Dynamic effects of low-velocity impact on composite plates

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Abstract. In low-velocity impact research on composites, quasi-static indentation experiments are typically used to make inner fractures. However, dynamic effects caused by impacts cannot be studied by quasi-static experiments. In this paper, the dynamic effects are discussed using simulation. Low-velocity impact processes were simulated through ABAQUS/Explicit software. Quasi-static processes were also simulated with ABAQUS/Explicit, in which very-low-speed displacement loadings were adopted to ensure that the kinetic energy could be ignored. The results show nearly no dynamic effect in the thickness direction, due to the thin nature of the composite plate and high-stress wave velocity in the through-the-thickness direction. In the radial direction, in contrast, apparent dynamic effects are observed, although the associated stress wave velocity is much higher. This may be attributed to the wave propagation from the impact site to the edge of the plate, reflecting repeatedly between the top and bottom surfaces of the plate.

1. Introduction
Carbon fiber composite laminates have been widely used in the field of engineering. The matrix cracks, interlaminar delamination, and fiber cracks can be easily induced in composite laminates when subjected to impact loading, which may lead to a serious degradation of load-carrying capacity of composite laminates. Therefore, to avoid catastrophic accidents, it is essential to carry out the damage assessment on composite structures. The stress condition of laminates under impact has not been defined.

Physical impact experiments are time-consuming and discrete compared with numerical simulation. Moreover, it is easier to observe stress changes using numerical models. However, theoretical analysis is an efficient tool for composite damage failure and strength prediction in impact experiments. After running the numbers in every possible combination, we can obtain a solution. Numerous studies have been undertaken to explore low-velocity impact by finite-element (FE) modelling, e.g., [1-6]. In the simulation model, a lot of delamination studies used cohesive elements to simulate interface absorption layer [4,7-9].

It is suggested that, re-expressed as “simulating with three-dimensional solid element models,” this study attempts to implement in Abaqus/Explicit software prediction of the damage type of the composite laminate. In this paper, cohesive zone method is chosen over other delamination modelling approaches. between the plies of the plate is inset cohesive to simulate delamination. The numerical predictions coincided considerably well with the experimental curve, in, e.g., impact force-time and displacement-time history curves.

2. Research object
To study the dynamic effects of low-velocity impact on composite plates, multiple models were built and simulation models of stress presented to depict the difference between dynamic states and quasi-static. As shown in table 1, multiple models were built that determine the wave velocity and to contrast the stress charts of the quasi-static state with those of the dynamic state. A round plate is simple to observe dynamic effects. Therefore, a finite-element model was built as shown in figure 1. The numerical model was cut into a circular composite plate with different diameters to study the influence of the plate’s length. As the plate’s thickness affects quasi-static and dynamic states, models with different thicknesses were also built.

### Table 1. Mechanical parameters of composite laminate.

| Case   | Diameter (mm) | Thickness (mm) |
|--------|---------------|----------------|
| Case 1 | 50            | 2              |
| Case 2 | 75            | 2              |
| Case 3 | 100           | 2              |
| Case 4 | 125           | 2              |
| Case 5 | 75            | 5              |
| Case 6 | 75            | 7.5            |
| Case 7 | 75            | 10             |

![Figure 1. FE model.](image)

### 3. Finite-element model

The laminate plate was manufactured with a carbon (Tenax HTS40 12 K 300)/epoxy (Cycom®977-2) composite. According to [10], the simulation model was cut into a circular plate modelled with a fully clamped edge and stacking sequence [0/90]s, which validated the feasibility of the FE modelling. The impactor material is analytical rigid, the diameter of which was 15 mm (see figure 1). From [7] and summarized in table 2, in the FE modelling, “general Contact” was used to define the contact schemes between the rigid impactor and the response of the impacted plate. Also, composite layer was contact by “general Contact”, by means of a penalty function, in ABAQUS/Explicit. In addition, the tangential behavior was defined between the laminate surfaces with a friction coefficient $\mu=0.6$. Between the rigid and the composite plate’s top surface, the friction coefficient was set as $\mu=0.3$.

