

Postprint: Through-Thickness Shear Fracture Behavior of Polymorphic Carbon Fiber Composites

Authors: Guo Yuqin, Yang Yan, Sun Minhang, Tang Pengpeng

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Abstract

For carbon fiber reinforced polymer (CFRP) composed of alternating epoxy resin films and reinforced carbon fiber fabrics, which exhibits dry state (room-temperature solid), soft state (glass transition temperature range), wet state (resin melting temperature range), and solid state (curing onset temperature) characteristics with temperature variation, a series of punching experiments were conducted using a self-designed shear punching die. The vertical shear fracture behavior and characteristics of multi-state CFRP materials under different process conditions were analyzed, and the corresponding influence mechanisms were explained. The results show that: compared with dry carbon fiber fabric, dry/solid, soft, and wet state CFRP materials exhibit typical nonlinear deformation, discontinuous, and delamination fracture characteristics during vertical shear fracture, but the maximum load required for shear fracture increases sequentially; additionally, smaller punching clearance and shear angle, as well as higher punching speed, are beneficial for reducing the discontinuous fracture of local fiber bundles, making the delamination fracture more concentrated and stable.

Full Text

Preamble

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Vertical Shearing Fracture Behavior of Carbon Fiber Reinforced Plastic of Different Status

GUO Yuqin, YANG Yan, SUN Minhang, TANG Pengpeng

(School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China)

Abstract

Carbon fiber reinforced plastic (CFRP) was fabricated by alternately laying epoxy resin films and carbon fiber fabrics for a desired number of layers. The prepared CFRP could be in different status such as dry, soft, wet, and solid corresponding to ambient temperature, and temperatures of glass transition, melting, and curing of resin films, respectively. Blanking tests were performed by means of a homemade shearing blanking die to characterize the vertical shearing fracture for the prepared CFRP of different status. Results show that the vertical shearing fracture of the dry/solid, soft, and wet CFRPs present characteristics of typical nonlinear deformation, discontinuous and delaminating fracture, and the required blanking forces increase in turn. Moreover, blanking with a small gap, proper angle, and high speed may be helpful to relieve the discontinuous fracture of partial carbon fiber yarns and promote the delaminating fracture of CFRPs to be much more concentrated and stable.

Keywords composites, CFRP, vertical shearing, fracture behavior, cutting

Introduction

Carbon fiber reinforced plastic (CFRP) is widely used in industry due to its high specific strength, high specific modulus, excellent fatigue resistance, and wear resistance [1-3]. Common manufacturing processes for CFRP include autoclave [4], resin transfer molding (RTM) [5], resin film infusion (RFI) [6], and integrated “shearing-blanking-curing” manufacturing processes [7]. These methods require cutting of dry carbon fiber fabrics, prepreg, resin films, or preformed CFRP laminates before molding, and trimming or punching of CFRP parts after molding to facilitate subsequent assembly. These processes involve not only cutting of dry and solid-state carbon fiber fabrics and their composites, but also wet cutting of carbon fiber fabrics infiltrated with molten resin and soft cutting of CFRP materials composed of softened resin films and carbon fiber fabrics (referred to as multi-state cutting). The fracture behavior and mechanisms of CFRP materials in different states vary under different process conditions, significantly affecting the final part’s section quality and joint service performance. Therefore, it is necessary to systematically investigate the fracture behavior of multi-state CFRP to enable rational selection of equipment and cutting process schemes.

Previous research on CFRP fracture behavior includes tensile fracture of 3D woven CFRP [8], low-velocity impact fracture [9], fatigue fracture under cyclic loading [10], and punching shear fracture under vertical pressure [11]. However, these studies were all based on cured dry CFRP materials. Epoxy matrix composites exhibit excellent wear resistance, high hardness, and poor thermal

conductivity, making them difficult-to-machine materials. Mechanical machining of cured composites often causes defects such as delamination, fiber tearing, pull-out, and entanglement, with rapid tool wear and high processing costs [12, 13]. Special machining methods such as laser cutting, electron beam machining, and plasma cutting produce obvious heat-affected zones, making it difficult to obtain uniformly high-quality surfaces [14, 15]. In view of this, this paper conducts a series of shearing blanking experiments based on the multi-state characteristics of matrix resin films that sequentially exhibit dry, soft, and wet states with increasing temperature. By investigating the fracture behavior of multi-state CFRP materials, this approach replaces post-cure machining and fundamentally changes the stress state and fracture mechanism during cutting, revealing the influence of factors such as carbon fiber fabric layer count, resin film layer count, test temperature, blanking gap, blanking speed, and shear angle on the vertical shearing fracture behavior of CFRP materials and explaining the corresponding mechanisms.

