Ultra High Molecular Weight Polyethylene (UHMWPE)

Technical Proposal

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1.0 Summary

The behaviour of polymer armour is well known to span several loading regimes and hence the use of a multi-scale and holistic modelling approach should yield the most accurate predictions. The proposed work should lead to much improved polymeric armour systems, optimised for specific ballistic threats and potentially focusing on weight challenged applications.

The following proposal aims to extend the developments from the previous polymer armour programme on computational investigations under the DSTL funded project DSTLX-1000109294 and co-funded via DTC at Imperial. The proposed programme aims to develop improved polymer composite armour systems using an integrated numerical modelling approach to incorporate non-prescribed material delamination sites and natural variation in terms of overall system response. The key activities are defined as:

- An unstructured approach to delamination modelling within a laminated panel subject to ballistic impact.
- To develop stochastic techniques to generate probabilistic output for ballistic impact simulations.

Contents

2.0 Introduction

The numerical activities will be led by Imperial College and will build upon techniques already developed on existing programmes and relationships. The use of new and state of the art modelling tools allows the possibility to employ advanced numerical optimisation tools to determine the most appropriate polymeric material within an armour for a specific threat and application. The behaviour of armour is well known to span several loading regimes and hence the use of a multi-scale, stochastic and holistic modelling approaches should yield the most accurate future predictions.

3.0 Background

High performance laminated composite materials have been extensively used in both military and civil applications, due to their excellent projectile capturing capabilities. This can be attributed to their high specific strength and multi-plied morphology which allows them to adopt a unique set of properties, usually tailored for the desired task. Consequently, they suffer from inter-laminar failure modes, commonly described as delamination, which can be considered as a crack or discontinuity propagating between the plies. While reducing the overall structural integrity, delamination has been proven beneficial to the impact performance of polymeric laminates as it allows for larger deformations and higher energy dissipation. Therefore, it is important to understand and control these mechanisms in order to enhance existing predictive tools and improve the ballistic performance of future protection systems.

Current trends in interface modelling rely on deterministic properties and pre-defined surfaces which dictate the planes of potential debonding. This can lead to unrealistic deformation and discrepancies in numerical simulations. A delamination detection methodology with respect to the uncertainty introduced by manufacturing defects and inherent in the material structure needs to be established, to allow for more realistic design practices that improve the accuracy over current simulation techniques.

3.0 Proposed Tasks

Following on from the conclusions from the recent DSTL funded project DSTLX-1000109294 (Iannucci, Del Rosso, Curtis, Pope, & Duke, 2018) programme. Two work packages are envisaged:

- An unstructured approach to delamination modelling with a laminated subject to ballistic impact.
- Develop stochastic techniques to generate probabilistic output for ballistic impact simulations.

3.1 Research plan

The purpose of this study is to further extend current state-of-the-art numerical techniques, developing an algorithm for automatic delamination identification and interface failure propagation. The proposed research aims to:

- Identify the most suitable FEM techniques for representing inter-laminar damage in composite materials.
- Develop a probabilistic methodology, based on a three-dimensional flaw distribution, for identifying potential delamination regions inside the element.
- Couple the proposed identification method to a crack propagation algorithm in a numerical framework.
- Compare the proposed method with existing pre-defined surface delamination techniques.

The impact of interface failure on the load transferring capabilities of high-performance polymeric laminates as well as its effects on the measured properties, has been demonstrated through both experimental and computational investigations under the DSTL funded project DSTLX-1000109294 (Iannucci, Del Rosso, Curtis, Pope, & Duke, 2018). Furthermore, micromechanical models that accurately predict the coupon level response of composite laminates under tension, compression and in-plane shear have been developed in (Kempesis D. , et al., 2021; Kempesis D. , et al., 2021), under the EPSRC project EP/N509486/1: Polymeric composite shield design for ballistic impact protection, (Kempesis D. , Multi-scale Polymeric Composite Design for Ballistic Impact Protection, 2021). The stochasticity of interface properties has also been considered to further understand how sub-fibre and fibre/resin interaction could affect the macro-mechanical performance of the composite, providing a strong basis for future probabilistic design studies (Kempesis D. , et al., 2021; Kempesis D. , et al., 2021). Knowledge derived from this study has been used to further improve a three-dimensional pressure, temperature and strain-rate dependent constitutive model that was implemented in the LS-DYNA explicit finite element code and led to accurate predictions of the impact performance of polymeric laminates (Kempesis D. , et al., 2021; Kempesis D. , et al., 2021). Discrepancies with respect to experimental observations were attributed to the pre-defined delamination surfaces and lack of fidelity in the interface constitutive response, further supporting the need for a novel modelling framework on interface failure.