The hemispherical impactor of 1 kg was modelled with rigid elements (R3D4) and a hexahedral mesh and algorithm based on sweeping with an element size of 1 mm. All of the degrees of freedom were fixed with the exception of the z axis. The composite plate used C3D8R eight-node reduced integration elements for each ply. To reduce the computational cost, the FE model was split into different regions and different mesh sizes/density were built, with the impacted zone comprising 1 mm × 1 mm elements (as in figure 1), while other regions were cut into slices by 2 mm × 2 mm elements. Hourglass control was introduced to avoid unrealistic deformation of the simulation model. To simulate the delamination of the inter-laminate, eight-node three-dimensional cohesive elements.
(COH3D8) were inserted between laminate faces, with a thickness of 0.0075 mm, and they were used to simulation model interface failure criteria. The max degradations were set to a value of 0.96 and when the elements failed the cohesive were removed from the finite element model until the failure criteria were satisfied.

Table 2. Mechanical parameters of composite laminate.

| Property                        | Value                           |
|---------------------------------|---------------------------------|
| Density                         | 1600 kg/m³                      |
| Intra-laminar Elastic properties| $E_1 = 153 \text{GPa}; E_2 = E_3 = 10.3 \text{GPa}$; $\nu_{12} = \nu_{13} = 0.3; \nu_{23} = 0.4$; $G_{12} = G_{13} = 6 \text{GPa}; G_{23} = 3.7 \text{GPa}$ |
| Strength (MPa)                  | $X^T = 2537; X_c = 1580; Y^T = 236; Y_c = 236$; $S_{12} = 90; S_{13} = 40; S_{23} = 40$ |
| In-plate fracture toughness (kJ/m²) | $G_{1c}^T = 91.6; G_{1c}^C = 79.9; G_{2c}^T = 0.22; G_{2c}^C = 1.1$; $G_5 = 0.7$ |
| Inter-laminar Elastic properties| $K_n = 2000 \text{MPa}; K_s = K_t = 1350 \text{MPa}$ |
| Strength fracture energy        | $T_n = 62.3 \text{MPa}; T_s = T_t = 92.3 \text{MPa}$ |
|                                 | $G_n = 0.28 \text{N/mm}; G_s = G_t = 0.79 \text{N/mm}$ |

The simulation model was computed in the finite element code of Abaqus/Explicit by a Fortran subroutine (VUMAT). The velocity loading was used in dynamic simulation analysis with an initial velocity of 3.83 m/s and the quasi-static process used displacement loading. The loading curve is shown in figure 2.

Figure 2. Spatial displacement along z axis.
## 4. Damage modelling

In general, FE models can be characterized by two main failure criteria: First, intra-laminar failure, due to fiber failure and matrix failure, matrix tensile and compressive damage or the damage of the fiber and matrix interface of the composite have disastrous consequences, and, second, inter-laminar failure and delamination that occurs between laminates. Composite damage mostly occurs in inter-laminar delamination with low-velocity impact.

### 4.1. Intra-laminar damage

Damage models can generally be studied by the number of failure criteria [11,12]. We used the Hashin criterion for the initiation criterion [13], which is one of the most widely used failure criteria for the modeling of initiation damage. The criterion has the following four different failure modes.

**Fiber tensile failure** ($\sigma_t > 0$):

$$F_{ft} = \left( \frac{\sigma_t}{X_t} \right)^2 + \alpha \left( \frac{\tau_{12}}{S_{12}} \right)^2 + \alpha \left( \frac{\tau_{13}}{S_{13}} \right)^2 \geq 1$$  \hspace{1cm} (1)

**Fiber compressive failure** ($\sigma_t < 0$):

$$F_{fc} = \left( \frac{\sigma_t}{X_c} \right)^2 \geq 1$$  \hspace{1cm} (2)

**Matrix tensile failure** ($\sigma_m > 0$):

$$\left( \frac{\sigma_m}{Y_t} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 \geq 1$$  \hspace{1cm} (3)

**Matrix compressive failure** ($\sigma_m < 0$):

$$\left( \frac{\sigma_m}{2S_{12}} \right)^2 + \left( \frac{\sigma_m}{Y_c} \right) \left[ \left( \frac{Y_c}{2S_{12}} \right)^2 - 1 \right] + \left( \frac{\tau_{12}}{S_{12}} \right)^2 \geq 1$$  \hspace{1cm} (4)

In equation (1), $\sigma_n$ denotes normal stress in the n direction, $\tau_{12}$ in-plane shear stress, and $\tau_{13}$ out-of-plane shear stress. $X_t$ and $X_c$ are the tensile and compressive strengths in the fiber direction, respectively; similarly, $Y_t$ and $Y_c$ are the tensile and compressive strengths in the transverse direction, respectively. $S_{12}$ and $S_{13}$ are the shear strengths in the fiber and transverse planes, respectively. The coefficient $\alpha$ in equation (1) is applied to determine the contribution to fiber tensile failure, which is uncontributed in this paper.

