Failure assessment of 3D woven composites under compression after low-velocity impact

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Abstract

The failure mechanism of 3D woven composites subjected to compression loading along principal/off-axis direction after low-velocity impact (LVI) was assessed by experimental and numerical methods. The low-velocity impacts under 26.8 J and 80 J energies were applied to the specimens with off-axis angles of 0° and 45°. It can be observed that the impact damages are direction-dependent, which is determined by the weft and warp orientations. By performing the compression-after-impact (CAI) tests, it is found that the CAI strength along principal direction is more sensitive to the low-velocity impact than that along off-axis direction. A finite element dynamic analytical method was established, considering four off-axis angles (0°, 30°, 45° and 60°). The results show that the extension direction of the impact damage changes regularly with the off-axis angle. During the compression, the small off-axis angle can make the specimen prone to produce a sudden crushing failure determined by the fiber failure due to the high axial stress. As the off-axis angle increases, the matrix damage gradually holds the dominant position due to the growing shear effect, which makes the specimen produce a ductile failure governed by the accumulated matrix failure.

1. Introduction

Composite materials are widely used in various fields including aerospace, ship, wind energy and construction due to their advantages of light weight, outstanding performance and flexible designability [1–6]. 3D woven composites possess higher interlaminar properties and impact damage tolerance than traditional laminated composites depending on their binder warp yarns in the thickness direction, which can maintain the structural integrity of the whole material [7–15]. The composites in service often suffer from low-velocity impact (LVI) damages due to the impact of tools, hail, runway sand, etc. The tiny marks left on the surface of the materials are visually difficult to detect or barely detectable, and a lot of damages even occur inside the materials. During the subsequent use, the impact damages may continue to expand and decrease the mechanical properties of the materials [16–18]. It is important to know whether the residual bearing capacity of the materials can still withstand a certain working loads before the impact damages are detected and repaired, thus the studies on the post-impact performance of the materials are necessary.

By now, a number of studies have been done on the impact resistance of 3D woven composites [19–22]. Compared with 2D woven composites, 3D woven composites could absorb more impact energy, and the pit depth and damage area were smaller [23]. The impact strength of 3D woven composites mainly depends on the in-plane fiber fracture while the energy absorption is governed by the binder yarns [24]. By contrast, 3D woven composites can effectively restrain the delamination propagation, depending on their z-yarns [25]. Thus 3D woven composites have been increasingly applied to the design of some power structures due to their superior impact resistance, and relative studies have focused on the relationships between impact parameters and response results [26]. Besides, the LVI behavior of 3D woven composites can be affected by impactor shape, temperature and other factors. For example, the blunter impactors lead to larger damage areas and higher...
threshold loads, and the impactor shape combined with the volume proportion of z-yarns greatly affect the
damage degree of the materials [27].

Relatively high impact resistance can cause the 3D woven composites a greater post-impact performance
[28–31]. Saleh et al [32] investigated the compression after multiple impacts behaviors of 2D and 3D woven
composites. The results showed that 3D composites experienced the accumulation of damage, leaving a
relatively high residual strength (~92%), while 2D composites demonstrated a sudden failure, producing a
residual strength of ~65%. By comparison, these two composites absorbed almost the same energy, and the
damage in 3D composites was relatively weaker.

Most current research pays attention to the compression-after-impact (CAI) performance of woven
composites just in the principal directions. However, the loads on the material affect its mechanical properties
in all directions, not just along the weft or warp direction [33, 34]. Besides, certain experimental studies on the
performance along the off-axis directions mainly focus on the undamaged materials. Yang [35] carried out
tensile, compressive and bending tests on various structures of 3D woven composites along 30°, 45° and 60°
directions respectively, and obtained the variation law of material performance with the off-axis angle. Zhang
[36] conducted three-point bending method to experimentally investigate the flexure properties of 3D woven
composites under four different off-axis angles. It was found that the principal direction specimens exhibited
some brittle characteristics, producing dominant damages of yarn fractures and delamination, while the off-axis
direction specimens showed significant ductile behaviors, resulting in primary damages of tows debonding and
matrix cracking.

