Effects of in-plane fiber waviness on the static and fatigue strength of fiberglass
by Lei Wang

A thesis submitted in partial' fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
Montana State University

Abstract:
The effects of in-plane fiber waviness on properties of E-glass fiber/polymer matrix composite laminates have been the subject of an experimental study. In-plane waviness was introduced by hand into the O°reinforcing fabrics which were then fabricated into [0/±45/0]s laminates. The effects of various factors on the compressive strength were investigated, including wave geometry, thickness position of the wavy layer, percentage of O° layers with waviness and the resin matrix toughness. The effects of in-plane waviness, through-thickness waviness and fiber orientation are compared. For selected cases, the effects of waviness on compressive fatigue behavior and static tensile strength were also determined.

A major finding of the study is that more severe wave geometries and higher percentages of layers with waviness produce a greater reduction in compressive strength. Wave severity, the ratio of wave amplitude to wavelength, correlates the data when both amplitude and wavelength are varied. The maximum angle of fiber rotation also correlates with wave severity for all cases. A tougher resin matrix reduces the effects of waviness. Comparison between in-plane and through-thickness waviness indicates a more severe effect on compressive strength for through-thickness waviness as it occurs in woven fabrics. Comparison of the in-plane waviness, in terms of the maximum fiber misalignment in the wave, with literature data for off-axis, +0 laminates indicates a similar effect of fiber angle on compressive strength for both cases. Severe in-plane waviness also causes a remarkable reduction in both compressive fatigue life and static tensile strength. The compression failure mode was characterized by a single fracture surface oriented at an angle through the specimen width along the inflection point of the wave; the tension failure mode was characterized by numerous fiber fractures and delaminations through the gage length of the specimen.

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APPROVAL

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Lei Wang

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The effects of in-plane fiber waviness on properties of E-glass fiber/polymer matrix composite laminates have been the subject of an experimental study. In-plane waviness was introduced by hand into the 0° reinforcing fabrics which were then fabricated into $[0/\pm45/0]_s$ laminates. The effects of various factors on the compressive strength were investigated, including wave geometry, thickness position of the wavy layer, percentage of 0° layers with waviness and the resin matrix toughness. The effects of in-plane waviness, through-thickness waviness and fiber orientation are compared. For selected cases, the effects of waviness on compressive fatigue behavior and static tensile strength were also determined.

A major finding of the study is that more severe wave geometries and higher percentages of layers with waviness produce a greater reduction in compressive strength. Wave severity, the ratio of wave amplitude to wavelength, correlates the data when both amplitude and wavelength are varied. The maximum angle of fiber rotation also correlates with wave severity for all cases. A tougher resin matrix reduces the effects of waviness. Comparison between in-plane and through-thickness waviness indicates a more severe effect on compressive strength for through-thickness waviness as it occurs in woven fabrics. Comparison of the in-plane waviness, in terms of the maximum fiber misalignment in the wave, with literature data for off-axis, $\pm\theta$ laminates indicates a similar effect of fiber angle on compressive strength for both cases. Severe in-plane waviness also causes a remarkable reduction in both compressive fatigue life and static tensile strength. The compression failure mode was characterized by a single fracture surface oriented at an angle through the specimen width along the inflection point of the wave; the tension failure mode was characterized by numerous fiber fractures and delaminations through the gage length of the specimen.

CHAPTER 1

INTRODUCTION

Waviness is a common occurrence in composite materials. It could be either unintentionally induced into composites during processing, or inherent in the fiber architecture. The unintentionally induced waviness is classified as two types: one is in-plane waviness or fiber waviness, the other is out-of-plane waviness or layer waviness. Both of them may be induced by manufacturing processes and may also be the result of residual thermal stresses that are caused by the different thermal expansion rates between fiber and matrix materials [1]. The through-thickness waviness in A130 woven fabric, which is inevitably caused by the woven architecture, is a typical inherent waviness. No matter that it is unintentionally induced or inherent, waviness is generally thought to be disadvantageous to properties of composite materials [2,3]. Although some efforts to reduce waviness have been successful, the problem has not been eliminated entirely.

While out-of-plane waviness (layer waviness) has been studied in depth [4-7], studies of in-plane waviness remain at a very basic conceptual level. The goal of this research was to comprehensively investigate the effects of in-plane waviness on properties of composite materials.

