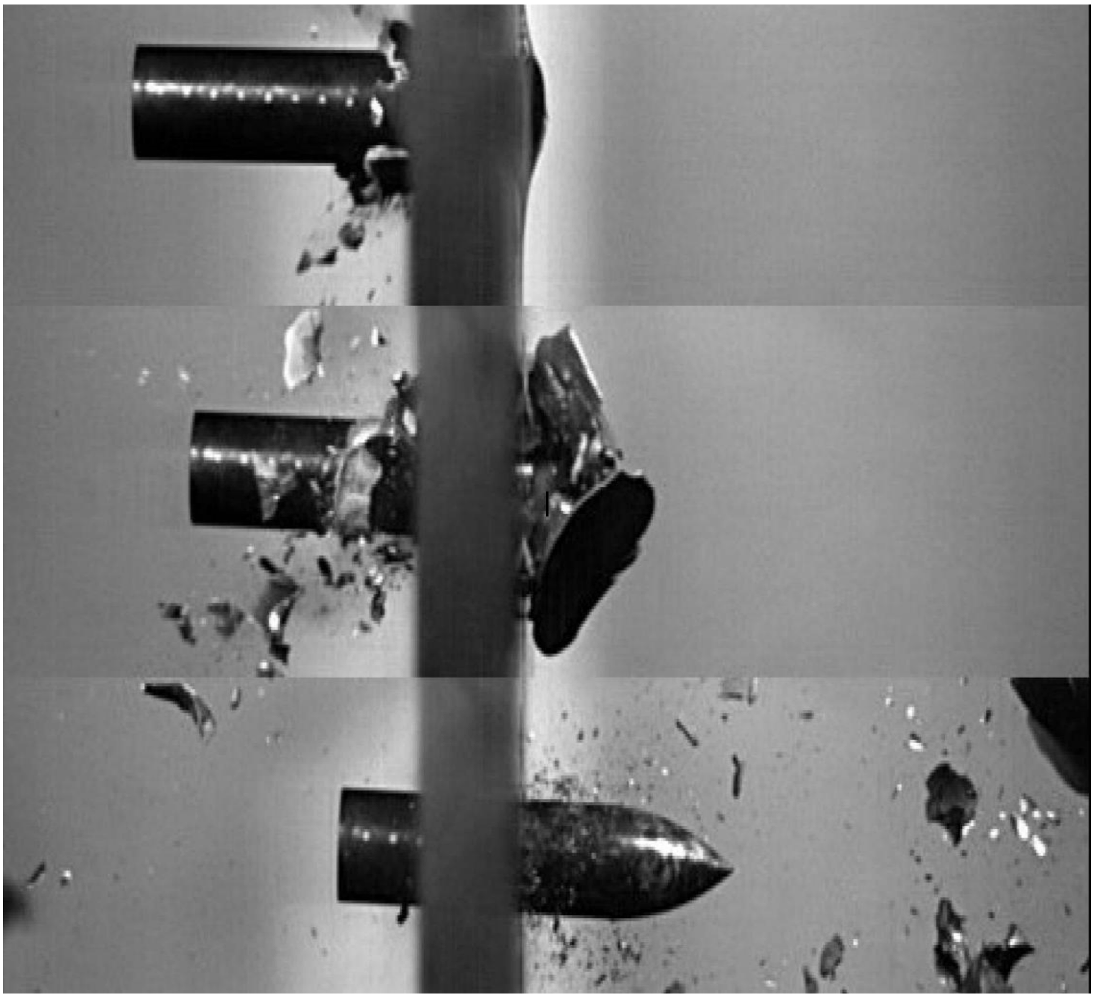
FORSVARSBYGG

NTNU
Norwegian University of
Science and Technology

LWAG 2026

Light-Weight Armour for Defence & Security

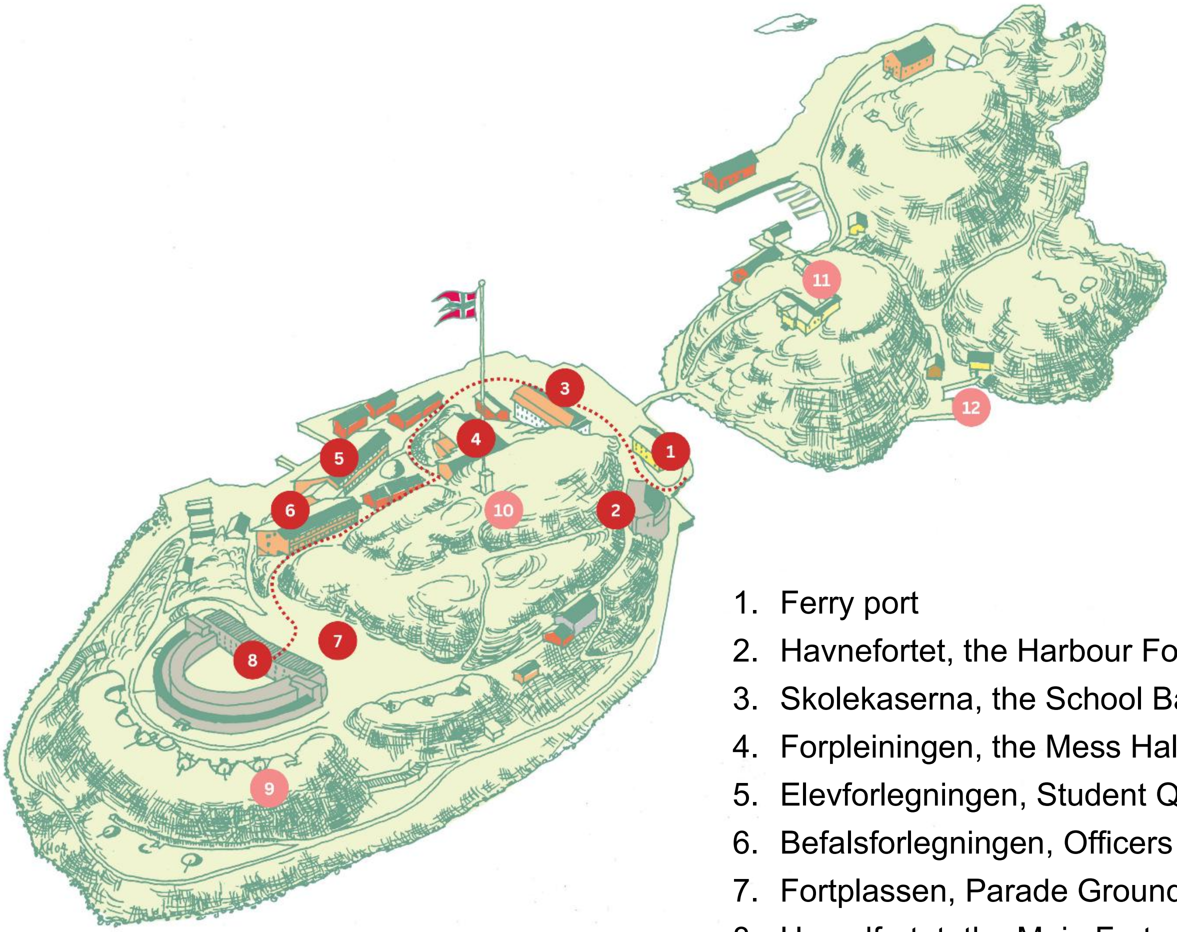
June 2nd-4th 2026
Oscarsborg, Norway



LWAG 2026

Welcome to Oslo and Oscarsborg. We look forward to spending two great days together.

This brochure contains some general information about your stay at Oscarsborg Hotel & Resort and the Oscarsborg Fortress, as well as the technical program and abstracts.



1. Ferry port
2. Havnefortet, the Harbour Fort
3. Skolekaserna, the School Barracks
4. Forpleiningen, the Mess Hall
5. Elevforlegningen, Student Quarters
6. Befalsforlegningen, Officers Quarters
7. Fortplassen, Parade Grounds
8. Hovedfortet, the Main Fort
9. Hovedbatteri, the Main Battery
10. Vakttårnet Kongen, Watchtower
11. Kommandantboligen, the Commandant’s Residence
12. Torpedobatteri, Torpedo Battery

TUESDAY, JUNE 2nd, 2026

16:00 - 16:45	Registration, **Rådhuskaia**
17:00 - 19:15	Boat trip Oslo - Oscarsborg, **Rådhuskaia** Scenic tour along the Oslofjord NOTE: Ferry leaves precisely at 17:00!
19:15	Hotel Check-In
20:00 - 23:00	Welcome dinner, Restaurant **Forpleiningen**

WEDNESDAY, JUNE 3rd, 2026

08:00	Setup for exhibitors booth & poster stands, **Skolekasernen**
09:00 - 09:10	Conference opening and administrative remarks, **Havnefortet**
SESSION 1	Keynote session: Lightweight protection in a new security landscape, **Havnefortet** Session chair - T. Børvik, NTNU
09:10 - 09:20	F. RONDOT, President of LWAG *Welcome and short introduction*
09:20 - 09:45	T. HORVEI, CTO NFM Group, Norway *Need for personal protection - Lessons learned from the war in Ukraine*
09:45 - 10:10	T. THORVALDSEN, A. WIEN, K. KARLSEN, Norwegian Defence Research Establishment/FFI, Norway *Use of high-performance fibre materials and optimized production techniques for more tailor-made lightweight, personal protective equipment*
10:10 - 10:30	Coffee break, **Havnefortet & Skolekasernen**
SESSION 2	Protection against ballistic impact and blast for soldiers, vehicles, aircraft and naval platforms #1, **Havnefortet** Session chair - T. Fras, ISL, France
10:30 - 10:50	M. WEIβE, R. BERTHELSEN, S. GROBERT, Bundeswehr, Germany *Introduction of the Bundeswehr "Competence Centre for Ballistic Body Armour"*
10:50 - 11:10	D. STAMM, N. ELSTER, S. DEMEZZO, S. ROTH, ISL & UTBM, France *Experimental analysis of the effectiveness of military helmet against blast threats*
11:10 - 11:30	Á MIRANDA-VICARIO, G. ALGARABEL, F. COGHE, RMA, Belgium *Experimental secondary fragment procedure for testing of light textiles*
11:30 - 11:50	S. REIMOLD, S. GREDNEV, A. JUNG, HSU, Germany *Reducing behind-armour blunt trauma with TPMS structures*
12:00 - 13:00	Lunch break, Restaurant **Forpleiningen**
SESSION 3	Exhibitors session, **Havnefortet** Session chair - S. Dey, NDEA/Forsvarsbygg, Norway
13:00 - 13:05	W. CHAN - Specialised Imaging Limited – UK
13:05 - 13:10	M. EDWARDS-MOWFORTH - IMPETUS Afea - Norway

13:10 - 13:15	P. MCDONALD - Viper Applied Science – UK
13:15 - 13:20	T. NICHOLLS - Photron / Serof/ Cavitar Ltd - UK
13:20 - 13:25	T.I. THUN - NFM Group – Norway
13:25 - 13:30	R. KIERULF - NTNU Societal Security – Norway
13:30 - 13:35	D. JERRAND - Scandiflash – Sweden
13:35 - 13:40	M. BEESTON - Oxford Lasers – UK
13:40 - 13:45	J. MARTINI - AMOtronics – Germany
13:45 - 13:50	J. TRUMPER - Hadland Imaging – USA
SESSION 4	POSTER SESSION & EXHIBITION, **Skolekasernen**
13:50 - 14:30	Poster session & exhibition with coffee break, **Skolekasernen**
SESSION 5	Dynamic testing and modelling of materials under ballistic impact and/or blast #1, **Havnefortet** Session chair - P.J. Hazell, UNSW, Australia
1430 - 14:50	L. CORALLO, P. VERLEYSEN, Ghent University, Belgium *Quantitative experimental assessment of failure in armour materials under ballistic-relevant loading*
14:50 - 15:10	R. WADDOUPS, S.D. CLARKE, R.J. CURRY, T. LODGE, A. HIBBERT, University of Sheffield, UK *DIC determination of localised loading on blast loaded plates from coarse soils*
15:10 - 15:30	H. VURAL, Y. E. OZSOY, T. YALÇINKAYA, METU, Turkey *Experimental and numerical Investigation of ballistic impact response in multilayer metallic systems using FE-SPH analyses with various damage criteria*
15:30 - 15:50	M. COSTAS, O. S. HOPPERSTAD, D. MORIN, T. BØRVIK, NTNU, Norway *Protection of Li-ion battery cells in electric vehicles: Tests, models and optimisation*
15:50 - 16:10	Coffee break, **Havnefortet & Skolekasernen**
SESSION 6	Dynamic testing and modelling of materials under ballistic impact and/or blast #2, **Havnefortet** Session chair - P. Verleysen, Ghent University, Belgium
16:10 - 16:30	M. DI FULVIO, L. LOMAZZI, A.MANES, Politecnico Di Milano, Italy *Finite element analysis of ballistic resistance performance degradation in damaged small arms protective inserts*
16:30 - 16:50	T. LEMIERE, P. FORQUIN, C. FRANCART, University Grenoble Alpes, France *New insight into the mechanical behavior of lightweight ceramic armor*
16:50 - 17:10	A. HEINE, R. RIETKERK, W. RIEDEL, Fraunhofer EMI, Germany *Calibration of four failure models for HHA and UHA steel*
17:10 - 17:25	LWAG Scientific Committee – OPEN meeting for all participants
17:25 - 17:30	Notifications regarding guided tour and banquet dinner
17:45 - 18:45	A guided tour of Oscarsborg fortress, meeting point outside **Skolekasernen**
19:45 - 19:50	Group photo, **Fortsplassen**
20:00 - 22:30	Banquet dinner, **Hovedfortet**

THURSDAY, JUNE 4th, 2026

NOTE: Hotel check-out before we start the technical program!

SESSION 7	New materials for ballistic protection and/or blast attenuation, **Havnefortet** Session chair - S. Clarke, University of Sheffield, UK
09:00 - 09:20	R.THIRY, L. ROELFS, F. BOUSSU, S. BELLAMY, TIBEKA PROTECTIONS & ENSAIT, France *3D woven fabric: efficient protection against high-speed explosive fragments*
09:20 - 09:40	Y. GÖÇMEN, L.E. DÆHLI, T. MANIK, T. BØRVIK, NTNU, Norway *On the ballistic performance of additively manufactured high-strength aluminium alloys: Scalmalloy, Scalmalloy CX and Scalmalloy HX*
09:40 - 10:00	K. KAPPE, A. PFAFF, Fraunhofer EMI, Germany *Additively manufactured cellular structures for enhanced blast and ballistic protection*
10:00 – 10:20	J. PERNAS-SÁNCHEZ, J.M. RODRÍGUEZ-SERENO, J.A. ARTERO-GUERRERO, A. VAZ-ROMERO, D. VARAS, UC3M, Spain *Experimental analysis of 3D-printed metallic auxetic protections subjected to deformable projectiles: ice and rubber impact*
10:20 - 10:40	C. IVÁNYI, W. VAN DER SLUIS, D. VAN VEEN, TNO, Netherlands *Ballistic performance of additively manufactured reaction bonded silicon carbide*
10:40 - 11:00	Coffee break, **Havnefortet & Skolekasernen**
SESSION 8	Damage and failure mechanisms under ballistic impact and/or blast, **Havnefortet** Session chair - A. Reyes, OsloMet, Norway
11:00 - 11:20	A. MONNET, T. FRAS, S. BAHI, A. GUITTON, A. RUSINEK, ISL & LEM3, France *Development and validation of lightweight ballistic protections based on multilayer hardfacing*
11:20 - 11:40	P.J. HAZELL, A. SERRUBIBI, UNSW, Australia *Aspects of fibre-metal laminate penetration*
11:40 - 12:00	E. CARTON, R. DEKKER, TNO, Netherlands *Ballistic performance of ceramic fibre reinforced ceramics*
12:00 - 13:00	Lunch break, **Hovedfortet**
SESSION 9	Protection against ballistic impact and blast for soldiers, vehicles, aircraft and naval platforms #2, **Havnefortet** Session chair - T. Thorvaldsen, Norwegian Defence Research Establishment/FFI, Norway
13:00 - 13:20	P. GARDÈRE, J. BOUTILLIER, S. DEMEZZO, R. DELILLE, F. LAURO, T. HIRSCHLER, S. ROTH, ISL & UTBM, France *Flexible protection and blast injury: Experimental and numerical study using biofidelic thorax dummy*
13:20 - 13:40	H. PERRUCHOT, O. PENNETIER, J.L. HANUS, N. PRAT, M. ARRIGONI, A. LANGLET, LaMé, France *Post-impact cavitation behind ballistic plates: Experimental evidence and velocity threshold*

13:40 - 14:00 K.-L. KRÜGER, S. ENGELBRECHT, V. PICHOT, T. GOEPFERT, A. BRACQ, N. MONTMASSON, L. SINNIGER, P. BEILLARD, A. JUNG, ISL & HSU, France & Germany
Transparent polymer armour: Influence of ageing on the protective performance

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14:00 - 14:20 S. ANDERSSON, P. APPELGREN, P. LUNDBERG, FOI, Sweden
Effect of consolidation pressure on the protection capability of Dyneema

SESSION 10 POSTER SESSION & EXHIBITION, **Skolekasernen**

14:20 - 15:00 Poster session & exhibition with coffee break, **Skolekasernen**
LWAG Scientific Committee meeting - Internal meeting

SESSION 11 Dynamic testing and modelling of materials under ballistic impact and/or blast #3, **Havnefortet**
Session chair – A. Heine, Fraunhofer EMI, Germany

15:00 - 15:20 J. RUDSHAUG, B.S. ELVELI, NDEA/Forsvarsbygg, Norway
Experimental and numerical investigation of near-field blast response in fully clamped S355 steel plates

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15:20 - 15:40 P. FORQUIN, P. LAROSE, C. FRANCART, F. BERNARD, S. LE GALLET, University Grenoble Alpes, France
Analysis of the mechanical properties of armour ceramics with heterogenous microstructure using macroscopic and microscopic scale experiments

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15:40 - 16:00 J.M. RODRÍGUEZ-SERENO, J.A. ARTERO-GUERRERO, J. PERNAS-SÁNCHEZ, J. LÓPEZ-PUENTE, UC3M, Spain
Experimental and numerical methodology for the analysis of composite laminate fragments as an impact threat in aerospace structures

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16:00 - 16:20 Final remarks, President of LWAG & the Organising Committee, F. RONDOT, T. BØRVIK, S. DEY
End of conference

16:45 - 17:00 Ferry: Oscarsborg fortress - Sjøtorget, Drøbak, **Havnefortet**
NOTE: Ferry leaves precisely at 16:45!
The ferry will also stop at Sundbrygga for those who have parked their cars there.

