Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 18. Improving survivability of protective structures through novel design and modelling

1. Summary of the impact (indicative maximum 100 words)

The vulnerability of both military and civilian infrastructure to the threat of terrorist activity has highlighted the need to improve its survivability, and this poses a significant design challenge to engineers. Research work at Imperial has led to the development of novel constitutive relationships for polymeric materials coupled to novel analysis procedures; software algorithms for effective simulations of blast and impact events; and enhanced experimental testing methods allowing a fundamental understanding of the structures. According to Dstl, this body of research has '*unquestionably improved the security and effectiveness of the UK armed forces operating in hostile environments abroad as well as the safety of citizens using metropolitan infrastructure within the UK'.* The techniques have been applied to vehicles and UK infrastructure, including for high profile events, such as the 2012 Olympics.

2. Underpinning research (indicative maximum 500 words)

Research projects funded by the EPSRC, European Union, TSB and MoD (Dstl) over the past ten years have contributed to the development of this research area. The overall aim of this research activity has been to develop sophisticated modelling techniques that are capable of simulating the complex phenomena associated with the deformation of polymeric armour materials under high velocity impact loadings [C, F]. The research has also contributed to the development of sophisticated meso-scale modelling methods for advanced materials and structures, which have been implemented into bespoke and (protected) commercially-available numerical simulation software [E,D,F]. The clearer insight into the dynamic response mechanisms of the current protective materials has also provided a strong foundation for the micro-scale design of significantly better systems in the near future [B], Figure 1 and 2.

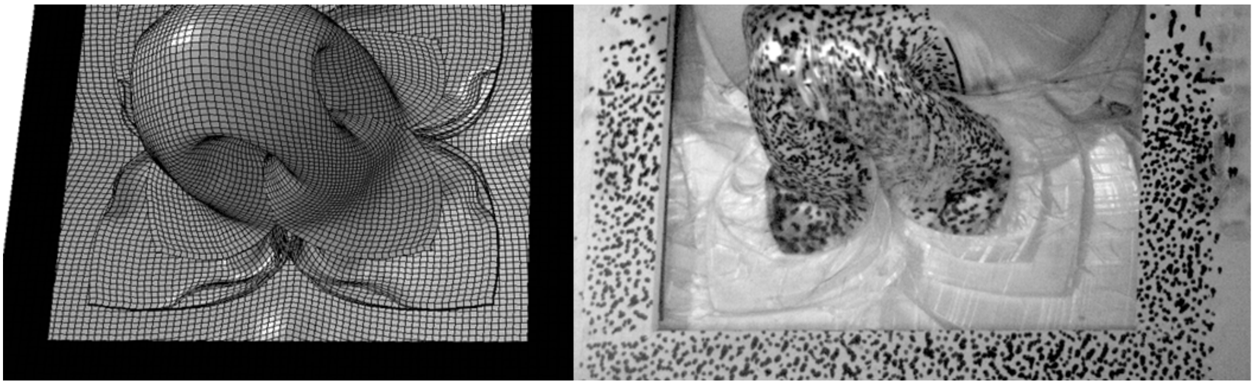

Figure 1: Ballistic impact into Dyneema armour panels at 1km/s with 60g copper projectile. Left: Improved numerical predictions; Right: Experimental test (from Figure 2 test).

The evolution of the modelling approaches for high performance composites can be divided into the development of delamination failure modelling and in-plane failure modelling techniques. Delamination failure modelling (using the cohesive element approach) was originally developed for implicit finite element codes within the Aeronautics Department by Professor Mike Crisfield [97-02] and later adopted for use in commercially available explicit finite element codes. In parallel with the original cohesive element approach a number of in-plane composite failure models were developed specifically for impact and blast and implemented into finite element codes [2, 3]. In recent years new advanced fracture-based failure models for in-plane failure were devised and these have been key in the development of new impact modelling approaches [3, 5]. In parallel with the modelling developments a number of novel testing and examination procedures [6] have been developed to understand the physical processes which occur during severe loadings and to measure key material parameters[1, A]. The resulting two- and three-dimensional numerical modelling of composite materials, validated with extensive experimental studies, has greatly improved the phenomenological understanding in this field and enabled a much more accurate response prediction of protective structures when exposed to blast and ballistic loading [5, B, F]. Most recently these modelling techniques have been applied to the development of techniques to improve the design of polymer armours and polymer composites [4, B] subject to severe loadings. This deeper understanding has also led to the development of fundamentally new armour concepts based on recycled and micro-braided materials [F].