In-plane waviness fabrication was the key step in this study. It was introduced and controlled carefully by hand. It was first demonstrated that the method of waviness introduction did not damage the fibers. This, and the fact that reproducible waves could be introduced over a range of wave parameters, were essential to allow a meaningful study to take place.

The effects of in-plane wave geometry on the compressive strength of composites were studied. One-layer surface in-plane waviness with different wave geometries was fabricated into otherwise wave-free composite laminates. Specimens with in-plane waviness as well as wave-free control specimens were tested under static compressive loading. Thus, reductions in static compressive strength due to specific in-plane waviness geometry have been determined.

Effects of in-plane waviness position through the thickness on compressive strength were also investigated. One-layer surface waviness and internal waviness were introduced into the otherwise wave-free laminates. Differences in compressive strength between the two laminates were studied.

Effects of multi-layer in-plane waviness on compressive strength were also studied. Laminates were fabricated with varying percentages of 0° plies containing in-plane waviness, but all with a constant wave severity. Effects of resin toughness on the compressive strength have also been studied using two resins of different toughness with laminates containing waviness. Effects on compressive strength of in-plane waviness, through-thickness waviness in A130 fabric and fiber orientation were analyzed and compared.

Besides static compression tests, compressive fatigue tests and static tension tests have also been conducted on one case of severe in-plane waviness. Failure modes from compression, compressive fatigue and tension tests were observed for failed specimens.

Together, all of the experimental studies and theoretical analysis are directed towards understanding of the effects of in-plane waviness on the strength properties of composite materials.

CHAPTER 2

BACKGROUND

Waviness can be either unintentionally induced into composites during processing, or inherent in the fiber architecture. The unintentionally induced waviness is classified as two types: in-plane waviness and out-of-plane waviness. In-plane waviness, or fiber waviness, describes the fiber deviations from straight 0^o in the plane of the fabric sheet. Out-of-plane waviness, or layer waviness, involves the entire layer of a multidirectional laminate undulating in the through-thickness direction. The two types of waviness are illustrated in Figure 1. The through-thickness waviness in A130 woven fabric, which is inevitably caused by the woven architecture, is a typical inherent waviness. It is neither in-plane waviness, nor the case of entire layer undulating in the through-thickness direction. The woven architecture it uses causes the fiber strand distortion in the thickness direction, which can be seen in Figure 2.