Typical delaminations observed during an impact can be seen in Figure1

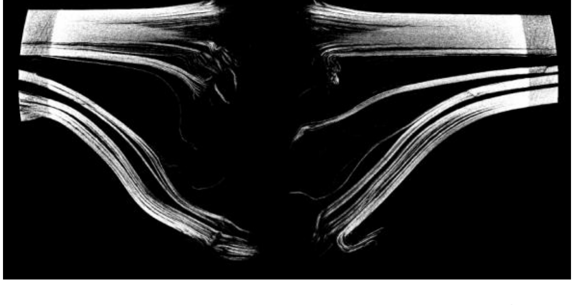

Figure 1: CT scanned of a Dyneema laminate subject to impact performed at *Southampton Univ*.

Difficulties associated with impact simulations of laminates modelled as a monolithic target have been demonstrated in (Lässig, et al., 2015; Nguyen, et al., 2015). A three-dimensional damage model accounting for in-plane and out-of-plane failure modes failed to accurately represent the laminate deformation due to limitations associated with Lagrangian finite elements. The excessive element distortion due to the low compliance of the damaged material, led to numerical errors affecting the accuracy of the simulation.

The existing methodology uses pre-defined contact definitions through the thickness as illustrated in Figure 2. However, in an idea case these should be generated ad-hoc during the simualtions.

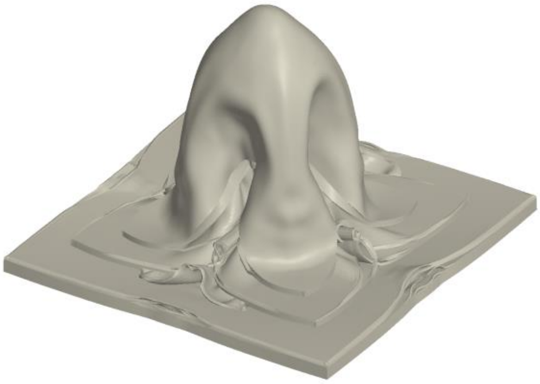

Figure 2: Numerical predictions of ballistic impact fabricated from Dyneema

Methods for arbitrary crack initiation and propagation have been proposed in the literature, in the form of the extended finite element method (XFEM) (Belytchko & Black, 1999), which is based on the partition of unity (Melenk & Babuška, 1996), and uses enrichment functions and extra degrees of freedom to allow for element splitting. Numerical techniques involving enriched elements have shown promising results in predicting the delamination area under dynamic events (Guiamatsia, Ankersen, Iannucci, & Fouinneteau, 2013). Problems associated with numerical implementation and the need for knowledge of the enrichment functions related to the investigated material has led the researchers to propose other techniques such as the phantom node method (PNM) (Hansbo & Hansbo, 2004). This promising alternative adds an extra element on top of the original, to account for material separation, which leads to the advantage of using standard FE shape functions and cohesive interaction models to connect the two. This method has also been used in dynamic crack propagation simulations (Song, Areias, & Belytchko, 2006). Extensions of this method can be found in the floating node method (FNM) which possesses a few advantages over PNM as it is can incorporate cohesive cracks readily and can handle the representation of multiple and complex networks of discontinuities (Chen, Pinho, De Carvalho, Baiz, & Tay, 2014).

All the crack propagation methods described above have been deterministic in nature, only accounting for an average value of strength and fracture energy. A technique for implementing material properties based on statistical distributions has been demonstrated in (Kempesis D. , Multi-scale Polymeric Composite Design for Ballistic Impact Protection, 2021), providing probability levels on the projectile residual velocity. This technique can be extended to interfaces for probabilistic modelling of delamination. Extra nodes can be distributed prior to failure, assigned with a value of flaw density, leading to intra-element regions where delamination is more likely to initiate. The process of node splitting can then be used to bisect and separate the element forming a cohesive crack.

3.2 Non-prescribed delamination

Existing techniques in delamination modelling require pre-defined surfaces which dictate the planes where de-bonding occurs. This can lead to unrealistic deformation and introduce discrepancies in numerical predictions. A numerical framework for simulating non-prescribed delamination is going to be investigated with focus on identifying regions where new crack surfaces need to be generated. The proposed technique should be in accordance with already established energy-based methods and simulate three-dimensional mixed-mode delamination. The methodology developed in this work will be implemented through user defined subroutines into software available to Dstl. The proposed numerical model will be compared to analytical solutions, where applicable, and to existing numerical methods that simulate delamination. The performance and accuracy of the proposed method will be assessed for multi-axial complex loading conditions that occur under impact simulations of composite plates.

3.3 Probabilistic

Prior to optimisation of a potential system for a specific impact threat, it is useful to understand the importance of the variability in the material properties, and how the ballistic limit is affected. The results of material testing at different scales level indicate the different sources of imperfections. Figure 3 and Figure 4 indicate the highly variable form of the resin bonded to the fibres which leads to the stochastic nature of these materials. Discontinuities introduced during the manufacturing procedure, affect the overall deformation through localisation phenomena that manifest in the microstructure and hinder the mechanical response of materials.

