Characterization of microscopic damage due to low-velocity and high-velocity impact in CFRP with toughened interlayers

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Abstract

In this paper the low-velocity and high-velocity impact damage in a carbon fiber reinforced plastic (CFRP) laminate with toughened interlayers was experimentally characterized. The low-velocity impact test was carried out by using a guided drop weight system while the high-velocity impact test was conducted by using a high-velocity impact testing machine. The damage in the laminate was then observed using optical microscopy and soft X-ray radiography. It was revealed from the observation that microscopic damage state and damage area varied with the impact velocity. The variation is ascribed to the fact that the low-velocity impact causes global deformation while the high-velocity impact energy is absorbed mainly by damage due to local deformation. Although the toughened interlayers suppress delamination for low impact energy, the high interlaminar fracture toughness sometimes causes the transition of interlaminar delamination to intralaminar one.

Key words : CFRP, Toughened interlayers, Impact damage, Low-velocity impact, High-velocity impact

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been used in many applications because of high specific strength and specific modulus as well as good fatigue properties. For example, CFRPs have been used in primary structures such as a fuselage, wing and turbofan engine of recent civil aircraft. In general, CFRPs are vulnerable to out-of-plane impact load, which may cause internal and external damage, leading to reduction of the strength and the stiffness of CFRP. The damage due to low-velocity impact like tool-drop can be classified into clearly visible impact damage (CVID) or barely visible impact damage (BVID). In the latter case, although only the small dent is created on the laminate surface, large-scale damage including matrix cracking and delamination is often generated inside the laminate. In contrast, high-velocity impact produces clear evidence such as a crater on the surface in addition to more catastrophic failure than low-velocity impact.

A lot of work has been conducted on low- and high-velocity impact damage. Abrate (1991, 1994, 1998) made an extensive review on impact dynamics, damage modes, failure criteria and residual properties for low-velocity impact as well as ballistic limit and ballistic impact damage for various kinds of composites. Regarding high-velocity impact, Goldsmith et al. (1995) carried out both quasi-static and ballistic impact tests for CFRP. They suggested that the damage process includes global plate deflection, fiber failure, crack propagation, petaling, delamination, hole enlargement and friction. Lopez-Puente et al. (2008) investigated quasi-isotropic and woven laminates subjected to high-velocity impact and their dependency on temperature. The delaminated area of the quasi-isotropic laminates is greater than the woven

laminates for any given impact velocity and temperature. Tanabe et al. (2003) studied the fracture behavior of CFRP using different types of carbon fiber and they concluded that the mechanical properties at rear layers contribute to improve the energy absorption. Hazell et al. (2008) studied damage mechanism of CFRP when subjected to normal and oblique impact at a high velocity. On the other hand, in terms of low-velocity impact, Mitrevski et al. (2005) studied the effect of various projectile shapes, namely, hemispherical, conical and ogival. Conical and ogival impactors generate permanent indentation and penetration whereas a hemispherical impactor produces BVID. The characteristics of low-velocity impact damage and its residual tensile strength were investigated by Wang et al. (2010). They observed that two different tensile damage modes are produced after different impact energies. Heimbs et al. (2009) studied impact load coupled with a pre-stress condition and found that delamination is a major energy absorption mechanism.

In order to improve the out-of-plane mechanical properties of composite laminates, several methods have been developed, for example, stitching (Dransfield et al., 1998) (Jain et al., 1998) (Parlapalli et al., 2007), matrix toughening (Yadav et al., 2006) (Wong et al., 2010), critical ply termination and edge cap reinforcement (Saghafi et al., 2014). One of the technique to increase the interlaminar fracture toughness is to introduce toughened interlayers including toughening particles or nanofiber. Several studies on low-speed impact for such CFRP laminates have been performed by Ito et al. (2012), Bull et al. (2014), and Xu et al. (2014). Morita et al. (1995,1997) studied the low-velocity and high-velocity (up to 130 m/s) impact damage for three types of material systems, carbon fiber/polyether-ether-ketone (CF/PEEK), CF/polyether-ether-ketone (CF/PEEK) with interlayers and CF/epoxy with toughened interlayers (T800H/#3900-2, Toray Industries Inc.). They found that both low- and high-velocity impact damage primarily consists of matrix cracking and delamination. Consequently, the failure modes for both impact tests become similar while the damage area is larger in high-velocity impact. Moreover, they focused on the final damage state and discussed the relationship between damage area and the impact energy.

