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Experimental Investigation of Low-Velocity Repeated Impacts on Glass Fiber Metal Composites

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The aim of this study was to experimentally investigate the effect of repeated low-velocity impacts on tensile strength of fiber metal laminates (FMLs) using instrumented drop weight impact tester. FMLs were fabricated layer by layer intercalating three layers of aluminum 6061 and two layers of glass fiber-reinforced epoxy. The FMLs were subjected to repeated low-velocity impacts (<10 m/s) at the same location on the FML. The degradation of mechanical property due to impact(s) was studied using Zwick UTM at distances of 0, 20, 40, and 60 mm from the impact point. Results indicate that ultimate tensile strength, failure strain, and ductility of all specimens initially decrease, and then remain constant with increase in number of impacts. A closer examination of impacted FML by scanning electron microscope indicates that thinning and shear fracture in aluminum layers, as well as delamination, and fiber failure in composites plies were present.

Keywords Delamination, FML, Low velocity impact, Tensile strength

1. Introduction

The fiber metal laminates (FMLs) are a relatively new type of material developed from the need for high-performance light-weight structures with excellent properties under tensile, flexure, and impact conditions. They combine the good characteristics of metals, such as ductility, impact resistance and damage tolerance, those of fiber-reinforced composites, such as high specific stiffness, corrosion, and fatigue resistance (Ref 1), which are important for their applications in aerospace industries. FMLs are composed of outer metal sheets such as Aluminum or steel, and inner layer fiber-reinforced polymers (FRPs), such as glass, carbon, or aramid FRPs (Ref 2). However, FMLs are very susceptible to impact damage, such as thinning of aluminum sheets, delaminating between metal and FRP, matrix cracking, and fiber failure (Ref 3, 4); these damages lead to significant reduction in the strength and stiffness of FML.

Abdullah and Cantwell (Ref 5) showed that the multilayered laminates require high impact energy than that of sandwich laminates for perforation given the same thickness. At low-velocity impact, a failure of FML in glass fibers was never detected before cracking of outer aluminum, and hence the aluminum plate acts as a sacrificing layer (Ref 6). Carrillo and Cantwell (Ref 7) reported that during impact, the fiber-metal interface does not become deboned, suggesting a high degree of adhesion across the interface. In addition, FML laminates in both systems (Al and FRP) exhibited a localized indentation failure was followed by progressive collapse of the laminate at higher impact energies. A better understanding of interfacial properties, characterization of interfacial adhesion strength, and failure mechanisms under repeated impacts on FML is therefore required for evaluating the degradation of mechanical properties.

However, to the best of our knowledge, damage accumulation mechanisms due to low-velocity drop weight impact onto composite panels have been studied extensively. Although study of single-hit low-velocity impact response of FML has been documented very well, no research study is focused on the effects of repeated impacts on failure mode and damage evolution of FML. The objectives of the research study are to investigate low-velocity repeated impacts on property degradation (tensile strength) and fracture behavior of Al-glass FRP laminates.

2. Experimental Studies

A square plate (180 mm × 180 mm × 0.8 mm) made of Al6061 was used for FML. Bidirectional-woven roving glass fiber of 600 gsm was reinforced with epoxy (LY 556 with HY556 hardener). The thickness of each layer of glass fiber-reinforced epoxy is 0.175 mm. The GFRPs are oriented parallel to the edges of Al panels and stacking sequence of A-G-A-G-A (A—Al and G—GFRP). Since GFRPs are more prone to absorb moisture from atmosphere, the Al used on exterior surface of FML prevents moisture absorption. Before stacking, the Al sheets were cleaned with acetone to remove grease and dirt. Cleaned Al plates were chromated for better adhesion between layers. FML panels were prepared by hand layup techniques followed by heating to 150 °C under pressure of

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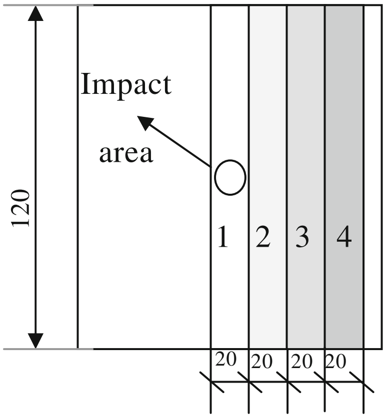

Fig. 1 Schematic representation of selection of tensile test samples

1 bar for five hours and cooled to room temperature. Four specimens were used for each condition, and average value is taken for discussion. Figure 2 shows one of typical online testing data. The mean and standard deviation are given in Fig. 3.

