Elastic Properties, Strength and Damage Tolerance of Pultruded Composites

Mrinal Chandra Saha
*Old Dominion University*

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ABSRACT

ELASTIC PROPERTIES, STRENGTH AND DAMAGE TOLERANCE OF PULTRUDED COMPOSITES

Mrinal Chandra Saha
Old Dominion University, 2001
Director: Dr. R. Prabhakaran

Pultruded composites are candidate materials for civil engineering infrastructural applications due their higher corrosion resistance and lower life cycle cost. Efficient use of materials like structural members requires thorough understanding of the mechanism that affects their response. The present investigation addresses the modeling and characterization of E-glass fiber/polyester resin matrix pultruded composites in the form of sheets of various thicknesses.

The elastic constants were measured using static, vibration and ultrasonic methods. Two types of piezoelectric crystals were used in ultrasonic measurements. Finally, the feasibility of using a single specimen, in the form of a circular disk, was shown in measuring all the elastic constants using ultrasonic technique.

The effects of stress gradient on tensile strength were investigated. A large number of specimens, parallel and transverse to the pultrusion direction, were tested in tension, 3-point flexure, and 4-point flexure. A 2-parameter Weibull model was applied to predict the tensile strength from the flexure tests. The measured and Weibull-predicted
ratios did not show consistent agreement. Microstructural observations suggested that the flaw distribution in the material was not uniform, which appears to be a basic requirement for the Weibull distribution.

Compressive properties were measured using a short-block compression test specimen of 44.4-mm long and 25.4-mm wide. Specimens were tested at 0°, 30°, 45°, 60° and 90° orientations. The compression test specimen was modeled using 4-noded isoparametric layered plate and shell elements. The predicted elastic properties for the roving layer and the continuous strand mat layer was used for the finite element study.

The damage resistance and damage tolerance were investigated experimentally. Using a quasi-static indentation loading, damage was induced at various incrementally increased force levels to investigate the damage growth process. Damage parameters were measured in the form of dent depth, back surface crack length, and damage area. The compression tests were performed, using an end-gripped compression test fixture, on both the damaged specimens and open-hole specimens. A relationship between the compressive strength and hole-diameter was established. The compressive strength of damaged specimens was compared to determine the "equivalent-hole-diameter." A correlation between damage parameters and the "equivalent-hole-diameter" was established to find a parameter that could be used as a measure of damage resistance and damage tolerance of pultruded composite structures.
To my family
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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Polymer matrix composites (PMCs) have grown in popularity as structural materials for several reasons, including high strength-to-weight ratio, corrosion resistance, resistance to reasonable temperature limits, etc. However, the manufacturing cost of PMCs is high as compared to conventional materials. A common and economical method for manufacturing PMCs is "pultrusion." Pultrusion is a process that offers advantages of a continuous production, as well as the integration of fiber impregnation and composite consolidation in one single process. Various structural shapes with a constant cross section, such as I-beams, hollow boxes and flat sheets, can be manufactured through pultrusion. Some of the advantages of pultruded shapes are ease of assembly, easy maintenance of the structures and lower life-cycle cost. In the pultrusion process, layers of unidirectional fibers in the form of roving bundles and randomly oriented mat are pulled through a polymer resin bath and then through a heated die. The die consolidates and provides the shape of the cross section of the final product while curing the polymeric matrix.

Pultruded composites find their greatest application in civil engineering where these materials are used in a wide variety of structural elements ranging from gratings and ladders to bridges and piers. Other applications include radar domes and high voltage
line insulators [1,2,3] to name a few. The wide range of applications for pultruded composites raises concerns regarding their mechanical performance. For example, composites' structural components have finite volume, and the state of stress in real applications may be substantially different from that of standard laboratory test specimens utilized to generate the design data. Polymer based composites are inherently brittle, hence their strength is a function of specimen volume and applied stress. Thus, it is necessary to determine the size effect and/or stress gradient effect of those composites and also to include these effects in structural design. Materials showing a size effect need special treatment in order to predict the strength because standard failure criteria cannot be used to account for the influence of size effect.

Designing composite structures with pultruded composites requires a knowledge of material properties, especially in compression. For example, compressive strength is considered prerequisite when designing structures against failure due to local bearing stress generated at loading and support positions. In general, composite materials are inherently weaker in compression than in tension. Hence, it is necessary to measure the compressive properties of the composite materials for reliable structural design. Composite materials also generally exhibit appreciable variation in their strength properties. This may be attributed to the variations in the manufacturing process parameters, test methods and the inherent heterogeneous nature of the materials. It is necessary for the designer to have some knowledge of the statistical variation of compressive strength in order to design structures with some degree of reliability. Statistical knowledge of compressive strength may increase the probability of survival of costly structures, as well as make the structures economical by reducing the safety

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factors. It is also essential that the effects of thickness and fiber orientation angle on compression behavior of composite materials be known for successful structural design.

PMCs are very strong and stiff in the direction of fibers. However, they are very weak in the transverse direction and are therefore susceptible to transverse damage. Incidents such as accidental tool dropping during assembly and regular inspection of the structures, highway debris and hailstorms may cause structural damage repeatedly during their service life. Damage in composite structures may affect not only the structural response during loading, but it may also reduce structural strength in subsequent static loading. Two important issues must be addressed in the design of damage tolerant structures: the damage resistance of the structural materials; and the damage tolerance of the damaged structures. The extent of the damage is considered as a measure of damage resistance of the composite structures, which can be determined by measuring damage parameters such as dent depth, back surface crack length and internal damage area. The damage tolerance issue relates the residual strength, residual strain to failure and residual stiffness due to presence of damage in the structure and is usually performed in either tension or compression. These two parameters are interdependent and must be characterized for successful structural design.

Finally, the accurate modeling of the composite materials is a must for stress analysis and structural design and also to predict the onset and development of failures. The finite element method is a desirable tool for performing such a rigorous analysis.

Far more is known about steel and concrete for structural applications than about PMCs. While various advantages of PMCs make them attractive for structural applications, the size and stress gradient effects, the compressive strength and its
variability and the damage resistance and damage tolerance of those materials make it difficult to design using PMCs. Without proper knowledge and thorough investigation, the design may result in a structure that would fail prematurely. Clearly, it is necessary to generate as much important information as possible for the survival of the costly structures, as well as to make the structures economical by reducing the safety factor.

This effort addresses the modeling and characterization of pultruded composites. While it is advantageous in many ways to use pultruded composites in structural design, careful consideration of prior research results must be employed to optimize safety and efficiency in realistic applications. This information will afford a wealth of knowledge regarding various characteristics of the material, including ultrasonic measurement of elastic constants, scaling and stress gradient effects, compressive properties and damage resistance and tolerance due to hole and static damage. These and other characteristics will become apparent, as will their correlations and interdependencies. With this knowledge, designers will become adept in understanding pultruded composites, their microstructures and various modeling issues, which will facilitate the utilization of realistic values for structural design and stress analysis.

1.2 Literature Review

The primary thrust of this investigation is to characterize and model pultruded composites. The characterization includes details, including static, vibration and ultrasonic measurements of elastic constants, size and stress gradient effects on tensile strength, compressive properties measurements and the statistical strength analysis, damage resistance due to indentation loading and damage tolerance due to open hole and
static damage in compression. The modeling includes the prediction of various layers’ properties and subsequent use of those properties for stress analysis using the finite element method. There exists a large body of work that addresses similar issues for various other types of composites. However, similar information on pultruded composites is far more limited, and must become accessible if important design data is to be generated.

To facilitate discussion, the literature review is subdivided into various subtitles that reflect the areas of investigation. Only crucial studies are discussed, and they include experimental details, material investigated and results to support the significant of the present investigation.

### 1.2.1 Elastic Constants of Composite Materials

Many test methods and specimen configurations have been proposed for measuring the in-plane elastic constants of composite materials. They are broadly classified into static method, vibration method and ultrasonic method. In the static method, strain gaged specimens with the axis oriented at 0°, 45° and 90° to the major reinforcement direction are tested in static tension to establish the principal elastic constants. In-plane shear modulus, $G_{12}$, is difficult to measure, however, a number of specimens and test procedures have been proposed. Some of the proposed methods are torsion of a thin-walled cylinder, $[\pm 45]_s$ coupon test, rail shear test, torsion test, Iosipescu test, picture frame and 10° off-axes. The angular dependence of the elastic constants (anisotropy) can be obtained by employing the transformation equations or by testing specimens with different fiber orientations. In a novel approach, Prabhakaran and
Chermahini [4] illustrated the feasibility of using a single specimen for measuring all the in-plane elastic constants of continuous glass-fiber-reinforced polymer material. The proposed calibration specimen simulated an orthotropic half-plane under a concentrated edge load, for which a closed-form theoretical solution was available. It was shown that all the in-plane elastic constants could be measured by measuring the strains at selected locations away from the loading point. The measured strains were used as input to the close form solution proposed by Green [5], which was solved using a non-linear-least-square technique to determine all the in-plane elastic constants of orthotropic composites. Grédiac et al. [6] proposed a T-shaped specimen to identify the in-plane elastic properties of balanced glass fabric reinforced epoxy panels from heterogeneous strain field. The T-shaped specimen was subjected to a complex stress state and the whole-filed displacements were recorded using a suitable optical method. The strain values were determined from the integration of the displacement fields. The stiffnesses such as \( Q_{xx} \), \( Q_{yy} \) and \( Q_{ss} \) were identified with a 10-15% difference as compared to the reference values. However, this method could not identify \( Q_{xy} \) accurately. Recently, Prabhakaran and Xu [7] utilized a circular disk specimen to determine all the in-plane elastic constants of pultruded composites. The circular disk specimen was instrumented with a number of strain gages, and the specimen was compressed diametrically. The measured strains were used along with the Okubo solution [8] to extract the in-plane elastic constants by utilizing the nonlinear least square method.

Several investigators have used vibration technique to measure the Young's modulus of various composites. Tauchert and Moon [9] tested unidirectional glass-epoxy and boron-epoxy composite specimens as cantilever beam. The specimens were excited
using a sinusoidal oscillator and an electromagnetic transducer with a resonant frequency as high as 17.7 kHz. A favorable agreement between the experimental and theoretical values of the Young's modulus for up to ten modes was reported. However, it was reported that Young's modulus computed from the measured frequency decreased slightly with increasing frequency. Schultz and Tsai [10] used vibration technique to measure the elastic modulus and damping ratios for a glass-fiber-reinforced, unidirectional composite beam over a frequency range of 5-10000 Hz. Both the free and forced vibrations of the cantilever beam making angles with the fibers with the beam longitudinal axis of 0°, 22.5°, 45° and 90° were studied. It was found that the Young's modulus varied with frequency of excitation and at lower frequencies, the moduli were reported 7-27 percent higher than the static values.

Ultrasonic wave speed measurement has also been used to determine the elastic constants of composites. Through-transmission measurements, requiring access to both sides of a specimen, as well as single sided measurements, have been reported. In some of the investigations [11,12], specimens have been cut along different angles with the major material symmetry axis, and the longitudinal and transverse wave velocities have been measured. In other investigations, the immersion technique has been used. That is, refraction and mode conversion at the interface have been used to generate the desired mode at various angles through the composite. Minachi et al. [13] proposed an acoustoultrasonic technique in which the elastic constants of transversely isotropic materials were deduced from the time-of-flight of obliquely reflected echoes received by another transducer located on the same surface of the specimen. Smith [14] used an ultrasonic immersion technique to measure the elastic constants of resin-matrix...
composites fabricated from a wide variety of carbon and graphite fibers. A 5 MHz transducer with 0.75-in diameter as a transmitter and a 10 MHz transducer with 0.5-in diameter as a receiver were used. Dally et al. [15] utilized specially fabricated transparent and birefringent composite model material to measure the velocities of the dilatational and shear waves from a source of dilatation in an orthotropic full-plane by dynamic photoelastic methods. Various stress waves and their propagation velocities were identified from isochromatic photoelastic fringes.

The ultrasonic measurement techniques developed and utilized in many of the investigations have been more scientific than engineering. In other words, they are not as simple as the engineering methods employing electrical resistance strain gages. In effect, the complexity of the anisotropic and inhomogenous composite materials has contributed to the complexity of the ultrasonic techniques. Zurbrick [16] and Schultz [17] reported measurements of composite Young's modulus as a function of the fiber orientation. They tested circular disk specimen of 25-mm and 32-mm diameter; the wave propagation velocities across the diameters at various angles were measured, and Young's modulus was determined as a function of the angle.

Piezoelectric transducers have been used in the shear wave velocity of soil specimens [18-20]. Bringnoli et al. [21] used piezoelectric ceramic transducers to measure the shear modulus of soil specimens. Both bender and shear plate ceramic elements were used to generate the shear wave through the soil specimens. They discussed the advantages and disadvantages of using bender transducers (producing dilatational waves), and shear plate transducers (producing shear waves) with reference to
soil testing. The interpretation of shear waveforms generated with each transducer and the optimum wavelength needed to obtain clear received waveforms were also discussed.

1.2.2 Stress Gradient Effects on Composite Strength

Many of the polymer-based composites, such as continuous glass or graphite fiber reinforced plastics, are brittle due to the brittleness of the matrix and the reinforcement. Therefore, such composites are susceptible to size effects or stress gradient effects. In other words, failure of such materials depends not only on the level of stress applied, but also on the volume of material subjected to this high stress. Two important manifestations are the higher flexural strength as compared to the tensile strength and the higher tensile strength as the specimen volume decreases. Such an effect has been repeatedly noted over time for static loading of brittle, and for fatigue loading of ductile, single-phase materials. Establishment of a viable relationship between the flexure strength and the tensile strength can provide a potential basis for using the flexure test in the generation of design tensile strength. Since the flexure tests are easy to run and are relatively inexpensive, a large statistical database obtained with this method rather than with tensile specimens is far more economical.

The Weibull statistical model has been applied to many materials, with varying degrees of success. Weil and Daniel [23] applied a two-parameter Weibull model, with success, to brittle steel and ceramic materials. Based on this success, attempts were made to extend the two-parameter Weibull model on random orientated short-fiber reinforced composites by Knight and Hahn [24] and on the unidirectionally fiber reinforced graphite-epoxy composites by Bullock [25]. Excellent agreement between the
measured values and the Weibull predictions for the ratio of three-point flexure strength to tensile strength was reported. However, Whitney and Knight [26] performed both three-point and four-point flexure tests in addition to tensile test for similar composites investigated by Bullock [25]. In addition, the influence of specimen thickness on tensile strength was also investigated. A significantly large variation in tensile strength and flexure strength was reported. The authors noted that such differences were not in accordance with the statistical strength theories based on a uniform flaw distribution. This discrepancy raised questions regarding the applicability of the Weibull statistical model for composite materials. Prabhakaran [27] pointed out the basic difference in the structures of composite materials (heterogeneous) from that of ceramics materials. For instance, while the inherent flaws in ceramic may predominantly influence the ultimate failure, the progressive damage in composites may lead to a flaw distribution which itself is dependent on the applied stress field. To account for the progressive failure of composites, Wisnom [28] proposed a model assuming unidirectional composite as a bundle, with each element of the bundle consisting of a number of fibers acting together. The number of elements in the bundle was assumed to be large, their size was taken to be uniform, and their strengths were assumed to follow a two-parameter Weibull distribution. It was found that the fiber bundle model could predict the higher flexural strength as similar to the classical Weibull strength model, without the need to assume catastrophic failure initiating from the critical defects.

Jackson et al. [29] investigated the feasibility of using a scale model for predicting the full-scale behavior of flat composite coupons loaded in tension and beam-columns loaded in flexure. They performed experiments on graphite-epoxy composite specimens.
with various laminate stacking sequences and a wide range of scaled sizes. Significant scale effect on strength was reported. The scale effect was analyzed using a Weibull statistical model and a fracture mechanics based model. The Weibull statistical model was reported to be better in correlating with the experimental results for both the tensile and flexural strength data than the fracture mechanics based model. Kellas and Morton [30] studied the strength scaling of graphite-epoxy composite laminates with four different layups and various scaled sizes. They reported nearly an 83% increase in strength in ¼-size specimens as compared to the full-scale size specimens for matrix dominated specimens. In contrast, the strength of the ¼-size specimens of the fiber-dominated layups was measured to be only 7% higher, as compared to full-scale size specimens. According to Kellas and Morton [30], full-scale strength was overestimated by the Weibull model and was underestimated by the fracture mechanics based model.

Recently, O'Brian and Salpekar [31] investigated the scale effect of AS4/3501-6 graphite/epoxy unidirectional composites in the transverse direction by conducting tensile tests, three-point bend tests and 0° curved beam-bending tests. They found that the matrix-dominated strength varied with the volume of test material, with the strength decreasing as the volume of the test material increasing. The transverse strength data were used in a volumetric scaling law based on Weibull statistical model to predict the transverse strength loaded in three-point bending. The transverse strength and the out-of-plane interlaminar tensile strength from curved beam bending tests were compared, and significant scale effects on matrix-dominated composites were reported.
1.2.3 Compressive Properties of Composite Materials

The compressive properties of fiber-reinforced composite materials have been the subject of investigation since the early 1960's. This is because polymeric matrix composites are inherently weaker in compression than in tension [33]. In addition, compressive properties of composite materials are very difficult to measure [34]. This difficulty is due to the material's strong tendency for premature failure due to geometric instability, local end crushing or local end brooming. Several complex loading fixtures and specimen configurations have been developed to address these premature failure modes for fiber-reinforced composites [35-40]. The compression test itself is sensitive to many experimental parameters such as alignment, specimen geometry, load introduction, stress concentration, buckling stability and specimen end crushing [41]. Piggott and Harris [43] investigated the compression behavior of a series of unidirectional composites reinforced with carbon, glass and Kevlar fibers in polyester resins, in the form of pultruded rods. The degree of cure of polyester resin, as well as various fiber volume fractions in compressive strength was also studied. The test specimens were 30-mm long and 6-mm diameter. A good correlation with the rule of mixture up to a limiting volume fraction of 0.31 for strength and of 0.46 for modulus was reported. Beyond this point, the compressive strength of the reinforced polyesters was found to be proportional to the matrix yield strength.

Shuart [44] investigated the effect of stacking sequences on compressive strength and compressive failure mechanisms of graphite-epoxy composite laminates. Specimens 44.5-mm long, 38-mm wide and 6.3-mm thick were tested using a short-block compression test fixture. The laminate's compressive strength and the failure modes
were compared with the proposed non-linear theory. Good agreement was found between the analytical and experimental results for $\theta<45$-degree, and excellent agreement for $\theta\geq45$-degree. The dominant compression failure modes were reported to be interlaminar shearing, in-plane matrix shearing and matrix compression.

Tomblin [45] developed a compressive strength model for unidirectional pultruded glass fiber reinforced composites. The author measured the compressive strength of pultruded rod specimens from various sources to verify the model. The model included the fiber misalignment and the composite shear response. The compression test specimens were 38-mm long with a diameter of 9.3-mm, and were tested using the direct end-loading fixture. The model prediction was reported to be a close approximation of the true compressive strength. The author also pointed out that the model required accurate characterization of the shear response and the fiber misalignment angle to accurately predict compressive strength.

Morttram [46] measured the compressive strength of pultruded E-glass fiber reinforced flat sheet materials. The test specimens were 70-mm long, 20-mm wide and 6.3-mm thick. The specimens were tested in the direction of pultrusion and transverse to the pultrusion direction. A compression test rig and test procedure was developed to test the composite specimens in compression. Over 100 specimens were tested to analyze the compressive strength data statistically, and the corresponding design allowables were determined. The design allowable strength was determined using a lognormal, a normal and a Weibull distribution. It was reported that the design allowable strength was 25% higher along pultrusion direction and 12% higher along transverse direction when
compared to manufacturer's allowables. The report did not include the effect of thickness and fiber orientation angle on compressive strength and the failure modes.

Hsiao et al. [47] developed a new test method to determine the compressive properties of thick composites. The test fixture was designed based on the concept of transmitting the initial load through the tabs by shear loading and thereafter engaging the ends to apply the additional load until the point of failure by end loading. The compressive strength of unidirectional graphite-epoxy specimens of 16-, 48- and 72-ply was measured. It was reported that the measured strength was the highest among the published data for similar composites. It was also stated that the test fixture could be used to test specimen as low as 10-plies. However, the researchers also suggested further investigation of the timing of end-loading engagement so that the highest compressive strength could be measured.

Haque et al. [48] studied the influence of long-term moisture exposure and temperature on the compressive properties of T-300/epoxy and APC-2 composites. A temperature range of 23-100°C was considered. The specimen was soaked for up to 360 days. Both experimental and finite element studies were performed to analyze failure mechanisms. An IITRI test fixture was used for compression test and the layered shell element based on the first-order shear-deformation was used in the finite element analysis. Good agreement was reported between the experimental and FEM results.

1.2.4 Damage Resistance and Damage Tolerance of Composites

Damage resistance of composites is usually performed either at low-velocity impact loading or at static indentation loading. The former is very difficult to perform
and requires sophisticated instruments as compared to the static indentation test. Moreover, much more data may be obtained from a static test than from an impact test. Damage tolerance of composites is usually performed by testing composite specimens with damage and/or hole in tension and/or in compression. One important aspect of damage tolerance study is that the residual properties of the damaged structures must be predicted based on the known damage parameters upon inspection. It is also important to correlate the residual properties of the damaged structures with the structures having holes to determine the "equivalent hole-diameter" of the damaged structures. This is because analytical tools are available to model and predict the strength of the specimen with hole, whereas it is very rigorous task to model damaged structure to predict the residual strength.

A number of studies have been conducted with actual impact loading to characterize the damage, while many researchers have dealt with quasi-static indentation loading and its correlation with transverse impact loading. Impact damage in composites is generally very complex. Impact damage appears in multiple forms of damage mechanisms such as matrix cracking, delamination and fiber breakage. This can occur at different stages during transverse loading and is also likely to be due to different stress components, so that these mechanisms may interact among themselves with one or two being dominant. The nature and extent of these damage mechanisms are affected, to different degrees, by a large number of parameters such as shape and mass of the impactor, impact velocity, types of fibers and matrix, interfacial treatment, fiber volume fraction, layup, laminate geometry and boundary conditions.
Tan and Sun [52] measured the contact stiffness for graphite-epoxy composites using static indentation testing. The measured stiffness was fed into the finite element program to study the dynamic response of a composite plate subjected to transverse impact from a hard object. It was shown that the predicted strain response using the finite element method agreed very well with the experimental results. It was also reported that the finite element solution for the contact force history matched very well with the measured contact force obtained using an impact-force transducer.

Lee and Zahuta [53] conducted instrumented impact and static indentation tests of graphite-epoxy composites of various fracture toughness. The impact behavior, defined by impact force, damage size and energy absorption, was found to be similar to the static indentation response. It was reported that the damage growth process, during impact as the force surged to its maximum value, could be visualized from the static indentation damage induced at incrementally increased force levels. Delamination impact damage was found to be dependent on laminate fracture toughness. It was mentioned that simple mode I or mode II delamination was not sufficient to describe all the possible failure modes involved in impact or in compression after impact tests.

Wu and Shyu [54] studied the response of graphite-epoxy composites to contact loads and its relationship to low-velocity impact. Various indentor sizes and laminate stacking sequences were included in the study. Good agreement in term of strain response was found between the contact load and the low-velocity impact load when the vibration effect was neglected. Vibration can cause the strain values to oscillate under low-velocity-impact test condition. The laminate stacking sequence and indentor size were found to produce an insignificant effect on the force-indentation relationship. The
modified Hertz law was found to be inappropriate for thin laminates indented by large indentors.

Wardle and Lagace [55] conducted impact and quasi-static indentation tests on plate and shell graphite/epoxy specimens to investigate whether the dent depth could be used as an impact damage metric for thin composite structures. Surface damage, in the form of dent depth, was compared with internal damage, and no correlation between the two was found. Furthermore, no correlation was found between the dent depth and the peak force. The applicability of dent depth as a measure of damage resistance for thin composites was questioned, and it was concluded that the use of dent depth as a metric could be misleading. Particularly, no dent depth was found in some cases where substantial subsurface damage was observed, and wherein substantial dent depth was found with no corresponding internal damage. The researchers showed in their previous work that the peak force correlated with the resulting internal damage for both shell and plate specimens.

Zhou [56] investigated the damage resistance and damage tolerance of woven roving E-glass-polyester and S-glass-phenolic laminate systems through instrumented drop-weight impact testing, ultrasocin C-scan, and CAI testing. The author pointed out that an experimentally determined impact force could be used as a measure of damage resistance and tolerance of composite structures. It was also demonstrated that the ratio of threshold impact forces could be used as an alternate method to measure of residual compressive strength for damage tolerance assessment. According to the author, this method could provide a rapid and inexpensive technique, without resort to complex and expensive CAI tests.
Kwon and Sankar [57] conducted the static-indentation-flexure and low-velocity impact tests on simply supported circular graphite/epoxy laminated plates. Two different radii indentors, three laminate configurations and three different plate radii were considered. The load-deflection curves for the static and impact loading were found to be very similar. It was reported that the impact force history and delamination area in composite laminates due to low-velocity impact could be predicted from few static-indentation-flexure tests.

Suemasu et al. [58] proposed a simple and consistent indentation theory for transversely isotropic plates to estimate contact force. The predicted results agreed well with the experimental results completed by Tan and Sun [52] and with the finite element results. It was concluded that the effect of the plate thickness on the indentation stiffness could be neglected when the plate became thinner and/or the load was larger. The effect of the in-plane stiffness on the indentation stiffness was not found to be significant.

Wu and Chang [59] investigated the effect of the loading rate on E-glass/epoxy woven composite laminates subjected to quasi-static contact and impact load. Various impactors' masses and loading rates up to ballistic range were studied. Significant loading rate effects were observed when comparing the laminates loaded quasi-statically to those struck by projectiles with varying masses. These effects included differences in the impact force history, an increase in peak force and absorbed energy and a completely different delamination damage pattern. It was concluded that the effect of the loading rate for composite laminates reinforced by glass fibers could not be overlooked.

Choi and Chang [60] developed a model for predicting the initiation of the damage and the extent of the delaminations in graphite/epoxy laminated composites.
resulting from the impact. Experiments were also performed to verify the model and computer simulations. It was concluded that there existed a threshold impact velocity below which there was no delamination. Delamination growth was found to be governed by the interlaminar longitudinal shear stress, the transverse in-plane stress in the layer below the delaminated interface and the interlaminar transverse shear stress in the upper layers immediately above the interface.

