

Research Article

Influence of Weakening Groove on Cutting Results of Composites Subjected to Shaped Charge Jet

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Carbon-fiber-reinforced polymer (CFRP) has been widely used in aerospace structures for its high strength to weight ratio and high stiffness to weight ratio. However, current pyrotechnic separation devices are mainly made of metal materials, the cutting research on CFRP composites is limited, and the effect of weakening groove on cutting results of composites is unclear under the action of shaped charge jet. In this paper, there firstly established a three-dimensional model of explosive cutting of CFRP composites by nonlinear finite element analysis (FEA), and based on the separation time, delamination, and kinetic energy of the laminate, the influence of weakening grooves on cutting results to the laminate is discussed. The results show that, in contrast to laminates with weakening grooves, laminates without weakening grooves increase the delamination of laminates. At the same time, here, we carried out the explosive cutting test on CFRP composites to verify the rationality of the simulation model. In addition, in order to obtain a better model under the action of shaped charge jet, we optimized the width and height of weakening groove by simulation calculation. Therefore, it proves that this study can guide the application of CFRP composites subjected to shaped charge jet in aerospace separation engineering.

1. Introduction

Based on the background of aerospace lightweight requirements, this study uses CFRP composites to replace metal separation shells to improve the lightweight efficiency of the structure. Furthermore, it is a forward-looking study for the lightweight requirements of the entire rocket transportation system. The stable operation of the pyrotechnics separation device will be affected by the separation shells, pyrotechnics products, and some protective measures, but the factor of the separation shell plays a decisive role in the separation efficiency. Therefore, this paper explores the influence of the weakening groove on the CFRP separation plate subjected to shaped charge jet. The related research work on the groove to the structure is shown as follows.

The groove plays an important role in the practical engineering. In the application of civil engineering, Wang et al. [1] studied the seismic behavior of self-buckling-restrained steel plate shear wall made by two incline-slotted infill plates,

which can avoid the cracks commonly encountered in solid steel filler plates under repeated shear buckling, and inclined steel strips are sequentially generated. Efforts are also made to influence the groove on the processing technology. Fan et al. [2] discussed the influence of spiral depth on melting process of PVC wood-plastic single screw extruder. In addition, in order to obtain the optimal structure of mechanical parts, some optimization work on grooves was carried out. Wang et al. [3] optimized the groove texture, resulting in greater bearing capacity. Numerical optimization of texture shape of parallel surfaces under unidirectional and bidirectional sliding conditions was implemented. The results showed that the best texture is chevron-shaped, with the front of one-way sliding, while the two-way sliding consists of paired trapezoidal shapes [4].

In particular, the application of weakening groove in the aerospace separation structure of mild detonating fuse is also introduced, as shown in Figure 1(a). The separation shell is usually made of metal material, which needs to be slotted in

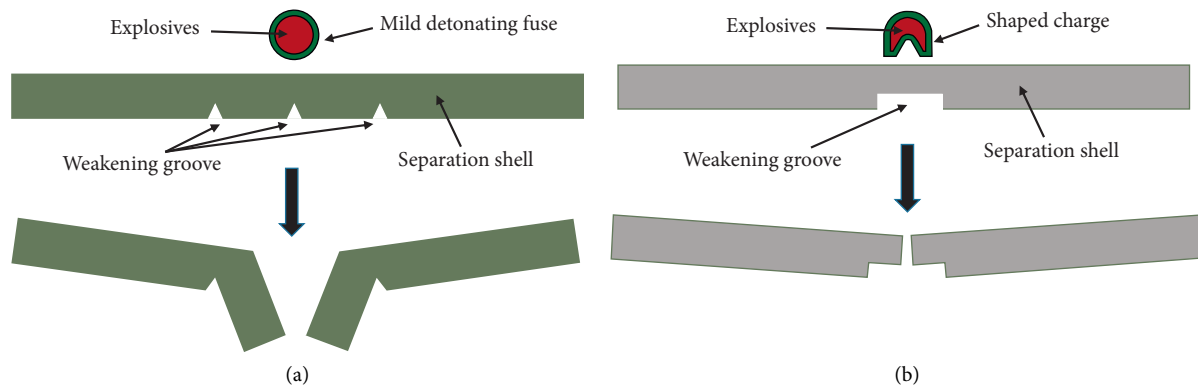


FIGURE 1: Separation structure: (a) mild detonating fuse; (b) shaped charge.

three places. The separation principle can be summarized as follows: after the explosive is detonated, it is disconnected along the prefabricated weakening groove under the action of the generated shock wave, so as to achieve the separation function [5, 6]. It can be seen that the weakening groove has an important application in the metal separation structure. The optimization of the weakening groove of the metal separation shell and the design of single graded groove heat pipe of the space station freedom heat rejection system have also been carried out [7, 8]. However, in this paper, composite materials are used instead of metal separation shell and the power source is a shaped charge which works differently from a mild detonating fuse (Figure 1(b)). Linear shaped charge is also an important pyrotechnic separation device for aerospace structures. The shaped charge cutting process of the composite materials is as follows: when the explosive in the shaped charge is detonated from the end, the detonation wave of the explosive acts on the metal liner and crushes it and then moves towards the central symmetry plane and impacts interact with each other [9, 10]. As a result, the inner wall of the metal liner forms a shaped charge jet, commonly known as the “shaped knife.” It is usually a high-speed metal flow in a plastic flow state with a head speed of several kilometers per second, which penetrates or cuts the target plate.