When a fan blade-out event in a turbofan engine is considered, a composite fan case needs to bear the impact with a velocity near and/or higher than the sound velocity. Recently, Yashiro et al. (2013, 2014, 2016) have studied the high-velocity (up to 900 m/s) impact damage process of CFRP laminates. They have experimentally characterized microscopic damage state and numerically reproduced the damage process using a smoothed-particle hydrodynamics (SPH) method. However, the difference of microscopic damage process between high- and low-velocity impact tests has not thoroughly been investigated for CFRP with toughened interlayers. In addition, the effect of toughened interlayers on low- and high-velocity impact damage is not fully understood yet because the delamination behavior depends on the loading mode.

This paper aims at characterizing microscopic damage in CFRP cross-ply laminates with toughened interlayers. The microscopic damage state is compared in detail between low- and high-velocity impact tests. Both impact tests were performed under the same conditions except for impact velocity. Since the present study simulates damage due to the fan blade-out event by broken fan blade pieces, the tip diameter of impactor and projectile is small. Instead, the impact damage was observed for a wide range of velocity while the incident energy range is relatively small. As a result, the degree of damage varies widely from BVID to perforation with fiber breakage. In addition, the effect of interlayers on impact damage is elucidated by means of microscopic damage observation, being focused on crack propagation in the vicinity of the interlayers.

2. Materials and test procedure

A carbon fibre-reinforced epoxy composite with toughened interlayers (T800S/3900-2B, Toray Industries Inc.) was used. The fiber strength of this material is about 10 % higher than that of T800H/#3900-2. The stacking sequence was cross-ply $[0^0/90^0]_{2s}$. Hereafter, the top and bottom plies are denoted as 0^0 plies. The total thickness of a cured laminate was 1.6 mm. The laminates were then cut into square specimens 55 mm wide and long.

Subsequently, the low-velocity impact test was conducted by using a guided drop-weight test jig illustrated in Fig. 1(a). The impactor consists of a 15 mm diameter circular rod and a 1.5 mm diameter circular rod with the hemispherical tip whose diameter is the same as the projectile diameter for high-velocity impact test (Fig. 1 (b)). The mass of impactors used was 62 g and 150 g. The impactor with a mass of 150 g is realized by screwing the additional mass to the impactor with a mass of 62 g. The impactor was suspended by a cable at a predetermined height to be dropped by free fall. The stopper was inserted to prevent the impactor from multiple impacts onto the specimen.

Figure 2 illustrates a high-velocity impact testing machine (Maruwa Electronic Inc.) used in the experiment. The machine consists of a control unit for the power source and a chamber in which a projectile is fired at a target as well as

a speed detector connected with a data logger. Steel balls with a diameter of 1.5 mm were used as projectiles. The projectile was set in a sabot and accelerated at high-temperature and high-pressure metal plasma. The metal plasma was generated by melting and evaporating an aluminum foil subjected to high-voltage pulse current. The impact speed was approximately controlled by adjusting the applied voltage and precisely calculated from the period of time during which the projectile travels the prescribed distance (300 mm) in the speed detector. The velocity can be varied in the range of 40 m/s to 1500 m/s. When firing, the sabot was stopped at the opening of the gun and only the projectile was shot by inertia.

Fig. 1 Schematic diagram of drop-weight test jig for low-velocity impact test. (a) Overall test setup and (b) illustration of (i) the impactor and (ii) the additional mass (unit: mm).

Fig. 2 Schematic diagram of high-velocity impact testing machine.

Fig. 3 (a) Fixture jig for low- and high-velocity impact tests and (b) detail illustration of the fixture.

Figure 3 presents the fixture jig supporting the specimen commonly used in the low- and high-velocity impact tests. The target specimen was rigidly fixed along its four sides by a square frame with inner width of 50 mm. Hence, this support allows bending deformation of the target during both impact loads.

The drop height H in the low-speed impact test was predetermined from the kinetic energy E_{impact} of the projectile in the high-velocity impact test as follows:

$$H = \frac{E_{\text{impact}}}{Mg} \quad (1)$$

with

$$E_{\text{impact}} = \frac{1}{2}mv^2 = MgH \quad (2)$$

where M is mass of the low-velocity impactor, g is gravitational acceleration, and m and v are mass and velocity of the high-velocity projectile, respectively. As mentioned above, the supporting conditions of the CFRP specimens, diameter of the projectile and the tip of impactor, and incident energy, which is variable, are the same in both impact tests.