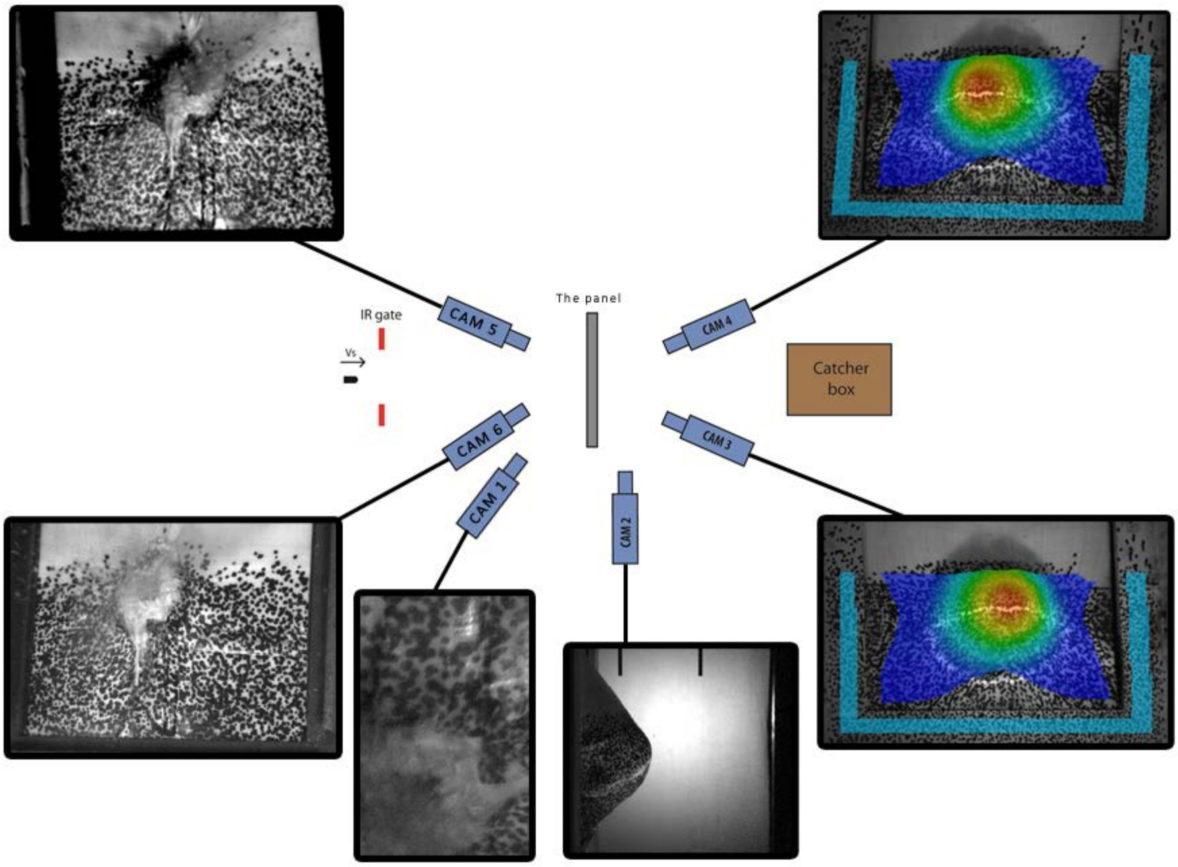

Figure 2: Enhanced ballistic testing of high performance composites

3. References to the research (indicative maximum of six references)
* References that best indicate quality of underpinning research.

*[1] S.T. Pinho, P. Robinson, L. Iannucci, “Fracture toughness of the tensile and compressive fibre failure modes in laminated composites”, Composites Science and Technology, Vol 66, pp. 2069-2079, (2006), DOI: 10.1016/j.compscitch.2005.12.023.
This original publication presents procedures to determine the intralaminar fracture toughness of composites which led to the successful award of the Dstl/EPSRC (C) project and has been incorporated into models used by Dstl for impact and blast and for AIRBUS vulnerability airframe design (F).

*[2] L. Iannucci, M.L. Willows, “An energy based damage mechanics approach to modelling impact onto woven composite materials - Part I: Numerical models”, Composites Part A – Applied Science and Manufacturing, Vol 37, pp. 2041-2056, (2006), DOI: 10.1016/j.compositesa.2005.12.013
The initial development work which led to the 3D constitutive model for high performance fibres. This was key background knowledge for the award of the Dstl/EPSRC (C) and MAAXIMUS (D) grants.

*[3] M.V. Donadon, L. Iannucci, B.G. Falzon, J.M. Hodgkinson, S.F.M. de Almeida, “A progressive failure model for composite laminates subjected to low velocity impact damage”,

Computers & Structures, Vol 86, pp. 1232–1252, (2008), DOI: 10.1016/j.compstruc.2007.11.004
The paper provides an original implementation into ls-dyna of an impact constitutive model with mesh objectivity for composites. This approach was used to successfully win the CEC MAAXIMUS (D) and the DTI IPSoFACTo (E) projects. The approach has also been used to support AIRBUS on their vulnerability studies, AIRBUS projects (F).

[4] L. Iannucci, D. Pope, "High velocity impact and armour design", eXPRESS Polymer Letters, Vol 5, No 3, pp. 262–272, (2011), DOI: 10.3144/expresspolymlett.2011.26
The original approach in this paper resulted in the award of the RAEng/Dstl chair (B) on multiscale armour design, and provided an outline procedure to develop the 3D modelling approaches (F).