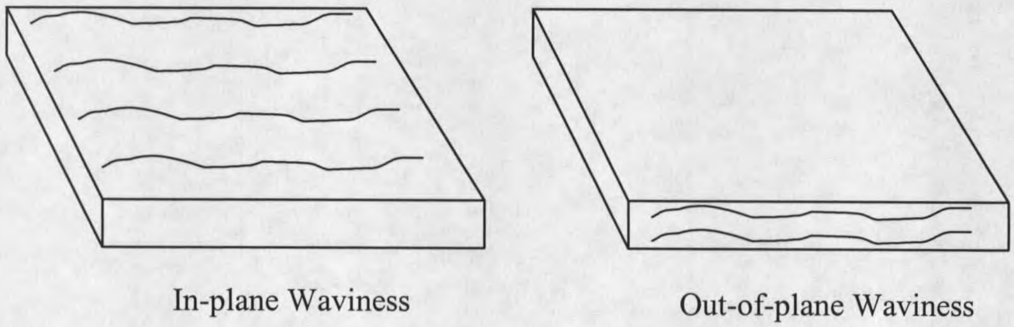

Figure 1. In-plane Waviness and Out-of-plane Waviness in Composite Laminates

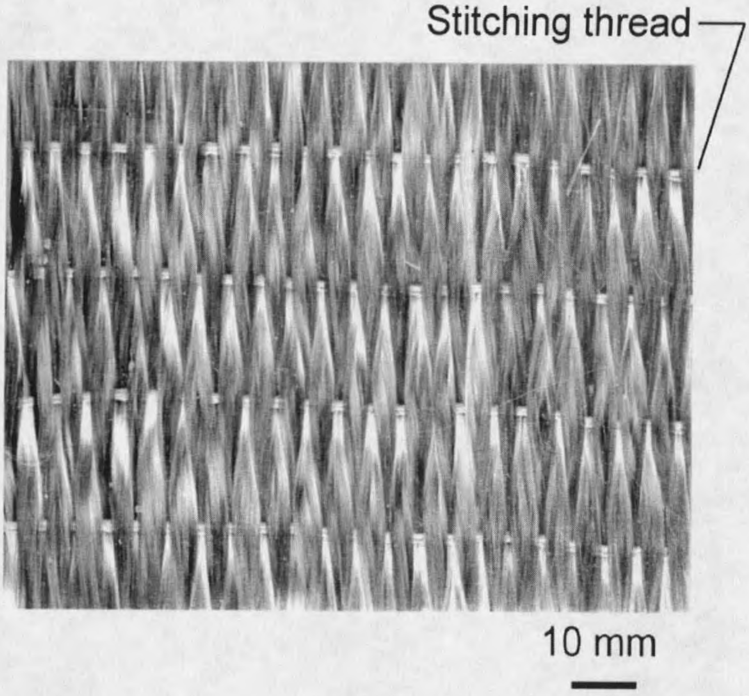

Figure 2. A130 Fabric Showing Fiber Strand Distortion in the Thickness Direction

In this section, previous studies related to the effects of waviness on properties of composite materials are reviewed. Studies of effects of waviness on static compressive strength are reviewed first, followed by those involving compressive fatigue and tensile strength.

Classic Compression Failure Theories

Before investigating the effects of waviness on compressive strength, review of classic compression failure models is necessary. The analytical models that have been the foundation of current understanding include fiber buckling models, transverse tension models, and fiber kinking models [8]. Microbuckling failure modes and kink band geometry are shown in Figure 3.

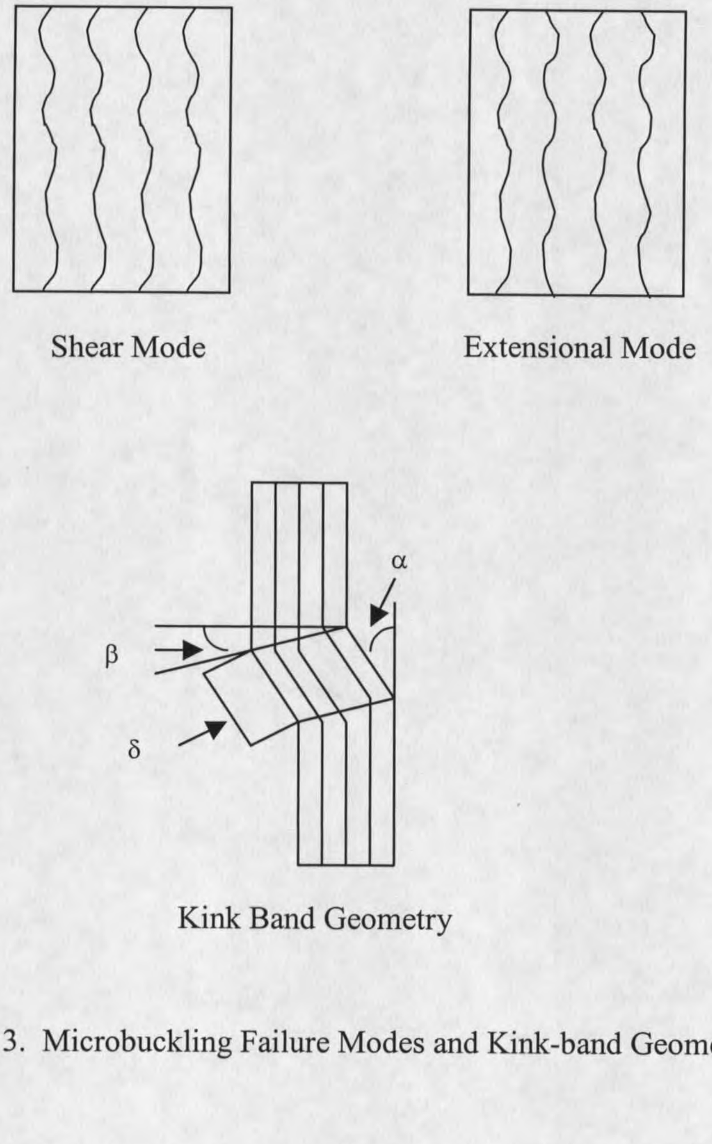

Figure 3. Microbuckling Failure Modes and Kink-band Geometry [8]

Fiber Buckling. Rosen [9] proposed that failure constituted the short-wavelength buckling of the fibers in two modes, an extensional mode and a shear mode. For fiber volume fractions less than 30%, the extensional mode dominates and the fibers buckle out of phase; for fiber volume fractions greater than 30%, the shear mode dominates and fibers buckle in phase. The matrix resists the buckling of fibers through its elastic modulus.

