Experimental and numerical investigation of fibre-metal laminates during low-velocity impact loading

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Abstract Fibre-metal laminates(FMLs) that consists of three layers of 2024-T3 aluminium alloy sheets and two layers glass/epoxy composite were studied in this work. The specimens were designed and produced. Low-velocity impact tests were performed successfully on FMLs, using an instrumented falling weight machine. For comparison purposes, similar tests were set up and were carried out on monolithic 2024-T3 sheets. Damage mode and feature of them were compared and studied. ABAQUS software was used to simulate dynamic response and damage evolution of FMLs during impact. It is shown that FMLs have better impact resistance properties than pure aluminum sheets because of the fibre. The damage of FMLs has three clear different steps to damage during impact. The simulation and experiment results agree well with each other.

Keywords Fibre-metal laminates(FMLs), low-velocity impact, damage mode

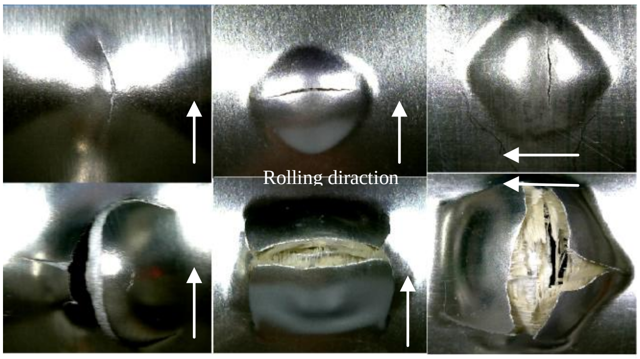
1. Introduction

Fibre-metal laminates(FMLs) is a type of hybrid material which consists of alternating layers of thin metallic sheets bonded together with fiber reinforced layers[1-8]. During the last decades the application of FMLs in various structures has become increasingly popular, especially in aerospace structures, for its improved fatigue and impact properties [1-5]. There are many articles about experimental [1-3] and modeling [6,7] investigation, regarding to impact resistance of FMLs. While there are a limited number of articles concerning theoretical modeling of impact response of FMLs [8]. Despite of lots of work concerning the impact of FMLs have done, their impact properties still need more understanding and attention.

In this study, low-velocity impact damage resistance of FMLs caused by dropped tools or collisions between service cargo (less than 10 m/s) in aircraft is investigated via both experimental and numerical simulations.

2. Experimental investigation

The FMLs studied in this work were consists of three layers of 2024-T3 aluminium alloy sheets 0.254 mm in thickness and two layers of [0/90/90/0] glass/epoxy composite with each prepreg 0.15 mm in thickness. For comparison purposes, monolithic 2024-T3 sheets of 2 mm in thickness were also studied. According to standard ASTM-D-7136[9]，All specimens were cut into rectangle panels with dimensions of $150\times100\ \mathrm{mm}^2$. There are two types of FMLs specimens, type A with the rolling direction of aluminium sheet or 0 fibre direction parallel to the short side and type B parallel to the long side, and one type of aluminium specimens with rolling direction parallel to the short side. The low-velocity impact tests were conducted using an Instron-Dynatup 9250 instrumented drop-weight impact tester and used an impactor with a 16 mm diameter hemispherical steel head of a total weight of 6.9025 kg. Tests were performed in the different energies ranging from 5J to 123J. The time history of impact force and impactor displacement was obtained by the test machine. After impact, the residual displacement, indentation depth and the crack length of back surface have been measured.



Up 2024-T3 AL/43.2J FMLs-A/62.3J FMLs-B/62.6J
Blow 2024-T3 AL/68.8J FMLs-A/91.9J FMLs-B/88.5J