A drop tower (Instron Dynatup make 8250) is used for low-velocity impact test. The machine is capable of impacting samples at energy up to 302 J. The FML specimen was clamped at the bottom of the machine between the two rectangular blocks, which has square opening of 76 mm × 76 mm at the center . The hemispherical tup of diameter 12.5 mm was used as impactor with 5.2-kg weight controlled by solenoid switch. The drop height was maintained 80 cm for all conditions. After the impact, the tup was captured by a stopper to avoid rebound. A velocity detector measures the velocity of tup just before it strikes the specimen. For each experimental study, a total of 4096 data points were collected during impact event by data acquisition system. The impact event was repeated until the perforation of the specimen. The low-velocity repeated impact load was chosen to avoid fast accumulation (instantaneous failure) of damage in the FML so that different damage modes can be analyzed. The impact energy is expected to increase for damaged specimens because of the increased in area of contact between impact tup and specimen and also additional drop height gained by previous impacts.

Impact parameters, such as energy at maximum load, deflection at maximum load, and impact velocity, are evaluated from the data acquisition system. The photographs of the front and back face of the impacted specimens were taken to study the failure modes. As per Wu and Wu (Ref 8), the four tensile, straight-sided specimens (120 mm × 20 mm × 4.5 mm) were cut as shown in Fig. 1 after impacts. The tensile strength test for each strip was carried out on Zwick/Roell Z-100 universal testing machine at strain rate of 10^{-3}/s up to failure of the specimen.

3. Results and Discussion

3.1 Impact Studies

Figure 2(a) shows a typical graph of load with time. It can be observed that the first impact event has a duration of 8 ms, while the subsequent events are shorter, being equal to 5, 4, and 4 ms, respectively. Although the magnitude of the repeated impact is the same for all the tests, different force waves propagate through different impacts. The first impact attained a maximum load of 3.2 kN between 3 and 4 ms, the second impact attained a maximum load of 4 kN between 3 and 3.5 ms, the third impact attained a maximum load of 4.6 kN at 2 ms, and the fourth impact at the maximum load at 3.1 kN between 2 and 3 ms. During the first impact, the tup impacted on FML surface with a point contact. The contact surface area between tup and FML subsequently increases; hence, the load-time curve is flattened. After the first impact, there was some rebound due to the elastic recovery of FML. In the second impact, owing to a higher contact area between tup and FML impact, the curve becomes flatter and the specimen is partially damaged. In the third impact, area of contact is predominantly higher than the first two impacts, and hence, the peak is sharper and the time drastically reduces. The specimen is then fully damaged. At the fourth impact, the tup pierces through the specimen, and the applied load is utilized for bending of specimen which enlarges the hole.

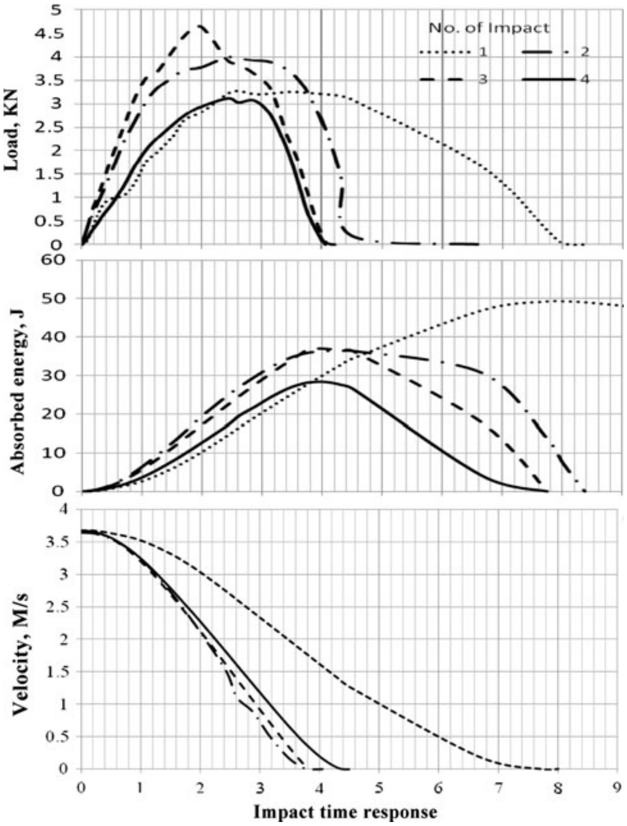

Fig. 2 Impact response (load, energy, and velocity) of Al/fiber laminates function impact time

Hence, the load decreases, and the curve looks flattened.

