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Analytical and numerical investigation of polyurea layered aluminium plates subjected to high velocity projectile impact

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ABSTRACT

This paper discusses on the penetration of high velocity projectiles through aluminium–polyurea composite layered plate systems. An analytical model has been proposed to predict the residual velocity of aluminium–polyurea composite plates, and validated with both experimental and numerical investigations. Full metal jacket (FMJ) projectiles (5.56 mm × 45 mm), corresponding to NATO standard SS109, were fired at the aluminium–polyurea composite layered plate systems from a distance of 10.0 m at a fixed velocity of 945 m/s. Four different composite plate configurations were used with thicknesses varying from 16 to 34 mm. Each configuration consisted of six specimens. Residual velocities for each individual test were recorded. Numerical simulations of the penetration process have been performed using advanced finite element code LS-DYNA®. The well-established Johnson–Cook and Mooney–Rivlin material models were used to represent the stress–strain behaviour of aluminium and polyurea in the numerical analysis. The analytical and numerical models provided good approximations for the residual velocities measured during the experimental tests. Polyurea layers contributed positively towards the reduction of residual velocity of the projectile in composite plate systems. In addition, ballistic limit curves for different composite systems have been established based on the validated models. As the results showed that polyurea contributes positively towards the reduction of residual velocity of projectiles, the findings of this study can be effectively used for the similar applications in future armour industry.

1. Introduction

For many decades, researchers have been focused on utilising high strength metallic alloys to combat the ballistic threats by increasing the strength of the materials. However, over the last few years, research interest has been tilted towards the investigation of light-weight materials, which can be used for blast and ballistic protective structures. Different composite and layered plate arrangements have been the focal point of such investigations. Different types of fabrics and elastomers have been researched as partial substitutes for the traditionally used metallic alloys.

Polyurea is considered as a candidate material for such applications. Due to its ability to absorb a considerable amount of energy before failure, polyurea has been investigated as a protective coating or as an interlayer material for structural and composite systems under dynamic loading induced by blast, ballistic and other impact events. In the event of blast, the loading induced by the source would be a distributed load with a high pressure wave front. In such instances, targets undergo severe deformation under the dispersed loading. However, the mechanism is quite different in the analysis of ballistic load. The loads transferred to the target by the projectiles are mainly concentrated loads, which cause localised failure instead of global deformations. Materials near the impact zone undergo severe deformations, which cause the materials to fail in shear, tension or compression. As such, projectile penetration is a unique process when compared with other types of dynamic loadings. A considerable amount of previous research work has been performed on the investigation of polyurea coated structural elements under blast loads [1–8]. On the other hand, research work investigating and describing the behaviour of polyurea coated plates under to ballistic threats tends to be limited.

Xue et al. [9] researched on polyurea coated DH-36 steel plates under projectile impact and observed the positive contribution of the polyurea coating in reducing the residual velocity of the projectile when the coatings were applied at the back face of the plates. Sayed et al. [10] investigated the use of polyurea coatings to

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retrofit high strength steel plates against a 145 g steel projectile travelling at a velocity of 280 m/s. The deformation profiles obtained from the numerical investigation were in good agreement with the experimental findings [10]. Ballistic tests on polyurea–high hardness steel (HHS) composites with a 0.5 calibre fragment simulating the projectile has been reported by Roland et al. [11]. Both the glassy transition properties and the effect of multiple layers on the residual velocities of the projectile have been addressed in this study. Significant work on nano-enhanced polyurea to mitigate ballistic threats has been reported by Al-Ostaz et al. [12] and Fowler [13]. On the other hand, the behaviour of bilayer steel–polyurea plates under impulsive loads have been studied by Amini et al. [14,15]. Both numerical and experimental investigations were performed on polyurea coated DH-36 steel plates to observe the transient response of the plates under impulsive pressure loads. Similar work has also been reported by Nemat-Nasser [16].

It should be noted that most of these work focussed on the ballistic response of large diameter projectiles than actual projectiles used in the battle field. Considering this limitation, it is therefore vital to investigate the behaviour of polyurea coated plates under the impact of real ammunitions. As ballistic load involves comparatively complex analysis, one cannot totally rely on analytical tools in the investigation of ballistic loads. With the advancement of computing technology and finite element codes over the last few decades, the numerical simulation technique is becoming a comparatively effective process to develop models in order to analyse the complete penetration process under projectile impact. Computer codes, such as LS-DYNA® [17] and ANSYS® [18], create comparatively user-friendly platforms to build the numerical models, which can be repetitively used to simulate the penetration process on different structures with different materials. A considerable amount of work has been undertaken in this area, especially for rigid projectiles penetrating through monolithic plate structures. Børvik et al. [19] reported the behaviour of five different steel alloys under the impact of an armour-piercing (AP) projectile and detailed analysis using numerical simulations was performed and reported. Adams [20] undertook a comprehensive numerical and experimental analysis of projectile penetration through metallic alloy plates, while Dey et al. [21] numerically analysed the effect of fracture criteria for projectile impact on steel targets.

