EFFECTS OF IN-PLANE FIBER WAVINESS ON THE STATIC

AND FATIGUE STRENGTH OF FIBERGLASS

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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^o 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^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, ±è 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^o 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.

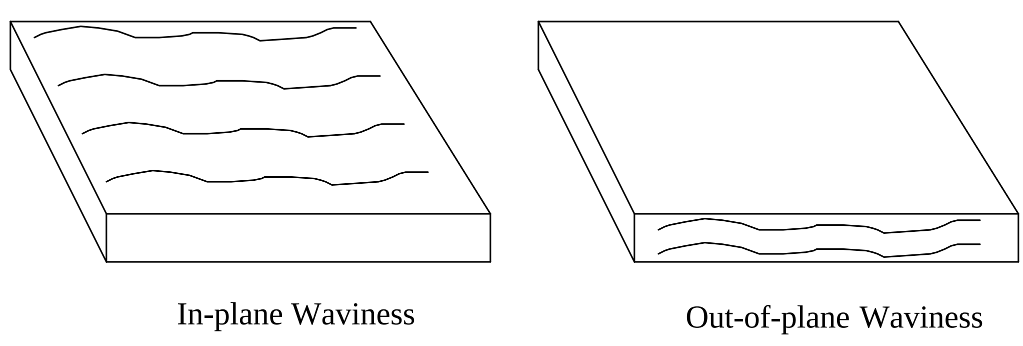


Figure 1. In-plane Waviness and Out-of-plane Waviness in Composite Laminates

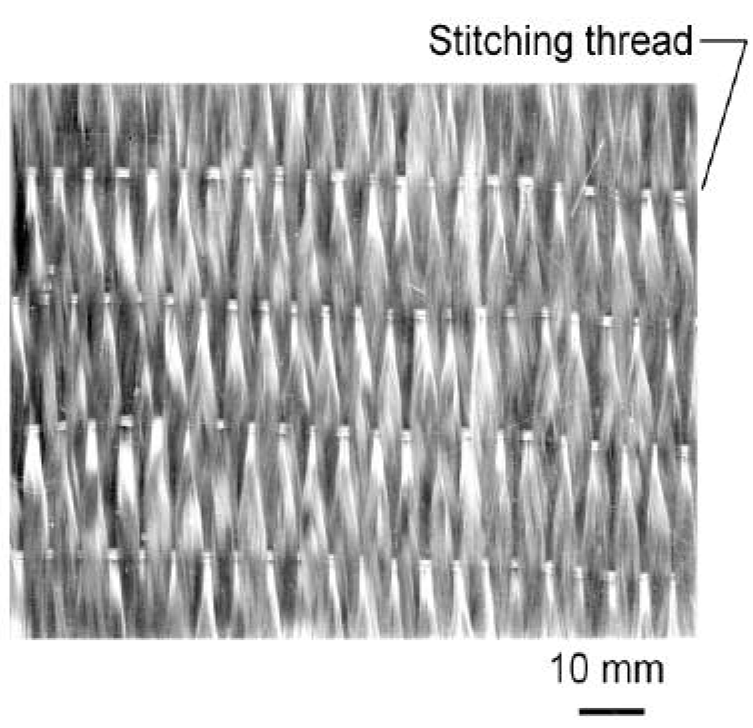


Figure 2. A130 Fabric Showing Fiber Strand Distortion in the Thickness Direction

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.

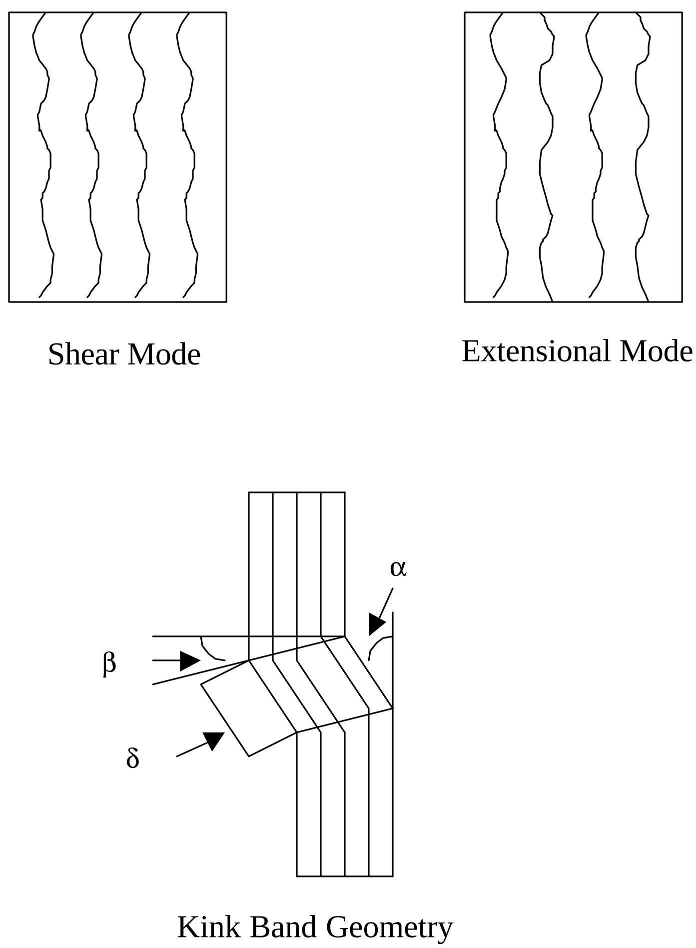


Figure 3. Microbuckling Failure Modes and Kink-band Geometry [8]

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

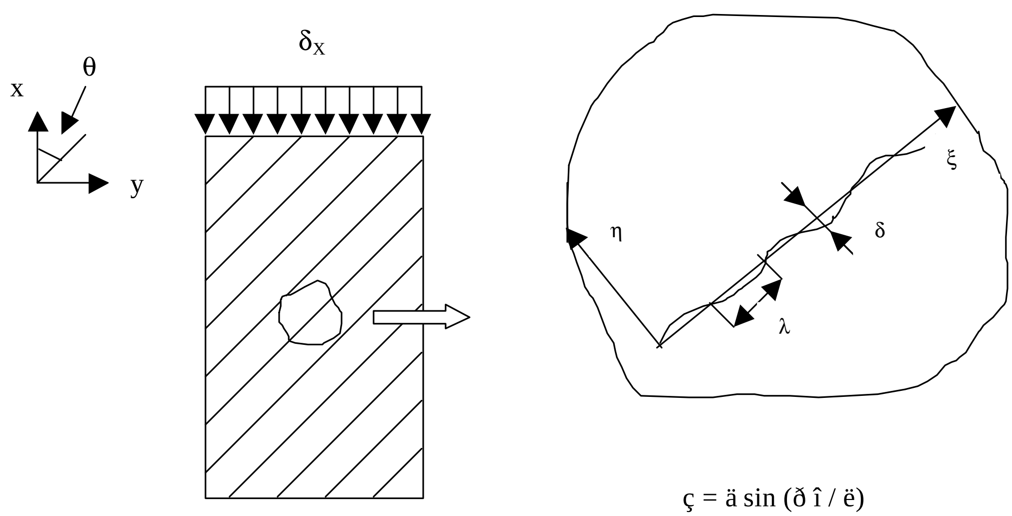
Shuart [1] modeled fiber waviness as illustrated in Figure 4. The wavy shape of a fiber in a +è angle ply is idealized as a sine function having amplitude ä and half-wavelength ë. This shape is expressed as

ç = ä sin (ðî/ ë) (1)

where ç is the fiber shape and î a coordinate parallel to a +è axis. A wavy fiber is globally oriented at è but also has local perturbations about that angle. The change in fiber angle Äè along the î axis can be expressed as

$$\text{Äè} = \tan^{-1}(\text{dç/dî}) \qquad (2)$$

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 +è, and the local perturbation Äè. The analysis indicated that the in-plane shear stress at some locations along a +è wavy fiber are greater than along a +è straight fiber.



ç = ä sin (ð î / ë)

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^{o} 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^o 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^o 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^o 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^o layers were fabricated into otherwise wave-free thermoset carbon/epoxy crossply laminates. Laminates were fabricated with varying percentages of 0^o 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^o layers contained waviness, the percentage reduction in compression strength was approximately equal to the percentage of wavy 0^o layers. However, a constant strength reduction of approximately 35% was observed when more than 33% of the 0^o 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 show that the compressive strength is a strong increasing function of matrix yield strength up to 60 MPa.

Mandell et al. [17] studied environmental effects on composite materials for wind turbine blades. The resins that have good environmental resistance while providing improved delamination resistance have been identified. It was found that the hot/wet properties including compression are much better for the iso-polyester and vinyl ester systems than for the ortho-polyester or the epoxy SC14. Thus, while the iso-polyester provides improved environmental resistance over the ortho polyester, the 411 and 8084 vinyl esters additionally provide much greater toughness and structural integrity. The fatigue resistance was not affected by the matrix.

Effects of Waviness on Compressive Fatigue

During literature search, only limited studies that are related to the effects of waviness to compressive fatigue were found.

Adams and Hyer [5] explored the effects of layer waviness on the compressive fatigue property. In the study, the laminate materials and laminate layup were the same as those used in the laminates in Ref 4. Results suggested that compression fatigue specimens with moderate layer waves (0.05 < wave severity < 0.06) exhibited a one and a half decade loss of compression fatigue life as compared to specimens without layer waviness. The stress level corresponding to the 10^6 cycle run-out for these layer wave specimens was reduced to approximately 45% of the static compressive strength of the wave-free laminate. Compression fatigue specimens with moderate layer waves failed at the location of the layer wave in a sudden manner. Brooming failure, similar to that observed in static compression testing in Ref 3, was the common failure mode. Layer wave specimens cycled to the 10^6 cycle run-out showed no evidence of delamination in the vicinity of the layer wave.

No studies related to the effects of in-plane waviness on the compressive fatigue property have been found.

Effects of Waviness on Static Tensile Strength

Mandell and Samborsky [3,14] found that although fabric weaves remarkably reduced the static compressive strength due to the through-thickness waviness, the tensile strength of the laminates still remained very high.

Poe, et al.[18,19] conducted a test program to determine the residual tensile strength of a thick filament-wound carbon fiber solid rocket motor case after low-velocity impacts. They reported that the undamaged tensile strength of specimens cut from a filament-wound case reinforced by unidirectional layers was 39% less than the expected strength. It was observed that the main load-carrying layers became wavy during manufacturing.

Makarov and Nikolaev [20] investigated the effect of curvature of the reinforcement on the mechanical properties of composites through an experimental study. The specimens were composed of grade NO-68-1 crude rubber and AMG-5P alloy wire and made by laying up the rubber and the wire in layers in a special mold. They concluded that the initial curvature of the reinforcing fibers must be taken into consideration in calculating the effective Young's modulus, E_1, in the fiber direction.

These studies support the belief that waviness in composite materials has significant influences on the compressive strength, compressive fatigue property and tensile strength of the composite materials. By generalization, Adams has deeply studied the effects of the layer waviness (out-of-plane waviness) on compressive strength and compressive fatigue based on T300/P1700 carbon/polysulfone composite laminates. As for the in-plane waviness, it is clear that additional research is needed to develop further understanding. The effects of in-plane waviness parameters, such as the amplitude, wavelength, etc., on laminate compressive strength have not been experimentally determined. The differences between the effects of surface in-plane waviness and internal in-plane waviness are still unknown. The effects of multi-layer in-plane waviness on the laminate compressive strength have not been understood. The role the resin matrix plays in the compressive strength of laminates with in-plane waviness has not been investigated. The influences of in-plane waviness on compressive fatigue and on tensile strength have not been reported. The present study attempts to address these issues, based on E-glass/polymer matrix materials and a $[0/\pm45/0]_s$ laminate layup, where the standard laminate notation indicates eight layers with the configuration 0/±45/0/0/±45/0 relative to the load direction; the $+45^o$ and -45^o layers are stitched together into one fabric layer.

CHAPTER 3

MATERIALS AND EXPERIMENTAL METHODS

Materials

Reinforcement Materials

The reinforcement throughout the experiments is E-glass fabric supplied by Owens-Corning Fabrics. Two kinds of stitched E-glass fabrics are used in laminate fabrication in this study. D155 stitched fabrics are used as the 0^{o} layers, and DB120 stitched fabrics are used as the ±45° layers. Fabric architectures of them are shown in Figure 5 and 6. Some results in this study are to be compared with the laminates reinforced with a woven A130 unidirectional fabric. Studies of A130 reinforced laminates are included in DOE/MSU Database [3]. Fabric architecture of A130 has been shown in Figure 2.

Resin Matrix Materials

Two different kinds of resins were used in this study: CoRezyn 63-AX-051 unsaturated orthophthalic polyester supplied by Interplastic Corporation and Derakane 8084 rubber-toughened vinyl ester supplied by Dow Chemical Company. Corezyn 63-AX-051 was cured by the addition of 1.5 to 2% methyl ethyl ketone peroxide (MEKP), and Derakane 8084 was cured by the addition of 1.5 to 2% Trigomox 239A. While polyester resin has the lowest cost of all the resins, the rubber-toughened vinyl ester has relatively high cost.

