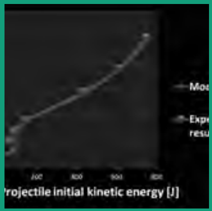
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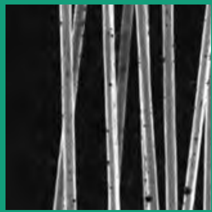
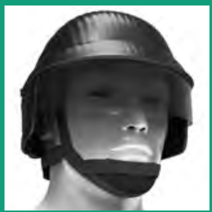
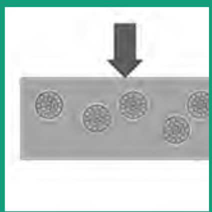
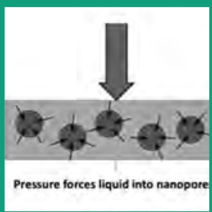


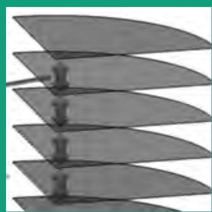


PROJECT 8




Pressure forces liquid into nanopore


PARK



Spider Silk

INSPIRED SUPER-TOUGH NANOARMOURS

Spider Silk
Inspired super-tough nanoarmours

project 8

The aim of the Spider silk project is to design a lightweight nanoarmour able to resist penetration of high energy fragments through its bio-inspired toughness

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PROJECT DESCRIPTION

THE CHALLENGE

Over the last few decades, the search for bio-inspired solutions has been widely accepted in many engineering and technological fields as the best way for optimizing and taking advantage of available resources. Nature over the ages has found its optimal solution for survival and our teams therefore looked at Nature for the design of device nanoarmour whose scope is essentially to save lives. Existing materials and technologies allow current engineering solutions to stop projectiles of different kinds but these existing devices do not safeguard against the penetration of minute fragments. The need for unconventional toughness suggests that we need to look for inspiration, for example, from spider silk or bombardier beetles. What follows is research at the leading edge of current material science and computational mechanics.

THE TEAMS

The two teams addressed the challenge of designing bio-inspired lightweight nanoarmour through alternative and complementary methods: an analytical/theoretic approach by the *MoDe* team, implementing and elaborating current theories of impact mechanics, and a numerical predictive approach by the *SaFe* team, using the most advanced multi-physics simulation codes currently available. As a case study we focused on military helmets. The “Giuseppe Maria Pugno” Laboratory of Bio-Inspired Nanomechanics at the Politecnico di Torino is an authority in the field of Nano-Bio-Inspiration (papers in *Nature* and *Nature Materials* and ERC Starting Grant Winner 2011) and supervised the two teams.

THE RESULTS

The *MoDe* and *SaFe* teams collaborated with one another in order to conceive and design an innovative and feasible protective armour concept. Based on the *MoDe* team’s analytical models of impacting projectiles and the *SaFe* team’s numerical simulations, a new-generation of a bio-inspired, undulated and multi-layered helmets is proposed. The *MoDe* team focused on the design of the internal safety system, especially looking at ergonomics, and how to integrate and implement the innovative external shape, while the *SaFe* team (in collaboration with AMET) verified the protective effectiveness and reliability of such a new design, carried out studies aimed at finding the best solution in terms of multi-layered structures and, last but not least, the feasibility of the production process. The proposed new concept has applications in several other fields: spin-offs could be directly or indirectly involved in the future and new stakeholders might be interested in it, from sport safety to hail resistant architectural roofs or to protective shells for strategic structures and plants.

project 8A

MoDe
Model & Design

TASKS & SKILLS

Sara Baronetto studied analytical models to understand how material characteristics affect bullet penetration; using these models, she compared different materials and layer configurations.

Stefano Bosetti built an analytical model to study the penetration of a projectile against a homogeneous target. He applied Cavity Expansion Analysis for the characterization of experimental parameters.

Flavio Caciuffo studied the effects of melting during bullet penetration and built an analytical model to describe bullet penetration in composite material targets. Finally he made a comparison of different materials using this model.

Anna Gabriella Ciriolo contributed by studying oblique impact mechanisms and proposed channeling as an alternative solution to reduce projectile penetration.

