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X-ray 3D microscopy analysis of fracture mechanisms for 3D orthogonal woven E-glass/epoxy composites with drilled and moulded-in holes

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ABSTRACT

As a promising structural material, three dimensional woven fabric reinforced composites are subjected to machining or drilling during manufacturing processes for components assembly. In-plane tensile and flexural properties of a three dimensional orthogonal woven E-glass/epoxy composites (3DOWC) with 4 and 6 mm drilled holes (DH) and moulded-in holes (MH) are investigated. 2D woven E-glass/epoxy laminated composites (2DWC) with the same drilled hole sizes are also tested for comparison. Two different calculation methods based on gross and net sectional area are adopted to evaluate the effects of the holes on mechanical performance of the composites. The 3DOWC-MH possesses the highest tensile and flexural strength, followed by 3DOWC-DH and 2DWC-DH. As the hole diameter increases, the mechanical properties of all the composites degrade, while those of the 3DOWC-MH increases when the net sectional areas are used for calculation. X-ray 3D microscopy and scanning electron microscopy are employed to analyze damages at submicron level resulted from the tests. Various failure modes such as fiber fracture, matrix cracking and tow debonding are observed, while serious delamination occurs in 2DWC but not in 3DOWC.

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1. Introduction

The fiber reinforced composites are extensively used as structural material due to the lightweight and high-strength characteristics [1–4]. Compared to conventional laminated materials, 3D textile structural composites have advantages in delamination resistance, damage tolerance and structural integrity [5–12], which make them attractive candidate structural materials in the fields of military equipment, recreational marine, wind energy, civil engineering and aerospace applications [13–17]. Due to the needs for components assembly in different structures, bolting and riveting are frequently used to form structural joints [18–22]. Thus, drilling is employed for secondary machining in composite structures [23–30]. For example, over 100 thousand holes are drilled for a small single engine aircraft and the numbers are much more for a large transport aircraft [31]. Therefore, the study of the influence of holes on the composite material is critical not only to the material properties, but also to the safety of composite structures.

In decades, many literatures on mechanical drilling for composites focused on machining parameters and drill geometry [32–36]. Besides, some studies paid attention to the effects of structure on the open-hole performance of composites, including unidirectional, laminated, 3D woven fabrics and so forth. The laminated composites with drilled holes, which were reinforced by the unidirectional fibers, fiber mat or 2D woven fabric, develop severe strength reduction due to the stress concentration, delamination and micro cracking [37–39]. Khashaba et al. [37] reported that the net and gross notched bending strength of notched glass fiber reinforced epoxy composites decreased linearly with increase of hole diameter and the maximum reduction ratio reached 50%. Zhang et al. [38] found that notched tensile strength of glass mat composite plates with open-hole decreased 20–40%, and the

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degradation became lower when the thickness increased. Haery et al. [39] reported that the tensile strength of 2D woven fabric glass/epoxy laminates decreased with increasing hole diameter from 5 to 10 mm and the maximum reduction ratio was 29%.

Meanwhile, 3D woven composites are shown to possess more stable open-hole mechanical behaviors [40–43]. Nakai et al. [40] reported that composites with braided holes showed superior mechanical property to those with drilled holes. Shaw et al. [43] found that the tensile strength of a 3D angle-interlock woven C/SiC composite with 1–2 mm holes exhibited a weak sensitivity to the presence of holes, regardless of the manner in which the holes were introduced.

Recently, 3D orthogonal woven composites (3DOWC) have received growing interests due to the advantages of relatively low processing cost and good structural integrity. Furthermore, 3DOWC structures are composed of straight fibers in three orthogonal directions, resulting in significantly higher in-plane strength and better integrated structures than laminated composites [44–46]. However, the mechanical properties and fracture mechanisms of 3DOWC with holes are rarely investigated.