Starnes et al. [61] investigated the effect of low-velocity impact damage and circular holes on the compressive strength of a 48-ply orthotropic graphite-epoxy laminate. It was reported that, for holes, delamination occurred near the hole boundary when the applied strain was sufficiently high to cause local failure, whereas, delamination occurred on impact for sufficiently high impact speed or energy regardless of the applied strain level. It was concluded that, because of this difference between holes and impact damage, the use of hole strength data to predict impact-damage strength might be questionable.

Shuart and Williams [62] investigated the compressive failure mechanisms and the compressive behavior of AS4/3502 graphite-epoxy composite laminates with a circular hole and an impact damage. The laminates were ±45° and ±45°, dominated with various percentages of 90° plies through the thickness. The compressive failure mechanism for the ±45° dominated laminates with a hole was found to be different from the failure mechanism for the ±45° laminates with a hole. In-plane shearing between fiber and matrix were found to be the primary compressive failure mechanisms for all ±45° laminates. The failure mechanisms for the ±45° dominated laminates with hole were observed to be a combination of delamination and matrix shearing. The failure
mechanisms for both $\pm 45^\circ$ laminates and the $\pm 45^\circ$ dominated laminates were unaffected by impact damage. The failure mechanisms for impact-damaged laminates were dominated by delamination and matrix shearing.

Chamis and Ginty [63] described the simplified predictive methods and model to evaluate structural durability and damage tolerance of polymeric matrix composites. The model allowed for fatigue and fracture with and without defects, impact resistance and residual strength after impact, thermal fatigue and combined stress fatigue. Several examples were discussed to illustrate the application of the theory and to identify significant parameters and sensitivities.

Kim et al. [66] evaluated the damage tolerance of carbon fiber-reinforced composites containing unmodified and rubber-modified epoxy resin using a sectioning technique. The residual strength and modulus were measured in flexure, and the residual stiffness and the mode I interlaminar fracture toughness were determine in DCB tests. It was demonstrated that the residual mechanical properties for all composites with rubber-modified matrices were better than those of the unmodified matrices, in varying degrees in the test method and test specimen locations.

Soutis [65] measured compressive strength for a wide range of T800/924C carbon fiber-epoxy multidirectional laminates containing circular hole, with the proportion of $0^\circ$ plies varying from 17% to 67%. It was observed that failure stress was generally well above the value one might predict from the elastic stress-concentration factor. The author believed that the composite material is not so brittle and some stress relief occurs around the hole. X-ray radiography revealed that damage was in the form of $0^\circ$ fiber microbuckling, delamination and matrix cracking. The damage growth and failure were
analyzed by a new fracture model [66] in which damage around the hole was represented by a through-thickness crack. It was reported that the model successfully predicted the notched strength of various multidirectional lay-ups and a wide range of hole sizes.

Lessard and Chang [67-68] investigated the damage tolerance of laminated composites containing an open hole and subjected to compressive loading. A progressive damage model was developed to predict the damage growth. The model was based on finite deformation theory with consideration of material and geometric nonlinearities. The extent of damage in the material was predicted by a failure analysis, which included a set of proposed failure criteria and material degradation model. Good agreement was reported between the prediction and the experimental test results.

Rodes et al. [69] conducted an experimental study to evaluate the effect of panel width on the compressive strength of 48-ply graphite-epoxy laminates with holes. The parameters for the point-stress failure criteria were evaluated to predict the compressive strength. Good agreement was obtained between the experimental and predicted values of failure for panels of different widths. The test results included panels with machined cracks, with punched holes and with drilled holes. The parameters were shown to have an upper limit given by the reduction in specimen cross-sectional area and a lower limit given by the effect of stress concentration.

Saha [70] investigated the impact performance and damage tolerance of woven carbon fiber-reinforced composite panels with various degree of resin toughness. Dynatup drop weight instrumented impact test and Boeing BS7260 type compression after impact (CAI) fixture was adopted. Numerical analysis based on Hertz contact law with various damping was also performed to predict the damage in the structure.
Very limited information is available related to pultruded composites. Recently, Wisheart and Richardson [71] investigated the low-velocity impact response of pultruded glass/polyester composite shapes. The impact behavior was evaluated using instrumented falling weight impact testing in conjunction with ultrasonic C-scan, optical microscopy and thermal deploy techniques to detect delamination, matrix cracking and fiber breakage. A pultruded box-section consisting of three- or five-box was tested. An important transition in impact response was observed when the impact site was varied from between webs (simple geometry) to impact over or near a web (complex geometry). The impact site near the web dominated by remote damage at the locations of stress concentration. For the later case, the damage sites were unpredictable.

1.3 Objectives and Scope of the Study

While steel and concrete have been tested and analyzed in great detail to determine the reliability of the structures, far less has been done regarding pultruded composites. It is necessary to generate material behavior, such as elastic and strength properties, stress gradient on tensile strength, statistical analysis, damage resistance and damage tolerance. With this information, designers can effectively determine necessary materials, the inspection required and anticipated life of the structure. Finally, modeling of pultruded composites is necessary for stress analysis and design of an optimum structure. Through this research, a wide body of information will be available to the designer regarding pultruded composite, their structure, properties and modeling.

The present investigation covers the complete mechanical characterization and modeling of pultruded composites. This includes developing of ultrasonic test procedure
to measure the elastic properties, the stress gradient effects on tensile strength, compressive behavior, damage resistance due to transverse loading and damage tolerance due to hole and damage in compression. The details of each investigation, including methods and procedures, are discussed in subsequent chapters.

Chapter II describes the details of pultruded composites: their construction, the lay-up sequences and the percent of glass in each layer for various thicknesses of pultruded composite sheets investigated.

Chapter III describes the various techniques for measuring of elastic constants of composite materials. Both static, vibration and ultrasonic methods are discussed. The ultrasonic technique includes the construction of E-crystals and G-crystals, the experimental set up and data reduction. Both bar and disk specimens are utilized. Finally, the procedures to extract all the elastic constants utilizing a circular disk specimen from the ultrasonic measurements are described.

Chapter IV describes the size effect and stress gradient effect on tensile strength of pultruded composites. This includes the detailed procedure for tension, 3-point and 4-point flexure tests. A 2-parameter Weibull statistical model and the prediction of the tensile strength from flexure test data are also discussed. The failure modes and microstructural examination are also discussed.

Chapter V describes the compression testing of pultruded composites. The compression test fixture and the test procedure are also described. The effect of
thicknesses and fiber orientation angle is included. Compressive failure modes are discussed to determine the failure initiation. Pultruded composites are modeled to predict the constituent layers' properties for the finite element study. Stress-strain response is predicted and compared to experimental data. The stress distribution through the thickness and across the width is also described.

Chapter VI describes the quasi-static indentation testing to characterize the damage resistance of pultruded composites. The damage parameters are measured and a correlation among them is discussed. The contact force-indentation relationship is also established experimentally and compared with modified Hertz law. The end-gripped compression test fixture utilized in damage tolerance characterization is also described. Damage specimens and specimens with hole are tested in compression to determine the "equivalent-hole specimen" of the damaged specimens. Finally a correlation between damage parameters and the "equivalent-hole-specimens" is established that can be used as a measure of damage resistance and damage tolerance of pultruded composite structures.

Chapter VII summarizes the findings at each phase of the investigation and presents conclusions about the material's elastic properties, stress gradient effects, compressive properties as function of orientation and thicknesses and the damage resistance and damage tolerance capability of this class of pultruded composites.
CHAPTER II

TEST MATERIAL – PULTRUDED COMPOSITE

The material tested in this investigation is E-glass fiber-reinforced polymer (GFRP) matrix pultruded composite. The material was manufactured by Creative Pultrusions of Alum Bank, PA [1]. The trade name is Pultrex-1500. The matrix material is isophthalic polyester. The pultruded composite consists of layers of unidirectional roving fibers in the direction of pultrusion sandwiched between layers of continuous strand mats (CSM). The construction of a typical pultruded composite sheet is shown in Figure 2.1. It can be seen from Figure 2.1 that the sheet consists of three types of layers: (1) a thin layer of randomly orientated chopped fiber (Nexus) veil placed on both the top and bottom surfaces. This is a resin-rich layer, primarily used as a protective coating, and its contribution to the laminate response can be neglected; (2) a continuous strand mats (CSM) layer, consisting of randomly oriented continuous fibers which improve the stiffness and strength in their planes; (3) a roving layer. The roving layer consists of unidirectionally aligned continuous fiber bundles that contribute the stiffness and strength in the pultrusion direction. The pultruded composite is available in different thickness and in different shapes. In this investigation, the pultruded composite sheets of 3.2-mm, 6.3-mm and 12.7-mm thickness are chosen. Devara [73] has determined experimentally the make-up of the pultruded composite sheets. The lay-up configuration and percent glass content are shown in Figure 2.2 for 3.2-mm thickness, in Figure 2.3 for 6.3-mm...
thickness and in Figure 2.4 for 12.7-mm thickness. It can be seen from those figures that
the 3.2-mm thick sheet contains three CSM layers and two roving layers through the
thickness. In the 6.3-mm and the 12.7-mm thick sheets, it can be seen that some of the
CSM layers are made up from a combination of fine and coarse CSM layers. The 6.3-
mm thick sheet has two roving layers sandwiched between five CSM layers of which one
is fine and four are coarse. While the 12.7-mm thick sheet has four roving layers
sandwiched between nine CSM layers of which three are fine and six are coarse. The
compositions of the constituent layers of the pultruded composite sheets investigated are
summarized in Table 2.1. It is interesting to note that the 6.3-mm thick sheet has the
highest amount of total glass, while the 3.2-mm thick sheet has the lowest amount of total
glass. However, the roving is found to be highest for the 3.2-mm thick sheet and to be
lowest for 12.7-mm thick sheet. The total CSM is found to highest for 12.7-mm thick
sheet and to be lowest for 3.2-mm thick sheet.
Figure 2.1: Structure of a pultruded composite sheet:
CSM - 13 % of total glass

Roving - 25 %

CSM - 28 %

Roving - 25 %

CSM - 9 %

Figure 2.2: Lay-up for 3.2-mm thick GFRP pultruded composite
Figure 2.3: Lay-up for 6.3-mm thick GFRP pultruded composite
Coarse CSM - 6%
Roving - 10%
Coarse CSM - 7%
Fine CSM - 4%
Roving - 7%
Coarse CSM - 10%
Fine CSM - 9%
Coarse CSM - 10%
Roving - 7%
Fine CSM - 4%
Coarse CSM - 7%
Roving - 12%
Coarse CSM - 7%

Figure 2.4: Lay-up for 12.7-mm thick GFRP pultruded composite
Table 2.1: Compositions of the constituent layers of the pultruded composite of different thicknesses

<table>
<thead>
<tr>
<th>Glass fiber reinforcement</th>
<th>Sheet thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.2-mm</td>
</tr>
<tr>
<td>Total glass in composite, percent</td>
<td>54</td>
</tr>
<tr>
<td>Roving as a percent of total glass</td>
<td>50</td>
</tr>
<tr>
<td>CSM as a percent of total glass</td>
<td>50</td>
</tr>
<tr>
<td>Coarse CSM as a percent of total glass</td>
<td>-</td>
</tr>
<tr>
<td>Fine CSM as a percent of total glass</td>
<td>-</td>
</tr>
</tbody>
</table>

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CHAPTER III

ULTRASONIC MEASUREMENT OF ELASTIC CONSTANTS

3.1 Introduction

Measurement of elastic constants of fiber-reinforced composites is an important part of their mechanical characterization. Many test specimen configurations and test methods have been used for measuring the elastic constants of composite materials. In this investigation, elastic constants of a pultruded composite sheet with a thickness of 6.3-mm were measured. Pultruded composites are mainly unidirectional and hence can be treated as orthotropic composites. Thus, only five independent in-plane elastic constants need to be determined. These are $E_1$, $E_2$, $\nu_{12}$, $\nu_{21}$ and $G_{12}$, where 1- and 2- refer to the longitudinal (along the pultrusion direction) and transverse (perpendicular to the pultrusion direction) material-symmetry axes respectively. In view of Maxwell’s reciprocal relationship involving the two Young’s moduli and the two Poisson’s ratios, the number of fundamental elastic constants can be considered to be four. The effort described in this chapter is focused on the measurement of all the required in-plane elastic constants of the pultruded composites. Three different measurement techniques, namely, static, vibration and ultrasonic are utilized. The main objective of this phase of the study is to utilize ultrasonic technique to measure all the in-plane elastic constants using a single specimen configuration. The static and vibration test methods are chosen to generate the baseline properties for the ultrasonic method.
3.2 Test Specimens and Experimental Procedure

3.2.1 Static Measurements

Tensile specimens, with their axes making different angles with the material symmetry axes and instrumented with electrical resistance strain gages, were used to measure the elastic constants of pultruded composites. The test specimens were 305-mm long, 25-mm wide and were cut from a pultruded sheet of 6.3-mm thickness. Seven specimens, with their axes making 0° to 90° in increments of 15° with the pultrusion direction, were prepared. The specimens were instrumented with strain gages (both longitudinal and transverse directions) and tested in static tension. The load and strain gage data were collected using a WIN5000™ data acquisition system. The test data were then processed, and the Young's modulus and the Poisson's ratio as a function of fiber orientation angle were determined. The shear modulus, $G_{12}$ was determined from measured value of $E_{\theta}$ (i.e., $\theta=45^\circ$) and the transformation equation given below:

$$
\frac{1}{E_{\theta}} = \frac{1}{E_1} \cos^4 \theta + \left( \frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1} \right) \cos^2 \theta \sin^2 \theta + \frac{1}{E_2} \sin^4 \theta \ldots \ldots \ldots (3.1)
$$

where $E_{\theta}$ is the Young's modulus measured in the $\theta$ direction.

Having obtained $E_1$, $E_2$, $\nu_{12}$ and $G_{12}$, the shear modulus ($G_{\theta}$) values for the other angles between 0° and 90° at 15° intervals were calculated based on the transformation equation given below:
\[
\frac{1}{G_o} = 2 \left( \frac{2}{E_1} + \frac{2}{E_2} + \frac{4\nu_{12}}{E_1} - \frac{1}{G_{12}} \right) \cos^2 \theta \sin^2 \theta + \frac{1}{G_{12}} \left( \sin^2 \theta + \cos^2 \theta \right) \cdots \cdots (3.2)
\]

### 3.2.2 Vibration Measurements

Seven bar specimens, similar to those described in the static measurements, were tested as a cantilever beam. The specimens were excited by an impulse force using a soft-tipped instrumented hammer near the clamp, and the strain gage was used to acquire the flexural response due to the impulse excitation. The impulse excitation was chosen to excite the beam at higher modes to study the effect of frequency on Young's modulus as a function of fiber orientation angle. In this experiment, only three modes were excited. The strain gage was connected to a Vishay signal conditioning unit P-3500, and the output of the signal conditioner was fed into a dual channel real-time oscilloscope (Tektronix TDS340) with a built-in FFT (Fast Fourier Transform) module. A schematic diagram of the vibration test setup is shown in Figure 3.1. The experimental time-domain data were averaged and transformed into frequency-domain using FFT. The natural frequencies were recorded and the dynamic Young's modulus was determined using the following relation:

\[
E_o = \frac{4\pi^2 f_n^2 \mu L^4}{I\alpha_n^2} \cdots \cdots (3.3)
\]
where \( \mu \) is the mass per unit length, \( L \) is the length of the beam, \( I \) is the moment of inertia, \( f_n \) is the natural frequency and \( \alpha_n \) are the \( n^{th} \) mode of eigen values of the frequency equation governing the flexural vibration (e.g., for a cantilever beam, \( \alpha_1=3.52 \), \( \alpha_2=22.4 \), \( \alpha_3=61.7 \) etc.). The length-to-thickness ratio of the specimens investigated was 36; therefore, the dynamic modulus calculated from equation (3.3) was corrected by multiplying a correction factor, \( c \). The correction factor proposed by Timoshenko for the isotropic beams was modified for the orthotropic composites as:

\[
c = \left[ 1 - \frac{\alpha_n t^2}{24L^2} \left( 1 + \frac{E_\theta}{0.833G_\theta} \right) \right]_{\ldots\ldots}(3.4)
\]

where \( t \) is the thickness of the specimen and \( G_\theta \) is the shear modulus (obtained from the static measurement).

### 3.2.3 Ultrasonic Measurements

#### 3.2.3.1 Piezoelectric Crystals

Two types of piezoelectric ceramic crystals were used. A PZT-5B Bimorph, manufactured by Morgan Matroc, was used to generate and receive a dilatational wave (P-wave). The PZT-5B crystals are referred as the E-crystals throughout the study and were used to measure the Young's modulus. These crystals have also the capability to produce the shear wave (S-wave), and with proper orientations, they can be used to
measure the shear modulus. A PZT-C1600 soft crystal, manufactured by Aura Ceramics, was used to produce and detect the shear wave. The PZT-C1600 crystals are referred as the G-crystals throughout the study and were used only to measure the shear modulus. Both the crystals were approximately 10-mm square and 0.6-mm thick. A schematic diagram of the E-crystal and the G-crystal, showing the transducer motion and the plane of wave propagation, is shown in Figure 3.2.

3.2.3.2 Calibration of the Crystals

Due to the experimental difficulties encountered with the E-crystals to measure the Young's modulus for the steel and the aluminum specimens, a polycarbonate sheet of thickness approximately 1-mm was glued with a two-part epoxy. This difficulty was due to the fact that the steel and the aluminum specimens are conductive; therefore, and thus the signals were transmitted electrically to the material. This made the receiving signal difficult to analyze. Thus, the calibration of the ultrasonic system is necessary so that any delay time introduced in the measurement by the electronics, ceramic crystals and backing materials can be determined. Calibration is carried out by placing the two similar crystals in direct contact with appropriate coupling agent and measuring the time interval between the initiation of the electrical impulse sent to the transmitter and the initial arrival of the waveform recorded at the receiver using peak-to-peak method. The calibration time ($t_c$) for the E-crystals was found 8.5 $\mu$s and for the G-crystals was found 0.5 $\mu$s. Typical waveforms for the calibration of the E-crystals measurement system are shown in Figure 3.3.
3.2.3.3 Measurements Technique

Direct-transmission measurement technique was used to measure the ultrasonic wave velocities. The crystals were positioned on the opposite faces of the test specimen through a coupling agent. The transmitter crystal was excited with a single-frequency sinusoidal pulse produced by a function generator (Hewlett-Packard HP 8111A). The ultrasonic wave was transmitted through the material and was then detected by the receiver crystal. Petroleum jelly and paraffin wax were used as coupling agents for the E-crystals and the G-crystals respectively. The pulse amplitude of 16.6 V peak-to-peak was used in all measurements due to the limitation of the function generator. The optimum frequency of excitation, which depends on the type of crystal and the size of the specimen, was chosen such that the ratio of specimen length to the wavelength was at least 3 to 4. The reason was to eliminate any near field effect that may cause distortion of the received signal. The range of the resonant frequencies for the E-crystals was 25-65 kHz and for the G-crystals was 45-105 kHz. All ultrasonic measurements were performed at a frequency for which a clear arrival signal was obtained. A schematic arrangement of the ultrasonic test setup is shown in Figure 3.4.

The wave propagation velocity was calculated from the distance between the two crystals and the actual time required by the wave to travel this distance as below:

\[
V_s(\theta)orV_L(\theta) = \frac{L}{t-t_c} \text{.........(3.5)}
\]
where $V_s(\theta)$ and $V_L(\theta)$ are the propagation velocities of the longitudinal waves (P-waves) and shear waves (S-waves) respectively. $L$ is the distance between the two crystals and $(t-t_c)$ is the actual time required by the wave to cover this distance. The propagation velocities of the P- and S-waves are related to the Young's modulus ($E_\theta$) and the shear modulus ($G_\theta$) according to the following equations:

$$E_\theta = V_L^2(\theta)\rho \ldots \ldots \ldots (3.6)$$

$$E_\theta = V_L^2(\theta)\rho(1 - v_\theta v_{\theta+90}) \ldots \ldots \ldots (3.7)$$

$$G_\theta = V_S^2(\theta)\rho \ldots \ldots \ldots (3.8)$$

where $\rho$ is the mass density of the material and $v_\theta$ and $v_{\theta+90}$ is the major and minor Poisson's ratios respectively for the angle specimens. Equation (3.6) can be used only when the specimen dimension can be treated as 1-D. For 2-D specimen, equation (3.8) can be used.

### 3.2.3.4 Validation of the Ultrasonic Measurements

Three bar specimens, 305-mm long, 25-mm wide and 6.4-mm thick, were made from aluminum, steel and polycarbonate to validate the ultrasonic measurements. Young’s modulus and the shear modulus were measured and compared with the reference
values. Table 3.1 shows the measured Young's modulus and shear modulus for all three materials using E- and G-crystals. It can be seen from Table 3.1 that the measured properties are very close to the reference values (differences less than 5%). This indicates that the ultrasonic technique is very accurate for measuring the elastic constants.

3.2.3.5 Pultruded Composite Test Specimens

In the present investigation, seven bar specimens, each 305-mm long and 25-mm wide, with $\theta=0^\circ$ to $90^\circ$ in $15^\circ$ increments with the pultrusion direction, were prepared. Apart from bar specimens, three circular disk specimens of 305-mm, 75-mm and 25-mm diameter were also prepared. Piezoelectric crystals were positioned on the opposite faces of the bar specimens and at the opposite ends of the diametral lines marked at different orientations on the circular disk specimens. The velocity of the P-waves and the S-waves were measured and Young's modulus and shear modulus were determined.

3.2.3.6 Repeatability and Effect of Frequency

The repeatability tests were performed to determine any error introduced during any ultrasonic measurement at a particular frequency. The results of the repeatability tests performed at a frequency of 40 kHz is shown in Table 3.2. It can be seen from Table 3.2 that the measured time of travel is fairly repeatable. The effect of frequency on ultrasonic measurements utilizing both the E- and G-crystals were also studied. The purpose of this study was to determine the best experimental frequency to be used for the ultrasonic measurement such that the P-waves and the S-waves can be received clearly. Table 3.3 shows the effect of frequency on measuring the time of travel using the E-crystals. The
ratio of specimen length to the wavelength at each frequency is also included. It can be seen from Table 3.3 that the measured travel time is fairly constant for a wide range of frequency studied.

3.2.3.7 Typical Recorded Waveforms

The typical P-waveforms of the ultrasonic measurement are shown in Figure 3.5. It can be seen from Figure 3.5 that the received P-waveform is very clear and easily identifiable. Identification of the P-waves was never a problem during the ultrasonic measurements. This is because P-waves are the fastest propagating waves and therefore the first ones to reach the receiver. In contrast to the P-waves, the S-waves' detection requires more care in signal analysis. Care is necessary because the waveform at the receiver is not only composed of the shear waves but also the P-waves. The shear waveform is even more complex for the E-crystals as compared to the G-crystals. Typical shear waveforms using the G-crystals and the E-crystals are shown in Figures 3.6 and 3.7 respectively. It can be seen from both the figures that the received shear waveform consist of P-waves and S-waves. The amplitude of the P-waves was found be very small as compared to the S-waves that in turn made the detection of the S-waves easier.

3.3 Results and Discussions

3.3.1 Measurement of Young’s Modulus

The variation of Young’s modulus as a function of fiber orientation angle measured from the static tension test, the vibration test and the ultrasonic test using bar
specimens is shown in Figure 3.8. In vibration test, the dynamic Young's modulus plotted for three modes show very little variation, showing the efficacy of the correction factor. These values are higher than the static values, especially for the larger angles. Young's moduli measured using ultrasonic technique are greater in magnitude than the values obtained from the static test, for all fiber orientation angles. At larger angles, the ultrasonic measurements agreed well with the results obtained from the vibration tests.

The variation of Young's modulus measured from the ultrasonic tests utilizing the disk specimens of 305-mm, 75-mm and 25-mm diameter is shown in Figure 3.9. For comparison purposes, the bar static results are also plotted. The Young's modulus for all the disk specimens was calculated from the 1-D wave propagation equation (equation 3.4), neglecting the effect of Poisson's ratio. It can be seen from Figure 3.9 that the results for the bar, 75-mm and 305-mm disks are close to each other while the Young's modulus obtained from the 25-mm disk specimen are significantly lower. The static bar results are lower than the piezoelectric results obtained with the 305-mm bar, 75-mm and 305-mm disk specimens, but are significantly higher than the piezoelectric results obtained with the 25-mm disk specimen. This suggests that the 25-mm diameter disk is not a satisfactory specimen for the ultrasonic measurements. In fact, the 25-mm disk specimen is too small to position and align the E- and G-crystals with the line marked diametrically. On the other hand, the difference between the static results for the bar on one hand and the piezoelectric results for the bar and the 75-mm and 305-mm disks can be explained on the basis of the dynamic effects in the ultrasonic tests; the dynamic modulus of the polymeric materials (and polymer based composites) is higher than their
static modulus. Another reason could be due to neglecting the effect of Poisson's ratio in determining the Young's modulus for the disk specimens.

3.3.2 Measurement of Shear Modulus using G-Crystals

In the case of fiber-reinforced composites, the use of G-crystals appears straightforward as long as a sufficiently high voltage signal can be applied at the required resonant frequency of the crystals. In the present investigation, a pulse amplitude of 16.6 V peak-to-peak was used due to the limitation of the function generator. This voltage was found sufficient for the E-crystals. However, the voltage was found insufficient for the G-crystals; therefore, these required an amplifier. The only amplifier available was designed for a gain of 6 at 13.5 kHz. The resonant frequencies of the shear transducers were much higher than 13.5 kHz and there was practically no gain at these frequencies. Consequently, the transmitted shear signals were very small and hard to detect, especially for the 305-mm long specimens due to energy dissipation. Thus, bar specimens of 75-mm long and the disk specimens of 25-mm and 75-mm in diameter were tested with the G-crystals for measuring the shear modulus.

The variation of the shear modulus ($G_\theta$) as a function of fiber orientation angle is shown in Figure 3.10. For comparison purposes, the $G_\theta$ values obtained from the static measurements on strain gaged specimens (applying the transformation equations) are also shown. From this figure, it can be seen that the results for the 25-mm diameter disk are the lowest almost for the entire range of $\theta$, while those for the 75-mm disk are the highest. The results obtained for the 75-mm bars are the closest to the strain gage results. It should be noted that all the curves show the same trend and are in a fairly narrow band.

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3.3.3 Measurement of Shear Modulus using E-Crystals

As mentioned earlier, because of the experimental limitations, a sufficiently large amplitude shear wave signal could not be transmitted from the G-crystals through the composite specimens at the desired resonant frequencies. This drawback resulted in a restriction on the size of the specimen that could be tested; the length of the bar and the diameter of the circular disk specimen were limited to 75-mm. Even for these small size specimens, the amplitude of the transmitted signal was small; this resulted in some error in the measurement of the time of travel of the shear wave.