Figure 2(b) shows a typical graph of the absorbed energy of FML with time (ms) of the impact. The energy/time curve shows the similar behavior of the load-time curve. However, all the specimens show that twice the time was taken to reach zero energy status compared with load-time curve.

Figure 2(c) shows a typical graph of impact velocity for impact time and number of impacts on FML. All the four curves show decrease in trend because of resistance offered by the FML. The first impact takes longer duration (8 ms), and subsequent impacts take half of the duration of the first impact. This may be attributed to three reasons: (i) initially, the FML is flat in nature and has therefore an infinite radius, but, in subsequent impact, there exists an indentation and a finite radius of curvature in the contact zone; and (ii) the first impact will be in contact with relatively softer matrix than the subsequent impacts; and (iii) The contact area between impactor and specimen increases with increasing number of impacts, which leads to increased energy absorbtion by each impact.

The average energy absorbed at each impact event is as shown in Fig. 3(a) for the FML. In the first impact, the energy absorption is lower than other impacts but during the second impact, the energy absorption is the maximum, then it decreases. Both the metal layer and the fiber are the load-bearing components, characterized by fiber and metal layer on the impacted face being in compression and on the other side being in tension. When the FML is first impacted, the fibers and metal layer store most of energy and little is dissipated as matrix cracking. In the second impact the higher energy is dissipated as matrix cracking, the propagation of crack appears as a curve shape. A drop in energy in the third and the fourth impacts may also be attributed to some form of damage, which may also be referred to as loss of stiffness with some strain energy stored, which later may be dissipated. The release of this energy helps in dampening the impact force and generating reactions to set the bodies apart.

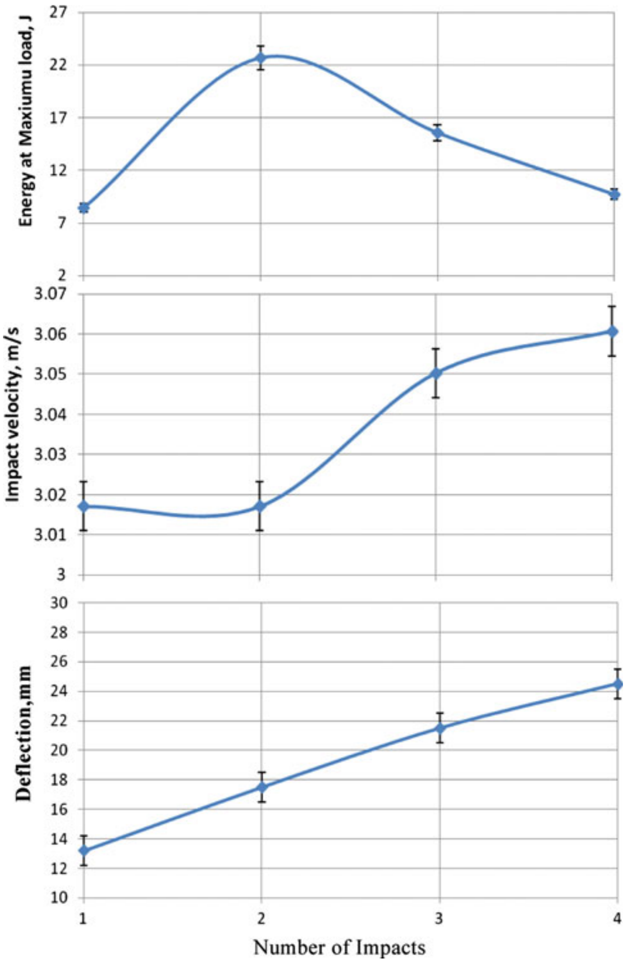

Fig. 3 Impact response (energy, impact velocity, and deflection) of Al/fiber laminates as function of the number of impacts

The increase of the velocity of an impact event with the number of impacts could be expected because the plates are more damaged, at least, locally under the indenter and therefore, they are more compliant. Therefore, when subjected to the same force, a damaged structure will deflect more, increasing the velocity at contact between the indenter and the specimen under the point of impact as shown in Fig. 3(b). The damage behavior observed reflects the restrictions imposed by the fiber to the composite to deform, as the number of fiber directions is increased (Ref 9).

