A COMPARISON STUDY OF COMPOSITE LAMINATED PLATES
WITH HOLES UNDER TENSION

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ABSTRACT

A Comparison Study of Composite Laminated Plates with Holes under Tension

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A study was conducted to quantify the accuracy of numerical approximations to deem sufficiency in validating structural composite design, thus minimizing, or even eliminating the need for experimental test. Error values for stress and strain were compared between Finite Element Analysis (FEA) and analytical (Classical Laminated Plate Theory), and FEA and experimental tensile test for two composite plate designs under tension: a cross-ply composite plate design of $[(0/90)_4]_s$, and a quasi-isotropic layup design of $[0_2/+45/-45/90_2]_s$, each with a single, centered hole of 1/8" diameter, and 1/4" diameter (four sets total). The intent of adding variability to the ply sequences and hole configurations was to gauge the sensitivity and confidence of the FEA results and to study whether introducing enough variability would, indeed, produce greater discrepancies between numerical and experimental results, thus necessitating a physical test. A shell element numerical approximation method through ABAQUS was used for the FEA.

Mitsubishi Rayon Carbon Fiber and Composites (formerly Newport Composites) unidirectional pre-preg NCT301-2G150/108 was utilized for manufacturing—which was conducted and tested to conform to ASTM D3039/D3039M standards.

A global seed size of 0.020, or a node count on the order of magnitude of 30,000 nodes per substrate, was utilized for its sub-3% error with efficiency in run-time.

The average error rate for FEA strain from analytical strain at a point load of 1000lbf was 2%, while the FEA-to-experimental strains averaged an error of 4%; FEA-to-analytical and FEA-to-tensile test stress

values at 1000lbf point load both averaged an error value of 6%. Suffice to say, many of these strain values were accurate up to ten-thousandths and hundred-thousandths of an in/in, and the larger stress/strain errors between FEA and test may have been attributed to the natural variables introduced from conducting a tensile test: strain gauge application methods, tolerance stacks from load cells and strain gauge readings.

Despite the variables, it was determined that numerical analysis could, indeed, replace experimental testing. It was observed through this thesis that a denser, more intricate mesh design could provide a greater level of accuracy for numerical solutions, which proves the notion that if lower error rates were necessitated, continued research with a more powerful processor should be able to provide the granularity and accuracy in output that would further minimize error rates between FEA and experimental. Additionally, design margins and factors of safety would generally cover the error rates expected from numerical analysis.

Future work may involve utilizing different types of pre-preg and further varied hole dimensions to better understand how the FEA correlates with analytical and tensile test results. Other load types, such as bending, may also provide insight into how these materials behave under loading, thus furthering the conversation of whether numerical approximations may one day replace testing all together.

Keywords: Composites, Finite Element Analysis, Tensile Tests,
Holes in Plates

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NOMENCLATURE

AIAA	- American Institute of Aeronautics and Astronautics
ARC	- Aerospace Research Central
ASME	- American Society of Mechanical Engineers
ASTM	- American Society for Testing and Materials
Avg	- Average
BC	- Boundary condition
CAE	- Computer-aided engineering
CF	- Concentrated force
E	- Modulus of Elasticity
E	- ABAQUS strain component
FEA/M	- Finite Element Analysis/Model
FRP	- Fiber-reinforced plastic/polymer
G	- Shear Modulus
GPa	- Giga-pascals
H	- Height
i	- Direction of fibers (subscript)
in	- Inch
j	- Direction of load (subscript)
KN	- Kilo-newton
L	- Direction of fibers (subscript)
L	- Length
Lbf	- Pound-force
Min	- Minutes
mm	- Millimeters
Msi	- Mega-pounds per square inch
NASA	- National Aeronautics and Space Administration
ODB	- Open database

Pre-Preg	- "Pre-impregnated" composite fibers
psi	- Pounds per square inch
Q	- Stiffness component of ply material
[Q]	- Stiffness matrix (per ply)
$[\bar{Q}]$	- Reduced (composite) stiffness matrix
Rev	- Revolutions
S	- ABAQUS stress component
Sec	- Seconds
T	- Direction transverse to fibers (subscript)
temp	- Temperature
Uni	- Unidirectional
v	- Poisson's Ratio
V	- Volt
V_0	- Initial voltage
Vac	- Vacuum
Vol	- Volume
W	- Width
°	- Degree
"	- Inch
ϵ	- Strain (in/in)
σ	- Stress (psi/Msi)
Σ	- Summation

I. INTRODUCTION

Motivation for Study

Fiber-reinforced polymer (FRP) materials were first introduced in the early 1930s, spurring a new age of manufacturing and mechanical design based on a Mesopotamian practice of mixing straw into mud to provide structural reinforcement to bricks and pottery. Today, the concept of combining various materials to produce a new discrete material with its own set of properties is not a novel concept; however, the latest advancements made in composites have proven to be invaluable in situations where low strength-and-stiffness-to-weight ratios, resistance to fatigue, or an inability to rust are found to be mission critical. As a result, composites, specifically FRP, have been widely adopted by the defense, aerospace, automobile, and sports-technology industries, where FRP materials are seen everywhere from bicycle frames to launch vehicle fuselages; reference Figure 1's Electron as an example.

Figure 1 - *Electron* was introduced as the first carbon-composite launch vehicle back in 2014, per Auckland-based aerospace company, Rocket Lab
(Henderson, 2014)

The stark differences in manufacturing FRP from traditional metals—procuring the raw fiber and matrix materials, the lay-up processes, the special tooling necessary for molding and testing fabricated specimens—drive up and front-load the production and testing costs. Studies have been conducted to show how high-speed drilling of FRP structures (tested up to 38,650 rev/min in a particular study), a significant source of tool wear, is considered to be a notable problem in the composites manufacturing world, especially since composites-compatible drill bits are upwards of ten times the cost of traditional drill bits.

Additionally, due to the inherent variability in manufacturing heterogeneous materials, structural analysis of composite materials have introduced different levels of complexity when compared to the analyses of isotropic, homogenous materials. Due to these intricacies, a level of unpredictability was to be expected of these results. Hence, researchers have relied heavily on testing different configurations of composite designs to build the fidelity of their numerical methods, such as Finite Element Analysis (FEA) models, to better predict how certain designs, holes, and cracks would behave under varying loading and environmental conditions.

Now, with decades of research and advancements in analytical and numerical tools, the motivation for this thesis is to better understand how the results of these numerical methods, specifically FEA, compare to the results of traditional analytical methods and tensile test results. With the high-cost of resources and knowledge-base required for manufacturing and testing composite specimens, the question to be ultimately answered is: have the advancements in numerical methods progressed enough such that its results are accurate enough to deem experimental testing superfluous in validating structural design?

To begin this discussion, databases such as American Institute of

Aeronautics and Astronautics (AIAA), National Aeronautics and Space Administration (NASA) Technical Reports Server, American Society of Mechanical Engineers (ASME), and Aerospace Research Central (ARC) were thoroughly researched with the focus on how error rates trended between numerical methods and testing results, regardless of test/specimen design. If a strong correlation existed, it could make way to begin the discussion that perhaps numerical methods could be sufficient in validating structural design. If a strong correlation did not exist, each study was further investigated to identify what worked well for their research, and what may have contributed to a higher error rate; these lessons-learned were folded into the design and numerical methods of this thesis.

