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Plastic deformation of polyurea coated composite aluminium plates subjected to low velocity impact

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ABSTRACT

The demand for protective measures for structures is on the rise due to the increasing possibility of structural damage due to threats such as natural disasters, collision of vehicles, and blast and ballistic impacts. Application of an elastomer as a composite material with other base materials such as aluminium, steel and concrete has been considered as one of the measures to mitigate such threats. However, very limited work has been conducted in this area, especially on the feasibility of polyurea (elastomer) as a composite material against low velocity impacts. The focus of this research is to investigate the behaviour of polyurea coated composite aluminium plates subjected to rigid blunt-nosed projectile impact. AA5083-H116 aluminium alloy plates with polyurea coatings of 6 mm and 12 mm thickness were investigated. A blunt cylindrical projectile of high strength steel travelling in the velocity range of 5–15 m/s impacted at the centre of the 300 mm × 300 mm square plates. A polyurea coating was used to absorb part of the impact energy and provide protection to the plates as an energy damping material through application on the impact side of the plates. In addition, uncoated aluminium plates of the same thickness were used in the test program. A gas gun mechanism was used to fire a 5 kg projectile, and laser displacement monitoring equipment was used to record the out-of-plane deformation history of the plate during the impact. The complete test setup has been modelled numerically using the advanced finite element (FE) code LS-DYNA. The models were validated with the experimental results. Deformation time histories obtained from both the experimental and numerical studies for the plates were used to compare the ability of polyurea to effectively mitigate the damage resulting from low velocity impact. The polyurea coated plates showed a considerable reduction in out-of-plane deformation when compared to the uncoated plates. These findings indicate that polyurea can be utilised as an efficient energy absorbing/damping material against low velocity impact damage.

1. Introduction

The application of composite structural systems has been a focal point of the modern design industry over the last few decades. With the emergence of materials such as polymers and engineered fabrics, interest in the application of such materials in structural systems has increased. Due to characteristics such as light weight, high elongation and high ductility, these materials have applications in a wide range of industries. In addition, these materials exhibit a proven capability of enhancing the stability of structures under both static and dynamic loadings. Impacts induced by different objects on structures are the type of dynamic load that many structures undergo during their lifespan. Therefore, it is important to understand the behaviour of such materials while undergoing varied loading arrangements, especially under impulsive loadings. This study investigates the behaviour of aluminium–polyurea (elastomer coated) composite plate systems subjected to low velocity impacts (5–15 m/s).

The behaviour of composite structural elements under different loadings is a complex phenomenon when compared with monolithic structural elements. Dynamic loading induced by an impact also involves complex analysis procedures to obtain reliable solutions. Further, if the system incorporates various materials in the composite arrangement, it makes the problem more complicated. Therefore, one needs to investigate the behaviour of layered composite structures carefully in order to evaluate the performance of such structural systems under impulsive loadings.

Aluminium alloys have been considered as one of the suitable materials to partially substitute structural steel in ballistic and marine applications. With advancements in the aluminium industry over the years, there is a possibility of producing comparatively higher strength alloys with considerably good ductility. The main advantage of using aluminium alloys as the base material of

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composite structures is its lower volumetric density compared to structural steel, which is commonly taken as 7850 kg/m^3 for steel versus 2700 kg/m^3 for aluminium alloys [1]. Therefore, the mass of the same volume of steel element is 2.5 times higher than the mass of aluminium. Besides, recent developments have indicated that aluminium manufacturers are capable of producing alloys with yield strengths in the range of 150–750 MPa. The aluminium alloy 5000–7000 series are good examples, as indicated by The Aluminum Association Incorporation [1]. Therefore, it shows characteristics for being a better substitute for structural steel when weight matters the most. With better alloying techniques, manufacturers are also able to increase the ductility of certain alloys so that these alloys are good for applications such as mitigating impacts. The anti-corrosive nature of aluminium alloys also improves the passivity of using them as structural materials, especially in naval and marine industries. Considering that there has been significant demand in the armour and defence industries towards researching light weight materials, there is a possibility of using light weight materials as composites with additional layers of harder materials such as concrete and steel, as well as in using light weight materials as an integral part in a composite system with softer materials, such as elastomeric polymers. This possibility of using aluminium–polymer composites to withstand for high velocity projectile impacts has been investigated by Mohotti et al. [2]. In a recent work, the authors investigated the behaviour of AA5083-H116 aluminium alloy under low velocity impact loads [2]. This paper extends the preceding investigation by investigating the behaviour of polyurea coated composite aluminium plates when subjected to low velocity impact loadings.

