The effect of impactor on CFRP with toughened interlayers when subjected to low-velocity impact: experiment and numerical analysis

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Abstract. This study aims to investigate the effect of impactor on the behaviour of CFRP with toughened interlayers when subjected to low-velocity impact. CFRP with toughened interlayers is different from a conventional CFRP laminate since it enhanced the toughness of CFRP laminate. In this study, CFRP with toughened interlayers laminate was subjected to low velocity impact by using a drop weight testing apparatus developed in the laboratory. Four sizes of impactor head diameter were used with three different masses. The impactor was suspended at a specified height and released for a free fall drop. The impact event was then reproduced numerically. Based on the results, it was observed that the degree of damage was increased as the mass of impactor increased. However, smaller head diameter of impactor produced greater damage. Hence, smaller contact area produces greater local deformation as opposed to larger contact area that generates global deformation. Numerical analysis is also capable to reproduce the impact event.

1. Introduction

Advanced composite materials have been used in many applications due to its favourable properties such as specific strength and stiffness. For example, the application of carbon fiber reinforced plastics (CFRPs) as a major contribution to the aircraft structures such as trim tabs, spoilers, rudders, and doors. Nevertheless, low-velocity impact due to runaway debris thrown up by the aircraft wheels and impact during manufacture or subsequent maintenance can cause damage on the part. It is because the CFRPs employed a brittle epoxy resin as matrix system that resulting poor tolerance to low-energy impact damage [1]. Therefore, understanding the mechanisms of low-energy impact damage in CFRP is essential for improving the tolerance and reliability against low-velocity impact.

As in the case of low velocity damage, the laminate can be subjected to a micro damage even though it is barely visible impact damage (BVID). It can significantly affect the strength, durability and stability of the laminate. Cantwell and Morton proposed a pine tree pattern for thick laminated composites and a reversed pine tree pattern for thin composite laminates to symbolise the matrix cracking upon impact.
load [2]. Freitas and Reis proposed pine tree pattern with vertical matrix cracking on the bottom layer [3].

Generally, the composite materials are produced by laying up the thin resin impregnated and aligned fiber layers (also known as prepreg) with optimized fiber direction in each layer using autoclave [2]. The composite laminated structures are reinforced by fibers only on the plane and there is no reinforcement in through-thickness direction. Thus, the interlaminar strength in laminated composite materials is still one of the design limiting factor for the laminate structures [4]. In order to improve the interlaminar fracture toughness, an interlayer is often introduced by replacing the resin at prepreg surface to a tougher system such as the inclusion of thermoplastic particles [5]. It has been reported that Mode I and Mode II interlaminar fracture toughness improved after adding the tough adhesive layers [6].

Apart from that, the shape of impactor also contributes the damage mechanism occurred in CFRP laminate. In a study by Mitrevski et al., the hemispherical impactor induced matrix cracking and crushing over a larger area. Penetration was observed by the conical impactor due to fibre breakage and a small amount of matrix cracking encircled the penetrated hole. The ogival impactor perforated the specimen but to a smaller degree than the conical impactor. It produced a larger area of matrix cracking but smaller than the hemispherical impactor. Though the front surface damage varied for each impactor, the back face damage pattern was visually similar [7].

Therefore, this study is carried out to investigate the effect of impactor on the damage of CFRP with toughened interlayers due to low-velocity impact. The investigation consists of both experiment and numerical simulation. Three parameters related to impactor were considered in this study: diameter of impactor head, mass and impact velocity. Thus, the relationship between these parameters and damage generation will be discussed.

2. Experiment and numerical modelling

2.1. Experiment
The specimens were manufactured by Toray Industries Inc. with a trade name of T800S-3900-2B. The laminate configuration was cross-ply [0/90°]₆ with a thickness of 1.53 mm. The specimens were cut on a diamond blade saw in a square shape and afterwards the edges were polished. The dimension was 55 mm long and wide. For impact testing, all edges of the specimen were clamped on a fixture. Figure 1 shows the schematic diagram of the experimental setup. The impactor was suspended at a specified height depending on the impact energy and then was released for a free fall. Table 1 shows the related value of mass of impactor, velocity and height of impactor with regard to impact event. The velocity, \( v \) of impactor was determined by using conservation of energy equation,

\[
U = mgh = \frac{1}{2}mv^2
\]

Where \( U \) is potential energy of the impactor, \( h \) is the height of the impactor, \( g \) is acceleration of gravity, \( m \) is mass of impactor. After the impact, the specimen was cut and polished near the impact point before damage observation. The damage on the specimen surface was observed by using stereoscopic microscope (OLYMPUS, SZX9) at a magnification of 50X, whereas in cross sectional area, the damage of the laminate was observed by using optical microscope (OLYMPUS, BX60M) at a magnification of 100X.