To contribute to the substantiation of this discussion, two composite laminate plate designs with different ply orientations, with two different hole dimensions per set, were studied for stress and strain under tensile loading at a point local to the hole; reference Table 1. Additionally, mesh designs were varied to consider how the number of nodes in a Finite Element Model (FEM) may affect the accuracy of the results, and how that accuracy may change depending on varied ply orientations and hole configurations—"configurations" defined as the quantity and geometry of the holes in the specimens of interest. The intent of adding variability to the study was to gauge the confidence of the FEA results: would introducing enough variability eventually necessitate a physical test? Coupling the findings from this thesis with the conducted research should provide a better understanding of to what extent varying structural designs, with their correlative mesh designs, impacts the accuracy and robustness of an FEM, providing structural design engineers more confidence and better insight into their FEA results.

ASTM D3039/D3039M, or *Standard Test Method for Tensile Properties*

of *Polymer Matrix Composite Materials* was consulted to identify the requirements for designing a proper composite tensile test. Figure 2, sourced from ASTM D3039/D3039M, identifies the proper geometry requirements for performing a composite tensile test.

Tensile Specimen Geometry Requirements	
Parameter	Requirement
Coupon Requirements:	
shape	constant rectangular cross-section
minimum length	gripping + 2 times width + gage length
specimen width	as needed ^A
specimen width tolerance	± 1 % of width
specimen thickness	as needed
specimen thickness tolerance	± 4 % of thickness
specimen flatness	flat with light finger pressure
Tab Requirements (if used):	
tab material	as needed
fiber orientation (composite tabs)	as needed
tab thickness	as needed
tab thickness variation between tabs	± 1 % tab thickness
tab bevel angle	5 to 90°, inclusive
tab step at bevel to specimen	feathered without damaging specimen

Figure 2 – Specimen Geometry Requirements from ASTM D3039/D3039M (ASTM, 2014)

In light of these requirements, Table 1 identifies the test specimens' design and geometry requirements:

Table 1 - Cross and Quasi-isotropic layup configuration requirements

	Single Hole, 1/8", 1/4"	Single Hole, 1/8", 1/4"
Ply Designs <u>Cross:</u> $[(0/90)_4]_s$ <u>Quasi:</u> $[0_2/$ $+/-45/90_2]_s$
Test Coupons (L x W x H)	10" x 1.0" x 0.12" (5 pieces per hole size, 10 pieces total)	10" x 1" x 0.10" (5 pieces per hole size, 10 pieces total)

Mitsubishi Rayon Carbon Fiber and Composites, formerly known as *Newport Composites*, unidirectional pre-preg NCT301-2G150/108 was utilized to manufacture these substrates.

Previous Works

With the growing popularity of composite applications over the last half-century, there have been countless studies conducted to better understand the structural behavior of composite laminates and how they're analyzed.

The initial set of previous works researched was inclusive of all variations of test parameters and objectives to better understand what has been studied in the world of composite research, and to what extent;

this would provide a scope of understanding of where this thesis would fall in the context of composite research.

The nature of the research conducted includes in-plane tensile and compressive loading, such as Ercin, G.H.'s *Size Effects on the Tensile and Compressive Failure of Notched Composite Laminates*, published in 2013, while ensuring variations in the types of composite materials studied, such as Haque, A.'s *Stress Concentrations and Notch Sensitivity in Woven Ceramic Matrix Composites Containing a Circular Hole – An Experimental, Analytical, and Finite Element Study*, published in 2005. More popular material selections of carbon-carbon, or carbon-epoxy, were also researched, i.e., Hatta, H.'s 2004 study *Fracture Behavior of Carbon-Carbon Composites with Cross-ply Lamination*, and Gan, K.W.'s 2013 study on the *Effect of High Through-Thickness Compressive Stress on Fibre Direction Tensile Strength of Carbon/Epoxy Composite Laminates*.

Some studies included specimens with holes and notches, such as Arslan, H.M.'s 2009 *Effect of Circular Holes on Cross-ply Laminated Composite Plates* – sometimes multiple holes and notches, as seen from Dan-Jumbo, E.'s 2009 research *Strength of Composite Laminate with Multiple Holes*. At times, studies focused on holes filled with pins – Atas, A.'s *Failure Analysis of Laminated Composite Plates with Two Parallel Pin-Loaded Holes* from 2008, and others in different temperature environments, such as Watanabe, S.'s *Evaluation of Tensile Strength of Woven Carbon/Epoxy Composite Laminates at Cryogenic Temperatures Using the Open Hole Specimens* from 2011.

Regardless of the test parameters selected for each study, the focus was placed on how the error rates trended between numerical results and experimental test. Hence, from the 30 sources that were studied in detail for this thesis, a concerted effort was made to include research that had attained both numerical and experimental results; ten of the research

reports had clear and reliable instances for comparison, providing a total of 175 data points of numerical-to-experimental comparisons that were able to be made. These sources can be found in the *Works Referenced* section of the thesis, as well as the appendix. Reference Figure 3 to see the frequency of error rates that was identified from these 175 instances.

Figure 3 - Frequency of error rates identified from the 175 instances of numerical and experimental comparisons

102 of the 175 instances, or 59% of the all comparisons, resulted in error rates less than 10%. Of those 102, 53 instances, or 30% of the 175 comparisons resulted in error rates less than 3%. However, 31 projects, or 18% of the total 175 comparisons, did experience error rates greater than 30%.

And although this small sample-size of 175 instances over 10 research projects may be insufficient to draw an adequate conclusion

regarding numerical-to-experimental error rates for every research conducted in composites, it can be an indicator of the capabilities of numerical methods.

Diving deeper into the greater-than-30% error comparisons, two sources stood out: Zhen, W.'s 2009 study *Stress Analysis of Laminated Composite Plates with a Circular Hole According to a Single-layer Higher-order Model*, and Xu, W.'s 2015 study *Experimental and Numerical Study on Cross-ply Woven Textile Composite with Notches and Cracks*.

Zhen's intent in this 2009 study was to study how current numerical methods could be improved by using a single-layer, higher-order numerical model instead for predicting stresses at curved free boundaries of laminated composite plates. His error rates ranged from 15-47% for his cross-ply substrates, and 15-43% for his quasi-isotropic substrates. Xu's 2015 study focused on validating the accuracy of the Cohesive Zone Model, comparing experimental results with predictions based on Max Strain, Max Stress, and Tsai-Wu criteria: the Max Strain approach averaged 8% error in tension, 21% error in compression, the Max Stress averaged 28% error in tension, 31% error in compression, and Tsai-Wu averaged 30% error in tension, 40% in compression.

It was inferred that when an author's objective was to study the accuracy of a new numerical approach, or a new numerical model, the error rates generally seemed to be larger – which contributed to the 31 projects at +30% error, per Figure 3. However, in the following example, Wang, Callus, and Bannister found the opposite to be true.

J. Wang, P.J. Callus, and M.K. Bannister performed a study evaluating the differences between experimental and numerical analysis of the tension and compression strength of un-notched and notched quasi-isotropic laminates. Using quasi-isotropic AS4/3501-6 pre-preg at [45/0/-45/90]_{2s} laminates in their study, Wang and company used two distinct

approaches to numerical methods: linear elastic and progressive damage. They discovered their linear elastic model either significantly underestimated (first-ply failure approach) or overestimated (last-ply failure approach) the strength of un-notched laminates, and that the progressive damage approach was able to better predict the un-notched specimens' strength, provided that the non-linear shear behavior was accounted for and that the appropriate failure criteria used (Wang, 2003).