As the number of impacts increases, damage increases as well as deflection of the FML as shown in Fig. 3(c). The extra heights gained—13, 18, and 22 mm—for the second, the third, and the fourth impacts, respectively, are shown in Fig. 3(c). Hence, this is not surprising given that the number of impacts lead to more damage in FML system. An examination of the perforated samples highlighted the presence of significant delamination between the composite and Al alloy layers. Also present were the regions of localized fiber fracture associated with the perforation process and extensive shear fracture in the upper and lower Al alloy skins.

3.2 Impact Damage Mechanism

The damage mechanisms (modes) examining the front and rear surface of the impact-damaged samples are shown in Fig. 4. The impact images are placed according to the sequence of impacts. In the first impact (Fig. 4a), damage takes the shape of circular dent at front end, followed by a localized bend at the back surface. As the number of impacts increases, the shape of the dent although circular, increases in size. During the second impact, a large dent and then a circular crack developed around the impactor and the uppermost aluminum layer. Then, the fiber plies try to push through the rear surface opening, but owing to sufficient structural support given by layers and back face as shown in Fig. 4(b), this does not happen. A similar damage trend can be seen in the third impact because of high strength of the back face to resist further damage as shown in Fig. 4(c). Increasing the number of impacts resulted in significant localized thinning of the back face of the metal layer before the fracture, because most of the boundaries of the specimen are rigidly clamped to the base of the machine, and the deformation is limited to small local area of the impact location. Here, the composite layer also fractures while the front face aluminum layer remains intact; hence, a cross-shaped petalling is seen on the rear side (Fig. 4d). Finally, the FML was fractured following the fourth impact. Front face exhibits smaller deflection, whereas the back face deflection is more because the back layers absorb most of the energy.

Scanning electron microscope was used to highlight the damage modes in the fiber-metal laminate interface subjected to low-velocity impact loading. The front and back faces deformed differently, particularly at the point of impact. This was due to the presence of transverse shear and through-thickness deformations in between layers. Figure 5 shows the relative deformation of the front face and the back face surfaces. The centerline radius of curvature of the back face surface is greater than that of the front face surface. From these observations, it is apparent that the effect of transverse shear and through-thickness deformations are important. Delamination occurred between the layers, because of limitations in adhesive bonding. This causes a greater drop in the shear strain than the bending strain because of permanent deformation in the layers.

