Rapid Communication

Ju Qiu*

Research and analysis on low-velocity impact of composite materials

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Abstract: In this article, the concept of low-velocity impact resistance in composite materials is presented. Three existing expressions (e.g., bilinear, parabola, and exponential) that show the relationship between the dent depth and impact energy of composite laminates subjected to low-velocity impact are presented. Because of some flaws in these expressions, new supposed functions between impact energy and impact dent have been established. By means of existing ASTM D 7136 tests and simulation analysis, the new expressions are verified, and the nature of dent formation in composite materials is well explained. The conclusion is reflected in the ending part.

Keywords: low-speed impact, dent depth, impact energy, composite

1 Introduction

In recent years, fiber-reinforced resin matrix composites have been extensively used in aerospace structures due to their high specific strength, specific stiffness, corrosion resistance, and fatigue resistance. Composites have successfully replaced aluminum in the complex shapes of rotor blades, wings, stabilizers, and fuselage structures. Boeing 787 and Airbus 380s use 50% or more of their structural weight in composite materials. It is anticipated that the use of composites will continue to increase in all types of aircraft.

The composite structures in aviation will encounter many kinds of impact, such as runway rubble, tool falls, bird strike, hail, collisions with ground equipment, and so on. Of all these impacts, low-velocity impacts (tool falls, etc.) are the most common and usually occur during assembly, daily use, and repair and maintenance. In particular, accidental collisions with ground-handling equipment account for 50% of the major damage to commercial aircraft and 60% of the minor damage, and they also cause significant internal damage to airframe structures.

The test results show that the low-velocity impact causes internal damage to the composite structure, which leads to large-area delamination and reduces strength (including tension, compression, shear, and bending) and stiffness. Composite structures may lose up to 50% of their carrying capacity due to delamination, so it is critical to understand and predict the response of the composite under different impact conditions before designing structures. Since the last century, researchers at home and abroad have carried out a great deal of research work in the field of testing and analysis of impact damage to composites. At the end of the last century, Rouchon [1] emphasized the need to clearly define two distinct energy cut-off thresholds, dedicated, respectively, to static strength and damage tolerance requirements for low-velocity impact. Shen et al. [2] did the standard test for low velocity from the ASTM D 7136 standard and studied its trend. Adin and Adin [3] also studied the mechanical properties of composite materials produced from woven jute type by the ASTM D standard test. After that, Zhang and Zhang [4] analyzed the damage to composite laminates under low velocity and gave the function of the dent depth. Hussain et al. [5] used drop-weight impact testing for the study of energy absorption.

In the last century, researchers also pointed out that the impact resistance of composite materials included damage resistance and damage tolerance, so the structural integrity requirements of composite aircraft also include these two aspects. In general, damage resistance is defined as a measure of the force, energy, or other parameters associated with an event or series of events. The impact damage resistance of composite laminates is different for different impact energies, so the relationship between impact damage size and different impact energy should be completely described. In fact, there are three

* **Corresponding author: Ju Qiu,** COMAC Beijing Aircraft Technology Research Institute, Beijing Key Laboratory of Civil Aircraft Structures and Composite Materials, Beijing, 102211, China, e-mail: qiu_x_j@126.com

methods to measure the damage size: the damage area, the damage width, and the impact dent depth. Therefore, the impact resistance can be expressed by the damage area, the damage width, and the dent depth after impact. Cantwell and Morton, Wilson Tsang and Dugundji, Shen et al., Safri et al., and Shah et al. [6–10] introduced the impact resistance of composites and relative parameter studies of it. Adin and Kilickap [11] introduced other resistances to seawater corrosion and good cold workability.

With the extensive application of composite materials in structures, the analysis of composite structures, especially that of impact dynamic response, appears to be of very practical significance. Owning to the long period, difficult operation, and huge cost, it is difficult to obtain the expected abundant data results. Since the 1980s, the dynamic response of the existing structure has been analyzed through simulation analysis, and good results have been obtained. With the development of computer technology and the deep research of finite element theory, numerical simulation technology has become more and more commonly used in all walks of life. In recent years, a large number of experts and scholars have carried out the finite element simulation analysis [12–17] of composite materials and the corresponding failure mechanism research [18–22], combined with tests to verify the rationality of the simulation analysis and failure criteria.

In the current study, the first part introduces three existing expressions (e.g., bilinear, parabola, and exponential) to show the relationship between the dent depth and the impact energy of the composite material. A new formula is also envisaged to express. Then, the impact simulation of the ASTM D 7136 test in ref. [2] was done. Compared with the experimental data in Figure 3 of ref. [2], the dent depth of impact resistance of composites has also been re-recognized, and the properties before and after the inflection point of dent depth are explained reasonably. The fitting data are defined as a function of the piecewise nonlinear relationship between the impact energy and the dent depth. Finally, the summary and conclusion are presented in the end part.

2 Preliminary study for impact resistance

After many scholars had summed up various experiments, they concluded that there existed a certain relationship between the dent depth and impact energy of composite laminates subjected to low-velocity impact, as discussed in Sections 2.1–2.4.

2.1 Bilinear expression

Through lots of tests for low-velocity impact, the engineers found that when the impact energy exceeded a certain value, the dent depth of the composite laminate rose sharply after impact, which is called the dent inflection point. The curve defined is shown in Figure 1.