Although linear shaped charge has been widely used in many engineering applications [11, 12], the research in the literature on cutting or penetration under shaped charge jet mainly focuses on metal materials, described in brief as below. Guo et al. [13] have conducted penetration tests of shaped charge jet on pure copper target, carbon steel target, and Ti-6Al-4V alloy target. The penetration test of TC4 target has been carried out. The results show that the cutting section can be divided into two parts: the side near the shaped charge looks smooth and metallic, while the other side away from the shaped charge has fish-scale fracture due to penetration and spallation [14]. However, the research on composite materials under the action of shaped charge jet is limited. For example, compared with double steel hull, the damaged area of sandwich panel system (SPS) is smaller and the jet tends to bend and become thinner due to the resistance of composite layer, which indicates that polyurethane layer may have protective effect [15]. Jia et al. [16, 17]

discussed the protection ability of different types of woven fabric rubber composite armor against shaped charge jet impact. The above research on composite material subjected to shaped charge jet is not a real CFRP composite. Although Kuai et al. [18] designed a separation system for composite laminates for shaped charge jet and pointed out that the design has a good cutting effect, the cutting results of composite laminates were not shown and the structure proposed does not have weakening grooves.

The previous research obviously shows that the influence of groove on structure is mainly reflected in metal structure. However, the essential difference between anisotropy of composite materials and isotropy of metals will lead to different results. In addition, the cutting research of shaped charge jet on CFRP composites is far less mature than that of metal materials. Therefore, the above investigation extends to the following two problems to be verified: (1) under the action of shaped charge jet, whether the composites laminate has the necessity of weakening groove needs to be explored; (2) the influence of weakening groove on the cutting result of composite material needs to be discussed and analyzed. In this study, first take the weakening groove as the only variable of CFRP composite subjected to shaped charge jet and realize the simulation of composite cutting and separation. Then, carry out the cutting test and verify the simulation prediction. Based on the above analysis, it is clear that the weakening groove has an important influence on the cutting results. Subsequently, the factor of the height and width of the weakening groove is discussed to optimize the CFRP composite model subjected to shaped charge jet and provide guidance for composite material separation device in aerospace engineering.

2. Materials and Methods

The FEA and cutting tests of laminates subjected to shaped charge jet are described in following sections.

2.1. FEA Model of Composites Subjected to Shaped Charge Jet. Figure 2 shows the FEA model of two different composite laminate structures subjected to linear shaped charge jet. The structure includes laminate, air, and shaped charge. The

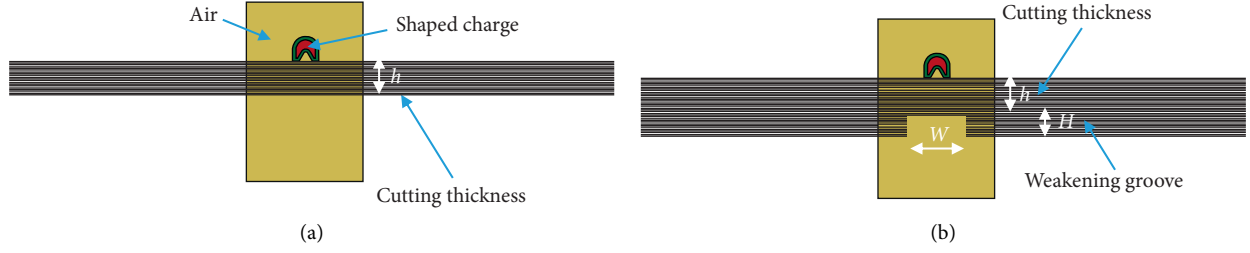


FIGURE 2: FEA model (a) without weakening groove and (b) with weakening groove.

shaped charge is made up of explosives, outer cases, and shaped charge liner. The outer case and the shaped charge liner are integrated. The width and height of the shaped charge are 2.3 mm and 2.1 mm, respectively. Arbitrary Lagrange-Euler (ALE) and Lagrange algorithm are used to deal with large deformation problems. For detonation loading, ALE elements are used for air and shaped charge and common nodes approach are applied. Considering deformation and failure of laminates, Lagrange algorithm is adopted.

For the laminate without weakening groove, the cutting thickness of the laminate is 3 mm in Figure 2(a). Considering that the weakening groove of the laminate is formed by machining, in order to avoid delamination damage of the laminate, the weakening groove is a rectangular groove. In Figure 2(b), the laminate includes a cutting thickness and a weakening groove thickness, and the thickness is 3 mm and 2.1 mm, respectively. The 1–20 layers of the laminate close to the shaped charge shows the corresponding cutting thickness, while the 21–34 layers are the region of the weakening groove. The basic lay-up direction of the laminates is $(\pm 45/90/0/(\pm 45)_4/0)_s$, and the thickness of each layer is 0.15 mm. According to different thickness requirements, there can have more lay or less lay. Based on linear cutting of the laminate, the cutting length of model is also 15 mm.

In detonation simulation, FEA models usually include the material constitutive model and the state equation. The constitutive model of related materials and the expression of state equation have been described in detail in the theoretical manual of LS-DYNA [19, 20]. The null constitutive model and linear polynomial equation of state are used to simulate air materials. The explosive is the modeling of the detonation of a high explosive and Jones-Wilkins-Lee (JWL) equation of state is chosen. The mass density, detonation velocity, and Chapman Joule pressure are 1.5 g/cm^3 , 7500 m/s , and 23.1 GPa , respectively. The outer case and shaped charge liner adopt Steinberg constitutive model and Gruneisen state equation. The orthogonal isotropic material model is used for the laminate, and the related material parameters are shown in Table 1. There are four failure modes of the material model: fiber tension mode, fiber compression mode, matrix tension mode, and matrix compression mode. Considering the delamination of the laminate, the tiebreak contact between layers is defined. The failure of layers will occur based on equation (1). $\text{NFLS} = 58.0 \text{ MPa}$ is the tensile failure strength, and $\text{SFLS} = 91.5 \text{ MPa}$ is the shear failure strength of layers.

TABLE 1: Material properties of unidirectional composite.