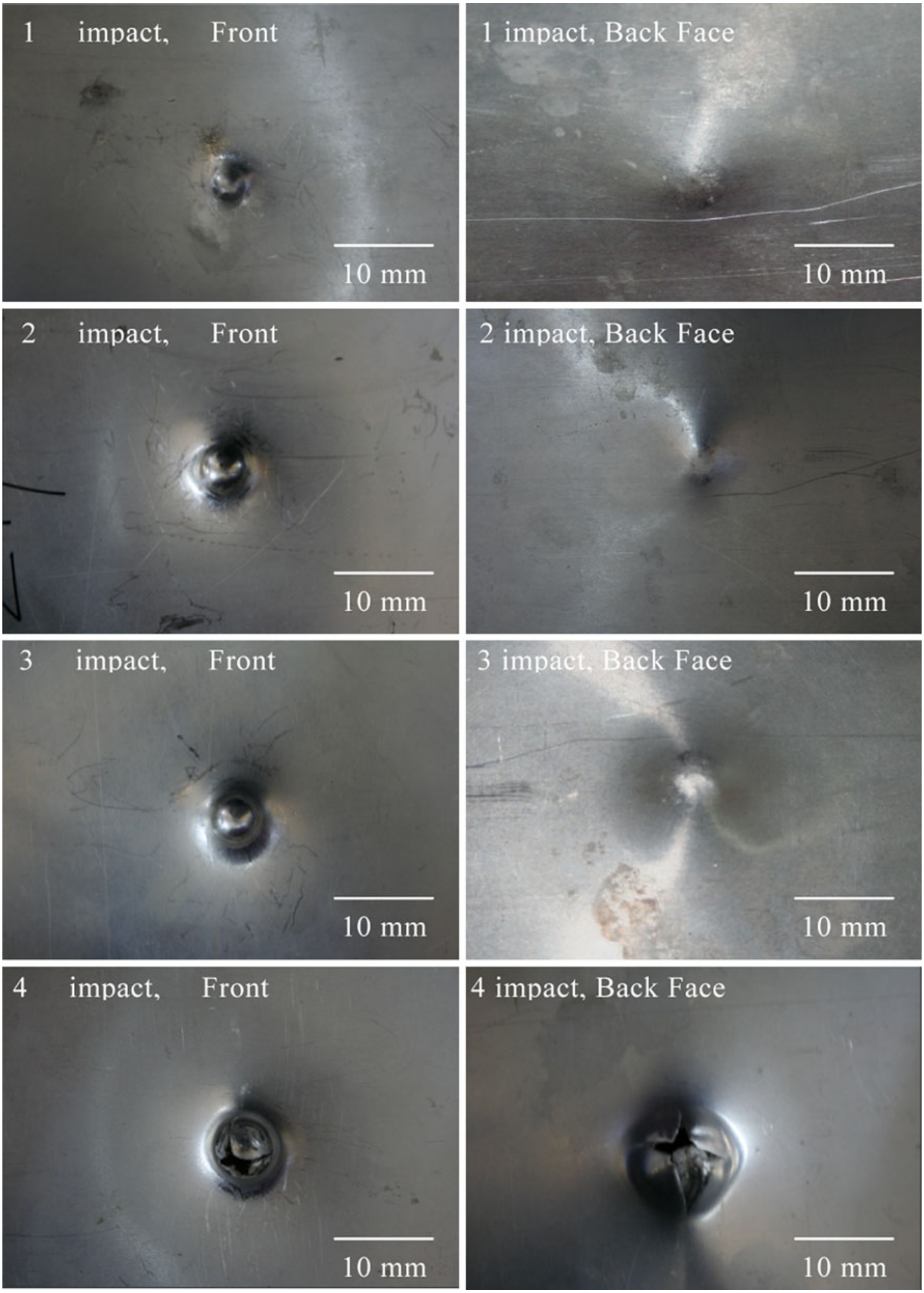

Fig. 4 Low magnification optical micrographs of impact-damaged Al FML (impacted surface and rear surface)

Figure 6 shows the response of inner layers against external impacts. Even at the first impact, the delamination within the composite layers was more pronounced with reference to back face layers as show in Fig. 6(a). The delamination and deformation are having semi-circular shape along with interlayer and intralayer matrix cracks. In the third and the fourth impacts, several damage modes can be seen in Fig. 6(b) and (c), respectively. The damage modes, such as delamination, fiber breakage, and matrix cracks, occur in both matrix and composite layers. The back face experiences larger inelastic

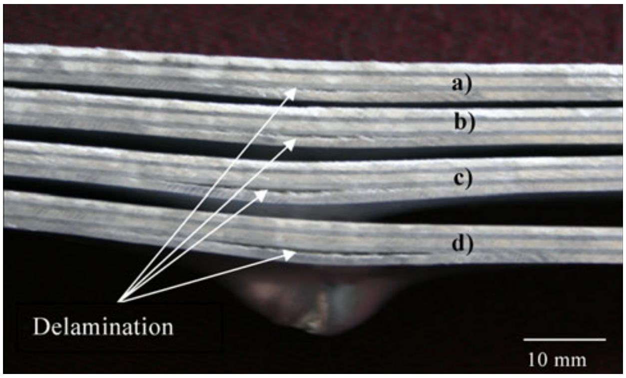

Fig. 5 Low magnification optical micrographs of cross section of Al FML (a—one impact, b—two impacts, c—three impacts, and d—four impacts specimens)