In Figure 1, E_0 shows the corresponding impact energy for the initial dent, while E_C shows the corresponding impact energy for the inflection point of the dent. From it, the curve is simple and rough, and it can be observed that the approximate linearity of the impact energy and the depth of the dent must be inaccurate.

2.2 Parabola expression

Based on the experiment, the impact energy and dent depth curve equation are fitted by Zhang XJ [4], while the impact energy is calculated according to the dent depth on the surface of the laminate. Then, the impact energy is taken as the external load to simulate the damage to the laminate.

According to Figure 2 of ref. [4], the fitted parabola of the dent depth vs impact energy is illustrated in equation (1) in terms of test data as follows:

$$E = k\delta^{1/3}, \quad (1)$$

where $k = \frac{1}{2}\sqrt{R}\left(\frac{1-v_s^2}{E_s} + \frac{1}{E_z}\right)^{-1}$ is the contact coefficient, which is related to the material characteristics of the impactor and the shocked object. In the formula, v_s and E_s are the Poisson's ratio and elastic modulus (MPa) of the punch, respectively; E_z is the elastic modulus (MPa)

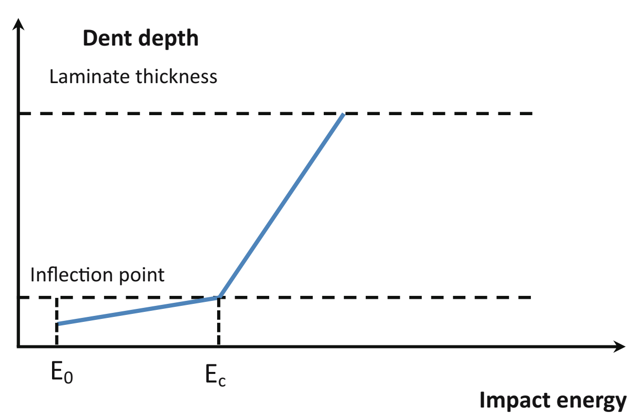

Figure 1: A diagram of the dent depth-impact energy curve of laminates under low-velocity impact.

of the outermost layer of the laminates in the thickness direction, which can be replaced by the transverse elastic modulus E_y of the unidirectional laminates in the absence of test data; R is the radius of the punch; δ is the dent depth (mm) of the laminate; and E is the corresponding impact energy (J).

There are two problems with this formula: (i) one is that the depth of the dent exists even when the impact energy is very small, but there are no dents on the surface of the composite laminate when the impact energy is very small, and (ii) the other is that the dent inflection point does not appear in the formula.

2.3 Exponential expression

According to the study by Rouchon [1], the depth of the dent in a laminate caused by a low-speed mechanical impact of an external object can be expressed as follows:

$$\delta = C_{m1}e^{C_{m2}\cdot E\cdot f(t)\cdot f(w)\cdot f(D)}. \tag{2}$$

In the formula, E is the impact energy; $f(t)$ is the thickness correction factor; $f(w)$ is the width correction factor; $f(D)$ is the punch diameter correction factor; and C_{m1} and C_{m2} are the empirical parameters related to material properties.

't' is the thickness of the laminate. If $\delta > t$, then order $\delta = t$. At this point, the laminate is penetrated, and even if the impact energy continues to increase, the depth of the dent does not vary. When the geometric characteristics of the material and the laminate are selected, the dent depth of the laminate can be expressed as an exponential function of impact energy, as shown in Figure 2.

From Figure 2, it can be seen that the curve after the inflection point corresponds to the onset of fiber fracture in the laminates. After the inflection point, the depth of the dent increases more rapidly with the increase in impact energy. However, when the impact energy is smaller (= 0), it is still possible to deduce that there is a dent () according to the formula, which is not consistent with the nature of the impact phenomenon.

2.4 Assumption of the new dent expression

Numerous investigations indicated that the inflection point of the impact energy or dent depth of composite laminates indeed existed. If it is divided into two parts from the inflection point, they are two-segment nonlinear curves. Therefore, the double nonlinear curve is proposed to represent the depth-energy curve of the dent under low-velocity impact. Refer to the red line in Figure 3.

3 Simulation of the ASTM D 7136 test

3.1 Analysis model

According to Zhen Shen's test [2], the finite element model is created in Figure 4.

The punch mass and diameter were 3 kg and 16 mm, respectively. The impact velocity ranged from 2 to 4.6188 m/s, whose impact energy was from 6 to 32 J. The four-sided edges were fixed. The size of the laminate was 150 mm × 100 mm. The ply order was [45/0/−45/90]4s. The laminate material was T300. The simulation size is shown in Table 1.

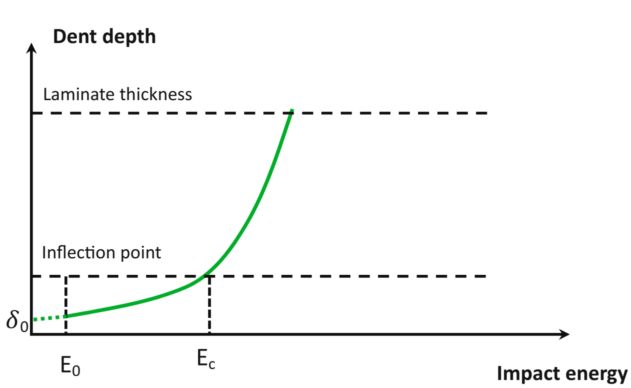

Figure 2: A diagram of the dent depth-impact energy curve of laminates under low-velocity impact.

