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STRUCTURAL DAMAGE CHARACTERISTICS OF A LAYER-TO-LAYER 3-D ANGLE-INTERLOCK WOVEN COMPOSITE SUBJECTED TO DROP-WEIGHT IMPACT

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Abstract:

The most attractive structural feature of the three-dimensional (3D) angle-interlock woven structure is that the straight weft yarns are bundled by the undulated warp yarns, which induces the overall good structural stability and a stable fabric structure. Thus the 3-D angle-interlock woven composite (3DAWC) prepared by the vacuum-assisted resin transfer molding (VARTM) curing process has excellent mechanical properties by using the fabric and epoxy resin as the reinforcement and matrix, respectively. The low-velocity impact damage properties of the composites under different drop-weight energies (70, 80, and 100 J) were tested experimentally. The load–displacement curves, energy–time curves, and the ultimate failure modes were obtained to analyze the performance of resistance to low-velocity impact, as well as the impact energy absorption effect and failure mechanism, especially the structural damage characteristics of the 3DAWC subjected to the low-velocity impact of drop weight. By analyzing the obtained experimental results, it is found that the fabric reinforcement is the primary energy absorption component and the impact energy mainly propagates along the longitudinal direction of the yarns, especially the weft yarn system, which is arranged in a straight way. In addition, as the impact energy increases, the energy absorbed and dissipated by the composite increases simultaneously. This phenomenon is manifested in the severity of deformation and damage of the material, i.e., the amount of deformation and size of the damaged area.

Keywords:

3-D angle-interlock woven composite; drop weight; low-velocity impact; energy absorption; structural failure characteristics

1. Introduction

Resin-based fiber-reinforced composite materials have been widely used in aerospace, transportation, construction engineering, sports equipment, personal protection, and other fields due to their significant advantages, such as lightweight, high strength, diversified structure, and good design ability.

Among them, especially the three-dimensional (3-D) textile structural composites (3DTSCs) with outstanding mechanical properties, such as 3-D woven, knitting, and braiding, indicate the better mechanical properties than the traditional two-dimensional (2-D) unidirectional composite materials. Due to the existence of the reinforcing fiber system in the thickness direction, the 3DTSCs can effectively avoid the delamination phenomenon and increase the inter-laminar shear strength, thus they have more obvious advantages in the external loading conditions such as bending, impact, and fatigue [1, 2].

Among the 3-D woven composites, two typical types are 3-D orthogonal and 3-D angle-interlock woven composites (3DOWCs and 3DAWCs), and each has its own advantages due to the specific structural characteristics [3–6]. The most prominent feature of the 3-D orthogonal woven structure is that the warp and weft yarns are arranged in a straight way and interlaced at 90°. Besides, they are bundled by the Z-yarn system in the thickness direction to form a tight and stable structure. The most prominent feature of the 3-D angle-interlock woven structure is that the straight-aligned yarn system and the yarns laid in the thickness direction are interwoven at a certain angle. The undulated warp yarn system is used to bind the weft yarn system that is arranged in a straight way, thereby effectively enhancing the connection strength between the layers and imparting good structural stability. Therefore, according to the count of interlaced layers, 3-D angle-interlock woven structures can be classified into layer-to-layer and through thickness [7]. In engineering applications, the mechanical advantages of the corresponding fabric structure should be fully utilized to choose the most suitable fabric structure.

Taking the 3-D angle-interlock woven fabric (3DAWF) or its reinforced composite material, i.e., 3DAWC subjected to the impact-type loads (including high and low velocities) into consideration, the mechanical contributions from the structure should be highlighted. On the one hand, due to the existence of the undulated yarn system along the thickness direction, the material is given a better performance of resistance to interlayer damage than the 2-D fiber-reinforced composite materials [8–10]. On the other hand, the straight-lined yarn system helps to rapidly propagate the impact energy to a large area of the structure with an ultrahigh stress wave velocity. The material is fully loaded to effectively improve the capacity of energy absorption and impact resistance. Such types of materials have great potential for applications in impact loading conditions [11–13].