What was discovered to be the more accurate numerical method through Wang's research could be implemented through the shell element model with basic material degradation laws found in commercially available FEM software, such as ABAQUS, which is the numerical method and FEA package that was used for this thesis.

Wang's experimental and FEA averaged an error of 1.5% when predicting peak loads, which differs from the objectives of this thesis, however, the study did provide a level of confidence that ABAQUS is a reliable numerical solution to compare with the experimental results. Wang's experiment did not include an analytical solution, it would have been interesting to see how his test and ABAQUS results compared with an analytical method of his choosing—as was seen through the completion of this thesis.

Much like error rates, several of the other sources provided constructive insight and lessons-learned on how to approach the design of this thesis.

Another study, conducted by Thomas M. Hermann and James E. Locke, focused on the failure analysis of anisotropic composites utilizing FEA software. Their application was a wind turbine blade structure constructed from 12k tex Toray T600 fibers consisting of a layer of 14.81 oz/yd² carbon fiber at 0°, a layer of 4 g/m² PES fibers at 90°, and 2 layers of 6 g/m² E-glass fibers oriented at ±60°, however, it was discovered that

the shear moduli of the composites from in-plane shear testing appeared to require correction (Hermann, 2005). Due to this, the study experienced an error average of 7.5%, ranging up to 19% error, between experimental and their most accurate prediction model used (Max Strain method).

This work was specifically referenced due to the difficulties Hermann faced with his shear test. As will be seen in Section III, the shear test coupons for this thesis did not fail due to the limiting capabilities of the INSTRON used. Hermann's study was instrumental to understanding how such issues with testing can affect critical test results, and was a good reminder and lessons-learned to reiterate the importance of attaining the correct material properties to reduce errors between prediction models and experimental results.

In 2007, Stephen R. Hallett, Wen-Guang Jiang, and Michael R. Wisnom conducted a study on how different ply stacking sequences can affect the open hole tensile strength of composite laminates. Using uni-directional carbon/epoxy pre-preg (Hexply IM7/8552), the strongest stack sequence was discovered to be $[-45/45/90/0]_s$, with a predicted FEA failure stress of 627MPa, and the weakest sequence was identified to be $[-45/90/0/45]_s$, with an FEA failure stress of 488MPa. It was concluded that stack sequences with 0° layer(s) at the surface or centerline were the strongest configurations per FEA, as are the ply stack sequences for this thesis—quasi-isotropic: $[0_2/45/-45/90_2]_s$, and cross-ply: $[(0/90)_4]_s$.

However, the average error between FEA and experimental was discovered to be slightly above 10%, which could be attributed to the modeling technique developed specifically for their research, which was used to capture the detail of sub-critical damage development at ply level in notched tensile test specimens (Hallett, 2007). Using a more traditional analytical method such as the Classical Laminated Plate Theory (CLPT), a lower error rate was seen for this thesis, as will be discussed

in Section VII.

In 2005, Anwarul Haque, Laboni Ahmed, and Arun Ramasetty performed a similar study to Hallett's, but focused on how stress concentrations may change based on varied ply sequences and notch configurations using a woven ceramic matrix composite; quasi-isotropic $[0/90/45/-45]_s$ and cross-ply $[0/90/0/90]_s$ laminates of woven SiC/SiNC were studied.

Per Haque and company's study, lay-up sequences were deemed to be insignificant for stress concentrations, and their notched strength data showed notch-insensitivity for specimens with smaller diameter holes (diameter-of-hole/width-of-specimen ratio of 0.2–0.3), but did, indeed, show a reduction in notch-insensitivity as the holes grew larger. However, Haque's error rates were larger than most from the selected studies: 31% between FEA and analytical, and 29% between FEA and experimental. An experiment with a more accurate FEA and/or analytical method may have delineated greater sensitivities to ply sequences and notch configurations, as was seen in the results of this thesis.

It would be expected that error rates less than 3% would be achievable if the lessons-learned from this body of research were taken into account and folded into the design of this thesis: using a point load to keep the analysis to a more predictable elastic region, using the shell element model through ABAQUS as discussed from Wang's research, and taking into account the ply-stack sequences and their effects from Hallett's and Haque's studies. Lower error rates between numerical and experimental results would provide higher confidence in numerical models, which would perpetuate and contribute to the discussion of retiring the experimental step all together.

Thesis Overview

Section I discusses the motivation for the thesis: are numerical methods, such as FEA, accurate enough to deem testing unnecessary? In order to prove this, it was established that the shell element model would be utilized through ABAQUS FEA, and the resulting stress/strain would be compared to analytical calculations and tensile test results.

Section II provides the manufacturing and testing steps for the composite specimens. The goal for this section was to determine the material properties of the pre-preg in use by completing tensile tests for the substrates identified in Table 2 below. Subsequently, a set of tensile tests was also completed for the cross-ply and quasi-isotropic substrates, found in Table 1, in order to consolidate all manufacturing and testing needs into one step (for efficiency).

These layups were baked in an autoclave at a cure cycle of 45psi, at a ramp rate of 5°/min, holding at 250° for 90 minutes, and cooling back down to ambient.

Five pull tests were conducted per layup, as dictated by ASTM D3039/D3039M. Per Hooke's Law, $\sigma = E\epsilon$, the slope of the stress/strain curves, or $E = \frac{\sigma}{\epsilon}$, from the pull tests for the specimens from Table 2 were leveraged to determine the Modulus of Elasticity in the direction of fibers (unidirectional 0°), E_L , the Modulus of Elasticity transverse to the direction of fibers (unidirectional 90°), E_T , and the Shear Modulus (angle ply, +/-45°), G_{LT} , of the pre-preg in use.

Table 2 - Layup designs for identifying material properties

	0°	90°	+/-45°
Ply Designs	[0] ₆	[90] ₁₂	[+/-45] ₈
Test Coupons (L x W x H)	10" x 1.0" x 0.04" (5 pieces)	7" x 1" x 0.08" (5 pieces)	10" x 1" x 0.12" (5 pieces)

Section III reviews the results from the tensile tests for material properties. An assessment was made to determine which test results would be included, which would be discarded, and if so, why. The averages for each case were then established and used as the material properties for the analytical and FEA studies.

Results from the cross-ply and quasi-isotropic cases were saved for discussion in Section VII.

Section IV provides an overview of the Classical Laminated Plate Theory. Having a firm grasp of the theory helps establish expectations for which results seem valid when exploring the tensile test and FEA results.

Section V delivers a validation for a baseline FEM by modeling the boundary conditions, reference points, and other test attributes from a published tensile test. When the baseline FEA's stress/strain output matches those of the published tensile test's, the baseline FEM will have been proven and would provide the foundation to now build the composite FEMs. A homogeneous material was used to simplify the FEM; this case is referred to as *the homogenous baseline*.

Section VI presents the methodology of how the FEA was run; what attributes went into the analysis, which point loads, and how post-processing of the resulting data was conducted.

Section VII is where all results were juxtaposed, comparing FEA results with those of the analytical calculations and tensile test results.

All studies were conducted in the elastic region to ease the comparison of analytical, test, and FEA. Unless proven otherwise, a baseline point load of 1000lbf was utilized for all analyses.

All cases studied entailed symmetrical laminates to simplify modeling and manufacturing—antisymmetric laminates require consideration of residual stresses from differences in elastic moduli and potential variations in coefficients of thermal expansion, which can also produce mid-layer, out-of-plane warping and other deformations.