In order to improve the amplitude of the transmitted shear wave signal and to increase the size of the specimen which could be tested, in the absence of a suitable amplifier, it was decided to use the E-crystal itself to transmit the shear waves in its own plane. It is recognized that a ceramic element that mainly produces shear displacements will also generate small compressive displacement [21]; transducers consisting of transverse-expansion mode E-crystals have been used to generate and detect shear waves [18-20].

In this phase of the study, seven pultruded bar specimens of 305-mm long, with the angle between the bar axis and the pultrusion direction varying from 0° to 90° in increments of 15°, and a 305-mm diameter circular disk specimen were tested. Slots were machined at the opposite ends of the bar specimens parallel to the bar axis, as shown in Figure 3.11(a). On the circular disk specimen, slots were machined at the opposite ends of diameters, which were oriented at angles 0° to 90° in increments of 15° with the pultrusion direction, as shown in Figure 3.11(b). In the slots at opposite ends of the bar or
the disk diameter, E-crystals were positioned with the coupling agent and were excited at one of their resonant frequencies. The shear wave velocity was determined from the S-wave travel time and the shear modulus was calculated. The variation of shear modulus, \(G_0\), as a function of fiber orientation angle is shown in Figure 3.12. For comparison, the static results obtained from the strain gaged bars (using transformation equations) are also shown. It can be seen from Figure 3.12 that the static results are the lowest, while the disk results are the highest for most of the range of \(\theta\). It should be noted that all the results fall in a fairly narrow band, indicating good agreement.

3.3.4 **Measurement of Elastic Constants using Single Circular Specimen**

An attempt was made to measure all the inplane elastic constants from a single specimen, because it is more convenient to use a single specimen to measure all the required elastic constants. Moreover, some composite materials are expensive in terms of material cost as well as specimen preparation. In this study, three independent methods were used to determine all the elastic constants using a 305-mm diameter circular disk specimen.

3.3.4.1 **Wave Propagation Velocity Method**

This method includes measuring the P-wave propagation velocities along the fiber and perpendicular to the fiber directions, \(V_{L1}\) and \(V_{L2}\) respectively, and the S-wave propagation velocities (\(V_s\)) along the 1-2 plane and the 45-degree plane. The expression
for the propagation velocities of longitudinal and shear waves in the principal directions as follows:

\[ V_{L1} = \sqrt{\frac{E_1}{\rho(1 - \nu_{12}\nu_{21})}} \] ........(3.9)

\[ V_{L2} = \sqrt{\frac{E_2}{\rho(1 - \nu_{12}\nu_{21})}} \] ........(3.10)

\[ V_S = \sqrt{\frac{G_{12}}{\rho}} \] ........(3.11)

where \( E_1, E_2 \) are the Young’s moduli in the fiber direction (1-direction) and perpendicular to the fiber direction (2-direction) respectively, \( \nu_{12} \) and \( \nu_{21} \) are the major and minor Poisson’s ratios respectively and \( G_{12} \) is the principal shear modulus. Using equations (3.9) and (3.10) along with Maxwell’s reciprocal relationship, the transformation equation of \( G_{45} \) (i.e., \( G \) at \( \theta = 45^\circ \)) can be expressed in terms of the Poisson’s ratio and the wave propagation velocities as follows:

\[ \nu_{12} = -\left(\frac{V_{S45}}{V_{L2}}\right)^2 + \sqrt{\left(\frac{V_{S45}}{V_{L2}}\right)^4 + \left(\frac{V_{L1}}{V_{L2}}\right)^2 - \left(\frac{V_{S45}}{V_{L2}}\right)^2 \left(\frac{V_{L1}}{V_{L2}}\right)^2 - \left(\frac{V_{S45}}{V_{L2}}\right)^2} \] ........(3.12)

\[ \nu_{21} = -\left(\frac{V_{S45}}{V_{L1}}\right)^2 + \sqrt{\left(\frac{V_{S45}}{V_{L1}}\right)^4 + \left(\frac{V_{L2}}{V_{L1}}\right)^2 - \left(\frac{V_{S45}}{V_{L1}}\right)^2 \left(\frac{V_{L2}}{V_{L1}}\right)^2 - \left(\frac{V_{S45}}{V_{L1}}\right)^2} \] ........(3.13)
Thus, the major and minor Poisson’s ratios can be determined from the propagation velocities of the longitudinal waves in two principal directions and the propagation velocity of the shear waves at an angle of 45-degree making use of equations (3.12) and (3.13). Having determined \( v_{12} \) and \( v_{21} \), Young’s moduli, \((E_1 \text{ and } E_2)\) were calculated from equations (3.9) and (3.10). The shear modulus, \( G_{12} \), was calculated from the expression (3.11). The Young’s modulus and the shear modulus for other fiber orientation angles were determined from the transformation equations for \( E_\theta \) and \( G_\theta \) as given in equations (3.1) and (3.2).

3.3.4.2 P-Wave Propagation Method

This method involves the measuring the P-wave velocities as a function of fiber orientation angle using the E-crystals. The P-wave velocities were measured along various fiber orientation angles using the 305-mm diameter disk specimen from 0° to 90° in 15° increments. Since the P-wave velocities are related to the Young’s modulus and the Poisson’s ratios (equation 3.9), the Young’s modulus was estimated using a 1-D wave equation (equation 3.6). In this method, Young’s modulus values \((E_\theta)\) were estimated for \( \theta \) of 15°, 30°, 45°, 60° and 75°, and used as input to the transformation equation of \( E_\theta \) (equation 3.1) to solve for the unknown parameters. The unknown parameters, such as \( E_1, E_2, v_{12} \) and \( G_{12} \), appear in the transformation equation as a non-linear form. Hence, this equation was linearized and the least-squares criteria were applied to the linearized equation and solved iteratively until convergence obtained. After solving the transformation equation, the unknown parameters were evaluated. With approximate values of the major and the minor Poisson’s ratios, the estimated \( E_\theta \) values were updated.
using a 2-D equation (equation 3.7). Updated values were then used as input to the transformation equation and solved. By repeating this procedure, upon convergence, all the elastic constants were determined. For this purpose, a code was developed using a MATLAB to solve the transformation equation.

3.3.4.3 S-Wave Propagation Method

This method involves of measuring the S-wave velocity as a function of fiber orientation angle using either the E-crystals or the G-crystals. In this method, the S-wave velocities were measured along various fiber orientation angles using a 305-mm diameter slotted disk specimen from 0° to 90° in 15° increments using E-crystals. Since the S-wave velocity is related to the shear modulus and the density of the material, there is no need to estimate the shear modulus. Shear modulus \((G_0)\) as a function of fiber orientation angles was measured only for \(\theta\) of 15°, 30°, 45°, 60° and 75°. The values of \(G_0\) were used as input to the transformation equations of \(G_0\) (equation 3.2) and solved for the unknown parameters, such as \(E_1, E_2, \nu_{12}\) and \(G_{12}\), which appear in the transformation equation as a non-linear form. A similar technique, described in previous section, was used to solve the non-linear transformation equation of \(G_0\) to evaluate all the in-plane elastic constants. Upon determination of \(E_1, E_2, \nu_{12}\) and \(G_{12}\), the transformation equation of \(E_0\) was used to determine Young’s modulus for other fiber orientation angles.

3.3.4.4 Results and Discussions

The predicted in-plane elastic constants are tabulated in Table 3.4 for all three methods discussed using a 305-mm diameter disk specimen. For comparison purposes,
the static values are also tabulated in Table 3.4. It can be seen from Table 3.4 that the predicted values of $E_{1,v_{12}}$ and $G_{12}$ are very close to the static values. However, the transverse modulus, $E_2$, was over predicted by all three methods.

The variation of Young's modulus ($E_0$) as function of fiber orientation angle is shown in Figure 3.13. For comparison purposes, the static values are also included. It can be seen from Figure 3.13 that Young's modulus was predicted better using the P-wave method as compared to the other methods for the lower fiber orientation angles. For the higher angles, all three methods predicted values that are very close to each other. These values are higher than the static values. Overall, the ultrasonic Young's modulus is found to be higher than the static values.

The variation of the shear modulus ($G_0$) as a function of fiber orientation angle is shown in Figure 3.14. For the comparison purposes, both the static and the piezo bar results were included. It can be seen from Figure 3.14 that the predicted values of $G_0$ for all three methods are higher than the static and the piezo bar measurements. In general, all the results fall in fairly narrow band, indicating good agreement.
Figure 3.1: Schematic diagram of vibration test setup
Figure 3.2: Schematic of E-crystal and G-crystal showing the plane of wave propagation
Figure 3.3: Typical waveforms for the calibration of E-crystal measurement system
Figure 3.4: Schematic arrangement of ultrasonic test setup
Table 3.1: Ultrasonic test results for Steel, Aluminum and Polycarbonate specimens*

<table>
<thead>
<tr>
<th>Test Material</th>
<th>Young's Modulus (GPa)</th>
<th>Shear Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>205.9 (0.4%)</td>
<td>79.7 (0.25%)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>65.5 (5%)</td>
<td>26.0 (0.9%)</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>2.7 (2.5%)</td>
<td>1.1 (5%)</td>
</tr>
</tbody>
</table>

* Parenthesis indicates percent error from reference values

Table 3.2: Repeatability of the ultrasonic measurements

<table>
<thead>
<tr>
<th>Measured Frequency (kHz)</th>
<th>Measurements</th>
<th>Time of Travel (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
<td>168.5</td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>166.5</td>
</tr>
<tr>
<td></td>
<td>3rd</td>
<td>167.5</td>
</tr>
<tr>
<td></td>
<td>4th</td>
<td>167.5</td>
</tr>
</tbody>
</table>

Table 3.3: Effect of frequency on ultrasonic measurements

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Ratio of Specimen Length to Wavelength (L/λ)</th>
<th>Time of Travel (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>4.0</td>
<td>167.5</td>
</tr>
<tr>
<td>40.0</td>
<td>6.4</td>
<td>167.5</td>
</tr>
<tr>
<td>55.5</td>
<td>8.8</td>
<td>167.5</td>
</tr>
<tr>
<td>62.0</td>
<td>10.0</td>
<td>166.5</td>
</tr>
</tbody>
</table>
Figure 3.5: Typical P-waveform for $0^\circ$ bar specimen
Figure 3.6: Typical S-waveform for 0° bar specimen using G-crystal
Figure 3.7: Typical S-waveform with slotted bar specimen using E-crystal
Figure 3.8: Variation of Young’s modulus ($E_\theta$) of bar specimens as a fiber orientation angle
Figure 3.9: Variation of Young's modulus (E<sub>f</sub>) of circular disk specimens as a fiber orientation angle
Figure 3.10: Variation of shear modulus ($G_0$) as a fiber orientation angle ($G_0$ measured using G-crystals)
Figure 3.11: Schematic diagrams of slotted bar and disk specimen
Figure 3.12: Variation of shear modulus ($G_\theta$) as a function of fiber orientation angle ($G_\theta$ measured using E-crystals)
Table 3.4: Comparison of measured in-plane elastic constants using a single circular specimen

<table>
<thead>
<tr>
<th>Properties</th>
<th>Static Method</th>
<th>Ultrasonic Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-Wave Propagation</td>
<td>S-Wave Propagation</td>
</tr>
<tr>
<td>$E_1$ (GPa)</td>
<td>19.1</td>
<td>19.2</td>
</tr>
<tr>
<td>$E_2$ (GPa)</td>
<td>10.7</td>
<td>12.1</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.31</td>
<td>0.377</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>4.6</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Figure 3.13: Variation of Young’s modulus ($E_0$) as a function of fiber orientation angle using 305-mm diameter circular disk specimen
Figure 3.14: Variation of shear modulus ($G_0$) as a function of fiber orientation angle using 305-mm diameter circular disk specimen
CHAPTER IV

STRESS GRADIENT EFFECTS ON STRENGTH

4.1 Introduction

Tensile strength data from flexure tests usually yields higher strength than observed from standard tensile coupon. Accordingly, different tensile strength data may be observed from tensile specimens of different sizes. According to statistical-strength theory based on a Weibull distribution, the presence of a stress gradient in the flexure specimen results in an apparent increase in tensile strength. Also, the presence of a size effect in tensile coupon results in different tensile strength. In this phase of the study, both the stress gradient effects and the size effects on the strength of pultruded composite sheets of 3.2-mm and 12.7-mm thicknesses were studied. A large number of specimens were tested in tension, 3-point flexure and 4-point flexure. The specimens were tested along the pultrusion direction (refers to 0-degree) and transverse to the pultrusion direction (refers to 90-degree). The strength data was analyzed statistically using a 2-parameter Weibull distribution and a normal distribution. The ratio of tensile strength-to-flexure strength and the strength ratios of two tensile specimens were predicted from the Weibull model and were compared with the experimental results. The test results include the stress vs. strain behavior, statistical data analysis, parameter extraction technique, Weibull prediction, failure analysis and microstructural examination.
4.2 Experimental Program

4.2.1 Specimens with 3.2-mm Thickness

Two sets of tensile specimens with the dimensions of 178-mm length and 12.7-mm width, and 305-mm length and 38-mm width were fabricated. The flexure specimens were 76-mm between the support span, except for the 0-degree specimens tested under 3-point loading. The 0-degree specimens did not fracture with the span length of 76-mm under 3-point loading while showing large amount of deflection. Thus, the span length of 51-mm was chosen for those specimens. The width of all flexure specimens was chosen to be 12.7-mm. The specimens were loaded at the midpoint of the support span for the 3-point flexure tests, while the load was applied at one-third point of the span length for the 4-point flexure tests. Two specimens were instrumented with the strain gages. One strain gage was placed on the tensile side of the flexure specimen for the 3-point flexure, and one strain gage was placed both on the tensile and the compression side of the specimen for the 4-point flexure. All of the strain gages were located at the center of the test specimen, and the strain gages' axis were orientated parallel to the length direction. The central deflection during the flexure tests was measured using a dial gage. The schematic diagram of the specimen dimensions and the loading for the 3.2-mm thickness is shown in Figure 4.1.
4.2.2 Specimens with 12.7-mm Thickness

Two sets of tensile specimens with the dimensions of 254-mm length and 12.7-mm width and 305-mm length and 38-mm width were prepared. All the flexure specimens were 152-mm between the support span and were 12.7-mm wide. The specimens were loaded at the midpoint of the support span for the 3-point flexure. In 4-point loading, two different loading spans were used. For the 0-degree specimen, a loading span of 38-mm was used and was located at a distance of 57-mm from the support. For the 90-degree specimen, a loading span of 76-mm was used and was located 38-mm from the support. The reason for using a shorter loading span is that the 0-degree specimen failed due to interlaminar shear with a 76-mm loading span. Two specimens were instrumented with the strain gages. One strain gage was placed on the tensile side of the flexure specimen for the 3-point flexure, and one strain gage was placed both on the tensile and the compression side of the specimen for the 4-point flexure. All the strain gages were located at the center of the specimen and the strain gages’ axis were oriented parallel to the length direction. The central deflection during the flexure tests was measured using a dial gage. The schematic diagram of the specimen dimensions and the loading for the 12.7-mm thickness is shown in Figure 4.2.

4.3 Weibull Statistical-Strength Model

According to the Weibull statistical-strength theory for brittle materials [32], the probability of survival, \( P \), at a maximum stress level \( S \) for a uniaxial-stress field in a homogeneous material governed by a volumetric flaw distribution is shown as:
\[ P(S_f \geq S) = R(S) = \exp[-B(S)] \]........(4.1)

where \( S_f \) is the value of the maximum stress at failure, \( R \) is the reliability, and \( B \) is the risk of rupture. A non-uniform stress field, \( \sigma \), can be written in terms of the maximum stress in the following manner

\[ \sigma(x, y, z) = S_f(x, y, z) \]........(4.2)

For a two-parameter Weibull model, the risk of rupture is represented as:

\[ B(S) = A \left( \frac{S}{S_o} \right)^m (S_o, m > 0) \]........(4.3)

where

\[ A = \int_V \left[ f(x, y, z) \right]^m dV \]........(4.4)

and \( S_o \) is the scale parameter, sometimes referred to as the characteristic strength, and \( m \) is the shape parameter which characterize the flaw distribution in the material. Both of these parameters are considered to be material properties independent of size. Thus, the
risk to break will be a function of the stress distribution in the test specimen. Equation (4.3) can also be written as:

\[ B(S) = \left( \frac{S}{S_A} \right)^m \] .......(4.5)

where

\[ S_A = S_o \frac{1}{A^n} \] .......(4.6)

and the reliability function, equation (4.1), can be written as a two-parameter Weibull distribution:

\[ R(S) = \exp \left[ -\left( \frac{S}{S_o} \right)^m \right] \] .......(4.7)

Thus, tensile tests from specimen containing different stress fields can be represented by a two-parameter Weibull distribution with the same shape parameter, but with a scale parameter, which will shift according to equation (4.6).

For the case of a simple tension under uniform stress, equation (4.6) takes the form
\begin{eqnarray}
S_A = S_t = S_0 (V_t)^{-1/m} \quad \text{(4.8)}
\end{eqnarray}

where the subscript \( t \) denotes simple tension and \( V \) is the specimen volume. Thus, the scale parameter for uniform tension is a function of specimen volume.

For flexural loading, the integration of equation (4.4) can be performed in closed form and results in the following relationships between the scale parameters for tension and flexure:

\begin{eqnarray}
\frac{S_b}{S_t} &=& \left[ \frac{2(m+1)^2}{(m+2)} \left( \frac{V_t}{V_b} \right)^{1/m} \right] (3 - \text{point}) \quad \text{.........(4.9)}
\end{eqnarray}

\begin{eqnarray}
\frac{S_b}{S_t} &=& \left[ \frac{4(m+1)^2}{(m+2)} \left( \frac{V_t}{V_b} \right)^{1/m} \right] (4 - \text{point}) \quad \text{.........(4.10)}
\end{eqnarray}

where subscript \( b \) denotes bending. Comparing equations (4.8), (4.9) and (4.10), it is clear that for equal volume of a given material, strength should always be greater in 3-point flexure than 4-point flexure, and greater in 4-point flexure than in tension. This is due the fact that 3-point loading produces maximum stress at the outer surface in the center of the beam, while 4-point loading produces the maximum stress at the outer surface throughout the center section. In particular, the smaller the volume under the maximum stress the higher the local strength. It should be noted that equations (4.9) and (4.10) are based on the assumption that failure in the flexure test is a direct function of normal stress on the tensile side of the beam. The effect of interlaminar stresses is neglected.
The effects of specimen volume in tensile strength are also investigated. For pure tension, equation (4.8) becomes

\[ S_i = S_o (Lht) \frac{1}{m} \] ........(4.11)

where \( L, h \) and \( t \) are the gauge length, width and thickness of the tensile coupon, respectively. For specimens of different gage length and width, equation (4.11) yields

\[ \frac{S_{i_2}}{S_{i_1}} = \left( \frac{L_2 h_2}{L_1 h_1} \right)^{1/m}, L_2, h_2 > L_1, h_1 \] ........(4.12)

Thus, the specimens with a higher gauge length and width will have a lower characteristic strength compared to the specimens with smaller gauge length and width.

4.4 Determination of the Weibull Parameters

The Weibull parameters such as \( S_o \) and \( m \) (equation 4.7) were determined using the strength values of \( n \) specimens determined in a specific test. The least-square fitting in a linearized form of distribution was used to determine the Weibull parameters. Taking the natural logarithm twice, the equation (4.7) can be written as:
\[ \ln\left[ \ln\left( \frac{1}{R_s} \right) \right] = m \ln S - m \ln S_0 \quad \text{(4.13)} \]

The Weibull parameters can then be determined by fitting a straight line to \( \ln\ln(1/R_s) \) as a function of \( \ln S \). The parameter \( m \) is simply the slope and \( S_0 \) is related to the intercept on the \( \ln\ln(1/R_s) \) axis at \( \ln S = 0 \) by

\[ S_0 = \left[ \exp(-\text{intercept}) \right]^{1/m} \quad \text{(4.14)} \]

In this study, the parameters were determined using a commercial software WeibullSMITH™. The survival probability was assumed to correspond to a median ranking of the data

\[ R_s = 1 - \frac{i - 0.5}{n} \quad \text{(4.15)} \]

where \( n \) is the total number of data points in the sample and \( i \) is the number of the data point in ascending order from 1 to \( n \).
4.5 Results and Discussions

4.5.1 Specimen Behavior

The tensile stress vs. strain responses obtained for the 3.2-mm thick specimens are shown in Figure 4.3 for the 0-degree, and in Figure 4.4 for the 90-degree. The effect of specimen volume on the stress vs. strain response is also shown. It can be seen from Figure 4.3 that the response is fairly linear up to failure for both the tensile specimens. The failure stress and strain is found to be higher for the 12.7-mm wide specimen as compared to the 38-mm wide specimen. It can be seen from Figure 4.4 that the response is quite non-linear up to failure load for both the tensile specimens. The failure stress is found to be very close in both cases; however, the failure strain for the 38-mm wide specimen is found to be smaller than the failure strain of the 12.7-mm wide specimen.

The tensile stress vs. strain responses obtained for the 12.7-mm thick specimens are shown in Figure 4.5 for the 0-degree and in Figure 4.6 for the 90-degree. The effect of specimen volume on tensile response is also included in both figures. It can be seen from Figure 4.5 that the response is fairly linear up to failure for the 0-degree; however, the response is quite non-linear for the 90-degree. The 38-mm wide, 0-degree specimen shows higher failure stress and strain as compared to the 12.7-mm wide specimen, while the 12.7-mm wide, 90-degree specimen shows higher failure strain as compared to the 38-mm wide specimen. The failure stress is found to be very close in both the 90-degree specimens.
The stress vs. strain responses obtained in tension, 3-point and 4-point flexure for the 3.2-mm thick specimens are shown in Figure 4.7 for the 0-degree, and in Figure 4.8 for the 90-degree. It should be noted that the strain gages failed well below the failure load in the cases of 3-point and 4-point flexure, while the strain gages failed at the failure load in the case of tension. It can be seen that the stress vs. strain responses are fairly linear for the 0-degree specimens, and are quite non-linear for the 90-degree specimens. The stress vs. strain responses for the 12.7-mm thick specimens exhibited in the three tests are shown in Figure 4.9 for the 0-degree, and in Figure 4.10 for the 90-degree. The strain gages failed before the specimens failed in the case of all flexure tests. It can be seen from Figure 4.9 that the response is practically identical for all three tests for the 0-degree specimens and is fairly linear up to failure. From Figure 4.10, it can be seen that the response is not identical for the 90-degree specimens and the stress vs. strain behavior is quite non-linear. It can be mentioned that failure stress is the lowest in tension and the highest in 3-point flexure.

The stress vs. strain responses of the tensile and compression sides of the 3.2-mm thick specimen loaded in 4-point flexure are shown in Figure 4.11 for the 0-degree specimen and in Figure 4.12 for the 90-degree specimen. It can be seen from those figures that the strain gage located on the tensile side of the specimen was subjected to higher strain as compared to the compression side. This indicates that the specimens failed due to tension. It is also evident that there is a good agreement between stress and strain for both the tension and the compression sides of the flexure specimen. The strain gage located on the compression side of the 0-degree specimen failed well below the failure stress. It is believed that the strain gage may be damaged due to excessive bending.
during flexure loading. The stress vs. strain responses for the 90-degree specimen are very close to each other up to 75 MPa, as illustrated in Figure 4.12. The stress vs. strain responses of the two back-to-back strain gages mounted on the tension and compression sides of the 12.7-mm thick specimen loaded in 4-point flexure are shown in Figure 4.13 for the 0-degree, and in Figure 4.14 for the 90-degree. It can be seen that the two strain gages readings are very close to each other for the 0-degree specimen as compared to the 90-degree specimen. The higher strain value on the tensile side indicates that the specimen failed due to tension.

The load vs. central deflection behavior of the 3.2-mm thick specimen subjected to 3-point and 4-point loading is shown in Figure 4.15 for the 0-degree and in Figure 4.16 for the 90-degree. It can be seen from Figure 4.15 that the behavior is fairly linear up to failure. It can be noted that the 0-degree specimen tested under 3-point loading had a support span of 51-mm, whereas the length of the support span for the 4-point loading was 76-mm. This is the reason for such deviation between the two curves. The load vs. deflection behavior is quite non-linear for the 90-degree specimen as seen in Figure 4.16. The deflection is found to be higher for the 4-point loading as compared to 3-point loading for both the orientations. The load vs. deflection curves generated for the 3-point and the 4-point loading are very close to each other and are fairly linear up to failure for the 0-degree specimen, 12.7-mm thickness as seen from Figure 4.17. However, the load vs. deflection behavior of the 90-degree specimen, 12.7-mm thickness is non-linear, as seen from Figure 4.18. The deflection is always found to be higher for the 4-point loading as compared to the 3-point loading.
4.5.2 Statistical Data Analysis

The probability of survival as a function of the stress for the 3.2-mm thick specimen is shown in Figure 4.19 for the 0-degree and in Figure 4.20 for the 90-degree. The strength data for tensile tests, 3-point and 4-point flexure tests are included in each figure. As illustrated in those figures, the test data agreed well with the 2-parameter Weibull distribution. It is also evident that the curve for the 3-point flexure loading is at extreme right, as expected, indicating highest strength and the curve for the tensile loading is at extreme left indicating the lowest strength. The curve for 4-point flexure loading is in the middle. Among the tensile tests, the curve for the 38-mm wide specimen is toward the left of the 12.7-mm wide curve for the 0-degree, as expected. However, the two tensile curves are very close to each other for the 90-degree, showing no size effect. The separation between the 4-point flexure curve to the tensile curve is greater for the 90-degree specimen as compared to the 0-degree specimen.

The probability of survival as a function of stress for the 12.7-mm thick specimen is shown in Figure 4.21 for the 0-degree and in Figure 4.22 for the 90-degree. Strength data for the tensile tests, 3-point, and 4-point flexure tests are also included in each figure. In general, the test data agreed well with the 2-parameter Weibull distribution. It can be seen that the curve for the 38-mm wide tensile specimen is toward the right of the 12.7-mm wide tensile specimen for the 0-degree. The tensile curves for both specimens are very close to each other for the 90-degree specimens. This is not expected according to the Weibull strength model. However, the curve for the 3-point flexure loading is at the right and the curve for the axial tension loading is at the left, while the curve for the
4-point flexure loading is in the middle, as expected. The 4-point flexure curve is close to the 3-point flexure curve for the 90-degree specimen as compared to the 0-degree specimen.