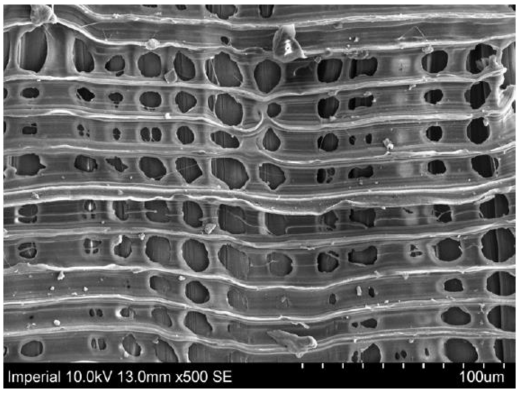

Figure 3: Interlaminar voids in Dyneema UD composites, placement of Dyneema fibre shown

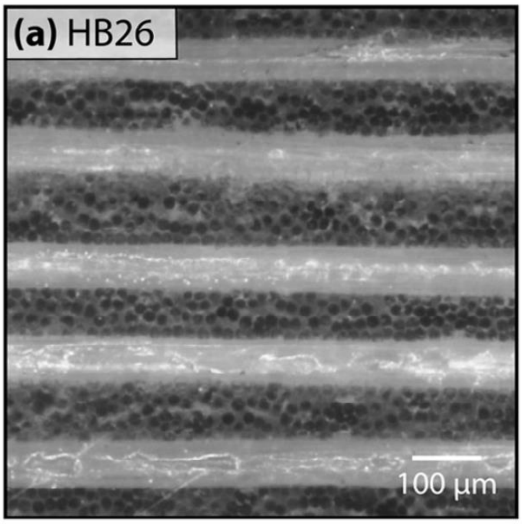

Figure 4: Optical micrographs of the X–Z plane cross-sections of a HB26 consolidated laminate

Current trends in material and interface modelling rely on deterministic properties, ignoring the presence of defects and failing to represent variations in the mechanical behaviour that can be crucial in safety-critical components and protective systems. An approach that considers stochastic material properties needs to be defined in order to quantify the uncertainty in highly dynamic events. Numerical methods utilising LS-OPT and user-defined subroutines can be used to adopt a probabilistic modelling approach implementing stochastic material properties as a function of the element size and loading rate. Results from micro-CT scans can be used to calibrate scaling methodologies associated with the defect size distribution in order to introduce length scale dependencies. The outcome of this work is expected to improve the accuracy of numerical predictions by capturing the uncertainty observed in experimental procedures.

3.2 Project management.

The project management will be performed by Imperial College. The implementation into LS-DYNA for commercial use of the developed material modelling approaches will be discussed with Dstl.

4.0 Project Gantt chart and Deliverables

The following page, Table 1 from Dstl ITT, illustrates the general timing of tasks and milestones are shown.

1.6	**Deliverables & Intellectual Property Rights (IPR)**					
Ref.	**Title**	**Due by**	**Format**	**Expected classification (subject to change)**	**What information is required in the deliverable**	**IPR Condition**
D-1	Monthly progress and technical work review	T0 + 1 month T0 + 2 months T0 + 3 months	Meeting	Official	Report to include but not limited to: a. Update on technical progress b. Progress report against project schedule c. Review of deliverables d. Risk/issues	DEFCON 705 shall apply (Full rights).
D-2	IEEE APS 2021 (Institute of Electrical Engineering and Antennas & Propagation Society)	31/03/2022	Final report	Official	Report to include but not limited to: a. Update on technical progress b. Progress report against project schedule c. Review of deliverables	DEFCON 705 shall apply (Full rights).
D-3	Material model (compatible with software available to Dstl)	T0 + 4 months	Material model template/User-subroutine/ equivalent	Official	Material model template/User-subroutine/ equivalent	DEFCON 705 shall apply (Full rights).

Table 1: Gantt chart for the UHMWPE project

5.0 Exploitation strategies

Developments of advantageous and exploitable technologies in the context of military applications are critical to the success of this programme. Imperial has constant communication with MoD researchers at all levels, associated with protection, by virtue of running other relevant DSTL projects. Hence developments can be readily disseminated through MoD and the wider government programmes. Such novel multi-scale, constitutive model and solver developments can result in superior and enhanced armour performance (both on vehicles and body armour). Close links with Dstl will be essential, both in their materials and armour systems area. It is anticipated that improved materials will be exploited into the Dstl applied armour programmes. Ballistic modelling codes will be migrated into Dstl vehicle modelling tools.