Figure 1. Damage at the non-impacted side of AL and FMLs

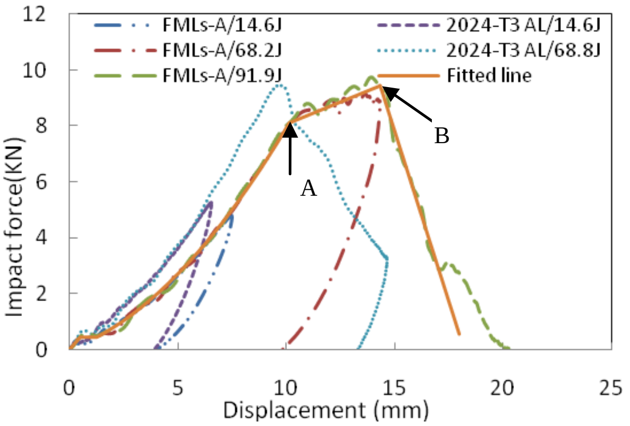


Figure 2.Force-displacement curves

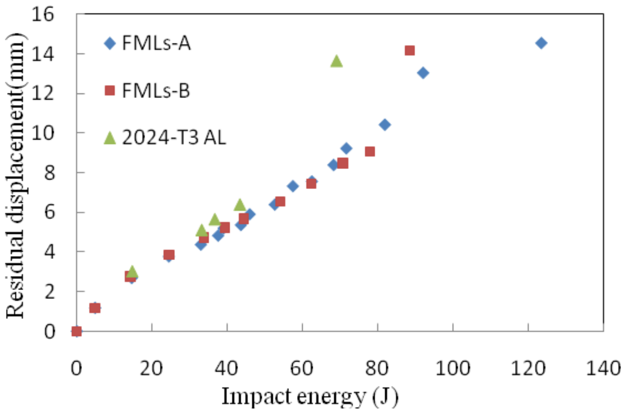


Figure 3.Residual displacement against impact energy

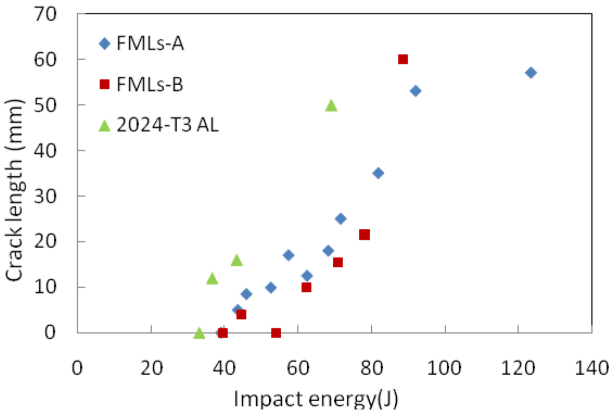


Figure 4. Crack length against impact energy

In Fig.1, damage after the different impact energy was shown and compared between FMLs and 2024T3 sheets. For monolithic 2024-T3 sheets, the first crack was found at non-impact side at impact energy of 36.5J, and almost completely penetrated at energy of 68.8J. The shape of crack was first in rolling direction and growth into "C" shape with high energies. Whereas, for both types of FMLs A and B, the initial crack at non-impact side were found at energy of 43.5J and crack at impact side appeared at 71.5J. It is differently from others work, the first crack found there were perpendicular to rolling direction of aluminium alloy sheets and the adjacent fibre direction. The shape of crack at non-impact side of FMLs was grown into "H" shape at energies of 71.5J. There are little difference between two types of FMLs for the force-displacement curves, indentation depth ,the crack length and others permanent were almost the same at one energy level (see figure 3 and 4). Force-displacement curves were compared in figure 2. It were shown that the route of them kept the same before crack were appeared during loading stage for FMLs and monolithic 2024-T3 sheets respectively, and the quadratic equation can be used to relate the force with displacement. While the path is not coincident in unloading stage, but their slope were basic paralleled that is the same quadratic equation can be used [5]. There are two inflection points A and B at the force-displacement curves of FMLs. Inflection point A was caused by the crack generation at non-impact side of aluminium alloy sheet, and point B was the ultimate load of FMLs under low-velocity impact which was closed to the ultimate load of monolithic 2024-T3 sheets. The FMLs exhibit aluminium dominated behavior before first crack generated and exhibit fiber dominated failure behavior after the crack generated. The solid line in figure 2 was acquired by fitting the force-displacement curves of FMLs using quadratic and liner segmented function.

3. Numerical simulation

To clarify the relationship between the internal and external damages, dynamic explicit analysis was carried out using the finite element software ABAQUS. The impactor and each layer in three dimensions in the FMLs were modeled as separate parts, see figure 5. Interface layers were inserted into each layer to model interlaminar delamination. The boundary conditions of model FMLs were held four edges fixed. An initial velocity in the vertical direction is prescribed to the impactor, simulating the impact velocity measured during the tests.

The Isotropic elasticity and metal plasticity with ductile damage initial criterion and linear fracture energy damage evolution were used to simulate aluminum alloy failure mechanisms. Orthotropic elasticity in the plane stress field was used for each of the prepreg layers and interfaces layers. The Hashin damage initiation criteria and fracture energy damage evolution implemented in ABAQUS was applied to each ply in the prepreg layers to simulate their failure mechanisms. While the failure of interface layers were modeled as cohesive layers with the max traction-separation damage initial criteria and linear fracture energy damage evolution laws [10].

