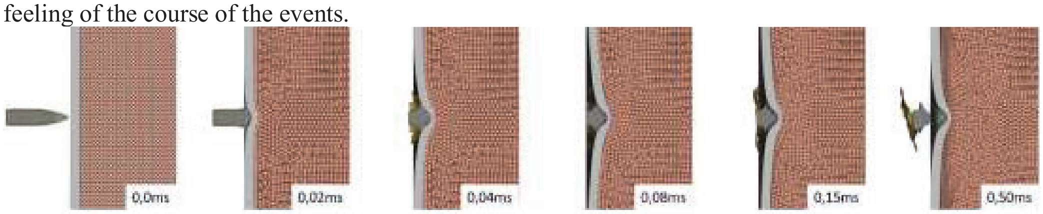

Figure 105 Characteristic time frames within the simulation

To cover all characteristic time frames within the simulation a description of the associated events was prepared and is shown in table 1.

Table 1. Associated events within the simulation of Domex Protect 500

Time	Investigation
0,00ms	Start of the simulation, the initial projectile velocity is 720m/s.
0,02ms	The tip of the projectile is already eroded and the deformation of the mild steel core has begun. The enlargement of the cross section of the projectile (mushrooming) is visible, as the local deformation of the monolithic steel plate. The projectile velocity is ~ 690m/s.
0,04ms	The deformation of the mild steel core is completed, resulting in a noticeable cross section enlargement of the projectile (mushrooming). The jacket flows off on the outside of the projectile and tears open multiple times. The projectile velocity is ~ 250m/s.
0,08ms	The deformation of projectile and armour plate are completed. Starting of the rebound of the monolithic steel plate and the projectile which has therefore a velocity of ~ 0m/s.
0,15ms	The projectile detaches from the decelerating plate.
0,50ms	End of the simulation

With an areal density 31,40kg/m² this approach leads to a SAPI-plate weight (Small Arms Protective Insert) in medium size (241 x 318 mm) [14] of 2,41kg for the wearer. Covering his chest and back a system like this would lead to a total weight of 6,32kg, assuming the plate carrier weights 1,50kg.
The force maximum which is transferred from the protective system to the ballistic clay was 77,86kN. Together with the BABT as dynamic deformation of the protective system and the BFS as plastic deformation this value is taken as reference value for the evaluation of the further investigated approaches. Considering the 44,00mm BABT threshold value for the permitted dynamic deformation of a body armour the achieved 6,43mm and the estimated ~ 3,00mm for the BFS seems to be very reasonable results and be taken as reference for the other approaches. Since steel is an extremely hard material compared to the ballistic clay and to the human body in general it is believed that one main goal of this study has to be the lowering of the transferred force maximum to further reduce the BABT injury probabilities and severities.

3.2 UHMWPE-Plate approach (DYNEEMA® HB212)

The next classic approach investigated is the UHMWPE-plate made of 92 hot-pressed plies of DYNEEMA® HB212. In figure 14 the general simulation setup is shown together with the mesh density in the impact region.

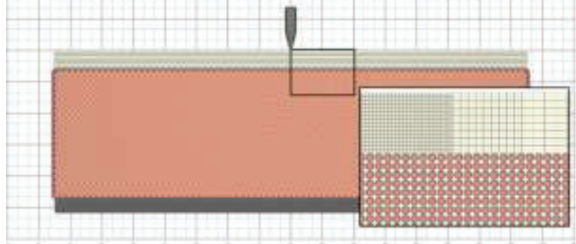

Figure 106 General simulation setup and mesh density in the impact region

In the impact area a mesh density of 0,82mm in thickness direction and 0,83mm in plane was chosen to achieve sophisticated material and failure behaviour of the hot-pressed fibre material. In figure 15 a row of six pictures, representing six characteristic time frames within the simulation are shown, to give a better feeling of the course of the events.

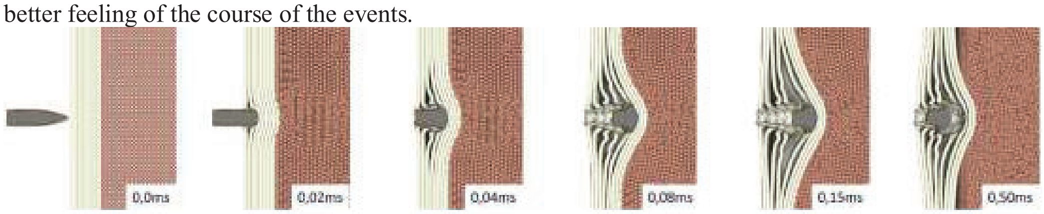

Figure 107 Characteristic time frames within the simulation

To cover all characteristic time frames within the simulation a description of the associated events was prepared and is shown in table 2.

