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# Quasi-static and impact perforation of polymer-metal bi-layer plates by a blunt indenter

I. Mohagheghian[a,b], G.J. McShane[b,*], W.J. Stronge[b]

[a] Department of Mechanical Engineering Sciences, University of Surrey, Guildford GU2 7XH, UK
[b] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

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ABSTRACT

The use of polymer layers to alter the impact response of metallic plates has emerged recently as an effective and economical means to enhance perforation resistance. However, the function of the polymer in such laminate systems remains unclear. In this investigation we aim to identify, through systematic experiments, the influence of a polymer layer on the perforation mechanisms and energy absorption of laminated plates. In particular, we consider the combination of a polymer with a thin metallic plate in a bi-layer configuration, subjected to either quasi-static or impact loading by a blunt indenter. Bi-layers are investigated which comprise an aluminium alloy layer (6082-T6) and a polyethylene layer (LDPE, HDPE and UHMWPE). It is found that the energy required to perforate the bi-layer plate can significantly exceed that of the bare metallic substrate (showing the potential for polymer coatings as an effective retro-fit solution) when the polymer is on the impacted face. Furthermore, bi-layer configurations are also shown to outperform the equivalent mass of monolithic metal if the correct thickness ratio of polymer and metal is selected. The effectiveness of a polymer layer in enhancing perforation energy is connected to its large ductility, allowing extensive deformation of the polymer under the indenter, which in turn suppresses plugging and diffuses plastic deformation in the metal layer. In this way the energy absorbed by the metal layer can be maximised. The thickness of the polymer layer is found to be a crucial parameter in maximising the effectiveness of the bi-layer target. An optimum polymer thickness is observed which maximises energy absorption per unit mass of bi-layer target (for a fixed substrate thickness). The synergy between metal and polymer layers also depends on the polymer type and the rate of loading. A polymer with high strain hardening performs best under impact conditions. However, under quasi-static loading, the bi-layer performance is less sensitive to the yield strength and strain hardening of the polymer.

## 1. Introduction

Enhancing the impact perforation resistance of materials at minimum weight is of value in applications such as lightweight vehicle construction and materials for security and defence. Layered materials, of either similar or dissimilar properties, have been investigated as a more effective alternative to monolithic plates of the same mass. Recently, attention has been given to the use of polymer layers to enhance the impact resistance of metallic plates. This has practical advantages: elastomers such as polyurea can be easily and economically applied to a wide variety of surfaces as a retro-fit coating. Initial results indicate promising performance for polymer-metal layered structures [1,2]. However, the mechanisms responsible for enhancing the performance are not clearly understood. In this investigation, we aim to study systematically the influence of a polymer layer on the quasi-static and impact perforation of thin metallic plates, with targets having a total areal density up to about 10 $\mathrm{kg\,m^{-2}}$. This range of target mass has practical significance for understanding the protection of lightweight and thin-walled structural components, either from a retro-fit perspective (i.e. adding the polymer for reinforcement) or for impact resilient design. Furthermore, we focus on indenters and projectiles with a blunt nose-shape (i.e. flat-nosed circular cylinders). This is an idealised geometry, but provides useful insights into the target response to sharp-edged projectiles such as those generated by the fragmentation of an explosive device. We first briefly review previous work on the impact perforation of laminates, including polymer-metal laminates.

### 1.1. Impact response of metallic laminates

Layering of metallic plates has been investigated as a strategy for enhancing impact perforation resistance. However, a consensus has not been reached about the effectiveness of layering for single-material

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[*] Corresponding author.
*E-mail address:* gjm31@cam.ac.uk (G.J. McShane).

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systems. The approach has its basis in the observation that when a thick metallic plate is struck by a projectile the deformation will be highly localised (at the projectile perimeter in the case of blunt projectile), whereas a thinner plate (and therefore a stack of thinner plates for heavier structures) achieves a contribution to energy absorption through extensive tensile stretching [3]. Some studies indicate that a monolithic plate is superior to the equivalent mass layered system [4–6], while contrary results have also been reported [7–9]. It appears that the effectiveness of layering depends on many parameters such as nose shape of the projectile [8,9], the number of layers [10], the ratio of the thicknesses of the layers [5,11,12] and the total thickness of the target [11,13,14]. Recently, it has been shown that using materials with dissimilar properties in metallic laminates can provide enhanced impact energy absorption. In a numerical investigation, Teng et al. [15] show that for low velocity impacts by blunt or conical projectiles, bi-layer metallic laminates absorb more energy than monolithic plates of the same mass if a more ductile metal is used in front (the impacted layer) with a higher strength, lower ductility metal behind. Flores-Johnson et al. [16] also show that using dissimilar materials in different layers in a metallic laminate can be superior to a single material configuration with the same mass. Their results suggest that a thin aluminium plate backed by a thick steel plate can deliver the best energy absorption. In a theoretical analysis of penetration of a layered target by a rigid projectile, Ben-Dor et al. [17,18] suggest that the ballistic limit is greatest if the plates are arranged with those having the smallest ratio of strength to density placed in front (i.e. nearest the impact surface). While these investigations reveal the potential benefits of combining layers with contrasting mechanical properties, the impact response of polymers differs greatly from that of metals, and so they do not provide a complete insight into the performance of polymer layers for impact mitigation.