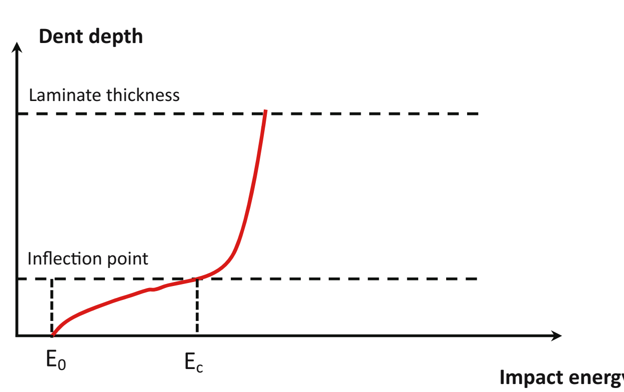

Figure 3: A diagram of the dent depth-impact energy curve of laminates under low-velocity impact.

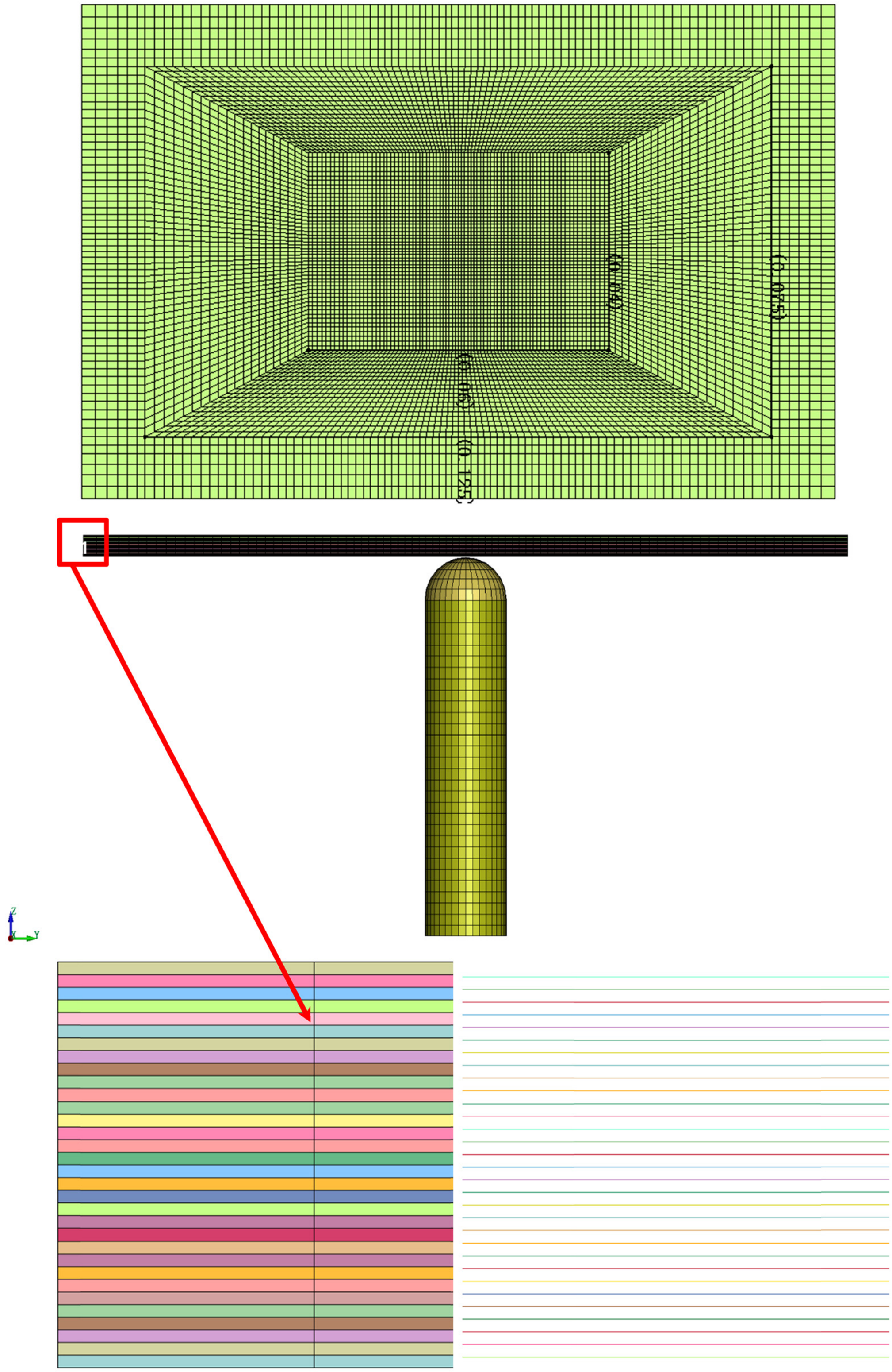

Figure 4: The finite element model of impact.

Table 1: The size of the finite element model

Parts	Nodes	Elements
Impactor	5003	4860
Laminate	707742	686952

3.2 Failure criteria

3.2.1 Composite failure criteria

In the current study, the LaRC criterion [23,24] that is based on the continuum damage model is applied.