Table 2. Associated events within the simulation of DYNEEMA® HB 212

Time	Investigation
0,00ms	Start of the simulation, the initial projectile velocity is 720m/s.
0,02ms	Penetration of the first layers of DYNEEMA® with visible tip erosion of the lead filler and beginning deformation of the mild steel core. The projectile velocity is ~ 650m/s.
0,04ms	The mushrooming and therefore the enlargement of the cross section of the projectile is visible while more and more layers of DYNEEMA® HB 212 are penetrated. This comes in combination with an increased loss in projectile velocity which is now ~ 450m/s.
0,08ms	The deformation of the mild steel core is almost finished, resulting in an enlargement of the cross section of the projectile (mushrooming). This effect leads to a higher penetration resistance, completing the penetration of DYNEEMA® plies at this point. The projectile itself (and therefore also the pressed UHMWPE-plate) has a velocity of ~ 70m/s, leading to further energy consumption by delamination and interlaminar failure.
0,15ms	The deformation of the projectile and the armour plate are completed. Starting of the rebound of the steel plate together with the projectile, which has a velocity of ~ 0m/s.
0,50ms	End of the simulation

With an areal density 12,84kg/m² this approach leads to a SAPI-plate of 0,98kg for the wearer. Covering his chest and back a system like this would lead to a total weight of 3,46kg, assuming the plate carrier weights 1,50kg. The weight saving is possible due to a significantly increased thickness of the 92 Plies of DYNEEMA® HB212 of 13,10mm compared to the 4,0mm thickness of the monolithic steel approach. The transferred force maximum from the protective system to the ballistic clay is 72,29kN in this approach which is just a little less than within the monolithic steel plate. Originally a significant reduction was expected here and is needed to lower the injury probability and severity of BABT. In addition to this the dynamic deformation as direct indicator for BABT doubles from 6,43mm to 13,89mm in comparison with the monolithic steel plate. This applies also for the estimated plastic deformation as BFS that is now ~ 7,00mm.

3.3 Stacked approach (DYNEEMA® HB212 / SKYDEX® Ballistic Trauma Reduction Layer)

The final approach investigated in this technical study is the combination of the UHMWPE-plate made out of 92 hot-pressed plies of DYNEEMA® HB212 and the SKYDEX® Ballistic Trauma Reduction Layer (BTRL). This approach is intended to combine the positive properties of the two classic approaches investigated before and to lower the probabilities and severities of BABT injuries even further than these. In figure 16 the general simulation setup is shown together with the mesh density in the impact region.

https://doi.org/10.52202/080042-0003

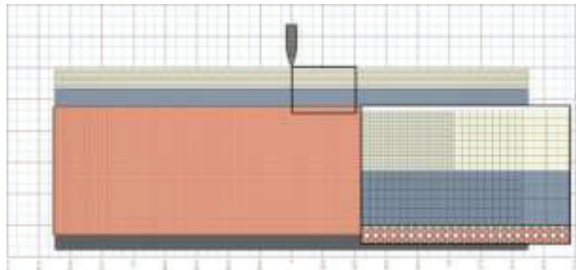

Figure 108 General simulation setup and mesh density in the impact region

In the impact area a mesh density of 0,82mm in thickness direction and 0,83mm in plane was chosen to achieve sophisticated material and failure behaviour of the hot-pressed fibre material and the BTRL. In figure 17 a row of six pictures, representing six characteristic time frames within the simulation are shown, to give a better feeling of the course of the events.

Figure 109 Characteristic time frames within the simulation

To cover all characteristic time frames within the simulation a description of the associated events was prepared and is shown in table 3.