After the impact test, the damage on the specimen surface was observed by optical microscopy. Next, the internal damage was quantitatively evaluated using soft X-ray radiography. Moreover, several specimens were cut for detail observation of the microscopic damage state on the cross-sections beneath the impact point.

3. Results

3.1 Low-velocity impact

Figure 4 depicts the damage generated on the front surface of the laminate at specified impact velocities and energies. A specimen with the highest velocity and energy (Fig. 4(d)) is fully penetrated by the impactor. All the specimens except specimen 1 have a dent or a crater with two cracks propagating in the transverse (normal to the fiber) direction while any splitting cracks parallel to the fiber direction are not generated. In contrast, the splitting cracks as well as bulging area are observed on the back surface of the laminate as depicted in Fig. 5. These cracks were generated only when the impact energy is the highest ($E = 2.92$ J).

Typical soft X-ray photographs of the laminates are presented in Fig. 6. The delamination propagates chiefly in the fiber direction, while the delamination propagation in the transverse direction is limited. The laminates without full penetration (Figs. 6(a) and (b)) exhibit a peanut-shape delamination while the delamination in the laminate with full penetration is in a galaxy-shape (Fig. 6(c)).

Fig. 4 Damage on the front surface of the laminates after low-velocity impact.

Fig. 5 Damage on the back surface of the laminate after low-velocity impact.

Fig. 6 Soft X-ray photographs of the laminates after low-velocity impact.

Figure 7 shows optical micrographs of cross-sections of the specimens after low-velocity impact. The interlayers are observed as resin-rich layers between the base 0° and 90° plies. It should be noted that the fiber directions in the top and bottom plies are normal to the photographs. Figure 7 (a) depicts the cross-section of the specimen 1 for $v = 2.4$ m/s and $E = 0.18$ J. No internal damage is observed. Figure 7 (b) depicts the damage state beneath the impact point for $v = 4.9$ m/s and $E = 0.74$ J. A dent, delamination and matrix cracks including bending cracks in the bottom ply and cone cracks in the middle plies are generated. The matrix cracks in the top ply are separated into two lateral cracks, one of which is delamination at the interface between the top ply and the first interlayer (arrow A), and the other is the lateral crack in the top ply (arrow B). Hereafter, this lateral crack is referred to as intralaminar delamination. Several bending cracks in the bottom ply is supposed to be due to global bending deformation during impact. Most of the matrix cracks stop at the interface between the base ply and the interlayer (arrow C). Figure 7 (c) depicts the damage state for $v = 6.0$ m/s and $E = 1.13$ J. The damage state is similar to that in Fig. 7 (b) although slight permanent deformation is observed after impact. Figure 7 (d) presents the damage state for $v = 6.0$ m/s and $E = 2.92$ J. Although the impact velocity in Fig. 7 (d) is the same as that in Fig. 7 (c), the impactor fully penetrates through the specimen because impact energy is higher due to increasing mass. The impact area on the top surface is no longer a dent but a crater with bulging and all the plies including interlayers break in the penetration region. In the vicinity of the penetration region, interlaminar delamination (arrows D) as well as matrix cracks (arrows E) are generated. The bottom ply bends downward and some broken fibers peel off from the laminate (see Fig. 5). This damage state is quite different from the above two conditions and rather similar to high-velocity impact damage state as will be shown later.

3.2 High-velocity impact

Figure 8 depicts the damage generated on the front and the back surfaces of the laminates after the high-velocity impact test. A crater and multiple splitting cracks propagating in the fiber direction are observed for three impact velocities. It is found that the length of the splitting cracks becomes longer as the impact velocity or energy increases. The several broken fibers inside the crater peel off from the laminate. On the other hand, the damage state on the back surface differs among the three velocities. At $v = 160$ m/s, the damage is barely visible on the back surface. A small bulge

is generated at $v = 327$ m/s whereas no cracking is observed. At $v = 651$ m/s, the laminate is fully perforated by a projectile, and multiple splitting cracks with fiber breakage appear on the back surface.

Fig. 7 Damage states beneath the impact point of the laminate after low-velocity impact.

Figure 9 presents soft X-ray photographs of the specimens after the high-velocity impact test. The fiber direction of the top and bottom plies is indicated by the arrow. At lower velocities (Figs. 9 (a) and (b)), the difference of delamination length between the fiber and transverse directions is minor. However, in the specimen after full penetration (Fig. 9 (c)), the delamination is in a galaxy-shape and is much longer in the fiber direction. As a result, the shape of delamination after high-velocity impact is similar to that after low-velocity impact with high impact energy.