The Weibull shape parameter and scale parameter experimentally determined for the tension, 3-point, and 4-point flexure are presented in Table 4.1 for the 3.2-mm thick specimen and in Table 4.2 for the 12.7-mm thick specimen. The test results for the 0-degree and the 90-degree fiber orientations are also included in each table. Both tables include the mean strength and standard deviation calculated from the Weibull distribution, as well as the normal distribution for comparison. It can be seen from Table 4.1 that the \( m \) values fall in a narrow range of 14 to 23 for the 3.2-mm thickness. The tensile strength is found to be higher for the 12.7-mm wide specimen as compared to the 38-mm wide specimen for the 0-degree, demonstrating size effect. However, the strength values are very close to each other for the 90-degree specimen, showing no size effect. It can also be seen that the 3-point flexure strength is the highest and the tensile strength is the lowest, which indicates that the material shows stress gradient effect. The mean strength found from the Weibull distribution is found to be very close to the normal distribution. For the 12.7-mm thick specimen, it can be seen from Table 4.2 that \( m \) values fall within a wide range of 16-65 for the 0-degree specimens and 20-51 for the 90-degree specimen. The \( m \) values tends to be larger for the smaller scatter, especially under direct tensile loading; this is probably due to the combination of the roving fibers placed in a perpendicular arrangement to the tensile load and the thicker sheet containing appreciable porosity. Interestingly, Bullock [24] reported the same \( m \) value for the three types of loading, while Whitney [25] reported different values. The 38-mm width specimens show.
higher tensile strength along the 0-degree and show very similar tensile strength along the 90-degree. This observation is not compatible with the Weibull strength model. This could be due to the presence of non-uniform void in the material, as will be discussed later. The 3-point flexure strength is the highest and the tensile strength is the lowest, which indicate that 12.7-mm thick materials also show stress gradient effect. The mean strength and the standard deviation found from Weibull distribution are very similar to the normal distribution for the 12.7-mm thick material.

4.5.3 Weibull Strength Prediction

The measured and the Weibull predicted ratios of flexure strength to tensile strength, and tensile strength ratios of the specimens having different volumes are shown in Table 4.3. It can be mentioned that the tensile 12.7-mm width specimen was chosen here as a basis for comparison. The table includes the results for both the thicknesses orientated at 0-degrees and at 90-degrees. It can be seen from the Table 4.3 that the measured and the Weibull predicted ratios do not show consistent agreement. The strength ratios are very close in some cases but quite different in others, and there appears to be no clear trend. A few attempts are made to calculate the strength ratios based on the bending specimen volume, namely, total volume, total tensile volume, local volume (thin layer) and local volume (tensile side). The results are presented in Table 4.4 for the 3-point flexure and in Table 4.5 for the 4-point flexure. It can be seen from both the tables that no such improvement in the trend could be seen.
4.5.4 Failure Analysis

The photographs of the typical failure specimens of 3.2-mm thickness loaded in tension, 3-point and 4-point flexure are shown in Figure 4.23. Those photographs illustrate that failure is limited to the gage section in tension and to the tensile side of the flexure specimens subjected to maximum tensile stress. The 0-degree tensile specimens failed initially by longitudinal splitting between the internal layers, and the 90-degree tensile specimens failed due to matrix tensile failure. In general, failure was progressive in the case of flexure loading and was catastrophic in the case of tension loading. The flexure specimens failed at the tensile side in the region of maximum tensile stress. The failure surface extends across the thickness at an angle especially in the case of 4-point flexure. The failure region is found to be the greatest in the case of tension and the least in the case of 3-point flexure.

The photographs of the typical failure of the 12.7-mm thick specimens loaded in tension, 3-point, and 4-point are shown in Figure 4.24. It can be seen from Figure 4.24 that the 0-degree specimens failed in tension due to longitudinal splitting between the internal layers. In flexure, the outer layer located on the tensile side failed first. The failure extends across the thickness in the form of delamination and fiber breakage as the load continues to increase. The failure surface is found to be more expensive in the case of 4-point loading as compared to 3-point loading. The failure surface of the 90-degree specimens forms an angle of 45-degree across the thickness in tension. The failure initiates on the tensile surface of the flexure specimen exhibiting maximum tensile stress.
The failure surface is very localized in the case of 3-point flexure, and extends across the thickness at an angle in the case of 4-point flexure.

Typical tensile failures of two different width specimens of 3.2-mm thickness are shown in Figure 4.25. Both the 0-degree and the 90-degree failed specimens are shown. The failure mode is found to be very similar for both the tensile specimens, with the exception of some special features. The failure surface extends at an angle across the width for the 0-degree, wider specimen. It is believed that the presence of more CSM layers in the wider specimen is responsible for such failure mechanism and hence exhibits lower failure strength. The failure mechanism exhibited by the tensile specimens of two different widths oriented at 90-degrees are very similar; therefore, the two exhibit similar failure strength. However, the failure mechanism of the wider specimens of 12.7-mm thickness is found to be different. As seen in Figure 4.26, there are three distinct failure modes for both the 0-degree and 90-degree specimens with 38-mm width. In tension, the outer layers of the 0-degree specimens failed first for all the tensile specimens. However, the failure of the bulk portion of the specimen is found to be different. The 90-degree specimens also show three distinct failure modes. Some specimens failed due to matrix tensile failure, some specimens failed due to a combination of tensile and shear, and some specimens failed due to shear. Such failure modes were not observed for the 12.7-mm wide tensile specimens. It is believed that the inherent defects in the 12.7-mm thick composite are responsible for such different failure mechanism in tension. To describe the defects in composites, the photographs of the surface of the 3.2-mm and 12.7-mm thick pultruded composites along the pultrusion direction are shown in Figure 4.27. It can be seen from the Figure 4.27 that while the 3.2-
mm thick specimen does not show any visible defect, the defects are quite visible for the 12.7-mm thick specimen. It can also be seen that the defects are non-uniform across the thickness for the 12.7-mm thick pultruded composites. In some areas the defects are so close that they resemble a crack. Such non-uniform defects are assumed to be responsible for such different failure modes for the wider specimens for the 12.7-mm thickness. In order to investigate the flaw distribution microscopically, the 12.7-mm thick specimens were cut along the longitudinal and transverse direction examined under the scanning electron microscope. The photomicrographs of the longitudinal section and the transverse section are shown in Figure 4.28 and 4.29 respectively. Photomicrographs were taken at two different magnifications to investigate the flaw distribution. It can be seen from both the figures that the defects vary in shape and size. Some defects are circular in shape, while some are in the form of a crack. The defects are not uniformly distributed across the thickness, which appears to be a basic requirement for the Weibull distribution.
Figure 4.1: Geometry of the test specimens (3.2-mm thick)
Figure 4.2: Geometry of the test specimens (12.7-mm thick)
Figure 4.3: Tensile stress vs. strain response for the 3.2-mm thick specimen (0-degree)
Figure 4.4: Tensile stress vs. strain response for the 3.2-mm thick specimen (90-degree)
Figure 4.5: Tensile stress vs. strain response for the 12.7-mm thick specimen (0-degree)

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Figure 4.6: Tensile stress vs. strain response for the 12.7-mm thick specimen (90-degree)
Figure 4.7: Stress vs. strain response for the 3.2-mm thick specimen (0-degree)
Figure 4.8: Stress vs. strain response for the 3.2-mm thick specimen (90-degree)
Figure 4.9: Stress vs. strain response for the 12.7-mm thick specimen (0-degree)
Figure 4.10: Stress vs. strain response for the 12.7-mm thick specimen (90-degree)
Figure 4.11: Stress vs. strain response for the 3.2-mm thick specimen in 4-point loading (0-degree)
Figure 4.12: Stress vs. strain response for the 3.2-mm thick specimen in 4-point loading (90-degree)
Figure 4.13: Stress vs. strain response for the 12.7-mm thick specimen in 4-point loading (0-degree)
Figure 4.14: Stress vs. strain response for the 12.7-mm thick specimen in 4-point loading (90-degree)
Figure 4.15: Load vs. central deflection behavior for the 3.2-mm thick specimen under 3-point and 4-point flexure (0-degree)
Figure 4.16: Load vs. central deflection behavior for the 3.2-mm thick specimen under 3-point and 4-point flexure (90-degree)
Figure 4.17: Load vs. central deflection behavior for the 12.7-mm thick specimen under 3-point and 4-point flexure (0-degree)
Figure 4.18: Load vs. central deflection behavior for the 12.7-mm thick specimen under 3-point and 4-point flexure (90-degree)
Figure 4.19: Probability of survival as a function of stress for the 3.2-mm thick specimen (0-degree)
Figure 4.20: Probability of survival as a function of stress for the 3.2-mm thick specimen (90-degree)
Figure 4.21: Probability of survival as a function of stress for the 12.7-mm thick specimen (0-degree)
Figure 4.22: Probability of survival as a function of stress for the 12.7-mm thick specimen (90-degree)
Table 4.1: Summary of the test results for the 3.2-mm thick specimens

<table>
<thead>
<tr>
<th>Fiber orientation</th>
<th>Type of Test</th>
<th>No. of Specimens</th>
<th>Weibull parameters</th>
<th>Mean strength, MPa</th>
<th>Standard deviation, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Scale parameter, $S_0$ (MPa)</td>
<td>Shape parameter, $m$</td>
<td>Weibull distribution</td>
</tr>
<tr>
<td>0-degree</td>
<td>Tension (12.7-mm wide)</td>
<td>20</td>
<td>379.6</td>
<td>15.5</td>
<td>366.9</td>
</tr>
<tr>
<td></td>
<td>Tension (38-mm wide)</td>
<td>20</td>
<td>360.1</td>
<td>21.1</td>
<td>351.1</td>
</tr>
<tr>
<td></td>
<td>3-point flexure</td>
<td>20</td>
<td>489.3</td>
<td>15.4</td>
<td>472.8</td>
</tr>
<tr>
<td></td>
<td>4-point flexure</td>
<td>20</td>
<td>429.5</td>
<td>15.3</td>
<td>415.1</td>
</tr>
<tr>
<td>90-degree</td>
<td>Tension (12.7-mm wide)</td>
<td>20</td>
<td>104.0</td>
<td>18.8</td>
<td>101.1</td>
</tr>
<tr>
<td></td>
<td>Tension (38-mm wide)</td>
<td>20</td>
<td>105.3</td>
<td>23.3</td>
<td>102.9</td>
</tr>
<tr>
<td></td>
<td>3-point flexure</td>
<td>20</td>
<td>171.8</td>
<td>15.3</td>
<td>166.0</td>
</tr>
<tr>
<td></td>
<td>4-point flexure</td>
<td>20</td>
<td>159.3</td>
<td>14.0</td>
<td>153.6</td>
</tr>
</tbody>
</table>
Table 4.2: Summary of the test results for the 12.7-mm thick specimens

<table>
<thead>
<tr>
<th>Fiber orientation</th>
<th>Type of Test</th>
<th>No. of Specimens</th>
<th>Weibull parameters</th>
<th>Mean strength, MPa</th>
<th>Standard deviation, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Scale parameter, $S_0$ (MPa)</td>
<td>Shape parameter, $m$</td>
<td>Weibull distribution</td>
</tr>
<tr>
<td>0-degree</td>
<td>Tension (12.7-mm wide)</td>
<td>20</td>
<td>230.1</td>
<td>18.0</td>
<td>223.4</td>
</tr>
<tr>
<td></td>
<td>Tension (38-mm wide)</td>
<td>20</td>
<td>235.5</td>
<td>65.2</td>
<td>233.4</td>
</tr>
<tr>
<td></td>
<td>3-point flexure</td>
<td>20</td>
<td>334.0</td>
<td>17.1</td>
<td>323.8</td>
</tr>
<tr>
<td></td>
<td>4-point flexure</td>
<td>20</td>
<td>299.2</td>
<td>16.6</td>
<td>289.9</td>
</tr>
<tr>
<td>90-degree</td>
<td>Tension (12.7-mm wide)</td>
<td>20</td>
<td>85.7</td>
<td>50.8</td>
<td>84.7</td>
</tr>
<tr>
<td></td>
<td>Tension (38-mm wide)</td>
<td>20</td>
<td>86.6</td>
<td>36.5</td>
<td>85.3</td>
</tr>
<tr>
<td></td>
<td>3-point flexure</td>
<td>20</td>
<td>140.3</td>
<td>20.8</td>
<td>136.7</td>
</tr>
<tr>
<td></td>
<td>4-point flexure</td>
<td>20</td>
<td>132.9</td>
<td>26.7</td>
<td>130.2</td>
</tr>
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</table>
Table 4.3: Measured and Weibull-predicted ratios of flexure strength to tensile strength and the ratios of tensile strengths

<table>
<thead>
<tr>
<th>Fiber orientation</th>
<th>Specimen thickness (mm)</th>
<th>3-point flexure to tensile</th>
<th>4-point flexure to tensile</th>
<th>Tensile strength ratio of 12.7-mm to 38-mm wide specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured</td>
<td>Weibull</td>
<td>Measured</td>
</tr>
<tr>
<td>0-degree</td>
<td>3.2</td>
<td>1.29</td>
<td>1.53</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m=15.4</td>
<td>m=15.3</td>
<td>m=15.5</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>1.45</td>
<td>1.46</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m=17.1</td>
<td>m=16.6</td>
<td>m=18.0</td>
</tr>
<tr>
<td>90-degree</td>
<td>3.2</td>
<td>1.64</td>
<td>1.51</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m=15.3</td>
<td>m=14.0</td>
<td>m=18.8</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>1.61</td>
<td>1.39</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m=20.8</td>
<td>m=26.7</td>
<td>m=50.8</td>
</tr>
</tbody>
</table>
Table 4.4: Effect of specimen volume on Weibull Prediction from the 3-point flexure data

<table>
<thead>
<tr>
<th>Fiber Orientation</th>
<th>Specimen Thickness (mm)</th>
<th>$\left(\sigma_{3pt}/\sigma_{t}\right)_{measured}$</th>
<th>$\left(\sigma_{3pt}/\sigma_{t}\right)_{prediction}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total volume</td>
<td>Total volume (tension side)</td>
</tr>
<tr>
<td>0-degree</td>
<td>3.2</td>
<td>1.29</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>1.45</td>
<td>1.46</td>
</tr>
<tr>
<td>90-degree</td>
<td>3.2</td>
<td>1.64</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>1.61</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Table 4.5: Effect of specimen volume on Weibull prediction from the 4-point flexure data

<table>
<thead>
<tr>
<th>Fiber Orientation</th>
<th>Specimen Thickness (mm)</th>
<th>$\left(\sigma_{4pt}/\sigma_{t}\right)_{measured}$</th>
<th>$\left(\sigma_{4pt}/\sigma_{t}\right)_{prediction}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total volume</td>
<td>Total volume (tension side)</td>
</tr>
<tr>
<td>0-degree</td>
<td>3.2</td>
<td>1.13</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>1.30</td>
<td>1.34</td>
</tr>
<tr>
<td>90-degree</td>
<td>3.2</td>
<td>1.52</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>1.54</td>
<td>1.19</td>
</tr>
</tbody>
</table>
Figure 4.23: Typical failures of 3.2-mm thick specimens loaded in tension, 3-point and 4-point flexure (a) 0-degree and (b) 90-degree

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Figure 4.24: Typical failures of 12.7-mm thick specimens loaded in tension, 3-point and 4-point flexure (a) 0-degree and (b) 90-degree
Figure 4.25: Typical failures of different width of 3.2-mm thick specimens loaded in tension (a) 0-degree and (b) 90-degree.
Figure 4.26: Typical failures of 38-mm width of 12.7-mm thick specimens loaded in tension (a) 0-degree and (b) 90-degree
(a) 3.2-mm thick

(b) 12.7-mm thick

Figure 4.27: Photographs of the surface of the pultruded sheets along the pultrusion direction (a) 3.2-mm thick and (b) 12.7-mm thick
Figure 4.28: Photomicrographs showing defects in the 12.7-mm thick pultruded composite (Longitudinal section)
Figure 4.29: Photomicrographs showing defects in the 12.7-mm thick pultruded composite (Transverse section)
CHAPTER V

MEASUREMENTS, MODELING AND FEM STUDY FOR

COMPRESSION LOADING

5.1 Introduction

Compressive properties such as compressive strength, strain to failure and compressive modulus were measured experimentally using a short-block compression specimens. Pultruded composite sheets with thicknesses of 6.3-mm and 12.7-mm were tested in this phase of the study. A large number of specimens were tested to generate enough information to perform a statistical analysis of the compression strength data. Three statistical models, namely normal distribution, lognormal distribution and Weibull distribution were used to determine the best distribution, and their corresponding design allowables were determined. Compressive properties for other fiber orientation angles for both the thicknesses were also measured. The compressive failure mechanisms were investigated using a stereomicroscope to determine the initiation of failure and failure mechanisms.

Pultruded composite materials were modeled to predict the elastic properties of constituent layers (roving and continuous strand mat) for the finite element study. The predicted material properties were compared with experimentally measured properties. A two dimensional finite element analysis was performed to study the (i) specimen behavior, (ii) in-plane stress distribution and (iii) stress distribution through the thickness
of the pultruded composite under compressive loading. The predicted specimen behavior was compared with experimental results.

5.2 Experimental Program

5.2.1 Compression Test Specimens

All test specimens were machined from pultruded sheets having a width of 2.4-m and a length of 3.6-m with thicknesses of 6.3-mm and 12.7-mm. Specimens with the axial direction oriented at 0°, 30°, 45°, 60° and 90° to the pultrusion direction were prepared. Twenty specimens were prepared for the 0° and 90° orientations, and six specimens were prepared for each of the other orientations. All specimens were rectangular with a length of 44.4-mm and a width of 25.4-mm. The specimens were cut using a water-cooled diamond saw. After cutting, the ends and sides of the specimens were prepared to final tolerances by grinding all sides flat, parallel and perpendicular to within ±0.012-mm.

5.2.2 Compression Test Fixture and Test Procedure

The compression test fixture design was based on the concepts of end loading mechanisms to test thick pultruded sheet specimens. The test fixture is similar to the NASA Short-Block fixture used by Shuart [44]. It has a pair of adjustable clamping blocks that accommodate specimens of different thicknesses. The major advantages of this test fixture are: 1) it is simple and compact; 2) it is easy to assemble and maintain;
and 3) it requires no specimen end tabs. A photograph of the test fixture and specimen is shown in Figure 5.1. Two side screws on each base plate allow the gripping of the specimen, simulating clamped boundary condition. The fixture was designed and fabricated from A-36 steel. All mating fixture and specimen surfaces were machined flat and parallel by grinding. Each end of the specimen was set 9.5-mm deep in the fixtures, for a test gauge length of 25.4-mm. The specimen is sufficiently thick to avoid global buckling and sufficiently long to produce a uniform state of stress within the test gauge section. A schematic diagram of the compression test fixture-specimen assembly is shown in Figure 5.2.

All compression tests were performed using a Tinius-Olsen electromatic-test machine with a 270 kN load capacity. A separate 220 kN load cell was mounted on the test machine cross head with adapter plates to provide digital load data. A spherically seated compression tool (shown in Figure 4.2), manufactured by Tinius-Olsen, was also mounted in series with the load cell. The purpose of the compression tool was to compensate for non-parallel loading platen surfaces. The test fixture assembly was placed between two flat steel support plates during compression. Two to four specimens were instrumented with pairs of back-to-back axial and transverse strain gages at the specimen center. These strain gages were used to monitor bending and buckling effects. The onset of global buckling was characterized by a sharp divergence of strain gage readings, while the bending effect was predominant when the difference between the back-to-back gages was more than 5 percent. Additionally, one specimen (in pultrusion direction only) from each thickness was instrumented with five axial strain gages across the width on the centerline of the specimen. The purpose of these additional strain gages
was to verify the existence of a uniform strain field within the small gage section of the short-block specimen. A Direct Current Differential Transducer (DCDT) was used to monitor the end shortening of each specimen. All of the strain gages, the DCDT, and the load cell were connected to a WIN5000™ data acquisition system, manufactured by the Vishay Measurements Group. The loading platen was leveled by applying 20 percent of the expected ultimate load while monitoring the back-to-back axial strain gages. A constant crosshead rate of 1.2 mm/min was applied by the test machine during the compression test.

5.3 Finite Element Study

A finite element analysis was performed included modeling of the pultruded composites and the prediction of specimen behavior during compression loading. The pultruded composite material was modeled to predict the elastic properties for the finite element study. Both the roving and the CSM layers were modeled. The elastic properties of pultruded composite were compared with experimental data. The compression test specimen of 6.3-mm thick was modeled using 4-noded isoparametric layered plate and shell elements. The analysis included both linear and non-linear effects. Both the inplane and through-the-thickness stress distributions were predicted across the specimen length and the width.
5.3.1 Modeling of Pultruded Composite

The structure of the pultruded composite materials is very complex. A typical cross-section includes three types of layers: (i) a thin layer of randomly oriented chopped fiber veil on the surface, (ii) continuous strand mat (CSM) layers and (iii) roving layers. The veil is a resin rich layer used primarily as a protective coating, and its contribution to the laminate response is neglected [74] in the finite element study. The pultruded composite, while not a laminated structure in a rigorous sense, was modeled as a laminated composite [75]. The laminated composite model assumes each layer as a homogeneous, linearly elastic and generally orthotropic material. The laminae properties were predicted from the constituent fiber and matrix properties tabulated in Table 5.1. The fiber volume fraction of each layer was not known, and in this study it was assumed to be the same as the composite fiber volume fraction, which was measured at 39.9% using a Mettler Toledo AG104 density determination kit.

**Roving Layer:** The roving layer consists of continuous fibers oriented in the direction of pultrusion and thus was treated as unidirectional composite material. The longitudinal modulus ($E_1$) and Poisson's ratio ($v_{12}$) were predicted from the well-known rule of mixture (ROM) formulae. Transverse modulus ($E_2$) and shear modulus ($G_{12}$) were predicted from the semiempirical Halpin-Tsai equations. The predicted properties of the roving layer are tabulated in Table 5.2.

**Continuous Strand Mat (CSM) Layer:** The continuous strand mat (CSM) layer is a fiber system containing randomly placed continuous roving held together by a binder. The elastic properties of the CSM layer were predicted assuming a random composite.
The random composite can be idealized as the laminated composite with a large number of thin unidirectional layers and with a different orientation, from 0° to 180°, in the plane of fiber. Thus, the properties of the CSM layer are the average properties of this fictitious laminate and hence are assumed in plane isotropic. There were various tools available in the literature to model the random composite [76-82]. In this study, the modeling of the CSM layer was limited to the Cox model, the Tsai and Pagano model and the quasi-isotropic model, with [60/0/-60] laminate only.

Cox [76] modeled the composite without matrix material as a planar mat of continuous fiber based on the concept of averaging the elastic constants over all possible orientations by integration. The Cox formulae for the averaged isotropic elastic constants of random arrays of fibers (2-dimensional case) are as follows:

$$\tilde{E} = \frac{E_f V_f}{3}, \tilde{G} = \frac{E_f V_f}{8}, \tilde{\nu} = \frac{1}{3} \text{.........(5.1)}$$

where $\tilde{E}$, $\tilde{G}$ and $\tilde{\nu}$ are the averaged Young’s modulus, shear modulus and Poisson’s ratio respectively, and $E_f$, $V_f$ are the Young’s modulus of fiber and fiber volume fraction of the random composite.

Tsai and Pagano [77] have developed the following approximate expressions for the average Young’s and shear modulus of the random composite:

$$\tilde{E} = \frac{3}{4} E_1 + \frac{5}{8} E_2 \text{.........(5.2a)}$$
\[ G = \frac{1}{8} E_1 + \frac{1}{4} E_2 \ldots \ldots (5.2b) \]

\[ v = \frac{\bar{E}}{2 \bar{G}} - 1 \ldots \ldots (5.2c) \]

where \( E_1 \) and \( E_2 \) are the longitudinal and transverse moduli of the fictitious unidirectional layer having the same volume fraction as the CSM layer that can be predicted from the ROM and the Halpin-Tsai equations (as similar to roving layer). The above equations are very straightforward and simple to use to predict the elastic constants of the random composite.

Randomly oriented fibrous composites could be modeled as quasi-isotropic laminates [82]. Although randomly oriented fibrous composites theoretically have an infinite number of fiber orientations to be isotropic, the behavior of such materials can be modeled by considering a quasi-isotropic laminate having only three or four laminae, namely \([60/0/-60]\) and \([90/45/0/-45]\) laminates. In this study, the CSM layer was assumed as a \([60/0/-60]\) quasi-isotropic laminate. Each CSM layer was divided into three thin unidirectional layers orientated as 60°, 0° and -60° with a reference x-axis, and making use of the classical lamination theory, the elastic constants of the CSM layer were predicted.

The predicted CSM layer properties from all three models studied are presented in Table 5.3. It can be seen from Table 5.3 that the Cox model predicts the lowest elastic constants when compared to the other two models. Specifically, the predicted Young’s modulus for the Cox model is approximately 55%-60% of the other two models.
5.3.2 Laminate Analysis

Classical laminated plate theory (CLPT) was used to predict the elastic constants of the pultruded composite sheet material. The orientation of the roving layer was chosen such that the pultrusion direction (0° orientation) matches with the reference x-axis. The orientation of the CSM layer is not important due to the in plane isotropic conditions, and was chosen at 0° for modeling purposes. The thickness of the individual layer was not known and was assumed proportional to the percent glass content of the corresponding layer in the laminate. The predicted thickness of each layer for the 6.3-mm thick pultruded composite sheet is shown in Table 5.4. The predicted elastic properties, thickness and orientation of each layer were input into the MSC/PATRAN modeling software for laminate analysis. The laminated analysis prediction from various CSM models for the 6.3-mm thick pultruded composite sheet is shown in Table 5.5. It can be seen from Table 5.5 that the Cox model was acceptable for predicting $E_1$, $E_2$ and $v_{12}$; however, other models better predicted $G_{12}$.