Table 3. Associated events within the simulation of DYNEEMA® HB 212 / SKYDEX® BTRL

Time	Investigation
0,00ms	Start of the simulation, the initial projectile velocity is 720m/s.
0,02ms	Penetration of the first layers of DYNEEMA® with visible tip erosion of the lead filler and beginning deformation of the mild steel core. Local deformation of the SKYDEX® BTRL. The projectile velocity is ~ 660m/s.
0,04ms	The enlargement of the cross section of the projectile (mushrooming) is visible while more and more layers of DYNEEMA® HB 212 are penetrated. The projectile velocity is ~ 480m/s. Further deformation of the SKYDEX® BTRL with first erosion of elements.
0,08ms	The deformation of the mild steel core is almost finished, resulting in a noticeable enlargement of the cross section of the projectile. This effect leads to a higher penetration resistance, which is the reason why the penetration of DYNEEMA® plies is completed at this point. The projectile (and therefore also the pressed UHMWPE-plate) has a velocity of ~ 130m/s at this point, leading to further energy consumption by delamination and interlaminar failure. Apparently a slower deacceleration of the projectile leads to smaller forces on the body of the wearer of the protective system.
0,15ms	The deformation of the projectile and the armour plate are completed. Starting of the rebound of the steel plate together with the projectile which has therefore a velocity of ~ 0m/s. The remaining layers hold the mushroomed projectile, thus further enlargement of the impact area. The erosion of elements from the SKYDEX® BTRL is now completed.
0,50ms	End of the simulation

With an areal density 18,74kg/m² this approach leads to a SAPI-plate of 1,44kg for the wearer. Covering his chest and back a system like this would lead to a total weight of 4,38kg, assuming the plate carrier weights 1,50kg. This is 1,85kg less than the monolithic steel approach, which will have positive effects for the wearer regarding moveability, agility and endurance. Otherwise, this amount of saved weight could be substituted by gear, ammunition or other equipment.

The BABT is with its 6,73mm of dynamic deformation on the level of the monolithic steel plate like the BFS with the estimated plastic deformation of ~ 3,00mm as well which were ambitious targets, but it is possible to achieve them with this configuration of the protective system. In addition, it has been possible to reduce the maximum force by more than 50% to 35.91kN. For this purpose, the force-time curves transferred from the protective system to the ballistic clay are shown in Fig. 18 (left chart).

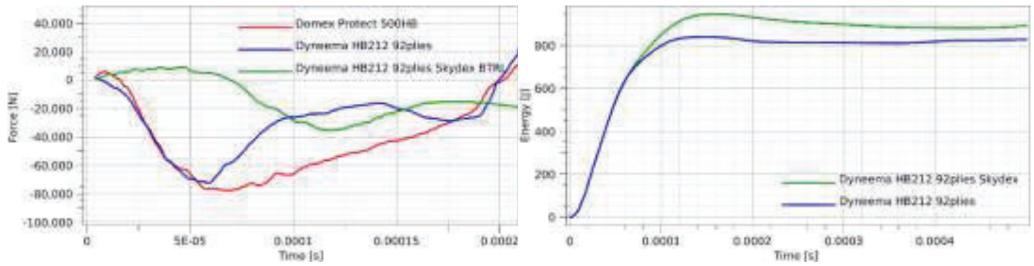

Figure 110 Force-time curves transferred from the protective system to the ballistic

By using the SKYDEX® BTRL as an additional layer between the 92 layers of DYNEEMA® HB212 and the ballistic clay, the force curve increases much later and the slope is generally less steep, which results from the slower deceleration of the projectile, since it is now decelerated over a longer distance and time. Furthermore, the locally impacting projectile energy is now distributed over a larger area using SKYDEX® BTRL. Due to the increased distance to the body, the protective capacities of the UHMWPE fibres can be used more effectively, and more energy can be absorbed through the inter- and intralaminar interactions within the UHMWPE plate. This is also illustrated in Fig. 18 (right chart) in which the combined elastic energy, plastic work and delamination energies for the UHMWPE DYNEEMA® HB212 layers of the two approaches are shown in comparison.

4. RESULTS AND CONCLUSION

In general, very positive results were achieved, all of which are within the permissible limit values of the test guidelines used. Following the results achieved in the simulations for the three different approaches examined are listed in table 4 below, with the monolithic steel approach serving as reference.