1 Experimental Methods

Blanking tests were performed on a CMT5105 MTS computer-controlled electronic universal testing machine using a self-developed reconfigurable blanking die and a heating temperature control device. The reconfigurable blanking die structure [Figure 1: see original paper] consists of an upper connector (1), punch holder plate (2), punch (3), pressure plate (5), die (6), positioning plate (7), base (8), lower connector (9), support block (10), etc. The specimen (4) is placed on the die (6) and clamped by the pressure plate (5). The blanking punch (3) has three angles: 60°, 45°, and 20°. The upper and lower connectors of the blanking die are connected to the testing machine's worktable flanges via long pins. The die (6) is split into left and right halves, and the gap between the left half of the die (6) and the punch (3) is adjusted using dimensionally calibrated spacers (11) to investigate the effect of blanking gap on fracture behavior. The installation effect of the die on the universal testing machine is shown in [Figure 1: see original paper].

To investigate the vertical shearing fracture behavior of multi-state CFRP, particularly the effects of carbon fiber fabric layer count (n_1), resin film layer count (n_2), test temperature (T), blanking gap (C), blanking speed (V), and shear angle (α), the experimental scheme in was adopted. Experiments 1-4 investigated the effect of carbon fiber fabric layer count on CFRP vertical shearing fracture behavior. Experiments 5-7 were compared with experiments 2-4 to study the effect of resin film and its layer count. Experiments 6, 8, 9, and 10 investigated the effect of material status determined by temperature. Experiments 9, 11, 12, 13, and 14 studied the effect of blanking gap. Experiments 9, 15, 16, and 17 examined the effect of blanking speed. Experiments 9, 18, and 19 investigated the effect of shear angle.

The experiments used Toray T300-3K twill fabric with a thickness of 0.22 mm as reinforcement. The matrix resin film was made from YPH-23 epoxy resin with a single-piece thickness of 0.02 mm. Carbon fiber fabrics and resin films were cut to 100 mm length and 20 mm width and laid up according to the experimental scheme in to prepare CFRP specimens. Based on the fiber volume fraction requirements for carbon fiber composites and previous infiltration experiments with fully melted resin (110°C), CFRP specimens were prepared by alternately laying 15 resin film pieces between every two carbon fiber fabric layers. This ensured sufficient infiltration of molten resin into carbon fiber fabrics without excessive resin causing resin flow at the cut section, which would affect section quality.

2.1 Effect of Experimental Temperature on CFRP Shear Fracture Behavior

Experiments 6 and 8-10 corresponded to room temperature (25°C), matrix resin softening temperature (80°C), melting temperature (110°C), and curing temperature (150°C), respectively, which determined that CFRP specimens were in dry, soft, wet, and solid states. Therefore, the load-time curves shown in [Figure 2: see original paper] reflect not only the effect of test temperature on CFRP laminate fracture behavior but also the fracture behavior of CFRP materials in different states. The results show that for CFRP specimens with the same layup, the soft-state blanking at 80°C required the smallest cutting force and the material fractured most easily. The dry-state (25°C) and solid-state (150°C) blanking required the next highest forces, while wet-state blanking at 110°C required the maximum cutting force, approximately 32.7% higher than soft-state blanking. Additionally, the shearing process for CFRP specimens in dry, soft, wet, and solid states exhibited neither the typical “linear elastic deformation-work hardening-necking” process of elastoplastic materials nor the brittle fracture of brittle materials, but rather obvious nonlinear shear deformation and discontinuous fracture characteristics, including local discontinuous fiber fracture and delaminating fracture. The former manifests as slight fluctuations in blanking force on the curves (see circled areas in [Figure 2: see original paper]), caused by fracture of a few carbon fiber yarns under blanking force. The latter appears as large amplitude fluctuations (see arrow-indicated areas in [Figure 2: see original paper]), caused by delaminating fracture of a CFRP layer relative to the main body. Furthermore, the long-duration deformation platforms at the later fracture stage in the load-time curves for different CFRP states result from the resin matrix changing the interlayer friction state of carbon fiber fabrics, combined with large punch shear angles causing relative slip of CFRP specimens during further shearing, which is also characteristic of discontinuous delaminating fracture in CFRP materials.

2.2 Effect of Carbon Fiber Fabric Layer Count on Dry CFRP Shear Fracture Behavior

The load-time curves and stress-strain curves for CFRP specimens with different carbon fiber fabric layer counts during shearing are shown in [Figure 3: see original paper]. As seen in [Figure 3: see original paper]a, the required maximum cutting force increases approximately proportionally with carbon fiber fabric layer count. [Figure 3: see original paper]b shows that when the carbon fiber fabric layer count is greater than 2, the local discontinuous fracture of carbon fiber yarns reduces the overall fracture strength of CFRP. The compression deformation of multilayer CFRP laminates along the thickness direction during initial vertical shearing also contributes to the nonlinear shear deformation behavior during vertical shearing blanking.

2.3 Effect of Resin Film and Its Layer Count on CFRP Shear Fracture Behavior

The curves in [Figure 4: see original paper] show the load-time curves for CFRP specimens with and without resin film between 2, 3, and 4 carbon fiber fabric layers during shearing blanking. Compared with specimens without resin film, the obvious fluctuations in maximum cutting force and the appearance of long deformation platforms in the later fracture stage indicate that resin film presence makes CFRP fracture behavior exhibit typical local discontinuous fiber fracture and delaminating fracture characteristics. [Figure 5: see original paper] shows the relationship between maximum cutting force and resin film layer count for CFRP specimens with and without resin film. The maximum cutting force increases significantly with resin film layer count. Compared with pure carbon fiber fabric laminates, resin film presence endows CFRP specimens with special shear deformation characteristics that require analysis from an elastic-viscoelastic coupling and fracture perspective rather than simple superposition or analogy.

