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The effect of the interlayer on the ballistic performance of ceramic/composite armors: Experimental and numerical study

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The effect of rubber, Teflon and aluminum foam interlayer material on the ballistic performance of composite armor was investigated both experimentally and numerically. Although, rubber interlayer did not cause any significant delay in the initial stress build-up in the composite layer, Teflon and aluminum foam interlayer caused a significant delay and reduction in the magnitude of the stress transmitted to the composite backing plate. Damage in the ceramic layer was found to be highly localized around the projectile impact zone for the configuration without interlayer and rubber interlayer while aluminum foam and Teflon interlayer spread the damage zone in the radial direction. Relatively large pieces of the ceramic around the impact axis in the rubber interlayer configuration were observed while the ceramic layer was efficiently fragmented in aluminum foam and Teflon interlayer configuration.

1. Introduction

Armor systems have been conventionally monolithic, typically composing of a high strength steel plate [1–4]. However, there is an increasing demand for the materials and multilayer material systems providing maximum ballistic protection at a minimum weight. Over the years, ceramics and polymer matrix composites have been increasingly incorporated into armor protection systems [5–13]. The composite armor, which is also known as multilayered armor system, is composed of a hard strike face made of ceramic tiles and a fiber reinforced composite backing plate. The main function of the front ceramic layer is to mitigate the local pressure imposed to the backing composite plate, by deforming and eroding the projectile. The composite backing plate absorbs part of the kinetic energy of the projectile. Metallic plates have also been investigated for the backing plate in multilayered armor systems [14–19].

When a projectile hits the ceramic layer at a relatively high velocity, a compressive stress wave is generated, propagating from the projectile hit/impact zone in the impact direction. Once this compressive wave reaches the back face of the ceramic layer, it is partially reflected back as tensile wave, causing the damage of the ceramic layer. Several studies have investigated the stress wave propagation in the composite armor both analytically and numerically [20–23]. The acoustic impedance mismatch between the ceramic and composite layer is known to play a key role in the ballistic performance of the armor system. In addition, the insertion of an interlayer between these two layers significantly alters the wave propagation characteristics and consequently the ballistic performance of the armor system. The effects of rubber interlayer and through-thickness wave propagation in an integrated composite armor system were previously studied [24,25]. It was reported that the rubber interlayer ensured a good resilient bond between the ceramic and composite and also enhanced the multi-hit capability of the armor system. The composite armor with an aluminum foam interlayer was shown to produce more extensive ceramic fragmentation and less volumetric delamination of the composite plate [26]. The effect of adhesive interlayer thickness on the ballistic efficiency of alumina/aluminum armor system was investigated both numerically and experimentally [16,27,28]. It was shown that the thicker layer of adhesive resulted in a wider plastic deformation area of the metallic backing plate and earlier shattering of the ceramic layer. The effects of wave speed, layer geometry and the mechanical properties of the layers on the load distribution between the layers were also investigated numerically [29,30]. It was reported that a single, thick, high strength and high wave speed layer for a fixed layer thickness provided the best lateral load spreading.

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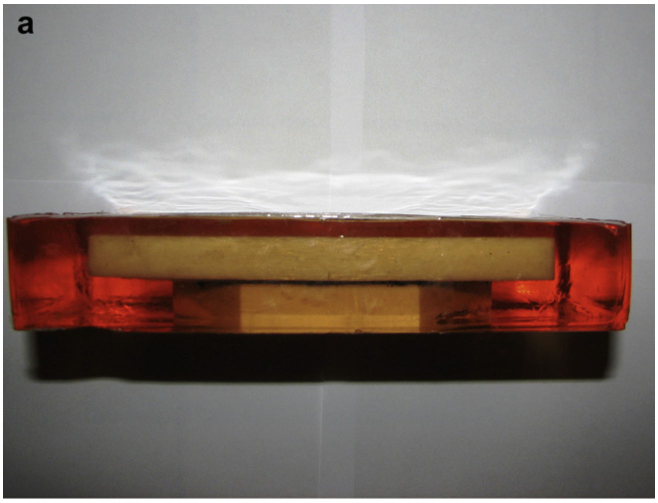

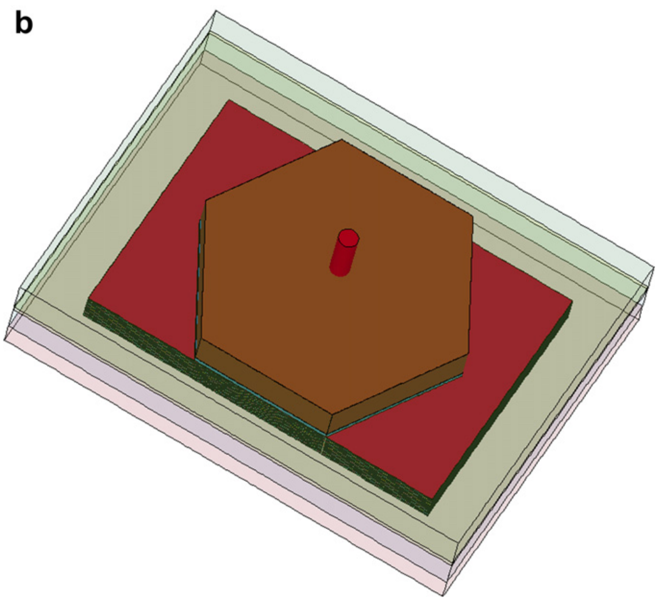

Fig. 1. (a) mounted ceramic/composite armor target and (b) finite element model of the projectile and target.