Table 4. Results of the comparative simulations

	Monolithic Steel approach (Domex Protect 500)		**UHMWPE-Plate approach** (DYNEEMA® HB212)		**Stacked approach** (DYNEEMA® HB212 / SKYDEX® BTRL)	
Areal density	31,40 kg/m²	100,00%	12,84 kg/m²	40,90%	18,74 kg/m²	59,70%
Thickness	4,00 mm	100,00%	13,10 mm	327,50%	26,10 mm	652,50%
Force maximum	77,86 kN	100,00%	72,29 kN	92,80%	35,91 kN	46,10%
BFS	~ 3,00 mm	100,00%	~ 7,00 mm	233,30%	~ 3,00 mm	100,00%
BABT	6,43 mm	100,00%	13,89 mm	216,02%	6,73 mm	104,67%

By combining DYNEEMA® HB212 and SKYDEX®, it was possible to develop an approach with a significantly reduced areal density in contrast to the monolithic steel plate, which enables despite of it the same low deformation values. Compared to the pure UHMWPE plate approach (DYNEEMA® HB212), the areal density and the overall thickness of the protective structure increase by 5,90 kg/m² and 13,00mm due to the additional ballistic trauma reduction layer (BRTL). However, this reduces the maximum contact force between the protective structure and the body (represented by the ballistic clay) by ~ 50% (36,38kN) compared to the UHMWPE plate approach, which further minimizes the risk of injury for the wearer of such vests. Further ballistic tests with the stacked approach (DYNEEMA® HB212 / SKYDEX® BTRL) are currently being carried out to confirm the initial positive results and establish this combined DYNEEMA® HB212 / SKYDEX® BTRL approach as a sophisticated solution for further development in personal armour systems.

References

[1] Prat, Nicolas, Frederic Rongieras, JeanClaude Sarron, Alain Miras und Eric Voiglio (2021). Contemporary body armor: technical data, injuries, and limits. BrétignysurOrge.
[2] Carr, Debra, Ian Horsfall und Chris Malbon (2016). Is behind armour blunt trauma a real threat to users of body armour? A systematic review. Cranfield: Cranfield University.
[3] Cannon, Leslie (2001). Behind Armour Blunt Trauma an emerging problem. Cosham.
[4] Olovsson, Lars. 2018. RE: General information about IMPETUS. [E-Mail] Huddinge, Schweden : s.n., 4. Juni 2018. 09:58.

https://doi.org/10.52202/080042-0003

[5] IMPETUS Afea AS (2021). MAT_METAL. URL:
https://www.impetus.no/support/manual/?command=MAT_METAL (Retrieved: 16-11-2021).
[6] CADFEM GmbH (2016). Composite. URL: http://www.cae-wiki.info/wikiplus/index.php/Composite (Retrieved: 24-09-2021).
[7] IMPETUS Afea AS (2021). MAT_FABRIC. URL:
https://www.impetus.no/support/manual/?command=MAT_FABRIC (Retrieved: 27-10-2021).
[8] IMPETUS Afea AS (2021). MAT_VISCOUS_FOAM. URL:
https://www.impetus.no/support/manual/ ?command=MAT_VISCOUS_FOAM (Retrieved: 17-12-2021).
[9] Vereinigung der Prüfstellen für angriffshemmende Materialien und Konstruktionen (2009). Prüfrichtlinie „Ballistische Schutzwesten “. Münster.
[10] Vereinigung der Prüfstellen für angriffshemmende Materialien und Konstruktionen (2010). Allgemeine Prüfgrundlagen für ballistische Material, Konstruktions und Produktprüfungen. Münster.
[11] Vereinigung der Prüfstellen für angriffshemmende Materialien und Konstruktionen (2021). ANSCHLUSSDOKUMENT zur VPAM–APR „Prüfmittel “. Münster.
[12] Precision Ballistics Laboratories UK (2022). 'Mild Steel' cores from 7.62x39mm PS Ball (MSC) bullets. URL: https://www.linkedin.com/posts/precision-ballistics-laboratories-uk_pbl-precision-ballistics-activity-7037429715405533184-ZMjl/?utm_source=share&utm_medium=member_desktop (Retrieved: 21-03-2022).
[13] Payne, Thomas, Sarah O'Rourke und Chris Malbon (2017). Body Armour Standard (2017). Sandridge: Centre for Applied Science und Technology (CAST).
[14] BAE Systems (2007). Hard Body Armor Insert Plates, Phoenix, AZ USA (Retrieved: 2008-11-11)