This thesis builds upon decades of research on stress distribution in holes in composite structures. With seemingly endless permutations of fiber-to-matrix ratios, ply-angles, and hole configurations, there will always be value add to exploring more efficient methods of extrapolating confidence in how composite structures are analyzed and/or tested.

II. Manufacturing and Test

Material properties for layup designs were determined by performing a series of pull-tests on the layups themselves, per ASTM D3039/D3039M. To do so, each layup design of Table 2 was crafted using *Mitsubishi Rayon Carbon Fiber and Composites* (formerly *Newport Composites*) unidirectional pre-preg NCT301-2G150/108, minimizing waste in material while still attaining the layups required to perform the appropriate tests.

Manufacturing for Pull Test

To kick off manufacturing, the following materials were required:

- One (1) roll of *Mitsubishi Rayon Carbon Fiber and Composites* unidirectional pre-preg NCT301-2G150/108
- One (1) roll of flow media
- One (1) roll of breather material, aero weave
- One (1) roll of vacuum bag (or, "vac-bag")
- One (1) machined aluminum plate – 36" x 24"
- Hi-temp vac-bag tape
- Acetone
- Rubber gloves
- Protective eye gear / goggles, rubber gloves
- Blue painter's tape
- Apron
- Roller
- Box cutter w/ extra cartridge-blades
- Scissors
- Paper towels
- 115V vacuum pump, tubing, vacuum connector

- Autoclave capable of accommodating pressure/temperature profiles

The quality of the layup's surfaces is impacted by how clean the surfaces of the aluminum plate is made: the smoother the surface, the less bumps and nicks, which means less points for stress concentrations to build.

To begin, the proper protective eye gear, rubber gloves, and ventilation steps were all administered. Then, the aluminum plate was wiped down vigorously with acetone to ensure a smooth surface; reference Figure 4.

Figure 4 – Acetone is used to smooth the surface of the aluminum tooling plate; residue will create points of stress concentration on the resulting composite plates

Two layers of flow media (34" x 22") were measured and cut to fit the aluminum plate with a 1" margin around the perimeter. Blue painter's tape was used to secure the first layer of flow media to the aluminum plate. It is important to minimize impingement in the 1" margin to provide sufficient spacing to apply the vac-bag tape; impingement increases the possibility of not securing a proper seal when pulling vacuum, which would result in warped, creased, or unusable layups.

With the plate prepped, the layup designs from Tables 1 and 2 were cut to size using the box cutter, and layered accordingly using the roller. When rolling to flatten the layers of pre-preg, it is critical to ensure all air bubbles are pushed out between the layers, or deformations within the layers may form. It is not uncommon to briefly pull vacuum after rolling each individual layer to ensure complete flatness; reference Figure 5.

Figure 5 – The pre-preg is rolled flat and laid on top of flow media; correct spacing was ensured to reduce impingement with the region where vac-bag tape will be applied to the aluminum plate

Once the first layup was prepped, it was laid on top of the flow media secured to the aluminum plate. The second layer of flow media was then overlaid on the prepped pre-preg. Subsequently, vac-bag tape was carefully massaged on the aluminum plate along the 1" margins, focusing on the corners to ensure no air would escape when vacuum is pulled from where the layers overlap.

A sheet of vac-bag was cut to measure approximately 40" x 30", and a 1" x 1" cross was knifed where the vacuum connector would be placed. With the connector situated, additional vac-bag tape was used to provide

an additional seal to ensure full vacuum would be reached. As needed, a piece of breather was placed beneath the vacuum connector to prevent imprints on the layup when vacuum would be pulled. With all pieces in their respective places, the vac-bag was pulled taught over the layup configuration, and massaged into the vac-bag tape frame that was previously laid out; reference Figure 6.

Figure 6 – The vac-bag is sealed with the layup secured on the plate, with the vacuum connector resting on top of the layup, situated in place

With the layup properly sealed, the vacuum connector was connected to the 115V vacuum pump line. With the vacuum pulled, the entire layup configuration was inspected for leaks through visual inspection; additional vac-bag tape was used, where necessary, to ensure a full vacuum seal. It was important to ensure wrinkles were not created in the vac-bag, particularly on the pre-preg surface, to ensure the layup would not have any creases on its surface; reference Figure 7.

Figure 7 – Vacuum is pulled through the vacuum connector to perform a visual inspection for leaks prior to entering the autoclave

When the vacuumed configuration was deemed acceptable, the vacuum connector was disconnected from the 115V pump. Without manually releasing the vacuum from the vacuum connector, the layup configuration was transferred into the autoclave. When connecting the layup configuration to the autoclave's vacuum line, it was, once again, ensured no creases were formed on the vac-bag surface; reference Figure 8.

Figure 8 – Layup is inserted into and connected to the autoclave's vacuum pump (green hose)

With the autoclave's chamber door shut and the appropriate temperature/pressure profile loaded, the layup was cured to match the

requirements from the pre-preg's manufacturer's specifications: 45psi at a ramp rate of 5°/min, holding at 250°F for 90 minutes, and cooling back down to ambient. Upon completion, the layup configuration was removed from the autoclave, the vac-bag was peeled off from the aluminum plate, and a visual inspection was performed to ensure the cured layup would be fit for cutting; reference Figure 9.

Figure 9 – Visual inspection conducted to ensure blemishes conducive to forming stress concentrations are mediated

With the layup cured, the composite plate was cut per dimensions outlined in Table 2. Prior to proceeding, the lab safety requirements of the Cal Poly Composite Structures Lab were thoroughly reviewed to place emphasis on safety. Table 3 was completed and reviewed prior to performing any manufacturing to meet lab safety requirements. Risk Ratings were determined through Figure 10, provided by the Aerospace Department; depending on the consequence and likelihood of a risky scenario unfolding, each risk is identified as "Low" (blue), "Medium" (green), "High" (yellow), and "Very High" (red). All steps were identified to be "Low" or "Medium".

Table 3 – Risk Ratings determined for lab tasks performed; this step will help identify the higher risk steps that will be taken throughout manufacturing and test, bringing to focus safety

Task/ Scenario	Hazard	Associated harm	Existing controls	Any additional controls required?	Risk Rating		
					Consequences	Likelihood	Risk
Cutting test coupons	Tile-saw imposes a hazard on user and those in proximity; potential cuts from sharp edges of test coupons	Flying projectiles, cuts, dismemberment	<ul style="list-style-type: none"> Proper-usage training, safety goggles, closed-toed shoes, face mask to prevent inhaling of fibers, wool gloves, pre-activity prep/warnings, communication 	No	4	D	M
Drill-press for adding holes to test coupon	Drill-press imposes a hazard on user and those in proximity; potential cuts from sharp edges of test coupons	Flying projectiles, cuts, dismemberment	<ul style="list-style-type: none"> Training, safety goggles, closed-toed shoes, face mask to prevent inhaling of fibers, wool gloves 	No	4	D	M
Emery cloth install	Potential cuts from sharp edges of test coupons	None	<ul style="list-style-type: none"> Training, safety goggles, closed-toed shoes, rubber gloves 	No	2	D	L
Prep test coupons for strain gage install	Acetone will be used to prep surface of test coupons	Inhaling acetone is hazardous; also highly flammable	<ul style="list-style-type: none"> Training, safety goggles, closed-toed shoes, face mask to prevent inhaling of fumes, rubber gloves, clean-up supplies on hand in case of spillage 	No	3	D	M
Installing strain gages	Potential cuts from sharp edges of test coupons	None	<ul style="list-style-type: none"> Training, safety goggles, closed-toed shoes, rubber gloves 	No	2	D	L
Performing pull-test	Instron may malfunction; installation of tooling/test coupons may cause injury	Flying projectiles, cuts, dismemberment	<ul style="list-style-type: none"> Proper-usage training, safety goggles, closed-toed shoes, rubber gloves, pre-activity prep/warnings, communication; plexi-glass protective screen 	No	3	D	M