17:00 - 18:00 Bus transport: Sjøtorget, Drøbak - Oslo Central Station

POSTERS for SESSION #4 & #10

#P1 T. FRAS, T. HACHAJ, ISL & AGH, France & Poland
Application of machine-learning approaches with physics-informed over-sampling to determine ballistic limit curves

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#P2 B. BETTER, M. ARRIGONI, A. EL MALKI ALAOUI, CH. ESPINOSA, S. GUETTA, ISAE & ENSTA, France
Production of large homogeneous delamination in aeronautical CFRP laminates from smaller laser shocks

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#P3 L. TETLOW, R. WADDOUPS, H. ALABDOULI, E. OSBORNE, R. CURRY, University of Sheffield, UK
Digital image correlation on blast loaded plates: Developments and applications at the University of Sheffield

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#P4 N. NSIAMPA, F. COGHE, RMA, Belgium
Numerical investigation of the performance of ballistic helmets against 9mm FMJ

#P5 M. FERNANDEZ-MELGOSA, A. AZEVEDO, F. COGHE, RMA, Belgium
Evaluating steel equivalence of soft ballistic protection materials through finite numerical models

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#P6 A. REYES, K. BREKKEN, O. VESTRUM, T. BERSTAD, S. DEY, T. BØRVIK, OsloMet, Norway
Impact loads on foam-based protective structures

#P7 J. BOUTILLIER, S. DEMEZZO, P. GARDÈRE, S. HENGY, ISL, France
Application of the SHIELD-FEM thorax model for assessing thoracic protective equipment in blast scenarios

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#P8 S. CLARKE, A. BARR, A. TYAS, R. WADDOUPS, University of Sheffield, UK
Armox 440T plates subject to buried blast: A benchmark for appliqué systems

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#P9 A. AZEVEDO, Á. MIRANDA-VICARIO, F. COGHE, RMA, Belgium
Influence of under-vest fabric type on back-face deflection

#P10 M. HINAUS, D. MORIN, T. BERSTAD, S. THOMESEN, T. BØRVIK, NTNU, Norway
Finite element modelling and optimization of UHMWPE composites in LS-DYNA and LS-OPT

#P11 D. SUBRAMANIAM, S. THOMESEN, T. BØRVIK, NFM Group, Norway
Experimental and numerical investigation of ballistic impact on composite materials

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#P12 S. ANNUNZIATA, G. MARCHESI, MURAGLIA, L. LOMAZZI, V. AUNE, A. MANES, Politecnico di Milano, Italy
Blast mitigation in sandwich plates using 3D-printed lattice metamaterial cores

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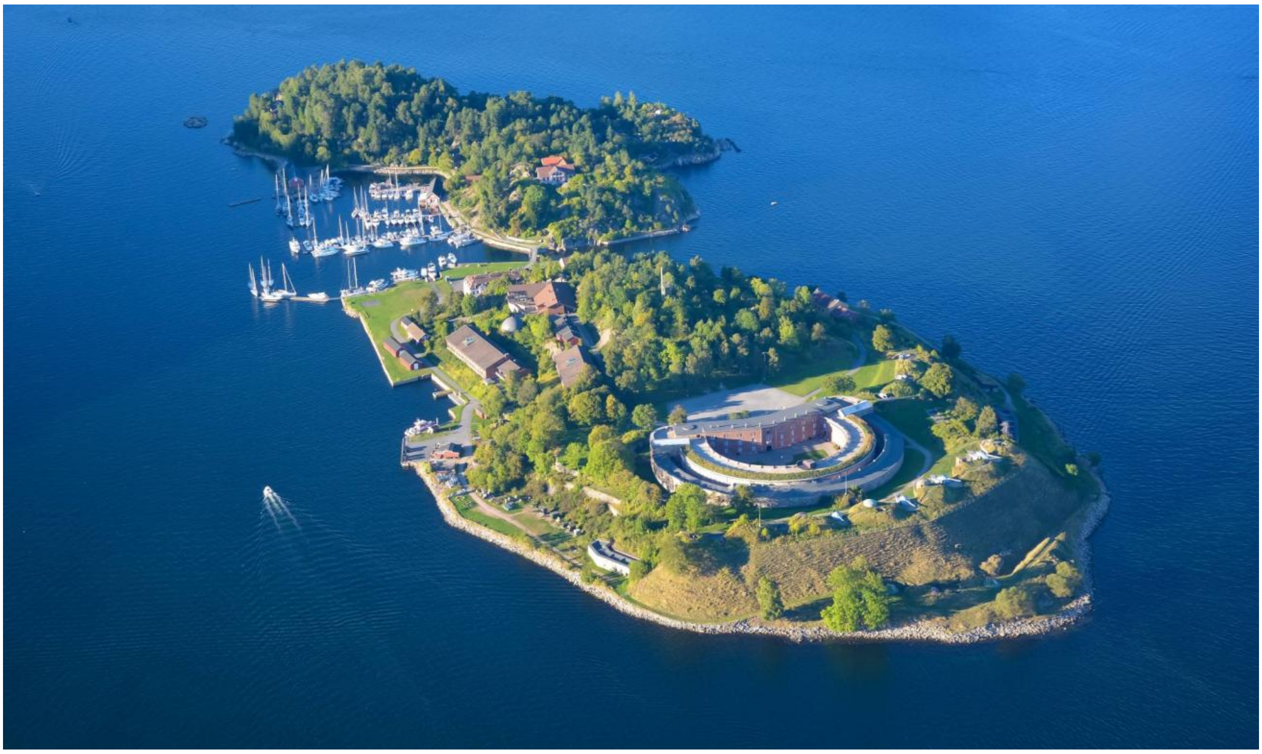
#P13 P. MALEKA, P. MANGORO, N. SINGH, C. DU PREEZ, Flamengro Armscor, South Africa
Design of a Split-Hopkinson Pressure Bar system



Oscarsborg & Practical Information

Oscarsborg Hotel & Resort (main accommodation)

Most participants will stay at Oscarsborg Hotel & Resort.

- The hotel is located on the island, where the conference takes place
- The reception is located in the building Forpleiningen
- A small shop for basic necessities is available in the reception

Reenskaug Hotel (for selected participants only)

A small number of participants (already informed) will stay at Reenskaug Hotel, in the nearby town of Drøbak, on the mainland.

Transport between Reenskaug Hotel and Oscarsborg

A ferry runs between the mainland and the island.

- Morning departure from Drøbak: **08:20** from Sjøtorget
- Evening return from Oscarsborg: **21:45**, **22:45,** and **23:45**

The ferry is free for conference participants (inform the ferry staff that you are part of LWAG)

Full ferry schedule: https://www.forsvarsbygg.no/en/festningene/oscarsborg-fortress/oscarsborg-ferry

Breakfast for these participants will be served at Reenskaug Hotel both days.

Havnefortet – the Harbour Fort ②

- Havnefortet was built in 1845 and was the first permanent defence estate on the island.
- All presentations will be held in Havnefortet.

Skolekasernen – the School Barracks ③

The School Barracks was built in 1892–1893 and originally served as accommodation for military personnel. The open area in front of the barracks was used for drills and gatherings, where soldiers assembled, received orders from their commander, and prepared for duty.

During the conference, Skolekasernen houses our main exhibition area on the second floor. Here you will find sponsor stands and poster presentations, offering a great opportunity to engage with our partners and presenters.

Skolekasernen also provides coffee and tea, light refreshments, as well as restroom facilities. The exhibition area will remain open throughout the technical program. We warmly encourage you to visit the sponsors and explore the posters.

Forpleiningen – the Old Mess ④

Forpleiningen is the old mess, where the soldiers ate their meals until 2002. It is now used as a restaurant and combines good food and drink with a fantastic fjord view.

Forpleiningen will host the welcome dinner on June 2nd, breakfast on both days, and lunch on June 3rd.

Elev- & Befalsforlegningen – the Student and Officer Quarters ⑤ ⑥

The hotel rooms are located in Elevforlegningen and Befalsforlegningen, the old student and commander accommodations.

Fortsplassen ⑦

The Fortsplassen has been used for drills and other gatherings. Fortsplassen hosts a memorial to coastal artillerymen who gave their lives for Norway's Freedom during the war of 1940-45 and a statue in memory of Colonel Birger Eriksen who was commander at Oscarsborg from 1933-1940.

Fortsplassen is the meeting spot for the photo session and banquet dinner on June 3rd.

Hovedfortet – The Main Fortress ⑧

During the German attack on Norway on the night of April 9th, 1940, Colonel Eriksen wrote himself into the nation's history. By engaging the German squadron, a delay was created that made it possible for the Royal Family, the Storting, and the Government to escape. For hours, Oscarsborg Fortress was bombed by German aircraft. The traces are still visible on the walls.

Oscarsborg Museum is located in the fort and shows the role of the fortifications in the defense of the capital from the mid-19th century until the closure of the fortress as an operational unit. Great emphasis is placed on the events surrounding April 9th, 1940. Here you will also find the Coastal Artillery Museum, which shows the emergence and role of the Coastal Artillery in the years from 1899 to the present.

On the third floor is the banquet hall which will host our banquet dinner and lunch on June 4th.

Historical background – Operation Weserübung

On April 7th, 1940, a large German fleet left Wilhelmshaven as part of the top-secret invasion plan "Weserübung." The fleet included destroyers, submarines, and major warships such as Blücher, Admiral Hipper, Königsberg, Karlsruhe, Lützow, Scharnhorst, and Gneisenau, under Vice Admiral Günther Lütjens. At sea, the fleet divided into six groups targeting Oslo, Narvik, Kristiansand, Stavanger, Bergen, and Trondheim. Around 1,200 aircraft, including 500 transport planes carrying paratroopers, supported the invasion.

By April 9th, German forces had reached the Norwegian coast. Norway was caught by surprise. Although Foreign Minister Halvdan Koht had received warnings of a possible invasion, he failed to inform the government or military. Even as reports confirmed German ships, the response remained slow, with mobilization orders issued with a three-day delay.

Three fortresses guarded the Oslofjord: Bolærne (west), Rauøy (east), and Oscarsborg near Drøbak. The outer fortresses fired warning shots but were hindered by poor visibility. They reported suspicious ships moving inward.

The German plan for Oslo aimed to land over 2,400 troops from Blücher, capture the government, royal family, and parliament, and force Norway into submission.

Around 01:30 on April 9th, Blücher and the Oslo fleet approached Oscarsborg, commanded by Colonel Birger Eriksen, who had limited trained personnel. The fortress was equipped with three 28 cm guns ("Joshua," "Moses," and "Aaron") and a torpedo battery.

Believing the ships to be German and noting they ignored warnings, Eriksen ordered fire. At about 1,000 meters, Oscarsborg hit Blücher, disabling its air defences and igniting a major fire after striking a hangar and fuel storage. Blücher returned fire, hitting Drøbak and causing Norway's first civilian casualty of the war.

As the ship continued, Eriksen ordered torpedoes launched, striking midships, destroying the engine and a munitions store. At around 06:20, Blücher sank north of Oscarsborg, killing about 800 people.

The sinking delayed the German advance, allowing the Norwegian government and royal family to escape. Although Norway was later occupied, it never accepted German terms. The government continued its work in exile in the United Kingdom, while the royal family relocated to the United States under protection from President Roosevelt.

- ABSTRACTS -

KEYNOTE LECTURER:

Lightweight protection in a new security landscape

Mr. Toivo Horvei,
CTO and co-founder of NFM Group

Dr. Tom Thorvaldsen,
Senior Principal Researcher at
Norwegian Defence Research Establishment / FFI

We appreciate that both Toivo and Tom have agreed to serve as keynote speakers at LWAG 2026. We are grateful for your willingness to contribute to the conference and highlight the work being carried out in Norway. Your participation adds real value to the program.

Your presentations align very well with several key themes of the conference, including:

- The geopolitical situation and the growing need for preparedness and protection in Europe, particularly in light of the experiences from Ukraine
- How Norway should approach the evolving nature of warfare, where traditional and modern threats operate in parallel – "new threats meet WWII-like warfare"
- The defence sector's needs in the field of protection, with a clear link between operational experience and technological and material solutions
- The increased focus on mobility and lightweight protection, where the balance between protection level and maneuverability is critical
- The soldier's needs in a changing battlefield environment, where personal protection must be adapted to both new threats and high-intensity conflict

We particularly see that the connection between:

- Toivo's keynote, *"Need for Personal Protection – Lessons Learned from the War in Ukraine"*, and
- Tom's keynote, *"Use of High-Performance Fibre Materials and Optimized Production Techniques for More Tailor-Made Lightweight Personal Protective Equipment"*

will provide a comprehensive and highly relevant entry point to the topic for both research communities and industry supporting total defence. We look forward to an interesting keynote session.

Use of high-performance fibre materials and optimized production techniques for more tailor-made lightweight personal protective equipment

Tom Thorvaldsen[a]*, Anders Wien[b], Kristin Karlsen[c]

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[b]NFM Technology AS, Glynitveien 15, N-1400 Ski, Norway
[c] Norwegian Defence Material Agency (FMA), Rødskiferveien 20, N-1352 Oslo, Norway

Abstract

Modern warfare is continuously developing, and ballistic protection systems and concepts must be adapted and adjusted accordingly to meet these requirements. For personal protective equipment (PPE) for ballistic protection of military personnel, a main goal is to develop more light-weight components and modular systems, also considering protection against emerging threats. As part of this development, new light-weight materials, such as ultra-high molecular weight polyethylene (UHMWPE) fibres, are applied. Combining such high-performance modern materials with new and optimized production techniques are believed to result in products with lower weight and similar, or hopefully improved, ballistic performance compared with current products on the market. Moreover, more optimized production methods are also believed to reduce the material waste as well as the overall production footprint.

In this presentation, we present some of the main results from a recently ended (in August 2025) five-year national research and development program. The overall objective of the program has been to develop next generation personal ballistic protection equipment that meets tomorrow's requirements and threats. To meet this goal, research activities have focused on exploring new ways of employing state-of-the-art high-performance fibre materials, in combination with filament winding and high-pressure consolidation.

New tools, methods and production units have been developed at FFI for filament-winding of non-axisymmetric complex structures, such as helmet shells. The filament-wound preforms are thereafter consolidated using NFM's FREC2 technology, using high pressure and temperature. As part of this work, UHMPWE fibres in combination with different resin systems have been explored and characterized to find a more optimal material system for improved ballistic performance. Also, the consolidation process and the FREC2 equipment has been further improved and optimized to better control the temperature during the consolidation, and at the same time significantly increasing the production capacity.