2.2. Numerical modelling
In numerical modeling, the impact event between the impactor and the laminate was modeled via ABAQUS/Explicit. The impactor was modeled as a rigid body with a mass of 135 g, 185 g and 235 g respectively. The shape of impactor head was hemispherical with a diameter of 5 mm, 10 mm, 15 mm and 20 mm. The impact velocity of the impactor was based on the experiment. On the other hand, the laminate was modeled as an orthotropic elastic deformable body that consists of 8 layers of carbon fiber and 7 layers of interlayer made of toughened thermoplastic particle. The lamination configuration of carbon fiber was [0°/90°]₆. Table 2 lists the material properties of CFRP with toughened interlayers. In
in accordance with the experiment, the specimen was fixed at the edges. Since the modeling was carried out in quarter model due to axisymmetric, the edges at the vicinity of impact were set x- and y-symmetry. The impactor was assigned the initial velocity and allowed for displacement in z-direction only. Figure 2 depicts finite element model of the laminate and impactor.

![Figure 2. Schematic diagram of experimental setup. The diameter of impactor; a) 5 mm, b) 10 mm, c) 15 mm, d) 20 mm](image)

Table 1. Parameter of impact testing

| Mass of impactor, $m$ (g) | Diameter of impactor head, $d$ (mm) | Height, $h$ (m) | Velocity, $v$ (m/s) | Impact energy, $U$ (J) |
|--------------------------|------------------------------------|----------------|---------------------|------------------------|
| 135                      | 5                                  | 1.35           | 5.15                | 1.79                   |
| 135                      | 5                                  | 1.5            | 5.42                | 1.98                   |
| 185                      | 5                                  | 0.98           | 4.40                | 1.79                   |
| 185                      | 5                                  | 1.5            | 5.42                | 2.72                   |
| 185                      | 10                                 | 1.5            | 5.42                | 2.72                   |
| 185                      | 15                                 | 1.5            | 5.42                | 2.72                   |
| 185                      | 20                                 | 1.5            | 5.42                | 2.72                   |
| 235                      | 5                                  | 1.5            | 5.42                | 3.45                   |

It is great important to model the contact interaction for the impact problem. The general contact algorithm was applied to the model to simulate the interaction between impactor and laminate. This contact was implemented by using penalty approach for the entire calculation. Since the contact surface produces shear or normal forces, specifying the surface friction that defines the force in resisting the contact surfaces was essential. The friction coefficient was set to 0.3 as proposed in previous study [8].

Table 2. Material properties of CFRP with toughened interlayers

|                           | Base ply [8] | Interlayer |
|---------------------------|--------------|------------|
| Young's modulus (GPa)     |              |            |
| $E$ (Longitudinal $E_1$  | 151          | 4.6 [9]    |
| Transverse $E_2 = E_3$    | 9.16         |            |
| Shear modulus G (GPa)     |              |            |
| $G_{12} = G_{13}$         | 4.62         | 1.6 [9]    |
| $G_{23}$                  | 2.55         |            |
| Poisson's ratio $\nu$     |              |            |
| $\nu_{12} = \nu_{13}$    | 0.302        | 0.44 [9]   |
| $\nu_{23}$                | 0.589        |            |
| Yield strength (MPa)      |              | 64 [10]    |
3. Results and Discussion

3.1. The effect of impactor head diameter, \(d\)

Figure 3 depicts the damage generated on the surface of laminate after the impactor with a mass of \(m = 185\) g impacted the laminate. The dent was generated and the crack was propagated in transverse direction of fiber for both diameters of \(d = 5\) mm and \(d = 10\) mm. The dent was also observed but no crack propagation generated on the front surface of laminate for \(d = 15\) mm and \(d = 20\) mm.

Figure 3. Front surface damage after impact \((m = 185\) g, \(v = 5.42\) m/s, \(U = 2.72\) J).

Figure 4 depicts the cross section of the laminate after the impact. The interlaminar delamination was not observed in all specimens. The dominant damage was matrix cracks and fiber breakage. In the case of \(d = 5\) mm, multiple bending cracks generated due to bending deformation in the lowest \((8^{th})\) layer. The crack propagates and forms main bending crack until fiber breakage occurred in the seventh \((7^{th})\) layer. Cone cracks were generated in the third \((3^{rd})\) and sixth \((6^{th})\) layers. These damages were similar for the case of \(d = 10\) mm.