At present, there are relatively few reports on the CAI performance of 3D woven composites along the off-
axis directions. In present work, the CAI properties of these composites along principal and off-axis directions
under given impact energies were experimentally and numerically studied, and corresponding damage types and
failure mechanisms were analyzed. The purpose of this study is to provide effective support for the more
reasonable application of 3D woven composites in engineering practice.

2. Experiment

Figure 1 describes the whole process of the experimental investigation. The LVI tests were first conducted on the
0° and 45° specimens prepared by the resin transfer molding (RTM) technology, and the impact damages of the
specimens were measured and analyzed with the help of optical microscope and ultrasonic C-scan technology.
Then the compression tests were carried out on the impacted specimens, and the CAI properties of the material
were discussed.

2.1. Materials

The adopted materials in this work are 3D angle-interlock woven composites which are made of T700 carbon
fibers reinforcing E-51 epoxy matrix. The woven structure and the mechanical properties of component
materials are shown in figure 2 and table 1, respectively. The weft and warp yarns are distributed in straight lines
oriented along x and y directions respectively, making the fabric achieve considerable in-plane mechanical
properties. The binder warp yarns (distributed along y direction) interlock with the weft layers in wavy form,
contributing z-direction performance to the woven reinforcement, which improves the fracture toughness in
thickness direction. The warp and binder warp yarns are alternately arranged with a ratio of 1:1. All yarns have a
density of 1.8 g cm⁻³, and the detailed parameters of yarns are listed in table 2. The RTM process was employed
to obtain the composite plates by injecting resin into 3D woven preforms. The specific parameters of 3D angle-
interlock woven composites are listed in table 3. Following the particular directions, the composite plates were
finally cut into the specimens with the dimension of 150 mm × 100 mm × 4 mm.

2.2. Low-velocity impact tests

The low-velocity impact tests were conducted according to the standard test method ASTM D7136. The
impactor adopts hemispherical shape with a diameter of 16 mm, and the total mass of drop hammer combined
with counterweight is 6.141 kg. To highlight the effect of different levels of impact energy on the response of the
specimen, the contrastive ratios of impact energy to specimen thickness are set to 6.7 J mm⁻¹ and 20 J mm⁻¹,

hence the corresponding total impact energies are 26.8 J and 80 J, respectively.

2.3. Compression tests after impact

CAI tests were performed using Instron 3385H universal testing machine, following ASTM D7137 standard. A
special fixture is prepared for the tests, and the loading rate is set to 1.25 mm min⁻¹. In addition, a maximum
loading displacement is set to ensure the safety of the tests.
2.4. Experimental device
The name, manufacturer, version and key parameters of various devices used in this study are listed in figure 3.

3. Numerical simulation
To evaluate the damage evolution and failure mechanism of the present 3D woven composites, a finite element dynamic analytical method was established based on ABAQUS software, considering four deflection angles (0°, 30°, 45° and 60°). The scale-span analytic process depending on the homogenization method is described in...
The representative volume element (RVE) was picked out from the studied 3D woven composites with periodic microstructure. By adopting the general periodic boundary conditions which can realize the application of periodic boundary conditions with aperiodic mesh [37–39], the mechanical properties of the RVE were calculated to characterize the performance of macro composite panel. By using the restart feature in ABAQUS, the low-velocity impact and CAI tests were simulated in turn. In this work, 3D Hashin orthotropic failure criterion which can depict different typical failure modes was employed to investigate the low-velocity impact and CAI failures of the composites, as shown in figure 4. In the criteria, \( S \) is shear strength, and the subscripts \( x, y \) and \( z \) represent the directions of global coordinate system as shown in figure 2. Besides, \( X_f, X_c, Y_f, Y_c, Z_f \) and \( Z_c \) are tensile strength in \( x \) direction, compressive strength in \( x \) direction, tensile strength in \( y \) direction, tensile strength in \( z \) direction and compressive strength in \( z \) direction, respectively.