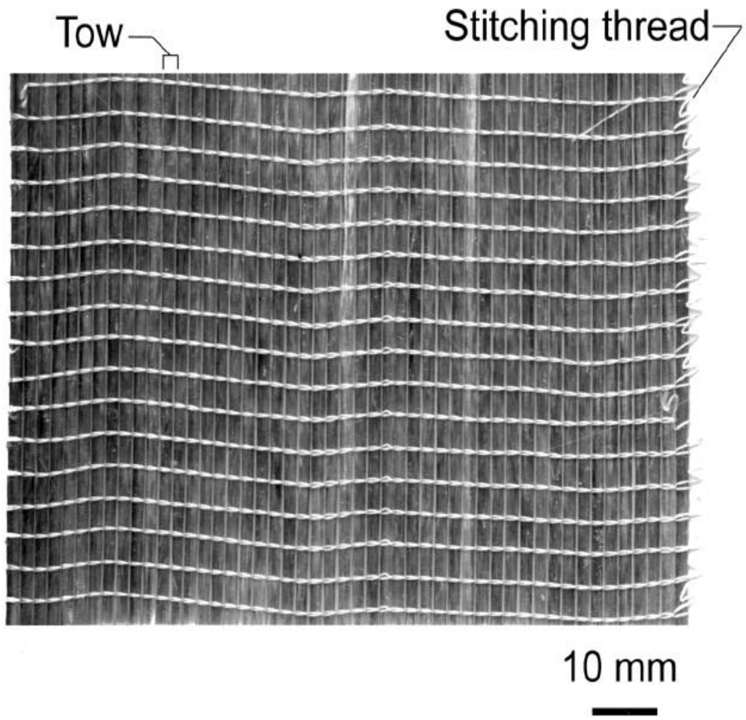


Figure 5. Fabric D155

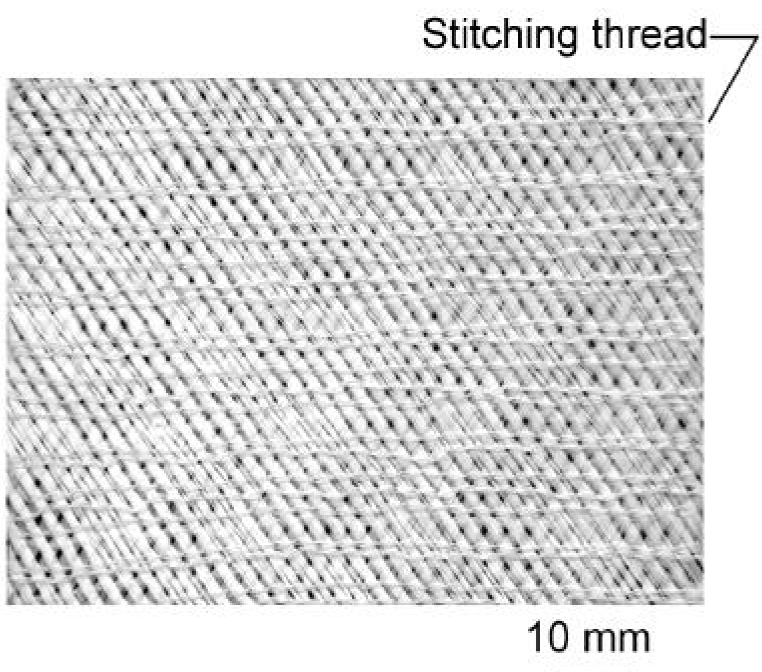


Figure 6. Fabric DB120

In-plane Waviness Characterization

Adams [5] characterized the wave geometry of out-of-plane waviness (layer waviness) by four parameters: wave amplitude (ä), wavelength (ë), wave severity (ä/ë), and maximum angle of fiber rotation (è). Since in-plane waviness has the very similar geometry characteristics to the out-of-plane waviness, it also can be characterized by the same four parameters, illustrated in Figure 7.

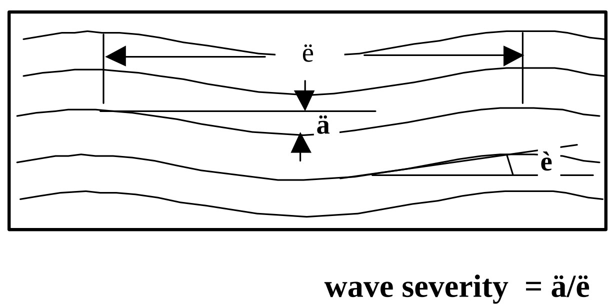


Figure 7. In-plane Waviness Characterization

In-plane Waviness Fabrication

A key step in this study was fabricating the in-plane waviness into an otherwise wave-free composite laminate. In-plane waviness was only introduced into the D155 fabric, the 0° layers of the laminate layup. The DB120 fabric, the ±45° layers of the laminate layup, was not altered. In-plane waviness was introduced by pulling the appropriate stitches by hand. The wavelength was controlled by removing different numbers of adjacent stitches, then leaving a stitch in place, removing more stitches, etc. Corresponding to removing one, two, three or five adjacent stitches, the wavelength was about 35 mm, 50 mm, 65 mm and 100 mm, respectively. The amplitude of the wave was controlled by how much the remaining stitches were pulled. The amplitude of the waves in this study was designed to be 0 mm, 2 mm, 4 mm and 6 mm. The method is illustrated in Figure 8.

Laminate Cases

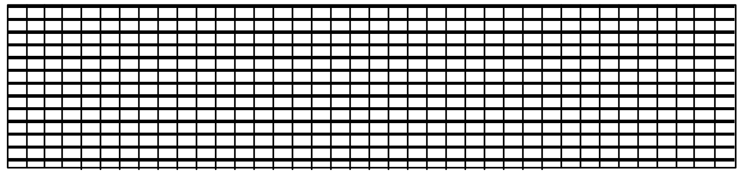
There are 6 laminate cases used in this study: 1) control laminate; 2) laminates with one layer on the surface containing in-plane waviness; 3) laminates with one internal layer containing in-plane waviness; 4), 5), 6) laminates with two, three and four layers of in-plane waviness.

In addition, laminates DD5P, DD11, DD12, 10D155, 20D155 and 30D155 in DOE/MSU Database [3] are used in this study for comparison. Their laminate configurations are also described in this section.

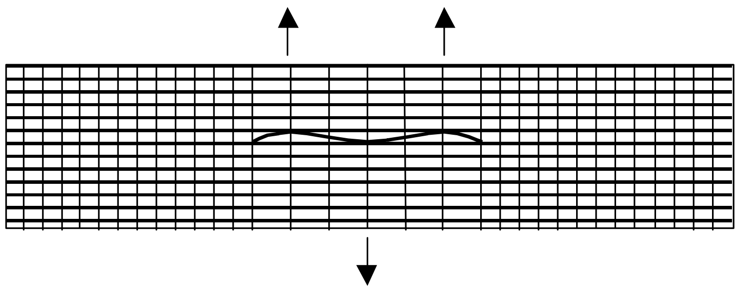
Control Laminate

As control laminate, no waviness was introduced. The layup of laminate DD5P in DOE/MSU Database [3] was chosen such that the control laminate layup in this study was $[0/\pm45/0]_s$, where, the 0^o layers are fabric D155, and the ±45° layers are fabric DB120. Control lamina and laminate configuration are illustrated in Figure 9.

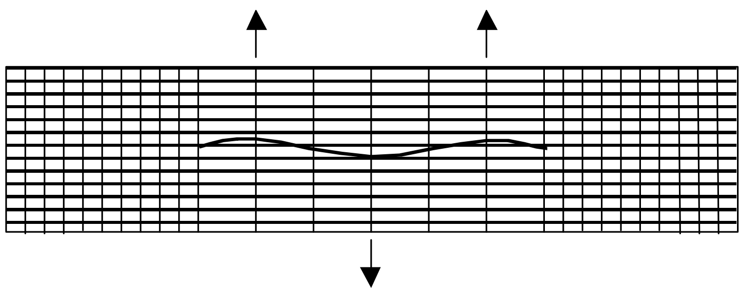
Based on the control laminate layup, in-plane waviness could be introduced into one, two, three or four (all) of the 0° layers (D155 fabric) of the laminates. By comparing the properties of laminates with in-plane waviness to the control laminates, the effects of in-plane waviness on properties were determined.



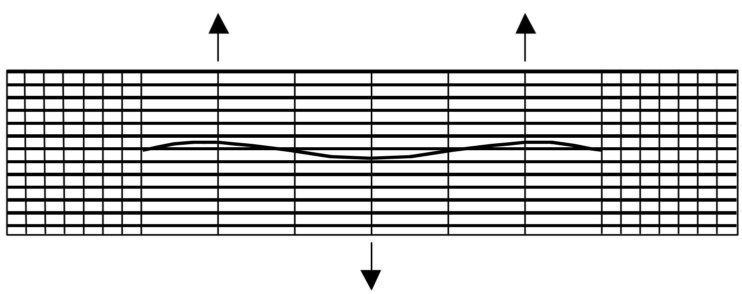
Fabric D155, No Stitch Removed



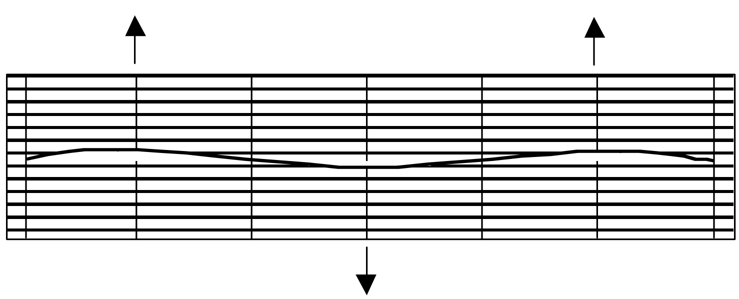
One Stitch Removed, Wavelength is about 35 mm