In practical engineering applications, compared with the high-velocity impact conditions with severe material damage which should take the high strain rate effect into consideration, the influence of low-velocity impact loading on the mechanical properties of the 3DAWC is relatively small but it cannot be ignored. At present, the research works on the failure behavior of the 3DAWC under low-velocity impact, taking into account room temperature, normal pressure, and various special working conditions, such as high temperature, thermal oxidation, and aging [14, 15]. However, the research on the structural failure mechanism of the 3DAWC under the drop-weight low-velocity impact needs to be further studied.

In this article, the experimental investigation on a typical layer-to-layer 3DAWC subjected to drop-weight low-velocity impact loading with different impact energy (70, 80, and 100 J) is carried out to obtain the load–displacement curve, energy–time curve, and the ultimate failure mode in order to analyze the performance of resistance to low-velocity impact, as well as the impact energy absorption effect and failure mechanism, especially the structural damage characteristics of the 3DAWC subjected to the low-velocity impact of drop weight, thus to guide the structural optimization design of low-velocity impact-resistant composites.

2. Materials and testing

2.1. Materials

The composite testing specimens used in the drop-weight impact tests consist of the 3DAWF reinforcement and resin matrix. The reinforcing phase material and the matrix phase material are carbon fiber (warp and weft fiber tows) and epoxy resin, respectively. The specifications of 3DAWF are listed in Table 1.

In this study, a typical layer-to-layer 3DAWF is used, which is composed of two systems, i.e., the undulated warp yarn system in the longitudinal direction and weft yarn system arranged in a straight way. For the weft yarn system, relying on the closed-knit effect provided by the warp yarn system, it forms a stable 3-D woven fabric structure with excellent mechanical properties.

The composite specimens were manufactured using vacuum-assisted resin transfer molding (VARTM) technique. According to ASTM D7136, the size of each composite specimen for drop-weight impact testing is 100 x 100 x 6 mm^3. Besides, the fiber volume fraction is approximately 45%. The surface and cross section of a testing specimen are shown in Figure 1.

2.2. Low-velocity impact tests

The drop-weight impact tests were carried out on the WANCE (Shenzhen, China) DIT302E-Z drop-weight impact tester, as shown in Figure 2. The composite specimen was fixed in the specific fixture and placed in the working area of the tester. The axis of the drop weight was aligned with the center point of the testing specimen. The impact energy was set as 70, 80, and 100 J by controlling the drop height. Besides, all the tests were performed at room temperature, approximately 25°C. Each test at one specific impact energy was repeated three times and the average value was obtained.

3. Results and discussions

3.1. Load–displacement curves

The load–displacement curves of the tested 3DAWC specimens under various impact energies are shown in Figure 3. It can be found that the trends of curves are similar under different impact energies. Furthermore, the impact process can be divided into three stages as described as follows.

In the initial stage, the curves show a significant linear rise, indicating that the composite specimens are deformed. At this stage, the deformation range of the tested specimens is approximately 0.5 –1 mm. Then entering the second stage, the curves begin to show a slight tiny fluctuation. It indicates that the initial damage of the composite specimens is mainly caused by the cracking failure of the resin and the resin–fiber interface after reaching the failure threshold. The cumulative deformation range of the specimen at this stage is approximately 0.5–1.5 mm. In the third stage, a series of continuous relatively larger fluctuations appear on the curves. The fiber reinforcement is the main load-carrying component of the composite, indicating that

Table 1. The specifications of 3DAWF

Yarn	Material	Layers	Linear density (Tex)	Weaving density (ends/cm)	Areal density (g/cm^2)	Thickness (mm)
Warp	T300-6K	7	400	8	0.45	6
Weft	T700-12K	6/8	800	4		

Notes: T300 and T700 are two types of carbon fiber tows provided by Toray Inc (Japan).
6K (12K) means there are approximately 6,000 (12,000) fibers in a single fiber tow (yarn).
“ends/cm” means the number of warp/weft yarns per unit length of the fabric.