2.4 Effect of Blanking Gap on Wet CFRP Shear Fracture Behavior

[Figure 6: see original paper] and [Figure 7: see original paper] show the load-time curves and maximum cutting force variation for CFRP specimens during wet-state shearing blanking at different blanking gaps. Analysis indicates that blanking gap variation does not fundamentally affect the nonlinear shear deformation, local discontinuous fiber fracture, or delaminating fracture behavior of wet CFRP, but significantly affects the required maximum cutting force. Specifically, the maximum cutting force decreases sharply with increasing blanking gap in the small gap range (0.05-0.1 mm) and large gap range (0.5-0.8 mm). In the 0.1-0.5 mm gap range, the maximum cutting force for multi-state CFRP remains relatively stable with variation amplitude not exceeding 5.13%. Additionally,

small-gap blanking (0.05 mm) shows more obvious concentrated delaminating fracture, as evidenced by violent large-amplitude fluctuations in blanking force (“double peaks” circled in [Figure 6: see original paper]) and rapid fracture in the later stage. As blanking gap increases, the fracture process becomes more dispersed with longer complete fracture duration, manifested by the appearance and prolonged duration of deformation platforms in the later fracture stage.

2.5 Effect of Blanking Speed on Wet CFRP Shear Fracture Behavior

[Figure 8: see original paper] and [Figure 9: see original paper] show the load-time curves and maximum cutting force variation for CFRP specimens during wet-state shearing blanking at different blanking speeds. The results show that as blanking speed increases, local discontinuous fiber fracture weakens or even disappears, while delaminating fracture becomes more obvious and concentrated, with material fracture dominated by concentrated, stable, delaminating fracture. At low speed (30 mm/min), the required maximum cutting force is relatively small, at 86.11%-90.78% of that at other speeds. At this speed, CFRP fracture is dominated by local discontinuous fiber fracture, which may adversely affect cut section quality. At 120 mm/min, the required maximum cutting force is about 3.66% and 5.42% lower than at 60 mm/min and 240 mm/min, respectively. Thus, within the 60-240 mm/min range, blanking speed has no obvious effect on maximum cutting force but significantly affects fracture behavior. Higher blanking speed promotes stable, concentrated cutting and improves cut section quality.

2.6 Effect of Shear Angle on CFRP Shear Fracture Behavior

The load-time curves and maximum cutting force variation for CFRP specimens during wet-state shearing blanking at different shear angles are shown in [Figure 10: see original paper] and [Figure 11: see original paper]. The maximum cutting force decreases approximately linearly with decreasing shear angle. Additionally, local discontinuous fiber fracture weakens while delaminating fracture intensifies, making the fracture process more concentrated and stable (marked by “double peaks” on the curves), which benefits section quality.

Conclusions

1. In vertical shearing blanking experiments on dry, soft, wet, and solid-state CFRP specimens, resins in different states cause multi-state CFRP to exhibit special nonlinear shear deformation processes and local discontinuous carbon fiber yarn fracture and delaminating fracture behavior. Local discontinuous carbon fiber yarn fracture appears as slight fluctuations in

blanking force on load-time curves, caused by fracture of a few carbon fiber yarns under blanking force, while delaminating fracture appears as large amplitude fluctuations, caused by delaminating fracture of a CFRP layer relative to the main body.

2. During CFRP specimen shearing blanking, the required maximum cutting force increases significantly with carbon fiber fabric layer count, resin film layer count, and shear angle, decreases obviously with increasing blanking gap, and shows no obvious effect from blanking speed within the 60-240 mm/min range.
3. Under the same layup conditions, soft-state CFRP specimens corresponding to the matrix resin glass transition temperature range require the smallest cutting force. Dry-state and solid-state CFRP specimens corresponding to room temperature and matrix resin curing temperature range require the next highest forces, while wet-state CFRP specimens corresponding to the matrix resin melting temperature range require the maximum cutting force.
4. Resin film layer count, test temperature, blanking speed, blanking gap, and shear angle significantly affect multi-state CFRP fracture behavior. Resin film layer count and temperature-dependent rheological properties directly determine CFRP material status and discontinuous delaminating fracture behavior. As blanking speed increases and shear angle decreases, local discontinuous fiber fracture weakens or even disappears while delaminating fracture intensifies. Within the 0.1-0.5 mm blanking gap range, CFRP fracture behavior and required maximum cutting force are relatively insensitive to gap variation.
5. For multi-state CFRP materials with the same layup, combinations of small blanking gap, small shear angle, and high blanking speed weaken local discontinuous fiber fracture, make delaminating fracture dominant, promote concentrated and stable material fracture, and improve shearing blanking section quality.

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