		CONSEQUENCES				
		1	2	3	4	5
LIKELIHOOD	A	M	H	H	VH	VH
	B	M	M	H	H	VH
	C	L	M	H	H	VH
	D	L	L	M	M	H
	E	L	L	M	M	M

Figure 10 – Risk rating matrix takes likelihood of an occurrence occurring with the severity of its consequences and assigns a rating of “Low” (blue), “Medium” (green), “High” (yellow), and “Very High” (red)

Figure 11 shows blue tape being used to mask-off each specimen for cutting. Having the proper orientations preset using the tape allowed the focus to remain on safety in using the tile saw. Figure 12

shows the completion of the cutting process utilizing the blue tape as guidelines:

Figure 11 – The laminate plate was measured to cut for each respective test coupon dimensions

Figure 12 – Blue painter's tape was used as a guideline for cutting, allowing the focus to remain on safety in using the tile saw

Figure 13 shows the coupons being prepped for the drill-press— they can be seen as blue stacks in the figure from the painter's tape; Figure 14 shows a test coupon being mounted and drilled.

Figure 13 - Coupons were prepped for the drill-press for those requiring holes

Figure 14 - Drill press used to put 1/8" and 1/4" holes in the applicable test coupons

For the sake of efficiency, all manufacturing was completed at the same time. Hence, the aforementioned steps were repeated for all remaining layup designs outlined in Tables 1 and 2. Table 4 contrasts test coupon requirements with the resulting test coupon dimensions and properties.

Table 4 - Specimen requirements compared to actual dimensions

Layups		Dimension Requirements (L x W x H)	Actual Dimensions (L x W x H)
Uni-Directional 0° [0] ₆		10" x 1.0" x 0.04" (5 pieces)	10" x 1.0" x 0.049" 6 ply (5 pieces)
Uni-Directional 90° [90] ₁₂		7" x 1" x 0.08" (5 pieces)	7" x 1" x 0.098" 12 ply (5 pieces)
Angle +/-45° [+/-45] ₈		10" x 1" x 0.12" (5 pieces)	10" x 1" x 0.13" 16 ply (5 pieces)
Cross, Single Hole 1/8" [(0/90) ₄] _s		10" x 1.0" x 0.12" (5 pieces)	10" x 1.0" x 0.13" 1/8" hole, 16 ply (5 pieces)
Cross, Single Hole 1/4" [(0/90) ₄] _s		10" x 1.0" x 0.12" (5 pieces)	10" x 1.0" x 0.13" 1/4" hole, 16 ply (5 pieces)
Quasi, Single Hole 1/8" [0 ₂ / +/-45 / 90 ₂] _s		10" x 1" x 0.10" (5 pieces)	10" x 1" x 0.098" 1/8" hole, 12 ply (5 pieces)
Quasi, Single Hole 1/4" [0 ₂ / +/-45 / 90 ₂] _s		10" x 1" x 0.10" (5 pieces)	10" x 1" x 0.098" 1/4" hole, 12 ply (5 pieces)

Prepping for Tensile Test

Tensile tests were conducted on an INSTRON 8801 servohydraulic testing system, located in Cal Poly's Aerospace and Mechanical

Engineering's Structures lab—reference Figure 15; the Instron was verified to meet the required rate of displacement of 0.05 in/min. Existing test jigs used previously for tensile tests meeting ASTM D3039/D3039M standards were installed on the INSTRON prior to testing.

Figure 15 - INSTRON 8801 utilized for pull tests

Strain Gauges: the primary concern with the test setup contributing to varying test results is the mounting method of the strain gauges; it is important strain gauges are mounted per manufacturer's recommendation with minimized variation from test specimen to test specimen. To note, the strain gauges used for the tensile tests were as follows—reference Table 5:

Table 5 - Strain gauges identified for reach ply design

Ply Design	Strain Gage Manufacturer & Model	Gage Factor (GF)	Resistance (Ohms)
Uni: $[0]_6$	Omega SGD-6/120-LY11	2.0	120 $\pm$ 0.35%
Uni: $[90]_{12}$	Omega SGD-6/120-LY11	2.0	120 $\pm$ 0.35%
Angle: $[\pm 45]_4$	Omega SGD-6/120-RY21	2.0	120 $\pm$ 0.35%
Cross: $[(0 / 90)_4]_s$	HBM 1-LY41-6/120	2.04	120 $\pm$ 0.30%
Quasi: $[0_2 / \pm 45 / 90_2]_s$	Micro-Measurements CEA-13-120FZ-120	2.12	120 $\pm$ 0.40%

Figures 16 through 19 show the strain gauges installed on the manufactured test coupons:

Figure 16 - Uni coupons, 0 and 90 with Omega strain gauges

Figure 17 - Angle-ply test coupons with Omega strain gauges

Figure 18 - Cross-ply with HBM strain gauges

Figure 19 - Quasi-isotropic coupons with Micro-Measurements strain gauges

Recall that:

$$V_f = \frac{V_o \text{ (strained)} - V_o \text{ (unstrained)}}{V_{EX}}$$

where $V_o \text{ (unstrained)}$ is the initial voltage at rest, $V_o \text{ (strained)}$ is the measured output during strain, and V_{EX} is the excitation voltage; depending on the Wheatstone bridge used, Figure 20 outlines which equation to use to determine the strain measured.

Figure 20 – Different Wheatstone bridges used to measure strain

The INSTRON has a built-in Quarter-Bridge to measure strain throughout the tensile test.

Tensile Test Challenges – Tabs

Tabs were a challenge. Initially going into the pull tests, emory cloth and/or sandpaper were recommended for use. However, the recommendation should have taken into account the maximum shear stress that would have been applied at the grips to sustain the necessary holding-power to complete the tensile tests. After a handful of failed attempts with extra sample coupons using sandpaper, the only available epoxy available in the lab, West System's Six10 thickened epoxy

adhesive, was identified for use, Figure 21; the epoxy would be used to secure 1" x 1" carbon composite squares leftover from manufacturing.

Figure 21 – West System's Six10 thickened epoxy adhesive's technical data sheet did not provide shear strength properties; a substitute epoxy would need to be identified

However, the Six10's technical data sheet did not provide specifications on the shear strength of the epoxy, thus, there was an inherent risk associated with utilizing this epoxy for all coupons. Hence, it was decided to only use the Six10 for the Unidirectional 0 and 90 coupons, as it was predicted these coupons would not require as much tensile stress to fail. Figures 22 and 23 show the application process:

Figure 22 - Six10 epoxy prepped to be applied to test coupons and carbon composite tabs

Figure 23 - Weighted plates were used to apply pressure while epoxy cured

The recommended cure time, according to the data sheet, was one to four days. With limited time in the lab, testing had to commence after one full day of cure. Figure 24 shows the test coupon mounted in the INSTRON for a tensile test.