Parameter	Value
Density (ρ_0)	1.80 g/cm^3
Poisson's ratio (ν_{ba})	0.02
Shear modulus (G_{ca})	6.02 GPa
Longitudinal compressive strength (X_c)	1550 MPa
Transverse compressive strength (Y_c)	252 MPa
Transverse tensile strength (Y_t)	58 MPa
Longitudinal modulus (E_a)	148 GPa
Transverse modulus (E_b)	10.3 GPa
Shear modulus (G_{ab})	6.02 GPa
Shear modulus (G_{bc})	3.93 GPa
Longitudinal tensile strength (X_t)	1930 MPa
Shear strength (S_c)	91.5 MPa

The subscript "a" is fiber direction and subscripts "b" and "c" are the transverse direction.

$$\left(\frac{|\sigma_n|}{\text{NFLS}} \right)^2 + \left(\frac{|\sigma_s|}{\text{SFLS}} \right)^2 \geq 1. \quad (1)$$

2.2. Cutting Tests of Laminates. In term of the presence or absence of weakening grooves, cutting tests have been carried out on different laminate with or without weakening grooves. The cutting test of composites separation device with weakening groove is shown in Figure 3, which is the same as the cutting test structure of the composites separation device without weakening groove. In the test, the structure consists of shaped charge and laminates. The shaped charge adheres to the surface of laminates. Then, the laminate is clamped to ensure the clamped state during cutting. After the explosive is detonated, the laminate is cut into two parts under the action of jet and stress wave to achieve separation. The cutting thickness of the laminate without weakening groove is 3 mm. Although the thickness of laminates with weakened groove is 5.1 mm, the actual cutting thickness is also 3 mm. The shape of the shaped charge liner is V-shaped, which can generate high-speed jet and improve penetration depth, and its material is lead. Hexogeon is used as explosive to improve cutting ability. The linear density of shaped charge is 2.3 g/m . Single-point initiation and linear cutting are adopted in the test. The laminate consists of carbon fiber and bismaleimide resin. The laminate is laid in the form of a stack according to the specified fiber direction and glued, followed by heating and curing processes. According to different requirements, lay-

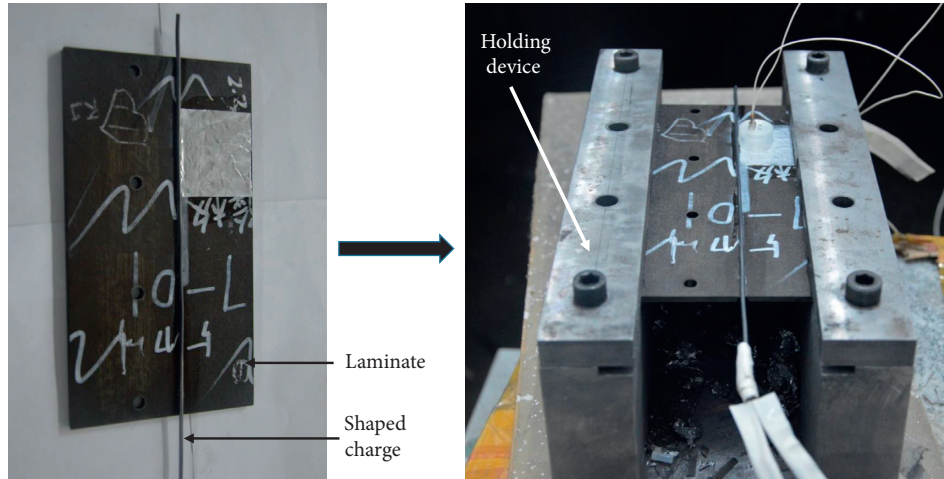


FIGURE 3: Cutting tests of composites subjected to shaped charge jet.

up method selection and thickness design are carried out. The lay-up of the laminate is consistent with that used in the above FEA model.

3. Results and Discussion

In the following sections, we will analyze and discuss the influence of weakening groove on cutting results based on the FEA and cutting tests.

3.1. Influence of the Weakening Groove on Cutting Results by FEA. The pros and cons of the whole structure are evaluated by the separation time and delamination as the evaluation criteria of cutting results. In particular, this paper focuses on the delamination of laminates. The separation time refers to the time required for the laminate to be divided into two parts. Generally, for aerospace structure, the less separation time, the better.

The delamination is a common failure mode of high-speed impact. In this paper, the delamination of laminates refers to the thickness change rate of laminates before and after cutting. Considering the difference between the displacement of feature points on the front and back of the laminate and the original thickness of the laminate, the delamination degree of the laminate in the thickness direction can be expressed as $\varepsilon = |u_{\text{back}} - u_{\text{front}}|/L_0$. The u_{front} and u_{back} represent Z displacements of feature points of the front layer and back layer, respectively. The L_0 represents the original thickness of the laminate. The distance between feature points and the centerline of the shaped charge is d . Each group of feature points has the same distance d , and 11 groups of feature points are extracted from the front and back of the laminate with $d = 5 \text{ mm} - 15 \text{ mm}$. Calculate the average displacement of each group of feature points. The calculation diagram of the ε and the distribution of feature points are shown in Figure 4.

Figure 5 shows the change of shaped charge jet morphology. When the explosive is detonated, a high-speed and slender jet is formed at $t = 1.75 \mu\text{s}$ and the jet has a strong cutting ability. At $t = 5 \mu\text{s}$, the jet continues to accumulate

and the shape of its head shows a “coarse” shape. Although the jet may be discontinuous, the laminate tends to shear failure. As the cutting progresses, at $t = 14.5 \mu\text{s}$, the jet velocity decreases and its shape has changed to a “double-wing” appearance. At this moment, the jet has no cutting ability and the laminate is more likely to have tensile failure under the tensile action of stress wave. More research on the cutting mechanism of laminates subjected to shaped charge jet can be referred to the literature [21].