5.3.3 Finite Element Study in Compression

A two-dimensional large-displacement finite element analysis was performed using commercially available MSC/NASTRAN software to study the response of the pultruded composite specimen under compression loading. A specimen of 44.4-mm length, 25.4-mm width and 6.3-mm thickness was modeled using 4-noded isoparametric layered plate and shell elements (CQUAD4 in MSC/NASTRAN). These plate elements
are based on the assumptions of the classical plate theory. Each node has five degrees of freedom: 1) two orthogonal in-plane displacements (u,v); 2) one out-of-plane displacement (w); and 3) two rotations about orthogonal in-plane axis (θx and θy). The discretized a 2-D model of the compression specimen and the associated boundary conditions of the compression specimen is shown in Figure 5.3. A uniform finite element mesh with element size of 0.63-mm square was used. All the degrees of freedom (u, v, w, θx and θy) of all the nodes at the end (x=0) were constrained to simulate the clamped conditions, and a uniform nodal axial displacement was applied at the opposite end (x=L) to simulate the compressive loading. A pseudo-clamped boundary condition (w=0) was applied to all the nodes up to 9.5-mm from both the ends to simulate the grip. The model included 2800 elements and 2911 nodes. Both linear and geometric non-linear analyses were performed. Multiple displacement steps and the updating of the stiffness matrices at each step were considered to account for the geometric non-linearity. The material properties of the roving layer and the CSM layer used in the finite element study are shown in Table 5.6.

5.4 Results and Discussions

5.4.1 Experimental Results

The experimental results obtained include stress-strain responses and photographs of the fractured specimens. The compressive strength, compressive modulus and failure strain were obtained from these stress-strain curves. The statistical analysis was included to determine the statistical compressive strength and design allowable. The failure
analysis was performed based on the examination of the specimen fracture surface. An attempt was made to evaluate the failure initiation and failure mechanism.

5.4.1.1 Compressive Properties

The stress-strain plots for a 6.3-mm and a 12.7-mm thick pultruded composite specimen, with loading along the pultrusion direction, are shown in Figures 5.4 and 5.5 respectively. The average strain obtained from back-to-back strain gages is also shown. The agreement between the two strain gage readings up to failure for both the specimens indicates that bending due to nonuniform load introduction was successfully minimized. The stress-strain behavior is very linear up to failure. The bending strain at failure was found to be less than 2 percent indicating a valid test for measuring compressive strength, compressive modulus and Poisson’s ratio. The compressive strength was determined by dividing the maximum load by the average cross-sectional area of the specimen. The compressive modulus was determined from the initial slope of the average stress-strain plot. The failure strain corresponds to the average strain at the point of failure.

The load-end shortening responses, with loading along the pultrusion direction, are shown in Figure 5.6 for the 6.3-mm thick specimen and in Figure 5.7 for the 12.7-mm thick specimen. It is seen from both the figures that the load-end shortening behavior is fairly linear up to failure except at the very beginning of the load introduction. It is believed that slipping between the test fixtures and the specimen occurred until complete contact between the machine platen and the test fixture/specimen. This is not unusual for this type of compression test.

The variation of the axial strain across the width of the 6.3-mm thick and a 12.7-mm thick specimen tested in the pultrusion direction is shown in Figures 5.8 and 5.9.
respectively. The strain distribution is shown at four different load levels including failure load to examine the compressive strain variation across the specimen width as load increases. It can be seen from these figures that the strain distribution across the specimen width is very uniform except near the failure load. Matrix cracking at these loads levels most likely initiates failure. A continuous cracking noise was heard with increasing load immediately prior to failure.

The axial stress-strain plots of the off axis specimens of 6.3-mm and 12.7-mm thick are shown in Figures 5.10 and 5.11 respectively. The strain data corresponds to the average of the back-to-back strain gage readings. The bending strains for all off axis specimens tested in compression were found to be less than 2%. It can be seen from both the figures that although the stress-strain behavior is very linear for the 0-degree specimen (pultrusion direction); this behavior is more nonlinear for the other angles. The stress-strain behavior of the off axis specimens are very close to each other except for the 30-degree. The compressive strength and compressive modulus of the off axis specimens were determined by procedures similar to those used for 0-degree specimens. Since strain gages of the off axis specimens failed prior to the specimen fracture for all angle specimens tests. Thus, stress-strain curves were extrapolated to failure to determine the failure strain.

The measured compressive properties of the 6.3-mm and the 12.7-mm thick pultruded composites are summarized in Table 5.7. In general, test results were repeatable with little scatter. The compressive strength, modulus and failure strain data were averaged for each group of specimens. It can be seen from Table 5.7 that the compressive strength for the 6.3-mm thick specimens is approximately 8 percent higher
in longitudinal direction and approximately 8 percent lower in transverse direction as compared to the 12.7-mm thick specimens. The compressive modulus is very similar for both the thicknesses. The longitudinal compressive failure strain for the 6.3-mm thick specimen is approximately 16% higher in longitudinal direction and approximately 14% lower in transverse direction as compared to the 12.7-mm thick specimens.

The variation of compressive strength as a function of fiber orientation angle is shown in Figure 5.12. It can be seen from Figure 5.12 that the 6.3-mm thick specimens exhibit higher compression strength in comparison to the 12.7-mm thick specimens in the pultrusion direction. This can be due to higher roving/mat ratio exhibited by the 6.3-mm thick specimens as compared to 12.7-mm thick specimens. However, the strength of the 12.7-mm thick specimens is somewhat higher when compared to the 6.3-mm thick specimens for other orientation angles. Figure 5.13 shows the variation of compressive modulus as a fiber orientation angle. It is seen from Figure 5.13 that the compressive modulus of the 12.7-mm thick specimens is higher than the 6.3-mm thick specimen for all orientation angles.

5.4.1.2 Statistical Analysis

The compressive strength data were analyzed using a 2-parameter Weibull distribution for both thicknesses only in the longitudinal and transverse directions. The characteristic strength and the shape parameter were determined and compared from rank-regression and maximum likelihood estimation (MLE) methods. The probability of survival plots were generated using a 2-parameter Weibull distribution for both the thicknesses in the longitudinal and transverse directions. Representative probability of
survival plots are presented in Figure 5.14 for the 6.3-mm thick specimens and in Figure 5.15 for the 12.7-mm thick specimens. It can be seen from both the figures that the compressive strength data were well fitted with both the methods. Compressive strength data were also analyzed using lognormal and normal distributions to determine the proper distribution to be used to evaluate the B-basis design allowable (DA). A B-basis allowable is defined as the strength above which 90 percent of the population is expected to fall with 95 percent confidence. Comparisons were made with the observed significance level (OSL) to determine the best distribution represented by the compressive strength data. The OSL was determined from the Anderson-Darling test [49]. If OSL exceeds 0.05, there is a high probability that the sample data fits the assumed distribution. Table 5.8 presents the summary of statistical parameters for lognormal, normal and Weibull distributions for the pultruded composite specimens. It can be seen from Table 5.8 that based on OSL values, compressive strength data fit well with a 2-parameter Weibull distribution for the 12.7-mm thick composites. However, lognormal distribution seems better for the 6.3-mm thick composites.

5.4.1.3 Failure Analysis

Failure analysis of pultruded composite specimens in compression was investigated for both the thicknesses. The effect of fiber orientation angle on compressive failure modes is also studied. An attempt was made to determine the compressive failure initiation and failure mechanisms. During the compression testing, it was observed that the specimen underwent continuous cracking noise with increasing load just prior to failure. Hence, it was decided to unload the specimen immediately once
cracking noise heard. The specimens were then examined under the stereo microscope (OLYMPUS SZ1145) to evaluate the initiation of failure. The failure mechanisms were evaluated on post-failure observations.

The photomicrographs, showing the compressive failure initiation, are shown in Figures 5.16 through 5.20 for the 6.3-mm thick specimens. It can be seen from Figure 5.16 that the fiber microbuckling triggered a shear type of failure for the longitudinal specimens. The 30-degree specimens were failed mainly due to delamination (Figure 5.17). The off axis specimens orientated at 45-degree to 90-degree were failed due to matrix compression (Figures 5.18 through 5.20). The matrix compression failure mode is characterized by a failure surface that extends through the laminate thickness and is orientated at 45 degrees. The photomicrographs, showing the compressive failure initiation, are shown in Figures 5.21 through 5.25 for the 12.7-mm thick specimens. It can be seen from Figures 5.21 to 5.23 that the specimens with fiber orientation angle up to 45-degree were failed due to delamination. From Figures 5.24 and 5.25, it can be seen that the failure mode was found to be matrix compression for the specimens beyond 45 degrees.

The photographs of the fractured specimens of the 6.3-mm thick are shown in Figures 5.26 through 5.30. It is seen from Figure 5.26 that the longitudinal specimens show extensive delamination, fiber microbuckling and shearing of the CSM layers. As the fiber orientation angle increases, as seen from Figures 5.27 through 5.30, the failure mode changes from delamination to shear type failure. The photographs of the fractured specimens of the 12.7-mm thick also show similar failure mechanisms as exhibited by the 6.3-mm thick specimens.
5.4.2 Finite Element Results

Figures 5.36 and 5.37 show the predicted versus experimental compressive stress-strain and load-end shortening response of the 6.3-mm thick pultruded composite specimen. The stress and strain values obtained from the finite element analysis correspond to the element center located at the center of the specimen. The predicted data for both the linear and the non-linear analysis were included. For the non-linear analysis, the values are taken from the last iteration. Five iterative steps with a modified Newton-Raphson scheme were used to implement the geometric non-linearity of the element. Stiffness matrices were updated at each step on the basis of the displacement undergone at each iteration. Fairly good correlation was found between the predicted and the experimental data in terms of stress-strain and load-end shortening response. This indicates that the isoparametric layered plate and shell element can be used successfully to model the pultruded composite materials. The effect of geometric non-linearity was found to be insignificant on specimen behavior in respect of stress-strain and load-end shortening response.

The deformed displacement plot of $U_x$ (along the applied load) is shown in Figure 5.38. It is seen from Figure 5.38 that the compression specimen deformed not only along the applied load but also in the transverse direction due to Poisson’s effects. The distribution of the in-plane normal stress ($\sigma_x$) is shown in Figure 5.39. The in-plane normal stress distribution is kind of symmetric with respect to the specimen width and length and is uniform at the center of the specimen across the width. The distribution of the homogeneous in-plane stresses across the length is shown in Figure 5.40 and across
the width is shown in Figure 5.41. It is seen from both the figures that a uniform uniaxial state of stress exists near the gage section, which supports the experimental measurements of compressive properties, especially the compressive modulus and the Poisson's ratio. Near the specimen ends, there exists a compressive stress in the transverse direction.

Figures 5.42 and 5.43 show the stress distribution of the roving layers and the CSM layers across the width of the specimen. It is seen from above figures that both the roving and the CSM layers subjected to a uniform and uniaxial state of compressive stress. The contribution of various layers on laminate response is shown in Figure 5.44. It is seen from Figure 5.44 that the roving layers are carrying approximately 67% of the applied load, while CSM layers are carrying only approximately 33% of the applied load. The variation of the in-plane stresses through the thickness of the composite specimen is shown in Figure 5.45. The roving layers are subjected to higher in-plane normal stresses as compared to the CSM layers. The in-plane normal stress varies linearly through the thickness.
Figure 5.1: Photograph of the test fixture and the specimen
Figure 5.2: Schematic diagram of the compression test fixture-specimen assembly
Table 5.1: Properties of E-glass fiber and polyester matrix

<table>
<thead>
<tr>
<th>Property</th>
<th>E-glass fiber</th>
<th>Polyester resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Modulus, GPa</td>
<td>72.35</td>
<td>3.45</td>
</tr>
<tr>
<td>Shear Modulus, GPa</td>
<td>29.63</td>
<td>1.27</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.22</td>
<td>0.35</td>
</tr>
<tr>
<td>Density, g/cc³</td>
<td>2.54</td>
<td>1.10</td>
</tr>
<tr>
<td>Failure strain, %</td>
<td>4.40</td>
<td>4.20</td>
</tr>
<tr>
<td>Tensile strength, MPa</td>
<td>3445.00</td>
<td>77.17</td>
</tr>
</tbody>
</table>

Table 5.2: Predicted material properties of roving layer (6.3-mm thick)

<table>
<thead>
<tr>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Modulus, $E_1$ (GPa)</td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>30.9</td>
</tr>
</tbody>
</table>
Table 5.3: Predicted material properties of CSM layer

<table>
<thead>
<tr>
<th>Properties</th>
<th>Various CSM Models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cox Model</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_1 = E_{22}$ (GPa)</td>
<td>9.6</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>3.6</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.330</td>
</tr>
</tbody>
</table>

Table 5.4: Predicted thickness of each layer

<table>
<thead>
<tr>
<th>Lay-up Information</th>
<th>Percent glass content*</th>
<th>Predicted Layer Thickness (mm)</th>
<th>Fiber Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSM layer</td>
<td>11</td>
<td>0.693</td>
<td>39.9</td>
</tr>
<tr>
<td>Roving layer</td>
<td>21</td>
<td>1.323</td>
<td>39.9</td>
</tr>
<tr>
<td>CSM layer</td>
<td>34</td>
<td>2.142</td>
<td>39.9</td>
</tr>
<tr>
<td>Roving layer</td>
<td>21</td>
<td>1.323</td>
<td>39.9</td>
</tr>
<tr>
<td>CSM layer</td>
<td>13</td>
<td>0.819</td>
<td>39.9</td>
</tr>
</tbody>
</table>

* The thickness of the veil was assumed equal to 0.203-mm
Table 5.5: Predicted elastic constants for the 6.3-mm thick pultruded sheet

<table>
<thead>
<tr>
<th>Properties</th>
<th>Experiment*</th>
<th>Cox Model</th>
<th>Tsai and Pagano Model</th>
<th>Quasi-isotropic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$ (GPa)</td>
<td>19.1</td>
<td>18.3</td>
<td>22.7</td>
<td>22.0</td>
</tr>
<tr>
<td>$E_2$ (GPa)</td>
<td>10.7</td>
<td>9.5</td>
<td>14.2</td>
<td>13.0</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.313</td>
<td>0.327</td>
<td>0.386</td>
<td>0.330</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>4.4</td>
<td>3.2</td>
<td>4.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>

* Experimental data were taken from the static measurement described in Chapter III
Table 5.6: Material properties used for the finite element analysis

<table>
<thead>
<tr>
<th></th>
<th>Roving Layer</th>
<th>CSM Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>=30.9 GPa</td>
<td>$E_1 = E_2 = 9.6$ GPa</td>
</tr>
<tr>
<td>$E_2 = E_3 = 8.8$ GPa</td>
<td></td>
<td>$E_3 = 5.6$ GPa</td>
</tr>
<tr>
<td>$G_{12} = G_{13} = 2.8$ GPa</td>
<td></td>
<td>$G_{12} = 4.3$ GPa</td>
</tr>
<tr>
<td>$G_{23} = 2.5$ GPa</td>
<td></td>
<td>$G_{23} = G_{13} = 1.4$ GPa</td>
</tr>
<tr>
<td>$\nu_{12} = \nu_{13} = 0.285$</td>
<td>$\nu_{12} = 0.285$</td>
<td>$\nu_{23} = \nu_{13} = 0.380$</td>
</tr>
<tr>
<td>$\sigma_{11}^T = 913$ MPa</td>
<td>$\sigma_{22}^T = 61$ MPa</td>
<td>$\sigma_{csm}^T = \sigma_{csm}^C = 172$ MPa</td>
</tr>
<tr>
<td>$\sigma_{11}^C = 517$ MPa</td>
<td>$\sigma_{22}^C = 61$ MPa</td>
<td>$\tau_{12csm}^u = 86$ MPa</td>
</tr>
<tr>
<td>$\tau_{12}^u = 60$ MPa</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

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Figure: 5.3: Discretized 2-D model and the boundary conditions
Figure 5.4: Stress vs. strain response of 6.3-mm thick specimen (longitudinal)
Figure 5.5: Stress vs. strain response of 12.7-mm thick specimen (longitudinal)
Figure 5.6: Load vs. end shortening plot for 6.3-mm thick specimen (longitudinal)
Figure 5.7: Load vs. end shortening plot for 12.7-mm thick specimen (longitudinal)
Figure 5.8: Distribution of axial strain across the width of 6.3-mm thick specimen (longitudinal)
Figure 5.9: Distribution of axial strain across the width of 12.7-mm thick specimen (longitudinal)
Figure 5.10: Axial stress vs. strain response of 6.3-mm thick specimen for various fiber orientation angles
Figure 5.11: Axial stress vs. strain response of 12.7-mm thick specimen for various fiber orientation angles
Table 5.7: Compressive properties of pultruded composites of 6.3-mm and 12.7-mm thick flat sheets

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Loading Direction</th>
<th>Average Compressive Modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Average Compressive Strength (MPa)</th>
<th>Average Failure Strain, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3-mm</td>
<td>0° (long.)</td>
<td>17.85</td>
<td>0.314</td>
<td>266.4</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>30°</td>
<td>11.23</td>
<td>0.378</td>
<td>164.0</td>
<td>1.73&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>9.78</td>
<td>0.307</td>
<td>153.6</td>
<td>1.96&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>60°</td>
<td>9.10</td>
<td>0.274</td>
<td>143.8</td>
<td>1.92&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>90° (trans.)</td>
<td>9.71</td>
<td>0.197</td>
<td>137.5</td>
<td>1.53&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>12.7-mm</td>
<td>0° (long.)</td>
<td>17.91</td>
<td>0.309</td>
<td>244.7</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>30°</td>
<td>11.92</td>
<td>0.304</td>
<td>182.4</td>
<td>2.14&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>10.48</td>
<td>0.363</td>
<td>168.1</td>
<td>2.22&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>60°</td>
<td>9.30</td>
<td>0.272</td>
<td>162.8</td>
<td>2.30&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>90° (trans.)</td>
<td>10.20</td>
<td>0.170</td>
<td>148.6</td>
<td>1.75&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Failure strains were calculated using extrapolation method.
Figure 5.12: Variation of Compressive Strength as a Function of Fiber Orientation Angle

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Figure 5.13: Variation of compressive modulus as a function of fiber orientation angle.
Figure 5.14: Probability of survival plot for 6.3-mm thick specimens
Figure 5.15: Probability of survival plot for 12.7-mm thick specimens
Table 5.8: Summary of statistical compressive strength of pultruded flat sheets

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Direction</th>
<th>Mean (MPa)</th>
<th>SD&lt;sup&gt;a&lt;/sup&gt; (MPa)</th>
<th>Scale Parameter (MPa)</th>
<th>Shape Parameter</th>
<th>B-basis DA&lt;sup&gt;b&lt;/sup&gt; (MPa)</th>
<th>OSL&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MLE</td>
<td>Rank</td>
<td>MLE</td>
<td>Rank</td>
</tr>
<tr>
<td>(a) Weibull distribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.3-mm</td>
<td>0° (long.)</td>
<td>-</td>
<td>-</td>
<td>273.8</td>
<td>273.3</td>
<td>19.2</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>90° (trans.)</td>
<td>-</td>
<td>-</td>
<td>141.3</td>
<td>140.8</td>
<td>17.1</td>
<td>23.2</td>
</tr>
<tr>
<td>12.7-mm</td>
<td>0° (long.)</td>
<td>-</td>
<td>-</td>
<td>251.2</td>
<td>251.4</td>
<td>22.4</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>90° (trans.)</td>
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<sup>a</sup>Standard Deviation; <sup>b</sup>Design Allowable; <sup>c</sup>Observed Significance Level
Figure 5.16: Photomicrograph of 6.3-mm thick specimen showing initiation of failure (longitudinal)
Figure 5.17: Photomicrograph of 6.3-mm thick specimen showing initiation of failure:
(30-degree)
Figure 5.18: Photomicrograph of 6.3-mm thick specimen showing initiation of failure (45-degree)
Figure 5.19: Photomicrograph of 6.3-mm thick specimen showing initiation of failure (60-degree)
Figure 5.20: Photomicrograph of 6.3-mm thick specimen showing initiation of failure (transverse)
Figure 5.21: Photomicrograph of 12.7-mm thick specimen showing initiation of failure (longitudinal)
Figure 5.22: Photomicrograph of 12.7-mm thick specimen showing initiation of failure (30-degree)
Figure 5.23: Photomicrograph of 12.7-mm thick specimen showing initiation of failure (45-degree)
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Figure 5.27: Photograph of 6.3-mm thick fractured specimen (30-degree)
Figure 5.28: Photograph of 6.3-mm thick fractured specimen (45-degree)

Figure 5.29: Photograph of 6.3-mm thick fractured specimen (60-degree)
Figure 5.30: Photograph of 6.3-mm thick fractured specimen (transverse)

Figure 5.31: Photograph of 12.7-mm thick fractured specimen (longitudinal)
Figure 5.32: Photograph of 12.7-mm thick fractured specimen (30-degree)

Figure 5.33: Photograph of 12.7-mm thick fractured specimen (45-degree)
Figure 5.34: Photograph of 12.7-mm thick fractured specimen (60-degree)

Figure 5.35: Photograph of 12.7-mm thick fractured specimen (transverse)
Compressive Stress (MPa)

FEA 2D Nonlinear
FEA 2D Linear
Experimental

Axial Strain (%)

Figure 5.36: Experimental vs. predicted stress-strain response (6.3-mm thick)
Figure 5.37: Experimental vs. predicted load-end shortening response (6.3-mm thick)
Figure 5.38: Deformed displacement plot of $U_x$ (6.3-mm thick)
Figure 5.39: Distribution of in-plane normal stress, $\sigma_x$ (6.3-mm thick)
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Figure 5.45: Stress distribution of through the thickness of the specimen, 6.3-mm thick
CHAPTER VI

DAMAGE RESISTANCE AND DAMAGE TOLERANCE OF
PULTRUDED COMPOSITES

6.1 Introduction

Damage resistance and damage tolerance of 6.3-mm and 12.7-mm thick pultruded composites were investigated experimentally. The plate specimens were tested under a quasi-static indentation loading to investigate the damage resistance of pultruded composites. Damage was introduced in the specimens at various incrementally increased force levels selected from the load-displacement behavior of the material up to the failure. The damaged specimens were sectioned along the longitudinal and transverse direction, and the sectioned specimens were photographed in order to determine the damage progression at each load level. The extent of damage was measured in the form of dent depth, back surface crack length, etc., and in the form of damage area obtained from the X-radiography technique. A correlation was established among the variables to extract a parameter that could be used to measure the damage resistance of composite structures. The contact behavior of the composite plate and the steel spherical indentor was also studied to determine the contact force-indentation relationship. The contact stiffness was measured and compared with modified Hertz law.
The end gripped compression test fixture was used to investigate the damage
tolerance of pultruded composites. Compression tests were performed on both the
damaged specimens and open-hole specimens. The undamaged specimens were
instrumented with several pairs of back-to-back axial strain gages to capture any evidence
of global buckling during the compression test. Both the damaged specimens and the
open-hole specimens were instrumented extensively with strain gages near damage or the
hole to measure the strain distribution. A relationship between the compressive strength
and hole-diameter was established and compared with residual compressive strength of
the damaged specimens to determine the "equivalent-hole specimens" of the damaged
specimens. A similar relationship was established in terms of the strain distribution due to
the hole and the damage in the specimen. Finally, a correlation between damage
parameters and "equivalent-hole specimens" was established, which could be used as a
measure of damage resistance and damage tolerance of pultruded composite structures.

6.2 Experimental Program

6.2.1 Quasi-Static Indentation Testing

6.2.1.1 Specimen Preparation and Test Procedure

Plate specimens of 6.3-mm and 12.7-mm thickness were prepared from the
pultruded composite sheets. Specimens with a length of 152-mm and width of 102-mm
were machined from a pultruded sheet of 6.3-mm thickness, and specimens of length
254-mm and width 178-mm were machined from a pultruded sheet of 12.7-mm thickness. A total of thirty specimens were machined from each thickness.

The quasi-static indentation tests were performed on a 89 kN servo hydraulic load frame manufactured by Tinius-Olsen. The platen, machined from a 51-mm thick aluminum plate with an outside square dimension of 406-mm, was rested on top of the 51-mm thick aluminum upright that can be removed without taking the fixture out of the test frame. The aluminum uprights were bolted to a 51-mm thick steel plate. The specimen was placed on the platen as a simply supported boundary condition on all four edges and was loaded transversely quasi-statically. The specimens of 6.3-mm thickness were tested with a 19-mm diameter steel spherical indentor on a platen with a 51-mm square cut out. The specimens of 12.7-mm thickness were tested with a 38-mm diameter steel spherical indentor on a platen with a 102-mm square cut out. Two direct current differential transformers (DCDT's) were used to measure the indentor movement and the central plate displacement directly under the indentor. The tests were conducted in a stroke control at a rate of 1.27-mm/min. The load and the displacements were recorded using a WIN5000™ data acquisition system during the experiment. The photograph of the quasi-static indentation test setup is shown in Figure 6.1.

### 6.2.1.2 Damage Evaluation

A total of four types of non-destructive analyses, dent depth, back surface crack length, x-radiography and sectioning, were performed to document the external and the internal damage. Dent depth was measured on the indentation surface of each specimen using the DCDT with a resolution of 0.0007-mm. The specimens were set aside for at
least 24 hours after testing so that the resulting dent would have time to relax to its equilibrium state. Specimens were held flat and the DCDT was traversed along the length and the width directions through the dent. The dent depth was measured from the relative distance between the flat surface and the maximum travel distance on the dent. Dent depth data were averaged. To measure the crack length, the specimen was rested on a flat surface with the non-indentation surface facing upward. Using a digital caliper, the visible crack length was measured.

The internal damage in the form of damage area was determined using x-radiography technique. The technique allows a through-thickness integrated view of delamination and matrix cracking. The specimens were soaked on both sides with a zinc iodide penetrant solution for 24 hours and were then x-rayed using a Faxitron™ x-ray machine. A piece of photographic film was placed directly under the specimen to capture the image of the internal damage in the form of a negative. The positives were made from the negatives and the planar damage area was calculated. Some specimens didn’t show any damage on the x-ray photograph, especially at low force level; therefore, a small hole of 0.8-mm was drilled near the damage. Dye-penetrant was injected via a syringe into the hole and the specimens were x-rayed again. The average damage area was determined from the x-ray photograph by superimposing on a grid of 2-mm square and by counting the number of squares that were within the damage map. The x-rayed specimens were then sectioned along the longitudinal and the transverse direction, and the sectioned specimens were then examined under a stereo microscope (OLYMPUS SZ1145).
6.2.2 Compression Testing

6.2.2.1 Test Specimen Preparation

All the compression plate specimens were fabricated from the pultruded composite sheets of 6.3-mm and 12.7-mm thicknesses. The widths and the lengths of the specimens were determined so that a strength failure would more likely to occur than a buckling mode failure. Thus, buckling analyses were performed on various plate specimens to determine the buckling load for various mode shapes. The predicted buckling load was used to determine the specimen dimension so that the expected failure load is lower than the buckling load. Two different plate specimens were made. The specimens of 152-mm length and 102-mm width were cut from the 6.3-mm thick sheet, while the specimens of 254-mm length and 178-mm width were cut from the 12.7-mm thick sheet. The length direction of all the specimens was chosen parallel to the pultrusion direction. After cutting, all four edges of each specimen were machined flat and parallel, using a surface grinding machine (Brown & Sharpe 510) within 0.0025-mm, to permit uniform compression loading. A total of thirty specimens for each thickness were prepared. Circular holes were machined in the center of fifteen specimens for each thickness with a diamond impregnated core bit. A wide range of diameter to width ratios of 0.075 to 0.75 was chosen. Two plexi-glass plates were placed on top and bottom of the composite specimens during the drilling operation to avoid any machining induced damage, especially on the exit side. The drilling operation was performed in three steps, starting with a small drill to the final hole size. For the case of bigger holes, a reamer tool was used with a very small radial feed until the required hole size achieved. Various
levels of damage were introduced in the center of some of the specimens using the quasi-static indentation loading as described in the previous section.