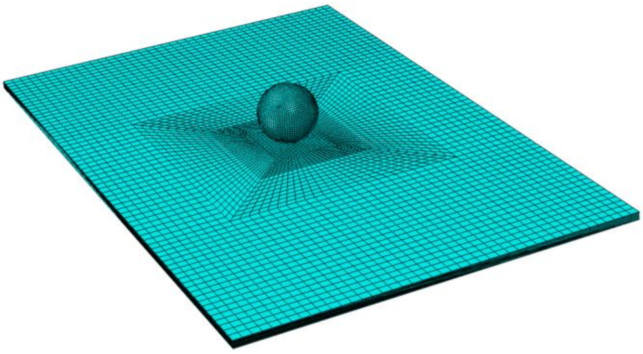


Figure 5. Finite element model

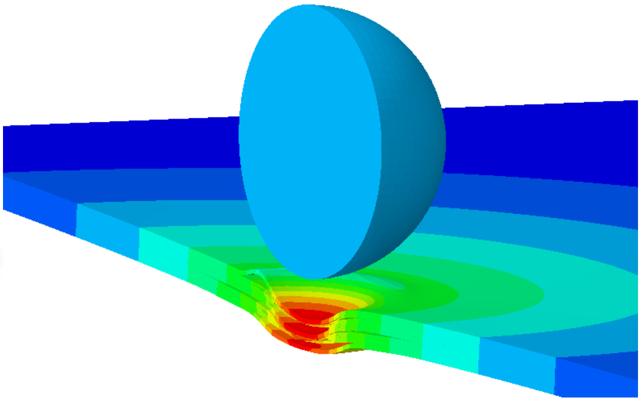
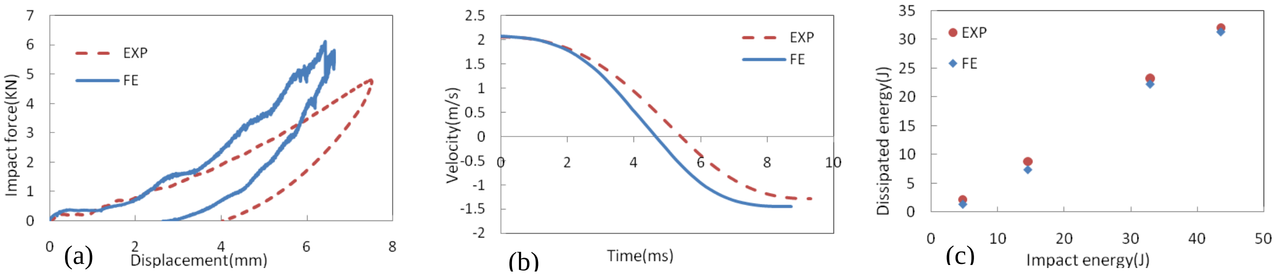


Figure 6. The failure mode of the FMLs subjected to 14.6J impact



(a) (b) (c)

Figure 7. The *F*-*d* (a), *v*-*T*(b) and U_d -*U*(c) curves of experiment and finite element results

The finite element model corresponds well with the test results reasonably. Figure 6 shows the damage of finite element model subjected to the impact energy of 14.6J. This half-specimen plot shows residual depth and interlaminar delamination occurring after impact completed. The experimental and simulated impactor reaction force-displacement and velocity histories curves corresponding to14.6J impacts on the FMLs were plotted in Figure 7(a, b). The experimental tests were not correctly replicated by the simulation results for the maximum impact force was higher, the maximum displacement was lower and impact time was shorter, while the tendency of them was reasonable the same, and the final velocities were much at one, that is the dissipated energies were almost the same. The dissipated energies against several impact energies were plotted in figure 7(c).

4. Conclusion

This study presented an experimental and numerical investigation on low-velocity impact behaviors of the fibre metal laminates (FMLs). Experimental results show that the impact resistance of FMLs was higher than monolithic 2024-T3 sheets for the first crack energy about 15% higher and completely penetration energy about 34% higher. While, the impact resistance of two types of FMLs, which were cut into rectangle panels with the long edge parallel to 90 and 0 fibre separately, were almost the same. Good agreement between finite element results and experimental results such as the internal delamination and dissipated energies were obtained, and hence the model was validated.

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