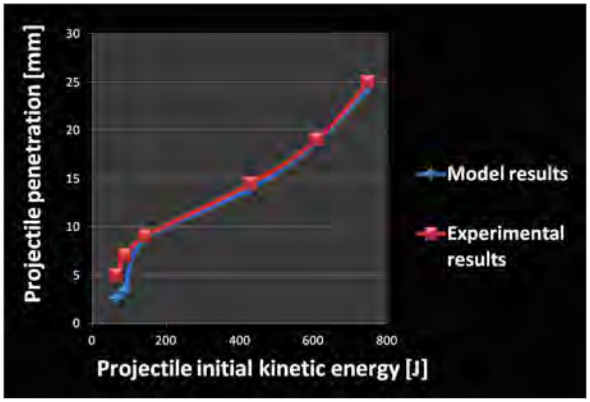
Bethany Neigebauer researched and explored alternative disciplines for the use of spider silk inspired materials, specifically looking at American football helmets and hail damaged architectural roofing.

Gianni Robert Rehkopf performed the material and state of the art research. He then defined the helmet ergonomics and shape, modelling the undulated surfaces and the overall geometry.

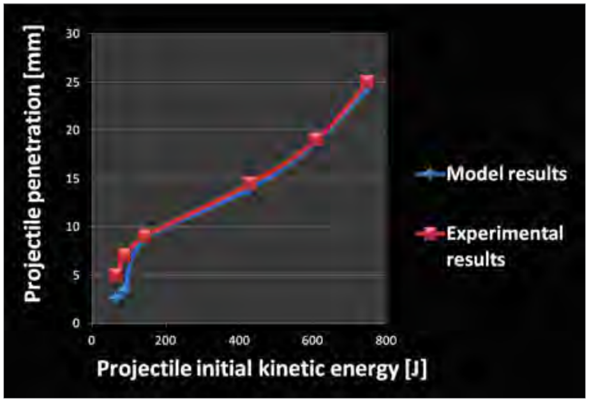
ABSTRACT

Protective armours, such as helmets, have undergone a continuous process of evolution over the ages, following the paths paved by technological progress. Ancient Greek and Romans developed bronze and iron models to defend their soldiers from swords and spears. These helmets were partially abandoned around 1200 A.D. because of their inefficiency against new firearms. Helmets, primarily composed of steel, reappeared during World War I to protect infantrymen from fragments generated during explosions. A new era started in 1972 with PASGT, the first helmet composed of high strength synthetic fibres. Today the majority of the shells are composed of woven layers of high resistance fibre immersed in a polymeric matrix, however a substantial amount of work has yet to be done in order to improve their performance. New directions in research have been opened by bio-sciences, allowing Nature to become a fundamental source of inspiration.
The general task of the MoDe team was to propose and develop innovative solutions in order to make armour both lighter and more resistant to fragment penetration, exploiting the objectiveness of analytical approaches in providing general guidelines. Starting from study of the literature, we focused on the analytical aspects of the specific physical phenomenon under investigation, i.e. bullet penetration into a target. Models were then developed and enhanced, until a satisfactory match with experimental results was reached, in order to obtains tools to study how to improve the performance of a target by modifying its main characteristics. These models were then exploited to test the mechanical performance of potential materials currently available on the market or in the advanced study phase, without forgetting issues related to feasibility in terms of total weight of the helmet. Bio-inspired solutions were integrated: we developed a shell shape inspired by the interior explosion chambers of the bombardier beetle.
Our efforts also polarized on:

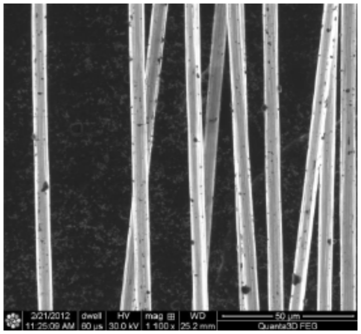
- developing a new ergonomic and safe padding system design;
- studying the possibility to improve ballistic performance in reducing fragment penetration by means of a configuration of inclined layers;
- researching and proposing other disciplines in which innovative helmet materials could be useful, in order to discover possible future applications for the work presented by the group.