In the progressive damage analysis, if one of the Hashin failure criteria is met, the corresponding failure mode weakens material stiffness in its own way by introducing the damage factors into the material degradation scheme. Once any damage is identified, the stiffness matrix is updated according to equation (1):

\[
C = \begin{bmatrix}
  d_f C_{11} & d_f d_m C_{12} & d_f d_z C_{23} & 0 & 0 & 0 \\
  d_f d_m C_{12} & d_m C_{22} & d_m d_z C_{23} & 0 & 0 & 0 \\
  d_f d_z C_{23} & d_m d_z C_{23} & d_z C_{33} & 0 & 0 & 0 \\
  0 & 0 & 0 & d_f d_m G_{12} & 0 & 0 \\
  0 & 0 & 0 & 0 & d_m d_z G_{23} & 0 \\
  0 & 0 & 0 & 0 & 0 & d_f d_z G_{13}
\end{bmatrix}
\]

(1)

where \( d_f = d_f d_g \), \( d_m = d_m d_m \) and \( d_z = d_z d_z \). The LVI and CAI damage analysis was conducted by compiling VUMAT subroutine with EXPLICIT solver, and the 8-node reduced integral solid element (C3D8R) was adopted for mesh generation.

### Table 1. Mechanical properties of component materials.

| Property                  | T700 carbon fiber | E-51 epoxy matrix |
|---------------------------|-------------------|-------------------|
| Elastic modulus (GPa)     | \( E_\text{f1} = 232 \) | \( E_\text{m} = 3.5 \) |
| Shear modulus (GPa)       | \( G_\text{f12} = 24 \) | \( G_\text{m} = 1.296 \) |
| Poisson’s ratio           | \( \mu_\text{f12} = 0.28 \) | \( \mu_\text{m} = 0.35 \) |
| Tension strength (MPa)    | \( X_\text{f} = 4850 \) | \( S_\text{m} = 80 \) |
| Compression strength (MPa)| \( S_\text{m} = 241 \) | \( S_\text{m} = 60 \) |

### Table 2. Parameters of yarns.

| Types of yarn | Number of carbon wires | Tex (g 1000m⁻¹) |
|---------------|------------------------|-----------------|
| Weft          | 24000                  | 1600            |
| Warp          | 12000                  | 800             |
| Binder Warp   | 6000                   | 400             |

### Table 3. Detailed parameters of 3D angle-interlock woven composites.

| Sample name | Fabric parameters | Composites parameters |
|-------------|-------------------|-----------------------|
|             | Number of layers | Warp density (tows cm⁻¹) | Binder warp density (tows cm⁻¹) | Weft density (tows cm⁻¹) | Thickness (mm) | Fiber volume fractions (%) | Impact energies (J) |
| 0° sample   | 4                  | 5                     | 5                     | 2.5                     | 4 ± 0.1         | 49.6 ± 0.3             | 26.8               |
| 45° sample  | 4                  | 5                     | 5                     | 2.5                     | 4 ± 0.1         | 49.6 ± 0.3             | 26.8               |
|             | 4                  | 5                     | 5                     | 2.5                     | 4 ± 0.1         | 50.5 ± 0.2             | 80                 |
4. Results and discussion

4.1. Low-velocity impact
4.1.1. Mechanical response

Figure 5 depicts the low-velocity impact response for both the tests and simulations. Since the hemispherical impactor is adopted, the difference of the impact response of the specimens at different off-axis angles is mainly caused by their boundary effects. In this work, the damage range of the specimens is quite limited under two given impact energies, which leads to relatively small differences in boundary effects, hence the impact responses of different off-axis angle specimens are relatively close under the same impact energy. It should be noted that the boundary effect is reduced to an acceptable level, but not completely eliminated.

Figure 5(a) and (c) show the contact force-time relations of the impacted specimens under the given impact energies. It is seen that the numerical results agree well with the experimental data, and the general trend of the curves under the same impact energy is similar. For the same off-axis angle, the contact force under the higher impact energy increases faster at the beginning, then it earlier reaches the peak value and undergoes a longer approximate plateau where the damages are continuously accumulated and more energies are absorbed. After that, it turns downward later when the specimen begins to rebound and produces larger unrecoverable deformation, leaving a deeper dent. The shapes and areas of impact damage were obtained by employing the ultrasonic C-scan technology. It is seen from the scanning results that the higher impact energy produces larger damage regions, forming an approximately elliptical shape, and the damage areas of the two off-axis angle specimens under each impact energy are similar within an error of 5%. The long and short axes of the ellipse are respectively along the warp and weft directions, which indicates the extension range of the damage along the warp direction is slightly larger than that along the weft direction.