In addition to the more specific goals of developing ballistic products, the program has also aimed at further developing the more fundamental understanding and knowledge of ballistic protection on national level, also considering aspects such as aging of materials used in protective systems and then the ballistic performance of the equipment over time.

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Introduction of the Bundeswehr “Competence Centre for Ballistic Body Armour”

WEISSE, Marina[a]*, Dr. BERTHELSEN, Rolf[b], Dr. GROBERT, Steffen[c]

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[b]Bundeswehr Technical Center for Weapons and Ammunition WTD 91, Schiessplatz,Meppen, 49716, Germany
[c]Bundeswehr Office for Defence Planning, Oberspreestr. 61, Berlin, 12439, Germany

Background

The global security situation is changing radically and rapidly, and threat scenarios are evolving. These challenges therefore necessitate immediate action for focused and comprehensive technological development and innovation, both generally and specifically in the field of ballistic personal protection. In response to the increasing challenges and the need for interdisciplinary research, in 2025 the Bundeswehr has established a new, cross-cutting research group – the Competence Centre for Ballistic Body Armour (German abbrev: KompSt BKS). The KompSt BKS has been embedded within the Bundeswehr Innovation Lab as a part of the Bundeswehr Innovation Centre. Further members are the Technical Centre for Weapons and Ammunition, and the Bundeswehr Office for Defence Planning, that provides scientific and organizational advisory support.

Objectives and Methods

The KompSt BKS consolidates key capabilities for ensuring and further developing the protection of soldiers. Therefore, the primary objective is to include the coordination and execution of interdisciplinary defence technology research. The group and its research focus on the following areas and aim to demonstrate the skills required for the following tasks:

- Coordination and execution of interdisciplinary defence technology research in the fields of ballistics, materials engineering, and biomechanics for short-term dynamic processes
- Development and updating of independent testing guidelines
- Analysis of threat scenarios using operational evaluations to derive requirements for ballistic body armour
- Conducting ballistic tests and scientific investigations on ballistic body armour components with continuous, short-term availability

Results (Expected/Initial Observations)

Early internal assessments indicate improved cross-unit coordination, reduced redundancy in planning processes in defence technology research and technology, and increased collaborative activity in research strategy and project planning. The integration of KompSt BKS into the Bundeswehr Innovation Centre enables the armed forces to adapt to and for new ideas and technologies and offers an innovation ecosystem of civil-military research cooperation.

Conclusion and Outlook

The introduction of KompSt BKS represents a strategic a strategic personnel investment of the Bundeswehr in an interoperable research environment. As the group matures, its contributions are expected to enhance translational efficiency, strengthen interdisciplinary discovery, and assumes an advisory function for end users, to support them in strategic armament decisions regarding ballistic body protection. One of the first scientific, interdisciplinary projects will be the development of injury risk analysis tools for BABT of head and body using measurement technology and finite element methods.

Experimental analysis of the effectiveness of military helmet against blast threats

Dune STAMM[a,b]*, Natacha ELSTER[a], Sébastien ROTH[b]

[a] French-German Research Institute of Saint-Louis, 5 rue du Général Cassagnou, BP 70034, 68301 Saint Louis CEDEX, France
[b] Laboratoire Interdisciplinaire Carnot de Bourgogne, site UTBM, UMR 6303 CNRS / Université de Technologie de Belfort-Montbéliard, Belfort, France

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Abstract

These past years, the limits of traditional combat helmets against blast threats, which have become more prevalent due to the rise in Improvised Explosive Devices, have been highlighted [1, 2]. However, the ability of helmets to mitigate primary shock waves remains unclear. With the aim of improving protective helmets for soldiers in the future, it is important to first understand the phenomena that occur, particularly how the shock wave interacts with the helmet.

For this reason, experiments were conducted on the Hybrid III head and neck, wearing a helmet and positioned at a height of 1.50m and at a distance of 1.80 m from the explosive charge. The whole head/helmet setup was mounted on a rigid fixed support that securely held the head in a fixed position throughout the test, while allowing height adjustment and rotation. Regarding the instrumentation, a probe sensor was installed to measure the parameters of the incident wave and six pressure sensors were placed all over the head namely at eye level, on the forehead, on the top, on the ears, and on the back of the head (covered and uncovered by the helmet). The experiments were conducted in order to see the interaction of the helmeted head with the shock wave. Furthermore, angular velocity data were recorded at the center gravity of the Hybrid III head as well as linear acceleration for both, head and helmet. Finally, influence of orientation (0°, 90° and 180°), load (200g, 500g and 1200g C-4) and pads materials were also investigated during the experimental campaign.

These experimental trials evidenced that tested helmet mitigate overpressure at the front but amplify it at the rear due to a phenomenon called, according to the literature, the "underwash effect" [3, 4]. Depending on the orientation of the head, this phenomenon is also observed. In addition, increasing explosive charge raises surface pressure, impulse, and positive phase duration, thereby amplifying head injuries despite helmet use, while comparisons with unpadded tests show that padding effectively attenuates pressure and impulse, underscoring its necessity. Moreover, both load and padding significantly influence acceleration and angular velocity, which may be the cause of head injuries [5].

Finally, this experimental campaign showed the limits of ballistic helmets, tested against blast threats with a concordance of previous studies in the literature. It seems necessary to improve the quality of helmets against such threats, by trying to add new materials to the helmet or by modifying its geometry.

Keywords: Blast-induced Traumatic Brain Injury (bTBI), Hybrid III headform, helmet

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Experimental Secondary Fragment Procedure for Testing of Light Textiles

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Abstract

The threat posed by Improvised Explosive Devices (IEDs) has grown significantly in recent years, with approximately 28,800 explosion events recorded between 2010 and 2020, causing over 35,000 casualties. Unlike conventional munitions, IEDs lack primary fragments and are often packaged in improvised containers, making secondary debris from the surrounding environment the main hazard. Existing standards, such as AEP 2920, rely on metal fragment-simulating projectiles, which do not accurately replicate the threat posed by soil and debris.

To address this gap, a new testing methodology was developed for lightweight armour garments (<0.5 kg/m²). This approach uses a controlled cloud of sand particles fired from a 12-gauge cartridge at approximately 550 m/s. The target consists of three layers: the fabric under test, chamois leather, and a foam witness sheet. Damage to the witness layer is used to rank fabric performance. Initial benchmarks confirmed the method's ability to better characterize protection against secondary debris compared to traditional fragment-based tests.

Following this first phase, additional studies were conducted to deepen understanding of fabric performance. Parameters involved in the manufacture of the fabrics were studied to identify their influence on resistance to sand particle impacts. Furthermore, tests on swine parts helped to better understand skin penetration, providing a critical reference for assessing real-world injury risks. These findings enable a more accurate correlation between laboratory results and operational protection requirements.

This integrated approach not only improves the evaluation of lightweight protective garments but also lays the foundation for future design optimization aimed at mitigating secondary debris threats in IED scenarios.

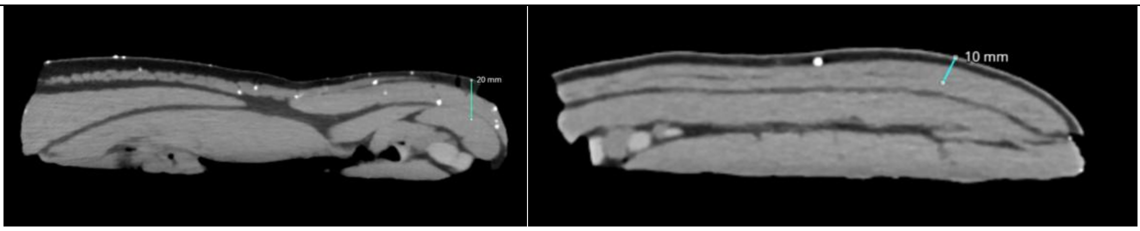

Figure 1: Comparison of the number of perforations. Left: Unprotected . Right: Protected.

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Reducing Behind-Armour Blunt Trauma with TPMS Structures

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Abstract / Extended Abstract

Behind-Armour Blunt Trauma (BABT) remains a critical challenge in personal ballistic protection, as severe internal injuries may occur even when projectile penetration is prevented. Lightweight, energy-absorbing structural concepts are therefore required to complement existing soft and hard ballistic systems without significantly increasing mass or thickness.

This contribution presents a combined experimental investigation into the manufacturability and protective potential of Triply Periodic Minimal Surface (TPMS) structures for ballistic protection. The work integrates systematic manufacturing trials of miniaturized TPMS lattices with their evaluation under quasi-static and ballistic loading. Four TPMS geometries (Diamond, Gyroid, I-WP, and Primitive) were manufactured in multiple configurations with varying cell sizes, relative densities, and graded transitions using high-resolution digital light processing (DLP) additive manufacturing (see Fig. 1.). The results demonstrate that highly detailed TPMS structures with sub-millimetre features can be produced reliably and reproducibly, even at overall structure heights of only 10 mm. Modified geometries with integrated reinforcement elements were additionally investigated to explore practical manufacturing limits. Based on the manufacturing study, selected TPMS configurations were integrated into ballistic protection systems and evaluated with regard to their influence on BABT. Quasi-static pre-studies were used to identify structures with favourable energy-absorption characteristics, followed by ballistic impact tests conducted in accordance with VPAM-based procedures. Both soft and hard ballistic systems (see Fig. 2) were examined with and without TPMS interlayers. The results show that TPMS structures significantly influence the deformation behaviour of ballistic protection systems. While TPMS interlayers in soft ballistic configurations were largely destroyed under impact, selected TPMS designs used in hard ballistic systems achieved a reduction of backing material indentation of up to 39%, indicating a substantial mitigation of BABT-relevant loading.

Overall, the findings highlight the potential of TPMS structures as lightweight, tailorable energy-absorbing elements in advanced ballistic protection concepts and provide guidance for their manufacturing, integration, and further optimisation.

Fig. 1: Unit cells of miniaturised modified TPMS strcutures.

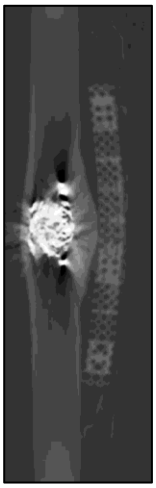

Fig. 2: Hard ballistic plate with attached TPMS plate to reduce BABT after hit.

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Quantitative Experimental Assessment of Failure in Armour Materials under Ballistic-Relevant Loading

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Abstract

The development of ballistic materials and protection systems requires mechanical data obtained under loading conditions representative of in-service impact scenarios. However, conventional full-scale ballistic testing programmes are resource-intensive and offer limited insight for efficient screening of multiple candidate materials and for supporting armour design. This contribution presents an in-service–driven framework for laboratory-scale ballistic testing to bridge the gap between full-scale experiments and conventional mechanical tests. In this study, we conducted finite element (FE) simulations replicating the ballistic tests reported by Børvik et al. [1] on a 12 mm-thick Weldox steel plate impacted by projectiles with different nose shapes with the aim of identifying the stress states and associated strain-rates governing the target deformation and failure. The target material was modelled using the isotropic von Mises yield criterion coupled with the Johnson-Cook (JC) hardening model. Damage was modelled using the JC damage initiation criterion [2], coupled with an energy-based fracture model accounting for the progressive degradation of material strength. The stress state in the target is analysed in the deviatoric π-plane, where each stress state is described by two polar coordinates R and γ expressed in terms of the second and third deviatoric invariants of the stress tensor $\boldsymbol{\sigma}$. Furthermore, the key role of pressure is examined through the hydrostatic stress, $\sigma_H = tr(\boldsymbol{\sigma})/3$, which was found to reach extremely low values, ranging from −5 to −2 GPa, depending on the projectile nose shape and target location. In the case of the blunt projectile, the deformation and failure processes were mainly dominated by shear stresses. A larger degree of stress heterogeneity was found for the hemispherical projectile, yet primarily dominated by compression and shear. For the conical projectile, the stress state near the impactor nose was characterized by almost purely compressive stress, whereas a more heterogeneous stress distribution developed at the target mid-thickness. Overall, the identified stress states lie well outside the range of hydrostatic pressure and triaxiality accessible through conventional laboratory-scale tests, emphasizing the need for experimental approaches capable of reproducing the extreme loading conditions met during ballistic impact. In this work, we propose a novel experimental technique to test material samples under the extreme high-pressure and high-shear loading conditions encountered during ballistic impact events within a controlled laboratory-scale environment.

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DIC determination of localised loading on blast loaded plates from coarse soils

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Abstract

Loading from buried charges can be devastating for structures in the vicinity. It is well established that buried charge loading varies considerably according to the geotechnical properties of the soil in which it is situated [1,2], with testing previously conducted across scales. It was previously suggested that localisations of specific impulse were introduced from testing with well-graded soils (such as the STANAG sandy gravel according to AEP-55) due to discrete particles striking a measurement surface with high individual momentum [3,4].

The current work has utilised high-speed digital image correlation (DIC) at 210,000 frames per second to determine the deformation of 4 mm thick S275 mild steel plates under buried charge loading. The setup uses 78 g PE4 charges for a quarter-scale version of the methodology described in AEP-55. This geometric setup was utilised to recreate the same loading conditions as used previously when recording pressure-time histories at discrete locations with Hopkinson pressure bars housed in a rigid plate [5]. The deformation of the plate, and the uptake of velocity across the recorded plate surface, was used to establish a high-fidelity spatial distribution of the loading.

Results from uniform sand, well-graded sandy gravel and uniform gravel were compared to establish the effect that large discrete particles have on the delivery of loading across the plate. All tests were conducted with fully saturated soils. The data indicates that the inclusion of large individual particles within the soil matrix leads to localised increases in loading, however the overall peak displacement was similar across soil types. Inspecting the development of velocity uptake across the plate demonstrated markedly different loading behaviours between the uniform sand and the soils containing coarser gravel particles. For lightweight armour systems this distribution of loading could have a profound impact on the protective capacities of the system.

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Experimental and Numerical Investigation of Ballistic Impact Response in Multilayer Metallic Systems Using FE–SPH Analyses with Various Damage Criteria

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Abstract

The ballistic impact response of multilayer metallic systems is of significant interest in both military and civilian protection applications, where combining materials with different mechanical characteristics is commonly adopted to improve energy absorption and delay perforation. Numerical methods such as the finite element (FE) method and smoothed particle hydrodynamics (SPH) are widely used for modeling ballistic impact phenomena, reducing the need for extensive experimental testing. In this study, the ballistic response of multilayer targets composed of aluminum alloys and high-strength steels with distinct mechanical characteristics, including Al7075-T651 [1], Al1100-H21 [2], Docol 600DL [3], and Armox 500T [4], is investigated using FE and SPH approaches under blunt and ogival projectile impacts. Explicit numerical simulations are carried out to evaluate the influence of projectile nose shape, material combination, and numerical formulation on the predicted ballistic response.

Fracture behavior is modeled using multi-parameter damage models, namely the Modified Mohr–Coulomb (MMC) and Johnson–Cook (JC) damage models, together with several uncoupled single-parameter damage criteria, including the Cockcroft–Latham (CL), Ayada, and OH criteria. These damage formulations are implemented via user-defined subroutines within Abaqus/Explicit and are selected based on their widespread use in ballistic impact studies [4,5], enabling a systematic comparison of their predictive capabilities. The predictive performance of the considered damage models is assessed in terms of penetration resistance and failure mode under blunt and ogival projectiles. The numerical results reveal clear differences in residual velocity and failure mechanisms depending on the material combination, projectile geometry, and impact conditions; accordingly, multilayer material configurations providing lightweight and high ballistic resistance are highlighted.

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Protection of Li-ion battery cells in electric vehicles: tests, models and optimisation.

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Abstract

This work summarises recent and ongoing activities on lithium-ion battery safety carried out at SIMLab, NTNU, combining experimental testing and numerical modelling across multiple length scales. At the cell level, large-deformation and fracture experiments were performed under different strain rates and used to calibrate computationally efficient models suitable for large-scale explicit simulations of battery systems. At the structural level, the focus is on the protection of electric-vehicle battery trays by means of aluminium sills and extruded profiles subjected to severe impact loading. Owing to the relatively large wall thicknesses typical of such components, their crushing response cannot be accurately represented using conventional shell-based models, particularly when shear-dominated cracking and complex fracture modes occur under dynamic loading. To address this, three-dimensional solid finite-element models are employed, enabling a more realistic description of deformation and failure while remaining compatible with large-scale simulations. The modelling framework is supported by material- and component-level experiments and is applied to the analysis and optimisation of multi-chamber aluminium extrusions for side-impact protection. The work highlights the importance of consistent modelling strategies for both cells and protective structures and demonstrates how advanced experimental characterisation and solid-element modelling can be combined to improve the predictive capability of battery safety simulations.