6.2.2.2 Instrumentation

One undamaged specimen (without a hole) at each thickness was instrumented with several pairs of back-to-back axial strain gages at various important locations. The locations of the strain gages are shown in Figure 6.2 for the 6.3-mm thick specimens and in Figure 6.3 for the 12.7-mm thick specimens. It can be seen from Figure 6.2 that the 152-mm x 102-mm plate specimen was instrumented with a total of three pairs of back-to-back strain gages, while the 254-mm x 178-mm plate specimen was instrumented with a total of five pairs of back-to-back strain gages. The purpose of these back-to-back strain gages was to capture multiple buckling modes and also to verify uniform introduction of compression loading.

At least one specimen with each hole size was instrumented with several strain gages: one pair of back-to-back strain gages was placed 25-mm below the loading end and oriented parallel to the direction of applied load. These gages were used to measure the surface strain; one strip gage, consisting of ten gages, along with several single gages were mounted on the section between the hole edge and the specimen edge along the horizontal axis of symmetry. The strip gage was placed very close to the hole edge. All the strain gages were orientated parallel to the direction of the applied load to capture the strain gradient due to strain concentration at the edge of the hole; three additional strain gages were placed inside the hole. At the intersection of the hole edge and the horizontal axis of symmetry, one strain gage was oriented parallel to the applied load to measure the
strain concentration, and one strain gage was orientated through the thickness of the specimen to monitor failure – in particular delamination that might initiate at the hole. At the intersection of the hole edge and the vertical axis of symmetry, one strain gage was orientated transverse to the applied load to monitor the tensile strain. A typical instrumented specimen with hole is shown in Figure 6.4.

One damaged specimen at each thickness was also instrumented with several strain gages orientated parallel to the applied load. The strain gages were mounted in the section between the damage and the specimen edge. Strain gages were mounted on both the indentation side and on the non-indentation side.

6.2.2.3 Compression Test Fixture and Test Procedure

The end-gripped compression test fixture was used in this study to test the plate specimens. This fixture has two pairs of adjustable grips to accommodate specimens of different thicknesses. The specimen was placed in between the adjustable end grips and was pressed against each other using two C-clamps. The screws were tightened while pressing the specimen-fixture together, so that the clamped boundary conditions can be applied at the loaded ends. Two side fixtures with knife-edge restraints attached were placed along the side of the specimen so that simply supported boundary conditions were applied to prevent wide column buckling. A gap of approximately 6.3-mm was left between the side supports and the end grips to allow for compression of the panel without loading the fixture. A typical specimen in the support fixture ready for testing is shown in Figure 6.5.
All the test specimens were loaded quasi statically in axial compression using a Tinius Olsen 1.78-MN capacity hydraulic testing machine. During the testing, two DCDT’s were used: 1) at the specimen center and oriented transverse to the specimen to measure the out-of-plane displacements (specimens with hole had the DCDT offset) and 2) alongside the specimen oriented parallel to the direction of load to measure the end shortening. All the electrical signals (strain gages, load and DCDT’s) were recorded continuously using a WIN5000™ data acquisition system. The loading platen was adjusted by applying 20 percent of the expected ultimate load while monitoring the back-to-back axial strain gages before final loading. The purpose was to place the specimen-fixture assembly so that it was aligned with the testing machine. A constant crosshead rate of 1.2-mm/min was applied during the test. Photograph of a typical experimental set up during the compression testing is shown in Figure 6.6.

6.3 Contact Force-Indentation Relationship

The Hertz [83] contact law has been used by many authors for studying of impact response of homogeneous and isotropic materials [84-85]. The Hertz contact law can be written as

\[ F = K\alpha^{1.5} \]  

(6.1)

where \( F \) is the contact force, \( \alpha \) is the indentation depth and \( K \) is the contact stiffness; \( K \) depends on the material properties of the target and the indentor as well as the radius of the indentor. The contact stiffness for laminated composite material has been proposed by Sun et al. [86] as
where $D$, $\nu$, and $E$ are the diameter, Poisson’s ratio and the Young’s modulus of the indentor, and $E_3$ is the Young’s modulus of the composite plate in the thickness direction. The $E_3$ was calculated from the laminate analysis and found to be 6.8 GPa for the pultruded composites. The contact coefficient, $K$ for the 6.3-mm and the 12.7-mm thick pultruded composites was calculated from equation 6.2 as 34.3 kN/mm$^{1.5}$ and 51 kN/mm$^{1.5}$ respectively.

6.4 Strain Concentration

The removal of potential load carrying material from the center of a panel causes internal load transfer and strain concentrations which not only depend on the shape of the cutout, but on the amount of material removed. For circular holes in infinite isotropic plates, the stress concentration factor on the hole centerline normal to load application is 3.0 [87]. The orthotropic extension of this theory, developed by Tan [89], expresses the stress concentration factor of an infinite, homogeneous orthotropic plate as a function of laminate material properties as follows:

$$K = \frac{\sqrt{8}}{3} \sqrt{D \left[ 1 - \frac{\nu^2}{E} + \frac{1}{E_3} \right]^{-1}} \text{(6.2)}$$

$$K_T^F = 1 + \sqrt{2 \left( \frac{E_{11}}{E_{22}} - \nu_{12} \right) + \frac{E_{11}}{G_{12}}} \text{(6.3)}$$

where $E_1$, $E_2$, $\nu_{12}$ and $G_{12}$ are the Young’s moduli in the load direction and perpendicular to the load direction, the Poisson’s ratio and the shear modulus respectively. This
relationship yields a value of 3.7 for the 6.3-mm thick specimens and a value of 3.7 for the 12.7-mm thick specimens. Any deviation from these values for different hole diameters must be due to the finite size of the specimen since hole size does not appear in the stress concentration factor. Thus, the finite width correction factor must be included to determine the stress concentration factor for finite size specimens. The approximate orthotropic finite width correction factor (FWC) is given by following expression [88]:

$$\frac{K_T^\infty}{K_{Tg}} = \frac{2 - \left(\frac{d}{w}\right)^2 - \left(\frac{d}{w}\right)^4}{2} + \left(\frac{d}{w}\right)^6 \left(K_T^\infty - 3 \left[1 - \left(\frac{d}{w}\right)\right]\right)$$

where $K_{Tg}$ is the stress concentration factor based on gross section area.

The improved theory for FWC factor is given by following expression [89]

$$\frac{K_T^\infty}{K_{Tg}} = \frac{3 \left[1 - \left(\frac{d}{w}\right)^2\right] \left[1 - \left(\frac{d}{w}\right)^3\right]}{2 + \left(1 - \left(\frac{d}{w}\right)^3\right)^2} + \frac{1}{2} \left(\frac{d}{w}\right)^6 \left(K_T^\infty - 3 \left[1 - \left(\frac{d}{w}\right)\right]^2\right)$$

where

$$M^2 = \sqrt{1 - 8 \left[\frac{3 \left[1 - \left(\frac{d}{w}\right)^2\right]}{2 + \left(1 - \left(\frac{d}{w}\right)^3\right)^2} - 1\right] - 1}$$
6.5    Results and Discussions

6.5.1    Damage Resistance Study

6.5.1.1    Repeatability Tests

The quasi-static indentation test program was begun with the repeatability tests. It was decided to test four identical specimens at each thickness under the same testing conditions. Each specimen was loaded up to the maximum indentation force and was unloaded once the indentation force started dropping. The indentation force-displacement data were compared among each group of specimens and are shown in Figure 6.7 for the 6.3-mm thick specimens and in Figure 6.8 for the 12.7-mm thick specimens. It can be seen from both the figures that the force-displacement behavior is fairly similar and repeatable. The loading parts of the force-displacement curves are very close to each other, which indicates that the static indentation tests are fairly repeatable in terms of the load-displacement behavior. The repeatability tests were also performed in terms of damage parameters, such as maximum deflection, dent depth, back-surface crack length, energy absorption and damage area. The test results of the repeatability tests are summarized in Table 6.1 for the 6.3-mm thick specimens and in Table 6.2 for the 12.7-mm thick specimens. It can be seen from both the tables that indentation tests are fairly repeatable in terms of damage parameters with the differences attributable to normal experimental variations.
6.5.1.2 Damage Characterization Tests

After the repeatability tests, an attempt was made to study the damage resistance of this class of composite. In this phase of the study, damage was introduced at various incrementally increased force levels, selected from the indentation force-displacement behavior of the material up to failure. The load-displacement curves for various load levels are shown in Figure 6.9 for the 6.3-mm thick specimens and in Figure 6.10 for the 12.7-mm thick specimens. At each load level, five specimens were loaded and unloaded. The surface damage was measured for all the specimens. However, only two specimens at each load level were sectioned along the longitudinal and the transverse direction followed by the x-radiography examination. The sectioned specimens were photographed using the stereo microscope. The rest of the specimens were reserved for the compression tests to be conducted later.

Typical photographs of the surface damage on the indentation side are shown in Figures 6.11 for the 6.3-mm thick specimens and in Figure 6.12 for the 12.7-mm thick specimens. It can be seen from these figures that the surface damage on the indentation side is in the form of dent. However, the surface damage on the opposite side, shown in Figures 6.13 and 6.14, is in the form of a crack that is oriented mostly along the length direction. The s-shaped crack is observed for the 12.7-mm thick specimens (Figure 6.14). Typical x-radiographs showing the internal damage of the 6.3-mm thick and the 12.7-mm thick specimen are shown in Figures 6.15 and 6.16 respectively. Damage is indicated by the black region on each photograph and is nearly elliptical for the 6.3-mm thick specimens (Figure 6.15) and was fairly elliptical in shape for the 12.7-mm thick specimens (Figure 6.16). The major axis of the elliptical shaped damage coincided with
the pultrusion direction. The ratio of the major axis length to the minor axis length of the damaged region for 12.7-mm thick specimens was higher compared to the 6.3-mm thick specimens. The x-radiographs for other damage levels also showed similar damage regions.

Summaries of the damage characterization test results are shown in Table 6.3 for the 6.3-mm thick specimens and in Table 6.4 for the 12.7-mm thick specimens. The tables include average damage area, dent depth, back surface crack length and energy absorption. It can be seen from both tables that the damage parameters within each group vary widely.

The average damage area vs. maximum indentation force relationship is shown in Figure 6.17. It can be seen from Figure 6.17 that the average damage area varies linearly with the indentation force for both the thicknesses. There exists a threshold indentation force to produce any damage in the structures, and this threshold force is higher for the thicker specimens. The dent depth vs. maximum indentation force is shown in Figure 6.18. There exists a threshold indentation force, as seen from Figure 6.18, to produce a permanent indentation on the structures, and this threshold force was found to be higher for the thicker specimen. The relationship between energy absorption and the indentation force is seen in Figure 6.19. The relationship is found to be linear for the 6.3-mm thick specimens; however, the relationship is non-linear for the 12.7-mm thick specimens (Figure 6.19). Specimens do not absorb any energy unless a threshold indentation force is applied. Beyond the threshold force, depending upon the level of indentation force, the material absorbs energy to produce damage in the structure.
The variation of energy absorption as a function of dent depth is shown in Figure 6.20. It can be seen that the variation is linear for both the thicknesses. The thicker specimens absorbed more energy to produce same amount of dent depth. The variation of back surface crack length as a function of dent depth shows a non-linear relationship for both the thicknesses (Figure 6.21). The average damage area varies linearly with the dent depth for both the thicknesses (Figure 6.22). It can be seen from Figure 6.22 that there exists a threshold dent depth below that no damage was observed. Actually, as mentioned, pultruded composites consist of thin resin rich layer on the top and bottom surface to protect the fiber. Thus, during the indentation test, a fairly sufficient dent depth was found with a very small indentation force, which is not sufficient to produce any damage in the structures.

The photomicrographs of the sectioned specimens are shown in Figures 6.23 through 6.28 for the 6.3-mm thick specimens. It can be seen from Figure 6.23 that there is no evidence of damage at 4.0 kN load level. This load level was not sufficient to produce any damage in the structure. The photographs at 4.9 kN damage level shown in Figure 6.24 show only a very few matrix cracks. The matrix cracks are observed in the transverse section. At 5.8 kN damage level, the transverse section (Figure 6.25b) show delamination between the roving and the CSM layer located in the tensile side of the specimens. In fact, the matrix cracks begins to propagate through the thickness of the specimen and eventually form delamination. The delamination is extended further as the indentation load increases. The photomicrograph at 6.7 kN damage level is shown in Figure 6.26. It can be seen from the figure that the delamination is also visible in the longitudinal section. The delamination grows even towards the indentation side at this
load level. Fiber breakage is also observed along with delamination. Extensive delamination accompanied by fiber breakage at 7.3 kN load level is shown in Figure 6.27, and the complete fiber breakage is observed in Figure 6.28.

Photomicrographs showing the damage progression through the thickness of the 12.7-mm thick specimen at different indentation loads are shown in Figures 6.29 through 6.33. No visible damage was found at 11.5 kN and 13.1 kN load levels, as shown in Figures 6.29 and 6.30. The dark region shown in these photographs are the inherent voids present in the 12.7-mm thick composites. A few matrix cracks is observed at 15.6 kN load level (Figure 6.31). Delamination between the roving layer and the CSM layer, and the failure of the CSM layer in the tensile side is observed from the Figure 6.32. At higher load levels the delamination is observed both on the indentation side and the tensile side of the 12.7-mm thick composite (Figure 6.33). Intraply delamination within the roving layers and failure of roving layer on the tensile side of the composite specimen are also observed. The delamination extends through the thickness in both longitudinal and transverse directions.

6.5.1.3 Contact Behavior

The contact behavior between the composite plate and the steel indentor was investigated to determine the force-indentation (F-α) relationship at various indentation stages. The F-α relationship at small indentation stage is shown in Figure 6.34 for the 6.3-mm thick specimens and in Figure 6.35 for the 12.7-mm thick specimens. In these figures, data for three specimens are shown and found to be representative of the material behavior. From Figure 6.34 for the 6.3-mm thick specimens, the contact stiffness was

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determined from the best-fit curve \((F = K\alpha^{1.5})\) and is found to be 34.3 kN/mm\(^{1.5}\). The modified Hertz law (equation 6.2) predicts a contact stiffness of 37.9 kN/mm\(^{1.5}\), which is 10% higher than the experimental value.

The force-indentation behavior for the 12.7-mm thick specimens is shown in Figure 6.35. Data for three specimens were included. It can be seen from Figure 6.35 that the data represent the material behavior. The contact stiffness was measured as 51.7 kN/mm\(^{1.5}\) using a similar curve fitting. The modified Hertz law predicts the contact stiffness of 53.5, which is 3.5% higher than the measured value. The ratio of predicted contact stiffness for the 6.3-mm to 12.7-mm thick specimen is found to be 0.708 as compared to the measured ratio of 0.66.

The F-\(\alpha\) relationship for large indentation depths is shown in Figure 6.36 for the 6.3-mm thick specimens and in Figure 6.37 for the 12.7-mm thick specimens. It can be seen from both the figures that the relationship is continuous up to a certain value of indentation. Beyond that value the relationship is no longer continuous, and the indentation decreases with increasing contact force. The indentation at which the behavior is no longer continuous can be referred as the critical indentation. This value is found to be approximately 0.23-mm for the 6.3-mm thick specimens and 0.43-mm for the 12.7-mm thick specimen. The critical indentation for the 12.7-mm thick specimens is approximately twice as compared to the 6.3-mm thick specimens.
6.5.2 Damage Tolerance Under Compression

6.5.2.1 Response of Undamaged Specimens

It was mentioned that one specimen of the 6.3-mm thickness was instrumented with three-pairs of back-to-back axial strain gages and one specimen of the 12.7-mm thickness was instrumented with five-pairs of back-to-back axial strain gages to capture the multiple buckling modes and to verify the uniform load introduction. The stress vs. strain response of the two back-to-back strain gages located at the plate center for the 6.3-mm thick specimen is shown in Figure 6.38. It can be seen from Figure 6.38 that the two back-to-back strain gage data are very close to each other up to 91% of the failure load. Beyond that load level, the two back-to-back strain gages readings show divergence until complete failure. The stress-strain behavior is very linear up to 91% load level. The load vs. displacement behavior of the same specimen is shown in Figure 6.39. Both the end-shortening and out-of-plane displacement curves are included. The out-of-plane displacement increased suddenly in this manner as shown in Figure 6.39 indicating the evidence of local buckling beyond 91% of the failure load. The end shortening behavior is fairly linear up to failure except at the very beginning of the load introduction.

The stress vs. strain response of the two back-to-back strain gages located at the plate center for the 12.7-mm thick specimen is shown in Figure 6.40. It can be seen from Figure 6.40 that the stress vs. strain behavior is linear and the back-to-back strain data are very consistent up to 96% of the failure load. The out-of-plane displacement behavior as shown in Figure 6.41 does not show any evidence of local buckling.
A summary of the test results for the undamaged specimens of both the thicknesses is shown in Table 6.5. The table includes the individual test results and the average values. The failure strain values shown in the parentheses were calculated from the failure stress and the compressive modulus. The measured failure strains are also shown in Table 6.5. It can be seen from Table 6.5 that the compressive strength and the failure strain are higher for the 6.3-mm thick specimens as compared to 12.7-mm thick specimens. This is because the 12.7-mm thick material has more internal flaws (discussed in Chapter IV).

Typical photographs of the fractured undamaged specimens are shown in Figures 6.42 for the 6.3-mm thick specimens and in Figure 6.43 for the 12.7-mm thick specimens. All the undamaged specimens fractured near the center of the specimen, and the failure surface extended across the width of the specimen. The failure modes indicated that specimens failed due to compression and not because of global buckling.

6.5.2.2 Response of Specimens with Holes

To facilitate discussion, the compression response of the specimens with circular holes will be discussed individually. The compression response includes the stress vs. strain response, load vs. displacement behavior, compressive strength, strain concentration, and strain distribution near the hole and the compressive failure modes. The strain gage data reported in each figure include the axial surface strain and the strains measured over the inside surface of the hole. As mentioned before, the surface strain gage was located 38-mm below the loading end and oriented parallel to the applied load. Strain values inside the hole were measured using strain gages orientated parallel to the loading direction, transverse to the loading direction and in the thickness direction.
6.5.2.2.1 Specimens with 6.3-mm Thickness

The stress vs. strain responses for the 6.3-mm thick specimens with different hole diameters are shown in Figures 6.44 through 6.46. It can be seen from those figures that the surface strain values are compressive in nature except for the specimen with large hole (D/W = 0.75). This is due to the fact that the surface strain gage is located very close to the edge of the hole for specimens with large hole, where the state of stress is tensile in nature. The magnitude of the surface strain decreases as the hole diameter increases. The strain gages located inside the hole and orientated parallel to the applied load failed before the specimen failure. The strain gages were out of range at approximately 1.625% strain. The behavior of the axial surface strain and axial strain inside the hole is fairly linear up to failure. However, the response of the thickness strain and the transverse strain inside the hole are nonlinear for the specimens with D/W = 0.25 and tends to show linear behavior for other as D/W values. The thickness gage and the transverse gage readings were very close to each other for the range of D/W investigated. The erratic behavior of the strain gages very near to failure load indicates that the strain gages loose contact with the specimen, possibly due to local damage in the composite.

Typical load vs. displacement behavior for the 6.3-mm thick specimen with D/W = 0.75 is shown in Figure 6.47. Both the end shortening and the out-of-plane displacement are shown. The out-of-plane displacement transducer was placed very close to the edge of hole and was located at the interaction of the hole edge and the axis perpendicular to the applied load. It can be seen from Figure 6.47 that out of displacement behavior didn’t show any evidence of buckling. The load vs. end shortening behavior is fairly linear up to failure except at the beginning of the load introduction.
The axial strain distributions for various hole-sizes on 153-mm wide specimens for the 6.3-mm thickness are shown in Figure 6.48. It can be mentioned that the strain values on the surface of the specimens hole were measured using special type strain gages except for D/W=0.075 and are included in this figure. For this specimen, the hole was so small to mount strain gage on the surface of the hole and only the surface strains near the hole were measured. The measured strain values were normalized by remote applied axial strain of 0.0009, which is well below the failure strain for any of the specimens tested. The horizontal axis is the distance measured from the plate center normalized by the half-width of the specimen. It can be seen from Figure 6.48 that the strain values are highest on the surface of the hole and are found to be higher as the size of the hole increases. The strain values are decaying as the distance from the edge of the hole increases. The decay rate is found to be higher as the size of the hole decreases. The variation of strain concentration ($K_T$) factor as a function of hole diameter for the 6.3-mm thick specimens is shown in Figure 6.49. The theoretical strain concentration factors for various hole diameters were calculated from equations (6.4) and (6.5) and superimposed in Figure 6.49. It can be seen from Figure 6.49 that the experimental values agreed well with improved theory as compared to approximate theory for larger hole diameter.

An attempt was made to determine the failure initiation mechanisms and the failure progression mechanisms of 6.3-mm thick specimens with holes. In order to determine the failure initiation, the plate specimens with a hole were loaded in compression until the first cracking noise was heard. At this load, at least one specimen for each hole size was unloaded and removed from the test fixture for microstructural examination. Specimens were sectioned and examined under a stereo microscope.
The photomicrographs of the 6.3-mm thick specimens with a hole are shown in Figures 6.50 for $D/W = 0.25$ and in Figure 6.50 for $D/W = 0.5$. It can be seen from those figures that the delamination initiated at the edge of the hole due to the stress concentration. Possibly, the delamination triggered to cause microbuckling of the roving layer. A typical photograph of the fractured open hole specimen is shown in Figure 6.52 for the 6.3-mm thick specimen. It can be seen from this figure that the failure initiated at the edge of the hole and extended toward the edges of the specimen. In order to examine the failure surface, the specimens with holes were sectioned along the length direction and photographs were taken. The photographs of the sectioned specimens for various hole diameters of the 6.3-mm thick specimens are shown in Figures 6.53 and 6.54. It can be seen from these figures that failure mechanisms consist of delamination, fiber microbuckling and shearing of CSM layer located in the middle. The delamination was found to be more pronounced as the hole diameter increased. The damage also depends on the load, i.e., how soon before the final failure the test was stopped.

6.5.2.2.2 Specimens with 12.7-mm Thickness

The stress vs. strain responses in compression for the 12.7-mm thick specimens with various hole sizes are shown in Figures 6.55 through 6.57. It can be mentioned that the surface strain gage was on the surface of the specimen, oriented parallel to the direction of applied load and was located 25-mm from the loading edge. The transverse strain gage, the thickness strain gage and the axial gage were on the surface of the hole. The transverse gage was oriented transverse to the applied load and was located at the interaction of the hole edge and the direction of applied load. The thickness gage and the axial gages were located at the interaction of the hole edge and transverse to the applied
load; the thickness strain gage was oriented through the thickness and the axial gage was orientated parallel to the applied load. It can be seen from these figures that the axial surface strain and the axial strain inside the hole vary linearly until the failure load. The axial strain inside the hole shows a little irregular behavior in the beginning of the load for the large hole diameter (\(D/W=0.75\), Figure 6.57). The behavior of the thickness strain is found to be different for the specimen with \(D/W=0.25\) as compared to other diameter investigated. For \(D/W = 0.25\) (Figure 6.55), the thickness strain varies linearly up to 90 MPa. Beyond that stress level the thickness strain variation is found to be nonlinear. In fact, matrix cracking was heard during the compression testing when the axial compressive stress reached approximately 90 MPa, and the cracking noise continued with increasing load until failure. The thickness strain behavior beyond 90 MPa suggests that delamination has occurred. It can be seen from Figure 6.56 that the thickness strain behavior and the transverse strain behavior are very similar for the specimen with \(D/W = 0.5\). The transverse strain tends to decrease while thickness strain tends to increase as the hole diameter increases. The surface strains are tensile in nature for the specimen with \(D/W = 0.75\) (Figure 6.57), which indicates that the stress distribution due to larger hole size affects the surface strain. This is due to the fact that the strain gage is located very close to the hole edge for \(D/W = 0.75\) specimen and influenced by the hole strain distribution.

Typical load vs. displacement behavior of the specimens with hole of \(D/W = 0.75\) is shown in Figure 6.58. The out of plane displacement behavior shows no evidence of local buckling. The end-shortening behavior is linear up to failure except at the beginning. In fact, the load vs. end shortening behavior was found similar for all the
compression testing with the end-gripped fixture. The out of plane displacement behavior was also very similar for other hole sizes, and did not show any evidence of local buckling.

The axial strain distributions for various hole-sizes on 254-mm wide specimens for the 12.7-mm thickness are shown in Figure 6.59. It can be mentioned that the axial strains on the surface of the specimens hole were measured using special type strain gages except for D/W=0.075 and are included in this figure. For this specimen, hole was so small to mount strain gage on the surface of the hole and only the surface strains near the hole were measured. The measured strain values were normalized by remote applied axial strain of 0.0011, which is well below the failure strain for any of the 12.7-mm thick specimens tested. The horizontal axis is the distance measured from the plate center normalized by the half-width of the specimen. It can be seen from Figure 6.59 that the strain values are highest on the surface of the hole and are found to be higher as the size of the hole increases. The strain values are decaying as the distance from the edge of the hole increases. The decay rate is found to be higher as the size of the hole decreases. The variation of strain concentration ($K_t$) factor as a function of hole diameter for the 12.7-mm thick specimens is shown in Figure 6.60. The theoretical strain concentration factors for various hole diameters were calculated from equations (6.4) and (6.5) and superimposed in Figure 6.60. It can be seen from Figure 6.60 that the experimental values agreed well with improved theory as compared to approximate theory for larger hole diameter.