The evolution of threshold (internal) variables is derived in equations (3) and (4) as follows:

$$\text{Compression}: r^{n+1}_{1-/2-} = \max\{1, r^{n}_{1-/2-}, \varnothing^{n}_{1-/2-}\}, \quad (3)$$

$$\text{Tension}: r^{n+1}_{1+/2+} = \max\{1, r^{n+1}_{1+/2+}, \varnothing^{n+1}_{1+/2+}\}. \quad (4)$$

Among them, r is the failure value for fiber or matrix tension or compression; $\varnothing$ is the fracture plan for pure tension or compression.

1) Tensile fiber mode (maximum strain – LaRC04)
   The tensile fiber mode is shown in Figure 5.
2) Compressive fiber mode (LaRC03)
   The compressive fiber mode is shown in Figure 6.
3) Tensile matrix mode (LaRC04)
   The tensile matrix mode is shown in Figure 7.
4) Compressive matrix mode (transfer fracture plane – LaRC04)
   The compressive matrix mode is shown in Figure 8.

The evolution of damage variables is shown in Figures 9 and 10.

In the above figures, l is the internal (characteristic) length for objectivity; X_{TO} is longitudinal tension strength at an inflection point; G_{XT} is fracture toughness for longitudinal (fiber) tensile failure mode; G_{XTO} is fracture toughness for longitudinal tension failure bi-linear damage; and G_{YT} is fracture toughness for transverse tension failure mode.

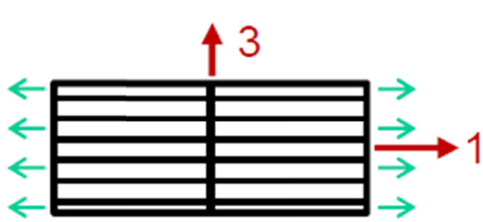

Figure 5: The tensile fiber mode.

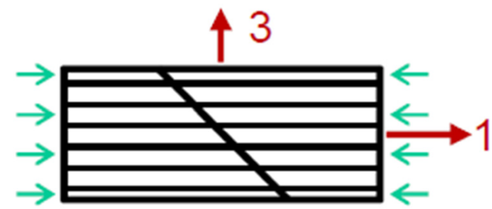

Figure 6: The compressive fiber mode.

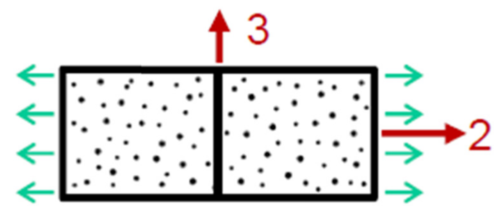

Figure 7: The tensile matrix mode.

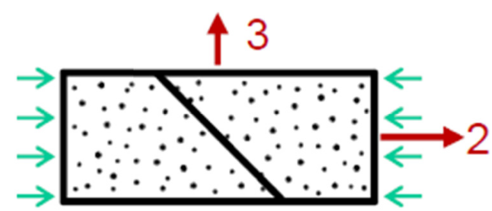

Figure 8: The compressive matrix mode.

3.2.2 The B–K fracture criterion for cohesive elements

The cohesive element [23,24] is defined in Figure 11.

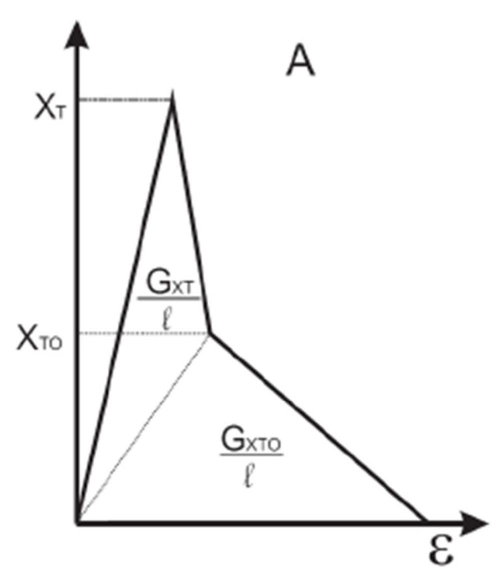

Figure 9: Bi-linear in the fiber direction.

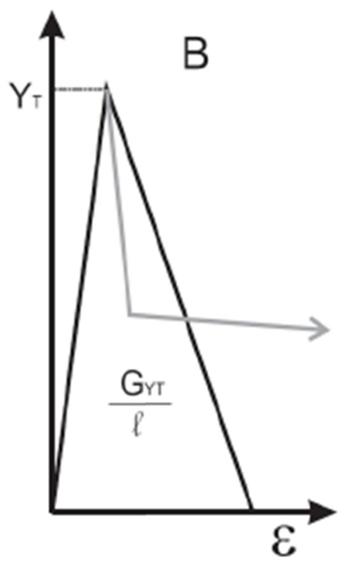

Figure 10: Linear in the transverse direction.

The B–K fracture criterion is particularly useful to describe delamination propagation, as in equation (5):

$$G^c = G_n^c + (G_s^c - G_n^c)\left(\frac{G_s + G_t}{G_s + G_n}\right)^{\eta}, \quad (5)$$

where G_n^C, G_s^C, and G_t^C are the critical fracture energies in the normal and first and second shear directions, while η is a cohesive property parameter.

3.3 Analysis results

LS-DYNA was applied to perform the impact analysis. The typical failure mode (3.5 J/mm) is shown in Figures 12 and 13.