As the multilayered armor systems are becoming increasingly complex, the analysis of the wave propagation between the layers requires both modeling and experimental efforts. Previous studies have provided the first precise theoretical and experimental insights into the details of the stress wave propagation in these materials [31–33]. The Split Hopkinson Pressure Bar (SHPB) was used as a probe for generating entry and exit of the stress waves of known characteristics. These known, measured, entry and exit waves were then reproduced in a finite element model of the multilayer material. It was confirmed that when the model data matched the output data from the bars, the model was accurately describing the stress-state within the multilayer material including single, double and triple layered materials. These studies were mainly focused on the simulations the initial few microseconds; however, during the course of ballistic impact, several different deformation and failure mechanisms involved, making the full penetration analysis of multilayer armor inevitable. Previous studies published on the penetration analysis of the armor systems are also noted to be limited to plates without an interlayer. The primary aim of the present work was to develop 3D finite elements models of armor systems with different interlayer materials in order to demonstrate the effect of interlayer material on the stress wave propagation in multilayer composite armor systems.

Table 1
Johnson–Cook material model parameters for hard steel core [34].

ρ (g/cm^3)	G (GPa)	A (MPa)	B (MPa)	n	m
7.83	81.8	1000	510	0.26	1.03
T_m (K)	T_r (K)	C	C_p (J kg K)	ε_f	$\dot{\varepsilon}_0$ (s)
1793	298	0.014	477	0.8	1.0

Table 2
Johnson–Holmquist material model parameters for ceramic layer [38].

Parameter	Description	Value
ρ_0	Density	3.89 g/cm^3
G	Shear modulus	123 GPa
HEL	Hugoniot elastic limit	8.00 GPa
A	Intact strength constant	0.949
N	Intact strength constant	0.2
C	Strain rate constant	0.007
B	Fracture strength constant	0.1
M	Fracture strength constant	0.2
SFMAX	Max strength of failed mat'l/HEL stress	1.0
T	Tensile strength	0.262 GPa
K1	Pressure (EOS) constant	186 GPa
K2	Pressure (EOS) constant	0
K3	Pressure (EOS) constant	0
BULK	Bulking constant	1.0
D1	Damage constant	0.001
D2	Damage constant	1.0

2. Experimental

The ballistic tests were carried out using 7.62 × 51 mm M61 type AP projectiles in a ballistic laboratory. Ballistic tests were performed on the targets composed of alumina tiles bonded to a composite plate with and without an interlayer (Fig. 1a). The armor plate was composed of a hexagonal Alumina ceramic tile ('CoorsTek' AD-995), 101.6 mm wide and 14.1 mm thick and a 22 layers of plain weave S2-glass fabric (areal density 0.81 kg/m^2), having a [0/90] lay-up orientation (i.e. the fabric warp direction is at 0° and the weft direction is at 90°), backing plate of 10.0 mm thick. EPDM rubber (Shore A 60), Teflon and aluminum foam were inserted between ceramic and composite layer. The thicknesses of EPDM rubber, Teflon and aluminum foam were sequentially 1.5, 2 and 18 mm. The targets were initially mounted into a polyester resin in a rectangular glass mold. The thickness of polyester layer at the back surface of armor system was around 10 mm and each polyester-mounted target was bonded to a 20 mm thick steel plate with dimensions of 500 × 500 mm^2 and this steel plate was firmly clamped to the testing frame and adjusted to the desired point of impact. This secured a fixed boundary at the back surface of the target. All the multilayered armor plates were impacted at 0° angle of attack with 7.62 mm AP NATO round using a gun mounted on a rigid mount with holding devices. The gun was properly aligned before each test. The velocities of impact were measured as 800 ± 10 m/s. The projectile was fired from a distance of 15 m. Four different configurations were tested; without an interlayer and with an interlayer of EPDM rubber, Teflon (Polarchip[1]) and aluminum metallic foam with a density of 0.438 g/cm^3. After the test the fracture pattern of the ceramic layer and the damage generated in the composite plate were investigated. During ballistic testing only partial penetration of the targets was observed. The tested armor plates were cut transversely using a low speed

[1] Polarchip™ is a trademark of W.L. Gore, Inc.