The outcome of this work should be applicable to current discretisation techniques, where numerous cross-ply layers are homogenised using one element through the thickness, and is expected to be coupled with the constitutive model for polymeric laminates developed in (Kempesis D. , Multi-scale Polymeric Composite Design for Ballistic Impact Protection, 2021; Kempesis D. , et al., 2021), providing a complete framework of both in-plane and out-of-plane failure. Results from this study will provide underpinning knowledge on probabilistic interface failure detection algorithms, under dynamic multi-axial loading conditions, which is expected to be seamlessly extended to other composite material and hybrid systems. It is envisaged that the proposed methodology will provide a powerful numerical tool suitable for replacing current methods which rely on assigning pre-defined delamination surfaces prior to the analysis.

6.0 Management

The project has been defined over a three-month period.

6.1 Risks

A risk register will be generated at the start of the programme and will be maintained and reviewed during progress reviews.

Initial risks are listed in the following table:

Risk description	Risk mitigation
1. The experimental and modelling tasks may not be efficiently aligned within the timeframe constraints, thereby delaying milestone delivery.	Early model developments may be based on approximated data, and supplemented when calibrated data is available. Also, we will make effective use of legacy knowledge and background literature.
2. The models developed do not capture all the features observed during the modelling of a protective armour system, thus reducing the veracity of the results.	Ensure that characteristics of actual threats are understood early in the project in order to confirm that the experiments will model the observed physics.

6.2 Exclusions

- Scope of the work and level of effort in the tasks will be commensurate with the allocated budgets.

- Access to background information from other related projects will be limited by existing IPR, commercial and/or confidentiality restrictions.

6.3 Quality Assurance

The ISO/IEC 12207 procedure will be adopted for creating and maintaining the software routines developed on the project.

6.4 Points of contact

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7.0 References

Belytchko, T., & Black, T. (1999). Elastic crack growth in finite elements with minimal remeshing. *International journal for numerical methods in engineering, 45*, 601-620.

Chen, B., Pinho, S., De Carvalho, N., Baiz, P., & Tay, T. (2014). A floating node method for the modelling of discontinuities in composites. *Engineering Fracture Mechanics, 127*, 104-134.

Guiamatsia, I., Ankersen, J., Iannucci, L., & Fouinneteau, M. (2013). Enriched finite elements for the efficient prediction of impact-induced damage in composite laminates. *Composite Science and Technology, 79*, 87-96.

Hansbo, A., & Hansbo, P. (2004). A finite element method for the simulation of strong and weak discontinuities in solid mechanics. *Compter methods in applied mechanics and engineering, 193*, 3523-3540.

Iannucci, L., Del Rosso, S., Curtis, P. T., Pope, D. J., & Duke, P. W. (2018). Understanding the thickness effect on the tensile strength property of Dyneema® HB26 laminates. *Materials, 11*. doi:10.3390/ma11081431

Kempesis, D. (2021). *Multi-scale Polymeric Composite Design for Ballistic Impact Protection.* PhD thesis, Imperial College London.

Kempesis, D., Iannucci, L., Del Rosso, S., Curtis, P., Pope, D., & Duke, P. (2021). A representative volume element model for ultra-high-molecular-weight-polyethylene composites. *Composite Structures, 262*, 113609.

Kempesis, D., Iannucci, L., Del Rosso, S., Curtis, P., Pope, D., & Duke, P. (2021). Ballistic impact numerical modelling of high-performance fibre composites. *Under submission*.

Kempesis, D., Iannucci, L., Del Rosso, S., Curtis, P., Pope, D., & Duke, P. (2021). High-performance polymeric laminate constitutive model for static and dynamic simulations. *Under submission*.

Kempesis, D., Iannucci, L., Ramesh, K. T., Del Rosso, S., Curtis, P., Pope, D., & Duke, P. (2021). Micromechanical analysis of Ultra High Molecular Weight Polyethylene composites using micrograph-based representative volume element models. *Under submission*.

Lässig, T., Nguyen, L., May, M., Riedel, W., Heisserer, U., van der Werff, H., & Hiermaier, S. (2015). A non-linear orthotropic hydrocode model for ultra-high molecular weight polyethylene in impact simulations. *International Journal of Impact Engineering, 75*, 110-122. doi:10.1016/j.ijimpeng.2014.07.004

Melenk, J., & Babuška, I. (1996). The partition of unity finite element method: Basic theory and applications. *Computer methods in applied mechanics and engineering, 139*, 289-314.

Nguyen, L., Lässig, T., S., R., Riedel, W., Mouritz, A., & Orifici, A. (2015). Numerical modelling of Ultra-High Molecular Weight Polyethylene Composite Under Impact Loading. *Procedia Engineering, 103*, 436-443.

Song, J.-H., Areias, P. M., & Belytchko, T. (2006). A method for dynamic crack and shear band propagation with phantom nodes. *International journal for numerical methods in engineering, 67*, 868-893.