1 *Projectile penetration vs. initial kinetic energy*



2 *Projectile penetration in different materials*



3 *SEM capture of carbon fibres*

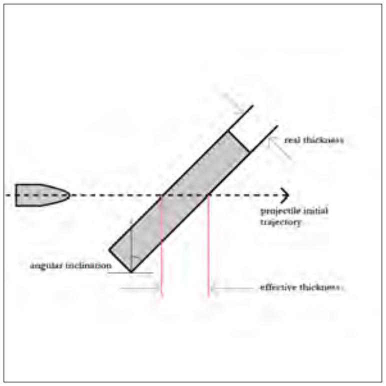
UNDERSTANDING THE PROBLEM

Nowadays, protective devices and armours are heavy and cumbersome in order to defend against penetration. However, preventing the penetration of fragments and chips remains a difficult issue. Our starting point as a source of inspiration was Nature. Exploring materials, we found spider silk to be stronger by weight than steel and to be one of the toughest materials that exists. Creating a body armour or a helmet with a similar material would lead to an ultra-light and super strong protective outfit. Exploring different shapes, we found that the structure of the multi-layer undulating walls of the bombardier beetle's interior body chambers efficiently absorb impact energy from explosions.

Therefore, our aim was to investigate, from an analytical perspective, the possibility of improving the mechanical behaviour of military helmets, making them lighter, and at the same time more comfortable and easier to handle, taking Nature as a constant point of reference. To achieve this goal, in-depth knowledge of ballistic impacts is required, since only understanding how they work is it possible to devise an efficient strategy and act on the parameters that mostly influence helmet resistance.

Also ergonomics is important when designing a helmet. Studying the history of helmet design and the pad systems currently in use, we tried to understand the requirements to achieve the best possible comfort and safety. Army helmets are usually planned to resist potential injuries, such as skull fractures and injuries due to shrapnel, fragments or bullet strikes. On the other hand, current army helmets do not offer enough safety against shock waves caused by IEDs (improvised explosive devices). In fact more than 150,000 soldiers (59%) have been diagnosed with TBIs (traumatic brain injuries) since 2001, mainly in conflicts in Iraq and Afghanistan.

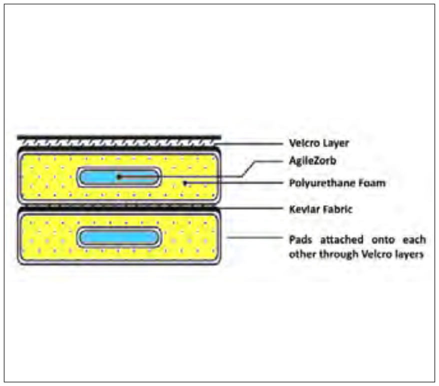
Finally, other fields of application were analysed. In particular, we focused on problems deriving from head collisions in American football players and similar athletic helmets. In addition, we studied the issue of impacts of hail on architectural roofing. In fact, apart from the specific objective of our project, other stakeholders can be identified as potentially interested in the production of efficient protective systems, such as manufacturers of motorcycle helmets, Formula 1TM helmets or protective coverings for the preservation of buildings and structures.



4 *Oblique impact: effective thickness enhancement*

5 *Frontal view of the helmet*

6 *Back view of the helmet*



7 *Removable pad structure*

EXPLORING THE OPPORTUNITIES

The process of bullet penetration in a target is influenced by several variables, among which bullet shape and resistance of the target material are only the most obvious. During the first phase of the project, research on existing studies of bullet penetration in a target were carried out. Since these studies did not exactly meet our requirements, it was necessary to create new analytical models starting from very simple ballistic situations and specifically basic formulas found in literature.

To adapt our results to real tests, research on NATO ballistic tests were conducted. As projectile shape affects the depth of penetration, it was decided to use NATO bullets and fragments for our analysis. In particular, more attention was paid to the behaviour of targets struck by fragments, since these have proven to be more difficult to stop.