The cutting process of two different laminate structures is shown in Figure 6. It should be pointed out that the cutting width represents the distance between the removed units of the laminates under detonation. Obviously, the cutting width is smaller near the side of the shaped charge, while it is larger near the weakening groove. The shear failure and tensile failure modes of the laminate are shown from the side near the shaped charge to the side near the weakening groove [21]. The reason for this phenomenon is that, under the high-speed jet, the laminate near the shaped charge has no time response to produce shear failure. However, the sublayer near the back of the composite tends to be tensile failure due to the complex coupling of shock wave and jet. References [22, 23] on high-speed impact of composites laminate give similar conclusions. In addition, it is obvious that the delamination near the weakening groove (or the back of the laminate) is greater than that near the shaped charge.

Figure 7(a) shows the separation time of the model without and with weakening groove. For the models without and with weakening groove, the separation time is $19.5 \mu\text{s}$ and $19.75 \mu\text{s}$, respectively. Obviously, the separation time is almost the same. It should be pointed out that, in the FEA, the statistics of separation time are not called separation until the cutting width of each sublayer has a through seam.

In addition, the delamination of the laminate with two structures is shown in Figure 7(b). Firstly, the closer it is to the centerline of the shaped charge, the more severe the delamination is. The cutting result of the model with weakening groove is obviously better than that of the model without weakening groove. Especially, when the distance is

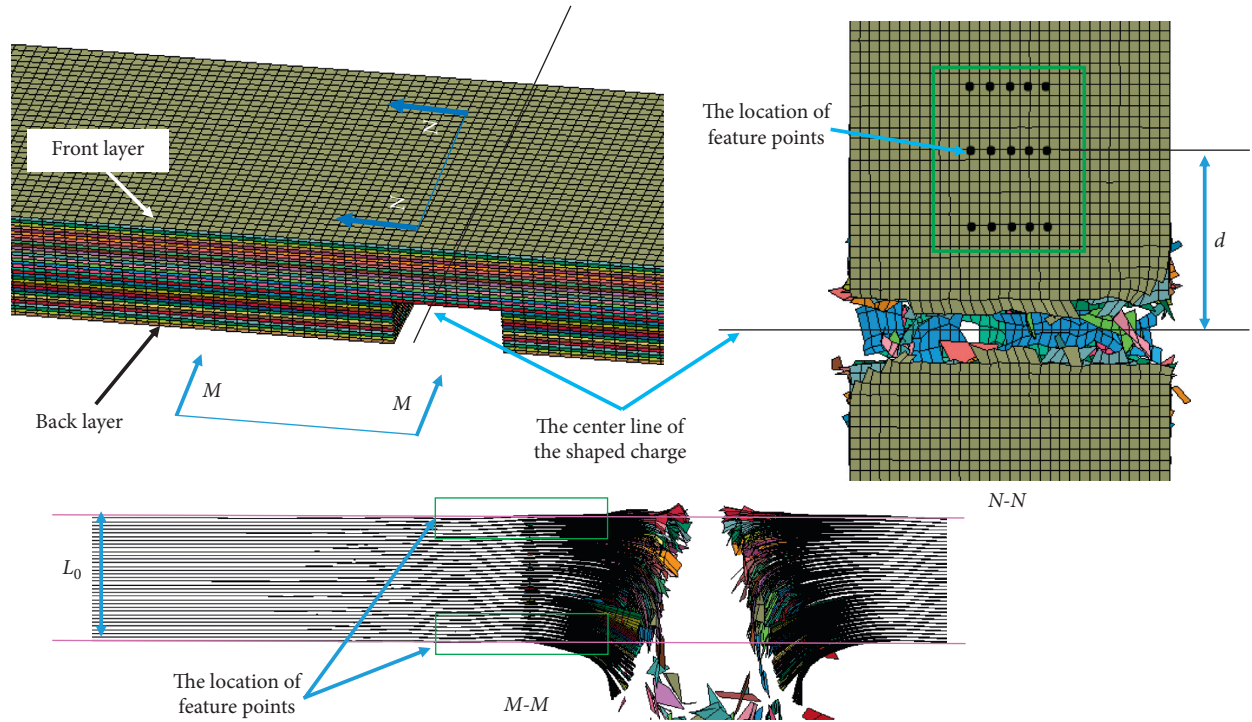


FIGURE 4: Evaluation of the delamination of the laminate.

$d = 5$ mm, the delamination degree is 0.371 and 0.214, respectively, and the delamination degree of the laminate without weakening groove is about 73% higher than that of the laminate with weakening groove. Therefore, it is obvious that the weakening groove plays an important role in the cutting process in the aspect of the delamination.

Next, the influence of weakening groove on delamination is briefly explained by the change of kinetic energy of sublayer with time in Figure 8. Generally speaking, the kinetic energy curve of sublayer shows a trend of increasing at first and then decreasing. The reduced kinetic energy is converted into deformation energy, delamination, etc.

First, for the model without weakening groove, it should be noted that the energy of the sublayers (17–20 layers) of the laminate is obviously greater than that of the 1–16 layers (Figure 8(a)). For the model with weakening groove, the energy of 1–20 layers is similar to that of the model without weakening groove, and the energy of the four sublayers (17–20 layers) near the weakening groove is greater than that of the adjacent sublayers (Figure 8(b)). In general, at about $7.5 \mu\text{s}$, because the sublayer near the shaped charge broken by jet, the value of the curve decreases to little, while the sublayer near the weakening groove (17–20 layers) keeps a certain value instead of decreasing. Sublayers (17–20 layers) are in tension state under the action of stress wave. The greater the kinetic energy, the stronger the inertial stretching effect, resulting in more serious delamination. In addition, Figure 8(c) shows the sum of kinetic energy of 17–20 layers. Obviously, in the later stage of jet cutting, the sum of kinetic energy of 17–20 layers of the model without weakening groove is 20% higher than that of the model with weakening groove.