Two Stitches Removed, Wavelength is about 50 mm

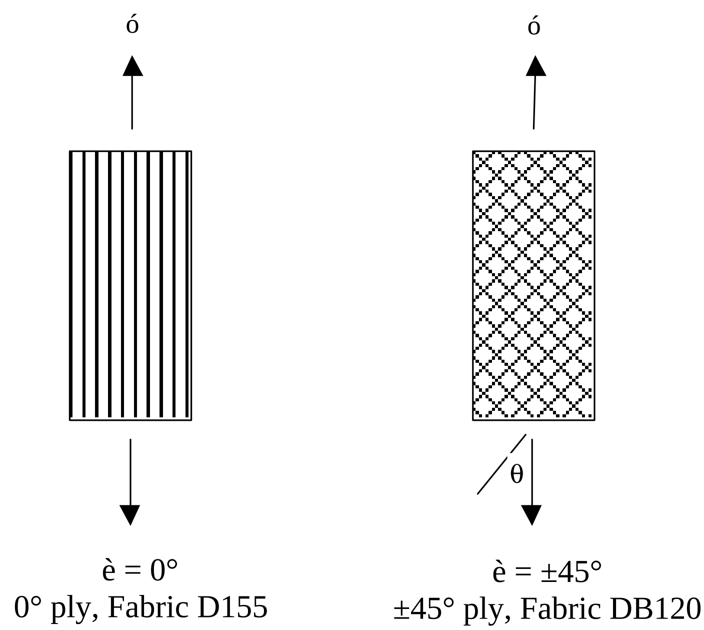


Three Stitches Removed, Wavelength is about 65 mm

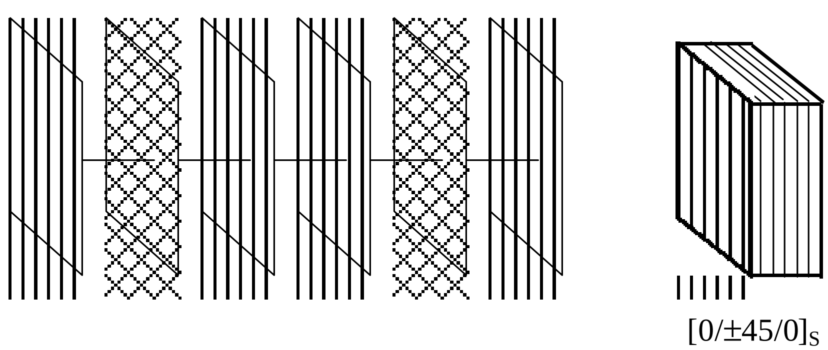


Five Stitches Removed, Wavelength is about 100 mm

Figure 8. In-plane Waviness Fabrication



Laminate Definition



Laminate Stacking Sequence

Figure 9. Control Lamina and Laminate Configuration

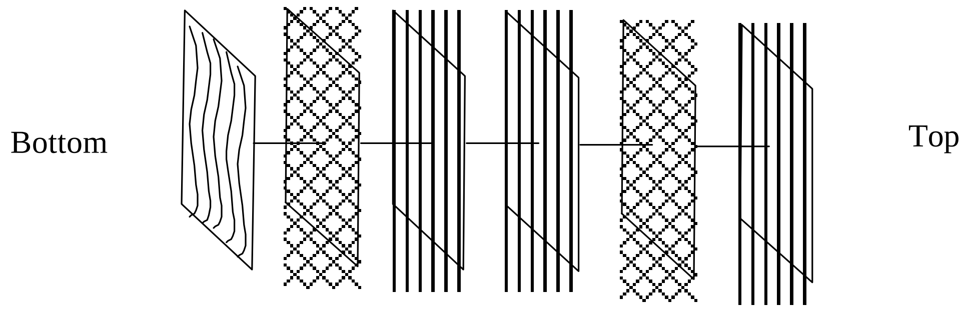


Figure 10. Laminate Configuration with One Layer of Surface In-plane Waviness

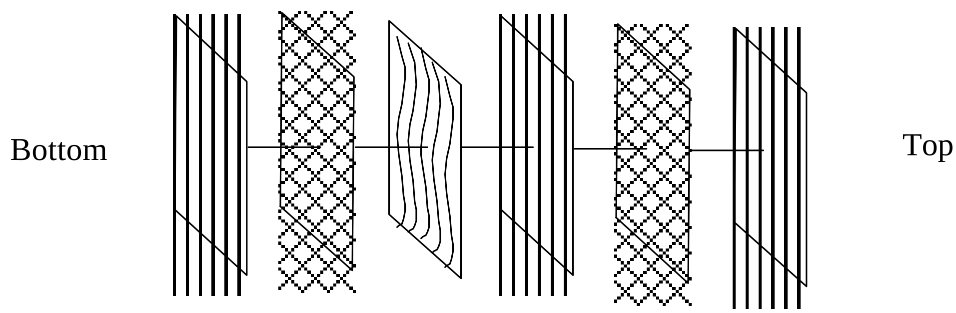


Figure 11. Laminate Configuration with One Layer of Internal In-plane Waviness

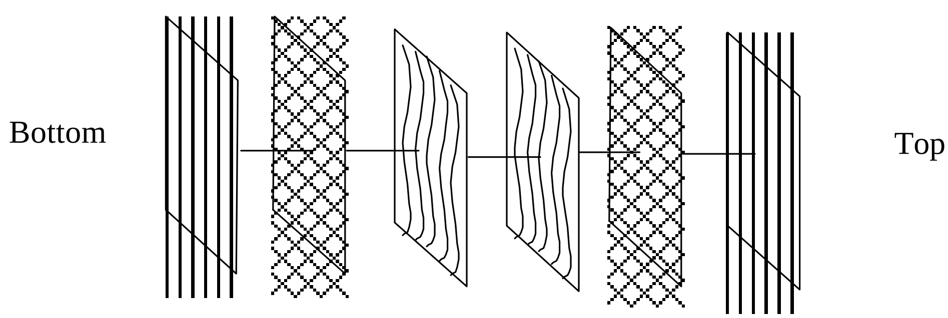


Figure 12. Laminate Configuration with Two Layers of In-plane Waviness

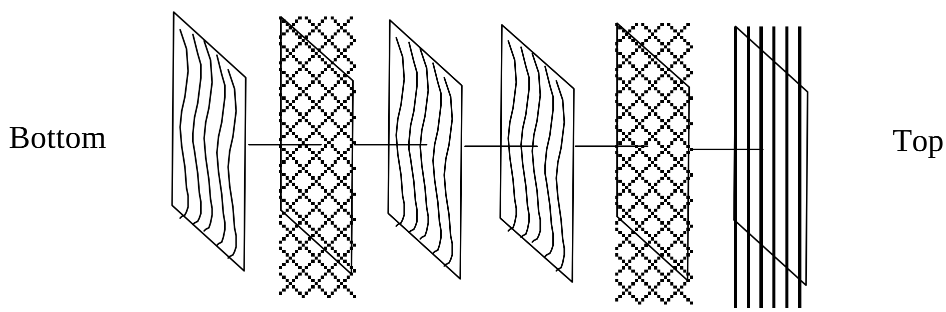


Figure 13. Laminate Configuration with Three Layers of In-plane Waviness

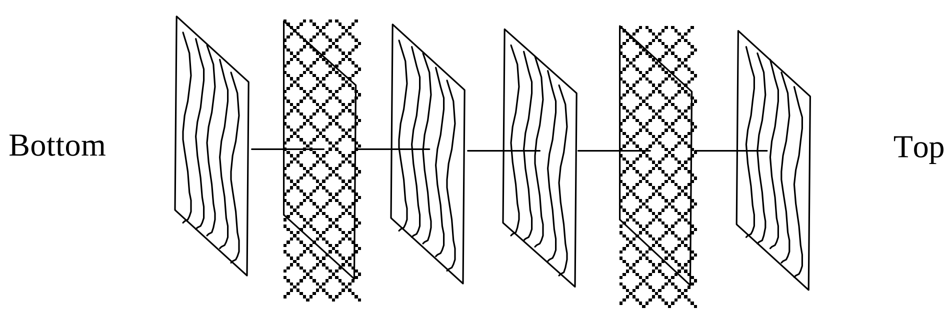


Figure 14. Laminate Configuration with Four Layers of In-plane Waviness

Laminates with One Layer of Surface Waviness

This configuration was used to study the effects of wave geometry on compressive strength. The in-plane waviness was introduced into the surface because fibers in the surface may be more likely to experience waviness during manufacturing. This configuration is illustrated in Figure 10.

Laminates With One Layer of Internal Waviness

This configuration was designed to compare with the surface in-plane waviness, illustrated in Figure 11.

Laminates with Two, Three and Four Layers of Waviness

Laminates with two, three and four layers of in-plane waviness were designed to investigate the effects of multi-layers of in-plane waviness on the properties. In addition, laminates with four layers (all 0^o layers) of waviness were also used for other subjects in this study. Since it was the most severe case for the laminates in this study, it can provide the bottom line properties of the laminate configuration of interest. The three configurations are illustrated in Figure 12 to 14.

Laminates DD5P, DD11, DD12, 10D155, 20D155, 30D155 in DOE/MSU Database [3]

Laminate DD5P has the identical configuration with the control laminate in this study. Its layup is $[0/\pm45/0]_s$, in which the four 0^o layers are D155 fabrics and the two $\pm45^o$ layers are DB120 fabrics; the matrix is polyester; the fiber volume fraction is 36%.

The layup of laminates DD11 and DD12 is $[0/\pm45/0]_s$, in which the four 0º layers are A130 fabrics and the two ±45º layers are DB120 fabrics; the matrix is polyester; the fiber volume fractions for DD11 and DD12 are 31% and 43%, respectively.

Laminates 10D155, 20D155 and 30D155 are angle ply laminates. Their layups are $[\pm10]_3$, $[\pm20]_3$, and $[\pm30]_3$ respectively. All layers in the laminates are D155 fabrics; the matrix is polyester; the fiber volume fractions for 10D155, 20D155 and 30D155 are 38%, 39% and 40%, repectively.

Laminate Fabrication

In order to tightly control the hand-made in-plane waviness in the manufacturing process, all of the laminates were fabricated using hand lay-up in this study. For hand lay-up processing, a flat plate mold was first coated with a mold release that could prevent bonding of the resin matrix material to the mold. Then the first layer of fabric and resin were put into the mold. A roller was used to eliminate air bubbles and squeeze out extra resin to consolidate the layer. After the first layer was consolidated, the rest of five layers followed one by one by the same way. A top glass plate was added and the composite laminate was left in the mold for 24 hours for curing.

The processing flow sheet of laminates with or without in-plane waviness in this study is illustrated in Figure 15.

Two laminates fabricated in this study are shown in Figure 16. One has one layer of in-plane waviness (laminate 36), the other has four layers of in-plane waviness (laminate 37).

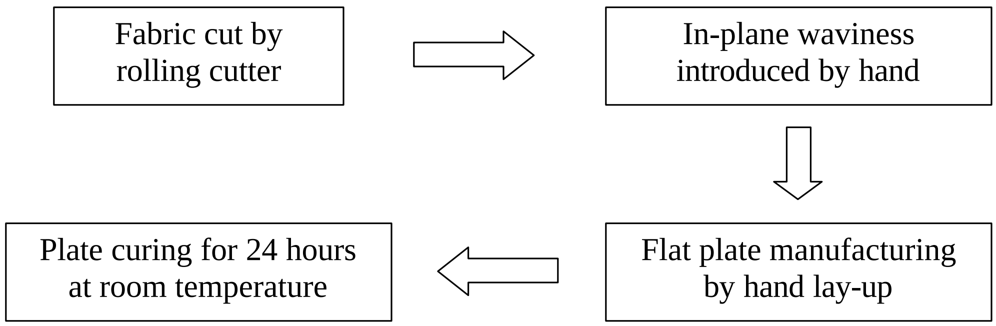


Figure 15. Processing Flow Sheet

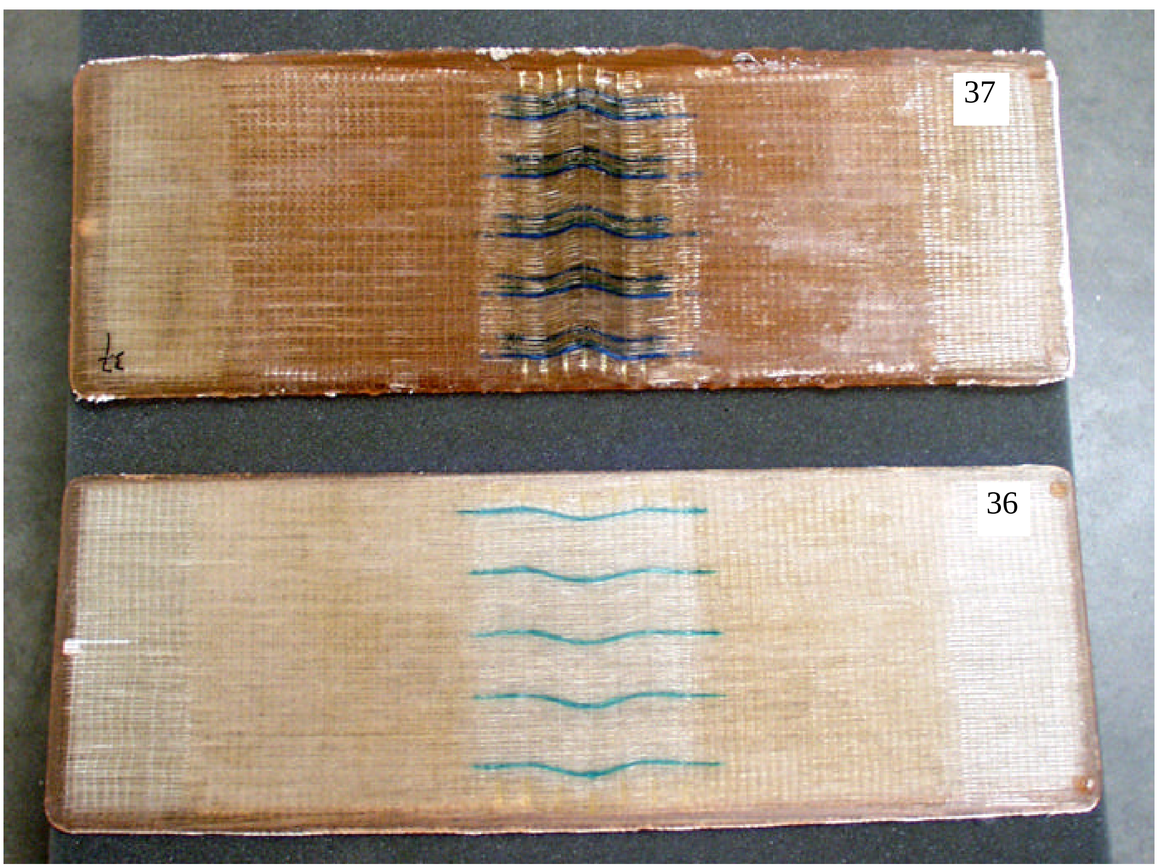
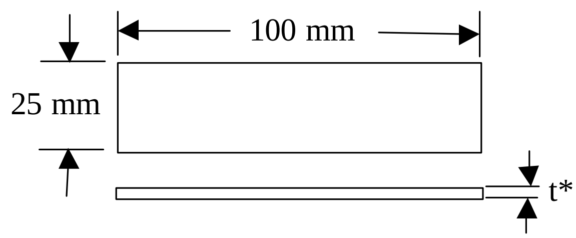


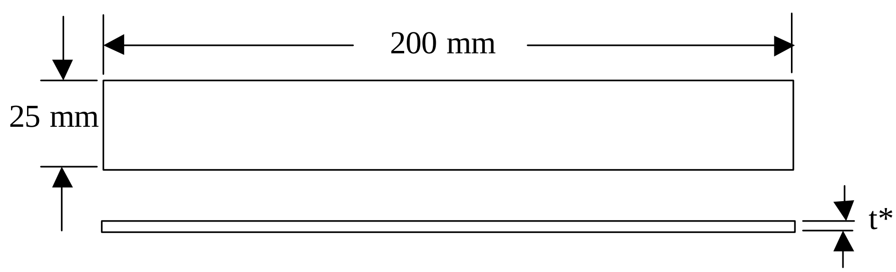
Figure 16. Laminates with One Surface and Four Layers of In-plane Waviness

Specimen Preparation

After plates were fabricated, the edges of the plates were trimmed off to eliminate any edge composition variability, ensuring representative, uniform material properties. The trimmed plates were then cut to produce flat rectangular coupons for testing. The plates were cut with a 20 cm diameter diamond coated blade rotating at 3,450 rpm (36 m/s), which was water cooled and lubricated. The feed rate of the composite plates during cutting was less than 5 mm/second to ensure a clean, perpendicular cut edge. The test specimens in this study included static compressive strength specimens, compressive fatigue specimens and static tensile strength specimens. Geometries of the test coupons are illustrated in Figure 3.17.



Static Compressive and Compressive Fatigue Test Coupon



Static Tensile Test Coupon

* Static compressive specimen thickness (t) generally ranges from 0.079 mm to 0.120 mm;
* Compressive fatigue specimen thickness (t) ranges from 0.103 mm to 0.107 mm;
* Static tensile specimen thickness (t) ranges from 0.080 mm to 0.101 mm.

Figure 17. Test Coupon Geometry

Test Methods

Static Compression Test

Compressive testing of materials is always a difficult and controversial process as premature failure or buckling of the coupon will undermine the test. Appropriate methods should be able to obtain representative compression properties of the material being tested while limiting the amount of elastic buckling. Buckling can be prevented by continuously supporting the faces of the coupon or keeping the gage length sufficiently short [3].

In this study, static compression tests were performed on an Instron 8501 servo hydraulic testing machine with a load capacity of 100,000 N. Load was applied to the specimen at a rate of 13 mm/sec until catastrophic failure occurred. The failure load was then recorded to determine the ultimate compressive strength.

In order to investigate the effects of in-plane waviness on the compressive strength of the composite materials, a relatively long gage length (25 mm) was adopted in this study so that the wavelength can be contained into the gage length as much as possible. Modified hydraulic grips were used to continuously support the faces of the coupon to prevent out-of-plane buckling, as shown in Figure 18.