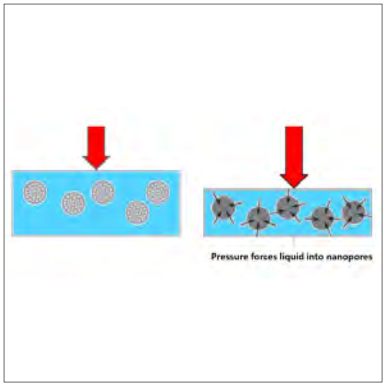
Furthermore, studies on multi-layer targets were investigated, in particular on the issue of delamination between layers. Materials composed of different layers bonded together can dissipate energy during ballistic impacts, also thanks to parting of the adhesive. In this way, the velocity of the projectile and the penetration depth can be reduced. However, to examine this issue properly, ballistic tests turned out to be necessary. To overcome this obstacle, estimated values were used.

Since the evolution of military helmets is interrelated with the development of weapon technologies, to absorb the increasing energy of bullets, fragments and blasts, helmets have become thicker and, as a consequence, heavier and less comfortable. In order to improve comfort and safety, padding systems and ergonomic measures of motorcycle and NFL helmets have been investigated. As a result, it turned out that many existing materials and technologies already used in other disciplines could be directly implemented in the design process.

GENERATING A SOLUTION

Our first step was to expand a model describing bullet perforation in a homogeneous material. Through appropriate calculations, coefficients for quantification of the projectile shape influence in penetration dynamics were determined. Furthermore, the potential presence of multiple layers was included.

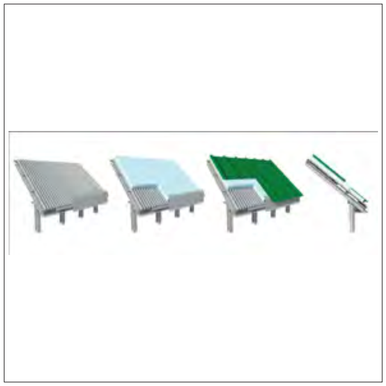
Subsequently, another model concerning composite materials was developed, formalizing aspects related to the mechanism of partial dissipation of a bullet's kinetic energy into thermal energy and adding the component of viscous friction. This second result was used to compare the mechanical performance of different materials already present on the market, without neglecting the final weight of the shell. Thanks to this comparative analysis we were able to identify the best material solution currently feasible. Among the materials considered, glass and



8 *AgileZorb® peculiar behaviour under compression*

9 *Inner view of the helmet (pad system) 1*

10 *Inner view of the helmet (pad system) 2*



11 *Building application of the MoDe concept*

ceramic fibres showed great resistance to penetration but had an excessive final weight. On the contrary, UHMWP fibres exhibited optimum performance in terms of shell weight but maintained low penetration resistance. Carbon fibres provided good responses in both cases, even though the optimal material solutions were represented by Kevlar®, M5® and Zylon®. Within the latter three compound subsets we must specify that Kevlar® is already widely used in protective applications but is still in a refinement phase.

This material analysis accompanied the design of the outer and inner shell shape for optimization purposes. Starting from the internal shape, an appropriate padding system was designed. This mainly consists of a first layer of force deflecting material, directly under the outer shell, to efficiently disperse the impact energy. Attached to it, a Velcro® layer ensures the customizable positioning of various pads. These pads are made of up to three polyurethane layers (positioned one on top of the other using Velcro® layers according to user comfort), including a very effective energy absorbing filler material called AgileZorbTM. They are also interspersed with Kevlar® fabrics to add the anisotropic component and thus further deflect the shock wave along the in-plane directions. For the outer shell, through FEM analyses carried out by the SaFe team, the performance of a particular undulating geometry inspired by bombardier beetle armour [2] was compared to a flat one, revealing better impact energy absorption by distributing it over a larger area. This particular shape was therefore selected. Taking into account all of these results and analyses, a new helmet concept was designed.

In parallel, alternative configurations for the internal architecture of anti-penetration systems was analytically studied. This led to the idea of inducing structural modifications to the standard juxtaposed multilayer solution, inserting an inhomogeneous layer, characterized by inclined layer components, to deflect and consequently reduce fragment penetration depth. In this sense, however, further studies are required in order to prove numerically and experimentally the significance and feasibility of results.

