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The modelling of impact loading on thermoplastic fibre-metal laminates

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ABSTRACT

This work presents the findings of a study to investigate the modelling of impact loading on fibre-metal laminates based on an innovative self-reinforced thermoplastic composite reinforcement manufactured from polypropylene. A finite element model of the thermoplastic fibre metal laminate (TFML) has been developed using the LS-Dyna software package, with input from data collected following mechanical tests conducted over a wide range of strain-rates. Plates having different stacking sequences were modelled numerically under both low and high velocity impact loading, where the effect of varying stacking sequence and the thickness of the constituent material were investigated. An improved TFML configuration is proposed which, when impact energy absorption is considered, should outperform both commercial FMLs as well as monolithic aluminium alloys. It is believed that these environmentally-friendly thermoplastic-based materials offer potential for use in lightweight structures subjected to impact loading, such as aircraft leading edges and automotive body panels.

1. Introduction

Composite materials offer many advantages compared to conventional metals, such as a high specific strength and stiffness, as well as a superior fatigue resistance. In recent years interest has focused on developing hybrid materials based on thin layers of metal sheet and a fibre-reinforced composite [1,2]. These so called Fibre-Metal Laminates (or FMLs) [1,2] exhibit superior fatigue and fracture properties, characteristics that are associated with the composite plies, combined with enhanced ductility, due to the metal layers, Fig. 1. FMLs structures offer attractive properties under impact loading conditions, such as those associated with hail, ballistic impact and explosions. Such characteristics make FMLs attractive materials for use in aircraft parts, such as in doors, in the nose structure, in wings and empennage leading edges, as well as in wall structures in the cargo hold.

Vlot [3,4] highlighted the impressive performance of GLARE©, a commercial FML, following quasi-static and both low and high velocity impact testing. In Vlot's studies, the properties of GLARE were compared to aerospace grades of aluminium alloy (such as the 7075-T6 or 2024-T3 alloys) and also a carbon fibre/epoxy composite. Fleisher [5] tested lightweight luggage containers based on GLARE© and reported that they are capable of absorbing the energy associated with a bomb blast greater than that used in the 1988 Lockerbie air disaster.

Despite the excellent impact performance and fatigue strength of GLARE© (or similar thermosetting-matrix FMLs), there are drawbacks associated with their relatively long processing cycles and modest interlaminar fracture toughness characteristics [6]. In an attempt to overcome many of these issues, a range of thermoplastic matrix FMLs, termed TFMLs, were developed and tested [7–12]. Reyes and Cantwell [9] studied TFMLs based on a glass fibre reinforced PP composite, reporting significant increases in fracture toughness and impact resistance, as well as reductions in processing time, compared to more conventional thermosetting-based FMLs.

Abdullah et al. [7] studied the behaviour of TFMLs based on polypropylene (PP) fibre reinforcements under both low and high velocity impact conditions. Different configurations of TFML were studied and 4/3 TFMLs were found to outperform 2/1 and 3/2 configurations. Múgica et al. [13] compared the impact performance of aluminium alloy and magnesium alloy-based TFMLs under low velocity impact loading. The authors noted that the perforation threshold of the aluminium-based TFMLs was more than double that of the magnesium-based TFML. The blast response of TFMLs was investigated by Langdon et al. [6] and Lemanski et al. [14]. They identified the failure mechanisms in the wide range of laminates that they considered, as well as those in a plain aluminium alloy.

Laliberte et al. [15] developed a user-defined material subroutine in

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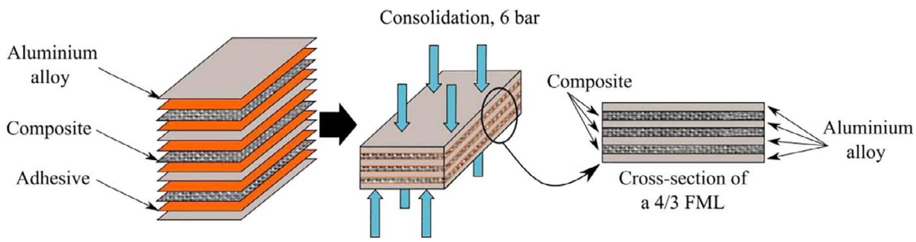

Fig. 1. Schematic construction of a 4/3 FML.

LS-Dyna to model the failure processes in GLARE. By using tiebreak interfaces and thick-shell elements, the model predicted the absorbed energy, the peak impact force and the size of the residual dent after impact testing. The low velocity impact response of FMLs plates was modelled numerically in ABAQUS/explicit by Fan et al. [16]. They developed predictions of the deformed cross-sections and compared them to similar images from the tested plates. Sadighi et al. [17] studied the low-velocity impact response of 5/4 GLARE using different modelling techniques in ABAQUS. They concluded that the element formulation is more important than the type of failure. Reasonably accurate predictions of the impact response were obtained using solid elements for both the metal and composite layers.