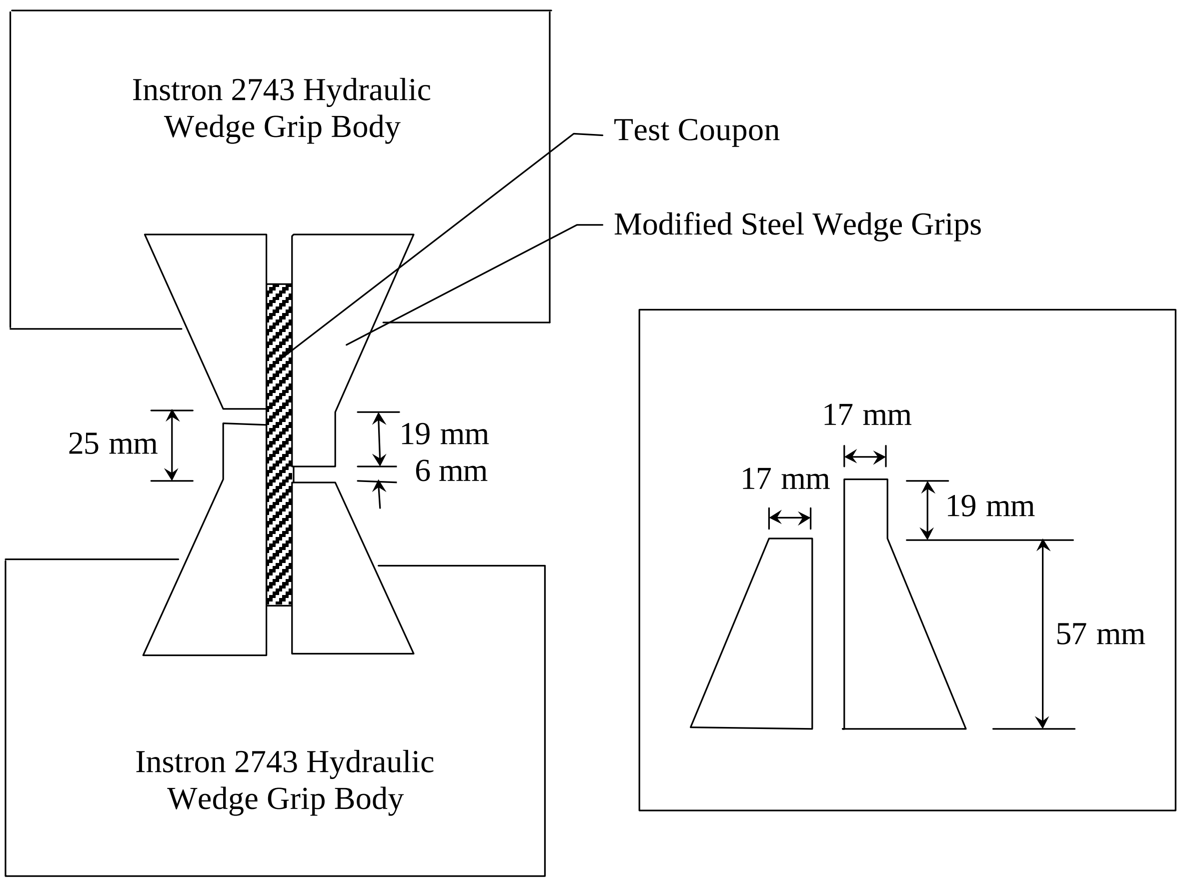


Figure 18. Compression Test Buckling Constraint for Long Gage Sections

Compressive Fatigue Test

The fatigue testing equipment used in this study was also the Instron 8501.

Fatigue tests used a sine-wave cyclic waveform with the testing machine under load control. This active amplitude control increased the internal gain as the coupon compliance changed during the testing. Fatigue tests were performed until coupon failure, which was defined as the inability of the coupon to sustain the applied fatigue loading. The number of cycles to fatigue failure, N, was recorded by the counter on the control panel. If the coupons did not fail, the tests were stopped due to testing and time constraints. These coupons were labeled as “run outs”.

Static Tension Test

Static tensile tests were also performed on the Instron 8501 servo hydraulic testing machine. An extensometer was attached to the specimen by a rubber band to measure axial strain. Load was applied to the specimen at a rate of 13 mm/sec until catastrophic failure occurred. Failure load and corresponding strain data were then recorded and the ultimate strength was calculated.

CHAPTER 4

RESULTS AND DISCUSSION

Results and related discussion of this study are presented in this chapter. The quality assurance of in-plane waviness fabrication is first addressed. Then, the effects of in-plane waviness on static compressive strength are presented and discussed in detail. The chapter also covers the effects of in-plane waviness on compressive fatigue behavior and static tensile strength. Complete data for each coupon test in this study are listed in Appendix A.

Quality Assurance of In-plane Waviness Fabrication

The process of in-plane waviness introduction in this study introduced the possibility of fiber damage, as the strands were disturbed when the stitches were pulled, as shown in Figure 8. This issue was investigated by conducting a group of tension tests. The most severe in-plane wave geometry in this study, 6 mm/35 mm*, was introduced into one layer of D155 fabric, then the wavy fibers were restraightened. This layer of restraightened fabric was laminated into a plate. Meanwhile, the control laminate, for which no layers were disturbed, was also prepared. Specimens cut from both laminates were tested in tension to failure. Results are shown in Table 1. In the table, the average tensile strength of the specimens with restraightened fibers was approximately equal to

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** 6 mm/35 mm represents the waviness with amplitude of 6 mm and wavelength of 35 mm. Similar notation is used throughout the thesis.*

Table 1. Quality Assurance of In-plane Waviness Fabrication

Laminate	Fiber Volume, %	*Average Tensile Strength (Standard Deviation), MPa	Difference, %
72 (control laminate)	49	971(20.9)	2
56 (with restraightened fibers)	54	995(19.7)	

* Data are average of tensile strengths of four specimens from each laminate.

that of the control specimens. Thus, the process of in-plane fiber waviness introduction by hand did not produce measurable fiber damage. This finding justifies laminate fabrication by this method.

Effects of In-plane Waviness on Static Compressive Strength

This topic is the focus of this study. Seven aspects were investigated:

1. Effects of in-plane wave geometry on static compressive strength for waviness in one surface ply.
2. Comparison between effects of surface waviness and internal waviness on compressive strength.
3. Effects of multi-layer waviness on compressive strength.
4. Effects of resin toughness on compressive strength with in-plane waviness.
5. Comparison between effects of in-plane waviness and through-thickness waviness (in A130 woven fabric) on compressive strength.

6. Comparison between effects of in-plane fiber waviness and simple fiber orientation on compressive strength.
7. Failure mode observations for failed specimens.

Effects of In-plane Wave Geometry

As indicated in Figure 7, in-plane wave geometry could be characterized by four parameters: wave amplitude (ä), wavelength (ë), wave severity (ä/ë) and maximum angle of fiber rotation (è). Effects of these parameters on the compressive strength of composites are explored in this section.

Although in-plane waviness in actual composite structures often exists in multi-layer regions with multiple wave shapes [13], the study of one isolated layer of in-plane waviness was deemed necessary to develop a fundamental understanding of its effects on compressive strength. Fundamental issues are included in this part of the study: in-plane waviness geometry in this section and in-plane waviness position through the thickness in the next section.

A group of laminates with one layer of surface in-plane waviness was fabricated as described earlier. Laminate configuration can be seen in Figure 10. For each laminate, the geometry of the in-plane waviness was different. By testing the compressive strength of specimens from these laminates, effects of wave geometry on compressive strength could be addressed.

Fifty-two specimens from thirteen laminates were tested: four control specimens from one laminate and forty eight specimens with in-plane waviness from twelve other laminates. Compressive strengths from the control specimens were averaged and used as a baseline to determine any strength reductions associated with specific in-plane wave geometry. The average compressive strength from the four control specimens was 509 MPa, ranging from 482 MPa to 538 MPa.

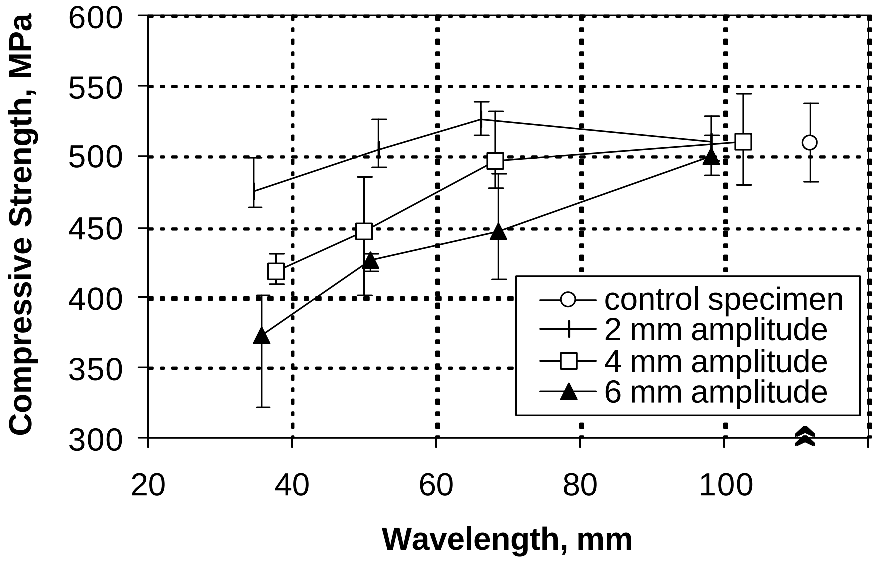


Figure 19. Effects of Wave Amplitude and Wavelength on Compressive Strength; Waviness in Single Surface Ply (bars on symbols indicate the range of individual test results)

Compressive strengths from specimens with in-plane waviness are plotted as a function of wavelength (ë) and wave amplitude (ä) in Figure 19. In the figure, at the fixed amplitude, compressive strength decreases as wavelength decreases. For the amplitude of 2 mm and 4 mm, the compressive strength is approximately constant when wavelengths exceed 65 mm. For the 6 mm amplitude, the compressive strength decreases with decreasing wavelength over the entire range. Stated differently, when wavelength is fixed, compressive strength decreases as amplitude increases. At a wavelength around 100 mm, compressive strengths for the three specific amplitudes converge to a similar range. Compressive strength is not solely dependent on wave amplitude or wavelength, but on both parameters.

Compressive strengths are plotted as a function of the wave severity, ä/ë, a combination of wave amplitude and wavelength, in Figure 20. Average compressive strengths from 13 laminates, including the control laminate, are indicated in the figure. The data appear to converge to a single trend with wave severity, with little loss in compressive strength for wave severities below 0.062. Adams [5] investigated the out-of-plane waviness (layer waviness) in T300/P1700 carbon/polysulfone composite laminates under static compression loading and the same conclusion was drawn: greater reductions in compressive strength are associated with larger values of ä/ë.

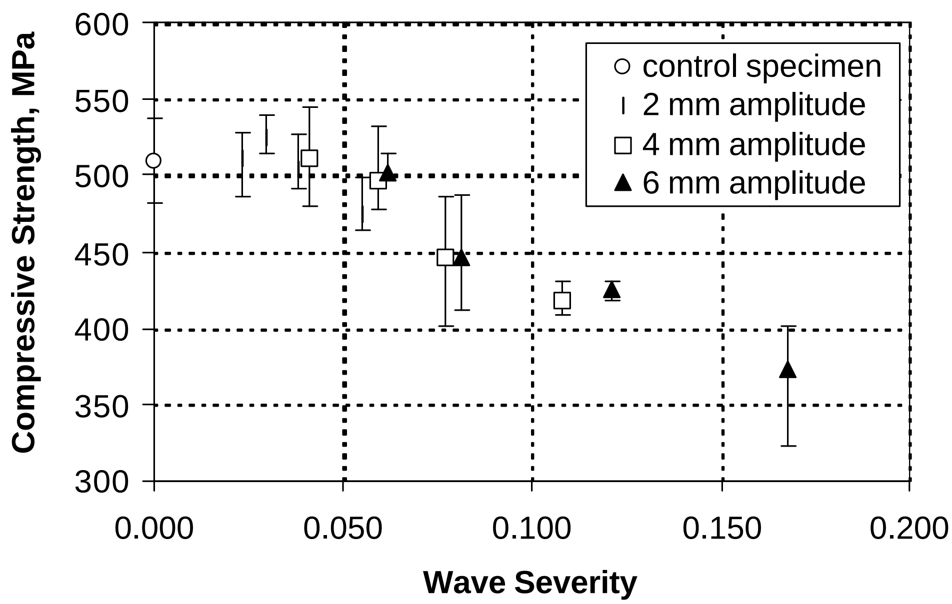


Figure 20. Effects of Wave Severity on Compressive Strength;
Waviness in Single Surface Ply

Compressive strengths of specimens with in-plane waviness are also plotted as a function of the maximum angle of fiber rotation, è, in Figure 21. The trend is similar to that in Figure 20, indicating that both parameters, è and wave severity, have similar effects. In fact, Figure 22 indicates a very precise correlation between è and wave severity for the wave shapes introduced in this study. Table 2 lists average values for both parameters. Wave severity and è (in degrees) correlate following the curve fit relationship:

è = 155.8(ä/ë) + 1.093 (3)

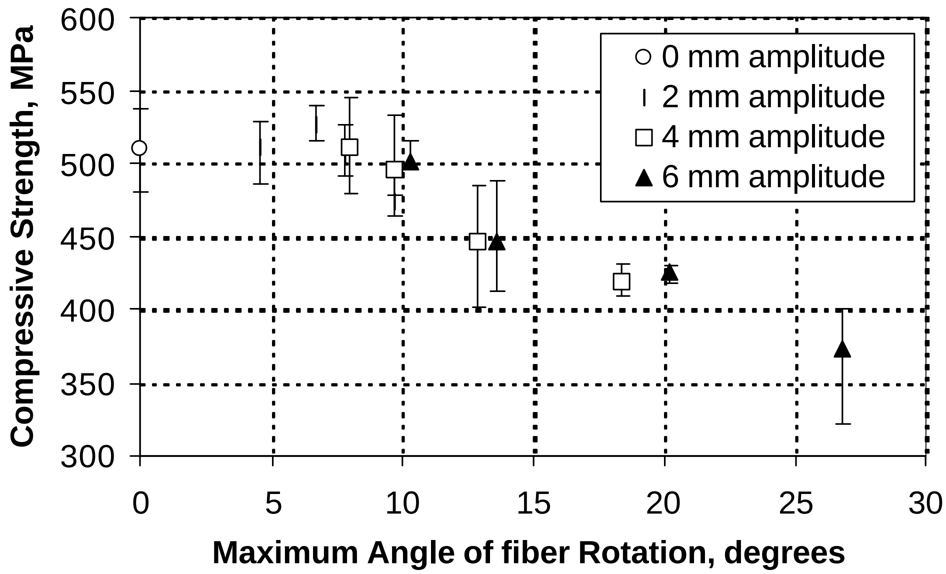


Figure 21. Effects of Maximum Angle of Fiber Rotation on Compressive Strength; Waviness in Single Surface Ply

Table 2. Average Wave Parameters for Each Laminate

Laminate	Amplitude (ä), mm	Wavelength (ë), mm	Wave Severity (ä/ë)	*Fiber Angle (è) degrees
0AS(9)c	0, control		0.000	0.0
33	2.26	98.12	0.023	4.6
24	1.96	65.98	0.030	6.7
16	1.98	52.00	0.038	7.8
32	4.20	102.38	0.041	8.0
64	1.92	34.80	0.055	9.7
65	4.02	67.96	0.059	9.7
31	6.04	97.92	0.062	10.3
74	3.88	50.10	0.077	12.9
69	5.58	68.60	0.081	13.6
1MS(8)	4.06	37.65	0.108	18.4
71	6.14	50.70	0.121	20.2
20	5.98	35.70	0.168	26.8

* Fiber angle represents the maximum angle of fiber rotation.