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Finite Element Analysis of Ballistic Resistance Performance Degradation in Damaged Small Arms Protective Inserts

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Abstract

Small Arms Protective Inserts (SAPIs) were developed as reliable stand-alone protection systems and have demonstrated high effectiveness against small- to medium-calibre threats, including armour-piercing projectiles. Despite their satisfactory nominal ballistic performance, during service in harsh environments SAPIs can experience off-design events, such as low velocity impacts or improper handling, which can induce non-visible or barely visible damage and drastically degrade their response to subsequent ballistic threats. These factors, combined with the complex damage mechanisms involved in their constituent materials, make assessing the damage state of SAPIs and predicting their residual ballistic performance particularly challenging.

This work aims to develop and validate a finite element modelling framework based on the literature [1] to assess the ballistic response of a pre-damaged SAPI. The armour configuration consists of a 12 mm thick silicon carbide (SiC) front layer backed by a 6.3 mm thick UHMWPE (Dyneema®) laminate. To assess behind-armour blunt trauma (BABT), a 50 mm thick Roma Plastilina® No. 1 layer is placed in contact with the rear face of the armour system.

Two damage scenarios are investigated: (i) a prior ballistic impact caused by a 7.62 APM2 projectile, as shown in Fig. 1, and (ii) a through-thickness crack in the ceramic layer. For each scenario, multiple impact simulations with the same projectile are performed by varying the distance between the impact point and the pre-existing damage location.

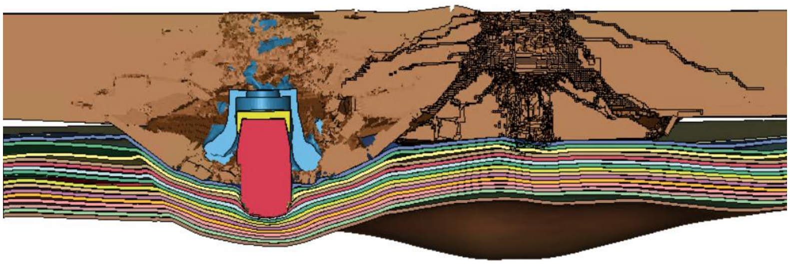

Figure 1: Second hit impact simulation.

The results highlight a strong correlation between the distance from the pre-existing damaged zone and the ballistic performance of the armour, quantified in terms of residual projectile velocity and back-face clay deformation.

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New insight into the mechanical behavior of lightweight ceramic armor

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Abstract

The increasing demand for lightweight, high-performance ballistic protection systems has driven significant research into advanced armor configurations combining ceramic strike faces with polymeric backing materials. Alumina (Al), Silicon carbide (SiC) and other technical ceramics have emerged as particularly attractive front-plate. However, the inherent brittleness of monolithic ceramics necessitates the integration of a compliant backing layer to provide structural support, absorb residual kinetic energy, and capture ceramic fragments during the ballistic event. Ultra-high molecular weight polyethylene (UHMWPE) composites have proven to be excellent backing materials, offering great specific energy absorption, high tensile strength, and superior multi-hit capability.

This study employs a combined experimental and numerical methodology to characterize the ballistic performance of SiC/UHMWPE and Al/UHMWPE armor systems. Experimental laboratory ballistics tests are conducted using a 25mm-caliber Thiot gas launcher. This setup allows precise control of the impact velocity and enables target retrieval after impact for post-mortem analysis (Figure 1). These analyses provide critical insights into ceramic fragmentation patterns, delamination at the ceramic-composite interface, and damage progression within the UHMWPE backing layers. Moreover, rear-face velocity measurements are performed to assess the residual velocity transmitted through the armor system and displacement of the rear face during time (Figure 2).

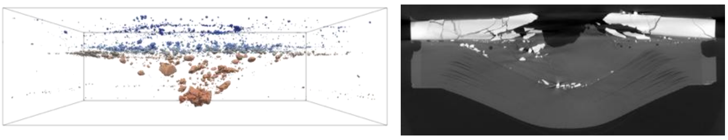

Figure 1: Projectile fragment analysis and post mortem RX tomography of the target (slice)

Complementing the experimental work, finite element simulations are performed using advanced constitutive models capable of capturing the complex material behavior under extreme loading conditions, including the coupled Denoual-Hild-Forquin [2] / Johnson-Holmquist-2 [1] model for ceramics and appropriate orthotropic damage models for UHMWPE composites (Elastic orthotropic with Hashin criteria model).

Validation of the numerical models against experimental data (Figure) enables parametric studies to optimize armor design parameters such as ceramic thickness, backing layer configuration, and interface bonding strength, ultimately providing design guidelines for enhanced ballistic protection efficiency.

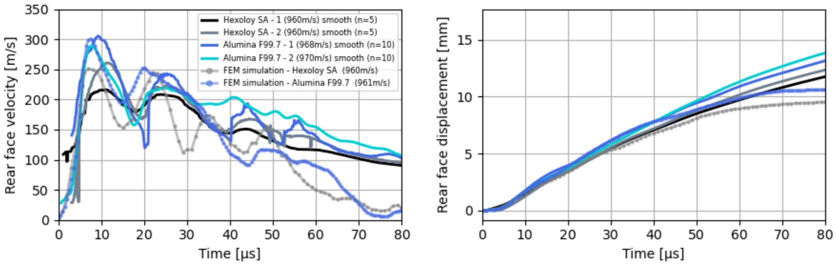

Figure 2: Experimental validation of FEM ballistic simulation

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Calibration of Four Failure Models for HHA and UHA Steel

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Abstract

As presented at prior LWAG meetings, we have taken steps toward a full characterization of high-hardness-armor (HHA) and ultrahigh-hardness-armor (UHA) steels [3], in order to obtain a predictive simulation capability for those most modern grades of armor steel. The widespread materials SECURE 500 and ARMOX 600 were considered as representatives of the HHA and UHA material classes, respectively, for this study.

A first major step was the derivation of a suitable plasticity model. For this purpose, an application of machine learning methods turned out to be most promising for efficient and unbiased calibration of a model [2]. In an inverse optimization process, parameters for the Johnson-Cook plasticity model were obtained that are perfectly reproducing the results of the material tests [3], thereby also confirming the general suitability of the Johnson-Cook strength model for HHA and UHA steels. That approach also shed new light in the interpretation of certain material tests and model parameters [6].

After a brief review of the above earlier findings, the present contribution complements those with recent results on the failure modeling of the same two steel grades. Four different failure models were included in this study – the Johnson-Cook failure model, its modification by Chocron-Erice-Anderson, the Xue-Wierzbicki model, and the Hosford-Coulomb model. These models consider in different ways the effects of stress triaxiality or Lode-angle dependence. For both materials and all four models, simulation parameters were derived. This derivation was done both in a purely experimental and in a combined experimental-numerical approach, the latter approach more realistically considering the actual loading paths. A quantitative comparison between the obtained models regarding their capability to reproduce the test data is presented, allowing to make statements about the suitability of the different models. Rather than providing an extended abstract or a full paper, we refer to the related journal publication [7].

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3D Woven Fabric: Efficient Protection Against High-Speed Explosive Fragments

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Abstract

Recent advancements in 3D weaving technology have demonstrated its ability to enhance mechanical performance while preserving flexibility, primarily due to improved cohesion between yarn layers [1]. In this context, an innovative and patented 3D warp interlock architecture has been developed, offering both high ballistic resistance and significant deformability [2]. This breakthrough enabled the design of the first ballistic vest specifically adapted to the female body shape. The ballistic performance of this architecture is now well established and has been validated from prototype scale to industrial production. The next step is to extend its application to combined blast and fragment protection. The main difference compared with standardized ballistic threats lies in the wide variability of fragment mass, geometry, and velocity. Additionally, blast loading introduces a distinct type of dynamic solicitation. In addition, fragments commonly present sharp cutting edges, which modify the perforation mechanisms compared with standardized bullets.

Fragment resistance will be quantified through STANAG 2920 V50 tests using 1.1 g FSPs (.22 caliber), with a target V50 in the 500-650 m/s range. A change in projectile type from bullets to FSPs also leads to a different mechanical response of the textile. Standardized bullets typically induce cone expansion as the first stage of fabric perforation. In contrast, the sharp edges of FSPs can initiate a cutting phase prior to membrane expansion. This may result in a distinct perforation mechanism, which in turn requires adaptations in the textile architecture to maintain effective protection.

Furthermore, previous experiments have highlighted the influence of fabric flexibility in multi-layer configurations under standardized ballistic impact. Rigid textile stacks tend to be perforated layer by layer, whereas more flexible systems allow multiple layers to deform simultaneously. This global deformation places a larger number of yarns under tension at the same time, potentially enhancing energy dissipation and improving fragment-stopping performance. Rigidity of the weave plays a critical role in energy absorption. If the structure is too rigid, yarn mobility is restricted and the impact load cannot be efficiently redistributed. Conversely, if the system is too flexible, excessive tensile deformation may occur, leading to premature yarn rupture.

To address this challenge, ongoing work focuses on adjusting weaving parameters and integrating complementary materials, guided by fragment-resistance testing, in order to better understand energy-dissipation mechanisms and to optimize protection without compromising flexibility.

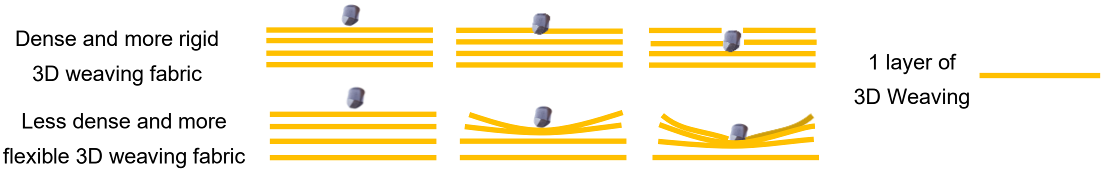

Figure 1: Ballistic perforation mechanism of multi-layer textile solution

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On the ballistic performance of additively manufactured high-strength aluminium alloys: Scalmalloy, Scalmalloy CX and Scalmalloy HX

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Extreme loading conditions are critical in defence and aerospace applications, where structural integrity directly affects mission success and human safety. In the defence sector, lightweight armour is required to protect against high-velocity threats. However, conventional armour systems are often limited by manufacturing constraints, cost, and restricted design flexibility, motivating the development of advanced manufacturing approaches capable of producing complex, lightweight, and optimised structures without compromising mechanical performance. Additive manufacturing (AM) has emerged as a promising alternative to traditional fabrication methods, offering significant design freedom, reduced material waste, and rapid prototyping. Recent studies have shown that additively manufactured metallic materials can achieve ballistic performance comparable to that of conventionally manufactured counterparts [1]. Despite this potential, AM components can suffer from process-induced defects such as porosity, anisotropy, residual stresses, and surface roughness, which may negatively influence their mechanical and ballistic behaviour. To address these challenges, novel alloys specifically designed for AM have been developed. Among these, Scalmalloy, an aluminium–magnesium–scandium alloy, exhibits high strength, excellent processability, and superior strength-to-weight efficiency, making it a promising candidate for lightweight protective structures. In this study, the ballistic impact response of three laser powder bed fused Scalmalloy variants (Scalmalloy, Scalmalloy HX and Scalmalloy CX) developed by APWORKS is investigated. Quasi-static tensile tests are conducted to characterise the strength and ductility of the materials, followed by ballistic impact experiments using 7.62 mm APM2 projectiles. The experimental data are used to calibrate a modified Johnson–Cook constitutive model [2] and Cockcroft–Latham fracture criterion [3], which is implemented in finite element simulations of the ballistic impact tests. Numerical results agreed well with the experiments. This demonstrates the strong potential of combining additive manufacturing, numerical modelling and numerical optimisation in the design of new and innovative protective structures.

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Additively Manufactured Cellular Structures for Enhanced Blast and Ballistic Protection

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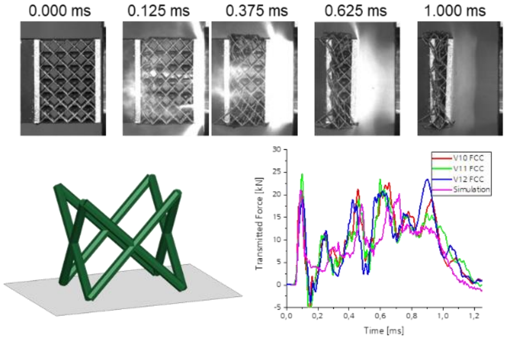
Abstract

Lightweight cellular structures, such as honeycombs, foams, and lattices, have gained significant attention in recent years due to their exceptional mechanical properties under compression, including high specific strength and stiffness, as well as excellent energy absorption capabilities [1, 2]. They find applications in dynamic load scenarios, such as crash, impact, or blast mitigation. Advances in additive manufacturing have enabled the fabrication of complex geometries with tailored properties, further enhancing the mechanical performance of cellular structures [3, 4]. However, optimizing cell geometries and configurations for varying requirements remains challenging, particularly for scenarios involving fundamentally different loading mechanisms, such as blast mitigation and ballistic protection.

This study investigates cellular structures as the core of sandwich structures designed to provide protection against both blast and ballistic threats. For blast loading, a novel design and optimization framework for graded lattice structures is introduced. The optimization process employs analytical pre-dimensioning, as well as numerical methods, combining surrogate models based on neural networks, trained on hundreds of automatically generated and validated finite element simulations, with a genetic optimization algorithm. The optimized structures are additively manufactured by laser powder bed fusion using 30CrMoNb5-2 steel powder and experimentally tested in an explosive-driven shock tube, where they are subjected to a blast loading corresponding to a scale distance of 0.64 m/kg$^{1/3}$. Results demonstrate good agreement between simulations and experiments, as can be seen in Figure 1, with minor deviations attributed to manufacturing inaccuracies.



Pre-dimensioning:
d_h: 0.82 mm
F_{PCF}: 19.8 kN

Detailed optimization:
d_l: 0.53 mm
d_m: 0.59 mm
d_u: 0.69 mm
F_{PCF}: 21.1 kN

Experiment:
F_{PCF}: 23.6 ± 0.8 kN

Figure 1: Response of an optimized sandwich structure with an FCC lattice core.

To enhance ballistic performance, solid elements are integrated into the cellular structure to initiate projectile core fragmentation. Numerical simulations reveal that these modified structures can achieve performance levels comparable to mass-equivalent monolithic plates, as can be seen in Figure 2. However, ballistic performance is shown to depend on the impact position.

Overall, the proposed novel concepts demonstrate strong potential for lightweight protective structures against both blast and ballistic threats. In particular, the optimization strategy regarding blast loading and the integration of solid elements enable targeted tailoring of the structural responses, showing good agreement between simulations and experiments and indicating ballistic performance comparable to monolithic plates, although further ballistic validation is required.

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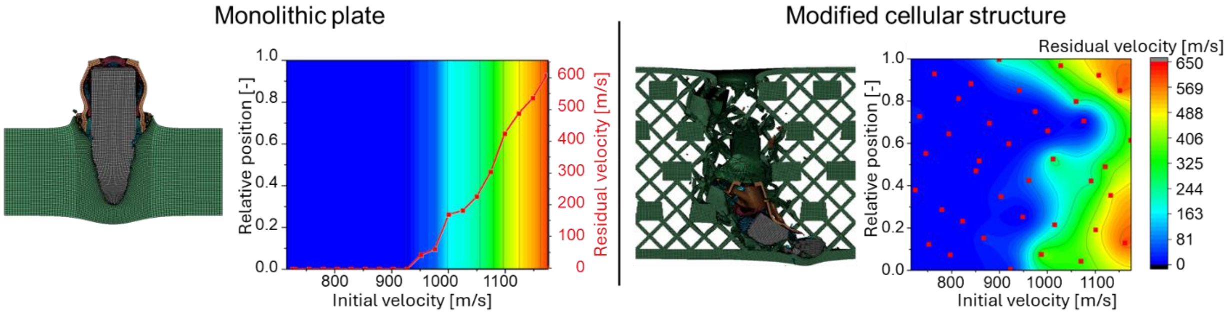

Figure 2: Residual velocity as a function of the initial velocity and relative position for the monolithic plate and the modified cellular structure for a ballistic impact with a 7.62 × 39 mm AP BZ projectile.