The contact force-displacement relations are shown in figures 5(b) and (d). The displacement measured in the experiment corresponds to that of the rebounding impactor. When the impactor leaves the specimen surface, the ultimate displacement will be recorded. However, the specimen may still rebound and does not fully return to a stable position where the ultimate displacement will be finally determined in the simulation [40, 41].

Figure 3. Basic information of experimental devices.
Therefore, between the experimental data and numerical results exists a certain deviation, and herein the FEM curve is recorded until the impactor just begins to rebound. Under each impact energy, although the curves of two off-axis angle specimens show approximately the same trend, the 45° specimen reaches a higher peak contact force and a smaller ultimate displacement than the 0° specimen, which is mainly attributed to the boundary effects mentioned above. However, their absorbed energies correlated with the area enclosed by the curve are almost the same. For each off-axis angle, the higher impact energy causes a higher peak contact force and a larger ultimate displacement, and a significantly longer plateau stage indicates more accumulated damage, which brings the specimen a relatively smaller rebound.

4.1.2. Damage analysis
Figures 6 and 7 demonstrate the damage morphologies of specimens under the two impact energies observed by the optical microscope. Binder warp yarns enhance the interlayer toughness of 3D woven composites, which can effectively resist the delamination. Under 26.8 J impact energy, there are some matrix cracks around the impact region of the two off-axis angle specimens, and the damage on the back side of the specimens is more serious with a larger damage area. The dent depths of the two specimens are similar, and there is obvious matrix cracking, fiber debonding and a small amount of fiber fracture on the back side. It can also be observed that the fiber debonding of both the specimens is distributed along the weft direction, and the matrix damage between the weft yarns is more serious than that in other areas. By comparison, the impact damages of the two off-axis angle specimens subjected to 80 J impact energy are more serious, and both of their dents are significant. There is notable matrix cracking and interface debonding around the impact region on the front of the specimens, and the fiber fracture can be found in the depth of the dents. On the back of both the specimens, a large number of fibers break along the weft and warp directions, and the fracture zone which is generally cross-shaped is relatively wider between the weft yarns. Most of the interface debonding and matrix cracking are distributed around the impact areas, and the debonding mainly extends along the weft direction. It is seen that the extension form of the damage is clearly affected by the orientation and distribution of yarns, which indicates that the impact damage of 3D woven composites has a certain directionality. This can also be found from the impact damage evolution of specimens obtained by the simulation, shown in figure 8, where more orientations were considered, and the typical fiber damage is displayed. For the same off-axis angle, the higher impact energy causes larger damage.
areas and more visible dents. Meanwhile, it is clear that the extension direction of the damage changes regularly with the off-axis angle, which is mainly determined by the weft and warp orientations. It can be concluded from both the experiment and simulation that the impact damage of 3D woven composites has obvious directional dependence, which may further determine their CAI properties along different directions.

4.2. Compression after impact

4.2.1. Mechanical response

The total and separate curves of CAI responses of the 0° and 45° specimens under different impact energies for both the tests and simulations are depicted in figure 9, where the compression response of the unimpacted specimen prepared for the subsequent strength analysis is also included. It is seen that the numerical results show good agreement with the experimental data. During the tests, the load-displacement curves of 0° specimens increase rapidly before reaching the peak value, and then show a significant decline till the failure. The peak load was recorded to calculate the compression strength under corresponding impact energy. By contrast, the 45° specimens produce much larger displacement. Their load-displacement curves show a non-linear growth and gradually stabilize. When the specimens were compressed to the set maximum safety distance, the tests terminated and the stable load was recorded for the calculation of corresponding compression strength. The 0° specimen produces notable crushing failure, and the damage almost covers the entire width of the specimen. For the 45° specimen, the fiber/matrix interface debonding occurs around the impacted region and is distributed along 0° and ±45° directions under 26.8 J impact energy, while nearly the same region exhibits obvious matrix cracking along ±45° directions under 80 J impact energy.

To enrich the study findings, more off-axis angles were considered in the simulations. The total and separate displays of the load-displacement responses of 0°, 30°, 45° and 60° specimens under different impact energies are given in figure 10. The peak value of the curve under each impact energy always falls first and then goes up as the off-axis angle increases with the turning point of 45° angle, while the corresponding displacement shows the opposite trend. On the other hand, with the growth of the impact energy, the peak value of the curve at the same off-axis angle declines while the corresponding displacement rises. It is seen that only the curves of 0° specimens
Figure 6. Damage morphologies of specimens under 26.8 J impact energy.