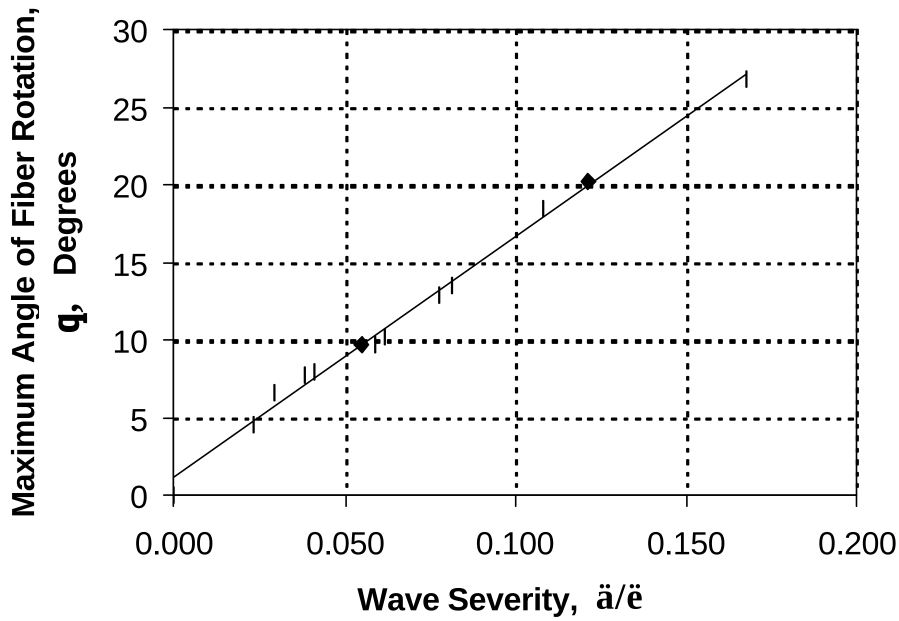


Figure 22. Correlation between Wave Severity and Maximum Angle of Fiber Rotation

Comparison between Surface and Internal Waviness

Two laminates with 6 mm/35 mm in-plane waviness were fabricated. One had one layer of surface waviness, the other had one layer of internal waviness. Laminate configurations can be seen in Figures 10 and 11, respectively. The 6 mm/35 mm wave geometry was chosen because it was the greatest wave severity in this study. If the position of the in-plane waviness has effects on compressive strength, this wave geometry could give us the most obvious evidence. Test results listed in Table 3 indicate that average wave severity and average compressive strength of laminates with surface waviness are 0.168 and 373 MPa respectively; the corresponding values for internal waviness are 0.162 and 419 MPa. By comparison, the average compressive strength of laminates with surface in-plane waviness is approximately 10% lower than for laminates with similar internal waviness, but the standard deviations overlap, so the difference may not be significant.

Table 3. Effects of Surface and Internal In-plane Waviness on Compressive Strength

Laminate	Wave Severity	*Average Compressive Strength(Standard Deviation), MPa	Difference, %
20 (with surface in-plane waviness)	0.168	373(35.3)	11
67 (with internal in-plane waviness)	0.162	419(13.3)	

* Data are average of compressive strengths of four specimens from each laminate.

Effects of Multi-layer Waviness

Since in-plane waviness in actual composite structures often exists in multi-layer regions, the loss in compressive strength for varying percentages of layers containing waviness is of interest.

Single layer and multiple layers of in-plane waviness with the same wave geometry were intentionally introduced into laminates. The numbers of layers with in-plane waviness in the laminate were varied to produce a variety of fractions of 0^o layers with in-plane waviness. As before, the $\pm 45^o$ layers did not contain any waviness. Since the control laminate in this study was $[0/\pm 45/0]_s$ and in-plane waviness was only introduced into the 0^o layers, there were at most four layers of in-plane waviness that could be introduced. With the control, this gives five fractions of 0° layers with waviness: 0.00, 0.25, 0.50, 0.75 and 1.00. Corresponding laminate configurations are shown in Figures 9, 10 and 12-14. In order to obtain more information, three series of each laminate case were fabricated, each series with a specific wave severity. Specimens from laminates in each series were tested and the compressive strengths are plotted as a function of fraction of 0° layers with in-plane waviness in Figure 23.

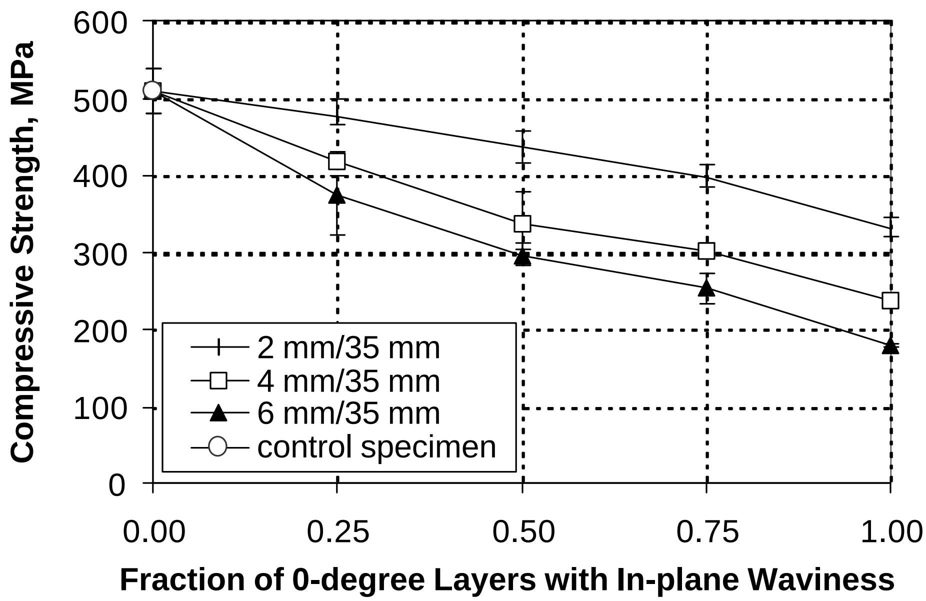


Figure 23. Effects of Multi-layer In-plane Waviness on Compressive Strength

In Figure 23, as expected, for each specific wave severity, a larger fraction of 0° layers with waviness resulted in a greater reduction in compressive strength; for each in-plane waviness layer fraction, greater wave severity produced a greater reduction in compressive strength. It is worth noting is that, for the series with a wave geometry of 6 mm/35 mm, when all four of the 0° layers contained waviness, the compressive strength of the laminate was reduced to 179 MPa, only 35% of the control specimens. In this case, unlike for the control specimens, the 0° layers may not dominate the load-carrying capacity, and the large part of the compressive strength of the laminate may be from the contribution of the ±45° layers. The ±45° layers, if tested alone, would have a compressive strength of about 174 MPa (Material CH9 in DOE/MSU Database [3]).

Unlike the results in Reference [6] for out-of-plane waviness, where the range over which the strength reduction was roughly proportional to the percent of 0° layers with waviness was only up to 33% of the 0° layers, with the reduction constant for higher percentages, Figure 23 shows a roughly proportional effect over the entire range to 100% 0° layers at all severity loads.

Effects of Resin Toughness

Tougher resin is usually used to resist the propagation of delamination [21]. Tougher resin often is associated with lower resin modulus, which means a tradeoff between delamination resistance and microbuckling initiation. For example, in Reference [17], of five resins tested in the laminate configuration used in the present study, the matrix which produced the highest interlaminar modes I and II toughness, epoxy SC14, had the lowest room temperature matrix modulus and the lowest compressive strength.

In order to investigate the effects of resin toughness on the compressive strength of laminates with in-plane waviness, two series of laminates, all with four layers of in-plane waviness, were fabricated. Laminate configuration can be seen in Figure 14. Laminate series one includes seven laminates with the polyester resin matrix. Laminate series two includes another seven laminates with the vinyl ester resin matrix. In each series, wave severities of in-plane waviness range from 0 to about 0.165 in all four 0° layers. The reasons that four layers of in-plane waviness were adopted in study of this section are: 1) laminates with in-plane waviness in all 0^o layers are more expected to be likely in natural occurrence, and 2) four layers of in-plane waviness gives the strongest effects on compressive strength. Both of these resins have about the same elastic modulus even though they differ greatly in toughness [3].

Test results are indicated in Figure 24. In this figure, first, for each series, as expected, greater wave severity results in greater reduction in compressive strength, with no clear area at low severities where the compressive strength is not affected, as was the case with one layer of waviness (Figure 20). Second, the vinyl ester matrix laminates have higher compressive strength than do the polyester matrix laminates over the wave severity range studied. At each wave severity, the absolute increase of compressive strength of the vinyl ester matrix relative to the polyester matrix appears to be uniform. Equations (4) and (5) give the regression fits for the compressive strength (CS) vs. (ä/ë) for the polyester and vinyl ester resins, respectively:

$$CS = 8861(\text{ä/ë})^2 - 3505(\text{ä/ë}) + 513 \qquad (4)$$

$$CS = 5015(\text{ä/ë})^2 - 2895(\text{ä/ë}) + 564 \qquad (5)$$

Similar trends can also be seen in Figure 25, in which the compressive strength of the laminates with waviness is normalized by the average compressive strength of control specimens. If the relative increase of compressive strength is considered, the percent of compressive strength increase due to the tougher resin matrix varies as listed in Table 4. From the table, it can be found that in a wave severity range from 0 to 0.10, the greater the wave severity, the larger relative increase of compressive strength the tougher resin will provide; at higher values of severities, the improvement is approximately constant at

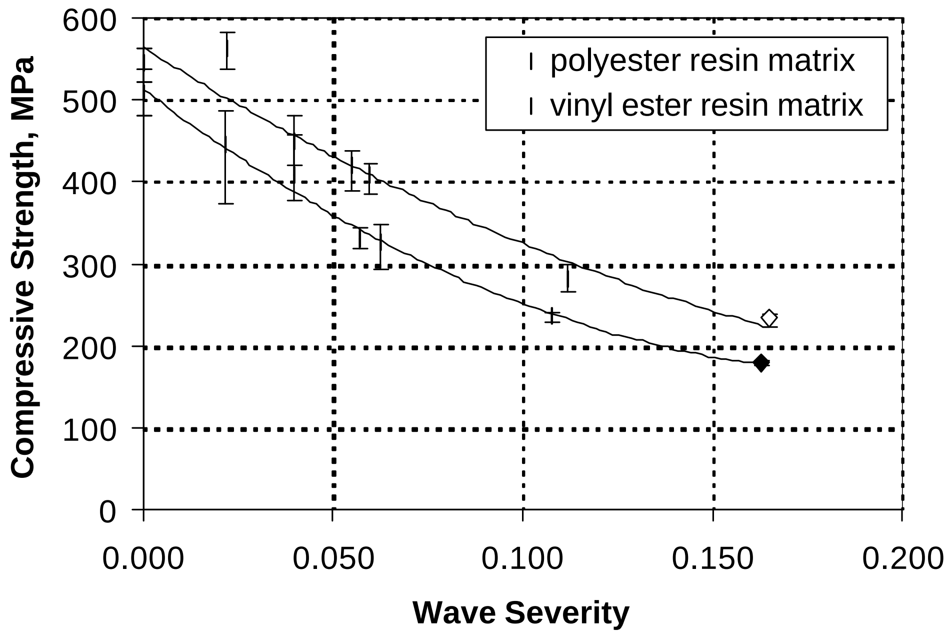


Figure 24. Effects of Resin Matrix Toughness on Compressive Strength Associated with Four Layer In-plane Waviness

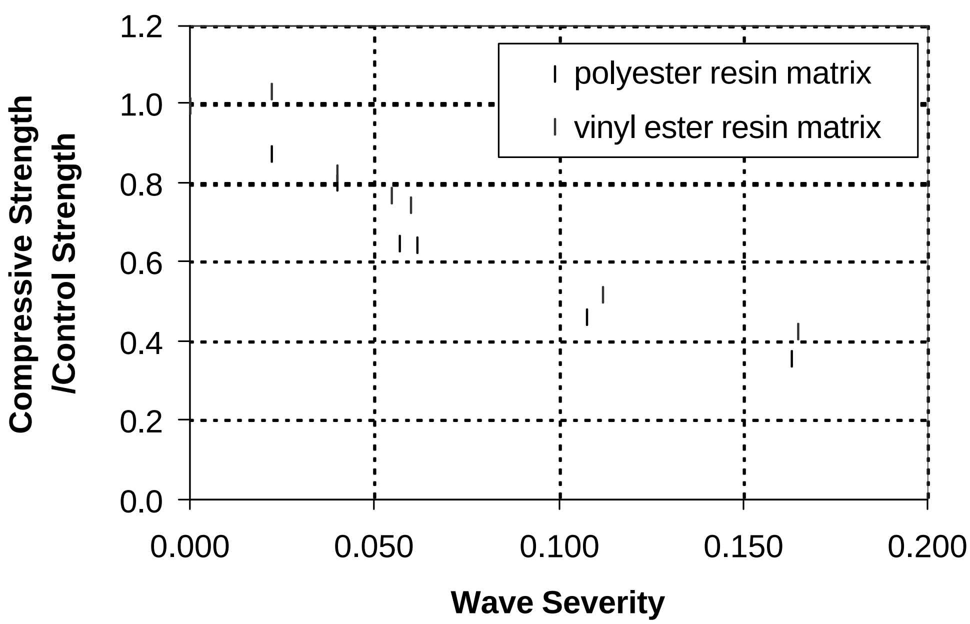


Figure 25. Effects of Resin Matrix Toughness on Compressive Strength Associated with Four Layer In-plane Waviness; Compressive Strength in Figure 24 is Normalized by the Compressive Strength of Control Specimens for That Resin

around 30%. This is a significant improvement, as the bars which indicate the range of the test data in Figure 24 do not generally overlap at the same wave severity for the two matrices.