### 4.2. Delamination

In work by Camano and Dávila, an inter-laminar failure criterion was proposed to judging damage for numerical simulation models [14]. The cohesive zone elements used mixed mode loading, which the model determined as damage modes I, II, and III simultaneously. The stress failure criterion used to estimate the delamination onset is given by:

$$\left( \frac{\sigma_n}{N} \right)^2 + \left( \frac{\sigma_s}{S} \right)^2 + \left( \frac{\sigma_t}{T} \right)^2 = 1$$  \hspace{1cm} (5)

where $\sigma_i$ ($i=n,s,t$) stands for tractions in each pure mode in the normal n and shear directions s and t, respectively, while N, S, and T are the inter-laminar strength normal strength and two shear strengths, which can be calculated as:

$$\sigma_i = K_i \delta_i (i = n, s, t)$$  \hspace{1cm} (6)
The Abaqus manual contains a detailed illustration regarding cohesive elements for the initiation criterion and failure criterion [15].

5. Results and discussion

The result of this experiment are similar to the simulation analysis results in [10]. During the impact process, the impact force-time, force-displacement, and energy-time history curves are captured. Additionally, the study of some impact dynamics problems was based on displacement load.

5.1. Validation of numerical model

The simulation prediction and experimental data were compared, including, e.g., impact force-time, force-displacement, and energy-time history curves under 7.4 J impact energies (see figure 3). The force-time history curves coincided, which upon initial contact reveal some oscillations in the time interval 0–0.5 ms. When the contact force approached the maximum value, strong variations of the force-time history occurred. The impactor velocity was reduced to zero and sprung back. The numerical simulation curve was higher than the experimental one and took a longer time to reach zero. This phenomenon may be because the damaged cohesive element being deleted, which thus produced contact forces between the delaminated plies.

![Figure 3](image1)

**Figure 3.** Numerical and experimental impact-force-time history curves.

![Figure 4](image2)

**Figure 4.** Experimental and numerical history curves: (a) force–displacement history curves and (b) energy-time history curves.

The experimental and numerical-simulation-predicted force-displacement curves are compared in figure 3. The numerical model takes more time than the experiment, as the time for maximum
displacement was larger. This is because the finite element model spent longer time release energy than experiment, and the impacted plate can return to their initial position completely. In figure 4(a) the simulation curves evidence crossover, indicating that the elastic model must be symmetric so that the value increases and is recovered. In this process, it may be acceptable that the force-displacement curve while unloading exceeds the loading curve. In figure 4(b) are shown the energy-time curves, in which the simulation-predicted curves have released all of the energy. A linear spring model is used in this paper, in which low-energy impact cannot destroy the composite plies, so the laminate was fully recovered.

Figure 5 shows energy-time history curves for the quasi-static state. The internal energy extends far beyond the kinetic energy. This phenomenon is consistent with the quasi-static model.

![Figure 5.](image)

**Figure 5.** (a) Internal energy and (b) kinetic energy for entire model.

### 5.2. Analysis of dynamical effects

![Figure 6.](image)

**Figure 6.** Plate stresses along radial direction and thickness.

The FEs were based on consideration of nonlinear dynamic analysis. In the dynamic model, there is a time difference between the side-point of the plate’s top face and the plate’s back face in the mid-point. To study the time difference, an FE model was built as impacted plate of thickness 10 mm and diameter 75 mm (table 1, Case 7). This case result is plotted in figure 6. The wave speed is the difference between the bottom and the radius. To further understand the difference, a variety of
thicknesses and ratios are modelled based on experimental design for a finite model; the composite plate size is presented in table 1. There is a clear difference between shock wave velocity along the thickness and along the length. The details are shown in tables 2 and 3. Apparently, propagation of shock waves in the thickness direction is slower than the orientation of plies in a laminate. The wave velocity is approximately 625 m/s along the z axis and the propagation speed is approximately 8000 m/s in the inter-laminate. This phenomenon may be because the speed of a shock wave is determined by Young's modulus and the density. In addition, the fiber modulus differs significantly from the resin modulus. In multilayer composites, the multilayer interfaces lead to the multiple reflections of acoustic waves. Thus, it can be seen that the propagation speed is slower in the thickness direction of shock waves.

