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Effect of temperature on kinking failure mode of non-slender glass fiber-reinforced polymer specimens

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ABSTRACT

The kink behavior of non-slender glass fiber-reinforced epoxy prismatic specimens of variable length and fiber volume fraction at temperatures ranging from 25 °C to 125 °C was investigated. Splitting failure occurred at the glassy state while kinking failure was observed at the glass transition state and buckling with subsequent post-peak kinking at the rubbery state. Kink initiation was caused by the initial imperfections, i.e. the waviness of the unidirectional fibers. Initiation occurred through fiber microbuckling caused by combined compressive and shear stresses at the glass transition state and predominant shear stresses at the rubbery state due to the preceding buckling. The kink band width was narrow at the glass transition state due to the significant compressive stresses and corresponded to the wavelength of the initial fiber waviness. The kink band width at the rubbery state was much wider and corresponded to the band width of the maximum shear stresses at the inflexion points of the buckling shape. The kink band angle depended on the ratio of compressive to shear stresses. The different specimen slendernesses and fiber volume fractions did not influence the kink initiation and kink band formation mechanisms.

1. Introduction

Compared to the tensile strength of fiber-reinforced polymer (FRP) materials, the compressive strength exhibits more scatter due to fiber misalignments and initial imperfections caused during fabrication. Furthermore, the compressive material properties of FRP composites are sensitive to temperature elevations usually occurring in engineering applications, either in hot environments [1], or when incidents such as fire [2] occur.

Fiber failure, splitting, kinking, buckling, and the combinations of the former are the most commonly observed failure modes associated with the compressive loading of FRP composite materials. Fiber failure is a common failure mode of weak-in-compression fibers, such as aramid fibers, however it is not observed as often when stronger-in-compression carbon or glass fibers are used [3]. Delamination and splitting are typical compressive failure modes of composites with low interlaminar or interfacial shear strength, e.g. carbon fiber-reinforced polymers (CFRPs), and are accompanied by crack propagation, inside the matrix or at the interface, along the loading direction [4]. 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 [5]. Buckling resembles bending or lateral deflection under axial compressive loads [6] and is a common failure mode for slender CFRP and GFRP specimens under axial compressive loads.

Kinking failure was first experimentally investigated by Rosen [7]. The microbuckling of fibers was observed during the cooling of GFRP specimens from curing temperature to room temperature. Microbuckling was initiated by the shrinkage of the resin, which induced compressive stresses in the fibers. In later studies [8–10], kinking was assumed to be a result of fiber microbuckling, based on the reported coexistence of microbuckling and kinking in CFRP laminates. Other studies, e.g. compressive experiments on CFRP specimens [11–13], focused on the kinking band propagation and broadening, providing only limited information about the factors leading to kink initiation. Contradictory conclusions were presented by Weaver and Williams [14], and Wronski and Parry [15] as neither observed any significant microbuckling before or after the kinking failure of examined GFRP specimens, and they therefore concluded that there is no relationship between microbuckling and kinking.

Temperature and specimen slenderness may affect the compressive failure mode and strength of composites. A shift from splitting to kinking failure at elevated temperatures was observed in [16,17] and was attributed to the softening of the matrix and

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increase of the shear interlaminar stresses. However, limited experimental evidence was provided in [16] regarding the formation of microbuckling due to shear interlaminar stresses. The failure mode of GFRP specimens with a slenderness ratio of 60 during temperature elevation was studied in [18]. It was found that the failure mode changed from buckling at ambient temperatures 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. Compressive experiments on short circular GFRP specimens (maximum length-to-diameter ratio of 2.0) were performed in [19]. It was found that the compressive strength of the specimens decreased sharply during the glass transition of the matrix, while the failure mode was fiber failure independent of the temperature range and material states.

The failure mode may further be affected by material imperfections, e.g. fiber waviness and voids. Typical wavelengths of CFRP prepregs were found to be between 2.1 mm and 5.6 mm [20]. With the increase of fiber waviness the width of the kink band increased by as much as 45% [21], while on the contrary the compressive strength decreased by up to 75%, as reported in [22]. As shown in [23], the failure mode of low-void-content materials was kinking while that of materials with a higher percentage of voids was splitting. Furthermore, the fiber volume fraction may influence the failure mode. Both kinking and splitting were observed in GFRP specimens with fiber volume fractions above 30% and splitting was the prevailing failure mode with lower fiber volume fractions [5].

The aforementioned works mainly focused on the investigation of kink band propagation and the effect of temperature and material imperfections on the failure modes of FRP composites. Even though certain phenomena, e.g. the coexistence of microbuckling and kinking, were observed, direct experimental evidence of the effect of microbuckling on kink initiation is still not provided in literature. Moreover, the failure modes of non-slender GFRP specimens under compression at elevated and high temperatures were not thoroughly investigated.