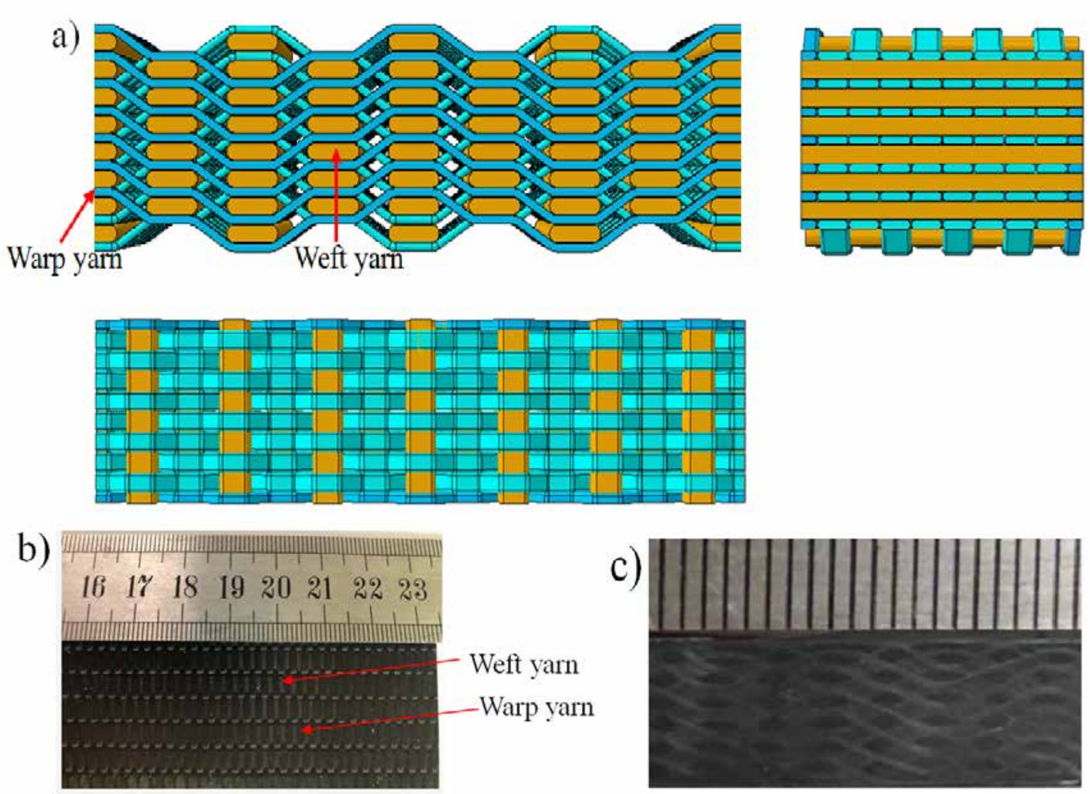

Figure 1. A testing 3DAWC specimen: (a) the structure of 3DAWF reinforcement, (b) surface, and (c) cross section.

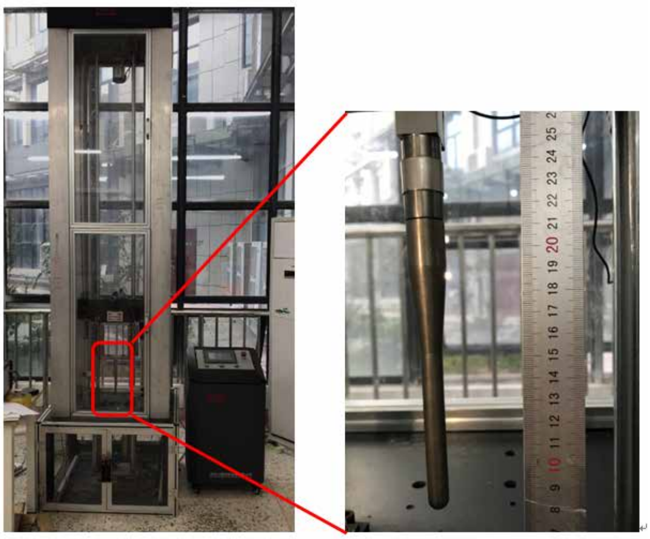

Figure 2. The drop-weight impact tester.