Figure 24 – Unidirectional 90 test coupon mounted for tensile test

With a successful suite of testing for the Unidirectional 90 coupons, the Unidirectional 0 test coupons were still problematic; slipping had occurred, aborting the first run of the Unidirectional 0. Figure 25 shows the slipped tabs:

Figure 25 – A tab is slipping on the Unidirectional 0 test coupon—
stronger epoxy required

After some research, it was discovered 3M Scotch-Weld's Off-White DP460NS two-part epoxy, Figure 26, was specifically developed for high-shear applications, rated up to 1379psi for FRP at substrate failure, per 3M's specifications. Thus, a 1.25oz tube was ordered and was applied to the remaining test coupons, Figure 27. Once applied, the test coupons were finally ready for tensile testing.

For future instances, aluminum or fiberglass tabs would also be explored, as it had been recommended for their ability to better imprint into the test coupons to provide a more robust grip.

Figure 26 - 3M Scotch-Weld's DP460NS two-part epoxy developed specifically for high-shear stress applications

Figure 27 - Remaining test coupons applied with 3M Scotch-Weld's
DP460NS

Tensile Test Challenges – Strain Gauges

Test gauges were difficult to come by. General Atomic of San Diego was gracious enough to donate 35 strain gauges for the purposes of my thesis. The most challenging aspects of the strain gauges were identifying an efficient and repeatable process to administering the gauges to the test coupons, followed by soldering on lead wires to each respective specimen's gauge, and finally, verifying electrical continuity through the leads that would connect to the quarter bridge in the INSTRON to read strain during the tensile tests. Figures 28 shows the process that was developed to secure strain gauge leads:

Figure 28 – Strain gauges were secured to test coupons with Super Glue; lead wires were molded to sit on the solder pads of the strain gauges and then taped down to the test coupon to secure its position—solder was then applied to secure the electrical connection

Once all strain gauges were fitted, the test coupons were ready for test. However, it was discovered during the tensile testing that the strain gauges for the quasi-isotropic test coupons were defective; their test coupons had to have their strain gauges replaced.

III. Material Properties

Figure 29 shows the failure mode of the Unidirectional 0; every specimen shattered. The Unidirectional 90 coupons failed as expected, with varying failure points between the two end tabs. The Angle-ply specimens, however, never failed. It could be argued that at 16 plies and 0.13 inch thick, the Angle-ply coupons would not have failed at 0.05 in/min, since after all, the coupons elongated by up to 0.5 inches during the tensile test before the load would taper off. A point of contention for future tests, a higher capacity Instron would be recommended to induce failure.

Figure 29 - Unidirectional 0 tensile failure mode

Recall: Young's Modulus (E_L) is the slope of the stress/strain curve, or $E = \frac{\sigma}{\epsilon}$, therefore, two additional elements are required to determine E: the cross-sectional area of each respective test specimen, and the force exerted over the course of each tensile test. With these points determined, Figure 30 plots the stress/strain curve for the $[0]_6$ tensile test, and Table 6 identifies the correlating data, e.g., a Young's Modulus of $E_L = 13.7$ Msi or 94.5 GPa.

Figure 30 - Stress/strain curve for the $[0]_6$ tensile test

The slight variation in slopes may have been an indication of slipping; however, the first three results were used in the average, as they seemed the most consistent of the five tests.

Table 6 - $[0]_6$ Attributes

	E (Msi)	Max Load (lbf)	Max Stress (Msi)	Max Strain (in/in)
Run 1	13.9	9228	0.1883	0.0143
Run 2	13.5	10271	0.2096	0.0151
Run 3	13.8	6630	0.1353	0.0102
Run 4	15.5	10452	0.2133	0.0146
Run 5	14.1	6291	0.1284	0.0092
Avg	13.7	8710	0.1778	0.0132

The test results for Unidirectional 90, Figure 31 and Table 7, were used to determine $E_T = 1 \text{ Msi}$ or 6.9 GPa .

Figure 31 – Stress/Strain curve for the $[90]_{12}$ tensile test

E_T can generally be estimated to be roughly 1/10th of E_L ; the first two runs were taken into the average to determine E_T , as they most closely resembled the expected outcome.

Table 7 – $[90]_{12}$ Attributes

	E (Msi)	Max Load (lbf)	Max Stress (psi)	Max Strain (in/in)
Run 1	0.9924	151	2152	0.0022
Run 2	0.9959	171	2442	0.0030
Run 3	0.5479	158	2264	0.0041
Run 4	0.6475	204	2907	0.0043
Run 5	0.6097	186	2662	0.0051
Avg	1	161	2297	0.0026

The test results for Angle-ply, Figure 32 and Table 8, were used to determine $G_{LT} = 1.6$ Msi or 11.24 GPa.

Figure 32 – Stress/Strain curve for $[+/-45]_8$ tensile test

Again, the test specimens for the Angle-ply did not fail, however, they pulled more consistently than the previous two sets. Run 2 had a unexpected return in the elastic region—perhaps the strain gauge connection was noisy; Run 3 did not reach the range of stress levels expected.

Table 8 – $[+/-45]_8$ Attributes

	E (psi)	Max Load (lbf)	Shear Stress Elastic (psi)	Shear Strain at Elastic (in/in)	Max Stress (psi)	Max Strain (in/in)
Run 1	1.6822	1815	11018	0.0075	18147	0.1227
Run 2	2.8716	1817	11283	0.0060	18175	0.0620
Run 3	1.3772	1567	10246	0.0081	15667	0.1191
Run 4	1.7801	1697	11776	0.0074	16967	0.1263
Run 5	1.4176	1762	12266	0.0092	17625	0.1274
Avg	1.6	1758	11686	0.0080	17579	0.1255

Finally, Table 9 summarizes the material properties of unidirectional pre-preg NCT301-2G150/108 determined through tensile testing. Due to limitations in strain gauge availability, the Poisson's Ratio could not be measured through test, therefore it was necessary to take an estimation. Poisson's Ratio, v_{LT} , ranged anywhere from 0.1 to 0.4 in spec sheets; due to the age of the material, the pre-preg was assumed to be more brittle than its intended design, therefore, the v_{LT} was estimated to be 0.25.

Table 9 - Material properties of unidirectional pre-preg NCT301-2G150/108

Modulus of Elasticity, Direction of Ply	E_L	13.7 Msi 94.5 GPa
Modulus of Elasticity, Transverse to Ply	E_T	1 Msi 6.9 GPa
Shear Modulus, in Axes L/T	G_{LT}	1.6 Msi 11.2 GPa
Poisson's Ratio, in Axes L/T	v_{LT}	0.25*

These material properties were utilized for the analytical and FEA throughout the remainder of this thesis. The cross-ply and quasi-isotropic results will be discussed in Section VII.

IV. The Analytical Method: Cross and Quasi-isotropic

Hooke's Law states that force and displacement, as well as stress and strain, are linearly related ($\sigma = E\varepsilon$). Classical Laminated Plate Theory leverages this relationship to identify the stress, strain, and/or material properties of a composite laminate plate.

When analyzing unidirectional pre-preg, a material with one plane of symmetry, or a material of "transversely isotropic" properties, the stiffness matrix, Q , reduces down to Equation 1. In other words, the Q matrix identifies how the material layer will behave holistically, and its components (Q_{11} , Q_{12} , et al) provide specificity on how the material will behave depending on which axis the loading is applied, i , and in which direction the fibers are running, j . For example, Q_{11} is the material property along the direction of fibers when the load is applied in the direction of fibers, Q_{12} is the material property transverse to the direction of the fibers when the load is being applied in the direction of fibers (essentially, Poisson's Ratio—how much would the width of the specimen shrink when the load is being applied along the direction of fibers, Q_{11}).

$$Q_{ij} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \quad (\text{Eq. 1})$$

These stiffness components are defined by the material properties discovered through the tensile tests in Section IV, where E_{11} is equivalent to E_L , E_{22} is equivalent to E_T , and G_{LT} is equivalent to Q_{66} ; reference Equations 2 through 5 in *Appendix: Classical Laminated Plate Theory Equations*.