When the impact energy increased to 8 J/mm, the laminate was penetrated (Figure 14) and the energy changed (Figure 15).

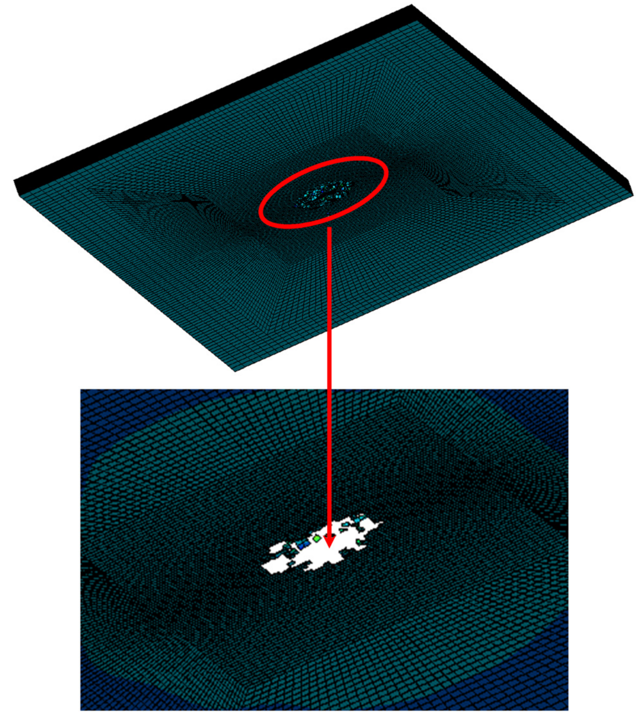

Figure 12: The typical dent shape.

4 Comparison of tests and simulations

According to the test data in Figure 3 of ref. [2], the least squares method is utilized to fit the impact damage resistance function, and the error analysis is based on the average absolute percentage error formula.

The dent depth of simulations compared with that of the test in ref. [2] is shown in Figure 16.

From the above curves, the inflection point of the test occurs at 3.5 J/mm, while that of the simulation is at about 4 J/mm. The functions of the dent depth in the test are

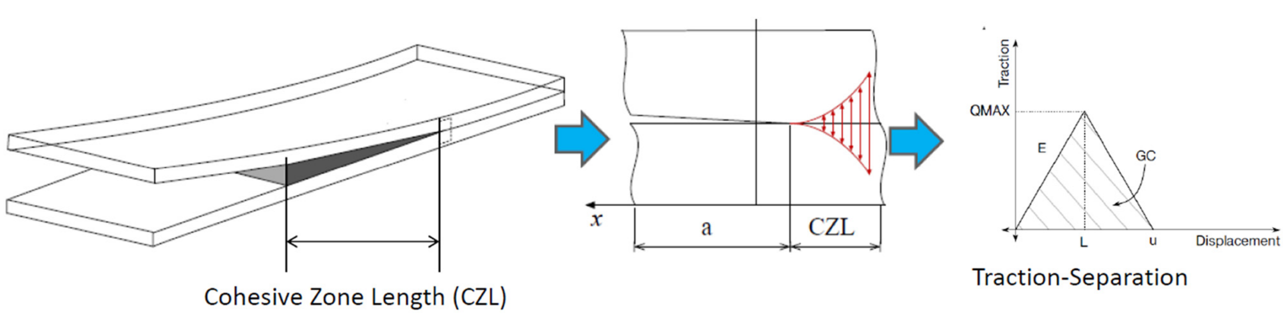

Figure 11: The cohesive element’s definition.

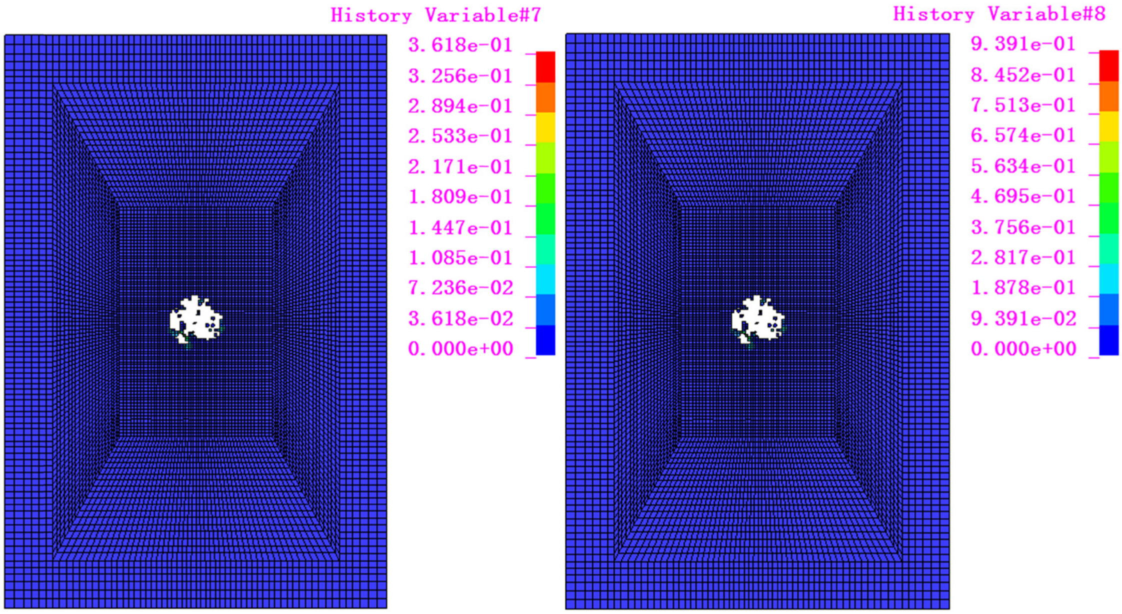

Figure 13: The typical transverse and in-plane shear damage.