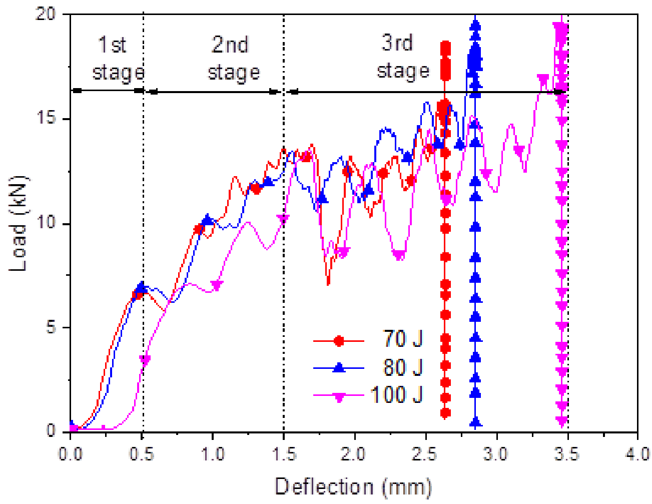

Figure 3. The load–displacement curves.

the fracture failure of the fiber reinforcement plays an important role in this stage. Furthermore, considering that the 3DAWC is reinforced by multilayers of warp and weft yarns, a similar large amplitude fluctuation occurs when each layer reaches its failure threshold and breakage occurs. According to the count of layers in the direction of impact, a total of approximately six or seven fluctuations can be found. This process continues until the breakage of the underlying yarns, which induces the ultimate punctured failure of composite. The cumulative deformation range is approximately 1.5–3.5 mm for this stage, and it is also the primary failure stage of the 3DAWC specimen under low-velocity impact loading.

3.2. Energy–time curves

In addition, the curves of the energy absorbed and dissipated by the 3DAWC specimens under various impact energies are shown in Figure 4. It can be found that the absorbed and dissipated energy increases simultaneously with the increase in the impact energy. Specifically, the absorbed and dissipated energy values corresponding to the initial impact energy of 70, 80, and 100 J are 25.24, 28.76, and 31.96 J, respectively.

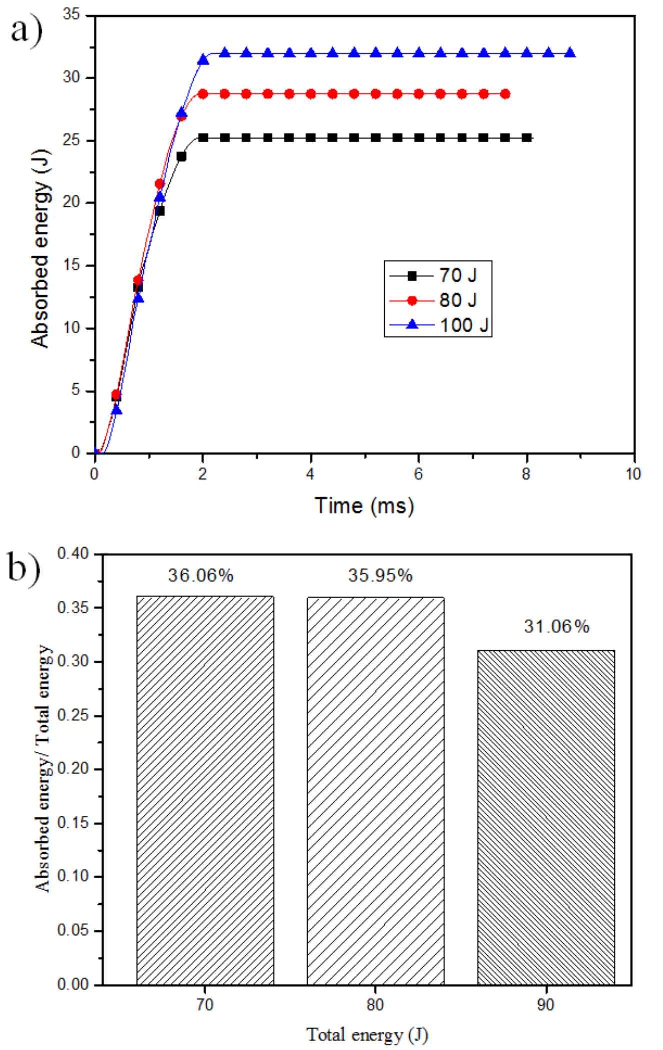

Figure 4. (a) Absorbed energy–time curves and (b) histogram of energy absorption ratio.