Figure 7. Damage morphologies of specimens under 80 J impact energy.
are followed by a sharp decline after the rapid rise, while other curves are initially linear followed by a non-linear phase till the peak values and then tend to be stable or decline slightly.

The specific CAI strengths respectively obtained by the tests and simulations are shown in figure 11. It should be noted that along different off-axis directions, the compressive strengths of the studied 3D woven composites which are anisotropic are different, even if the materials are not impacted. In this paper, the change of compression strength along principal/off-axis direction caused by the impact rather than the architecture characteristics of the material itself is the main concern. In view of this, not only the specific value of compression strength under each impact energy, but also its variation amplitudes against the strength of unimpacted specimen should be discussed. As a contrast, the static strength of unimpacted specimens is also measured and listed as CAI strength under 0 J impact energy in the figure. Comparing the numerical results with the experimental data, the errors of 0° specimen under 0 J, 26.8 J and 80 J impact energies are 7.09%, 8.12% and 7.32%, and those of 45° specimen under the three impact energies are −3.25%, 4.67% and 0.06%. The maximum error is within 10%, which proves the numerical model reliable for this study.

It is seen from the experimental data depicted in figure 11(a) that under each impact energy, the CAI strength of 0° specimens is always greater than that of 45° specimens. As the impact energy increases, the value of 0° specimens decreases more obviously than that of 45° specimens, and both their decline amplitudes are getting smaller. Compared with the compression strengths of unimpacted specimens, the CAI strengths of 0° and 45° specimens at 26.8 J impact energy are 34.6% and 19.7% lower, and the values at 80 J impact energy decrease by

![Figure 8. Impact damage evolution with various fiber orientations.](image-url)
49.3% and 25.2%, respectively. It can be concluded that the CAI strength along principal axis direction is more sensitive to the low-velocity impact than that along off-axis direction.

From the numerical results shown in figure 11(b), it can be found that when raising the impact energy, the decline amplitude of CAI strength drops first and then grows as the off-axis angle increases, leaving a minimum value at the 45° angle, and the decline amplitude under every off-axis angle is getting smaller with the increasing impact energy. Compared with the compression strengths of unimpacted specimens, the values of 0°, 30°, 45° and 60° specimens under 26.8 J impact energy decrease by 34.1%, 17.4%, 13.1% and 20.9%, and the values under 80 J impact energy are 49.2%, 30.0%, 22.6% and 30.4% lower, respectively. The numerical results not only verify but also enrich the experimental conclusions that the closer to the principal direction, the more sensitive the CAI performance of 3D woven composites is to the low-velocity impact.

4.2.2. Failure mechanism

From the above, the low-velocity impact brings 3D woven composites directional damages determined by the weft/warp orientation, which further causes different CAI responses along principal/off-axis direction. The question, then, is what is the failure mechanism leading to these responses. Since the FEM possesses unique advantages in demonstrating the stress distribution and damage evolution of the material, some useful numerical results were employed for the failure analysis. The surface damage appearance, the stress distribution before the imminent failure of specimens, and the representative damage mode are described in figures 12–14, where FT, FC, MT and MC are fiber tensile failure, fiber compressive failure, matrix tensile failure and matrix compressive failure, respectively. During the simulation, the initial damage conditions of the fiber are relatively higher than those of the matrix, thus the matrix damage always occurs first while the fiber damage appears relatively late or even barely occurs in some cases. Under the compression load, the specimens are usually in the pressure-shear coupled stress state, therefore the distributions of not only the axial stress along weft direction (S11) but also the in-plane shear stress (S12) are displayed.