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Experimental Analysis of 3D-Printed Metallic Auxetic Protections Subjected to Deformable Projectiles: Ice and Rubber Impact

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Abstract

The aerospace and transport industries continuously demand lightweight, high-performance structures capable of withstanding impulsive loads without compromising structural integrity. Traditional composite laminates, while offering high specific mechanical properties, exhibit limited resistance to perpendicular impacts, often resulting in critical internal damage such as delamination. This work investigates the use of 3D-printed metallic auxetic lattice structures as an innovative protective solution against highly deformable impactors, specifically focusing on ice spheres and rubber balls representative of hail, secondary engine debris and tire fragments.

The proposed protection consists of a thin aluminium alloy front plate backed by a reticular auxetic core, manufactured via Selective Laser Sintering (SLS) in AlSi10Mg. The core's geometry is designed with re-entrant unit cells that provide a negative Poisson’s ratio (NPR). This unique behaviour promotes localized material densification towards the impact zone, significantly enhancing indentation resistance and energy absorption compared to conventional cellular materials. The experimental methodology utilizes a gas gun system to launch impactors at high velocities (ranging from 50 to 250 m/s) against the auxetic specimens. The lateral and frontal dynamics of the protection was recorded using high speed video imaging and 3D Digital image correlation of the back face of the protected specimens was perfomed in order to evaluate the protection capability of the structure.

Preliminary results demonstrate that the deformation of the projectile increases the active auxetic volume of the protection, allowing for a reduction in peak force transmitted to the underlying structure compared to traditional foams. This study highlights the predominant role of cell scale and material flow in tuning the dynamic energy absorption (SEA) of auxetic metamaterials. Moreover, lattice structures allow to new behind the leading edge developments such us ultra high laminar flow or other active protections. The findings contribute to the development of safer, more efficient protective systems for the next generation of aerospace structures.

Keywords: Auxetic structures, 3D printing, High-velocity impact, Deformable impactors, Energy absorption, AlSi10Mg.

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Ballistic performance of additively manufactured reaction bonded silicon carbide

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Abstract

Lightweight ceramic materials play a key role in modern ballistic protection systems. Additive manufacturing (AM) of ceramics is gaining interest in this context, as it enables mould-free production of complex geometries, large or curved components, and application-specific parts that are challenging or economically unfeasible to realise with conventional ceramic processing. Potential applications include curved vehicle and naval armour panels, large-area protective panels, and customised or modular personal protection systems.

However, the ballistic performance of additively manufactured ceramics remains insufficiently understood. Only a limited number of manufacturing routes are currently capable of producing thick (≥ 10 mm), monolithic, near-fully dense ceramic components suitable for ballistic applications. Among these, AM of reaction-bonded silicon carbide (RB-SiC) has been identified as one of the viable options.

In this approach, binder jetting is used to fabricate thick porous ceramic preforms, after which full density is achieved during a subsequent reaction-bonding step. The resulting material consists of primary and secondary SiC phases with a residual silicon content of approximately 15%. While RB-SiC generally exhibits lower ballistic performance than fully sintered monolithic SiC, the material is already in use for personal protection due to its favourable balance between performance, manufacturability, and cost. The combination with binder jetting offers additional advantages in terms of scalability, large build volumes, and geometric freedom, without fundamentally altering the conventional reaction-bonding process.

Prior to ballistic testing, extensive material characterisation of the additively manufactured RB-SiC has been performed, including measurements of density, porosity, hardness, elastic properties derived from sound velocity measurements, microstructural analysis, and initial impact screening using impact of steel ball bearing spheres. These results showed no major deviations from conventionally manufactured RB-SiC, supporting further ballistic evaluation.

A dedicated ballistic test campaign has been designed to determine both the V50 ballistic limit and the residual velocity and energy in the case of perforation, enabling a direct comparison between additively manufactured RB-SiC, conventionally manufactured RB-SiC, and fully sintered SiC under equivalent conditions. This approach aims to link manufacturing route and material properties directly to ballistic performance. Ballistic testing is planned for early 2026, and the results will be presented as well.

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Development and validation of lightweight ballistic protections based on multilayer hardfacing

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Abstract

Hardfacing process is currently widely used for the protection of materials and structures exposed to complex and severe environments. This technique involves the fusion application of a protective coating onto a surface, significantly enhancing its resistance to wear, corrosion, and other forms of degradation [1,2]. In sectors such as aerospace and automotive, hardfacing extends the lifespan of components and preserves their performance over time. However, its application in the field of ballistic protection remains relatively unexplored, even though research and development of new armor systems are crucial in light of the rapidly evolving current kinetic threats. The use of this technique could not only significantly increase the impact resistance of armor but also maintain the mobility of structures and the cost-effectiveness of deployed solutions [3]. In this context, the work presented here focuses on the analysis of a bilayered passive protection composed of a S355MC steel substrate (C < 0.2% by weight) with a thickness of 8 mm, onto which a material of the same thickness, equivalent to a highly alloyed chromium cast iron (Cr: 27-30% by weight; C: 4-6% by weight), is applied using flux-cored arc welding (FCAW). Impact tests were conducted on several units using a 7.62x51 mm caliber projectile, equivalent to the M61, on the instrumented ballistic testing facility of the Franco-German Research Institute of Saint-Louis (ISL). A comprehensive microstructural analysis of the composite is proposed and linked with target damage during impact. Additionally, a model of the welding deposit used is proposed with a view to the numerical simulation of ballistic tests.

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Aspects of fibre-metal laminate penetration

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Abstract

Aluminium – carbon fibre metal laminate (FML) targets were investigated under high-velocity impact to quantify the combined effects of fibre architecture and projectile obliquity on ballistic performance and damage evolution. Impact experiments were conducted using a 12 mm diameter projectile over velocities ranging from 184 m/s to 775 m/s, under both normal and oblique incidence. Nominal obliquity angles were varied to assess angular sensitivity in energy absorption, penetration dynamics, and failure mechanisms. Three fibre architectures—unidirectional, cross-ply, and pseudo-woven—were evaluated. The composite backings were applied to AA 5005-H34 aluminium face sheets and manufactured via automated fibre placement to ensure controlled, repeatable fibre architectures.

High-speed imaging (e.g., see Figure 1) was used to characterise projectile kinematics, penetration and perforation behaviour, and energy dissipation, while ultrasonic C-scan and X-ray computed tomography (CT) were employed to resolve internal damage mechanisms. Across the investigated velocity range, fibre architecture exerted only a marginal influence on global energy absorption under both normal and oblique impact conditions. However, architecture strongly governed localised failure modes and damage morphology. At lower impact energies, unidirectional laminates primarily failed via wedge-in and fibre-splitting mechanisms, whereas cross-ply laminates exhibited progressive dishing and petalling. Pseudo-woven laminates consistently demonstrated enhanced damage containment.

As expected, projectile obliquity significantly influenced energy dissipation and damage development at lower velocities (<300–350 m/s), with increasing incidence angle promoting higher kinetic energy absorption. At higher velocities, the effect of obliquity diminished, and all architectures exhibited comparable ballistic response irrespective of impact angle. Ultrasonic inspection revealed a strong correlation between fibre layout, impact angle, and delamination footprint. While higher obliquity generally promoted increased delamination, oblique impacts produced fewer but larger interlaminar delamination cracks compared to normal incidence. X-ray CT confirmed extensive through-thickness delamination remote from the impact site and severe fibre fracture proximal to impact, providing new insight into the three-dimensional delamination topology in obliquely loaded FML systems.

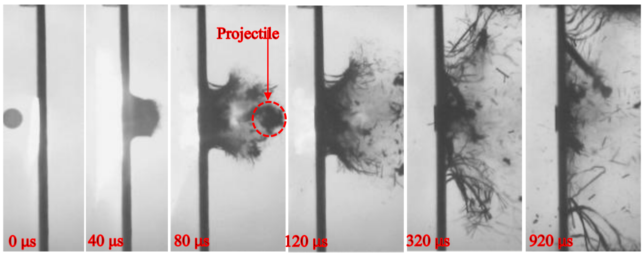

Figure 2: Impact behaviour of a woven FML target at 759 m/s.

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Ballistic Performance of Ceramic Fibre Reinforced Ceramics

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Abstract

Lightweight ceramic materials are fundamental to the advancement of modern ballistic protection systems. For armour applications, ceramics must exhibit significant hardness to effectively erode the hardened core of armour-piercing (AP) munitions. However, this high hardness is accompanied by low toughness, resulting in extensive crack propagation throughout impacted ceramic tiles.

The most prominent and frequently occurring cracks within ceramic tiles are radial cracks. These form due to local deflection of the tile when struck by a projectile at the strikeface. Upon impact, the tile bends, which creates a biaxial tensile load on the rear surface and a biaxial compressive load on the strikeface. As ceramics are brittle and notably weaker under tension than compression, radial cracks initiate at the rear of the tile, directly beneath the point of impact. These cracks travel rapidly and extensively across the tension-loaded rear, and when they reach the edges of the tile, they produce fragments that diminish the ballistic efficiency of ceramic-based armour.

To mitigate radial crack formation, it is essential for the ceramic tile, particularly the rear section, to possess both toughness and strength under tension. The incorporation of fibre reinforcement in ceramics has demonstrated increased toughness through mechanisms such as crack bridging and fibre pull-out.

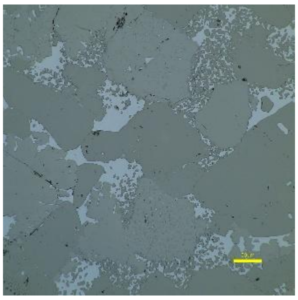
This study involved the fabrication, characterisation and ballistic testing of fibre-reinforced ceramics. Two distinct material combinations were utilised:

- Silicon carbide (SiC) whiskers within an alumina matrix
- Carbon fibres within a silicon-infiltrated silicon carbide (Si-SiC) matrix

For both combinations, samples were prepared with either a constant or a graded fibre fraction. Attempts to manufacture samples with a high fibre volume fraction (15–50%) resulted in a substantial number of cracks within the matrix material. Consequently, only samples with a fibre volume fraction below 15% were subjected to ballistic testing using the residual energy method (REM).

The ballistic performance of the fibre-reinforced ceramics was evaluated in comparison to samples composed solely of the matrix material. Additionally, the microstructure of the tested materials was examined and discussed. Efforts to manufacture samples with a high fibre volume fraction (15–50%) resulted in a substantial number of cracks within the matrix material. Consequently, only samples with a fibre volume below 15% were used.

The ballistic performance of the fibre-reinforced ceramics was evaluated in comparison to samples composed solely of the matrix material. Additionally, the microstructure of the tested materials was examined and discussed.



Silicium infiltrated SiC

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Flexible protection and blast injury: experimental and numerical study using biofidelic thorax dummy

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Abstract

Recent military conflicts and terrorist actions have highlighted the growing exposure of military personnel to explosive threats. Despite this rising risk, the effectiveness of flexible shock wave protection remains poorly understood, with some studies suggesting that certain chest protectors may aggravate injuries [1]. This study aims to better characterize the interaction between blast waves and flexible protection systems, combining experimental and numerical approaches to support improvements to current protective equipment.

Experimentally, a blast test campaign was conducted using the SurHUByx dummy [2], which incorporates biofidelic materials and replicates human anatomical geometry. This dummy, previously validated for non-penetrating projectile impacts, was exposed to blast loading with and without flexible protection. Internal pressure, organ-level forces, and sternal acceleration were measured to quantify physical injury thresholds. Comparison with the ISL biological test database [3], which links blast exposure to injury severity, enabled correlations between the physical metrics measured on the dummy and injury severity.

In parallel, a finite element (FE) model of the experimental setup was developed. Experimental measurements were used to calibrate and validate the FE model, which can then be employed to predict the effectiveness of different individual protective systems. The combined experimental and numerical results reveal the complex nature of injury amplification caused by flexible protection during blast exposure. The defined physical injury thresholds, together with the validated FE model, provide a basis for evaluating and optimizing the blast performance of future individual protective equipment.

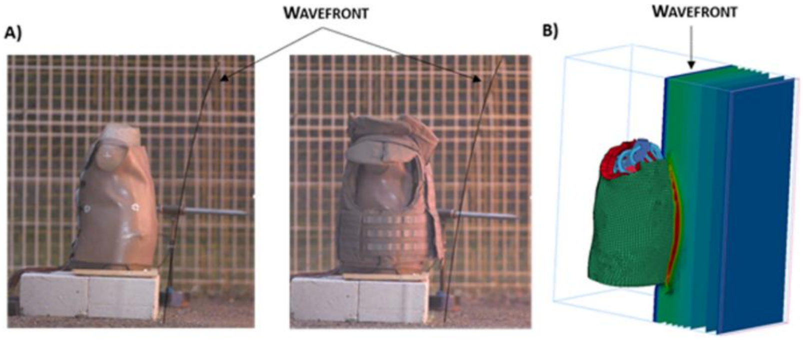

Figure 1.A : Photo of SurHUByx dummy during blast testing with and without flexible protection
Figure 1.B: Numerical simulation of the test scenario using LS-DYNA software.

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Post-impact cavitation behind ballistic plates: experimental evidence and velocity threshold

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Abstract

Light-weight ballistic protections are subjected to large deformation under ballistic impact. They are commonly evaluated, among other criteria, based on their back-face deformation (Back Face Signature – BFS) [1]. However, under impact, the ballistic protection can transmit a shock wave to the underlying biologic tissue (skull, chest…), which may be followed by a pronounced pressure drop in biological fluids [2]. This rapid pressure decrease can induce cavitation, characterized by the nucleation, growth, and unstable collapse of vapor bubbles, whose dynamics may lead to additional internal lesional damage [3]. In this context, the present study aims at identifying the impact velocity threshold that engenders the onset of the cavitation in a fluid located behind a plate.

Laboratory-scale experiments were performed using a Thiot pneumatic launcher (0–100 m/s). High-speed imaging allows visualization of cavitation bubble formation and collapse (with bubble radii approximated using the Rayleigh-Plesset model), while pressure sensors record the dynamics of the pressure waves in the liquid volume.

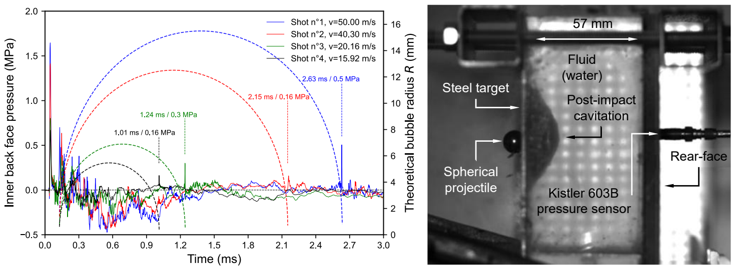

Figure 1: Comparison between cavitating pressure signals (left) and post-impact cavitation imaging (right)

Results confirm the occurrence of post-impact cavitation (Figure 1, right) and identify a minimum impact velocity threshold of 15 m/s for a 12 mm diameter steel ball. Future works will incorporate biologically relevant tissue simulants and more realistic impact geometries. They also bring a new insite in the interpretation of injury mechanisms. These results suggest that the residual velocity of the back face of the ballistic protection could serve as a complementary criterion to BFS to assessing the risk of internal injuries.

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Transparent Polymer Armour: Influence of Ageing on the Protective Performance

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Abstract

Multi-layered transparent composite-structures composed of Polycarbonate and PMMA, are often used in personal protection devices such as in bulletproof visors. Their performance might be strongly affected by environmental exposure for example to ultraviolet radiation, temperatures and humidity, all of which can drive ageing and degradation phenomena. These are known to alter the mechanical and chemical composition [1].

This contribution investigates the influence of ageing on the structural integrity, mechanical properties and the ballistic resistance of multi-layer visor systems. These were studied by non-destructive testing methods, quasi-static 4-point bending tests (as shown in Fig. 1) and projectile impact tests according to NIJ IIIA, respectively.

To support the lifetime assessment, artificial ageing cycles are compared to the naturally aged material samples. Here, a good agreement of the behaviour of the artificially to the naturally aged systems was found, emphasizing the validity of the artificial ageing approach. A pronounced ageing effect becomes evident, after 2000 h of artificial exposure, resulting in a distinct difference breaking behavior.