Finally we explored the possible fields of application that our protective armour design strategy could directly or indirectly affect. In fact, not only body defence, but also a number of other disciplines, such as building preservation, could benefit from advances in penetration resistance technology. On the one hand, American football helmets and similar athletic helmets were considered. On the other, an architectural study specifically regarding the protection of roofs from hail storms, a phenomenon which has impact statistics similar to ballistics, was carried out. Even in these completely different scenarios, the potential application of bio-inspired materials can lead to the discovery of additional multidisciplinary opportunities.

project 6B

SaFe
Safety & Feasibility

TASKS & SKILLS

Francesco Buonora analysed the resistance properties of a multi-layered surface. He also studied the applicability of bio-inspired solutions and materials. He also coordinated collaboration both inside and outside the team.

Vito Mario De Leonardis studied the effects of geometric modifications on the impact performance of isotropic materials and helped create a model to predict penetration depth in metal targets.

Lorenzo Rossini analysed different manufacturing processes for composite materials and worked on a possible production cycle.

Stefano Signetti studied numerical techniques and issues in modelling composite materials subjected to high-velocity impact and performed sensitivity analyses on the main material model parameters.

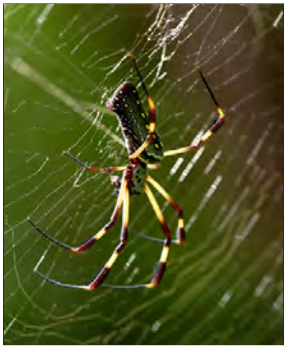
ABSTRACT

The problem of protective devices, especially armours, has been treated so far by a “rough” empirical approach, following the philosophy “add material until it stops”. Over the last decades the invention of new materials such as Kevlar® has driven armours towards resistance levels previously unimaginable. However, the current request for lightweight devices and the desire for a solution age-old problems, such as high penetration of minute fragments, question the ability of this approach to produce an effective device. Military helmets, since their issues in terms of design, resistance and production processes are extreme, were chosen as a case study.

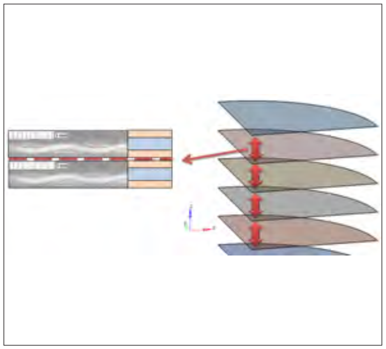
Computer-Aided Engineering (CAE) is the exploitation of computer software to aid in engineering tasks. Its use has enabled many industry fields to reduce product development costs and time while improving safety, comfort, and durability. The predictive capability of CAE tools has progressed to the point where a large part of design and verification is done using numerical simulations rather than physical prototype testing. Our team focused on this engineering approach in the structural design of the helmet, through the use of the most advanced FEM codes for non-linear problems currently available. Studies were also performed in order to establish how performance could be improved by optimising dissipative phenomena and adopting an unconventional profile for the helmet surface.

The productive collaboration with AMET S.r.l., a high-tech CAE company, and with an external composite producer, allowed us to optimize our analyses, to verify our results by experimental testing and to highlight new issues at the forefront of the capability of numerical simulation techniques. This collaboration also helped manage the basic product requirements, both in terms of safety, ergonomics and production feasibility, in order for an innovative production chain to be conceived and proposed.

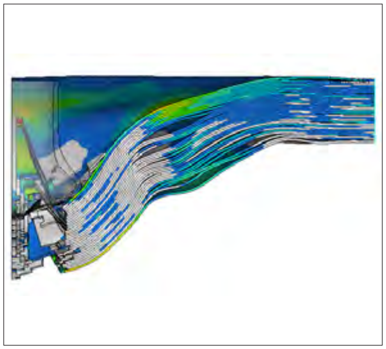
1 *Headquarters of AMET, Environment Park - Torino*



2 *Nephila clavipes and its web*



3 *Numerical model of multi-layered composite material*



4 *Side view of impacted plate, contour of maximum principal stresses*

UNDERSTANDING THE PROBLEM

The SaFe team decided to investigate the effectiveness and feasibility of a bio-inspired solution by use of numerical analysis tools, focusing in particular on performance improvement of multi-layered composite panels.