[5] L. Raimondo, L. Iannucci, P. Robinson, P.T. Curtis, "Modelling of strain rate effects on matrix dominated elastic and failure properties of unidirectional fibre-reinforced polymer-matrix composites", Composites Science and Technology, Vol 72, pp. 819-827, (2012), DOI: 10.1016/j.compscitech.2012.02.011
This paper presents a fundamental output of the TSB IPSoFACTo (E) and Dstl/EPSRC (C) grants on impact, and has led to a new US-UK government collaboration on high velocity impacts, via grants (A) and (B).

[6] E.S. Greenhalgh, V.M. Bloodworth, L. Iannucci, D. Pope, "Fractographic observations on Dyneema® composites under ballistic impact", Composites Part A: Applied Science and Manufacturing, Vol 44, pp. 51-62, (2013), DOI: 10.1016/j.compositesa.2012.08.012
This paper presented a detailed examination of a polymer armour panel. This led to the award of the MAST polymeric armour project (March 13, £480k) and the multiscale polymer design grant (B). The insight also allowed the successful award of Dstl PhD CASE award (F) and CDE award (F) on novel recycled approaches to armour.

3.1 Grants supporting the research

[A] Dstl, **Development of improved of improved modelling and materials for protective/armour systems**, 24 months, July 2012, **£200k**, L Iannucci(PI).

[B] RAEng/Dstl, **Chair: Multiscale Armour Design**, 60 months, April 2011, **£455k**, L Iannucci(PI).

[C] EPSRC/Dstl, **Development of improved of improved modelling and materials for protective/armour systems**, 36 months, Oct 2009, **£1275k**, L Iannucci(PI), L Louca, P Robinson.

[D] CEC, **MAAXIMUS: more affordable aircraft through extended integrated and mature numerical sizing**, 36 months, Nov. 2008, **£230k**, L Iannucci(PI).

[E] DTI/TSB, **IPSoFACTo, Shock and impact for hostile environments**, 36 months, April 2006, **£336k**, L Iannucci(PI), P Robinson.

[F] Approximately **£800k** of further funding via projects from Dstl, EPSRC, AIRBUS, and EU.

4. Details of the impact (indicative maximum 750 words)

Improving the survivability of vital infrastructure is vitally important to the development of military technology, and, due to the increased threat of terrorist activity, to civilian installations. Research at Imperial between 1993-2013 led to a major advance in the ability to virtually design a range of protective components, which are often very expensive or impractical to test, and provided improved performance and significant cost savings to the UK between 2008 and 2013. New blast, impact and ballistic modelling techniques developed at Imperial were applied in the military sector to investigate improved materials and designs for protective components. As a result Dstl has been able to develop lighter, more effective armour for both military vehicles and the dismounted soldier, providing personnel with better protection and superior operational performance. These improvements were achieved with significant cost savings and, more importantly, have ultimately contributed to the saving of many lives during expeditionary operations. Within the UK MOD the development and procurement of military vehicles represents a significant portion of the annual defence budget. A typical development cost for a single vehicle is £500M. A critical part of this process is to ensure that the occupants of the vehicles are properly protected against potential explosive and penetrative threats present in the current theatres of operation. While initial financial outlay for the protection of a vehicle would typically amount to £10M, the total cost for protection development over the lifetime of each vehicle will be significantly higher due to the need for system retrofitting as new threats or operational requirements emerge. [a]

The research findings have also been used to address the emerging and increasingly severe threat of terrorist activity, which has highlighted the vulnerability of vital infrastructure. Testing undertaken at Imperial to characterise the structural components of civilian aircraft has enabled Government scientists to better simulate the failure mechanisms associated with internal explosive detonations, and therefore identify and mitigate potentially critical terrorist scenarios. This capability has been used to assess the explosive performance of a wide range civil aircraft structures manufactured by Airbus and Boeing. Quick-running algorithms developed by Imperial to predict blast effects for operational analysis have been integrated within the Government-developed HIP (Human Injury Prediction) code. This is now being used by security analysts both within the UK and in friendly nations abroad to implement appropriate security measures within transport infrastructure and high-profile public events (such as the London Olympics[a]).

Dstl has summarised the benefits of this research activity as follows:

> '*The Department of Aeronautical Engineering at Imperial College London have provided key expertise to Dstl in the field of physical protection for many years. Although it is difficult to place a financial value on these state of the art, technical advancements, their contributions have unquestionably improved the security and effectiveness of the UK armed forces operating in hostile environments abroad as well as the safety of citizens using metropolitan infrastructure within the UK.*'

The resulting improvement in model fidelity has led to a vast reduction in the number of expensive tests required to confirm the veracity of a particular amour variant. A typical purely experimental trial to assess an armour design against one of the many potential threats costs over £100K. Conservative estimates indicate that the cost of undertaking the same design exercise but replacing all but the key experiments with numerical simulation are one third of this amount.

5. Sources to corroborate the impact (indicative maximum of 10 references.)

[a] Capability leader, Structural Dynamics, Dstl Porton Down, Physical Protection Group & Material and Structures Group. *(for corroboration of the Dstl statements regarding the impact of this research)*