Transverse Tension. In unidirectional composites, transverse tensile stress exists when the composite is subjected to axial compression loading. Even though the resulting transverse tensile stress is small, it can be significant enough to cause failure in unidirectional composites due to their low transverse strength. Greszczuk [10] analytically studied this failure model.

Fiber Kinking. Kink band formation in composites subjected to compressive load is also a failure mechanism that has been proposed as contributing to the low compressive strength of composites. Argon [11] suggests that the regions in a composite in which fibers are not aligned with the compression axis will form a failure nucleus that undergoes kinking and occurs at a stress lower than the ideal buckling strength.

Effects of Waviness on Static Compressive Strength

Shuart [1] modeled fiber waviness as illustrated in Figure 4. The wavy shape of a fiber in a $+\theta$ angle ply is idealized as a sine function having amplitude δ and half-wavelength λ. This shape is expressed as

$$\eta = \delta \sin (\pi\xi / \lambda) \qquad (1)$$

where η is the fiber shape and ξ a coordinate parallel to a $+\theta$ axis. A wavy fiber is globally oriented at θ but also has local perturbations about that angle. The change in fiber angle $\Delta\theta$ along the ξ axis can be expressed as

$$\Delta\theta = \tan^{-1}(d\eta/d\xi) \qquad (2)$$

The in-plane shear-stress distribution along the fiber was calculated using classical laminated plate theory as a function of the applied load, the global angle $+\theta$, and the local perturbation $\Delta\theta$. The analysis indicated that the in-plane shear stress at some locations along a $+\theta$ wavy fiber are greater than along a $+\theta$ straight fiber.

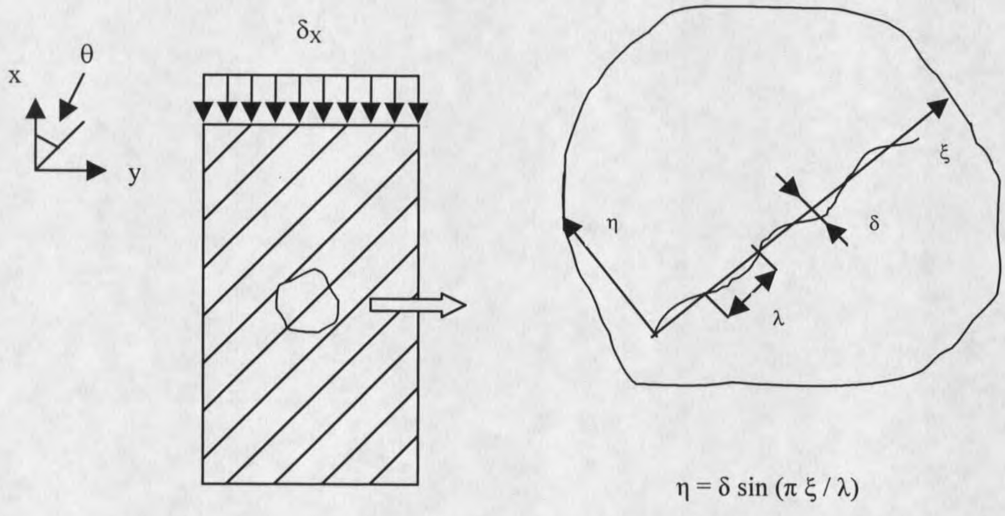

Figure 4. Idealized In-plane Waviness [1]

Martinez [12] investigated the effects of misaligned and kinked fibers on compression strength of composites using a glass/polyester laminate specimen. Fiber misalignment was introduced by twisting the tows of fibers a certain amount before the addition of the resin. It was found that the misalignment of the fibers reduced the compressive strength when the average angle of misalignment exceeded about 10° for glass and carbon fibers. Fiber kinking was introduced by pressing rounded blades into opposite sides of the uncured rod at certain intervals. The severity of fiber kinking was controlled by the distance that the blades were pressed into the rod. The kinking was characterized by the minimum fiber curvature. It is concluded that failure due to fiber curvature only occurs when a limiting curvature is present or when curvature equivalent to 5 mm minimum radius is introduced by the manufacturing process.