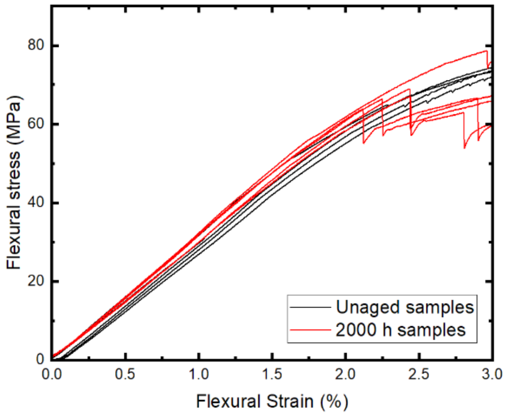

Figure 1: Results of the 4-point bending tests – Unaged (black), 2000h - 70 °C, 98% RH (red)

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Effect of consolidation pressure on the protection capability of Dyneema

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Extended Abstract

Introduction

To investigate whether increased consolidation pressure during the manufacture of fibre-composite plates made of UHMWPE (Ultra High Molecular Weight Polyethylene) will improve their ballistic performances, plates pressed at normal and at elevated pressure were produced. The UHMWPE used was Dyneema HB210 from Avient. Each plate consisted of 74 layers of HB210 and had final dimensions of 167×167×10 mm. Because UHMWPE surfaces are difficult to bond directly, the outermost layer of each plate was covered with a glass-fibre fabric to facilitate adhesive bonding.

The Dyneema plates pressed at normal pressure were manufactured by a composite company using standard methods, while the other plates were consolidated by the isostatic pressing specialist Quintus. Due to industrial confidentiality, the precise processing parameters are not publicly available. However, the plates pressed at normal pressure were manufactured by heating the stacked HB210 layers to approximately 100 °C while applying ~20 bar of uniaxial pressure for roughly 10 minutes and then subsequently increase the temperature to about 125 °C and the pressure to 150–200 bar for an additional ~30 min. The high-pressure consolidation was performed at the Quintus Application Centre in Västerås using a Quintus Flexform press (model QFC0.7×1.8-1400). The manufacturing cycle included preheating and degassing of the stacked HB210 foils and then consolidation at 1400 bar pressure for 2.75 hrs at a nominal temperature of 130 °C.

Two types of targets were manufactured, one ceramic/Dyneema composite target and one made of a 10 mm Dyneema plate only. The ceramic target consisted of a 7.1 mm silicon carbide tile (Hexaloy SA, Saint-Gobain), bonded onto the 10 mm Dyneema plate using epoxy adhesive (Collano RS 6400). The ceramic tiles and the Dyneema plates had outer dimensions of 101×101 mm and 167×167 mm, respectively, resulting in an areal density of 33 kg/m² for the assembled target (calculated over the area of the ceramic).

Ballistic testing and material characterisation

The influence of consolidation pressure on the ballistic performance of the ceramic/Dyneema target was evaluated through a series of ballistic tests using an AP surrogate projectile developed by FOI. To enable comparison with published literature data, additional tests were conducted on Dyneema plates alone, impacted by standardised fragment-simulating projectiles (1.1 g FSP). Both the plates pressed at normal pressure and at 1400 bar were tested. In parallel with the ballistic experiments, FOI examined how the fibre architecture and the thickness of individual fibre layers were affected by the consolidation pressure, with the aim of identifying microstructural mechanisms responsible for possible differences in ballistic performance.

For the test of the ceramic/Dyneema targets, an in-house AP-projectile made of cemented carbide was used. The projectile was 25 mm long and had a diameter of 5,6 mm and was fitted with a 55° conical tip, see Figure 3. The projectile was launched using a plastic sabot (Duratron) fired through a smoothbore 7.62 mm barrel. To eliminate projectile yaw, the muzzle was placed 15 mm from the ceramic target, i.e., the projectile impacts the target while still guided by the bore. The projectile velocity was measured by filming the movement through a horizontal slit in the barrel close to the muzzle using a high-speed camera model FASTCAM Nova S16, see Figure 4.

For the tests of the Dyneema plates alone, fragment simulating projectiles (FSP) of mass 1.1 g were used. The FSP with skirt was launched from a 5.56×45 mm barrel with 1:7” twist. The distance between muzzle and target was 2 m and the velocity was measured using an optic screen, HPI B472, placed with its centre 0.5 m from the target. The target was aligned using laser and a mirror to ensure 0° obliquity. The FSP was filmed using a high-speed camera model FASTCAM Nova S16 to monitor the yaw at impact.


(a) (b) (c)

Figure 3. FOI:s test projectile (a) and when mounted in a plastic sabot of Duratron (b). The projectile length was 25 mm, the diameter 5.6 mm and the pointed 55° tip. The fragment simulating projectile FSP of mass 1.1 g (c).

(a) (b) (c)

Figure 4: Test setup with the weapon with barrel and high-speed camera for the velocity measurement (a). The barrel with a slit (b) and examples of a pictures from the film for velocity measurement (c).

Measurement of the ballistic limit

The ballistic limit velocities corresponding to 50% and 5% probability of perforation (v50 and v5) were determined according to the Army criterion. Under this definition, a perforation is recorded if the target exhibits any through-passage that allows visible light to pass. A test is also classified as a perforation if the projectile has become lodged within the target but remains visible from the rear face. In the present experiments, the penetration channels were usually well defined, although often closed due to partial melting or charring of the composite material. Therefore, each plate was inspected visually to determine the outcome. The ballistic tests were conducted in accordance with the procedures in AEP-2920 [1], with adjustments to impact velocity to ensure a mixed zone of partial penetrations (PP) and complete penetrations (CP) within an appropriate velocity range. AEP-2920 prescribes a statistical evaluation method based on maximum likelihood estimation (MLE). Using this approach, the mean value μ and standard deviation σ of the assumed normal distribution describing the transition from low to high perforation probability are estimated. The mean value μ corresponds to the ballistic limit velocity. The method also yields confidence intervals for the estimated limit. To achieve a sufficiently narrow confidence interval, as well as enough mixed PP/CP outcomes to reliably determine the standard deviation, practical experience shows that a minimum of 20 shots is typically required.

Material characterisation

To assess the influence of consolidation pressure, the microstructure of the Dyneema plates were examined. However, preparing the Dyneema for microstructural examination proved to be challenging, as the material is difficult to section and polish in a manner suitable for analysis using optical microscopy or scanning electron microscopy (SEM). An initial attempt was made to generate a brittle fracture surface by cooling specimens in liquid nitrogen and mechanically breaking them. Despite the fact that the glass-transition temperatures of UHMWPE and the binder used (thermoplastic polyurethane) are around –150 °C and –50 °C, respectively, and that liquid nitrogen reaches –196 °C, a brittle fracture surface could not be achieved. As a result, the specimens were instead cut and mechanically polished, and a subset were additionally “etched” using ethanol to enhance contrast. Figure 5 presents two representative microstructural images obtained using this method. A layered structure can be distinguished, although the individual UHMWPE fibres themselves cannot be resolved.

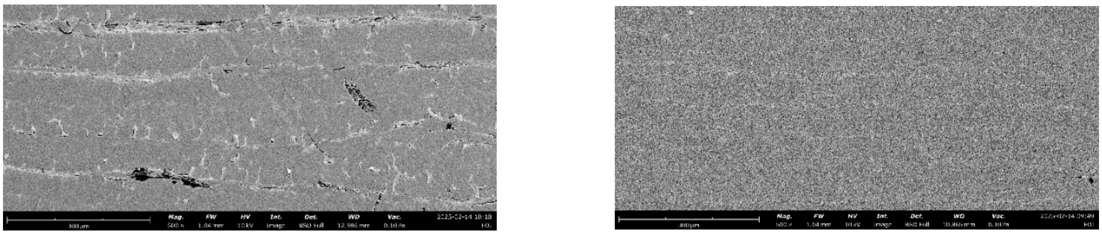
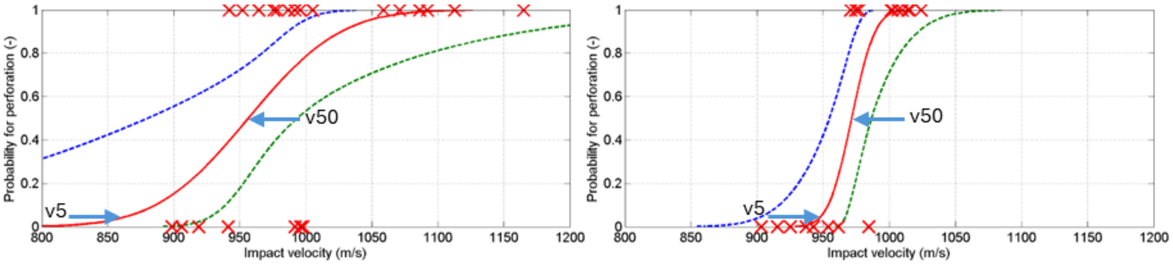

(a) (b)

Figure 5. Representative cross-sections of Dyneema HB210 consolidated at normal pressure (a) and at 1400 bar (b).

Results for AP against ceramic/Dyneema targets

In total, 16 shots were fired against the ceramic target with Dyneema pressed at normal pressure and 19 shots against the ceramic target with the Dyneema pressed at 1400 bar. The v50 and v5 was evaluated for both materials, see Table 1 and Figure 6.



(a)

(b)

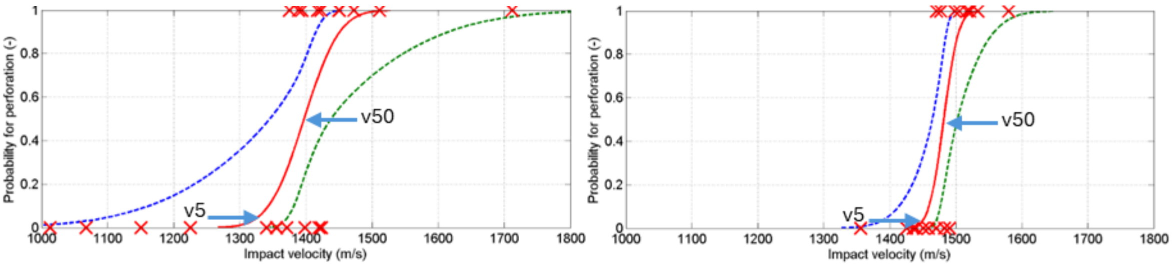
Figure 6. Probability for perforation for FOI test-projectile as function of impact velocity for ceramic/Dyneema manufactured at normal pressure (a) and at 1400 bar (b).

Table 1. Evaluated v50 and v5 from ballistic tests with FOI test projectile.

Projectile	Ceramic/Dyneema target	v50	v5
FOI test projectile (length 25 mm, diameter 5,6 mm)	HB210 (normal pressure)	956 m/s	866 m/s
FOI test projectile (length 25 mm, diameter 5,6 mm)	HB210 (1400 bar)	972 m/s	949 m/s

Results for 1.1 g FSP against Dyneema targets

In total 23 shots were fired against the Dyneema plate targets pressed at normal pressure and 19 shots against the one pressed at 1400 bar. The v50 and v5 was evaluated for both materials, see Table 2 and Figure 7.



(a)

(b)

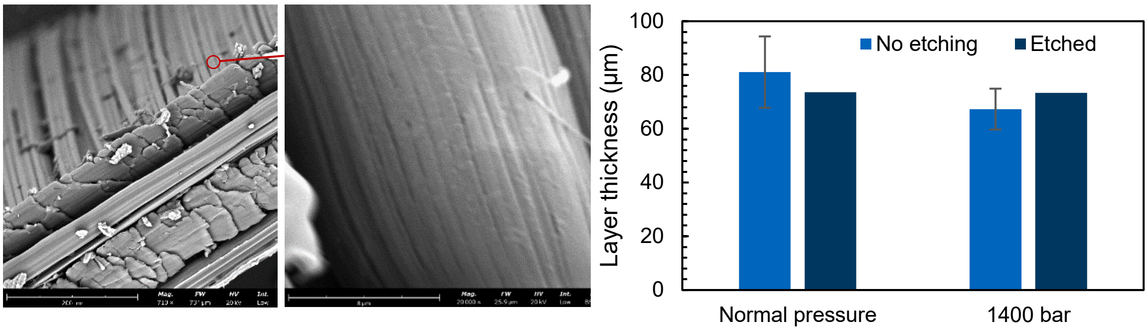
Figure 7. Probability for perforation for FSP versus impact velocity for normal pressed (a), and for pressed at 1400 bar (b).

Table 2. Evaluated v50 and v5 from ballistic tests with 1.1 g FSP.

Projectile	Dyneema target	v50	v5
Fragment (FSP) 1,1 g	HB210 (normal pressure)	1397 m/s	1328 m/s
Fragment (FSP) 1,1 g	HB210 (1400 bar)	1482 m/s	1453 m/s

Layer thickness as a function of consolidation pressure

Figure 8(a) shows a single sheet of Dyneema HB210, revealing that each sheet consists of four orthogonally oriented layers of so called unidirectional (UD) tape. The average thickness of the HB210 sheet is 0.190 mm, implying that each individual UD layer is approximately 50 μm thick. A magnified image of a fibre bundle, highlighted in red in Figure 8(a) is shown in (b). This image suggests that the diameter of the individual UHMWPE fibres is less than 1 μm. Figure 8(c) summarises the evaluated layer thicknesses in Figure 5, as function of consolidation pressure. Because the individual fibres could not be resolved in the micrographs shown in Figure 5, it is not possible to conclusively determine which specific structural features the measured thickness values represent. Nevertheless, the data indicate that the layer thicknesses do not change appreciably with increasing consolidation pressure.



(a) (b) (c)

Figure 8. HB210-foil with four orthogonal UD-layers (a). Close view of a fibre bundle where individual UHMWPE fibres are visible (b) estimated layer thickness as function of pressure (c).

Discussion

Both the tests with the FOI test projectiles fired against the ceramic/Dyneema targets and the fragment-impact tests on the Dyneema plates demonstrate that ballistic performance improves with increasing consolidation pressure, as show previous by others, e.g., [2,3]. At a 50% probability of perforation, i.e., v50, the ballistic limit increased by approximately 2% for the ceramic/Dyneema configuration and 6% for the Dyneema targets when the consolidation pressure was raised from 150–200 bar to 1400 bar. At the more stringent 5% perforation probability, i.e., v5, the corresponding improvements were 10% and 9%, respectively. In addition to increasing the ballistic limit, the transition from low to high perforation probability became noticeably sharper, and the associated confidence intervals narrowed. The observation that v50 increases by only 2%, while v5 increases by 10% for the ceramic/Dyneema targets, together with the sharper probability transition, suggests that pressing at 1400 bar primarily makes the material more homogeneous. If the plates had also become substantially stronger or stiffer, for example through an increased fibre-to-matrix ratio, one would expect a more pronounced increase in v50 as well.

Thus, some effect on the overall strength of the Dyneema plates of the consolidation pressure may be seen in the fragment tests, where v50 increased by 6%. Although the dataset is limited, the soft steel fragments perforating the 1400 bar plates were, on average, 4% shorter than those perforating the normal pressed plates. This indicates a higher resisting force in the Dyneema plates pressed at 1400 bar compared to the one pressed at normal pressure. A possible explanation proposed in [3], is that this is due to the reduced void content and improved interlayer bonding in the Dyneema pressed at 1400 bar.

Conclusions

The results of this study indicate that the ballistic performance at low probabilities of perforation (v5) for ceramic body armour plates can be improved by approximately 10% when the Dyneema backing is consolidated at pressures higher than those typically used in current industrial practice. At the same time, the protective performance becomes more predictable, as evidenced by the sharper transition from low to high perforation probability. These improvements arise from the increased material homogeneity achieved at elevated consolidation pressures, i.e., reduced void content and improved interlayer bonding. While manufacturing techniques are primarily the responsibility of armour producers, it remains in the interest of end users to influence technological development toward more weight-efficient protection systems. By specifying stricter requirements for the quality and consistency of key material components, users can achieve measurable benefits. A 10% improvement in v5 corresponds, for a given threat, to an increase in protection equivalent to reducing the required stand-off distance by up to 100 meters. To achieve improvements beyond those demonstrated here, further optimisation of the UHMWPE-tape is likely required, specifically, increasing the fibre volume fraction relative to the thermoplastic matrix.

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Experimental and Numerical Investigation of Near-Field Blast Response in Fully Clamped S355 Steel Plates

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Abstract

Near-field blast loading from drone-borne explosives introduces severe demands on structural façades, requiring accurate characterization of material and structural response under high strain rates. This study investigates fully clamped S355 steel plates (2 mm thickness) subjected to blast loads at varying scaled distances. Each experiment produced extensive datasets, including full-field displacement and strain fields via 3D Digital Image Correlation (3D-DIC), boundary reaction forces, and high-speed pressure measurements, enabling detailed analysis of deformation modes, strain localization, and failure progression.

Quasi-static material characterization tests were performed to calibrate constitutive models for the steel plates. Numerical simulations employed LS-DYNA with multiple multi-physics solvers to capture fluid–structure interaction (FSI), shock wave propagation, plastic flow, and localized fracture. Model predictions were validated against experimental data to assess solver performance and predictive fidelity. Results demonstrate the influence of scaled distance on energy dissipation and plate integrity, providing critical insights for the design of ductile, energy-absorbing steel façades in lightweight protective systems.

