Numerical Study on the Energy Absorption and Damage Characteristics of Aluminum Alloy Carbon/Glass Fiber Laminates under Different Impact Velocities

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Abstract: To study the dynamic response of metal fiber laminates subjected to the same energy and different velocities, a finite element model of aluminum alloy-carbon/glass fiber laminates was constructed to analyze the impact dynamic response and discuss the characteristics of interlayer damage. The results show that under the same impact kinetic energy conditions, the higher the initial velocity of the bullet is, the faster the velocity decays during the impact, and the more kinetic energy is consumed overall. On the whole, the shape of the failure area of the metal layer is similar to the shape of the bullet plane, and the failure area of the fiber layer will extend along the direction of the fiber layer. Whether it is a carbon fiber layer or a glass fiber layer, the tensile failure area is larger than the compression failure area. The fiber tensile/compression failure area is the largest, followed by the tensile/compression delamination failure area, and the matrix tensile/compression failure area is the smallest. As the bullet velocity increases, the failure area of the glass fiber layer in different forms becomes smaller, while the failure area of the carbon fiber layer in different forms does not change significantly.

1. Introduction

Metal fiber laminate is made of metal sheet and fiber sheet by a certain order of bonding. The structural plate combines the advantages of fiber composite material, such as fatigue resistance, high specific strength, high specific modulus, and the characteristics of metal material, such as good fracture toughness and strong impact resistance. So, it is widely used in the aerospace field. Although metal fiber laminates have many advantages, the interface strength is limited due to the interlayer connection. The engineering application of metal fiber laminates inevitably suffers from mechanical impacts. The impact load will cause serious damage to the inside of the metal fiber laminates, reduce its load-bearing capacity, and threaten the overall safety of the structure. Therefore, many scholars have done a lot of research on the energy absorption and damage characteristics of metal fiber laminates. Khan [1] used the Hashin puck failure criterion to simulate the impact process of metal fiber laminate, compared the metal layer at the top and bottom of the laminate, the metal layer in the middle, and no metal layer, and concluded that the existence of metal layer can greatly improve the damage resistance of the laminate. Chang [2] adjusted the interlaminar properties by changing the curing pressure of fiber laminates and established a finite element model to compare with the experimental verification, and studied the influence of interface strength on the delamination behavior. Lu [3] studied the multiple impact behavior of metal fiber laminates under the same total energy. The results show that the multiple impacts with lower energy division and smaller initial impact energy will cause less damage to metal fiber laminates. Zhang [4] explored the influence of the change of
impact energy on the damage form of metal fiber laminates under low velocity impact. With the development of the research, some scholars are not satisfied with a kind of fiber material. Megeri [5] used the finite element method to simulate the low velocity impact behavior of carbon fiber and glass fiber hybrid metal fiber laminates, and the results show that the impact load of hybrid fiber is higher than that of glass fiber under the same impact energy. Although a large number of scholars have studied the impact resistance of metal fiber laminates, the energy absorption and damage characteristics of aluminum alloy carbon/glass fiber laminates under the same energy and different velocity impact load are rarely mentioned. In the past, the impact velocity on the energy absorption characteristics of metal fiber laminates only changed the initial impact velocity of the bullet, and the initial impact energy also changed with the velocity, so it is difficult to distinguish the impact velocity on the internal damage.

In view of this, the impact process of bullets with the same impact energy and different impact velocities on the metal fiber laminate is simulated by ABAQUS software. The energy absorption characteristics of aluminum alloy carbon/glass fiber laminated plate are discussed, and the impact velocity on the interlayer damage is analyzed.

2. Finite element model
The finite element model is shown in Figure 1, and the size of aluminum alloy carbon/glass fiber laminated plate (hereinafter referred to as “laminated plate”) is 50mm×50mm×2mm, and the laying sequence from top to bottom is [Al1/C0°/C390°/G40°/G90°/C90°/C0°/C390°/G40°/G90°/G90°/Al10], each layer is 0.2mm thick, including 12420 C3D8R elements. The bullet has a diameter of 5.55mm and 16140 elements.

Figure.1. Finite element model
The metal layer of the laminate is characterized by Johnson-cook material model, and the material and model parameters are shown in reference literature [6]. The connection relationship between metal layer and fiber layer is characterized by cohesive model, and the interface parameters are consistent with literature [7]. See literature [8] for material performance parameters of fiber layer. The failure behavior of fiber layer is characterized by three-dimensional Hashin criterion, and the stiffness reduction scheme is consistent with literature [8]. The bullet is a rigid body and fixed around the laminated plate. The initial impact conditions are shown in Table 1.

| case | case1 | case2 | case3 | case4 | case5 | case6 | case7 |
|------|-------|-------|-------|-------|-------|-------|-------|
| \(V_0\) | -200m/s | -250m/s | -300m/s | -350m/s | -400m/s | -450m/s | -500m/s |