Mrse and Piggott [13] studied the effects of unintentional and intentional fiber misalignments on the compressive properties of unidirectional carbon fiber laminates. Unidirectional laminates were made with AS4 carbon reinforced PEEK prepreg that had been crimped to various degrees to vary the fiber waviness in the composite. Wavelengths and amplitudes of waviness were estimated using a microscope, and correlated with compressive strength and modulus. It was observed that fiber waviness decreased the compressive modulus approximately as the square of the mean fiber angular deviation. Compressive strength also decreased.

Through-thickness waviness effects for woven fabrics have been studied in some detail by Mandell and Samborsky [3,14]. A large testing program reported by them led to the conclusion that fabrics with woven strands have through-thickness strand distortion, which significantly reduces the compressive strength for the woven fabrics when compared with fabrics which have straight strands, usually stitched together.

Adams [4,5,7] investigated out-of-plane waviness (layer waviness) in T300/P1700 carbon/polysulfone composite laminates under static compression loading. Isolated layer waves were fabricated into the central 0° layer of $[90_2/0_2/90_2/0_2/90_2/\underline{0_{2w}}]_s$ laminates. Layer wave severity, defined as the amplitude, δ, divided by wavelength, λ, ranged from 0.023 to 0.077. Layer waviness in the central 0° layer of the $[90_2/0_2/90_2/0_2/90_2/\underline{0_{2w}}]_s$ laminate produced reductions in static strength of between 1 and 36%, although the wavy 0° layers account for only 21% of the load carrying capacity of the laminate. Specimen failures were sudden and catastrophic. Brooming failure, characterized by through-the-thickness splaying of the layers and numerous delaminations near the waves, was the common failure mode.

Adams and Bell [6] also investigated compression strength reductions in composite laminates due to multiple-layer waviness. Multiple-nested wavy 0° layers were fabricated into otherwise wave-free thermoset carbon/epoxy crossply laminates. Laminates were fabricated with varying percentages of 0° layers containing layer waviness, but with a constant layer wave severity. Testing was performed to determine the effects of multiple-layer wave regions on compression strength. Results suggest that when no greater than 33% of the 0° layers contained waviness, the percentage reduction in compression strength was approximately equal to the percentage of wavy 0° layers. However, a constant strength reduction of approximately 35% was observed when more than 33% of the 0° layers contained waviness.

Effects of Resin Toughness on Compressive Strength

The effects of resin toughness on compressive strength have been studied, but not with the waviness present.

Sohi, Hahn, and Williams [15] investigated the influence of resin on compressive strength of 24-ply $[45/0/-45/90]_{3s}$ quasi-isotropic laminates reinforced with T300 and T700 graphite fibers. The resins in this study ranged in toughness from 5208 (failure strain 1.4%) to BP907 (failure strain 4.8%). The effect of resin toughness on the failure progression was that failure was quite sudden and arrest of fiber kinking was difficult for the T300/5208 (brittle) laminates, while, when the T300/BP907 laminate was loaded to 81% of the ultimate compressive strength, failure was limited to kinking of the 0^{o} plies, and no delamination was present. Although the tougher resin resists the propagation of delamination, the tough BP907 resin allowed fiber kinking at lower strains than the other resins. This observation again points up the dependence of microbuckling initiation on resin modulus, and signals the need for awareness that the lower modulus usually associated with tougher resins means a tradeoff between delamination resistance and microbuckling initiation.

Piggott and Harris [16] also conducted an experimental study to determine the effect of resin properties on compression strength of composites. Short pultruded solid cylinders were tested with high-strength graphite fibers, high-modulus graphite fibers, E-glass fibers, and Kevlar 49 fibers. The cylinders were manufactured such that the polyester resin was in various stages of cure resulting in varying degrees of matrix modulus and strength. The fiber volume content of the composites in this study was 30%. The graphical results included in this paper are for the E-glass composites and