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Analysis of the mechanical properties of armour ceramics with heterogeneous microstructure using macroscopic and microscopic scale experiments

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Abstract.

Over the past ten years, new grades of armour ceramics with highly heterogeneous microstructure have appeared on the market. Among these microstructures are RBBC ceramics based on B4C grains. RBBC process consists in infiltrating molten silicon in a previously sintered B4C green body. The silicon phase infiltrated through the green body fills all pores leading to a dense microstructure with low porosity, while limiting sintering temperatures and production costs. Adding silicon to B4C-based ceramics produced by SPS (Spark-Plasma-Sintering) can yield similar gains [1]. However, the role of heterogeneities and grain size on the ballistic performance of these ceramics remains to be demonstrated.

To achieve this, 4 grades of RBBC type ceramic or produced by SPS were studied within the framework of the FAMAG project [2] using innovative experimental methods recently developed at the 3SR Laboratory. On the one hand, plate impact experiments were conducted to determine the Hugoniot Elastic Limit (HEL) [3] and the spall strength [4] of these ceramics. These tests made it possible to identify the mechanical tensile and compression behaviours of these ceramics in their virgin (non-damaged) state under high-rate loadings. In addition, tandem tests [5], consisting of two consecutive impacts, were performed on the same microstructures to fragment these materials (first impact) and characterize their mechanical response in the fragmented state (second impact). These macroscopic-scale tests allowed for the identification of parameters for a DFH-JH2 type model describing the fragmentation properties (DFH anisotropic damage model) and the behaviour of these ceramics under confinement in both the intact and fragmented states (JH2 model).

On the other hand, nanoindentation and micropillar compression tests were performed using a nano-mechanical testing apparatus on these microstructures to study the mechanical properties of each phase at the microscopic scale. These tests enable the mapping of the mechanical properties of each microstructure at small scale.

Finally, a few laboratory ballistic tests were conducted to evaluate the ballistic performance of these materials considering API-BZ type armour-piercing projectile impact. A sarcophagus-like configuration was implemented to recover the target after impact and to analyse, by microtomography, the damage patterns generated in the ceramic plate used for the front face and in the composite used as backing. All of this work provides a better understanding of the mechanical behaviour of each microstructure and the potential beneficial role that heterogeneities present within the microstructure of these ceramics can play.

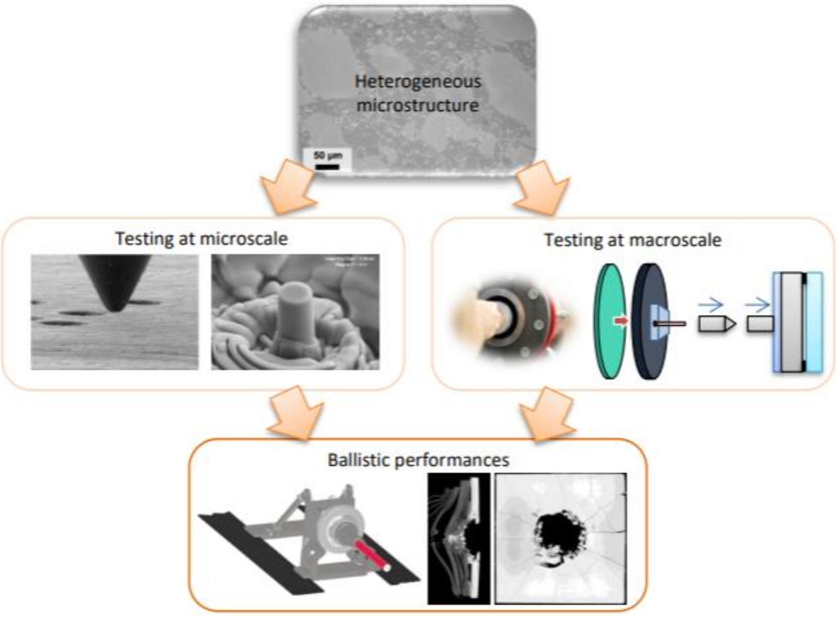

Figure 1. Macroscopic and microscopic scale experiments for analysing the mechanical properties of armour ceramics with heterogeneous microstructure

Acknowledgements

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Experimental and numerical methodology for the analysis of composite laminate fragments as an impact threat in aerospace structures.

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Abstract

Within the framework of aerospace safety and the development of new propulsion technologies, such as Counter-Rotating Open Rotor (CROR) engines, blade failure represents a critical threat to the fuselage. Unlike conventional studies that analyse composites as static targets, this work investigates the behaviour of carbon fibre (CFRP) fragments acting as high-velocity projectiles. The objective is to improve the design of lightweight protection systems through a deep understanding of the impactor's damage mechanics.

For the present work, it is proposed a combined methodology integrating: experimental test, advanced monitoring and numerical modelling. It has been used a compressed gas gun to launch woven CFRP fragments against an instrumented Hopkinson bar at velocities up to 160 m/s. Two type of projectile are selected with different stacking sequence: in one case all laminates are oriented longitudinally with the impacted bar (0º laminate), in the other, plies are rotated (45º laminates). High-speed cameras and 3D Digital Image Correlation (DIC) are used to evaluate failure modes and accelerations, along with strain gauges placed on Hopkinson bar to measure impact force. Finally a finite element model in Abaqus/Explicit has been used. The model incorporate a VUMAT subroutine which includes strain rate dependency into the material's constitutive behaviour [1].

The main failure mechanisms identified includes erosion on the impact face, delamination, and fibre breakage. It was determined that the peak impact force is significantly higher in 0º fragments compared to 45º ones. Furthermore, the validated numerical model demonstrated that strain rate dependency is a determining factor for accurately predicting both material strength and the resulting failure mode. A parametric study revealed that even small deviations in the fragment's trajectory (yaw and pitch angles) drastically affect the impulse and damage mechanisms.

This research provides a robust methodology for the study of impacts threats of composite fragments, highlighting the importance of considering strain rate effects. These findings are essential for advancing the design of lightweight armour and safer aerospace structures against high-energy impacts.

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Application of machine-learning approaches with physics-informed oversampling to determine ballistic limit curves

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Abstract

The proposed study investigates the application of physics-informed oversampling in machine-learning models to approximate ballistic curves and ballistic limit velocities that represent the resistance of targets made from S355 steel under impacts of 7.62 × 51 mm P80 (0.308 Win) small-caliber projectiles. Through a detailed terminal ballistic experimental investigation, ballistic limit velocities, along with the corresponding limit curves, were determined for the four target thicknesses, i.e., the plates of the thickness of 20 mm, 16 mm, 8 mm, and 5 mm were used. The experimental results concerning the four impact configurations were further used to validate the finite element analysis, resulting in the identification of an additional set of eleven ballistic limit curves and ballistic limit velocities for a total of fifteen configurations of the S255 steel plates, with thicknesses ranging from 4~mm to 18~mm. Finite element simulations were used to complement the experimental data and further characterize the effects of varying plate thickness on their protection level. Several machine-learning approaches, including deep neural networks (DNN), Random Forests (RF), Support Vector Machines (SVM), and XGBoost (XGB), were trained on a part of the data. Their efficiency and accuracy in predicting experimentally identified ballistic limit features were then evaluated for the remaining data subset, Figure 1. By leveraging available data and incorporating specific physical mechanisms into machine-learning algorithms, the study analyses the applicability and limitations of these approaches.

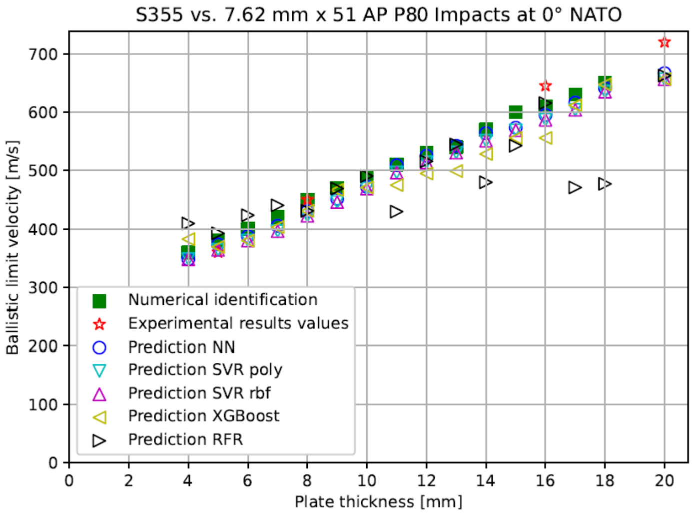

Figure 9: Ballistic limit velocities for the S355 steel plates impacted by the projectiles of caliber 7.62 mm x 51 P80 – experimental values and their predictions obtained with FEM modeling, as well as: Neural Networks (NN), Support Vector Regression poly-kernels and radial-based functions (SVR poly and SVR rbf), Extreme Gradient Boosting (XGBoost) and Random Forests (RFR) methods in leave-one-out cross-validations..

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Production of Large Homogeneous Delamination in Aeronautical CFRP Laminates from Smaller Laser Shocks

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Abstract

The switch from metal to composite in aeronautical structures led to changes in lightning strike certification due to the low electric conductivity of polymer-based light-weight structures [1]. A metallic protective grid is placed between the external protective paint and the CFRP structure. It acts as a sacrificial layer to dissipate the high current impulsion. In some configurations damage still appears in the core of the composite structure. The physical events behind these damage mechanisms are not yet fully understood but some authors link them to successive electric confined explosions of the protective layer creating thermomechanical shocks. While the total delaminated area can be reproduced with a mechanical impact of similar impulse on bare CFRP [2], the spatial distribution of lightning strike damage does not present the typical conical shape of mechanical impacts. A deeper analysis of mechanical contribution to the damage is thus necessary. Following previous works [3] which highlighted analogies between the damage of lightning strike and laser shocks on CFRP, this paper studies the possibility of creating a large homogeneous delamination from a series of laser shocks of smaller radius arranged in a grid pattern. After selecting the appropriate energy density level and grid size, the proposed protocol is conducted on a disk-shaped sample. The damage position variability is studied and the tomographic analysis of the post-mortem sample (Figure 1) is used to validate the methodology. Strategies to improve the homogeneity of the delamination are discussed.

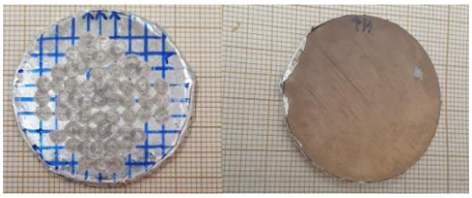

Figure 10: Post-mortem top (left) and rear (right) view of the Φ35 CFRP sample after 57 laser shocks. An aluminium adhesive layer and a water confinement were used to control the laser-matter interaction.

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Digital Image Correlation on Blast Loaded Plates: Developments and Applications at the University of Sheffield.

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Abstract

Experimental research of blast loaded structures typically focuses on one of either: (i) characterisation of the load applied or (ii) structural response. The extreme nature of close-proximity blast loading (with respect to magnitude, timescale and temperature) are factors that impede experimental instrumentation in terms of accuracy and resolution, both temporally and spatially. Recent studies at the University of Sheffield have employed digital image correlation (DIC) of plates under various types of blast load scenarios. The application of this measurement technique has been notable for its ability to record data at a high spatial resolution. This allows the characterisation of both the response of a structure and the applied load. This presentation is a case study of the recent developments and applications of DIC at the University of Sheffield. The specific challenges and benefits that its implementation poses are described for each study, as well as the future questions that have been revealed.

Numerical investigation of the performance of ballistic helmets against 9mm FMJ

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Abstract

Combat helmets are designed to protect military personnel during impact events by defeating incoming threats (blunt, ballistic, or blast threats) without inflicting serious or fatal injury to the head. To enhance protection while maintaining comfort, combat helmet manufacturers try to maximize protection for a minimum weight by using advanced materials with a higher strength-to-weight ratio.
Two types of materials meeting this characteristic have emerged in the design of modern ballistic helmets: aramid fibers represented by Kevlar developed in 1960 by Dupont and Ultra-High-Molecular-Weight Polyethylene (UHMWPE) with Dyneema as its leading commercial form. These materials exhibit different mechanical properties, which significantly influence the energy absorption during impact.

Kevlar and UHMWPE composite helmets provide more effective protection and comfort against small arms projectiles and fragments compared to traditional metallic helmets.

In this study, combat helmets made with Kevlar and Dyneema fibers are evaluated using a finite element head model developed within the framework of kinetic energy non-lethal applications. The model is subjected to a frontal impact from a 9 mm Full Metal Jacket (FMJ) projectile at an impact velocity of 435 m/s under identical loading conditions (Figure 1). Key response metrics, including intracranial pressure and impact force, are monitored to assess and compare the protective performance of the two helmet materials.

The use of numerical simulations is essential to better understand and predict the effects of the helmet material on the ballistic performance and consequently, the risk of head injury to soldiers.

Figure 11: Setup.

Evaluating Steel Equivalence of Soft Ballistic Protection Materials through Finite Numerical Models

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Abstract

The main text, Font text Arial, Font size: 9, Regular. Line spacing 1,2. Paragraphs are justified (straight- edged) on both left and right. Do not chan Abstract. Soft ballistic plates are flexible, multilayered protective inserts made from high strength synthetic fibers such as Aramid or UHMWPE, which are specifically designed to absorb and dissipate the kinetic energy of low velocity ballistic threats. These soft armor protections can be used either as primary protective elements or as backing layers combined with harder materials-such as ceramic or steel plates-to mitigate residual projectile energy and control armor deformation. However, the numerical modeling of soft ballistic plates is challenging due to the anisotropic behavior of the constitutive materials and the presence of specific failure mechanisms, including fiber breakage and delamination, all of which have an influence on the ballistic performance of the plates. In this study, a numerical investigation of a UHMWPE material (Dyneema) soft ballistic laminates are carried out with the objective of developing an equivalent rigid target made of Armox steel that can replicate the ballistic response of the soft panels. To achieve this, the LS-DYNA solver is employed to perform ballistic simulations on both Dyneema laminates and Armox steel plates impacted by different types of projectiles. The Dyneema laminates are modeled as orthotropic materials, while the Armox steel plates are described using the Johnson–Cook constitutive and failure models. The projectiles are treated as rigid bodies of known geometries. The expected outcomes of this work include determining the ballistic limit of both Dyneema and Armox plates as a function of projectile type and armor thickness, comparing the numerical results obtained off Armox steel with analytical ballistic models available in the literature, and establishing an equivalent Armox thickness capable of replicating the ballistic performance of the soft Dyneema panels. The proposed equivalence approach aims to simplify armor design studies by replacing detailed soft-armor modeling with an equivalent rigid steel representation, thereby reducing computational effort while preserving predictive accuracy.

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Impact Loads on Foam-Based Protective Structures

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Abstract

Cellular materials such as polymer and aluminium foams are widely used as energy-absorbing components for mitigating impact and blast loads on critical structures. Recent studies have clearly demonstrated the effectiveness of various foam-core sandwich systems in enhancing crashworthiness and impact [1-9]. Building on this body of work, the present study combines experimental characterization and numerical modelling to improve the design of foam-core sandwich elements subjected to extreme loading. Static and dynamic material tests were conducted to capture the behaviour of the highly inhomogeneous aluminium foam-core and the high-strength steel skins, while ballistic impact tests on sandwich components were conducted to provide data for model validation. The numerical model was based on a non-linear finite element framework with a crushable-foam constitutive law to reproduce progressive densification, rate effects, and localized deformation and fracture of the foam-core material, while a modified version of the well-known Johnson-Cook model was used to represent the skins. Model parameters were calibrated against material tests and X-ray Micro Computed Tomography (XRMCT) data. Overall, the numerical model was able to reproduce the complex response of the sandwich component under impact loading. The validated numerical model was then employed for structural optimization aimed at maximizing the energy absorption while controlling weight. This integrated experimental–numerical approach supports the development of safer and more efficient foam-based protective structures.

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Application of the SHIELD-FEM thorax model for assessing thoracic protective equipment in blast scenarios

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Abstract

When designing protective equipment for soldiers and law enforcement officers, blast threats are rarely considered, with development efforts primarily focused on protection against ballistic impacts, knives, and fragments. However, primary blast injuries predominantly affect air-filled organs such as the lungs and gastrointestinal tract, and previous studies have shown that certain thoracic protective equipment (TPE) may actually exacerbate injury severity under blast loading [1-5], although findings are inconsistent [6-7].

