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Experimental investigation of kink initiation and kink band formation in unidirectional glass fiber-reinforced polymer specimens

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ABSTRACT

The failure mechanism of non-slender glass fiber-reinforced epoxy prismatic specimens subjected to axial compression and different temperatures was investigated. Digital image correlation was used to map and derive the failure modes. The failure mode changed from splitting failure at ambient temperature to kinking at the onset of the glass transition temperature. The kink initiation mechanism could be clearly observed. Based on the initial waviness of the fibers, the wave amplitude disproportionally increased at one specific location up to fiber microbuckling and surrounding matrix failure; the wavelength of the initial imperfection was thereby maintained. The kink band then rapidly propagated through alternating horizontal and inclined segments leading to an overall inclined kink band of 31° on average. The kink band width doubled from around three to six times the average wavelength of the initial imperfection.

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1. Introduction

Fiber-reinforced polymer (FRP) components used in civil engineering applications are often subjected to compressive loads. Compared to the tensile strength of FRP materials, the compressive strength is usually lower and shows more scatter due to fiber misalignments and initial imperfections caused during fabrication. Furthermore, the compressive material properties of composites are sensitive to temperature elevations occurring in engineering applications, as for example below the asphalt layer in FRP composite bridge decks. Temperatures in such cases can reach 90 °C [1], approaching the glass transition temperature (T_g) of the resin and softening the composite material.

The compressive failure mode of FRP specimens can be associated with fiber failure, splitting, kinking, or the combination of kinking and splitting. Fiber failure is a common failure mode of fibers that are weak in compression, like aramid fibers, and an unusual failure mode for carbon or glass fibers [2]. Splitting is a typical compressive failure mode of composites with low interfacial shear strength, e.g. carbon fiber-reinforced polymers (CFRP), and is accompanied by crack propagation, inside the matrix or at the interface, along the loading direction [3]. Kinking is a failure mode in which one part of the material is displaced relatively to another along an inclined path with respect to the loading direction. Kinking failure has been observed in both CFRP and glass fiber-reinforced polymer (GFRP) composites [4]. Compared to the mechanisms dominating fiber failure, splitting, and kinking development, those causing kinking initiation are more complicated and a generally accepted explanation of their initiation based on solid experimental evidence is still lacking.

The first works concerning the experimental investigation of the kinking failure in fiber-reinforced composites can be traced back to 1964. Rosen [5] observed the microbuckling of fibers during the shrinkage of the resin as the GFRP specimen was cooled from its curing temperature to room temperature. It was therefore derived that kinking under compression is caused by microbuckling since shrinkage is followed by an increase of the compressive stress in the matrix. Later studies [6–8] reported the co-existence of microbuckling and kinking in CFRP laminates and assumed that kinking was a result of the microbuckling.

Kinking resulting from compression fatigue loading of notched specimens was also attributed to microbuckling induced by the crack propagation near the notch tip [9], however, no experimental proof was reported to validate this assumption. Compressive experiments on CFRP specimens [10–12] focused on the kinking band propagation and broadening, contributing only with limited information to the identification of the factors leading to kinking. Schultheisz and Waas [2], Weaver and Williams [13], and Wronski and Parry [14] doubted the validity of the causality between microbuckling and kinking since they did not observe any significant microbuckling before or after the kinking failure of the examined specimens.

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Elevated temperature can also affect the failure mode of composites in compression. A shift from splitting to kinking, under elevated temperatures, was observed in [15–16] and was attributed to the softening of the matrix and increase of the shear interlaminar stresses. Limited experimental evidence was provided by Grape and Gupta [15] regarding the formation of microbuckling due to shear interlaminar stresses. Although Bazhenov and Kozey [16] failed to observe the failure process experimentally, they measured the compressive strength as a function of fiber volume at an elevated temperature. The relationship followed Rosen's microbuckling theory [5] indicating, indirectly, that microbuckling caused the eventual kinking. The failure mode of GFRP specimens with a slenderness ratio of 60 was studied during temperature elevation in [17]. The failure mode changed from buckling at ambient temperature to kinking at 220 °C, at which the rubbery state of the examined matrix was reached. A temperature-dependent non-dimensional slenderness ratio was proposed to describe the effects of both geometry and matrix softening during temperature elevation on the failure mode.

The variation of the failure mode can also be affected by material imperfections, e.g. fiber waviness and voids. Typical wavelengths of prepreg CFRP are between 2.1 mm and 5.6 mm [18]. The compressive failure strength can be significantly decreased, e.g. by 75% reported in [19], while on the contrary, the width of the kink band can be increased by as much as 45% [20] with the increase of fiber waviness. As shown by Hancox [21], kinking can be observed in low void content materials while splitting failure occurs in the case of materials with a high percentage of voids.

The aforementioned works focused on the investigation of kink band propagation and the effect of temperature and material imperfections on the kinking failure of FRP composites. Even though some phenomena, e.g. the co-existence of microbuckling and kinking, were observed, direct experimental evidence of the effect of microbuckling on kinking initiation, either under ambient or elevated temperature, is still lacking in the literature.