Table 4. Relative Increase of Compressive Strength due to Tougher Resin Matrix

Wave Severity	Relative Increase of Compressive Strength for Tougher Resin, %
0.000	10
0.025	15
0.050	20
0.075	25
0.100	29
0.125	31
0.150	30
0.163	27

Comparison between In-plane and Through-thickness Waviness

A130 Fabrics use a woven architecture, which causes fiber tow waviness in the thickness direction, shown in Figure 2. Previous study at MSU found that laminates with A130 fabrics have much lower compressive strength than laminates with D155 fabrics. It has been argued that the reduction in compressive strength is caused by the through-thickness waviness in woven fabric A130 [14]. Since in-plane waviness also remarkably reduces compressive strength of the composites, whether through-thickness waviness and in-plane waviness have the same intensity of effects and the same mechanisms of compressive strength reduction is of interest.

This problem was studied based on comparison between laminates DD11 and DD12 in DOE/MSU Database and laminates fabricated in this study. DD11 and DD12 in DOE/MSU Database represent a category of laminates with the same lay-up as laminates in this study, $[0/\pm45/0]_s$. The difference is that the four 0° layers in DD11 and DD12 are A130 fabrics bearing the through-thickness waviness, while the four 0° layers in laminates fabricated in this study are D155 fabrics but with intentionally introduced in-plane waviness in them. Since amplitude of through-thickness waviness in A130 is limited by the ply thickness of the laminae, it is assumed that the A130 ply thickness equals to the amplitude of the through-thickness waviness. Previous study at MSU has established a correlation between laminate fiber volume fraction and A130 ply thickness, which means that if the fiber volume fraction of the laminate is known, the A130 ply thickness, namely the amplitude of the through-thickness waviness in A130 would be known. The wavelength of the through-thickness waviness in A130 is long and stable enough to be measured easily. By dividing amplitude by wavelength, the severity of A130 through-thickness waviness could be obtained. The width of each wave in A130 fabric is one strand, with each strand having waviness in the opposite direction.

For laminates DD11, the fiber content is 31%. According to the correlation between laminate fiber content and A130 ply thickness, a 31% fiber volume corresponds to 0.53 mm A130 ply thickness. Thus the amplitude of through-thickness waviness in DD11 is 0.53 mm. The wavelength of A130 through-thickness waviness was measured to be 35 mm. The severity of through-thickness waviness in DD11 was calculated to be 0.015. In the same way, for laminates DD12, for which the fiber content is 43%, the corresponding severity is 0.011.

Laminates DD11 and DD12 have compressive strengths listed in Database. The compressive strengths of laminates with four layers of in-plane waviness corresponding to wave severities of 0.011 and 0.015 are calculated by substituting wave severity 0.011 and 0.015 into equation (4) for the polyester matrix curve in Figure 24. Results are presented in Table 5.

Table 5. Effects of Four Layer In-plane Waviness and Through-thickness Waviness on Compressive Strength

Laminate	Waviness	Fiber Volume, %	Wave Severity	Compressive Strength, MPa
DD11 in DOE/MSU Database	Through-thickness	31	0.015	319
DD12 in DOE/MSU Database	Through-thickness	43	0.011	302
*Laminate fabricated in this study	In-plane	37	0.011	476
			0.015	462

* Interpolated to wave severities of 0.011 and 0.015 using regression in Figure 24.

Table 5 indicates that under the conditions of the similar laminate lay-up, fiber volume fraction and wave severity, the compressive strength of DD11 and DD12 with through-thickness waviness is much lower than for laminates with in-plane waviness fabricated in this study. It appears that through-thickness waviness in A130 woven fabric has stronger negative effects on compressive strength than does in-plane waviness. This may be because: 1) fiber tows of D155 fabrics are tighter than those of A130 fabrics, so the D155 tows need higher compressive loads to cause further buckling; 2) the A130 fabrics are free to buckle off of the outside surface, while the in-plane case is constrained from buckling by being bonded to the ±45° layers. In fact, the basic mechanisms of compressive failure may differ. As shown later, the in-plane waviness appears to be simply a reduction in strength due to fiber misalignment, while, for the woven fabrics, the through-thickness waviness contributes to easier buckling of the strands (Figure 3).

Comparison between In-plane Waviness and Fiber Orientation

Fiber orientation relative to the load direction causes significant changes in properties. In-plane fiber waviness and fiber orientation are illustrated in Figure 26. Since both rotate the fibers through an angle relative to the load, it is of interest to compare their effects on the compressive strength, to see whether the waviness effect can be explained by the misalignment factor.

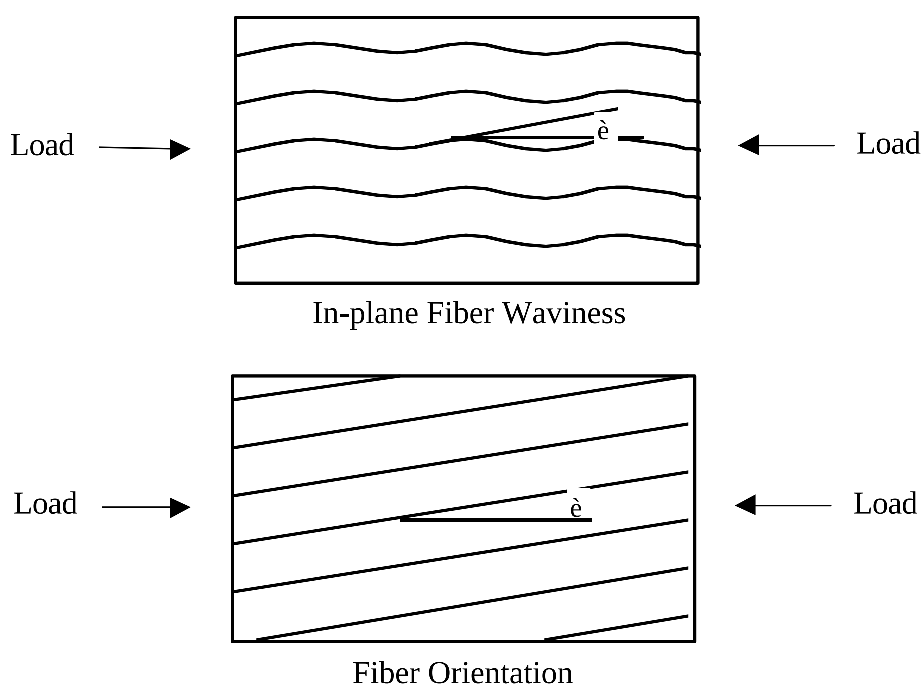


Figure 26. In-plane Fiber Waviness and Fiber Orientation

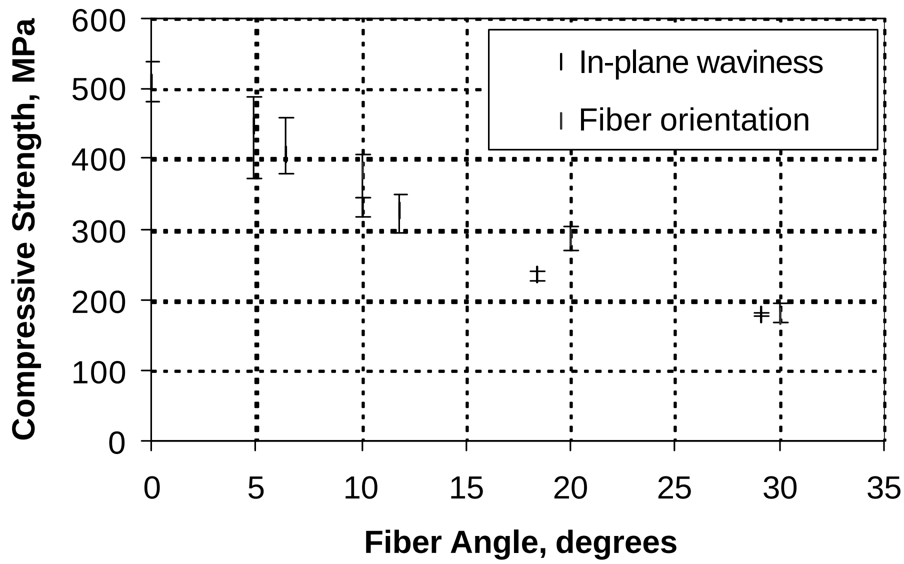


Figure 27. Comparison between Four Layer In-plane Waviness and Fiber Orientation

In Figure 24, corresponding to the wave severity of each point, the maximum angle of fiber rotation was measured to be 0°, 4.9°, 6.4°, 10.0°, 11.9°, 18.4° and 29.1°, respectively. Since the maximum angle of fiber rotation can also represent the wave severity, as shown earlier, compressive strengths of the seven laminates could also be plotted as the function of maximum angle of fiber rotation, shown in Figure 27. The DOE/MSU Database [3] contains compressive data for $\pm\theta$ angle ply laminates using D155 fabric and polyester matrix at a fiber content of about 39%. Data for $\pm 10^o$, $\pm 20^o$ and $\pm 30^o$ angle ply laminates (laminate 10D155, 20D155 and 30D155 respectively in the database) are used for comparison. Figure 27 compares these two data sets. It can be seen from the figure that, in the fiber angle range of 10^o to 30^o, the compressive strengths for the two types of misalignment are similar. It should be noted that the two layups differ significantly in that in-plane waviness laminates also contain $\pm 45^{o}$ layers, which may contribute significant strength at higher fiber angles of the 0^{o} layers, but reduce the strength with lower angles. The $\pm\theta$ laminate will also have somewhat different strength than a unidirectional $+\theta$ laminate [22]. Despite these differences, the general similarity of the strengths for the two cases in Figure 27 suggests that the strength drop in the waviness laminates could be explained entirely by the fiber orientation. Failure modes tend to support this view, in that they appear similar to simple off-axis ply failures.

Failure Modes

Failure modes are described for the failed specimens in this section.

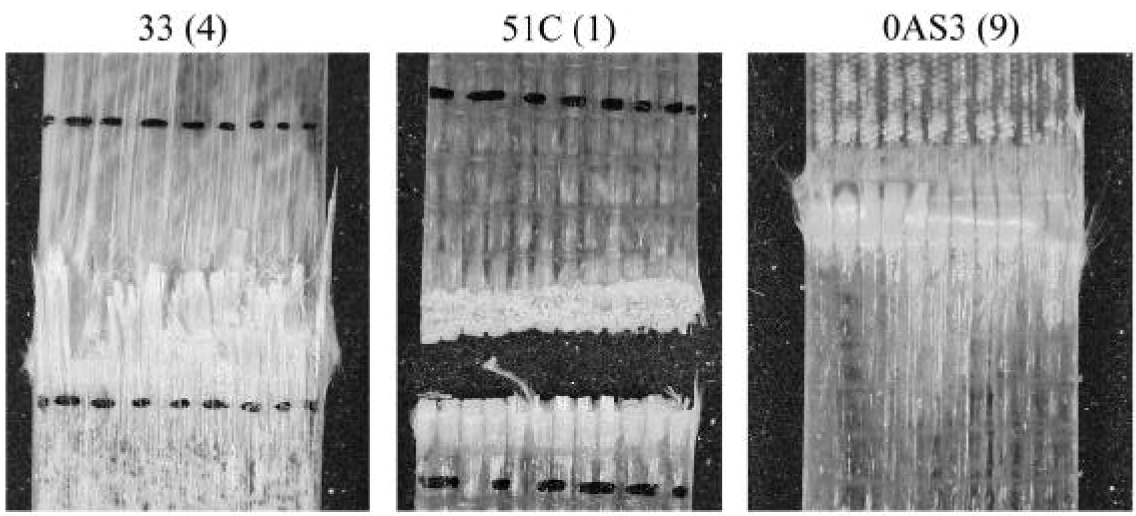


Figure 28. Static Compression Failure
0AS3(9): control specimen from polyester matrix laminate
51C(1): control specimen from vinyl ester matrix laminate
33(4): specimen with very moderate in-plane waviness from polyester matrix laminate