The photomicrographs showing the initiation of failure for the 12.7-mm thick specimens with holes are shown in Figures 6.61 for D/W = 0.50 and in Figure 6.62 for
D/W = 0.75. It can be seen from Figure 6.61 that the specimen with hole of D/W = 0.50 failed due to delamination, which was initiated at the edge of the hole and possibly triggered to cause fiber microbuckling of the roving layer. However, the specimens with hole of D/W = 0.75 show delamination and shearing of the CSM layers. A typical photograph of the fractured open hole specimen is shown in Figure 6.63 for the 12.7-mm thick specimen. It can be seen from the figure that the failure initiated at the edge of the hole and extended toward the edges of the specimen. In order to examine the failure surface, the specimens with holes were also sectioned along the length direction and photographed. The photographs of the sectioned specimens for various hole diameters of the 12.7-mm thick specimens are shown in Figures 6.64 and 6.65. It can be seen from those figures that failure mechanisms consist of delamination, fiber microbuckling and shearing of CSM layer.

6.5.2.3 Compressive Strength of Specimens with Holes

The summary of the compression test results with various hole diameters is shown in Table 6.6 for the 6.3-mm thick specimens and in Table 6.7 for the 12.7-mm thick specimens. The individual test results and the average values are also shown. The failure stress was calculated from the failure load by dividing the cross-sectional area. The failure strains were determined from the failure stress dividing the compressive modulus. It can be seen from the both the tables that data with in each group of specimens are very close.

The variation of compressive strength as a function of hole diameter to width ratio for both the thicknesses is shown in Figure 6.66. The compressive strengths of the specimens without holes were also included. It can be seen from Figure 6.66 that
although the compressive strength of undamaged specimens is higher for the 6.3-mm thick specimens compared to 12.7-mm thick specimens, the differences decrease for the specimens with holes.

6.5.2.4 Compression Behavior of Damaged Specimens

6.5.2.4.1 Specimens with 6.3-mm Thickness

The stress vs. strain response for the 6.3-mm thick specimen, damaged by transverse loading at 7.3 kN load, is shown in Figure 6.67. The strain gages were located very close to the damage region on both the indentation side and the opposite side. It can be seen from Figure 6.67 that the magnitude of the strain on the indentation side is higher than the opposite side. This could be due to the fact that more damage present in the opposite side causes local stiffness degradation, which results lower local strain as compared to the indentation side.

The load vs. displacement response is shown in Figure 6.68. Both the end shortening and the out of plane displacement data are included. The out of plane displacements were measured using two DCDT’s placed transversely on both sides at the plate center. The behavior of the two DCDTs shows local buckling after the applied load of 33% of the failure load. Multiple steps on load vs. end shortening curve showed load drop and rise after approximately 65 MPa until failure. A continuous cracking noise was heard with increasing load until failure occurred.

The strain distribution in the vicinity of the damaged region for the 6.3-mm thick specimen is shown in Figure 6.69. Several pairs of strain gages were mounted both on the indentation side and on the opposite side to capture the strain gradient due to presence of
damage. It can be seen that the strain concentration was present on the indentation side. It can also be noticed that the strain gages reading on both side of the specimen merge together far away from the damage. This behavior indicates that there was no damage after 40-mm distance from the center of the specimen.

The photograph of the typical fractured specimen with prior indentation damage is shown in Figure 6.70 for the 6.3-mm thick specimen. It can be seen from the figure that the failure initiated at the damaged region and propagate across the width.

6.5.2.4.2 Specimens with 12.7-mm Thickness

The stress vs. strain response for the 12.7-mm thick specimen, damaged at 18.7 kN load, is shown in Figure 6.71. The strain gages were located on the indentation side and on the opposite side of the specimen very close to the damaged region. It can be seen from Figure 6.71 that the magnitude of the strain on the indentation side is higher than the back surface strain reading, which is similar to 6.3-mm thick specimen. The strain gage located on the opposite side shows irregular behavior until failure with very little change in strain with the applied stress. The strain gage located on the indentation side shows fairly linear behavior at higher load as compared to the very beginning of the load.

The load vs. displacement response is shown in Figure 6.72. Both the end shortening and the out-of-plane displacement data are included. Two out-of-plane displacement transducers were used to record the out-of-plane displacement. One transducer was placed at the indentation side and was located on the center of the dent. The other transducer was placed at the opposite side and was located on the center of the damage. The two out-of-plane displacements show local buckling approximately 40% of
the failure load. The load vs. end shortening curve is very linear up to failure load without any load drops.

The strain distribution in the vicinity of the damage for the 12.7-mm thick specimen is shown in Figure 6.73. Several pairs of strain gages were also mounted both on the indentation side and the opposite side to capture the strain gradient on both sides due to presence of damage. To check the repeatability of the strain measurements, the strain data for two independent tests are shown in this figure. It can be seen from Figure 6.73 that the strain data are very much repeatable. It can also be seen that the strain concentration was present on the indentation side only. It is noticed that the strain gages reading on both side of the specimen are approaching together far away from the damage.

The photograph of the typical fractured specimen with prior indentation damage is shown in Figure 6.74 for the 12.7-mm thick specimen. It can be seen from the figure that the failure initiated at the damaged region and propagated across the width.

6.5.2.5 Residual Compressive Strength After Indentation Damage

The summary of the compression test results of the damaged specimens of both the 6.3-mm and 12.7-mm thick specimens are shown in Tables 6.8 and 6.9 respectively. The individual data were included at each damage level. The failure strain was calculated from the failure stress dividing the compressive modulus. The measured strains were also included for some specimens. The measured strain values were found to be lower than the failure strain calculated from the failure load for both the thicknesses. The failure stresses at each indentation damage were found very close showing less scatter. This is because the damage in the composite controlled the compressive failure for both the thicknesses.
6.5.2.6 Correlation between Damaged and Open Hole Specimens

The compressive strength and the strain distribution due to the hole and prior indentation damage in the specimens were compared to extract a parameter that could be used as a measure of damage resistance and tolerance of pultruded composites.

The strain distribution in the vicinity of the hole and the damage are shown in Figure 6.75 for the 6.3-mm thick specimens and in Figure 6.76 for the 12.7-mm thick specimens. The strain distribution for various hole sizes was included in each figure; however, only strain distribution due to indentation damage was included for the damage level of 7.3 kN for the 6.3-mm thickness and of 18.7 kN for the 12.7-mm thickness. It can be seen from both figures that the strain distribution the hole specimen with \( D/W = 0.075 \) is found to be very close to the 7.3 kN indentation damage for the 6.3-mm thickness and 18.7 kN indentation damage for the 12.7-mm thickness. It is to be noted that the strain concentration for this hole size \( (D/W=0.075) \) was not measured because of the difficulties due to the small size hole.

The residual compressive strength as a function of hole size was established by fitting a best fit curve, and the residual compressive strength of the damaged specimens were superimposed on the best fit curve to determine the "equivalent-hole-diameter" of the damaged specimen. The superimposed compressive strength data for the damaged specimens and hole specimens is shown in Figure 6.77 for the 6.3-mm thickness and in Figure 6.78 for the 12.7-mm thickness. The scatter band of the experimental data is also shown as an error bar. It can be shown from both the figures that scatter was found higher for the damaged specimens as compared to the open hole specimens. The "equivalent-
hole-diameter" was extracted from each figure and was plotted as a function of various damage parameters.

The relationship between the "equivalent-hole-diameter" and the back surface crack length for both the specimens is shown in Figure 6.79. A best-fit straight line was also shown to represent the data for each thickness. It can be seen from Figure 6.79 that the experimental data fall very close to the best fit lines, which indicates that the relationship can be represented as linear. The slope of the curve is found to be higher for the 6.3-mm thick specimens as compared to 12.7-mm thick specimens. The relationship between the "equivalent-hole-diameter" and the dent depth is shown in Figure 6.80. It can be seen from Figure 6.80 that the relationship is very non-linear and this relationship can be represent by a single curve for both the thicknesses. The "equivalent-hole-diameter" as a function of damage diameter is shown in Figure 6.81 for both the thicknesses. It can be seen from Figure 6.81 that the relationship is linear. However, the different best-fit straight-line equation is needed to represent the behavior for each thickness.

The residual compressive strength data were also plotted as a function of damage parameters. The variation of residual compressive strength as a function of dent depth is shown in Figure 6.82 for both the thicknesses. It can be seen from the figure that the relationship can be represented using a single curve for both the thicknesses. The compressive strength vs. damage area for both the thicknesses is shown in Figure 6.83. It can be seen from this figure that a single curve can be drawn to represent the relationship for both the thickness. The residual compressive strength as a function of indentation force for both the thicknesses is shown in Figure 6.84. The corresponding undamaged strength was also included. It can be seen from this figure that the damaged specimens

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did not show any degradation of compressive strength unless the threshold indentation force was exceeded. This threshold force is found to be higher for the thicker specimens. The residual compressive strength as a function of back surface crack length is shown in Figure 6.85 for both the thicknesses. It can be seen from this figure that a single curve can also be drawn to represent the relationship both the thicknesses.
Figure 6.1: Photograph of the quasi-static indentation test setup
Figure 6.2: Strain gages locations (back-to-back) for the 152-mm x 102-mm plate specimen (6.3-mm thick)
Figure 6.3: Strain gages locations (back-to-back) for the 254-mm x 178-mm plate specimen (12.7-mm thick)
Figure 6.4: Typical instrumented open hole specimen
Figure 6.5: Typical specimen in the support fixture ready to test
Figure 6.6: Photograph of the typical compression testing showing the data acquisition system and the DCDT’s

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Figure 6.7: Indentation force as a function of plate center displacement for the repeatability test (6.3-mm thick)
Figure 6.8: Indentation force as a function of plate center displacement for the repeatability test (12.7-mm thick)
Table 6.1: Summary of the repeatability test results for the 6.3-mm thick specimens

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Max. deflection (mm)</th>
<th>Max. Indentation force (kN)</th>
<th>Damage area (cm²)</th>
<th>Dent depth (mm)</th>
<th>Back surface crack length (mm)</th>
<th>Energy absorbed (N-m)</th>
</tr>
</thead>
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<tr>
<td>408-26</td>
<td>5.8</td>
<td>6.9</td>
<td>17.0</td>
<td>1.9</td>
<td>51.3</td>
<td>30.5</td>
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<td>1.7</td>
<td>43.2</td>
<td>26.0</td>
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<td>12899-03</td>
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<td>47.2</td>
<td>32.1</td>
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<tr>
<td>12899-02</td>
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<td>2.0</td>
<td>50.5</td>
<td>32.2</td>
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Table 6.2: Summary of the repeatability test results for the 12.7-mm thick specimens

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<th>Specimen ID</th>
<th>Max. deflection (mm)</th>
<th>Max. Indentation force (kN)</th>
<th>Damage area (cm²)</th>
<th>Dent depth (mm)</th>
<th>Back surface crack length (mm)</th>
<th>Energy absorbed (N-m)</th>
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<td>2.9</td>
<td>96.5</td>
<td>123.1</td>
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<td>2.0</td>
<td>73.7</td>
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<td>-</td>
<td>1.7</td>
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<td>99.6</td>
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<td>507-22</td>
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<td>-</td>
<td>2.1</td>
<td>97.3</td>
<td>101.4</td>
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Figure 6.9: Indentation force as a function of plate center displacement at various unloading stages for 6.3-mm thick specimen
Figure 6.10: Indentation force as a function of plate center displacement at various unloading stages for 12.7-mm thick specimen
Figure 6.11: Photograph showing front surface damage at static indentation load of 7.3 kN (6.3-mm thick)
Figure 6.12: Photograph showing front surface damage at static indentation load of 16.8 kN (12.7-mm thick)
Figure 6.13: Photograph showing back surface cracks at static indentation load of 7.3 kN (6.3-mm thick)
Figure 6.14: Photograph showing back surface cracks at static indentation load of 16.8 kN (12.7-mm thick)
Figure 6.15: Typical x-radiograph showing the internal damage due to quasi-static indentation loading up to Failure (6.3-mm thick)
Figure 6.16: Typical x-radiograph showing the internal damage due to quasi-static indentation loading up to Failure (12.7-mm thick)
Table 6.3: Summary of the damage characterization test results for the 6.3-mm thick specimens

<table>
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<tr>
<th>Specimen ID*</th>
<th>Load level</th>
<th>Damage area (cm²)</th>
<th>Dent depth (mm)</th>
<th>Back surface crack length (mm)</th>
<th>Energy absorption (N-m)</th>
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<td>-</td>
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<td>0.102</td>
<td>-</td>
<td>0.93</td>
</tr>
<tr>
<td>406-5</td>
<td></td>
<td>No damage</td>
<td>0.109</td>
<td>-</td>
<td>0.98</td>
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<td></td>
<td></td>
</tr>
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<td>0.239</td>
<td>23.6</td>
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<td>2.8</td>
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<td>2.6</td>
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<td>0.178</td>
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<td>2.5</td>
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<td>0.254</td>
<td>23.6</td>
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<td>C (5.8 kN)</td>
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<td>40.4</td>
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<td>0.533</td>
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<td>35.1</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI406-16</td>
<td>D (6.7 kN)</td>
<td></td>
<td>0.813</td>
<td>43.9</td>
<td>14/2</td>
</tr>
<tr>
<td>CAI406-17</td>
<td></td>
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<td>0.806</td>
<td>43.7</td>
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</tr>
<tr>
<td>CAI406-18</td>
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<td></td>
<td>0.826</td>
<td>46.0</td>
<td>13.1</td>
</tr>
<tr>
<td>406-19</td>
<td></td>
<td>15.0</td>
<td>0.927</td>
<td>47.2</td>
<td>14.2</td>
</tr>
<tr>
<td>406-20</td>
<td></td>
<td>13.7</td>
<td>0.851</td>
<td>43.9</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI408-21</td>
<td>E (7.3 kN)</td>
<td></td>
<td>1.753</td>
<td>51.1</td>
<td>22.2</td>
</tr>
<tr>
<td>CAI408-22</td>
<td></td>
<td></td>
<td>1.00</td>
<td>50.8</td>
<td>15.6</td>
</tr>
<tr>
<td>CAI408-23</td>
<td></td>
<td></td>
<td>1.143</td>
<td>45.0</td>
<td>17.1</td>
</tr>
<tr>
<td>408-24</td>
<td></td>
<td>17.0</td>
<td>1.041</td>
<td>45.7</td>
<td>17.0</td>
</tr>
<tr>
<td>408-25B</td>
<td></td>
<td>15.7</td>
<td>0.902</td>
<td>46.2</td>
<td>13.8</td>
</tr>
</tbody>
</table>

* Specimen ID starts with CAI are for the damage tolerance study and specimen ID without CAI are for the damage characterization.
Table 6.4: Summary of the Damage Characterization Test Results for 12.7-mm thick specimens

<table>
<thead>
<tr>
<th>Specimen ID*</th>
<th>Load level</th>
<th>Damage area (cm²)</th>
<th>Dent depth (mm)</th>
<th>Back surface crack length (mm)</th>
<th>Energy absorption (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAI420-4</td>
<td>A (11.5 kN)</td>
<td>No damage</td>
<td>0.18</td>
<td>17.8</td>
<td>6.9</td>
</tr>
<tr>
<td>CAI420-6</td>
<td>A (11.5 kN)</td>
<td>No damage</td>
<td>0.19</td>
<td>22.6</td>
<td>7.5</td>
</tr>
<tr>
<td>CAI420-7</td>
<td>A (11.5 kN)</td>
<td>No damage</td>
<td>0.23</td>
<td>19.6</td>
<td>8.4</td>
</tr>
<tr>
<td>420-11</td>
<td>A (11.5 kN)</td>
<td>No damage</td>
<td>0.20</td>
<td>20.8</td>
<td>9.7</td>
</tr>
<tr>
<td>420-12</td>
<td>A (11.5 kN)</td>
<td>No damage</td>
<td>0.19</td>
<td>14.7</td>
<td>7.7</td>
</tr>
<tr>
<td>CAI420-3</td>
<td>B (13.1 kN)</td>
<td>-</td>
<td>0.52</td>
<td>47.5</td>
<td>23.3</td>
</tr>
<tr>
<td>CAI420-5</td>
<td>B (13.1 kN)</td>
<td>-</td>
<td>0.42</td>
<td>41.91</td>
<td>15.8</td>
</tr>
<tr>
<td>CAI420-8</td>
<td>B (13.1 kN)</td>
<td>-</td>
<td>0.50</td>
<td>39.9</td>
<td>24.6</td>
</tr>
<tr>
<td>420-1</td>
<td>B (13.1 kN)</td>
<td>13.0</td>
<td>0.34</td>
<td>34.3</td>
<td>16.4</td>
</tr>
<tr>
<td>420-2</td>
<td>B (13.1 kN)</td>
<td>10.8</td>
<td>0.48</td>
<td>40.9</td>
<td>27.0</td>
</tr>
<tr>
<td>CAI420-15</td>
<td>C (15.6 kN)</td>
<td>-</td>
<td>0.90</td>
<td>70.6</td>
<td>41.9</td>
</tr>
<tr>
<td>CAI420-14</td>
<td>C (15.6 kN)</td>
<td>-</td>
<td>0.84</td>
<td>66.3</td>
<td>36.7</td>
</tr>
<tr>
<td>CAI420-13</td>
<td>C (15.6 kN)</td>
<td>-</td>
<td>0.66</td>
<td>65.0</td>
<td>29.2</td>
</tr>
<tr>
<td>420-9</td>
<td>C (15.6 kN)</td>
<td>24.3</td>
<td>0.81</td>
<td>62.2</td>
<td>35.9</td>
</tr>
<tr>
<td>420-10</td>
<td>C (15.6 kN)</td>
<td>28.5</td>
<td>0.80</td>
<td>60.5</td>
<td>37.9</td>
</tr>
<tr>
<td>CAI507-16</td>
<td>D (16.8 kN)</td>
<td>-</td>
<td>1.40</td>
<td>79.8</td>
<td>64.4</td>
</tr>
<tr>
<td>CAI507-17</td>
<td>D (16.8 kN)</td>
<td>-</td>
<td>1.12</td>
<td>77.7</td>
<td>48.5</td>
</tr>
<tr>
<td>CAI507-18</td>
<td>D (16.8 kN)</td>
<td>-</td>
<td>1.35</td>
<td>91.9</td>
<td>63.2</td>
</tr>
<tr>
<td>507-19</td>
<td>D (16.8 kN)</td>
<td>49.0</td>
<td>1.69</td>
<td>88.9</td>
<td>67.3</td>
</tr>
<tr>
<td>507-20</td>
<td>D (16.8 kN)</td>
<td>40.9</td>
<td>1.13</td>
<td>77.2</td>
<td>55.3</td>
</tr>
<tr>
<td>CAI507-21</td>
<td>E (18.7 kN)</td>
<td>-</td>
<td>1.65</td>
<td>81.3</td>
<td>99.6</td>
</tr>
<tr>
<td>CAI507-22</td>
<td>E (18.7 kN)</td>
<td>-</td>
<td>2.12</td>
<td>97.3</td>
<td>101.4</td>
</tr>
<tr>
<td>CAI507-23</td>
<td>E (18.7 kN)</td>
<td>-</td>
<td>2.03</td>
<td>88.9</td>
<td>81.5</td>
</tr>
<tr>
<td>507-24</td>
<td>E (18.7 kN)</td>
<td>65.4</td>
<td>2.92</td>
<td>96.5</td>
<td>123.1</td>
</tr>
<tr>
<td>12899-02</td>
<td>E (18.7 kN)</td>
<td>68.3</td>
<td>1.99</td>
<td>73.7</td>
<td>115.1</td>
</tr>
</tbody>
</table>

* Specimen ID starts with CAI are for the damage tolerance study and specimen ID without CAI are for the damage characterization.
Figure 6.17: Damage area as a function of indentation force
Figure 6.18: Dent depth as a function of indentation force
Figure 6.19: Energy absorption as a function of maximum indentation force.
Figure 6.20: Energy absorption as a function of dent depth
Figure 6.21: Back surface crack length as a function of dent depth
Figure 6.22: Damage area as a function of dent depth
Figure 6.23: Photomicrographs showing no damage at 4 kN load (6.3-mm thick)
Figure 6.24: Photomicrographs showing few matrix cracks at 4.9 kN load (6.3-mm thick)
Figure 6.25: Photomicrographs showing matrix cracks and delaminations at 5.8 kN load (6.3-mm thick)
Figure 6.26: Photomicrographs showing delamination accompanying with fiber breakage at 6.7 kN load (6.3-mm thick)
Figure 6.27: Photomicrographs showing extensive delamination and fiber breakage at 7.3 kN load (6.3-mm thick)
Figure 6.28: Photomicrographs showing extensive delamination and fiber breakage at failure load of 7.3 kN (6.3-mm thick)
Figure 6.29: Photomicrographs showing no damage at 11.5 kN load (12.7-mm thick)
Figure 6.30: Photomicrographs showing no damage at 13.1 kN load (12.7-mm thick)
Figure 6.31: Photomicrographs showing matrix cracks at 15.6 kN load (12.7-mm thick)
Figure 6.32: Photomicrographs showing matrix cracks and delamination at 16.8 kN load (12.7-mm thick)

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Figure 6.33: Photomicrographs showing extensive delamination and fiber breakage at failure load of 18.7 kN (12.7-mm thick)
Figure 6.34: Contact force vs. indentation relationship at small indentation stage for 6.3-mm thick specimens

$F = 34.3 \alpha^{1.5}$
Figure 6.35: Contact force vs. indentation relationship at small indentation stage for 12.7-mm thick specimens

$F = 51.7 \alpha^{1.5}$
Figure 6.36: Contact force vs. indentation relationship at various indentation stages for 6.3-mm thick specimens.
Figure 6.37: Contact force vs. indentation relationship at various indentation stages for 12.7-mm thick specimens
Figure 6.38: Compressive stress vs. strain response for 6.3-mm thick plate specimen with back-to-back strain gages near plate center (3,6)
Figure 6.39: Load vs. displacement plot for 6.3-mm thick specimen
Figure 6.40: Compressive stress vs. strain response for 12.7-mm thick specimens with back-to-back Strain gages located at plate center (4,9)
Figure 6.41: Load vs. displacement plot for 12.7-mm thick specimen

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Table 6.5: Summary of the Test Results for Undamaged Plate Specimens in Compression

<table>
<thead>
<tr>
<th>Specimen Thickness (mm)</th>
<th>Specimen ID</th>
<th>Failure Load (kN)</th>
<th>Failure Stress (Mpa)</th>
<th>Failure Strain* %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>183.6</td>
<td>266.4</td>
<td>1.52(1.49)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>183.8</td>
<td>261.9</td>
<td>(1.49)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>165.5</td>
<td>256.3</td>
<td>(1.44)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>177.6</strong></td>
<td><strong>261.5</strong></td>
<td><strong>1.52</strong></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>491.1</td>
<td>226.6</td>
<td>1.33(1.27)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>486.3</td>
<td>220.7</td>
<td>(1.23)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>508.7</td>
<td>231.0</td>
<td>(1.29)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>495.4</strong></td>
<td><strong>226.1</strong></td>
<td><strong>1.33</strong></td>
</tr>
</tbody>
</table>

*Failure strain in parenthesis calculated from failure load
Figure 6.42: Photograph of a typical fractured undamaged specimen (6.3-mm thick)
Figure 6.43: Photograph of a typical fractured undamaged specimen (12.7-mm thick)
Figure 6.44: Compressive stress vs. strain curves for 6.3-mm thick plate specimen with $D/W = 0.25$
Figure 6.45: Compressive stress vs. strain curves for 6.3-mm thick specimen with D/W = 0.50
Figure 6.46: Compressive stress vs. strain curves for 6.3-mm thick plate specimen with $D/W = 0.75$
Figure 6.47: Load vs. displacement plot for 6.3-mm thick plate specimen with \( D/W = 0.25 \)
Figure 6.48: Axial strain distribution in the vicinity of a hole for several hole diameters in 102-mm wide plate specimens of 6.3-mm thickness
Figure 6.49: Variation of strain concentration factor as a function of hole diameter to width ratio (6.3-mm thick)
Figure 6.50: Photomicrograph of specimen with hole (D/W =0.25) showing initiation of failure (6.3-mm thick)
Figure 6.51: Photomicrograph of specimen with hole \((D/W = 0.5)\) showing initiation of failure \((6.3\text{-mm thick})\)
Figure 6.52: Photograph of a typical failed specimen with hole (6.3-mm thick)
Figure 6.53: Photographs of the cross section of the failed specimens with various diameter holes (6.3-mm thick)
Figure 6.54: Photographs of the cross section of the failed specimens with various diameter holes (6.3-mm thick)
Figure 6.55: Compressive stress vs. strain curves for 12.7-mm thick plate specimen with 
$D/W = 0.25$
Figure 6.56: Compressive stress vs. strain curves for 12.7-mm thick plate specimen with 
D/W = 0.50
Figure 6.57: Compressive stress vs. strain curves for 12.7-mm thick plate specimen with D/W = 0.75
Figure 6.58: Load vs. displacement plot for 12.7-mm thick plate specimen with $D/W = 0.75$
Figure 6.59: Axial strain distribution in the vicinity of a hole for several hole diameters in 178-mm wide plate specimens of 12.7-mm thickness
Figure 6.60: Variation of strain concentration factor as a function of hole diameter to width ratio (12.7-mm thick)
Figure 6.61: Photomicrograph of specimen with hole (D/W =0.50) showing initiation of failure (12.7-mm thick)
Figure 6.62: Photomicrograph of specimen with hole (D/W =0.75) showing initiation of failure (12.7-mm thick)
Figure 6.63: Photograph of a typical failed specimen with hole (12.7-mm thick)
Figure 6.64: Photographs of the cross section of the failed specimens with various diameter holes (12.7-mm Thick)
Figure 6.65: Photographs of the cross section of the failed specimens with various diameter holes (12.7-mm thick)
Table 6.6: Summary of the Test Results for 6.3-mm thick specimens with Hole