Damages resulted from external forces applied to composite materials or structures during testing or service may be inspected using various techniques such as visual and microscopic analyses, as well as non-destructive testing (NDT) methods [47]. Moreover, these traditional techniques are either destructive or cannot provide a reasonable spatial resolution. Non-destructive X-ray micro-computed tomography (micro-CT) technique, on the other hand, allows us to visualize the 3D internal deformation and damage behavior of tested composites with a high resolution [48]. Originally adopted in medical field to obtain non-invasive images of the bones and tissues in human body, X-ray micro-CT technique has been recently used and proved as an effective way to characterize the micro-structure of textile composites and has now gained popularity as an NDT technique to evaluate defects and damage in materials [49]. Furthermore, post-mortem X-ray micro-CT has been employed to inspect damage in composites such as matrix cracks [50,51], fiber fractures [52,53], delamination [54] and kink bands [49] at micron-range. Meanwhile, it has also been adopted as a pre-check method to examine voids [55,56] and 3D micro-structure for modeling virtual textile specimens [57]. X-ray 3D microscopy, one kind of micro-computed tomography (micro-CT) that combines conventional CT technology with optical microscopy, provides a new type of 3D perspective microscopic imaging system with high spatial resolution of sub-micron level, which can serve as a powerful tool of failure analysis for composite structures.

In this study, 3D orthogonal woven E-glass/epoxy composites (3DOWC) with drilled and moulded-in holes and 2D woven laminated composites (2DWC) with drilled holes were prepared and compared. The effects of the open hole on the performance of composites were investigated by tensile and bending tests. Furthermore, the fracture mechanisms of all composites were analyzed using X-ray 3D microscopy and scanning electron microscopy (SEM).

2. Experiment

2.1. Materials and fabrication

The 3D orthogonal woven fabric (3DOWF) and 2D plain woven fabric (2DWF) were made of E-glass fiber tows supplied by Jushi Group Co Ltd. The weave architectural parameters were listed in Table 1. The vacuum-assisted resin transfer molding (VARTM) technique was adopted to manufacture the composites. Epoxy resin and curing agent were mixed in a mass ratio of 3:1 and the woven fabrics were infused with the above mixture. The employed JL-235 epoxy resin was manufactured by Jiafa Chemicals Co. Ltd. After the impregnation, the composites were kept in the mould under the pressure at a cure temperature of 50 °C for 1 h followed by a 7 h post-cure at 70 °C. The fiber volume fraction of the 3DOWC and 2DWC were both approximately 47% tested by density method. The thickness of 3DOWC and 2DWC were around 2.5 and 2 mm, respectively. The structures of 3DOWC and 2DWC were shown in Fig. 1.

Table 1
Weave architectural parameters of the 3DOWF and 2DWF.

	Yarn	Layers	Linear density (tex)	Weaving density (ends/10 cm)
3DOWF	warp	2	1102	50
	weft	3	600	40
	binder	–	370	50
2DWF	warp	1	1102	50
	weft	1	600	40
	binder	–	–	–

The holes in composites were introduced by two methods: by inserting fugitive rods into the woven preform during weaving process namely moulded-in hole (MH) or by drilling with a standard twist drill after a panel fabrication namely drilled hole (DH). In order to investigate the effects of hole size on composites, both 4 and 6 mm diameter holes were introduced in the middle of the specimens. Fig. 2 presented the images of the three types of composites with holes. For the composites with drilled holes as shown in Fig. 2 (a) and (b), fibers around the hole were cut off, and the amount of load bearing fibers decreased. However, for the composites with moulded-in holes as shown in Fig. 2(c), the fibers were still kept continuous and condensed around of the hole.

2.2. Mechanical tests

2.2.1. Tensile testing

Tensile tests were performed with a universal testing machine (WDW-20, HUALONG) using 50 KN load-cell. The composite plate was cut into coupons along the warp direction. According to ASTM Standard D5766 [58], the specimen size was 250 mm × 25 mm with glass reinforced plastic tabs of 50 mm in length glued to the ends of the specimens, leaving a free length of 150 mm. Five samples were tested at a cross-head speed of 2 mm/min; no external measurement of composites strain was used, i.e., the strain is the nominal tensile strain.

2.2.2. Flexural testing

Three-point bending tests for flexural properties were performed with a universal testing machine (WDW-20, HUALONG) using 50 KN load-cell. The composite plates were cut into coupons by saw blade cutter along the warp direction. According to ASTM Standard D7264 [59], the specimen size was 60 mm × 15 mm, and the support span was 40 mm. Five specimens were tested for each sample at a cross-head speed of 2 mm/min; the bending strain was also nominal strain.

2.3. Characterization of damage morphology

Scanning electron microscope (SEM, Hitachi TM3000) images was used to characterize tensile fracture surfaces. In preparation for damage characterization by SEM, the specimens of 5 mm–10 mm high were cut with a saw from the tested specimens and placed on the sample stem vertically to observe the edges of the holes. Moreover, because the samples under bending load did not break completely, X-ray 3D microscopy (Sanying Precision Instruments

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