Therefore, on the one hand, the tensile tendency of the sublayer near the weakening groove is more obvious, which is more likely to lead to delamination damage. On the other hand, based on the sum of kinetic energy of 17–20 layers, the delamination degree of the model without weakening groove is more serious than that of the model with weakening groove. In short, weakening groove plays an important role in the delamination of the laminate.

3.2. Test Results. Figure 9 shows the cutting tests results of the laminate without and with the weakening groove. In term of cutting damage of the laminate, it is clear that the laminate with the weakening grooves is cut apart and the cutting fracture is obviously neat in visual inspection, while the laminate without weakening grooves is not cut apart and shows long fibers pullout, surface shedding, and serious delamination failure. To characterize the delamination of the laminate in the thickness direction, in a similar way to the simulation acquisition layering, the thickness change rate can be expressed as $\varepsilon = |D - D_0|/D_0$, where D represents the thickness of the laminate after cutting and separating and D_0 represents the initial thickness of the laminate.

In the test, ε of the laminate with the weakening groove is 0.232 at $d = 5$ mm. With the comparison between the FEA and the experimental results, the error of ε is 8%. It shows that the FEA model can reproduce the experimental results in a reasonable range, which proves the rationality of the simulation model. It is also found that the delamination near the weakening groove is larger than that near the shaped charge. For laminates without weakening groove, ε is 0.765, and the error between FEA and test is as high as 51%.



FIGURE 5: Change of shaped charge jet morphology.

Obviously, the simulation results are quite different from the experimental ones. It should be pointed out that because the shaped charge is lead material, and its soft property cannot guarantee that shaped charge is completely vertically adhered to the upper surface of the laminate, which will cause

the shaped charge jet not cut the laminate vertically. In the test, such a phenomenon may lead to insufficient use of shaped charge, thus weakening the cutting ability. The existence of such phenomenon may cause the uncut laminate to be pulled by its own inertia all the time, resulting in more



FIGURE 6: Cutting process of the laminate (a) without and (b) with weakening groove.

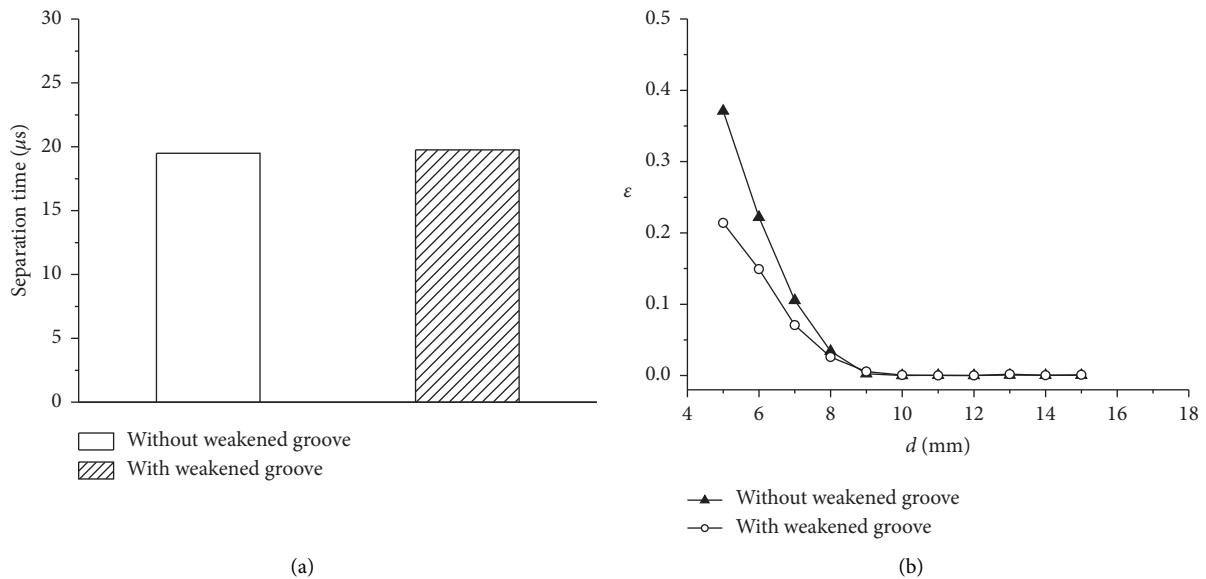


FIGURE 7: Influence of weakening groove on cutting results: (a) separation time; (b) delamination.

serious delamination, which will lead to greater difference between simulation prediction and test results.

In addition, the high-altitude and high-speed shedding may cause damage to related instruments of rockets or ground objects. For the laminate without the weakening groove, the surface of laminated plates will fall off and crack seriously, which is caused by tensile stress wave generated by the impact on the free surface [24], while for the laminate with weakening grooves, there are only few cracks on the surface of laminates.

Considering the amount of explosive will affect the cutting results of the laminate without weakening groove, the linear density of shaped charge increases to 4.0 g/m and the protective cover is added, as shown in Figure 10. In the process of cutting and separating, the protective cover can

protect the internal instruments from the strong shock wave caused by explosion and debris destruction after separation. The test results show that, although the laminate is cut apart, the delamination is still serious. It is seen that for the above mentioned laminate which has not achieved cutting separation, the weakening groove is the dominant factor.

To sum up, from the cutting test results, it proves that the weakening groove has an important influence on the cutting of the laminates. Weakening grooves can effectively reduce the delamination degree and surface damage of laminates. Therefore, the above conclusions can verify the rationality of the simulation model to a certain extent. At the same time, it is necessary to design weakening grooves to get the optimal structural model for the aerospace applications under the action of this kind of shaped charge.