$$\begin{cases} \delta = -0.0017E^4 + 0.039E^3 - 0.2026E^2 + 0.4177E - 0.1195, & 0.33\ \mathrm{J/mm} < E \ll 3.5\ \mathrm{J/mm} \\ \delta = 0.0387e^{0.5789E}, & E > 3.5\ \mathrm{J/mm}. \end{cases} \tag{6}$$

The fitting errors are 13.28 and 14.69%, respectively.

The functions of the dent depth in the simulation are

$$\begin{cases} \delta = -0.01E^3 + 0.0621E^2 + 0.0304E - 0.0061, & 0.32\ \mathrm{J/mm} < E \ll 4.0\ \mathrm{J/mm} \\ \delta = 0.0498e^{0.5553E}, & E > 4.0\ \mathrm{J/mm}. \end{cases} \tag{7}$$

The fitting errors are 30.16 and 18.84%, respectively.

The damage area of simulations compared with that of the test in ref. [2] is shown in Figure 17.

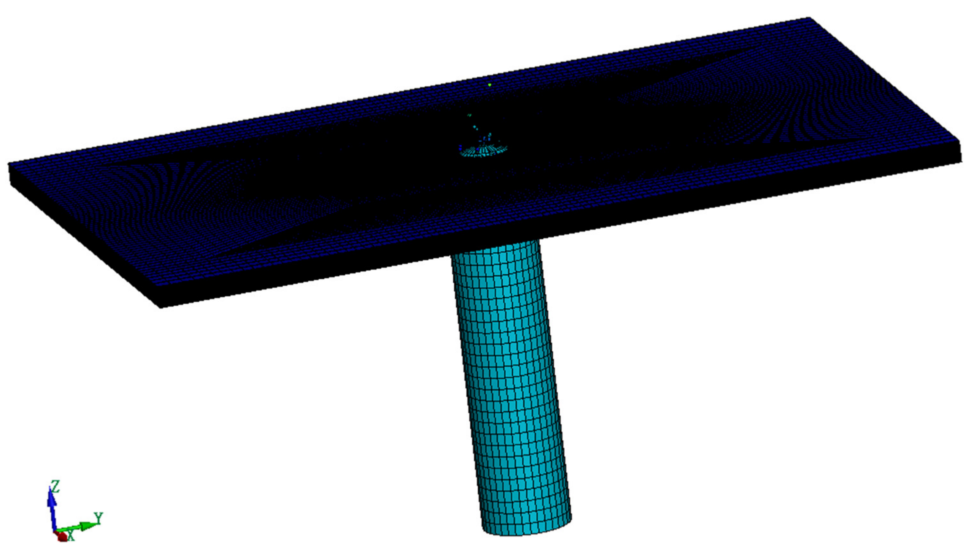

Figure 14: The model of the penetrated laminate (8 J/mm).

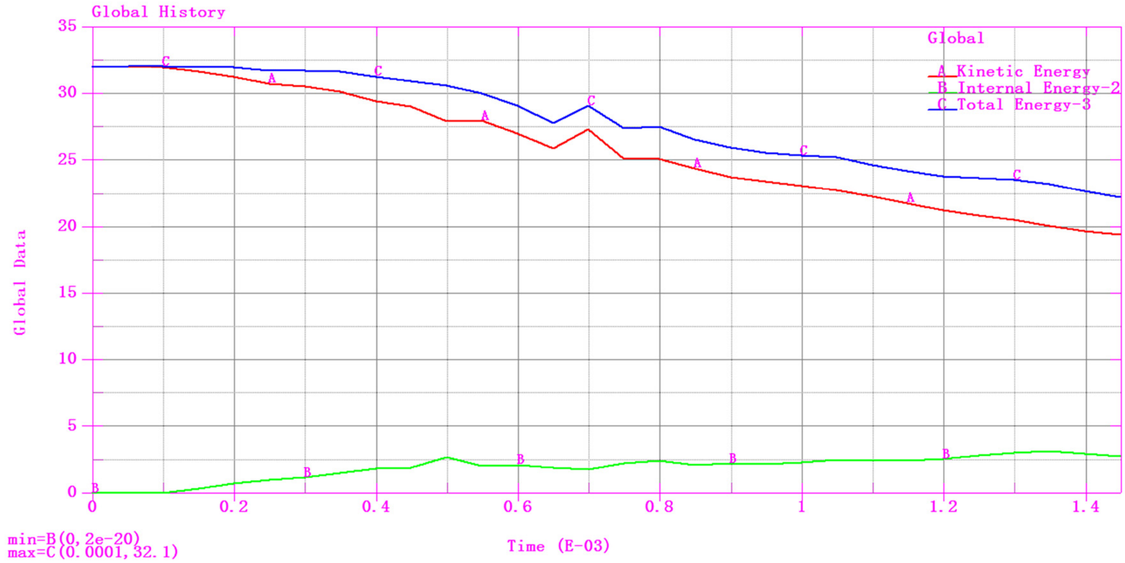

Figure 15: The changing energy over time.