Since this study only consists of one type of pre-preg, Equations 2 through 5 need only be calculated once from the values in Table 9. Results are as follows:

$$Q_{11} = 13.70 \text{ Msi}$$

$$Q_{12} = 0.25 \text{ Msi}$$

$$Q_{22} = 1.00 \text{ Msi}$$

$$Q_{66} = 1.60 \text{ Msi}$$

With different ply angles, each stiffness component will now need to be translated into the direction in which the fibers are arranged; in other words: a ply's material property will shift with its orientation. Equations 6 through 11 in *Appendix: Classical Laminated Plate Theory Equations* calculate how each material property component transforms when placed in the ply stack at a ply angle θ ; assembling them all together produces the reduced stiffness matrix, Equation 12:

$$\overline{Q}_{ij} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix} \quad (\text{Eq. 12})$$

Each ply's $\overline{Q}_{ij}$ is then summed per its proportion to the total number of plies in the stack—reference Equation 13:

$$[\overline{Q}_{ij}]_{Total} = \sum_{m=1}^{n_{total}} \frac{n_{\theta_m}}{n_{Total}} [\overline{Q}_{ij}]_{\theta_m} \quad (\text{Eq. 13})$$

And subsequently, the strain is determined from finding the inverse of the reduced stiffness matrix, multiplied by the stress (force/cross-sectional area).

$$\varepsilon = [\overline{Q}_{ij}]_{Total}^{-1} [\sigma] \quad (\text{Eq. 14})$$

Cross-ply

Stress is defined for the two hole sizes for the cross-ply laminates:

$$\sigma_{Cross_{1/8",1000lbf}} = 8,791 \text{ psi}$$

$$\sigma_{Cross_{1/4",1000lbf}} = 10,256 \text{ psi}$$

Leveraging Equations 6 through 11 from *Appendix: Classical Laminated Plate Theory Equations*, the following reduced Qs were determined for the 16 layer $[(0/90)_4]_s$ cross-ply laminate:

$$[\bar{Q}]_{\theta_{0^\circ}} = \begin{bmatrix} 13.70 & 0.25 & 0 \\ 0.25 & 1 & 0 \\ 0 & 0 & 1.6 \end{bmatrix} \text{ Msi}$$

$$[\bar{Q}]_{\theta_{90^\circ}} = \begin{bmatrix} 1 & 0.25 & 0 \\ 0.25 & 13.70 & 0 \\ 0 & 0 & 1.6 \end{bmatrix} \text{ Msi}$$

Where:

$$[\bar{Q}]_{Cross} = \begin{bmatrix} 7.35 & 0.25 & 0 \\ 0.25 & 7.35 & 0 \\ 0 & 0 & 1.6 \end{bmatrix} \text{ Msi}$$

And its inverse:

$$[\bar{Q}]_{Cross}^{-1} = \begin{bmatrix} 0.1362 & -0.0046 & 0 \\ -0.0046 & 0.1362 & 0 \\ 0 & 0 & 0.6250 \end{bmatrix} \mu\text{si}$$

The strains for 1/8" and 1/4" hole cross-ply plates:

$$\varepsilon_{x_{Cross_{1/8"}}} = 0.0012 \text{ in/in}$$

$$\varepsilon_{x_{Cross_{1/4"}}} = 0.0014 \text{ in/in}$$

Quasi-isotropic

Stress is defined for the two hole sizes for the quasi-isotropic laminates:

$$\sigma_{Quasi_{1/8''}} = 11,662 \text{ psi}$$

$$\sigma_{Quasi_{1/4''}} = 13,605 \text{ psi}$$

Leveraging Equations 6 through 11 from *Appendix: Classical Laminated Plate Theory Equations*, the following reduced stiffness components were solved for the 12 layer $[0_2/+45/-45/90_2]_s$ quasi-isotropic laminate to determine the strain experienced for each hole size plate.

The strains for 1/8" and 1/4" hole quasi-isotropic plates:

$$\varepsilon_{xQuasi_{1/8''}} = 0.0017 \text{ in/in}$$

$$\varepsilon_{xQuasi_{1/4''}} = 0.0020 \text{ in/in}$$

V. The Homogenous Baseline

Research report *Correlation between Engineering Stress-Strain and True Stress-Strain Curve* conducted by Iman Faridmehr, Mohd Hanim Osman, and co, published in the American Journal of Civil Engineering and Architecture, 2014, Vol. 2, No. 1, 53-59, was utilized to validate the homogenous baseline; their methodology followed was in conformance to ASTM E8, reference Figure 33:

Figure 33 - Standard Tensile Specimens, according to ASTM E8

The three test specimens, developed from low carbon steel, used for validation had the following dimensions, reference Table 10, Figure 34:

Table 10 - Specimen Dimensions

Specimen	Thickness (mm)	Cross Section Area (mm ²)	Gauge Length (mm)
1	10	380	50
2	8	304	50
3	6	228	50

For the sake of the homogenous baseline, only the 10mm case was considered.

Figure 34 - Test specimens for Homogenous Baseline FEA validation

At the end of the tensile test, the following material characteristics were determined; reference Table 11.

Table 11 - Material Characteristics of Low Carbon Steel

Specimen	Yield Load (KN)	Yield Strain	Yield Strength (N/mm ²)	Young's Modulus (N/mm ²)	Max Load (KN)	Ultimate Tensile Strength (N/mm ²)	% Elongation	Fracture Strain (mm/mm)
1	119	0.0013	279	2.1E5	110	361	17.5 %	0.16
2	85	0.0013	282	2.1E5	106	351	18 %	0.15
3	86	0.0013	275	2.1E5	108	358	18.2 %	0.15

Specimen 1 was replicated in ABAQUS to validate the homogenous baseline FEA model.

The failed test specimens from the tensile loading, is shown in Figure 35:

Figure 35 - Failed specimens under tensile loading

The Stress/Strain curve produced from the tensile test is shown below in Figure 36:

Figure 36 - Specimen with 10mm thickness

PlotDigitizer was used to replicate the stress-strain curve from Figure 36. The slope of the elastic region—or up to the yield strength—was used to determine the Young's Modulus, E , of the specimen. This E was used for the Young's Modulus data field of the *Elastic* material definition section of the FEA model; the rest of the digitized curve—up to ultimate tensile strength—was used to define the *Plastic* section of the FEA's

material definition. To note, it was an accepted risk that using *PlotDigitizer* may have introduced some inaccuracies in the resulting data.

Building a Homogenous FEA Baseline

The software used to perform FEA was ABAQUS version CAE 6.14. The steps taken to conduct the FEA can be found in Appendix B.