In this study, a finite element model (FEM) of the human torso, SHIELD-FEM for “Simplified Human thorax for Injury EvaLuation in Defense – Finite Element Model”, is employed to investigate thoracic response to blast exposure. The model has been previously validated under two experimental configurations: impact tests using non-lethal projectile impacts from Bir [8] and blast loading from Gardère et al. [9]. This latter configuration exposed a dummy called SurHUByx to various blast intensities, with and without a soft body armor vest. The validated model is then used to simulate the response of the human torso to a single, high-intensity blast, considering scenarios with and without soft thoracic protection.

FEM responses are compared with available data on biological model to compare tendencies regarding blast amplification or reduction behind the protection. In addition, a parametric study is conducted to evaluate the influence of vest tightness on thoracic wall kinematics and internal organ pressures. The results provide insight into the mechanisms by which soft body armor may alter blast transmission to the thorax and contribute to injury risk. These findings highlight the importance of incorporating blast considerations into the design and evaluation of future thoracic protective systems.

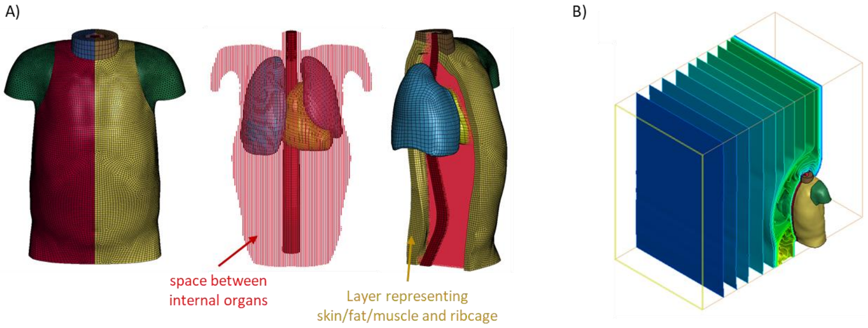

Figure 12: SHIELD-FEM simplified thorax of a 50th percentile male (left); Blast wave interaction with SHIELD-FEM (right).

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Armox 440T plates subject to buried blast: a benchmark for appliqué systems

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Abstract

Loading of vehicle undercarriages from the detonation of shallow-buried explosives remains a serious threat. One method to protect lightly-armoured vehicles is to retrofit them with appliqué armour. A key performance metric of this armour is its deformation under loading, which must be limited to avoid impact upon vehicle occupants. Armox 440T is commonly used due to its high load capacity, strength-to-weight ratio, ductility and low cost.

Here, we present the development of an appliqué system test apparatus. This is designed to provide both repeatable loading and boundary conditions to enable the comparison of newly produced armours against a developed Armox 440T benchmark.

The work builds on the authors' previous work to establish a methodology that produces very consistent loading from shallow-buried detonations. Tests were conducted with a range of explosive masses and plate thicknesses. Plate deformations have been captured by stereo high-speed digital image correlation and were compared to a commonly-used low-cost peak deflection method.

Since the benchmark trial series, a new reduced scale apparatus has been developed to enable reduced cost testing of armour system prototypes (450 mm vs the original 955 mm). A proof of concept dataset is provided for Armox 440T, alongside data from a novel new armour steel.

Influence of Under-Vest Fabric Type on Back-Face Deflection

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Abstract

Soft ballistic vests are typically worn over regular clothing, yet the influence of under-vest fabrics on Behind-Armour Blunt Trauma (BABT) remains insufficiently characterized. This study investigates how different under-vest fabrics affect back-face deflection in a modelling clay backing under 12-gauge shotgun projectile. Four fabrics representative of under-vest garments were evaluated: 100% Dyneema with a fibre diameter of 0.2 mm (Fabric 1), a Dyneema (90%)–Elasthan (10%) blend with a fibre diameter of 0.25 mm (Fabric 2), an aramid fabric with 52% aramid fibres and a fibre diameter of 0.3 mm (Fabric 3), and an aramid fabric with 49% aramid fibres and a fibre diameter of 0.4 mm (Fabric 4). Each fabric was placed between a soft ballistic vest (Dyneema material) and a Roma Plastilina modelling clay used as a soft-tissue surrogate. Back-face deflection in the clay was measured after 12-gauge impacts under controlled laboratory conditions and compared across fabric types. A baseline series without any under-vest fabric (vest only) was also performed. Across all impacts, maximum back-face deflection ranged from about 57 mm to 65 mm, with the vest-only baseline exhibiting the largest deflection and the aramid fabrics (Fabrics 3 and 4) showing a modest reduction in clay deformation relative to the Dyneema-based fabrics and to the baseline. The results demonstrate measurable differences in back-face deflection as a function of under vest fabric type, even when the ballistic vest remains unchanged. Rather than prescribing specific clothing configurations, this study aims to provide quantitative data that can support informed decisions by end users, procurement agencies regarding under vest garment selection and test conditions.

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Finite Element Modeling and Optimization of UHMWPE Composites in LS-DYNA and LS-OPT

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Abstract

Ultra-high molecular weight polyethylene (UHMWPE) composites enable lightweight, high-performance personal protective equipment, leading to increased adoption across demanding applications. This growing usage creates a need for more efficient performance prediction, moving beyond costly and time-intensive experimental ballistic testing. In response, this study introduces a computational methodology to simulate the impact response of UHMWPE composites, offering a resource-efficient alternative for material and design evaluation.

A finite element model was developed in LS-DYNA to simulate the ballistic impact response of UHMWPE composites, capturing both intralaminar and interlaminar failure mechanisms. The composite plies were modeled using the *MAT_054-055 material formulation to represent in-ply damage, while interfacial delamination was simulated using independently defined cohesive layers with the *MAT_138 constitutive model. An initial sensitivity analysis was performed by systematically varying key material properties of both the plies and the cohesive layers to identify those with the greatest influence on simulated residual velocity. These critical parameters were subsequently optimized in LS-OPT to align the simulation's ballistic limit curve with a reference Recht-Ipson curve derived from physical experimental testing. This optimization process refined the input material properties, enabling the model to accurately replicate the residual velocity results of the experimental data.

The resulting optimized model exhibits strong predictive capability for the ballistic performance of UHMWPE composites, confirming that this optimization approach effectively captures the complex failure mechanisms of the material. This methodology offers a valuable, resource-efficient tool for the virtual performance assessment of advanced protective materials, with the potential to accelerate development cycles and reduce the reliance on exhaustive physical testing.

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Experimental and Numerical Investigation of Ballistic Impact on Composite Materials

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Abstract

Poster for Session 4 & 10

stic behaviour of ultra-high-molecular-weight polyethylene (UHMWPE) composites, used in hard armour plates and manufactured by NFM Technology AS (NFM). The rstanding of deformation and failure mechanisms of composites under high-velocity impact loading, and to develop predictive numerical tools that can accelerate armour design.

The experimental work in this study involved 20 ballistic tests conducted at SIMLab, NTNU, using the set-up shown in Figure 1. Two plate variants with a thickness of 5 mm, designated P2 and P3, differing solely in consolidation parameters, were impacted using rigid steel spheres at controlled velocities. A Phantom TMX 7510 high-speed camera captured the failure process with high temporal and spatial resolution. P2 reached a ballistic limit of 627 m/s, 20% higher than P3. Post-impact images showed that P2 dissipated energy through delamination and bulging, while P3 failed mainly by local fibre rupture and showed a steeper ballistic limit curve as shown in Figure 2.

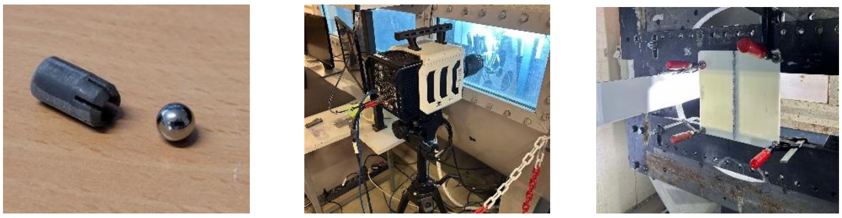

Figure 1: Rigid steel sphere used as projectile in the ballistic tests, followed by the high-speed camera used for recording and how the plate was clamped during the tests. [1].

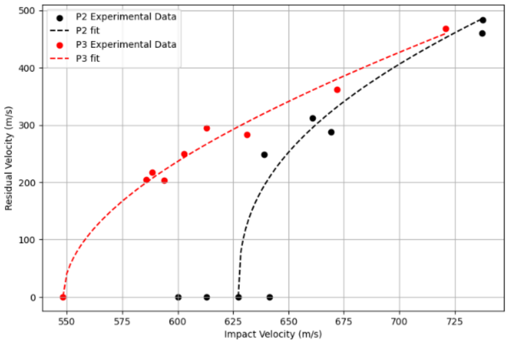

Figure 2: Ballistic limit curves obtained from the ballistic impact tests for the P2 and P3 plates [1].

Numerical simulations were carried out in LS-DYNA® using *MAT_221, an orthotropic simplified damage model, which was calibrated through inverse modelling. The model reproduced qualitative failure mechanisms of the composite as seen in Figure 3, but on the other hand, gave a lower ballistic limit compared to the experimental results. A systematic parametric study showed that the fibre stiffness and tensile failure strain were the most influential factors in the numerical model.

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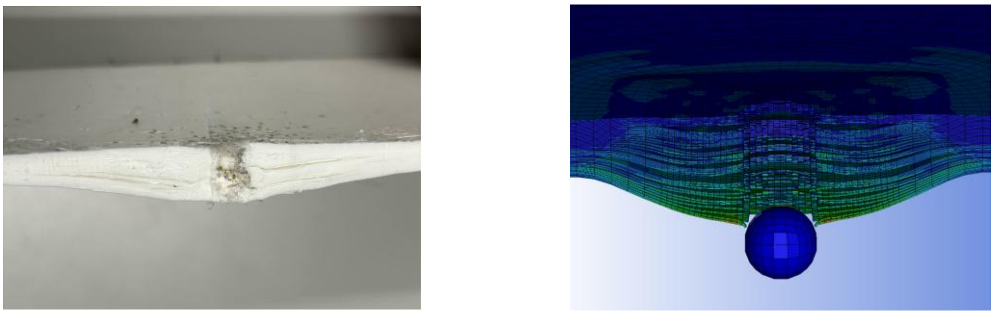

Figure 3: Comparison between experimentally observed deformation of UHMWPE plate after ballistic impact (left) and numerically predicted deformation using LS-DYNA® (right) [1].

This work provides insight into how processing affects ballistic performance in UHMWPE systems and offers validated finite element models for future use. The combined experimental and numerical findings provide guidance for improved material calibration strategies and contribute to more reliable numerical prediction of composite materials in armour design.

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Blast Mitigation in Sandwich Plates Using 3D-Printed Lattice Metamaterial Cores

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Abstract

Protection systems against air-blast loading are often based on monolithic plates or conventional sandwich panels, where weight and transmitted impulse must be traded against survivability. Cellular cores have long been proposed as sacrificial layers to mitigate shock, yet their effectiveness is not guaranteed: depending on core strength, thickness, and face-sheet inertia, the core may either attenuate or even enhance the load transmitted to the protected structure. Analytical–numerical studies have formalized this attenuation/enhancement boundary for claddings consisting of a face plate and a crushable cellular layer, highlighting the key roles of dynamic compaction, densification, and fluid–structure interaction (FSI) in shaping the reflected pressure history and the resulting structural response [1]. Complementary FSI-resolved numerical frameworks have further shown that coupling effects are most pronounced early in the blast event and that energy transfer, compaction kinetics, and critical core lengths govern whether a porous layer dissipates impulse effectively or continues compacting due to retained kinetic energy [2].

Building on these foundations, this work investigates blast-loaded sandwich plates in which the intermediate sacrificial layer is a 3D-printed lattice metamaterial, composed of periodic unit cells whose topology and relative density can be engineered. A finite element workflow is developed to model the full sandwich assembly under a dynamic load representative of a shock wave, capturing large deformation and progressive core compaction. A topology-driven parametric campaign is then used to identify unit-cell architectures that minimize peak transmitted stress and back-face response while reducing areal density relative to an equivalent solid-core solution.

The expected outcome is a set of lightweight, manufacturable lattice-core designs and quantitative design maps linking topology and relative density to blast-mitigation performance, supporting the adoption of custom metamaterial cores as tuneable sacrificial layers for protective panels.

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Design of a Split-Hopkinson Pressure Bar System

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Abstract

The Split Hopkinson Pressure Bar (SHPB) is a widely used experimental technique for characterising the dynamic mechanical response of materials at high strain rates. Commercial SHPB systems can be costly and may not offer the flexibility required for specialised research applications. This work presents the systematic design, development, and validation of an in-house SHPB system, emphasising design methodology, material selection, manufacturability, and experimental reliability. The developed system is intended to provide a cost-effective, modular, and repeatable platform for high-strain-rate testing of engineering materials for defence and security applications. This paper presents the methodology and engineering design of the Flamengro developed SHPB system, intended to support ballistic-relevant dynamic testing capabilities. The design process followed a systematic methodology encompassing requirements definition, numerical method which involved computational modelling of the system and the experimental method which consisted of a physical testing under controlled conditions. Particular emphasis was placed on achieving repeatable striker bar velocities and strain-rate control. Key design considerations included gas cannon configuration, bar material selection, bar length optimisation, instrumentation layout, and wave dispersion minimisation to ensure accurate stress–strain measurements. The SHPB system was designed to test light weight armour materials at a maximum striker bar velocity of 100m/s and a strain rate of 10 000 s^{-1}.

Figure 13: Schematic of the SHPB principle[1]

The paper details the mechanical design employed to accurately capture incident, reflected, and transmitted stress waves. Validation of the system was conducted through baseline testing and comparison with theoretical predictions, demonstrating reliable stress equilibrium and acceptable signal quality.

Table 3 outlines the design specifications of SHPB system. The Hopkinson bar materials will vary depending on the test sample.

Table 3: Product design specifications

Design parameters	
Maximum strain rate	10 000 s^{-1}
Temperature range	Room temperature up to 400 ℃
Maximum striker bar velocity	100 m/s
Maximum tank pressure	16 bar
Tank volume	20L
Barrel length	6m, 4m, 2m
Barrel diameter	25mm, 32mm, 40mm nominal bore
Specimen size	From ∅ 2mm×2mm up to ∅ 10mm×10mm
Hopkinson Bars dimensions	
Length of the experimental set-up	10 m
Length of striker bar	0.35m, 0.5m (∅20mm for all striker bar)
Length of incident bar	2m, ∅20mm
Length of transmission bar	2m, ∅20mm

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Hopkinson Bars materials	
Material of striker bar	Maraging steel (350 grade)
Material of incident bar	Maraging steel (350 grade)
Material of transmission bar	Maraging steel (350 grade)
Material of specimen	Armox 500T
High speed Data acquisition system	
Number of channels	2 channels
Sampling rate	2×10^6 samples per second
Band Width frequency of amplifier	0 to 500 kHz
Strain gauge resistance	350 ohm

The system was designed using the adiabatic model for the gas-gun system, with striker impact velocity calculated using the following equation[1]:

$$v_{st} = \sqrt{\frac{2}{m_{st}}\left\{\frac{C_P.P.V}{\gamma - 1}\left[1 - \left(\frac{V}{A_{st}.l_{bref} + V}\right)^{(\gamma-1)}\right] - F_f.l_{bref}\right\}} \qquad [1]$$

The nominal strain rate in the specimen was determined from the striker bar velocity using the following relation[1]:

$$\acute{\varepsilon}_{sp} = \frac{2C_0\left(v_{st}.A_i.\rho.C_0.\beta - A_{sp}.\sigma_{sp} - A_{sp}.\sigma_{sp}.\beta\right)}{A_i.E.l_{sp}(1+\beta)} \qquad [2]$$

The following design parameters were calculated.

Table 4: SHPB optimised design calculations

Wave speed	4950.40 m/s
Striker bar velocity	99.53 m/s
Incident pulse velocity	49.76 m/s
Transmitted pulse velocity	18.37 m/s
Strain rate	10520.99 s^{-1}

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NTNU is Norway's largest university, with its main campus in Trondheim and additional campuses in Gjøvik and Ålesund. It specializes in science and technology but offers a broad range of academic disciplines.

NTNU's vision is to "create knowledge for a better world", and it is known for its strong focus on innovation, interdisciplinary research, and international collaboration.

SIMLab – Structural Impact Laboratory – is a research group located at the Department of Structural Engineering, NTNU.

SIMLab focuses on understanding how materials and structures behave under impact and extreme loading conditions, such as collisions, explosions, and ballistic impacts.

Their goal is to develop advanced computer models that accurately simulate these behaviours, contributing to safer and more efficient designs in industries like automotive, energy, and defence.

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