3. Analysis and discussion of simulation results
3.1. Analysis of overall impact performance
Figure 2 shows the damage evolution process of the bullet penetrating the laminate at the velocity of 200m/s. In order to clearly see the internal damage, adjust to the section view. When \(t=6\mu s\), seeing Figure 2(a), which is the initial stage of impact compression contact, and the aluminum alloy plate on
the upper layer of the laminate has been deformed by compression; When \( t=9\mu s \), as shown in Figure 2(b), the top layer of the aluminum alloy plate forms pits, resulting in plastic deformation, while the local area of the fiber reinforced material is crushed, resulting in fiber compression failure; When \( t=15\mu s \), as shown in Figure 2(c), the plastic deformation of the upper aluminum alloy plate is too large and cracks, the middle fiber layer is impacted and compressed, and gradually fails, and the lowest aluminum alloy plate has been raised; When \( t=24\mu s \), the lower aluminum alloy plate cracked due to excessive plastic deformation; When \( t=33\mu s \), the underlying aluminum alloy plate is penetrated, and the fiber layer in the middle is subjected to interlaminar shear and tensile stress when the sphere impacts the underlying aluminum alloy plate, resulting in delamination, which leads to interlaminar failure in some areas, and the penetration process of spherical bullet ends.

![Damage evolution process of projectile penetrating laminates](image)

**Figure 2.** Damage evolution process of projectile penetrating laminates

**Figure 3.** Kinetic energy time history curves of bullets with different initial velocities

**Figure 4.** Acceleration-time curve of bullet with different initial velocities
Figure 3 shows the kinetic energy time history curves of bullets with different initial velocities. It can be seen from Figure 3 that under the same initial kinetic energy condition, the higher the impact velocity, the more kinetic energy loss of the bullet. In the initial stage, the bullet compresses the laminate, and the laminate will be destroyed when it is compressed to a certain extent. The higher the velocity of the bullet, the more serious the compression degree of the laminate is, and the overall stiffness of the laminate increases with the increase of the compression degree. The bullet needs to consume more kinetic energy to break through the laminate with relatively large stiffness. Due to the different impact velocities, the energy transfer velocity between the bullet and the laminate is also different. This is because the time required for the bullet with high velocity to penetrate the laminate is shorter, that is, the contact energy exchange time between the bullet and the laminate is shorter. Therefore, when the initial velocity is 500m/s, the kinetic energy consumption velocity of the bullet is obviously faster than that of other cases.

Figure 4 shows the time curve of bullet acceleration with different initial velocities. It can be seen from Figure 4 that there are two peaks in the bullet acceleration curve under different working conditions. It is obvious that these two peaks are generated by the bullet penetrating the upper and lower aluminum alloy plates. The metal laminate has high strength and good impact resistance. It can bear the impact load efficiently and reduce the bullet velocity sharply. According to the comparison of acceleration curves in Figure 4, under the same energy condition, the initial velocity of the bullet is different, and the velocity decay rate is also different. In the process of impact, the higher the initial velocity of the bullet is, the faster the velocity attenuation.

3.2. Interlaminar damage analysis

Figure 5 shows the failure area diagram of each layer of laminate under the impact load with 200m/s. It can be seen from Figure 5 that the shape of the failure area of the metal layer is similar to that of the bullet plane, while the shape of the failure area of the fiber layer extends along the ply direction. This is because the fiber layer is an anisotropic material, and its modulus is high only in the ply direction. The force acting on the fiber layer will extend along the fiber ply direction, resulting in a large damage failure area in the ply direction. But the metal layer is isotropic material, and the elastic modulus of metal is much higher than that of fiber material, so the shape of the damaged area is compact and the divergence is small.

Figure 5. Failure area diagram of each layer of lower composite plate under the impact load with 200m/s
Figure 6 shows the area of damage area between different failure modes of the fiber layer. According to the comparison of matrix tensile failure (a), fiber tensile failure (c), tensile delamination failure (e), matrix compression failure (b), fiber compression failure (d) and compression delamination failure (f) in Figure 6, the failure area caused by tensile action is larger than that caused by compression action. The tensile force extends along the fiber direction, which makes the fiber layer produce further delamination failure, so the failure area caused by tensile force is large. Comparing the matrix tensile/compression failure area curve (a)/(b), fiber tensile/compression failure area curve (c)/(d) and tensile/compression delamination failure area curve (e)/(f) in Figure 6, fiber tensile/compression failure area is the largest, followed by tensile/compression delamination failure area, and finally the matrix tensile/compression failure area is the smallest. Under the initial conditions of the same kinetic energy, as the initial velocity of the bullet increases, the failure area of the glass fiber layer in different forms becomes smaller. This is because the higher the impact velocity, the shorter the contact time between the bullet and the laminate, so the damage to the laminate is relatively small. The change of impact velocity has little effect on the failure area of different forms of carbon fiber.

4. Conclusion

The process of bullets with the same energy and different velocities penetrating the aluminum alloy-carbon/glass fiber laminate was simulated, and draw the following conclusions: Under the condition of
the same kinetic energy, the higher the initial velocity of the bullet is, the faster the velocity of the bullet decays during the impact, and the more kinetic energy is consumed overall. On the whole, the shape of the failure area of the metal layer is similar to the shape of the bullet plane, and the shape of the failure area of the fiber layer will extend along the direction of the fiber layer. Whether it is a carbon fiber layer or a glass fiber layer, the tensile failure area is greater than the compression failure area. The fiber tensile/compression failure area is the largest, followed by the tensile/compression delamination failure area, and the matrix tensile/compression failure area is the smallest. As the bullet velocity increases, the failure area of the glass fiber layer in different forms becomes smaller, while the failure area of the carbon fiber layer in different forms does not change significantly.

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