This work investigates the compressive behavior of GFRP prismatic specimens, aiming to reveal the mechanisms initiating kinking failure at temperatures up to 90 °C, which corresponds to the onset of glass transition (93 °C) of the selected material. Furthermore 90 °C represents the maximum temperature to which engineering structures such as bridges may be exposed in service conditions [1]. The initiation of kinking failure and the kink band formation are experimentally investigated by surface strain and lateral deformation measurements using digital image correlation (DIC).

2. Experimental work

2.1. Material characterization

E-glass fiber-reinforced polymer (GFRP) composites, a typical material used in civil engineering applications, were examined in this work. The matrix of the GFRP specimens is a thixotropic bi-component polymer from Swiss Composite AG [22]. The base resin is an epoxy type L and the hardener is EPH 161; the resin to hardener mixing ratio is 4:1. This epoxy has a low viscosity and is free of fillers, which is ideal for impregnating glass fibers. The polymer is reinforced by unidirectional E-glass fiber fabrics (EC 9-68) from Swiss Composite AG, having an area density of 425 g/m^2 and layer thickness of 0.45 mm [22].

A GFRP laminate with nominal dimensions of $22 \times 240 \times 500\ \text{mm}^3$ was fabricated by hand-layup achieving a fiber volume fraction of 44% as determined by burn-off experiments. The laminate was initially cured at room temperature for 48 h and then post-cured at 100 °C for 72 h to approach full curing. Ten non-slender specimens with nominal dimensions of $12.7 \times 12.7 \times 50\ \text{mm}^3$ according to ASTM D695-10 [23] were cut from the GFRP laminate and the cut surfaces were flattened by a lathe. The sample designation and exact dimensions of the examined specimens are shown in Table 1.

An optical scanning microscope was used for the investigation of the microstructure of the specimens. A specimen with dimensions 13 × 13 × 13 mm (see Fig. 1a) was cut from the same laminate and appropriately prepared. Several consecutive scans were performed on the surface that is perpendicular to the lamina plane; the obtained microstructure is shown in Fig. 1b and c. As shown in Fig. 1b, the rovings were not perfectly straight and exhibited initial imperfections. Average measured wavelengths and amplitudes were 3.23 ± 0.17 mm and 0.036 ± 0.003 mm respectively, see Table 2 (data from nine measurements). Voids, created from air trapped during the hand lay-up fabrication, were also observed in the epoxy near the rovings. Their diameters were similar to the thickness of the epoxy layers. Voids can also exist inside the rovings, as shown in Fig. 1c, due to insufficient impregnation of individual fibers during fabrication. Both the fiber waviness and the voids inside and in between the rovings can be locations for crack initiation under the applied compressive loads.

In addition to the GFRP specimens used for the compression experiments, epoxy matrix specimens were also investigated. The storage modulus/temperature curve of the epoxy matrix was measured via dynamic mechanical analysis (DMA) at 1 °C/min since

Table 1
Specimen dimensions and compressive results at 25 and 90 °C.

Temperature (°C) and sample number		Dimensions (mm)	Specimen stiffness (kN/mm)			Failure load (kN)	Kink band		Storage modulus
			1st linear stage	2nd linear stage	3rd linear stage		Width (mm)	Angle (°)	Epoxy (GPa)
25	25a	12.9 × 12.7 × 54.4	30.5	22.3	18.7	69.0			
	25b	12.7 × 12.8 × 49.9	31.1	23.0	17.1	70.9			
	25c	13.0 × 12.8 × 54.4	28.1	22.9	18.5	66.7			2.1
	25d	13.1 × 13.1 × 55.0	29	23.2	17.9	62.7			
	25e	13.1 × 13.0 × 55.0	30.5	22.9	18.2	64.2			
Average			29.8 ± 1.3	22.9 ± 0.3 (24.1%)*	18.1 ± 0.6 (39.0%)*	66.8 ± 3.3			
90	90a	12.7 × 12.7 × 50.5	29.2	20.1	–	38.0	2.0	31.2	
	90b	12.9 × 12.8 × 54.5	25.9	18.7	–	42.3	2.0	30.3	
	90c	13.0 × 12.8 × 54.3	26.5	18.4	–	42.5	1.8	32.2	
	90d	12.9 × 13.0 × 55.1	27.9	19.8	–	40.5	1.7	32.2	1.7
	90e	12.9 × 12.9 × 55.0	27.6	19.3	–	40.8	1.7	30.2	
Average			27.4 ± 1.3	19.3 ± 0.7 (27.7%)*	–	40.9 ± 1.7	1.8 ± 0.1	31.2 ± 1.0	
Decrease (%)			8.1**	15.7**		38.8**			19.0**

* Average decrease compared to stage 1.
** Average decrease compared to 25 °C.

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