Karagiozova et al. [18] conducted a numerical study on glass fibre/PP-based FMLs that were manufactured and subjected to explosive loading in an earlier study by Langdon et al. [6]. The authors showed that by using solid elements for both the composite and metals layers in ABAQUS/Explicit, as well as adhesive elements for interface modelling, it was possible to successfully predict the experimentally-observed failure modes.

The present work aims to model the impact response of the TFMLs based on an innovative self-reinforced PP reported in an earlier study by Santiago et al. [19]. Here, different methods for numerically modelling TFMLs are explored using the LS-Dyna commercial software package, and the predictions are compared with experimental data. The impact behaviour of a 4/3 TFML is then studied in order to investigate the effect of varying the weight fraction of the constituent materials, the layer thickness as well as the stacking sequence. Finally, an improved TFML configuration is proposed, that should, in principle, offer a superior resistance to localised impact loading.

2. Materials and impact testing procedures

The thermoplastic fibre metal laminates (TFMLs) investigated in this study were based on a 4/3 configuration, i.e. four 0.4 mm thick 2024-T3 aluminium layers and three plies of a 0.3 mm thick self-reinforced polypropylene (SRRP), named as PURE and provided by Lankhorst Composite Bv, which presents promising performance for impact application [20]. The reinforcement was supplied in form of balanced plain-weave fabric made by co-extruded PP tapes. Each individual tape is 4 mm wide and 0.2 mm thick, manufactured by using different compositions of PP on the inner and outer regions of the filament. The inner PP has a high molecular orientation providing the mechanical resistance. The outer PP is designed to offer an increase in adhesion between the tapes. The manufacturing process melts the outer PP, providing the structural shape, whilst the inner PP is not affected by this process. The external PP layer represents a small fraction of the tape (approximately less than 5% by weight) and the tapes are not impregnated during the thermoforming process. Thus, the outer PP cannot be considered as a matrix, in the way that it is usually defined for thermoset composites [19]. The TFML panels were compression moulded at 135 °C under a pressure of 6 bar, Fig. 1. A 0.4 mm thick PP adhesive was placed at each of the TFML interfaces in order to enhance the level of bonding between the composite and metal plies. TFMLs based on 3/2 and 5/4 configurations were also manufactured using the procedure outlined above.

Low and high velocity impact tests were performed using a drop-weight machine and a gas-gun, respectively and these tests are described in detail in Ref. [19]. In both cases, 100 mm × 100 mm TFML panels were placed in a rigid circular ring, with an internal diameter of 80 mm and impacted at their centres. The low velocity impact tests were conducted at velocities between 2 m/s and 5 m/s, using a 4.65 kg impact mass with a 20 mm hemispherical indenter. High velocity impact tests were conducted using rigid steel spheres with a diameter of 20 mm diameter and a mass of 32 g. The projectiles were pneumatically launched at velocities between 70 m/s and 110 m/s. Laser velocity sensors, high frame-rate recording cameras and displacement gauges were used to monitor the tests.

The mechanical properties of the TFMLs and the materials on which they are based, were characterized from quasi-static (10^{-3}/s) up to elevated rates of strain (400/s) using both universal testing machines and a specially-designed rig that employs a dropped mass to generate high strain-rates. The Digital Image Correlation (DIC) technique was used to measure the strain field up to failure in the tensile specimens. These test techniques are described in detail in Ref. [19].

3. Modelling of the TFML panels

3.1. Theoretical modelling

In an earlier study, one of the authors explored the use of rigid-plastic models for modelling the low velocity impact response of FML panels [21]. Although the model was applied to predict the response of a similar FMLs, it is not applicable to the material here studied. However, this approach produced promising results when compared to available experimental data and it worth considering here. Therefore, a brief evaluation of this rigid-plastic model applied to TFMLs is presented in Appendix A, along with a discussion of its limitations and suggestions for further development.

3.2. Finite element model for low and high velocities impact loadings

Finite element models of the TFML panels were prepared using the LS-Dyna software package. The panels were 80 mm in diameter, with their external edges fully clamped. Impact loading was applied at the centre of the panel using a rigid 20 mm diameter hemispherical indenter. In each case, the concentrated mass and initial velocity of the projectile were selected to correspond to the impact event to be modelled. The 2024-T3 aluminium layers were modelled using solid elements, while solid and thick-shell elements were used for the SRPP layers. The metal/polymer interfaces were defined as being fully bonded (i.e. sharing nodes) and tied nodes (i.e. a tie-break condition). In order to identify an appropriate numerical modelling procedure for the TFMLs, three numerical models were defined by changing the SRPP elements and composite-metal interface and details are summarized in Table 1. The interfacial energy release rates, G_I and G_{II} that were used are given in Table 2.

An impact velocity of 50 m/s was applied in order to undertake a mesh sensitivity analysis, in which elements with edge lengths varying from 0.1 mm to 2.0 mm were considered. It was noted that elements with average edge lengths between 0.15 mm and 0.35 mm offered the