This phenomenon is manifested in the severity of deformation and damage of the 3DAWC specimens. For the impact-induced deformation of the 3DAWC specimens, the deformation in the impact direction increases simultaneously with the increase in the initial impact energy, i.e., the normal impact deformation amounts corresponding to various impact energies of 70, 80, and 100 J are 2.64 , 2.85, and 3.46 mm, respectively. As for the size of the impact-induced damaged area, it becomes larger with the increase in the initial impact energy.

It is worth pointing out that a relatively small part of the energy (approximately 30–35%) is absorbed and dissipated by the 3DAWC specimens during the impact process, which results in a certain degree of damage. Also most of the energy (approximately 65–70%) is taken away via the rebound effect of the drop weight due to the reverse force from the 3DAWC specimens.

3.3. The ultimate damage mode

During the drop-weight low-velocity impact process of the layer-to-layer 3DAWC specimen, the impact energy is mainly absorbed and dissipated via the damage modes such as resin cracking, fiber breakage, and de-bonding of the resin–fiber interface.

As shown in Figure 5, a similar damage mode occurs for the three impact energies. It can be found that clear impact-induced pits are generated in the central region of the composite surface in which they are directly impacted by the drop-weight impactor, accompanied by the cracking of fibers and resin. On the back side of each 3DAWC specimen, in addition to the cracking of matrix and fiber breakage, the cracks parallel to the longitudinal direction of fibers can also be found and accompanied by a significant protrusion.

It is worth mentioning that the damage in resin and fibers mainly propagates along the longitudinal direction of the warp and weft yarns on both sides of the 3DAWC specimen, especially of the weft yarns that are arranged in a straight way. In addition, it can be found that the greater the energy absorbed and dissipated by the 3DAWC specimen, the larger the area of damage, which is mutually confirmed by the phenomenon shown in Figure 5.

3.4. The impact failure mechanism

According to the earlier description, three main aspects on the damage of resin, fiber tows, and resin–fiber interface are involved in the drop-weight low-velocity impact process of the layer-to-layer 3DAWC. Therefore, the impact damage mechanism is divided into three parts and they are summarized as follows.

3.4.1. Resin

When the drop-weight impactor contacts with the resin on the surface of the 3DAWC, the composite enters the stage of deformation and progressive damage. The resin is influenced by the continuously strengthened stress and strain. Cracking is generated to absorb the impact energy when the stress and strain exceed their limit. Since the matrix absorbs only a small portion of the impact energy, a tiny fluctuation occurs in the load–displacement curves.

3.4.2. Resin–fiber interface

The impact energy propagates at a certain stress wave velocity during the impact process, resulting in a certain bending deformation and damage to absorb and dissipate the impact energy, as well as improving the load-carrying capacity of 3DAWC.

Since the stress wave velocity is much greater than the drop-weight velocity, stress wave is generated as the impactor contacts the composite surface, i.e., compression wave. It propagates rapidly along the lateral and longitudinal directions of the material, and then the reflected wave is generated when a free surface or interface is encountered, i.e., tensile wave. Under the joint action of compression wave and tensile wave, the onset of de-bonding phenomenon can be found at resin–fiber interface in the composite structure. Moreover, it mainly propagates into the interior of the composite structure along the longitudinal direction of the fiber tows. Similarly, the tiny