In a previous work of the authors [24], the failure mode of non-slender GFRP prismatic specimens was investigated at 25 °C and 90 °C (the onset of glass transition of the resin). Kinking failure was observed at 90 °C and it was experimentally demonstrated that fiber microbuckling was responsible for kink initiation at that temperature and degree of slenderness. The current work investigates the kink behavior of the same type of GFRP prismatic specimens with different lengths (slenderness) and fiber volume fractions at elevated temperatures up to 125 °C, at which the resin is in the rubbery state. The experimental results, including surface strain and lateral displacement measurements obtained by digital image correlation (DIC), confirmed the results obtained in [24] and showed, more generally, that fiber microbuckling led to kink initiation and kink band formation, either before kinking failure at the onset of glass transition or during the post-failure stage after buckling at higher temperatures.

2. Experimental work

2.1. Material characterization

Glass fiber-reinforced polymer (GFRP) composites, a material typically used in civil engineering applications, were selected in this work. The matrix is a thixotropic bi-component polymer from Swiss Composite AG [25], composed of type-L epoxy base resin and EPH 161 hardener; 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 [25].

Two GFRP plates were fabricated by hand-layup achieving a fiber volume fraction of 44% and 31% respectively as determined by burn-off experiments. The two plates were left at ambient temperature for 48 h and were then post-cured at 100 °C for 72 h to complete the curing. Three groups of 18 specimens each with nominal dimensions of 12.7 × 12.7 × 35 mm^3, 12.7 × 12.7 × 50 mm^3, and 12.7 × 12.7 × 75 mm^3, according to ASTM D695-10 [26], were cut from the high fiber volume fraction plate. Two groups of six specimens each with nominal dimensions of 12.7 × 12.7 × 35 mm^3 and 12.7 × 12.7 × 50 mm^3 were cut from the low fiber volume fraction plate. Each group of the high fiber volume fraction specimens was examined at temperatures of 25, 90, 100, 105, 115, and 125 °C with three specimens at each temperature. The selected

Table 1
Compressive results at temperatures from 25 to 125 °C.

Specimen				Specimen initial stiffness (kN/mm)	Peak load (kN)	Kink band	
Fiber volume fraction	Length (mm)	Series number	Temperature (°C)			Width (mm)	Angle (°)
High	35	35H025	25	35.9 ± 2.0	64.1 ± 2.8		
		35H090	90	35.6 ± 1.5	46.2 ± 4.3	1.9 ± 0.2	28.8 ± 2.2
		35H100	100	32.9 ± 1.0	33.2 ± 6.5	1.9 ± 0.2	29.5 ± 2.5
		35H105	105	26.8 ± 2.2	10.6 ± 1.8	6.0 ± 0.9	39.7 ± 0.6
		35H115	115	22.5 ± 1.2	5.1 ± 1.2	6.5 ± 0.5	42.2 ± 0.3
		35H125	125	16.4 ± 1.1	4.0 ± 0.5	6.1 ± 0.1	42.5 ± 0.9
	55	55H025	25	30.0 ± 1.6	68.0 ± 2.2		
		55H090	90	27.2 ± 1.7	41.0 ± 2.4	1.9 ± 0.1	31.2 ± 1.0
		55H100	100	26.0 ± 1.1	23.1 ± 3.5	2.3 ± 0.6	33.3 ± 1.5
		55H105	105	23.1 ± 1.2	6.8 ± 0.8	5.9 ± 0.5	40.4 ± 1.7
		55H115	115	18.0 ± 1.8	4.7 ± 0.6	6.2 ± 0.3	40.4 ± 1.7
		55H125	125	15.0 ± 1.2	4.2 ± 0.2	5.8 ± 0.3	41.8 ± 0.4
	75	75H025	25	26.9 ± 0.9	61.6 ± 1.6		
		75H090	90	23.8 ± 0.9	40.9 ± 0.4	2.4 ± 0.3	29.5 ± 2.5
		75H100	100	22.9 ± 0.9	25.1 ± 2.5	1.9 ± 0.4	33.7 ± 1.2
		75H105	105	18.2 ± 1.2	5.5 ± 0.9	7.7 ± 0.6	41.7 ± 0.6
		75H115	115	15.4 ± 1.2	4.1 ± 0.2	7.8 ± 0.6	43.0 ± 1.0
		75H125	125	11.8 ± 1.3	3.9 ± 0.2	7.2 ± 0.3	43.3 ± 2.3
Low	35	35L025	25	30.5 ± 1.9	54.6 ± 3.1		
		35L090	90	28.5 ± 2.0	32.2 ± 1.1	2.0 ± 0.1	26.6 ± 0.5
	55	55L025	25	26.3 ± 1.0	46.6 ± 6.0		
		55L090	90	24.2 ± 0.6	34.5 ± 0.5	1.7 ± 0.3	29.0 ± 0.7