From the above curves, the function of the damage area in the test is

$$\delta = -20.1507E^2 + 321.7023E - 121.6212. \quad (8)$$

The fitting error is 16.26%.

The function of the damage area in the simulation is

$$\delta = -23.8207E^2 + 359.2008E - 135.9495. \quad (9)$$

The fitting error is 10.64%.

The damage width of simulations compared with that of the test in ref. [2] is shown in Figure 18.

From the above curves, the function of the damage width in the test is

$$\delta = -0.7566E^2 + 11.9803E - 3.725. \quad (10)$$

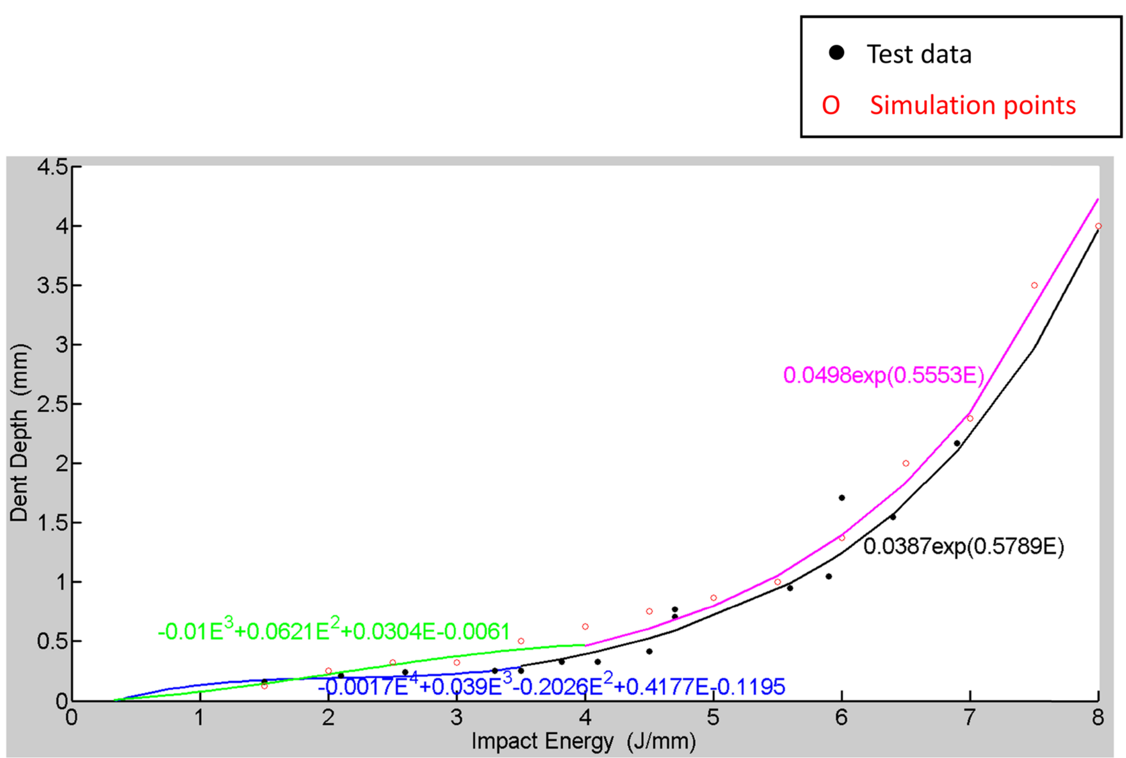

Figure 16: Impact energy vs dent depth.

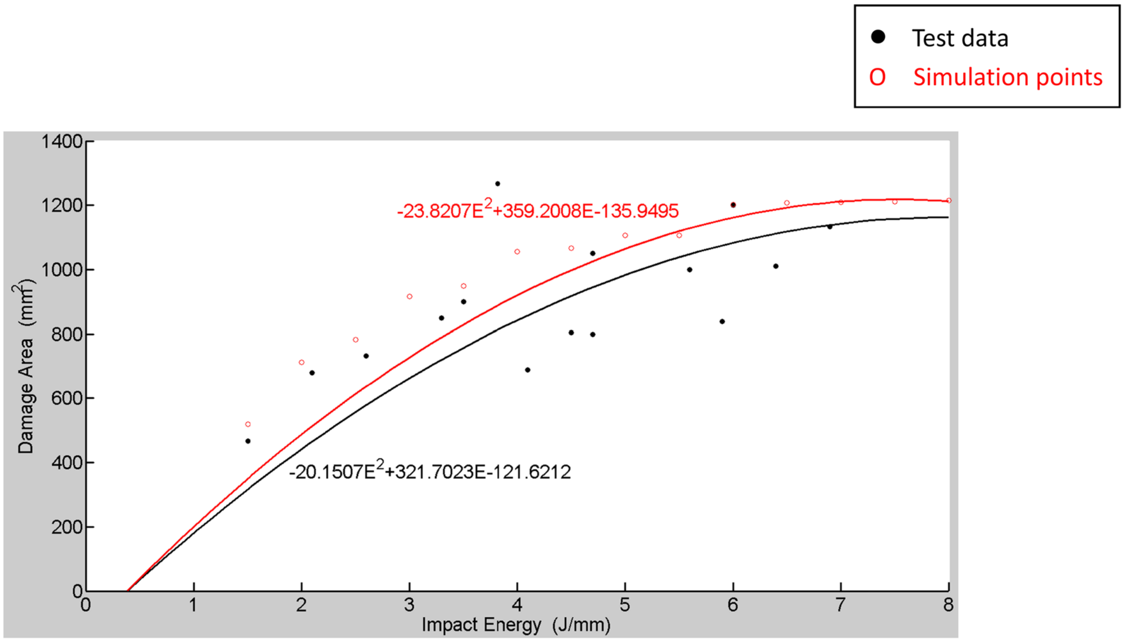

Figure 17: Impact energy vs damage area.