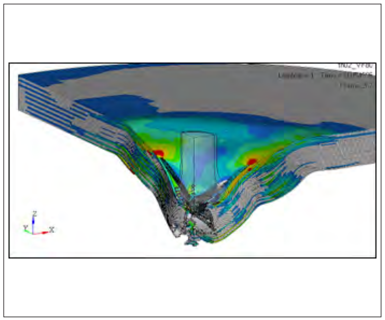
The use of composites is the first fixed point of the solution: since a "perfect" material does not exist, their strength derives from the combination of two or more materials that can combine very different (and in many cases incompatible) properties in the same material, each enhancing its own characteristics and compensating the deficiencies of the others. The second point of the solution is the multi-layer ply: delamination energy is proportional to the fracture surface, and therefore to the number of available interfaces, and not to the helmet thickness (except for the capability to insert a given number of layers in a certain thickness); this aspect is strategic in reducing helmet weight and making it more ergonomic.

Starting from these considerations, spider silk toughness and non-linear hyper-elastic behaviour were borrowed for improvement of material properties and structural behaviour, while the example of the bombardier beetle [2] suggested adoption of an unconventional corrugated surface as a first level defensive mechanism.

Generation of an innovative solution for armour, as any other engineering problem, does not take place in a vacuum. Collaboration with an external company was therefore essential. Besides validation of our models, this also provided an understanding of the technical feasibility of the proposed solution. Current production processes of multi-layer composite panels present certain issues that can affect the real effectiveness of the optimal solution. It is therefore a necessity to adjust initial forecasts or discover new production solutions to move from "idea" to "innovation".

EXPLORING THE OPPORTUNITIES

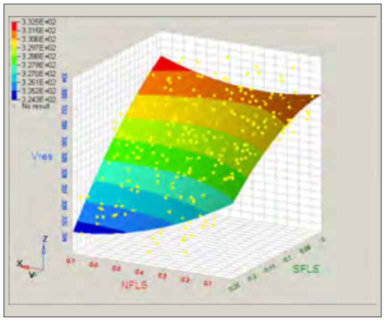
The parameter that establishes the capability of materials to dissipate energy at failure is the work to fracture. Spider silk is the toughest material known in nature with a specific work to fracture of the order of 170 J/g. Only recently, with the advent of nanotubes, carbon nanotube/polyvinyl alcohol gel composites have been produced, achieving the world record with a work to fracture per unit mass of 570 J/g. However, toughness is not the only goal to be achieved. The helmet must maintain its resistance properties in the most adverse climatic conditions and therefore thermal resistance and low humidity absorption are key requirements; the material must be stable under processing that involves high pressure and temperature; toughness itself is not sufficient but rather high performances with low level of deformation must be guaranteed, since extreme buckling of the helmet is just as dangerous. Along this direction, a wide range of



5 *Isometric view of impacted plate, contour of maximum principal stresses*

6 *Ballistic test on Kevlar® composite panel: full penetration*

7 *Ballistic test on polyethylene composite panel: no penetration with delamination visualisation*



8 *DOE results: sensitivity on residual velocity of normal (NFLS) and shear (SFLS) delamination strengths*

available traditional and unconventional materials were examined in order to find the best balance of the required properties. Where it is not possible to further improve material performance, Nature teaches us to use it in the best way: the choice of fibre orientation in the successive layers, the alternation of different materials and the presence of strategic voids are all aspects subjected to the optimization process. The reaction chamber of the bombardier beetle [2] provided us with a second inspiration: even if its purpose is not to resist impact penetration, we decided to investigate the performance of undulating shapes in our problem, finding unexpected results.

Correct representation of the real problem through a numerical model then becomes a central issue. The aim is to represent the phenomenon as realistically as possible, always bearing in mind that the model has its own intrinsic limitations and requires a certain level of simplification due to the compromise between complexity of available models and computational costs. The collaboration with AMET guaranteed the necessary know-how for starting the analysis and, following implementation of this unconventional problem, new numerical techniques and methodologies were explored.