Table 3. von Mises stress in plate along longitudinal direction.

| Length (mm) | Dynamic (μs) | Quasi-static (μs) |
|-------------|--------------|------------------|
| 25          | 4            | 1200             |
| 37.5        | 4            | 1200             |
| 50          | 6            | 1200             |
| 62.5        | 6            | 1200             |

Table 4. von Mises stresses in plate along thickness direction.

| Thickness (mm) | Dynamic (μs) | Quasi-static (μs) |
|----------------|--------------|------------------|
| 2              | 4            | 1300             |
| 5              | 6            | 1300             |
| 7.5            | 12           | 1300             |
| 10             | 16           | 1300             |

In the quasi-static model, the stress on each element arrives at the same time; the results are shown in tables 3 and 4. Displacement loading stresses the plate structure evenly. A composite plate is uniformly stress under quasi-static stress, and it was especially easy to draw this conclusion.

Table 5. von Mises stresses in plate (0.18 ms).

| Case | Static Max | Dynamic Max | S/D |
|------|-----------|-------------|-----|
| 1    | 1.665 × 10^2 | 1.984 × 10^2 | 0.839 |
|      | 1.487 × 10^-1 | 4.279 × 10^-2 | 3.48 |
| 2    | 1.166 × 10^2 | 2.072 × 10^2 | 0.563 |
|      | 4.676 × 10^-2 | 1.120 × 10^-2 | 4.18 |
| 3    | 1.032 × 10^2 | 2.067 × 10^2 | 0.499 |
|      | 4.325 × 10^-2 | 1.128 × 10^-2 | 3.83 |
| 4    | 8.325       | 2.057 × 10^2 | 0.405 |
|      | 3.180 × 10^-2 | 2.971 × 10^-2 | 1.07 |
| 5    | 1.656 × 10^2 | 2.759 × 10^2 | 0.6 |
|      | 4.249 × 10^-2 | 1.372 × 10^-2 | 3.10 |
| 6    | 2.089 × 10^2 | 3.137 × 10^2 | 0.666 |
|      | 2.919 × 10^-2 | 1.029 × 10^-2 | 2.84 |
| 7    | 3.145 × 10^2 | 4.127 × 10^2 | 0.762 |
|      | 3.874 × 10^-2 | 5.970 × 10^-2 | 0.649 |
In the nonlinear dynamic analysis and dynamic stability analysis of impact under low energy, the loading mode will affect the distribution of stress. In figure 7, to facilitate observation, the difference between static and dynamic stress, three kinds of models are shown with the same loading distance. There is a clear difference between figures 7(c) and 7(d). The plate radius is an important factor for determining the composite stress state. The ratio of the maximum force and the minimum force is shown in table 5. From details presented in this table, a trend can be seen, namely, that the stress is more similar in both dynamic states and quasi-static when the plate is smaller. Upon changing the plate length, the stress will change significantly in the quasi-static state, while in the dynamic process, the stress remains the same with length variation. From the simulation chart in figure 7, a small influence of the variation of media thickness is observed, and both static and dynamic model stresses have increased. According to the results, although the shock wave is faster in an intra-laminate in the thickness direction, the dynamic stress effect is more visible in the length direction. One possible reason for this is that most of the shock-wave propagation undergoes multiple reflections inside the material, which leads to the length direction time difference being greater than that of the material thickness. The time difference is approximately an order of magnitude of 10 μs along the thickness direction. Minor effects occur with changing thickness.

Figure 7. Plate stress deformation charts in quasi-static (a,c,e) and dynamic (b,d,f) models. FE models with (a,b) diameter 50 mm and thickness 2 mm, (c,d) diameter 125 mm thickness and 2 mm, and (e,f) diameter 75 mm and thickness 10 mm.

6. Conclusions
In this paper, first, a delamination analysis process for composite laminates under low-velocity impact was presented. Next, a calculation method was summarized and compared with quasi-static and dynamic models through corresponding finite-element analysis. Contrasting the velocity loading with distance loading, the FE model obviously changed with different model lengths. Ratio is an important parameter in analyzing dynamics effects. In multilayer composites, the multilayer interfaces lead to multiple reflections of acoustic waves. Hence, there is sufficient time difference along the length...
direction, rather than along the thickness direction, with the wave speed being slower.

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