Figure 10 shows the cross-sectional views of the damage generated beneath the impact point for three velocities. Even when the impact velocity is relatively low (Fig. 10 (a)), both a crater and matrix cracking are observed in the top ply. In addition, the delamination is also generated at the interface between the interlayer and the base 0° ply (arrow A), not in the interlayer. At a middle impact velocity (Fig. 10 (b)), a crater, matrix cracking including cone cracks and bending cracks and fiber breakage are generated in all the plies. Most delaminations are generated at the interface between the interlayer and the base ply (arrows B) although several cracks are observed inside the interlayer (arrows C). At the highest impact velocity (Fig. 10 (c)), the specimen exhibits a catastrophic damage state consisting of a crater, matrix cracking and fiber breakage as well as large-scale delamination. It is interesting that the intralaminar delamination is generated in the laminate at this velocity only. For example, the delamination at the interface between the interlayer and the base ply (arrow D) is connected with the intralaminar delamination (arrow E).

4. Discussion

4.1 Comparison of damage between low- and high-velocity impacts

As shown in the experimental result, low- and high-velocity impacts produce different damage states. The schematic

illustrations for low- and high-velocity impact damage are depicted in Figs. 11 and 12, respectively. The damage mode for low-velocity impact is almost the same as that for high-velocity impact since the damage consists of a dent or crater, matrix cracking, interlaminar delamination, intralaminar delamination and fiber breakage. The delamination shape is also similar between the both impacts although the delamination size is different as shown later.

Fig. 8 Damage on the front and back surfaces of the laminates after high-velocity impact.

Fig. 9 Soft X-ray photographs of the laminates after high-velocity impact.

However, several differences between the two impact damage states are found from the microscopic observations. First, a crater with multiple splitting cracks are generated on the surface of the laminate subjected to high-velocity impact. Similar damage is observed in a general-purpose CFRP laminate (Yashiro et al., 2013). The splitting cracks are generated probably because local delamination beneath the impact point enables the shear deformation of the top surface. In contrast, since such delamination is hardly generated in low-velocity impact, fiber breakage occurs mainly due to compressive stress. Figure 13 shows fiber failure in the top ply which is presumed to be due to global deformation of the laminate and the compression of the fiber during the impact (Moran et al., 1995, Narayanan and Schadler, 1999). Consequently, two cracks propagating in the transverse direction from the dent or crater are generated as shown in Fig. 4.

Secondly, the splitting cracks on the back surface is observed for both impacts when the impact velocity or energy is high (Figs. 5 and 8). In the low-velocity impact, the global deformation of the laminate produces bending cracks in the bottom ply, which appears as the splitting cracks with bulging on the back surface. On the other hand, in the high-velocity impact, local bending-induced tensile stress causes multiple splitting cracks together with fiber breakage on the back surface (Yashiro et al., 2014).

Fig. 10 Damage states beneath the impact point of the laminates after high-velocity impact.

(c) Specimen 4: $m = 150$ g; $v = 6.0$ m/s; $E = 2.92$ J

Fig. 11 Schematic diagrams of low-velocity impact damage.

(a) Specimen 5: $m = 13.8$ g; $v = 160$ m/s; $E = 0.18$ J

(b) Specimen 6: $m = 13.8$ g; $v = 327$ m/s; $E = 0.74$ J

(c) Specimen 7: $m = 13.8$ g; $v = 651$ m/s; $E = 2.92$ J

Fig. 12 Schematic diagrams of high-velocity impact damage.

Thirdly, the damage state for the same impact energy but different impact velocity is discussed. From Figs. 7 (b) and 10 (b) ($E = 0.74$ J), the damage state in the high-velocity impact seems to be much more severe than that in the low-speed impact. In the high-velocity impact, a deep crater, delamination, cone cracks and bending cracks are observed from the top to the bottom plies in that order. In contrast, in a low-velocity case, a dent, matrix cracking and delamination are generated only in the top ply in addition to a few bending and cone cracks in the lower plies.