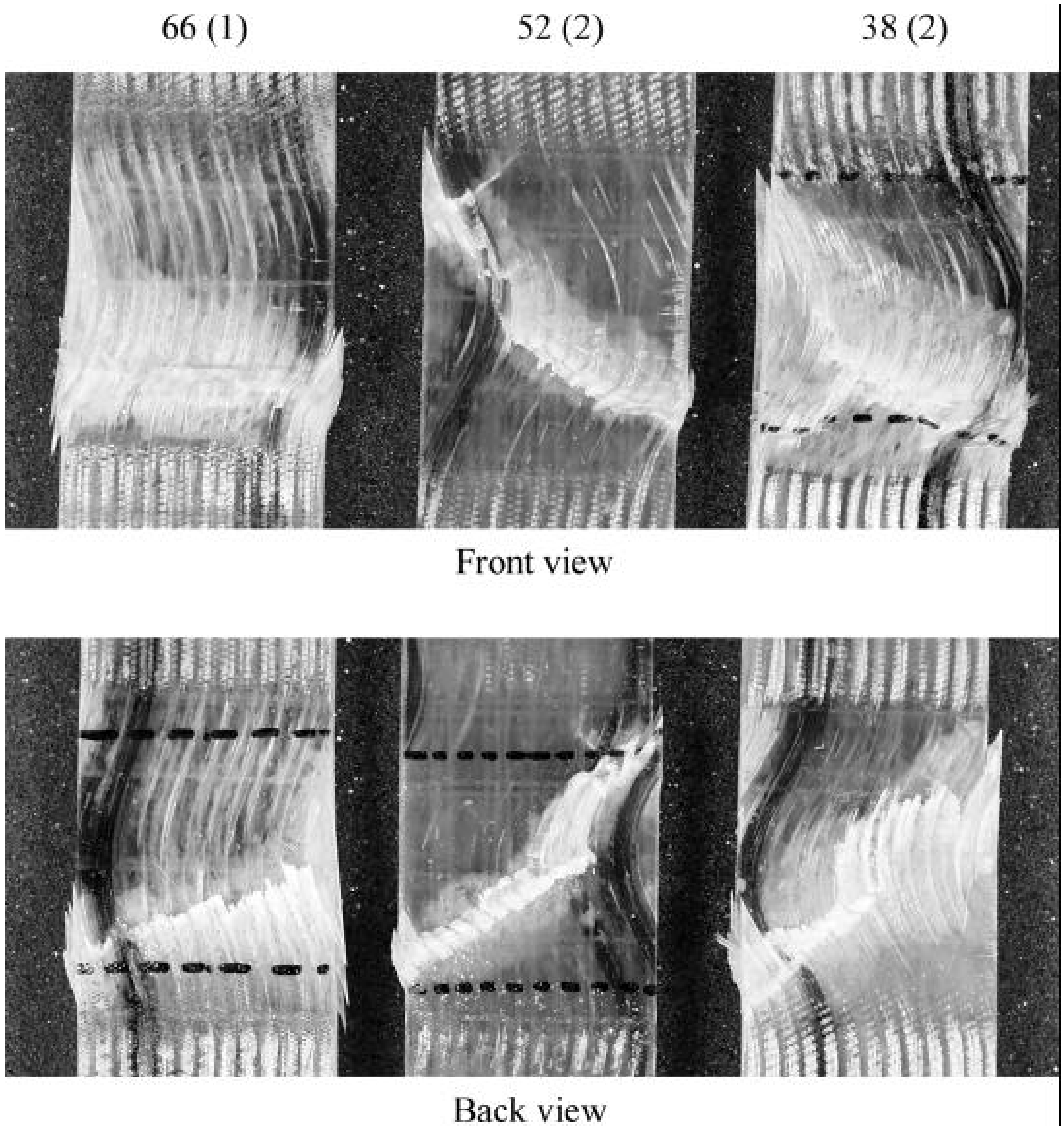


Figure 29. Static Compression Failure and Fatigue Compression Failure
52(2): static compression specimen with severe in-plane waviness from vinyl ester matrix laminate
38(2): static compression specimen with severe in-plane waviness from polyester matrix laminate
66(1): fatigue compression specimen with severe in-plane waviness from polyester matrix laminate

For control specimens with both polyester and vinyl ester matrices, failures were characterized by a single crushing/buckling plane perpendicular to the load direction. The main difference between the two matrices was that, as expected, numerous delaminations between plies existed in polyester matrix laminates but very little delamination existed in vinyl ester laminates, as seen in specimens 0AS3(9) and 51C(1) in Figure 28. The classic outward buckling of the strands is evident in specimens 33(4) and 0AS3(9).

For specimens with very mild in-plane waviness, the failure mode was similar to the control specimens, which can be seen in specimen 33(4) in Figure 28. For specimens with strong in-plane waviness, an angled fracture across the specimen width was observed in nearly all of the failed specimens, characteristic of a shear failure mode, which can be seen in specimens 52(2) and 38(2) in Figure 29. Additionally, the through-the-width angled fracture planes were found to have a preferred orientation, passing through the inflection point of the in-plane wave. This preferred failure orientation can be seen in Figure 29, and is illustrated in Figure 30. These failures appear to be matrix

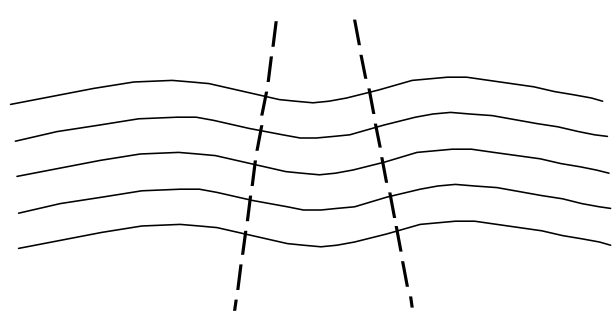


Figure 30. Preferred Failure Orientation

fracture followed by crushing, as expected, rather than classic out-of-plane buckling of the strands as in Figure 28. This contrasts with out-of-plane waviness in woven fabrics such as A130, which serves to enhance the strand buckling mode [3].

Effects of In-plane Waviness on Compressive Fatigue Behavior

Effects of In-plane Waviness on Compressive Fatigue

Other studies [3] have shown that the slope of normalized compressive S-N fatigue curves tends to be about the same for most laminates, with the main differences occurring in the static strength. In the present study, laminates with four layers of in-plane waviness with a severe wave geometry of 4 mm/35 mm (Figure 14) were tested in compressive fatigue.

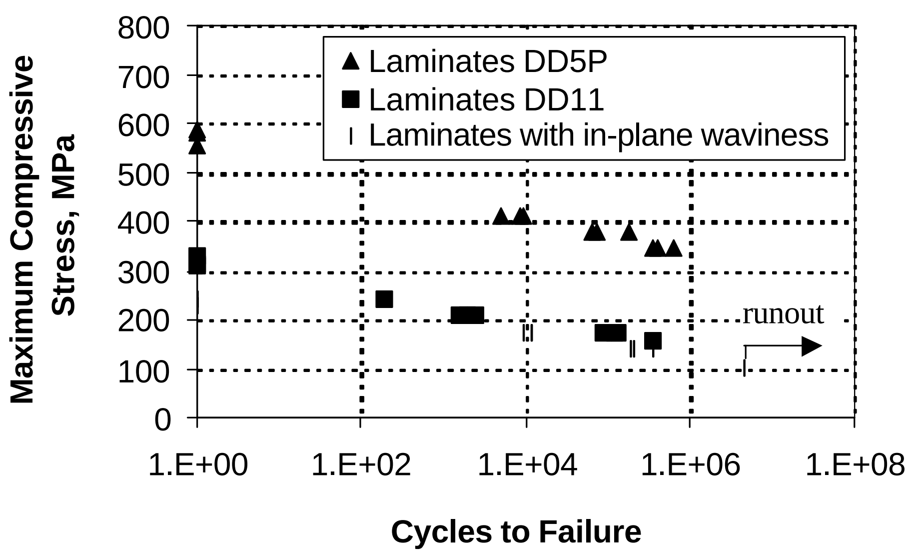


Figure 31. Compressive Fatigue Properties for Laminates with Four Layer In-plane 4 mm/35 mm Waviness and Through-Thickness (DD11) Waviness and Control Laminate DD5P, R = 10.

Seven specimens from two laminates were tested. Figure 31 compares test results to the DOE/MSU Database [3] data for laminates DD11 and DD5P. All laminates had the same $[0/\pm45/0]_s$ layup and used the same polyester matrix; fiber contents are: 40% for two laminates with in-plane waviness fabricated in this study; 36% for DD5P; and 31% for DD11. Fiber content differences do not significantly affect compressive strength on fatigue [3]. The four 0º layers in laminates fabricated in this study were D155 fabric with 4 mm/35 mm in-plane waviness introduced in them; the four 0º layers in laminate DD11 were A130 fabric and thus with though-thickness waviness due to the weave; for laminate DD5P, the four 0º layers were D155 fabric with straight strands (no waviness). DD5P is the control laminate for the fatigue behavior study. By comparing the fatigue behavior of these three laminates, any reductions in fatigue life can be directly attributed to the in-plane or through-thickness waviness.

Figure 31 compares the data for the three laminates (DD5P and DD11 data are taken from the DOE/MSU Database [3]). Results in the figure clearly show a considerable reduction in the compressive fatigue life due to both in-plane waviness and the through-thickness waviness. At the applied stress level of 150 MPa, for example, laminates with four layers of 4 mm/35 mm in-plane waviness and laminates DD11 would fail around 2×10^5 cycles, but control specimens from DD5P have a lifetime which would be off of the scale shown here, at least 10^{10} cycles by extrapolation of the DD5P data to 150 MPa.

When compared on the basis of stress which can be withstood for a given number of cycles, DD11 and the laminates with in-plane waviness have similar fatigue behavior, especially after 10^4 cycles. The 10^6 cycle maximum compressive stress of the two laminates was about 140 MPa, while for the control DD5P laminate the 10^6 cycle stress is about 330 MPa, more than twice as high.

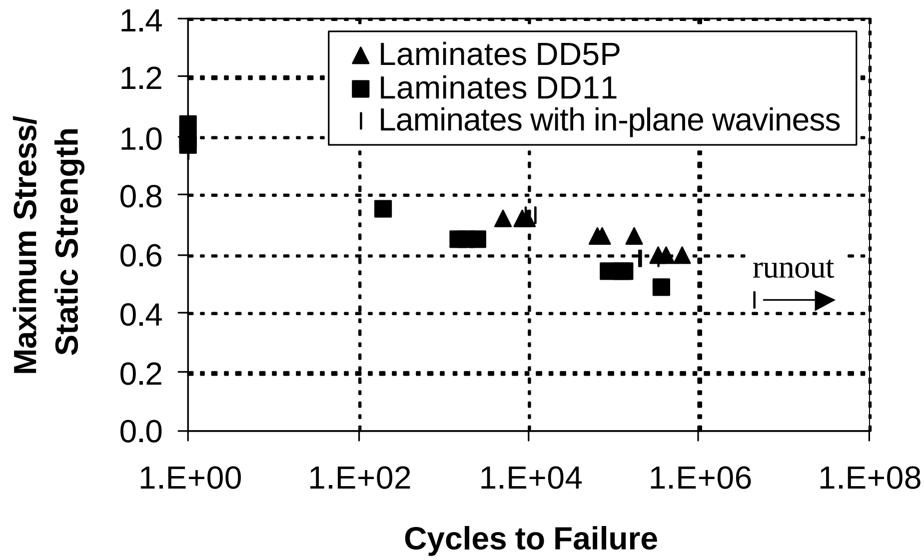


Figure 32. Normalized Compressive Fatigue Properties for Laminates with Four Layer In-plane 4 mm/35 mm Waviness and Through-Thickness (DD11) Waviness and Control Laminate DD5P, R = 10.

When the data are normalized by the static strength, the three laminates show similar trends in Figure 32. Thus, significant differences occur in the static strength, not the fatigue response.

Failure Modes

Of the seven compressive fatigue specimens tested, six had the same failure mode. Failure planes on two sides of the specimens were not same. One was oriented at an angle through the specimen width, similar to static compression tests. The other was perpendicular to the load direction near the grip position. This can be seen in specimen

66(1) in Figure 29. The remaining one specimen did not fail prior to termination of the test (termed a runout).

Effects of In-plane Waviness on Tensile Strength

Previous study at MSU [3] indicates that, although A130 woven fabric (with through-thickness waviness) has a significantly lower compressive strength compared with laminates based on D155 fabric, the tensile strength of the laminate remains similar to D155 laminates. Effects of in-plane waviness on tensile strength have been experimentally determined in this study.

Effects of In-plane Waviness on Tensile Strength

In order to get a general trend for effects of in-plane waviness on tensile strength, three laminates were fabricated. Laminate 72 was a control laminate without any waviness. Laminate 70 was a laminate with severe in-plane waviness of 4 mm/35 mm, corresponding to wave severity of 0.107. Laminate 73 was a laminate with very moderate in-plane waviness of 1.4 mm/101.1 mm, corresponding to wave severity of 0.014. Tension tests were performed on twelve specimens from these three laminates. Average tensile strengths for the three laminates are listed in Table 6.

In Table 6, considering that fiber volume fraction will greatly influence the tensile strength, the average tensile strength of specimens from control laminate (laminate 72) was adjusted in proportion to the fiber content from 49% fiber content to 43% fiber content to allow comparison of the three laminates under the same condition. The tensile strength of the adjusted control laminate is 852 MPa.

Table 6. Average Tensile Strengths for Three Laminates

Laminate	Fiber Volume, %	Wave Geometry	Wave Severity	*Average Tensile Strength(Standard Deviation), MPa
72(control)	49	no waviness	0	971 (20.9)
Adjusted 72	43	no waviness	0	852
73	43	1.4 mm/101.1 mm	0.014	829 (38.0)
70	43	3.9 mm/36.6 mm	0.107	512 (26.1)

* Data are average of tensile strengths of four specimens from each laminate

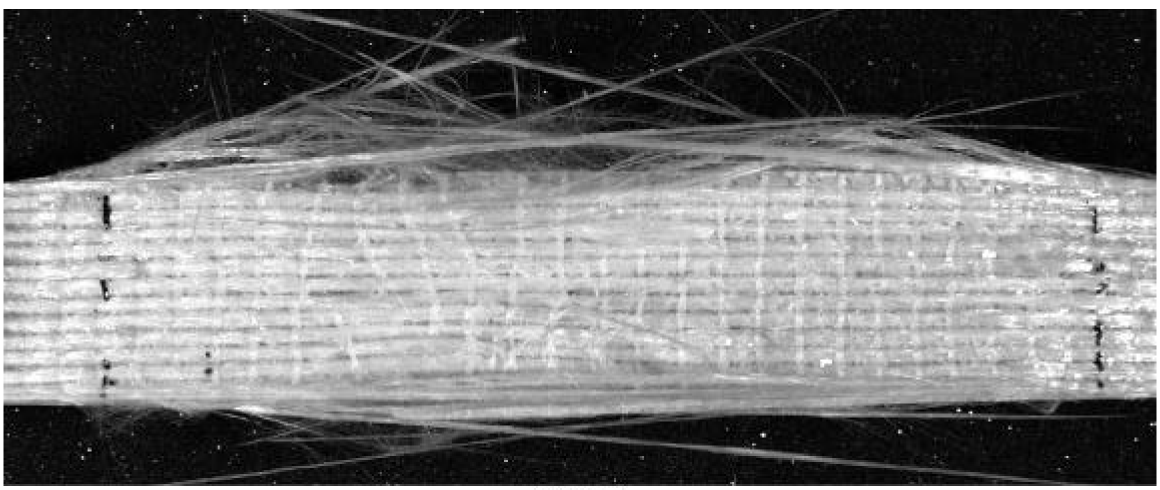
The tensile strength of laminate 73, in which very moderate in-plane waviness was introduced, is 829 MPa. This is very close to the tensile strength of the adjusted control laminate, indicating that the very moderate in-plane waviness did not change the tensile strength significantly. This is consistent with the A130 fabric case, for which the wave severity is also small, about 0.014. The wave severity for both cases corresponds to an orientation angle of less than 5^o.