The fitting error is 19.03%.

The function of the damage width in the simulation is

$$\delta = -0.7805E^2 + 12.2777E - 4.0962. \quad (11)$$

The fitting error is 11.53%.

5 Conclusions

Through the comparison of the data from the standard test and simulation analysis, the relationship between the depth of the dent, damage area, or damage width

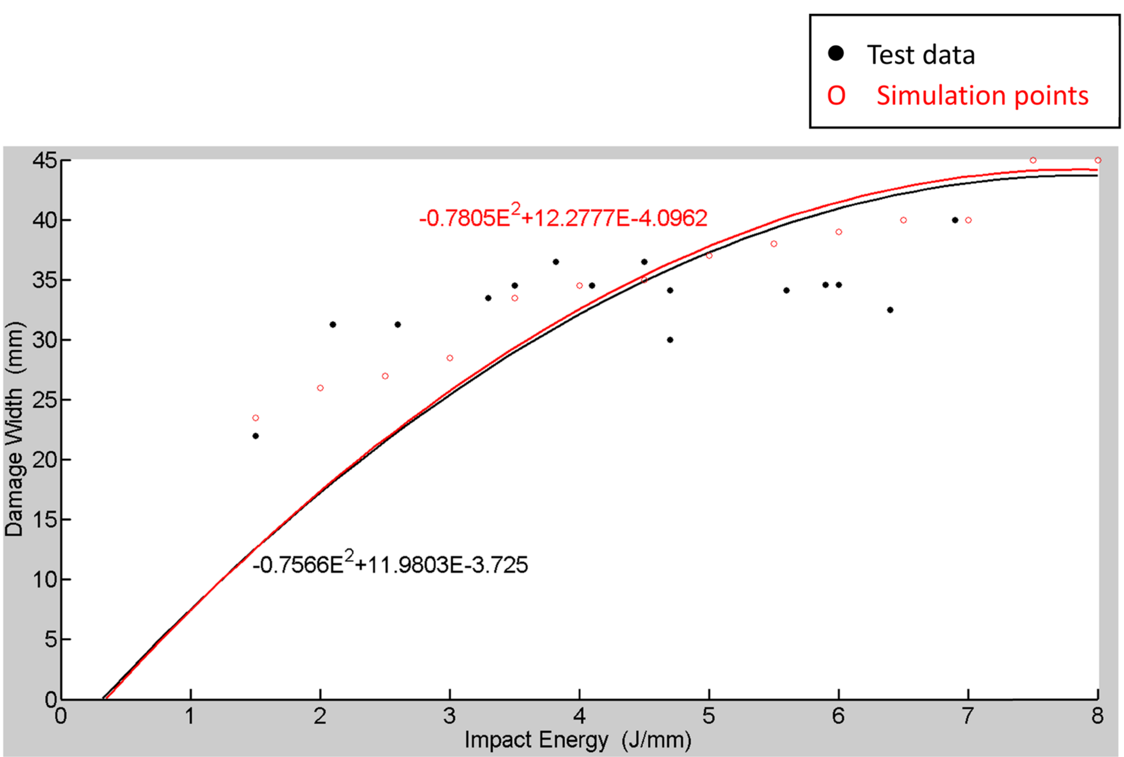

Figure 18: Impact energy vs damage width.

and the impact energy is formed. Certain fitting errors are also observed, in which some errors are as high as 30% and low errors are also more than 10%. The dispersion of the composite characteristics and the unconsidered effect of the composite strain rate in the simulation analysis are relevant.

From the test and simulation data, it can be seen that when the impact energy is lower than E_0, the matrix and fiber of the composite material keep the linear elastic status, so after the impact, there are no dents on the surface of the structure. When the impact energy continues to increase, the fiber is not broken, which is still linearly elastic, but the matrix has been crushed and cracked, which is entering the non-linear. The surface of the laminate leaves a shallow dent. When the impact energy is greater than E_C, the fiber and the matrix of the composite are destroyed at the same time, and the contact boundary between the punch and the structure produces an obvious large deformation. The material nonlinearity and the contact boundary nonlinearity make the dent depth increase exponentially, and the impact energy increases until the structure penetrates. Therefore, the piecewise nonlinear formula conforms to the physical essence of low-velocity impacts of composite materials, where the impact response characteristics of the composites before and after the inflection point of the dent depth are reasonably explained.

6 Final remarks

In this article, the relationship between the energy of low-velocity impact and the depth of the dent is discussed, and the properties of composites just after impact are presented. However, when the impact has been completed for some time, the dent will become shallower with time, which is the obvious rebound phenomenon of composites and is also determined by their unique viscoelastic properties.

Conflict of interest: Author states no conflict of interest.

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