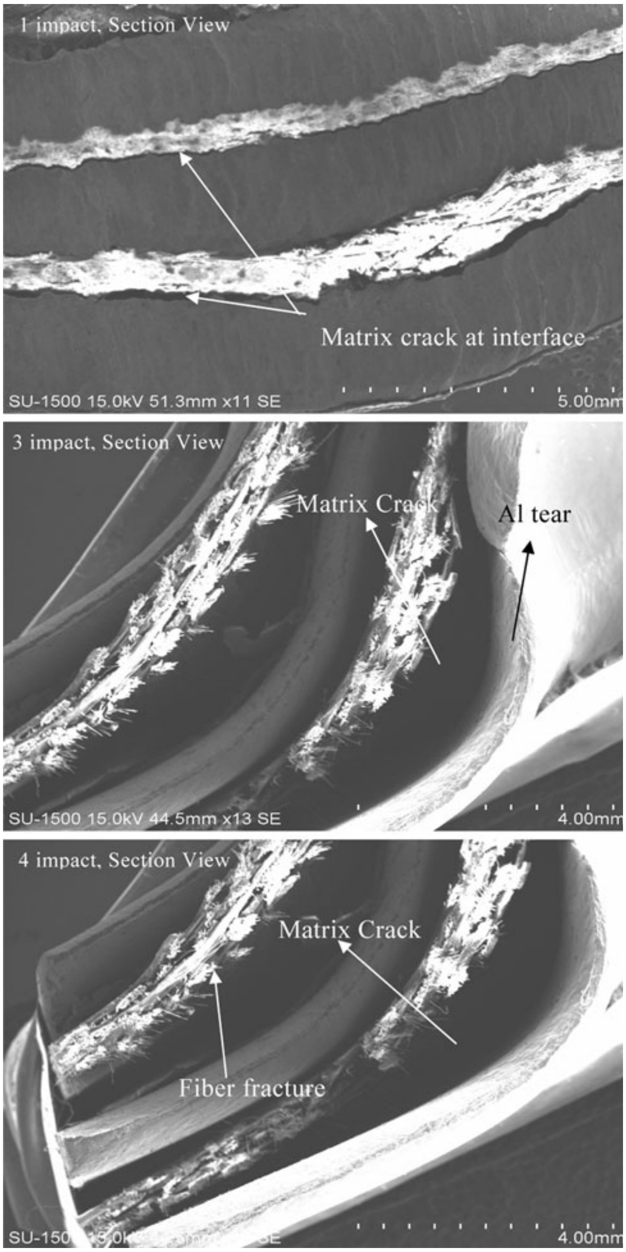

Fig. 6 SEM showing the impact damage on Al/glass fiber FML

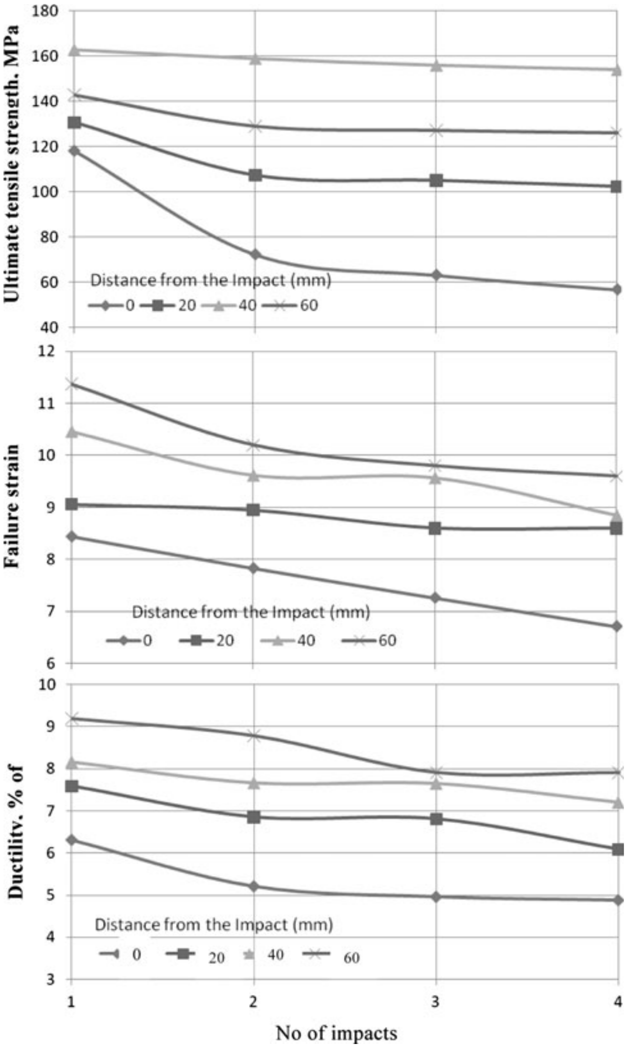

Fig. 7 Effect of the number of impacts on mechanical properties of Al/fiber laminates (a) ultimate tensile strength, (b) failure strain, and (c) ductility (% of elongation), respectively

deformation than the front face because the layers in the front face are supported by the layers behind. More delamination occurs on back face because local curvature leads to greater material strain on back face than the front face i.e., the damage is conical with the maximum damage on the back surface.