As for \(d = 15\) mm and \(d = 20\) mm, fiber breakage in the seventh \((7^{th})\) layer was not observed but bending cracks and cone cracks were generated. As such, bending cracks of the lower layer, particularly the seventh \((7^{th})\) and eighth \((8^{th})\) layers, increases when \(d\) are small. Since the deformation of the specimens at the impact differs depending on the value of \(d\), deformation becomes localized as the value of \(d\) becomes smaller. Crack and fiber breakage were generated due to tensile stress immediately beneath the impact point. On the contrary, when \(d\) is large, deformation becomes global and the load is dispersed. Thus, the load point is considered to be small.
Figure 4. Internal damage after impact ($m = 185 \text{ g}$, $v = 5.42 \text{ m/s}$, $U = 2.72 \text{ J}$) at different diameter of impactor head.

3.2. The effect of impactor mass, $m$

Figure 5 depicts the damage generated on the surface of laminate after the impact with three different masses. All laminates exhibited dent with crack extending in transverse direction. However, splitting crack was only generated in the laminate with the largest mass of impactor ($m = 235 \text{ g}$).

Figure 6 depicts the internal damage for three different impactor masses when impacted at velocity of $v = 5.42 \text{ m/s}$ and the diameter of impactor head of $d = 5 \text{ mm}$. At a mass of $m = 135 \text{ g}$, there were multiple bending cracks in the lowest layer and corn cracks in the other layers. Meanwhile, for the mass of $m = 185 \text{ g}$, bending cracks were generated in the lowest layer and progress to the seventh ($7^{th}$) layer as a main bending crack, thus lead to fiber breakage. A more severe damage was observed in the laminate.
when the mass of impactor \( m = 235 \) g was used. Bending crack in the lowest layer propagated to the 7th layer, thus produced main bending crack and fiber breakage. Apart from fiber breakage, in the 6th layer, intralaminar delamination was also generated due to the inclusion of toughened interlayers as reported elsewhere [11].

**Figure 6.** Internal damage for three different masses \((d = 5 \text{ mm}, \nu = 5.42 \text{ m/s}, U = 2.72 \text{ J})\)

3.3. The comparison between mass of impactor and impact velocity on damage

Figure 7 depicts the damage mechanisms when subjected to impact energy of 1.79 J by using impactor with a head diameter of \( d = 5 \) mm. Based on the figures, for a given impact energy, higher impact velocity produces greater damage such as matrix cracks, cone crack and bending crack in the lowest layer. Fiber breakage was also generated in the 7th layer of the laminate. This behaviour was similar with the study reported in [10] since higher velocity generates local deformation and lead to more severe damage.

**Figure 7.** Internal damage for different mass and velocity but same impact energy \((d = 5 \text{ mm}, U = 1.79 \text{ J})\)
3.4. The stress analysis of laminate after the impact

Figure 8 depicts the stress contour on the surface of laminate after the impact event. The stress was concentrated at the impact point and impactor with head diameter of $d = 10$ mm was the highest and followed by $d = 5$ mm, $d = 15$ mm and $d = 20$ mm. The stress was concentrated at the center of laminate due to the contact between head of impactor and the laminate. Figure 9 depicts the stress contour inside the laminate. The stress contour corresponds to the damage observed in Figure 4 b) especially the main bending crack at the lowest ply.

![Stress Contours](image)

**Figure 8.** Stress contour on front surface of laminate for different diameter of impactor head after impact at velocity of $v = 5.42$ m/s and mass of impactor $m = 185$ g.

![Stress Contours](image)

**Figure 9.** Stress contour inside the laminate after impact at velocity of $v = 5.42$ m/s and mass of impactor $m = 185$ g. The diameter of impactor head, $d = 10$ mm.
4. Conclusion
The effect of impactor on CFRP with toughened interlayers when subjected to low-velocity impact was successfully characterized experimentally and numerically. In summary, the study concludes:
1. The impactor with smaller head diameter generates transverse crack on the front surface of laminate while no crack is visible for larger head diameter.
2. The impactor with small mass but high velocity generates more severe damage.
3. The intralaminar delamination was generated instead of interlaminar delamination when the impact energy is large.
4. The stress contour on the front surface was in agreement with the damage generated in experiment.

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