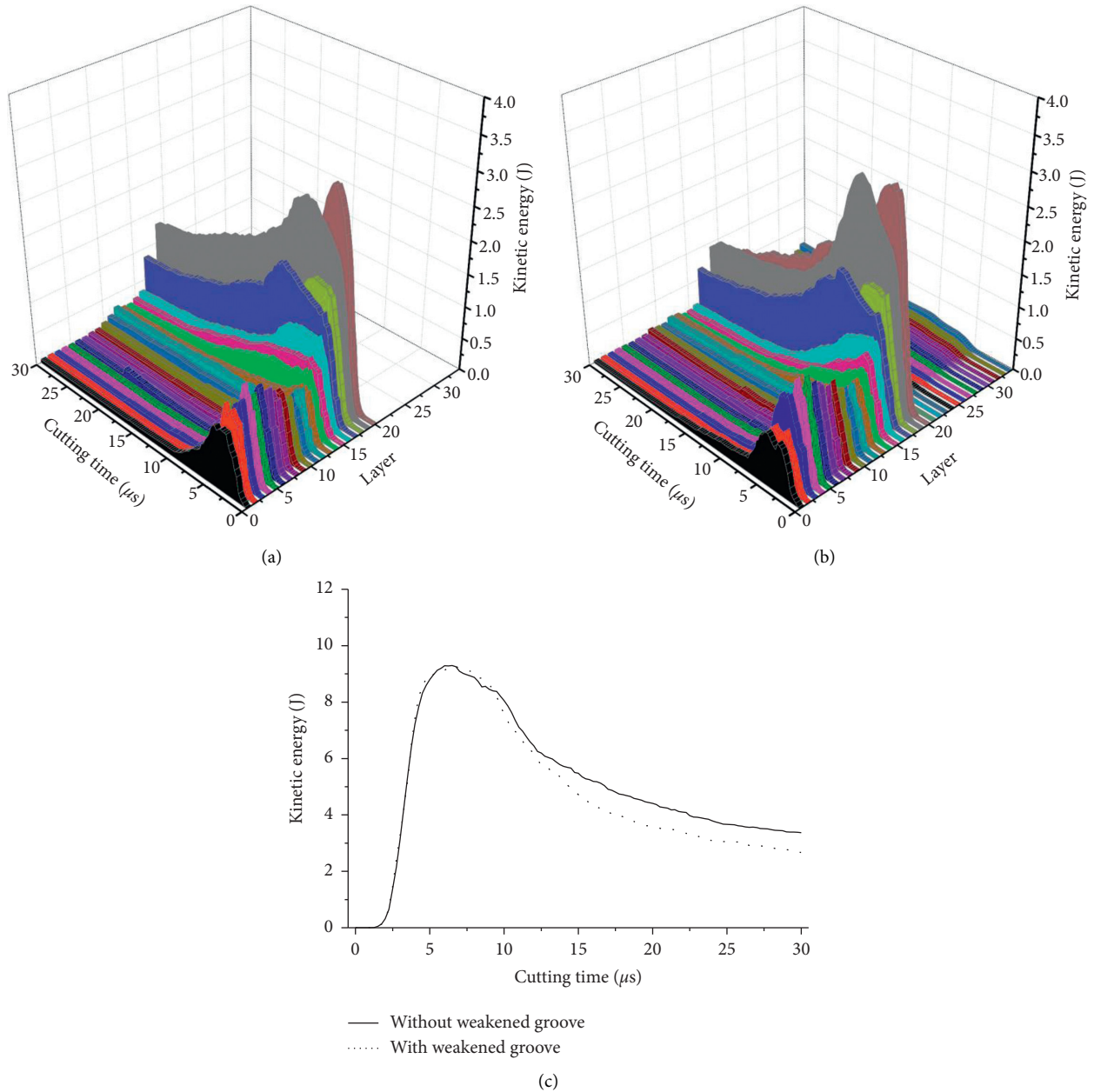


FIGURE 8: Changes of kinetic energy of sublayers (a) without and (b) with weakening groove; (c) sum kinetic energy of 17–20 layers.

3.3. Influence of Width and Height of Weakening Groove on Cutting Results. Although we have previously discussed the effects of cutting thickness, interlaminar tensile strength, and linear density of shaped charge on delamination before [25], the study on the cutting results of weakening grooves on laminated plates is not in depth. In this section, we will discuss the width (W) and height (H) of the weakening groove (marked in Figure 1) and analyze the cutting results of the laminate according to the separation time and delamination of the laminate. In particular, the delamination of laminates is the key point. The basic lay-up direction of the laminate is $(0/+45/-45/-90)$ based on subsequent design requirements, and the thickness of the laminate can increase or decrease the

layering according to basic lay-up. The cutting thickness is still 3 mm. According to the actual width requirement of the shaped charge, the width of the weakening groove (W) is 3 mm, 5 mm, 10 mm, and 20 mm. The height of the weakening groove is 0.6, 1.2, 1.8, 2.4, and 3 mm, respectively, and the ratio of the thickness of the weakening groove to cutting thickness (H/h) is $1/5$, $2/5$, $3/5$, $4/5$, and 1, respectively. Therefore, a total of 20 models have been simulated and predicted, aiming at selecting the best structural model to achieve better cutting results in this cutting environment. It should be noted that, in the following articles and figures, the 3 mm- $1/5$ represents that W is 3 mm and the H/h is $1/5$. The representation of other models is similar.