For the unimpacted specimens, the compressive response is closely related to their fiber configuration, especially the fiber orientation. Since the weft direction of 0° specimen is consistent with the loading direction, its weft yarns are the main pressure-bearing structure. The continuous rise of the load causes the specimen a...
small deflection bending, forming the compressed regions on one side and the stretched areas on the other, and the S11 produces significant stress concentrations in the center of both sides. When the axial compression stress (the value of S11 is negative) on the pressed side grows to a certain level, the specimen is suddenly crushed, leaving the fiber compressive failures on this side. Simultaneously, the other side of the specimen, namely the stretched side, produces obvious fiber tensile failures. As mentioned above, the matrix damage actually occurs earlier, but the final failure of 0° specimen is governed by the fiber failure, because the compression load is mainly borne by the fiber, and its sudden failure under a high axial stress can lead to the crushing of the specimen. In addition, the S12 has symmetrically distributed stress concentrations on the compressed side and presents a more even distribution on the other. Due to the deviation between the fiber axial direction and the loading direction, the bearing capacity of the fiber is not fully mobilized, and the S11 value
Figure 12. Failure information of each off-axis angle specimen without impact.

Figure 13. Failure information of each off-axis angle specimen under 26.8 J impact energy.
is obviously smaller than that of 0° specimen, which leads to comparatively few fiber tensile/compressive damages. Meanwhile, the off-axis angle makes the specimen more obviously affected by the shear action, hence the whole specimen is under pressure-shear coupled stress state, producing significant concentration of S12 in its center region and matrix compressive damage along 45° direction. Since the shear resistance of the specimen is relatively weak, the damage appears early and then continuously accumulates. As the compression load increases, it is difficult for the specimen to reach high stress level and to produce sudden failure like the 0° specimen. Only in this case, the normal deformations on both sides of the specimen are symmetrical, and the damage of the two sides are almost the same. The response results of 30° and 60° specimens are the intermediate cases between those of 0° and 45° specimens. The weft/warp orientation of 30°/60° specimen is closer to the loading direction than that of 45° specimen, and the yarns along this direction contribute more to bear the load, which causes the specimen a higher S11 value and a certain bending, hence more obvious fiber compressive/tensile damage is produced on the pressed/pressed side. A notable difference between 30° and 60° specimens is that the yarns with 30° to the loading direction are respectively along weft and warp directions, and the former possesses a better mechanical properties as shown in table 2, which can make 30° specimen more prone to achieve relatively high stress and to produce fiber compressive damage on the pressed side. By contrast, the matrix compressive damage holds dominant position on the same side of 60° specimen.

For the impacted specimens, the compression responses are influenced by not only the fiber architecture but also the impact damage. On the one hand, the impact deformation is easier to cause the specimen a certain degree of bending, which may bring the stress concentration on its horizontal midline. At a small deflection angle, the specimen is prone to be suddenly crushed under a high level of stress, and the failure of the whole specimen is determined by the fiber failure. As the off-axis angle increases, the shear effect is more and more obvious, and the accumulated matrix damage takes over the dominant position by degrees, hence the specimen failure is gradually governed by the matrix failure and shows a certain ductile characteristic. On the other hand, the impact damage reduces the load capacity of the impacted region, and the greater the impact energy, the weaker the carrying capacity. As a result, the load is mainly borne by both sides of the impacted area. By comparing the S11 distribution and the fiber damage of impacted 0° and 30° specimens with those of unimpacted 0° and 30° specimens, it is seen that both the stress concentration and damage regions are transferred from the center to both sides.

Figure 14. Failure information of each off-axis angle specimen under 80 J impact energy.
5. Conclusion

The failure mechanism of 3D woven composites subjected to compression loading along principal/off-axis direction after low-velocity impact was assessed experimentally and numerically. The weft and warp orientations of 3D woven composites determine that the impact damages including matrix cracking, fiber debonding and fiber fracture are direction-dependent, which means that the damage degree along each direction is different, and the extension direction of the damage changes regularly with the off-axis angle. The CAI strength along principal direction is always greater, while the CAI strength along off-axis direction is different, and the extension direction of the damage changes regularly with the off-axis angle. Under each impact energy, the CAI strength of small off-axis angle specimen is always greater, while the CAI strength along principal direction is more sensitive to the low-velocity impact than that along off-axis direction. During the compression, the small off-axis angle can cause the specimen a sudden crushing failure determined by the matrix failure and shows a certain ductile characteristic. Since the impact damage reduces the load capacity of the impacted region, both the stress concentration and damage regions are transferred from the center to both sides.

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Data availability statement

All data that support the findings of this study are included within the article and any supplementary files.

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