Severe in-plane waviness was introduced into laminate 70, for which the average tensile strength was only 512 MPa. By comparing the tensile strength of laminate 70 to tensile strength of adjusted control laminate, it is found that a remarkable reduction in tensile strength was caused due to the severe in-plane waviness. The wave severity of 0.107 for laminate 70 correlates to a misorientation of about 18^o. In Reference [3], the $\pm\theta$ database cited earlier shows a tensile strength of 268 MPa for $\pm 20^o$ laminate; this value is reduced by the edge delamination mode of failure which is not be present in the waviness case.

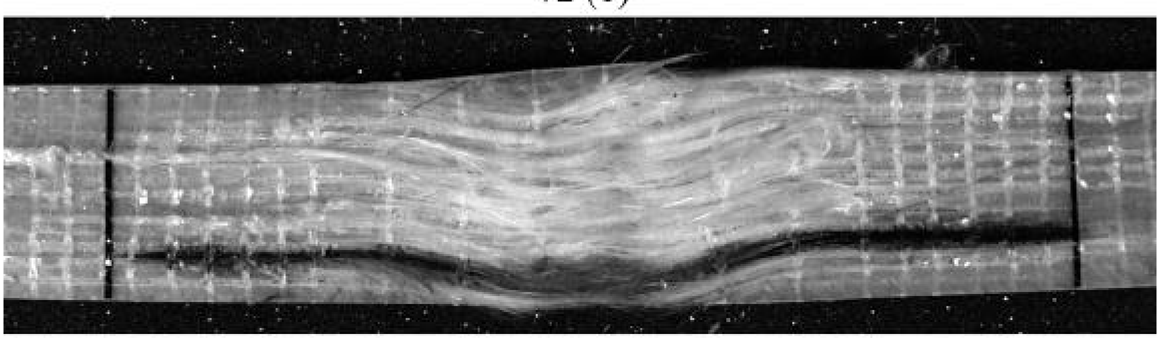
From the above results and discussion, it can be concluded that while very moderate in-plane waviness does not influence the tensile strength significantly, severe in-plane waviness remarkably reduces the tensile strength. This would be expected for the larger angles of fiber misorientation.

Failure Modes

Failure in tensile specimens, whether with or without in-plane waviness, is characterized by numerous fiber fractures and delaminations through the gage length of the specimen, shown in Figure 33.



72 (1)



70 (1)

Figure 33. Static Tension Failure
72(1): control specimen from polyester matrix laminate
70(1): specimen with in-plane waviness from polyester matrix laminate

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Conclusions drawn from this study are grouped into four areas.

Fabrication

* The process of in-plane fiber waviness introduction by hand produces reproducible waves of the desired geometry and does not cause fiber damage.

Effects of In-plane Waviness on Static Compressive Strength

* The reduction in compressive strength increases similarly with increasing values of both ä/ë (amplitude/wavelength) and è (maximum angle of fiber rotation); these two parameters provide correlations of the data for all values of ä and ë studied.
* The higher the percentage of layers with in-plane waviness in the laminate, the greater is the reduction in compressive strength.
* A tougher resin slightly reduces the effects of waviness on compressive strength.
* For the same wave severity, through-thickness waviness in woven fabric A130 causes a greater reduction in compressive strength than does in-plane waviness. This may indicate a fundamental difference in failure modes: in-plane waviness causes an effect similar to simple fiber orientation, while through-thickness waviness results in easier out-of-plane buckling of the strands.
* In-plane fiber waviness and fiber orientation have similar effects on the compressive strength in the range of fiber angles studied.

* Under compression loading, specimens with in-plane waviness fail at the maximum fiber orientation, passing through the inflection point of the wave.

Effects of In-plane Waviness on Compressive Fatigue Behavior

* Severe in-plane waviness causes a significant reduction in fatigue life at a given stress. The reduction is almost entirely due to the static strength reduction; the slope of the normalized S-N curve is not significantly changed.
* For compressive fatigue specimens, fracture surfaces of the two specimen faces are different. One orients at an angle, similar to the static compression failure. The other is perpendicular to the load direction near the grip position.

Effects of In-plane Waviness on Static Tensile Strength

* In-plane waviness causes a significant reduction in static tensile strength. The more severe waviness, the greater the reduction in tensile strength.
* Tension failure for specimens with in-plane waviness is characterized by numerous fiber fractures and delaminations.

Recommendations for Future Work

* Determine whether other factors, such as longer time under load and hot/wet conditions, further reduce the compressive strength with waviness present.
* Explore manufacturing methods which can eliminate waviness in thick low cost structures like wind turbine blades.
* Explore effective nondestructive evaluation methods which can cheaply detect significant waviness.

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APPENDIX A

TEST RESULTS

Static Compressive Strength

One Layer of Surface In-plane Waviness (Polyester Resin Matrix)

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Compressive Strength, MPa **Average(Standard Deviation)**
0AS9(1)	53.0	0, control specimens		0	0	481.5
0AS9(2)						530.2
0AS9(3)						487.1
0AS9(4)						537.6
						509.1(28.9)
64(1)	49.7	1.92	34.80	0.055	9.7	464.9
64(2)						464.1
64(3)						499.6
64(4)						468.5
						474.3(17.0)
16(1)	52.3	1.98	52.00	0.038	7.8	508.9
16(2)						491.8
16(3)						526.0
16(4)						492.7
						504.8(16.1)
24(1)	51.6	1.96	65.98	0.030	6.7	539.4
24(2)						533.1
24(3)						514.7
24(4)						516.5
						525.9(12.2)
33(1)	50.1	2.26	98.12	0.023	4.6	513.5
33(2)						516.0
33(3)						486.4
33(4)						528.3
						511.0(17.7)
1MS8(1)	48.6	4.06	37.65	0.108	18.4	417.5
1MS8(2)						431.1
1MS8(3)						409.1
1MS8(4)						416.1
						418.5(9.2)
74(1)	47.9	3.88	50.10	0.077	12.9	485.5
74(2)						415.6
74(3)						400.8
74(4)						485.0
						446.7(44.9)

(continue)

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Compressive Strength, MPa **Average(Standard Deviation)**
65(1)	47.8	4.02	67.96	0.059	9.7	532.3
65(2)						491.2
65(3)						482.3
65(4)						478.0
						496.0(24.8)
32(1)	51.3	4.20	102.38	0.041	8.0	545.0
32(2)						479.4
32(3)						528.3
32(4)						490.3
						510.8(31.0)
20(1)	51.1	5.98	35.70	0.168	26.8	321.9
20(2)						400.3
20(3)						378.0
20(4)						391.9
						373.0(35.3)
71(1)	48.1	6.14	50.70	0.121	20.2	430.5
71(2)						417.6
71(3)						427.9
71(4)						428.2
						426.1(5.7)
69(1)	48.7	5.58	68.60	0.081	13.6	411.9
69(2)						487.4
69(3)						451.4
69(4)						437.6
						447.1(31.5)
31(1)	49.0	6.04	97.92	0.062	10.3	496.2
31(2)						514.7
31(3)						495.9
31(4)						497.5
						501.1(9.1)

* Angle represents the maximum angle of fiber rotation.

One Layer of Internal In-plane Waviness (Polyester Resin Matrix)

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Compressive Strength, MPa **Average(Standard Deviation)**
67(1)	47.2	6.04	37.30	0.162	28.3	430.7
67(1)						427.2
67(1)						400.9
67(1)						417.9
						419.2(13.3)

* Angle represents the maximum angle of fiber rotation.

Two Layers of In-plane Waviness (Polyester Resin Matrix)

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Compressive Strength, MPa **Average(Standard Deviation)**
62(1)	47.6	1.98	34.16	0.058	9.8	445.8
62(2)						456.6
62(3)						416.6
62(4)						427.5
						436.6(17.9)
60(1)	46.6	4.00	37.40	0.107	18.3	378.4
60(2)						347.1
60(3)						319.0
60(4)						304.3
						337.2(32.7)
58(1)	49.8	5.96	39.10	0.152	26.1	312.0
58(2)						298.1
58(3)						283.3
58(4)						291.3
						296.2(12.2)

* Angle represents the maximum angle of fiber rotation.

Three Layers of In-plane Waviness (Polyester Resin Matrix)

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Compressive Strength, MPa **Average(Standard Deviation)**
63(1)	41.3	2.02	35.73	0.057	9.4	413.8
63(2)						405.6
63(3)						390.0
63(4)						385.6
						398.7(13.2)
61(1)	42.5	4.00	33.51	0.119	18.0	294.6
61(2)						297.2
61(3)						310.8
61(4)						297.8
						300.1(7.2)
59(1)	42.1	5.99	38.60	0.155	25.4	245.9
59(2)						273.6
59(3)						269.9
59(4)						233.8
						255.8(19.2)

* Angle represents the maximum angle of fiber rotation.

Four Layers of In-plane Waviness (Polyester Resin Matrix)

Laminate (Specimen)	Fiber Volume, %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Compressive Strength, MPa **Average(Standard Deviation)**
39(1)	38.7	1.97	34.52	0.057	10.0	344.3
39(2)						318.8
39(3)						319.8
39(4)						336.5
						329.9(12.6)
40(1)	38.7	4.01	37.20	0.108	18.4	241.3
40(2)						228.7
40(3)						241.0
40(4)						230.2
						235.3(6.8)
38(1)	34.8	6.22	38.13	0.163	29.1	178.2
38(2)						175.9
38(3)						181.5
38(4)						181.8
						179.4(2.8)
44(1)	42.0	2.22	101.99	0.022	4.9	373.0
44(2)						488.3
44(3)						466.1
44(4)						458.8
						446.5(50.6)
41(1)	39.8	4.04	101.47	0.040	6.4	409.9
41(2)						458.3
41(3)						377.3
41(4)						383.8
						407.3(36.8)
43(1)	37.4	6.29	100.96	0.062	11.9	349.1
43(2)						333.4
43(3)						329.8
43(4)						294.5
						326.7(23.1)

* Angle represents the maximum angle of fiber rotation.

Four Layers of In-plane Waviness (Vinyl Ester Resin Matrix)

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Compressive Strength, MPa **Average(Standard Deviation)**
51c(1)	53.5	0, control specimens		0	0	522.7
51c(2)						562.2
51c(3)						558.3
51c(4)						539.7
						545.7(18.2)
55(1)	41.6	2.04	37.05	0.055	9.1	423.6
55(2)						389.0
55(3)						439.2
55(4)						426.7
						419.6(21.5)
53(1)	39.2	4.17	37.28	0.112	19.9	270.8
53(2)						298.9
53(3)						267.5
53(4)						286.5
						280.9(14.6)
52(1)	37.4	6.11	37.03	0.165	26.8	237.8
52(2)						231.5
52(3)						224.4
52(4)						238.2
						233.0(6.5)
48(1)	37.9	2.22	101.78	0.022	3.5	538.6
48(2)						583.2
48(3)						567.5
48(4)						559.8
						562.3 (18.6)
49(1)	37.6	4.08	102.28	0.040	4.9	480.1
49(2)						456.4
49(3)						419.7
49(4)						441.3
						449.4(25.4)
50(1)	40.4	6.03	101.13	0.060	8.3	396.1
50(2)						422.6
50(3)						423.2
50(4)						387.0
						407.2(18.5)

* Angle represents the maximum angle of fiber rotation.

Laminates DD11, DD12
Referring to DOE/MSU Database [3].

Laminates 10D155, 20D155 and 30D155

Referring to DOE/MSU Database [3].

Compressive Fatigue

Laminates with Four Layers of Severe In-plane Waviness (Polyester Resin Matrix)

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	Number of Cycles N	Compressive Strength MPa
40(1)	38.7	4.01	37.20	0.108	1	241.3
40(2)					1	228.7
40(3)					1	241.0
40(4)					1	230.2
66(1)	42.5	3.99	36.45	0.109	347549	137.9
66(2)					192168	137.9
66(3)					208206	137.9
66(4)					4500000	103.4
68(1)	41.6	4.10	38.28	0.107	11606	172.4
68(2)					11660	172.4
68(3)					9151	172.4

Laminates DD5P

Referring to DOE/MSU Database [3].

Laminates DD11

Referring to DOE/MSU Database [3].

Static Tensile Strength

Laminate (Specimen)	Fiber Volume %	Amplitude mm	Wavelength mm	Wave Severity mm/mm	*Angle degrees	Tensile Strength, MPa **Average(Standard Deviation)**
72(1)	51.0	0, control specimens		0	0	941
72(2)						980
72(3)						990
72(4)						975
						971(20.9)
56(1)	55.3	0, restraighten	33.92	0	0	977
56(2)						1006
56(3)						1017
56(4)						979
						995(19.7)
73(1)	44.5	1.42	101.16	0.014	1.9	871
73(2)						826
73(3)						780
73(4)						839
						829(38.0)
70(1)	44.6	3.91	36.63	0.107	16.2	486
70(2)						500
70(3)						547
70(4)						514
						512(26.1)

* Angle represents the maximum angle of fiber rotation.