In comparison to monolithic plates, comparatively less focus has been paid to investigate the ballistic effect of laminated or layered plate structures. Jackson and Shukla [22] have researched on the performance of sandwich composite plates subjected to sequential impact and air blast loading. Even though this study has been focused on the behaviour of pre-impacted composites plates subjected to blast loading, it also highlights the effectiveness and possibility of using multilayered (foam core with face sheet) composite system against projectile penetration. Børvik et al. [19] and Dey et al. [23] analysed the behaviour of layered high strength armour steel plates through both experimental and numerical investigation. Flores-Johnson et al. [24] reported a comprehensive numerical study on the penetration process of APM2 projectiles through layered metallic alloys. Weldox 700E and Al 7075-T651 plates were modelled in contact as double and triple layers, and were simulated under penetration by the projectiles [23].

Numerical simulations of ballistic penetration through soft elastomer coated plates, such as polyurea, are not well-established yet. Numerical investigations of polyurea coated plates subjected to ballistic impacts have been reported by Amini et al. [15], by extending the investigations reported in [14] to numerically analyse the response of monolithic and bilayer plates under impulsive loads. Sayed et al. [10] used the smooth particle hydrodynamics (SPH) technique in LS-DYNA [17] to model the behaviour of polyurea coated plates. Xue et al. [9] used the Lagrangian technique to numerically simulate the penetration process of rigid projectiles through polyurea coated DH-36 plates. A comprehensive investigation on impact energy absorption capacity and the deformation-induced glass transitions of polyurea coated steel plates subjected to blunt nose projectiles has been investigated by Grujicic et al. [25]. Meanwhile, Tan [26] investigated the effect of debonding and pre-existing delamination towards the performance of the double layer composites. The advanced finite element code AUTODYN [18] was utilised to effectively predict the failure mechanism of SiC and Kevlar–epoxy double layer composites.

Due to the advancement of computer codes, a descending trend has been observed in the interest for utilising analytical tools in analysing such complex engineering problems. Analytical models can still be effectively used to pre-estimate parameters such as projectile residual velocity and ballistic limit. In addition, a validated analytical model can be used to compare the accuracy of the results predicted by numerical simulations. At the same time, an analytical model must be simple in its formation and should not contain a large number of parameters which would demand considerable amounts of experimental data. There are a few analytical models commonly used to predict the residual velocity of projectiles penetrating through plate structures. The Recht–Ipson [27] model is one of the commonly used models, where the relationship between incident, residual and ballistic limit velocities are established using two empirical constants, which can be defined by conducting penetrations at different velocities. Gupta and Madhu [28] have proposed a simple analytical model for layered plate systems. Residual velocity is expressed in terms of incident velocity and thickness of the plates. One unknown is involved in this equation, which can be derived by conducting penetration tests at a constant velocity.

Most modern protective structures are designed with laminated or layered materials rather than using monolithic materials. Therefore, several materials can be present in the laminated structural element and the volumetric density can vary along the cross-section. In addition, layered plate systems can have different materials with different thicknesses. Hence, both plate thickness and the density of the material in each layer, play a significant role in the penetration resistance process. As such, it is important to establish a relationship with the residual velocity of the projectile in terms of incident velocity, thickness of individual plates and densities of each material.

As highlighted above, penetration of real-scale projectiles (as used in battlefield guns) through polyurea coated plates is rarely investigated. Therefore, there is a knowledge gap in this area to understand the applicability of such composite systems to combat real life ballistic threats. This paper presents comprehensive experimental, numerical and analytical investigations on the process of full metal jacket (FMJ) projectiles penetrating through polyurea coated aluminium alloy (AA5083-H116) plates. A simple analytical model has been proposed to predict the residual velocity of projectiles penetrating through multilayered plate system based on the areal density of the composite plate systems. Numerical investigations have been performed to compute the residual velocities of four different configurations. The ballistic limit curve for each configuration has been established using both numerical and analytical models. All the results were validated using experimental findings.

2. Experimental setup and design requirements

Many norms and standards have been developed over the years to provide guidelines for the design of protective structures against ballistic threats. Fourteen international standards and norms have been summarised and presented in the Close Focus Research [29].