3.3 Effect of Impacts on Tensile Strength

Investigations into post-impact load-bearing capabilities of FML involving different modes of stresses have received a lot of attention. It is of particular interest to understand to what extent the impacted materials can sustain further loading. It has been found that tensile strength is reduced when impact damage is present in the composites (Ref 10). In this study, tensile test was carried out to evaluate post-impact properties, namely, tensile strength, failure strain, and ductility. It was anticipated that a correlation between the impact energies, the damage magnitudes, and tensile properties would be established.

The relationships of tensile properties (UTS, failure strain, and ductility) with the number of impact are illustrated in

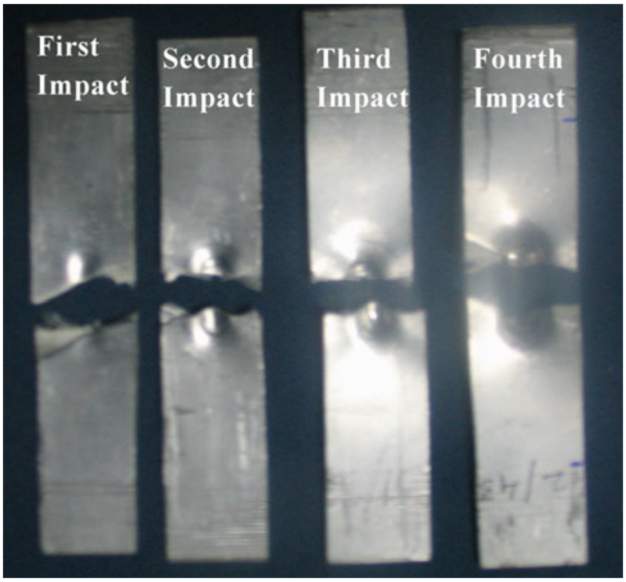

Fig. 8 Lower magnification of tensile fracture at the impacted location

Fig. 7. It indicates that the number of impacts results in reductions in UTS, failure strain, and ductility to varying degrees. Comparatively, UTS is more severely affected by impact damage, leading to more degradation. Degradation of UTS is more at the impact point, and it reduces at distances away from impact point. The maximum UTS reduction is approximately 25%. This higher sensitivity can be explained by the fact that the impact damage is localized in most cases, and therefore, it has less effect on global properties, such as UTS, failure strain, and ductility. Although GFRP composite layers have good strength and specific stiffness, poor energy absorption (impact) is the main weakness of GFRP layers, which leads to delamination between GFRP and aluminum layers. Figure 8 shows the modes of failure at impact zone for the number of impacts. The mode of failure generally changes from global node, to local, and to mixed modes as the delamination length increases. Due to impact the energy waves propagates throughout the FML structure. The energy wave is different in FRP and Metal laminates due to deformation which leads to delamination between aluminium and FRP interface. Fracture-damage mode interaction must also be understood when attempting to predict initiation and propagation of a particular form of damage. For the first and the second impacts, specimens showed irregular fracture (ductile failure) surface on both aluminum and GFRP layers, because the glass fiber can reduce matrix-dominated damage. For the third and the fourth impacts, specimens showed straight fracture (brittle failure) which is related to the major damage mode. This is due to a combination of tensile and higher impact energy (repeated impacts).

4. Conclusion

The study presents an experimental investigation of mechanical degradation of flat glass fiber epoxy aluminum plates which were subjected to repeated low-velocity impacts. The specimens were tensed after impact. On the basis of the experimental data collected, the main conclusions are as follows:

- Peak load, impact energy, and failure strain decreased with increasing number of impacts because of degradation of FML.
- There is sudden drop of UTS after the first impact, but has little significance as number of impacts increased.
- Degradation of UTS is more at the impact point, and subsequently is lesser as we move away from the point of impact, but decreases further at the end of the specimen because of stress waves.
- Failure mechanism during penetration impacts is preferentially dominated by the plastic deformation of the glass fiber epoxy, and the resulting penetration mode is highly localized, almost similar to that of the cross-shaped hole.
- The damage consisting of residual plastic deformation, delamination, and even aluminum cracking is found in the FML with increasing the number of impacts.

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