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Hole Diameter (mm)</th>
<th>Hole Diameter to Width Ratio</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain(^2), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.6</td>
<td>0.07</td>
<td>131.6</td>
<td>193.2</td>
<td>1.08</td>
</tr>
<tr>
<td>1</td>
<td>15.4</td>
<td>0.15</td>
<td>106.0</td>
<td>153.9</td>
<td>0.86</td>
</tr>
<tr>
<td>1</td>
<td>22.3</td>
<td>0.22</td>
<td>93.3</td>
<td>133.7</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>22.4</td>
<td>0.22</td>
<td>99.6</td>
<td>144.1</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>22.3</td>
<td>0.22</td>
<td>92.2</td>
<td>141.3</td>
<td>0.79</td>
</tr>
<tr>
<td>Average</td>
<td>22.3</td>
<td>0.22</td>
<td>95.0</td>
<td>139.7</td>
<td>0.78</td>
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<tr>
<td>1</td>
<td>33.0</td>
<td>0.32</td>
<td>71.2</td>
<td>103.7</td>
<td>0.58</td>
</tr>
<tr>
<td>1</td>
<td>44.5</td>
<td>0.44</td>
<td>64.9</td>
<td>97.8</td>
<td>0.55</td>
</tr>
<tr>
<td>2</td>
<td>44.5</td>
<td>0.43</td>
<td>63.7</td>
<td>97.3</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>44.5</td>
<td>0.44</td>
<td>60.8</td>
<td>94.2</td>
<td>0.53</td>
</tr>
<tr>
<td>Average</td>
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<td>0.44</td>
<td>63.1</td>
<td>96.4</td>
<td>0.54</td>
</tr>
<tr>
<td>1</td>
<td>56.0</td>
<td>0.54</td>
<td>56.4</td>
<td>81.9</td>
<td>0.46</td>
</tr>
<tr>
<td>1</td>
<td>66.7</td>
<td>0.65</td>
<td>45.0</td>
<td>67.4</td>
<td>0.38</td>
</tr>
<tr>
<td>2</td>
<td>66.7</td>
<td>0.65</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>66.7</td>
<td>0.65</td>
<td>40.2</td>
<td>62.4</td>
<td>0.35</td>
</tr>
<tr>
<td>Average</td>
<td>66.7</td>
<td>0.65</td>
<td>42.6</td>
<td>64.9</td>
<td>0.37</td>
</tr>
</tbody>
</table>

\(^1\)All Compression Specimens have L = 153.4-mm, W = 102.6-mm and \( t = 6.6\)-mm

\(^2\)Failure Strains were calculated based on the failure stress and the Young's modulus found from the short-block compression tests.
Table 6.7: Summary of the Test Results for 12.7-mm thick specimens with Hole\(^1\)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Hole Diameter (mm)</th>
<th>Hole Diameter to Width Ratio</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain(^2), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.5</td>
<td>0.07</td>
<td>342.7</td>
<td>158.6</td>
<td>0.89</td>
</tr>
<tr>
<td>1</td>
<td>26.7</td>
<td>0.15</td>
<td>279.0</td>
<td>129.1</td>
<td>0.72</td>
</tr>
<tr>
<td>1</td>
<td>41.3</td>
<td>0.23</td>
<td>270.6</td>
<td>121.8</td>
<td>0.68</td>
</tr>
<tr>
<td>2</td>
<td>41.2</td>
<td>0.23</td>
<td>267.3</td>
<td>123.0</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>41.2</td>
<td>0.23</td>
<td>257.2</td>
<td>117.0</td>
<td>0.65</td>
</tr>
<tr>
<td>Average</td>
<td>41.2</td>
<td>0.23</td>
<td>265.0</td>
<td>120.6</td>
<td>0.67</td>
</tr>
<tr>
<td>1</td>
<td>62.3</td>
<td>0.35</td>
<td>222.1</td>
<td>102.1</td>
<td>0.57</td>
</tr>
<tr>
<td>1</td>
<td>82.6</td>
<td>0.46</td>
<td>200.4</td>
<td>90.7</td>
<td>0.51</td>
</tr>
<tr>
<td>2</td>
<td>82.5</td>
<td>0.46</td>
<td>200.1</td>
<td>90.3</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>82.5</td>
<td>0.46</td>
<td>197.6</td>
<td>89.9</td>
<td>0.50</td>
</tr>
<tr>
<td>Average</td>
<td>82.5</td>
<td>0.46</td>
<td>199.4</td>
<td>90.3</td>
<td>0.50</td>
</tr>
<tr>
<td>1</td>
<td>101.5</td>
<td>0.57</td>
<td>130.8</td>
<td>60.8</td>
<td>0.34</td>
</tr>
<tr>
<td>1</td>
<td>123.6</td>
<td>0.69</td>
<td>112.1</td>
<td>50.8</td>
<td>0.28</td>
</tr>
<tr>
<td>2</td>
<td>123.6</td>
<td>0.69</td>
<td>100.6</td>
<td>45.7</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>123.5</td>
<td>0.69</td>
<td>106.4</td>
<td>48.0</td>
<td>0.27</td>
</tr>
<tr>
<td>Average</td>
<td>123.6</td>
<td>0.69</td>
<td>106.4</td>
<td>48.2</td>
<td>0.27</td>
</tr>
</tbody>
</table>

\(^1\)All Compression Specimens have L = 255.0-mm, W = 178.8-mm and t = 12.3-mm

\(^2\)Failure Strains were calculated based on the failure stress and the Young’s modulus found from the short-block compression tests.
Figure 6.66: Compressive strength as a function of hole diameter to specimen width ratio for 6.3-mm and 12.7-mm thick plate specimens
Figure 6.67: Stress vs. strain curves for 6.3-mm thick plate specimen with damage at 7.3 kN load (Strain gages are back-to-back near damage)
Figure 6.68: Load vs. displacement curves for 6.3-mm plate specimen with damage at 7.3 kN load (DCDT’s are located at center of damage)
Figure 6.69: Axial strain distribution in the vicinity of the damaged region for 6.3-mm thick plate specimen at a load of 7.3 kN.
Figure 6.70: Photograph of a typical failed damaged specimen (6.3-mm thick)
Figure 6.71: Stress vs. strain curves for 12.7-mm thick plate specimen with damage at 18.7 kN load (Strain gages are back-to-back near damage)
Figure 6.72: Load vs. displacement curves for 12.7-mm plate specimen with damage at 18.7 kN load (DCDT’s are located at center of damage)
Figure 6.73: Axial strain distribution in the vicinity of the damage for 12.7-mm thick plate specimen at a load of 18.7 kN
Figure 6.74: Photograph of a typical failed damaged specimen (12.7-mm thick)
Table 6.8: Summary of the Test Results for 6.3-mm thick specimens with Static Damage

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
<td>146.9</td>
<td>212.0</td>
<td>1.19</td>
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<tr>
<td>2</td>
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<td>186.0</td>
<td>265.0</td>
<td>1.49</td>
</tr>
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<td>3</td>
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<td>165.5</td>
<td>236.0</td>
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<td>Average</td>
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<td>166.1</td>
<td>237.7</td>
<td>1.33</td>
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<th>Specimen</th>
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<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>4.9</td>
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<td>172.2</td>
<td>0.97</td>
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<td></td>
<td>121.9</td>
<td>173.5</td>
<td>0.97</td>
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<tr>
<td>3</td>
<td></td>
<td>117.1</td>
<td>168.3</td>
<td>0.94 (0.86)</td>
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<tr>
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<td>120.1</td>
<td>171.3</td>
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<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
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<tr>
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<td>85.4</td>
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<td></td>
<td>85.5</td>
<td>130.7</td>
<td>0.73</td>
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<td>3</td>
<td></td>
<td>89.0</td>
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<tr>
<td>Average</td>
<td></td>
<td>86.6</td>
<td>132.6</td>
<td>0.74</td>
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<table>
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<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
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</thead>
<tbody>
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<td>124.1</td>
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<td>86.9</td>
<td>128.7</td>
<td>0.72</td>
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<td>80.2</td>
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<td>Average</td>
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<td>83.1</td>
<td>125.3</td>
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<table>
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<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.3</td>
<td>84.0</td>
<td>124.5</td>
<td>0.70 (0.67)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
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<td>3</td>
<td></td>
<td>79.1</td>
<td>115.8</td>
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<tr>
<td>Average</td>
<td></td>
<td>81.6</td>
<td>120.2</td>
<td>0.68</td>
</tr>
</tbody>
</table>

\(^1\) All Compression Specimens have L = 152-mm, W = 102-mm and t = 6.3-mm
\(^2\) Failure Strains were calculated based on the failure stress and the Young’s modulus found from the short-block compression tests. The measured strain values are the parenthesis.
Table 6.9: Summary of the Test Results for 12.7-mm thick specimens with Static Damage

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
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<td>366.7</td>
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<tr>
<td>Average</td>
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<td>397.7</td>
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<table>
<thead>
<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
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</thead>
<tbody>
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<td>313.7</td>
<td>143.3</td>
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<td>381.8</td>
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<td>0.96</td>
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<tr>
<td>3</td>
<td></td>
<td>315.5</td>
<td>143.0</td>
<td>0.80 (0.73)</td>
</tr>
<tr>
<td>Average</td>
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<td>337.0</td>
<td>152.7</td>
<td>0.85</td>
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</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>326.2</td>
<td>147.2</td>
<td>0.82</td>
</tr>
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<td></td>
<td>296.8</td>
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<td>0.74</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>297.3</td>
<td>134.6</td>
<td>0.75</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>306.8</td>
<td>138.4</td>
<td>0.77</td>
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</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>284.4</td>
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<td>0.66</td>
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<td>3</td>
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<td>298.6</td>
<td>135.2</td>
<td>0.75</td>
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<tr>
<td>Average</td>
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<td>281.9</td>
<td>127.5</td>
<td>0.71</td>
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</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Damage Level (kN)</th>
<th>Failure Load (kN)</th>
<th>Failure Stress, (MPa)</th>
<th>Failure Strain, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>265.2</td>
<td>120.0</td>
<td>0.67</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>263.4</td>
<td>121.0</td>
<td>0.68 (0.49)</td>
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<td>Average</td>
<td></td>
<td>262.5</td>
<td>119.5</td>
<td>0.67</td>
</tr>
</tbody>
</table>

1 All Compression Specimens have L = 254-mm, W = 178-mm and t = 12.7-mm
2 Failure Strains were calculated based on the failure stress and the Young's modulus found from the short-block compression tests. The Measured strain values are in parenthesis.
Figure 6.75: Axial strain distribution for the 6.3-mm thick specimens with various hole sizes and with damage at 7.3 kN load.

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Figure 6.76: Axial strain distribution for 12.7-mm thick plate specimens with various hole sizes and with damage at 18.7 kN load.
Figure 6.77: A comparison of compressive strength of damaged specimens and specimens with hole (6.3-mm thick)
Figure 6.78: Comparison of compressive strength of damaged specimens and specimens with hole (12.7-mm thick)
Figure 6.79: Relationship between the equivalent hole diameter of the damaged specimens and the back surface crack length
Figure 6.80: Relationship between the equivalent hole diameter of the damaged specimens and the dent depth.
Figure 6.81: Relationship between equivalent hole diameter of the damaged specimens and the average damage diameter

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Figure 6.82: Compressive strength as a function of dent depth
Figure 6.83: Compressive strength as a function of projected damage area
Figure 6.84: Compressive strength as a function of indentation force
Figure 6.85: Compressive strength as a function of back surface crack length
CHAPTER VII

SUMMARY AND CONCLUSIONS

7.1 Summary

The primary thrust of the present investigation is to characterize and model the pultruded glass fiber reinforced polymer composites. The characterization includes details such as: measurement of elastic constants; the stress gradient effects on tensile strength; compressive properties measurements; modeling of compression test specimens and finite element study of compressive behavior; statistical treatment of strength data; damage resistance due to static indentation loading; and damage tolerance due to hole and damage in compression. The modeling of material include the prediction of layers elastic and strength properties and subsequent use of these data for stress analysis using finite element method.

The elastic constants (both E and G) were measured for the 6.3-mm thick sheet. Static tensile tests, vibration tests and ultrasonic tests were performed. Both the bar and disk specimens were used to measure E and G in different inplane directions. The main purpose of this study was to determine the elastic constants of pultruded composite utilizing a single specimen, in the form of circular disk, to measure all the elastic constants using ultrasonic method. Piezoelectric transducers (E- and G-crystals) were used to produce and detect dilatational waves (P-waves) and shear waves (S-waves) in
ultrasonic method. E-crystals were used to only measure the P-wave velocity. The S-wave velocity was measured using both the E-and G-crystals. Ultrasonic data generated from the bar specimens were verified with the static tensile tests and vibration tests data. Using a circular specimen, three independent methods were developed to measure all the elastic constants from ultrasonic method.

The effects of specimen size and stress gradient on tensile strength were also studied. Specimens were prepared from the sheets of 3.2-mm and 12.7-mm thicknesses with the fiber orientation along the pultrusion direction and transverse to the pultrusion direction. Specimens were tested in tension, 3-point flexure and 4-point flexure. A large number of data were generated for statistical analysis using a 2-parameter Weibull, normal and lognormal distributions. The statistical parameters were determined and compared for each test. The tensile strength was predicted from the flexure test data and compared with the experimental results. The stress vs. strain response, the microstructural examination and the failure analysis were also performed.

Compressive properties such as compressive strength, strain to failure and compressive modulus were determined experimentally using a short-block compression test specimen. Compression test specimens were prepared from the pultruded sheets with thicknesses of 6.3-mm and 12.7-mm. Specimens with the axial direction oriented at 0°, 30°, 45°, 60° and 90° to the pultrusion direction were prepared. The test specimens were rectangular with a length of 44.4-mm and a width of 25.4-mm. The specimens were instrumented with a pair of back to back strain gage at the center of the specimen to check bending and global buckling. Five axial strain gages were also mounted across the width of some of the specimens to check the uniform stress distribution. The ends and
sides of each specimen were machined flat and parallel. A large number of specimens were tested to determine the compression strength variability and also to determine the design allowable. The failure analysis was performed using a stereo microscope to determine the compressive failure initiation and post failure mechanisms.

The damage resistance and damage tolerance of 6.3-mm and 12.7-mm thick pultruded composites were investigated. The plate specimens were tested under a quasi-static indentation loading to investigate the damage resistance. Damage was induced in the specimens at various incrementally increased force levels, selected from the load-displacement behavior of the material up to failure. The extent of damage was measured in the form of dent depth, back surface crack length, etc., and in the form of damage area obtained from the x-radiography technique. The damaged specimens were sectioned along the longitudinal and transverse direction, and the sectioned specimens were photographed using a stereo microscope in order to determine the damage progression at each load level. A correlation was established among the variables to extract a parameter that could be used to measure the damage resistance of composite structures. The contact behavior of composite plate and the steel spherical indentor was also studied to determine the contact force-indentation relationship. The contact stiffness was measured and compared with modified Hertz law.

The end-gripped compression test fixture was used to investigate the damage tolerance of pultruded composites. Compression tests were performed on both the damaged specimens and the open-hole specimens. Damaged specimens were instrumented extensively with strain gages near the damage. The hole specimens were instrumented with strain gages near the hole to measure the strain distribution and inside.
the surface of the hole to capture the strain concentration as well as interlaminar strain. The undamaged specimens were instrumented with several pairs of back-to-back axial strain gages to capture any evidence of global buckling during the compression test. A relationship between the compressive strength and hole-diameter was established and compared with the residual compressive strength of the damaged specimens to determine the "equivalent-hole-diameter" of the damage specimens. A strain distribution due to hole and damage was compared. Finally, a correlation between damage parameters and the "equivalent-hole-specimens" was established, which could be used as a measure of damage resistance and damage tolerance of pultruded composite structures.

Pultruded composite materials were modeled to predict the elastic properties of the constituent layers (roving and continuous strand mat) for the finite element study. A compression test specimen was modeled using two-dimensional layered plate and shell elements. The finite element analysis was performed to study the (i) specimen behavior, (ii) in-plane stress distribution and (iii) the stress distribution through the thickness under compressive loading.

7.2 Conclusions

7.2.1 Measurement of Elastic Constants

In-plane elastic moduli of pultruded composites have been determined by static (strain gages), vibration (natural frequencies) and ultrasonic (piezoelectric transducers) methods. Seven bar specimens, 305-mm long and 25-mm wide with their axis making 0° to 90° in increment of 15° with the pultruded direction, were tested in static tension (with
strain gages), in flexural vibration (with accelerometer and impact hammer) and in ultrasonic with piezoelectric sensors. In ultrasonic method, Young’s modulus was measured with E-crystals, and shear modulus was measured with E and G-crystals. Slotted and unslotted bars and three circular disks (305-mm, 75-mm and 25-mm diameter) were used as test specimens. The static results were used as a base line data for the ultrasonic results. Dynamic modulus was measured using flexural vibration of bar specimens for three modes, and was found negligible effect on excitation frequencies. However, the Young’s modulus, measured using ultrasonic methods, was found to be higher than the static values for bar and disk specimens. This could be due to the effect of dynamic effects in ultrasonic tests. The 25-mm diameter disk specimen was found to be inappropriate for the ultrasonic measurement. Shear modulus measured using G-crystals and E-crystals on bar and disk specimens was found to be agreed well when compared to the static results. Finally, ultrasonic method was used to measure from all the in-plane elastic constants using the 305-mm disk specimen. Three independent test procedures were developed and utilized, namely, wave propagation velocity, P-wave propagation and S-wave propagation, to determine all the elastic constants of pultruded composites. It was found that the in-plane elastic constants measured all three ultrasonic methods were very close to the static values, except for the transverse modulus. The E(θ) and G(θ) as function of fiber orientation angles were found to be higher for all three ultrasonic methods as compared to the static method.
7.2.2 Stress Gradient Effects on Strength

A large number of specimens were tested in tension, 3-point flexure and 4-point flexure to investigate the stress gradient effect on tensile strength. Twenty identical specimens for each case were prepared from 3.2-mm and 12.7-mm thick sheet along the 0° and 90° directions. The two-parameter Weibull model was applied to analyze the test data. The shape parameter and the scale parameter were determined for each case using least square fitting in a linearized form of distribution, and the probability of survival plots were compared with the experimental data for tension, 3-point flexure and 4-point flexure. A good agreement between experimental and Weibull prediction was observed for all cases. However, the shape parameter was found to be a narrow range of 14 to 23 for the 3.2-mm thickness and was found to be a wider range of 16 to 65 for the 12.7-mm thickness. It can be mentioned that Bullock [25] reported the same shape parameter and that Whitney [26] reported different values for the graphite/epoxy composites. The measured and Weibull-predicted ratios of bending strength to tensile strength, and the tensile strength ratios of two different sized tensile specimens did not show consistent agreement. However, it was always found the trend that the tensile strength was lower than 4-point flexure than 3-point flexure showing the stress gradient effect. The tensile test is not so difficult; in other words, the pultruded composite is not so brittle that we have to conduct flexure test to estimate the tensile strength. On the other hand, higher tensile strength of smaller specimen was not observed, showing no size effect. Failure analysis indicated that failure modes of the tensile specimens of 38-mm wide specimens were different when compared to the 12.7-mm wide tensile specimens. Microstructural
observation also suggested that the flaw distribution in the materials was not uniform, which appears to be a basic requirement for the Weibull distribution.

7.2.3 Measurements, Modeling and FEM Study for Compression Loading

Compressive properties were measured for the 6.3-mm and the 12.7-mm thick pultruded composites. Compressive strength, strain-to-failure and compressive modulus were measured as a function of fiber orientation angle. Specimens were instrumented with back to back axial strain gages and with various axial strain gages across the width. Evidence of two back-to-back strains reading indicated that buckling and bending was not observed. The axial strain distribution across the width of the specimen indicated that the compressive load was introduced successfully through the material during the compression test. Most of the specimens failed near the gage section. End crushing was not observed. The longitudinal compressive strength was found to be 8% higher for the 6.3-mm thick composites when compared to 12.7-mm thick composites. However, the transverse compressive strength for the 12.7-mm thick composites was found to be 8% higher than the 6.3-mm thick composites. The compressive strength data were analyzed using a 2-parameter Weibull, normal and lognormal distribution to determine the proper distribution to be used to evaluate the B-basis design allowable. The compressive strength data for the 12.7-mm thick composite were found to be well fitted with 2-parameter Weibull model. However, lognormal distribution was found to be better for the 6.3-mm thick composites. The failure analysis suggested that fiber microbuckling triggered shear failure for the 6.3-mm thick composites and delamination was responsible for failure of 12.7-mm thick composites.
The pultruded composite materials were modeled as similar to laminated composites. The roving layer was modeled as unidirectional composite and the CSM layer was modeled as random composite. The elastic properties were predicted using various micromechanics equations. The elastic properties were used for laminated plate analysis to predict the elastic constant of pultruded composite. The predicted material properties were found to be very close to the experimental results except for the transverse modulus ($E_2$). The predicted layer properties were used in the finite element analysis to predict the compressive behavior. The compression test specimen was modeled using a 4-noded isoparametric layered plate and shell element. Both linear and geometric nonlinear analysis was performed to evaluate the specimen behavior and the stress distribution under compressive loading. Fairly good correlation was found between the predicted and experimental data in terms of stress-strain and load-end shortening response. The state of stress within the gage section of the short-block compression test specimen was found to be fairly uniaxial, which supports the measurement of the compressive modulus and the Poisson’s ratio.

7.2.4 Damage Resistance and Damage Tolerance of Pultruded Composites

Damage resistance and damage tolerance of 6.3-mm and 12.7-mm thick pultruded composites were investigated experimentally. The plate specimens were tested under a quasi-static indentation loading to investigate the damage resistance of pultruded composites. Damage was introduced in the specimens at various incrementally increased force levels selected from the load-displacement behavior of the material up to the failure. The surface damage in the form of dent depth, the back surface crack and the
internal damage in the form of delamination area obtained from the X-radiography were measured. The delamination area was found to be elliptical for both the thicknesses. The damaged specimens were sectioned along the longitudinal and the transverse direction, and the sectioned specimens were photographed in order to determine the damage progression at each load level. The photographs of the sectioned damaged specimens showed that the matrix cracks occurred first followed by delamination and finally fiber fracture. The delamination extended through the thickness in both longitudinal and transverse direction. At each load level, a total of five specimens were tested, and it was found that the damage parameters within each group vary widely. A correlation among the damage parameters was attempted to determine a single parameter that could be used as a measure of damage resistance for both the thicknesses.

The contact behavior between the composite plate and the steel indentor was also investigated to determine the force-indentation relationship (Hertz contact law). The contact stiffness was measured 34.3 kN/mm$^{1.5}$ for the 6.3-mm thick composites and 51.7 kN/mm$^{1.5}$ for the 12.7-mm thick composites. The modified Hertz contact law predicted the contact stiffness about 10% higher for the 6.3-mm thick composites and 3.5% higher for the 12.7-mm thick composites. The critical indentation was measured to be 0.23-mm for the 6.3-mm thick composites and to be 0.43-mm for the 12.7-mm thick composites.

The end-gripped compression test fixture was used to investigate the damage tolerance of pultruded composites. Compression tests were performed on both the damaged and open-hole specimens. The undamaged specimens were instrumented with several pairs of back-to-back axial strain gages to capture any bending and buckling. The stress-strain responses of the back-to-back pairs of strain gages showed no evidence of
bending or global buckling. The out-of-displacement behavior, measured using DCDT, also showed no evidence of global buckling. Both the damaged and open-hole specimens were instrumented extensively with strain gages near damage or the hole to measure the strain distribution. The strain at hole-edge was found to be higher as the diameter of hole increased. The measured strain concentration factor based on the gross area agreed well with the theory. Failure analysis of the compressive failed specimens showed that delamination, fiber microbuckling and shearing of CSM layer were responsible for compressive failure. The compressive strength as a function of hole-diameter for both the thicknesses was established and it was found that a single curve could be fitted for both the thicknesses.

The strain distribution near the damage on both sides of the specimen indicated that the strain concentration was present only on the indentation side. The strain distribution due to damage and hole on the specimen were found to be dissimilar when it was compared with the "equivalent-hole-diameter" of the damaged specimen. This equivalent-hole diameter was calculated by superimposing the compressive strength of damaged specimens on the compressive strength as a function of hole diameter plot. The "equivalent-hole-diameter" was found to be much smaller that the hole-diameter calculated based on damage area.

The calculated "equivalent-hole-diameter" and residual compressive strength of damaged specimen was plotted as function of various damage parameters. The objective was to extract a parameter that could use as a measure of damage resistance and damage tolerance of pultruded composites. It was concluded that the dent depth could be used as a measure of damage resistance and damage tolerance of pultruded composites studied.
REFERENCES


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CURRICULUM VITA
for
MRINAL CHANDRA SAHA

NAME: Mrinal Chandra Saha
DATE OF BIRTH: July 10, 1963

DEGREES:
- Doctor of Philosophy (Mechanical Engineering and Mechanics), Old Dominion University, Norfolk, Virginia, May 2001
- Master of Science (Mechanical Engineering), Tuskegee University, Tuskegee, Alabama, May 1996
- Master of Science (Mechanical Engineering), Bangladesh University of Engineering & Technology, Dhaka, March 1992
- Bachelor of Science (Mechanical Engineering), Bangladesh University of Engineering & Technology, Dhaka, August 1988

PROFESSIONAL CHRONOLOGY:
- Department of Mechanical Engineering, Tuskegee University, Tuskegee, Alabama
  - Lecturer, September 2000 – Present
- Department of Mechanical Engineering, Old Dominion University, Norfolk, Virginia
  - Teaching and Research Assistant, January 1996 – August 2000
- Department of Mechanical Engineering, Tuskegee University, Tuskegee, Alabama
  - Teaching and Research Assistant, September 1993 – December 1995
- Department of Mechanical Engineering, Bangladesh University of Engineering & Technology, Dhaka
  - Assistant Professor, October 1992 – August 1993
- Department of Mechanical Engineering, Bangladesh University of Engineering & Technology, Dhaka
  - Lecturer, August 1988 – October 1992

CONSULTING/PART TIME EMPLOYMENT:
- With various industries in testing PVC pipes, strainers, hand siren and hand pumps

SCIENTIFIC AND PROFESSIONAL SOCIETIES MEMBERSHIP:
- American Society for Mechanical Engineers (ASME)
- Society for Experimental Mechanics (SEM)
HONORS AND AWARDS:
Outstanding Teaching Assistant Award 2000, College of Engineering and Technology, Old Dominion University
Nominated for University Best Graduate Teaching Assistant Award 1999/2000, Old Dominion University
Selected as a member of Phi Kappa Phi honor society 1999, Old Dominion University
Special Doctoral Research Assistantship (SDRA) Award 1998, Old Dominion University
University Merit Scholarship 1982-1988, Bangladesh University of Engineering & Technology
Merit Scholarship of Education Board 1980-1982, Bangladesh Education Board

COURSES TAUGHT DURING LAST FIVE YEARS:

MAJOR SERVICE ACTIVITIES:
Assisted Department and College in conducting laboratory demonstration experiments for engineering open houses and freshman preview sessions
Upgraded the Solid Mechanics Laboratory
Supervised undergraduate students project

SCHOLARLY ACTIVITIES COMPLETED:
Refereed Journal Articles


Refereed National/International Proceedings


Technical Reports

Presentations not Published in Proceedings (International)