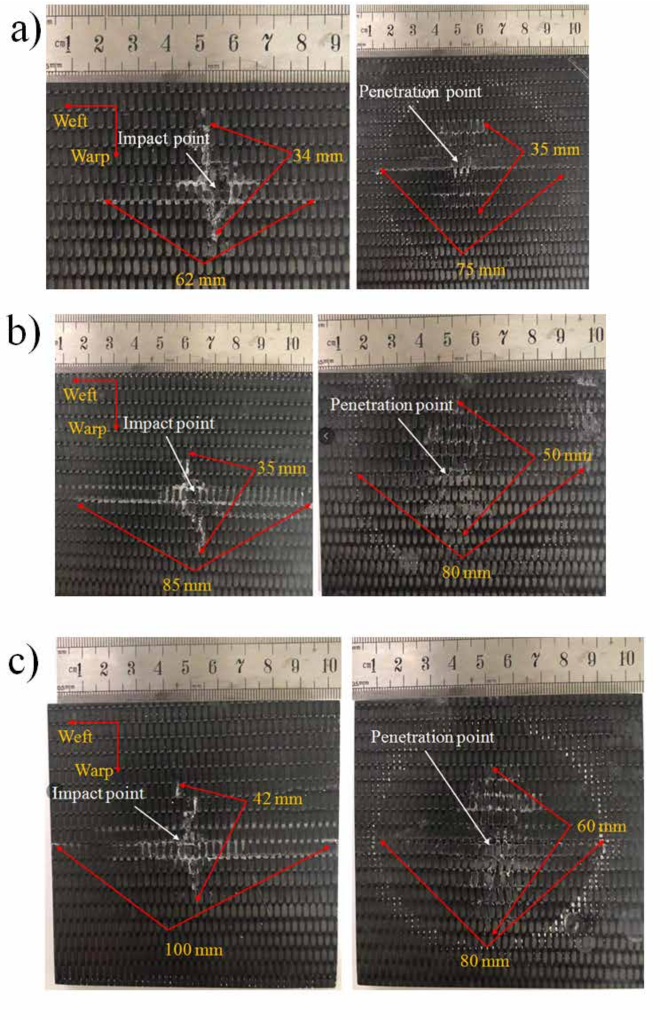

Figure 5. The ultimate impact damage modes: (a) 70 J, (b) 80 J, and (c) 100 J.

fluctuations in the load–displacement curves occur since relatively small portion of impact energy is absorbed by the interface de-bonding.

3.4.3. Fiber reinforcement

With the continuation of the impact process, due to the distribution of a certain amount of yarn reinforcement on the path of the drop-weight impactor, the breakage of fiber tows occurs after reaching the failure threshold. Since the fiber tows can no longer carry loads after breakage, the number of co-load-carrying fiber tows during the penetration process is constantly changing, and the load applied to the composite material is also constantly changing. Furthermore, since the fiber reinforcement absorbs most of the energy during the impact process, which causes a huge change in the force acting on the impactor, the continuous fluctuations with large amplitude occur on the load–displacement curves.

4. Conclusions

In this article, the energy absorption mechanism and structural failure characteristics of a layer-to-layer 3DAWC under drop-weight low-velocity impact loading are studied. The damage performance for different impact energy cases (70, 80, and 100 J) is tested. By analyzing the experimental results, the following conclusions have been obtained.

1. In view of the 3-D angle-interlock woven structure, the impact energy mainly propagates along the longitudinal direction of the straightly arranged weft yarns, instead of the undulated warp yarns, thus the impact energy propagates at a certain stress wave velocity. The capacity of impact resistance for the 3DAWC has been effectively improved.

2. According to the variation characteristics of the load–displacement curves, the drop-weight impact process can be divided into three stages: the initial stage of deformation; the second stage of initial damage, which is mainly due to the cracking or de-bonding of resin and resin–fiber interface; and the third stage of layer-by-layer style fracture failure of fiber reinforcement.

3. As the impact energy increases, the energy absorbed and dissipated by the composite increases simultaneously. This phenomenon is manifested in the severity of deformation and damage of the 3DAWC specimens. For the impact-induced deformation, the deformation in the impact direction increases simultaneously with the increase in the initial impact energy. As for the size of the impact-induced damaged area, it becomes larger with the increase in the initial impact energy.

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