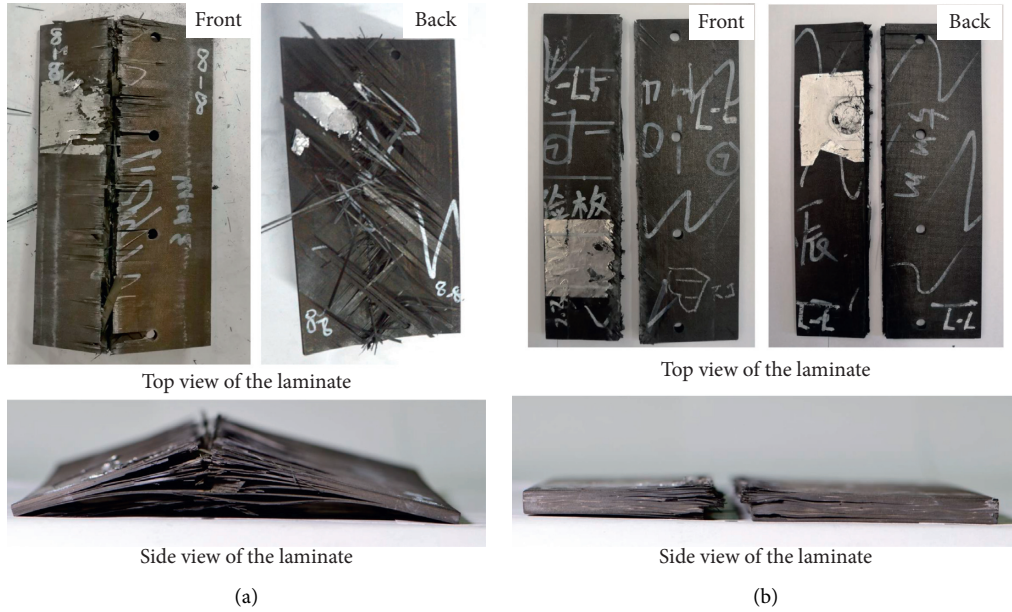


FIGURE 9: Cutting tests results of the laminate (a) without and (b) with weakening groove.

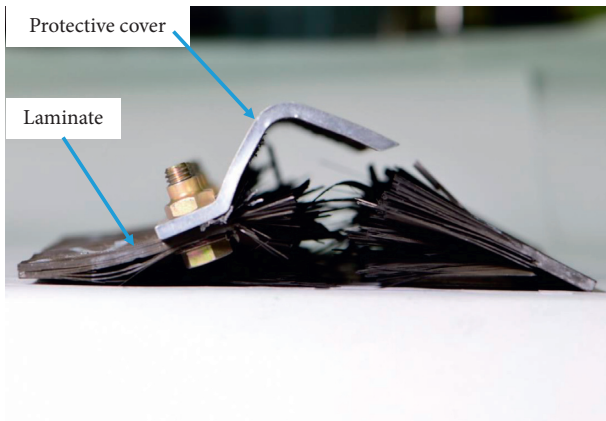


FIGURE 10: Cutting tests results of the laminate when the linear density of shaped charge is 4.0 g/m.

Figure 11(a) shows the separation time corresponding to different models. The average separation time of the 20 models is 18 μ s. It is found that the change of other models is almost controlled at 10%, except for the long separation time of some models. Figure 11(b) shows the delamination of the laminate of different models. It is seen from the curve trend that, for all models, the closer the center line of the shaped charge, the more obvious the delamination. In case of different models, the value is almost zero after the distance $d = 9$ mm, which means that there is no delamination outside 9 mm. Based on the above analysis, the value ϵ at $d = 5$ mm and the average of ϵ from $d = 5$ mm to $d = 8$ mm are analyzed.

For the ϵ at $d = 5$ mm in Figure 11(c), it represents the maximum delamination acquired in this paper. The maximum delamination can directly characterize the delamination of laminates. Affected by the volatility of stress wave and weakening groove parameters, ϵ is not a monotonous increase or decrease, but a certain degree of dispersion. The

value of ϵ at $d = 5$ mm is 0.098, 0.123, 0.127, 0.134, and 0.146 for the model of the 10 mm-1, 10 mm-4/5, 5 mm-1, 5 mm-4/5, and 10 mm-3/5, respectively. Compared to the other 15 models, it is clear that ϵ at $d = 5$ mm of these 5 models is the smallest by getting the top 25% of models, indicating that these models can be used as the optimization model in terms of maximum delamination. The average of ϵ from $d = 5$ mm to $d = 8$ mm also is acquired in Figure 11(d), and its trend is almost consistent with ϵ at $d = 5$ mm. Obviously, when the width of the weakening groove is set to $W = 3$ and $W = 20$, it is not appropriate. When W is 3, the boundary is closer to the shaped charge than other weakening groove widths. The greater detonation action of the boundary will cause greater delamination of the laminate. In terms of $W = 20$, for a shaped charge with a linear density of 2.3 g/m, the laminate structure is very close to the case without weakening grooves.

To sum up, through the above argumentation, the separation time of all models is μ s level, which is relatively close at present. As mentioned above, the delamination is an important failure mode of the laminate in shaped charge cutting. For all models, the horizontal delamination of the laminate is controlled within 9 mm. In terms of delamination in thickness direction, the models of 10 mm-1, 10 mm-4/5, 5 mm-1, 5 mm-4/5, and 10 mm-3/5 are better. On the one hand, from the perspective of aerospace lightweight, it is not recommended to have too thick weakening grooves, so the 10 mm-1 and 5 mm-1 models are not considered for the time being. On the other hand, although the best model can be selected by separation time, it is unreasonable to make such a discrete comparison. Therefore, for the shaped charge cutting design of the laminate, this study gives a certain range, which are as follows: if $W = 5$ mm, it shall be $(3/5) < (H/h) \leq (4/5)$, and if $W = 10$ mm, it shall be $(2/5) < (h/H) \leq (4/5)$.