In general, the energy balance during impact is expressed as;

$$E_{\text{impact}} = E_{\text{rebound}} + E_{\text{damage}} + E_{\text{dissipated}} \quad (3)$$

where E_{impact} denotes the incident impact energy, E_{rebound} the kinetic energy of the rebounding impactor, E_{damage} the energy consumed by generation of damage and $E_{\text{dissipated}}$ the energy dissipated as vibration, heat, inelastic deformation of the impactor or the fixture and so on (Delfosse and Poursartip, 1997). In the low-velocity impact without full penetration, $E_{\text{dissipated}}$ is relatively larger than E_{damage} due to global deformation while E_{damage} is dominant in the high-velocity impact because of local deformation (Yashiro and Ogi, 2016). As a result, the degree of damage becomes greater in the high-velocity than in the low-velocity impact for the same incident impact energy. However, when full penetration (Figs. 7 (d) and 10 (c) ($E = 2.92$ J)) occurs, the damage state is very similar. This is probably because the ratio of E_{damage} to E_{impact} increases with increasing impact velocity in the low-velocity impact test.

Finally, delamination area for both impacts is plotted against incident impact energy in Fig. 14. The delamination area increases with impact energy for both impacts. Contribution of matrix cracking to energy dissipation is supposed to be small. Fiber breakage requires greater impact energy, however, fiber breakage area is much smaller than delamination area. Accordingly, the energy dissipation due to damage is mainly done by delamination. Moreover, as mentioned above, most part of the incident impact energy is consumed by damage generation in the high-velocity impact since the deformation is local. In contrast, the greater part of incident impact energy is absorbed by global deformation in the low-velocity impact. As a result, the high-velocity impact exhibits delamination area larger than the low-velocity impact for the same incident impact energy. In addition, Fig. 14 indicates that the threshold incident impact energy is approximately 0.18 J for both impacts. Numerical simulation including interlayers is necessary to quantitatively discuss the damage behavior and will be made in future work.

Fig. 13 Fiber failure after low-velocity impact.

4.2 The influence of toughened interlayers

The interlayers have a significant effect on both low- and high-velocity cases. It is found from the microscopic observation that matrix cracking due to low-velocity impact is clearly arrested by the interlayers (see the magnified views in Figs. 7 (b) and (c)). However, in the low-velocity impact with high energy and the high-velocity impact, matrix cracking does not always stop at the interlayer. This result suggests that matrix cracking propagates to the interlayers when the impact energy density (impact energy per volume) is greater than a critical value. In this case, impact energy cannot be fully dissipated by cracking and plastic deformation of the interlayers.

As shown in Fig. 10 (c), interlaminar delamination sometimes transits to intralaminar delamination. The Mode I interlaminar fracture toughness of a similar composite laminate (T800H/#3900-2) is about three times as conventional CFRP laminates (T800H/#3631) (Hojo et al., 2007). This high interlaminar fracture toughness causes the transition of the delamination in the toughened interlayer to that in the untoughened base ply.

Figure 15 depicts the surface of delamination between the 7th and 8th plies just below the impact point in the specimen after the low-velocity impact with the highest impact energy ($E = 2.92$ J). The resin rich region is prominent on this fracture surface although the base ply (arrow A) is partly observed. From this figure, it is concluded that the delamination propagates at the interface between the bottom (7th) interlayer and the bottom (8th) base ply. The fracture mode seems to be brittle because the surface exhibits little plastic deformation. The delamination initiation and propagation modes below the impact point are rather complicated because not only the stress state but also the damage process can affect the modes. At the present stage, it can be said from the previous numerical simulation (Yashiro et al., 2014) that Mode II propagation becomes dominant as the delamination propagates away from the impact point.

Fig. 14 Relationship between delamination area and impact energy for low- and high-velocity impact.

Fig. 15 SEM photo showing the surface of delamination in the specimen after the low-velocity impact.

5. Conclusions

The low-velocity and high-velocity impact damage in CFRP with toughened interlayers was experimentally characterized. The conclusions obtained in this study are as follows:

1. The splitting cracks on the front surface of the laminate propagate in the fiber direction in the high-velocity impact. In contrast, in the low-velocity impact, the cracks normal to the fiber direction are generated on the front surface.
2. The interlaminar delamination tends to propagate in the fiber direction for both impacts, resulting in a galaxy shape delamination.
3. The degree of damage is relatively large in the high-velocity impact even though the deformation is localized. In contrast, in the low-velocity impact, the damage is relatively mild because the ratio of dissipated energy to incident impact energy is larger than in the high-velocity impact.
4. The interlayers suppress the delamination when the incident impact energy is smaller than the threshold value (approximately 0.18 J). The high fracture toughness of the interlayers sometimes produces the transition of interlaminar delamination to intralaminar delamination.

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