### 1.2. Impact response of polymer-metal laminates

An early investigation into polymer-metal laminates was conducted by Radin and Goldsmith [4], comparing the combination of polycarbonate and aluminium alloy (2024-O) plates with equal mass monolithic metal and polymer plates under projectile impact. Although the response of monolithic aluminium and polycarbonate plates were investigated for both blunt and conical nose projectiles, all of the tests performed on the bi-layer configuration were with the conical projectile. Their results indicated that for the same mass per unit area, a bi-layer with the metal layer facing the conical projectile had a ballistic limit above that of monolithic metal, but below that of monolithic polycarbonate. The polycarbonate layer appeared to alter the failure mode in the metal layer when these materials were combined in a laminate configuration. Low-velocity drop-weight impact tests were conducted by Liu and Liaw [19] on PMMA-aluminium bi-layers with an epoxy adhesive interface. In contrast to [4], their experiments showed that the impact damage (including delamination, and fracture of the polymer) is more severe when the aluminium plate is located on the impacted face. The impact response of an elastomer-steel laminate was investigated by Roland et al. [2]. They considered a variety of elastomers backed by thick High Hard Steel (HHS) plates, and concluded that the glass transition of the polymer is a key parameter. They argue that the greatest improvement in the ballistic limit is achieved for polymers that undergo an impact-induced glass transition, due to the increase in viscoelastic dissipation associated with the transition from rubbery to glassy behaviour. However, the results show a modest (~10%) variation in performance for a wide range of glass transition temperatures, and so, as pointed out by these authors, there are likely to be other significant parameters. Indeed, the importance of polymer layer thickness also emerges from this study: a thin polymer coating can produce a significant increase in energy absorption, yet further increases in thickness have only a small effect. Roland et al. [2] also investigated the effect of the attachment method between the steel and the polyuria on the ballistic perforation. Two methods were considered: i) attachment using mechanical fasteners (i.e. screws) and ii) attachment using adhesives. No measurable difference in the ballistic limit was observed between the two methods. The role of polymer thicknesses was investigated further by Roland et al. [20], impacting polyurea coated metallic plates with a fragment simulating projectile. Again, energy absorption appears more sensitive to the polymer thickness than the chosen polymer type. It is further shown that it is preferable to position the polymer on the impacted face. Xue et al. [21] conducted a series of numerical calculations on steel plates backed by a polyurea coating impacted by blunt and conical projectiles. The simulations were compared with the experimental results of Mock et al. [1]. It was found that a polyurea backing is more effective for the conical projectile than the blunt projectile. They suggest that, for conical projectiles, the energy absorption in the metal layer is increased due to the polymer retarding the onset of fracture in the steel plate. However, for the blunt projectile, the polyurea backing decreases the energy absorbed by the steel layer, with an overall increase in energy absorption accounted for by stretching of the polyurea.

Polymer layers used in conjunction with a metallic substrate therefore appear to show promise for enhancing perforation resistance. However, the precise function of the polymer layer in altering the dissipation of energy during the impact, and hence the optimal choice of polymer type and thickness for a particular metallic substrate and impact threat, remains unclear. The goal of the current investigation is to address these issues for one impact scenario: the impact of thin metallic plates by a non-deforming blunt projectile. We support the impact results with quasi-static puncture experiments to gain clearer insights into the mechanisms of energy dissipation and the effect of the polymer layer throughout the perforation process.

### 1.3. Outline of the current investigation

This paper focuses on bi-layer laminates with one metal and one polymer layer (in addition to monolithic plates of either material for comparison). This laminate is particularly relevant to inform the design of retro-fit polymer coatings that aim to mitigate impact damage. By understanding the interactions between the two layers and the mechanisms of energy absorption, we gain insights into optimisation of the laminate for perforation resistance. To ensure controllable, repeatable layer properties and thicknesses, we opt for aluminium alloy 6082 for the metallic layer and extruded polyethylene sheets of various types for the polymer layer (providing a variety of mechanical properties, while maintaining other parameters, such as polymer density and glass transition temperature, approximately constant). In this study, no adhesive is used between the polymer and metal layers. We acknowledge that at an adhesive may be necessary in practice, e.g. for large-scale application of polymer coatings. However, in the current investigation we opt for a simplified arrangement, with the layers in frictional contact only. As will be discussed subsequently, the key deformation mechanisms that we identify are not expected to be sensitive to the interface bonding conditions. This is also consistent with the findings of Roland et al. [2], that the regimes of response under consideration are largely independent of interface strength. Removing this additional variable allows the number of experimental parameters in this investigation to be better controlled.

The paper is structured as follows. The quasi-static perforation behaviour is first investigated, gaining insight into the stages of deformation and failure in the absence of significant inertia and strain-rate effects (Section 2). This research indicates that a polymer layer placed between the indenter and the metallic layer can enhance energy absorption, not directly through dissipation within the polymer itself, but indirectly, by altering the mode of failure, and hence plastic dissipation, in the metal layer. This is pursued further in Section 3 by determining how this effect varies as the polymer layer thickness is changed. This study shows clearly that the function of the polymer in