Among many elastomers, polyurea has been identified as a potential material to be used in combination with different structural materials to mitigate severe dynamic loadings. A comparatively large amount of work has been done on high and low strain rate behaviour of polyurea [3–8]. Many researchers have worked on its application on concrete and steel structures to mitigate blast and impact damages [9–15]. Recent investigations by Mohotti et al. [2] reported that polyurea is capable of reducing the damaging effect from armour projectiles on structural systems. In addition, the behaviour of polyurea composite plates subjected to high velocity impacts have also been investigated by Roland et al. [16], Xue et al. [17] and Al-Ostaz et al. [18]. Grujicic et al. [19] have reported on a comprehensive computational investigation of polyurea-AISI 4340 steel composite plates under the impact of a blunt, flat-nosed projectile. A computational and experimental investigation on polyurea coated high strength structural steel has been reported by Sayed et al. [20]. They used an impactor with a 145 g mass at a velocity of 280 m/s. Numerical modelling of polyurea coated laminated steel plates subjected to impulsive loadings have been investigated by Amini et al. [21,22] and Amini et al. [22]. They have reported the transient response of the polyurea–steel composite plates by focusing on the relative position of the polyurea with respect to the loading direction, thickness of polyurea layer, and bonding strength between the two materials. Nemat-Nasser [23] has also reported similar experimental results on polyurea coated steel plates. A comprehensive analysis of punch indentation of polyurea at different loading velocities have been reported by Shim and Mohr [24]. However, very limited work has been undertaken to investigate the feasibility of elastomer coatings on aluminium composites when subjected to low velocity impact damage.

In addition, literatures discussing the numerical simulation of low velocity impact behaviour on composite structural systems has also been limited and scattered. With the advanced material models available in modern advanced computational codes such as LS-DYNA [25], one can represent the true material behaviour of different materials in numerical simulations. One such model is the Johnson–Cook material model [26], which has been used extensively by researchers to represent the stress–strain behaviour of metallic alloys. Similarly, the Mooney–Rivlin model [27] has been used to represent the elastomeric behaviour of polymers under both quasi-static and dynamic loading conditions. One can use the validated models to compute the essential parameters, such as time history of energy absorption, deformation, and stress–strain development. Therefore, it is important to develop a reliable numerical technique to assist the demand from the design industry.

The objective of the present study is to investigate the out-of-plane deformation of polyurea coated aluminium composite plates subjected to low velocity impact loadings. Out-of-plane deformation has been measured and compared with the numerical results. A complete test setup has been modelled in finite element (FE) code LS-DYNA and validated using the experimental results. The validated models were subsequently used to predict permanent plastic deformation, deformation history, stress distribution and energy absorption of the composite plates. In addition, the energy absorption of polyurea coatings in different configurations have also been quantified and discussed.

2. Composite plate configurations and experimental setup

2.1. Plate configurations

Table 1 shows a schematic representation of the different plate configurations used in this study. Six different configurations consist of two different base plate thicknesses of AA5083-H116 aluminium plates (3 mm and 5 mm) combined with two different thicknesses of polyurea coatings (6 mm and 12 mm). The dimensions of the plates were 300 mm × 300 mm (square plates). Each test was conducted with a pre-estimated velocity as given in Table 1. Fig. 1 shows an example of two different plate configurations used in the test program.

2.2. Experimental setup

The study was performed using advanced laboratory facilities consisting of a gas gun mechanism-based projectile launching system. Due to the unavailability of relevant test standards, a customised experimental setup (Fig. 2) has been used to induce low velocity impacts on rectangular plates by following a similar approach to that used by Mohotti et al. [28]. A 300 mm × 300 mm × 40 mm (10 mm thickness) test frame made of high strength steel with a bolt assembly was used as the supporting fixture for the plates. No permanent deformations were observed in the frame after the tests. Therefore, the boundary conditions were assumed as fixed. All the dimensions of the plate are given in Fig. 2(c). A pressure-based projectile launching system was used to supply the initial energy to the projectile.

A 37 mm diameter cylindrical projectile manufactured of 4340 high tensile steel bar, having a flat impact surface was used in the tests. The approximate weight of the projectile was 5 kg. The velocity of the projectile was recorded just before the impact using a velocity meter with two laser screens. A laser Doppler sensor was attached to the safety protection frame used in the testing program (Figs. 3(b) and 2(c)). The line-of-sight of this instrument was aligned along the axis of motion of the projectile so that the readings for absolute deflection time histories of the specimens were recorded for the impact tests. A laser displacement meter was connected with an oscilloscope to record the time versus voltage history, which was later converted into time versus displacement history. Using a laser displacement recorder, the time history of the out-of-plane deformation of the plate centre was recorded. A