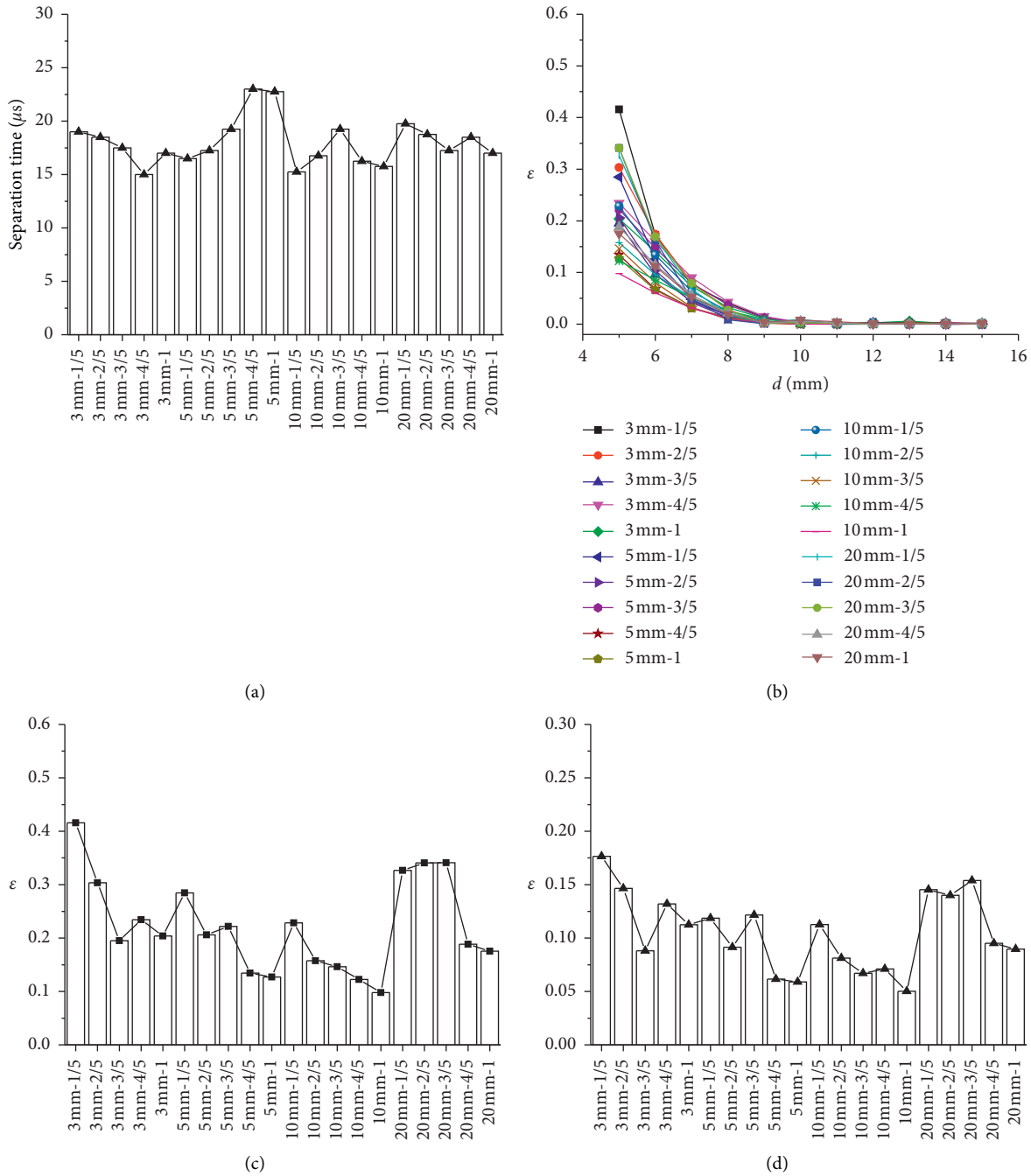


FIGURE 11: Effect of weakening grooves on cutting results: (a) separation time; (b) ϵ at different distance; (c) ϵ at $d=5$ mm; (d) average of ϵ from $d=5$ mm to $d=8$ mm.

4. Conclusions

In this work, the FEA method with ALE and Lagrange element is employed to simulate the cutting process of CFRP composites, and shaped charge jet cutting tests are carried out on the laminate without and with weakening grooves. From the aspect of weakening groove, based on the separation time, delamination, and kinetic energy of the laminate, this paper discusses and analyzes the influence of the weakening groove on cutting results of the laminate. In addition, the width and height of the weakening groove are

optimized to obtain the best cutting model. The following conclusions are drawn.

- (1) For the delamination of the laminate with weakening groove, the FEA results agree well with the experimental results, which verify the rationality of the simulation method. This method can provide guidance for the optimal design of CFRP-based pyrotechnic separation devices in the future.
- (2) For the FEA prediction and cutting tests, the weakening groove plays an important role in the

cutting process of the laminate and the cutting results of the laminate with the weakening groove is better than that without the weakening groove. In addition, the influence of the weakening groove on the cutting results of the laminate is illustrated by obtaining the kinetic energy of the sublayer. Especially, based on the total kinetic energy of 17–20 layers, the delamination of the model without weakening groove is more serious than that of the model with weakening groove.

- (3) In the process of verifying the importance of weakening groove, although the linear density of shaped charge is increased from 2.3 g/m to 4.0 g/m and the cutting separation of 3 mm laminate without weakening groove has been realized, the cutting results show that the delamination of the laminate is very serious. Therefore, for the cutting design of CFRP composites, it shall not blindly increase the explosive quantity to realize separation but consider the characteristics of the separation plate.
- (4) For the shaped charge with a linear density of 2.3 g/m, in order to achieve better cutting results, this study completed the simulation calculation of 20 models with different widths and heights of weakening grooves. The results show that, on the one hand, due to the influence of the width of the shaped charge, the boundary of the laminate with $W = 3$ mm is subjected to greater detonation, which leads to greater delamination. While if $W = 20$ mm, the laminate is equivalent to that without weakening groove. On the other hand, for all models, although the separation time does not change much, based on the maximum delamination and average delamination in thickness direction and the lightweight requirements of the aerospace structure, this study gives a better design scheme, when $W = 5$ mm, $(3/5) < (H/h) \leq (4/5)$, and for $W = 10$ mm, $(2/5) < (H/h) \leq (4/5)$.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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