Production of this kind of helmet is quite a complex process and would require significant changes in the industrial process, challenging economic and technical feasibility: this led to the study and proposal of a new production process to actually manufacture our product in acceptable terms.

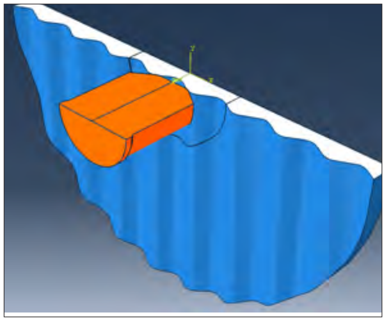
GENERATING A SOLUTION

A new concept of a multi-layered undulating helmet is proposed and developed in holistic complementary collaboration with the MoDe team. Several procedures may be adopted to model the composite material layers: woven fibre can be represented in both its constituents by use of solid or beam elements which assign both the fibre and matrix properties. On the other hand, the ply can be translated into a homogeneous equivalent continuum and the composite properties result from the weighted average of its fractions. This option can be implemented by modelling each layer with shell elements or with one or more solid elements throughout its thickness. Following this direction, the choice fell on the new LS-DYNA® thick shell element (TSHELL) [3], provided that its efficiency in describing the problem could be proved.

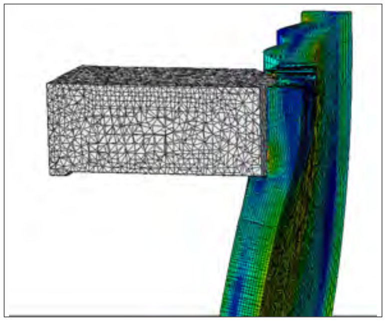
As also confirmed by experimental tests, delamination was shown to be important but not as dominant as expected: rather the adhesive strength has to be carefully balanced because it can cause transition from ductile and dissipative behaviour, due to the material plastic work, to local punching fragile failure. As plastic deformation is the key for dissipation, the material must guarantee high toughness even at low deformations, and high post-peak residual strength.

Inspired by the resistance to high pressure shock waves of the bombardier beetle endoskeleton, the team decided to evaluate whether macro-geometric changes to the exterior surface of the

9 *The undulated shell of the bombardier beetle (Brachinus crepitans)*



10 *FEM model of fragment impacting on the corrugated surface*



11 *Projectile inversion caused by the corrugated surface*

12 *The resultant surface of the helmet*

helmet could lead to better ballistic performance without increasing its weight. Numerical simulations were therefore conducted to compare the behaviour of undulating and flat targets. Several sinusoidal surfaces were designed, changing wavelength and amplitude. Simulations showed that a fragment with a specific initial velocity completely penetrates the flat plate, while corrugated surfaces can block the projectile. This holds true only if the diameter of the fragment is larger than the wavelength of the sinusoidal function, since otherwise the projectile might hit an area with a reduced cross section. The behaviour of plates with a triangular wave profile were also tested, but the V-notch discontinuities caused decreasing performance due to local intensification of the stress field, especially in the case of thin targets.

These optimised structural solutions must find effective feasibility with regard to composite materials and production processes. So far, helmets have generally been produced with a lay-up technique consisting of adding one layer on top of another. However, in order to generate the complex undulated outer surface, this composite manufacturing process appears to be not fully suitable. To overcome this limitation, Resin Transfer Molding (RTM) was chosen as an alternative method. This solution consists of using a closed mold in which the dry reinforcement fibres (including those providing the wave shapes) are placed in the chosen direction. In turn the resin is injected into the mold and allowed to flow over the fibres until fully impregnated. The helmet is cured in a single operation, allowing the product to achieve the highest quality standards and obtain the desired undulated surface. This production method requires a precisely shaped mold and analysis of the resin flow in order to perform at its best. However, the process can be highly automated with high production rates, requiring limited manual work, no autoclave for curing and no refrigeration system, as opposed to other composite manufacturing processes.

Finally, the proposed concepts could be extensible and applicable to a wide range of fields in which sandwich/laminated composite panels are used, such as other parts of protective armours, underwater structures, protective shells for nuclear plants and road retaining devices.

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