Analyzing the Results

To review, the following attributes went into developing this FEA model:

- Young's Modulus: 225,456N/mm²
- Poisson's Ratio: 0.29
- Plastic Yield Stress/Strain: Reference *Table 5*
- Step: Time Period = 2, Incrementation: Max = 100, Initial Size = 0.05, Minimum = 2E-005, Maximum = 0.15
- Constraint: Coupling, Kinematic; constrain: U1, U2, U3, UR1, UR2, UR3
- Amplitude: Time (s)/Frequency(Hz) and Amplitude: 0, 0 / 1, 1
- Load: CF2 = 100KN
- Boundary Condition (BC) #1: ENCASTRE, bottom grip
- BC #2: Displacement/Rotation, U1, U3, UR1, UR2, UR3
- Global Seeds: Approximate global size = 3; Curvature Control = 0.1, Minimum Size Control: By fraction of global size = 0.1

Plot Contours on Deformed Shape visualizes the effects of the load on the specimen. Though difficult to read the values, the important takeaway from Figure 37 are how the stress/strain results are visually represented, with the red regions representing the regions most stressed, and blue showing the least impacted by the load (the grips).

Figure 37 – ABAQUS output screenshot: Homogenous Baseline FEA

ABAQUS can portray the results through a two-dimensional plot as well. To do so, click on *Create XY Data > ODB field output*, and under the *Variables* tab, *E: Strain components*, select *E22*; under *S: Stress Components*, select *Mises*. Click over to the *Elements/Nodes* tab, *Edit Selection*, and highlight a node/element to plot (hold down *Shift* to select multiple nodes/elements). Click *Plot* to complete this step; reference Figure 38. Again, difficult to read values, however, the intent of Figure 38 is to emphasize the post-processing steps necessary to acquire the desired values to develop Figures 39 and 40.

Figure 38 – ABAQUS output screenshot: Stress and Strain portrayed as dependent on time for homogenous baseline (stress: N/mm^2 , strain: mm/mm , time: sec)

To present the plot in Stress dependent on Strain, click on the *Create XY Data* button once more, but now click on the *Operate on XY Data* option. On the far right of the popup, under Operators, scroll down and click on *combine(X,X)*. Here, the E22 Strain and Mises Stress line items will be visible; single-clicking on each line item will populate the *combine(X,X)* operator with the strain and stress. Clicking *Plot* results in Figure 39:

Figure 39 – ABAQUS output screenshot: Stress dependent on Strain of 10mm specimen for homogenous baseline FEM (stress: N/mm², strain: mm/mm)

ABAQUS can also show the results in tabular form, allowing users to create their own stress/strain curve. To do this, click on *XY Data Manager*, and with the stress/strain curve highlighted, click *Edit*. A popup enumerating the stress/strain values will display; reference Figure 40:

Figure 40 – Tabulated Stress and Strain from ABAQUS for homogenous baseline FEM (stress: N/mm², strain: mm/mm)

Table 12 enumerates the true stress/strain results from the tensile test. Line items three through five were utilized to determine the slope of the elastic region, or E , as show in Figure 41:

Table 12 – True Stress/Strain from test results

Test	
True Stress (N/mm ²)	True Strain (mm/mm)
0	0
17.90	0.00064584
101.43	6.62E-04
200.47	8.95E-04
282.81	1.13E-03
269.66	5.62E-03
287.48	1.83E-02
293.39	2.73E-02
302.90	3.37E-02
318.37	4.14E-02
332.64	5.04E-02
357.57	7.16E-02
376.54	9.26E-02
397.81	1.27E-01
400.11	1.42E-01
397.70	1.46E-01

Figure 41 – Determining plastic E , through slope of Stress and Strain

The values from the FEA results were overlaid with the results from the tensile test, as shown in Table 12; reference Figure 42. Orientation: tension through length of specimen (y-axis).

Figure 42 – Low carbon steel 10mm thickness specimen FEA compared to tensile test results

Validating the Homogenous Baseline

The yield tensile strength was denoted as 282MPa for the tensile test; the ABAQUS results indicate yield strength of 220MPa, a discrepancy of 22% from test. The ultimate tensile strength was determined to be 389MPa per test, 400MPa per FEA; a discrepancy of 3%.

With the variables introduced with *PlotDigitizer*, and the possible differences in the test specimen compared to the one modeled in the FEA, a 22% and 3% discrepancy were deemed acceptable for the sake of validating the FEA model. With how dynamic the elastic region is, with both the load and at what rate the load is applied contributing to the behavior of elasticity, it was less disconcerting to see the discrepancy. A 3% discrepancy at fracture provided the necessary vote of confidence in the finite element model.

These same steps were taken to develop the FEA models for the four composite laminate cases in the following section.

VI. Finite Element Analysis Methodology

The FEA models' attributes were as follows:

- E_L : 13.7 Msi
- E_T : 1 Msi
- G_{LT} : 1.6 Msi
- Poisson's Ratio: 0.25
- Step: Time Period = 1, Incrimination: Max = 100, Initial Size = 1, Minimum = 1E-005, Maximum = 1
- Constraint: Coupling, Kinematic; constrain: U1, U2, U3, UR1, UR2, UR3
- Load: CF2 = 1000 lb_f at Reference Point 1 (top center node)
- Boundary Condition (BC) #1: ENCASTRE, bottom grip
- BC #2: Displacement/Rotation, constrain: U1, U3, UR1, UR2, UR3
- Global Seeds: Approximate global size = [0.05:0.010]; Curvature Control = 0.1, Minimum Size Control: By fraction of global size = 0.1

The starting mesh's global seed size was set to 0.05, or a node count of 4713, per Figure 43. Once the part was submitted for analysis, Figure 44 shows the spectrum of stresses experienced throughout the substrate, denoted by the legend in the upper left corner of the screen; reference *Appendix: Creating an FEA Model in ABAQUS*.

Figure 43 – For the first iteration of FEA, the global seed size was set to 0.05, or a node count of 4541

Figure 44 – FEA result for 1/8" cross-ply substrate

Table 13 delineates the node variations for the 1/8" cross-ply substrates. The ideal node count for these specimens was determined to be 29333, or a global seed size of 0.020; the run-time-to-accuracy factor

was the most ideal, especially when running so many FEA scenarios. However, the advantage of conducting this study is that if the error rates are larger than expected when comparing FEA results with analytical and tensile test results, there is a solution to improve on those error rates: increase the node count.

Table 13 - Node variations for 1/8" cross-ply substrate

	Point Stress (psi)		Point Strain (in/in)		Run-Time (sec)
Analytical	8791	-	0.00120	-	-

Seed Size/Node Count	Avg Stress at SG (psi)	% from Analytical	Point Strain (in/in)	% from Analytical	Run-Time (sec)
0.05 / 4541	7565	-13.95%	0.00110	-8.38%	45
0.03 / 12800	7647	-13.01%	0.00111	-7.37%	51
0.020 / 29333	8022	-8.74%	0.00117	-2.90%	89
0.015 / 51996	8005	-8.94%	0.00116	-3.21%	315
0.010 / 118006	8182	-6.93%	0.00119	-1.01%	450

With a global seed size of 0.020 set for all finite element models, a point load of 1000lbf was set and analyzed. Upon attaining results, the nodes in the area where the strain gauges were installed were highlighted, and the average of the stresses and strains were taken therein. An important factor to keep in mind: the sensitivity of which nodes are selected to determine the average stresses and strains is indeed a factor—this variability leaves room for a higher than desired error rate. It is crucial that the exact location of strain gauge and its nodes are analyzed. Figure 45 shows the highlighted nodes.

Figure 45 – Strain gauge areas were highlighted for average stresses and strains

Figure 46 shows the strain of each node highlighted, graphed as a function of time; Figure 47 shows the usage of the “combine” and “avg” functions used to plot the average of each node.

Figure 46 – The strain (in/in) of highlighted nodes, as a function of time (sec)

Figure 47 – Highlighted nodes selected to calculate average strain (in/in) using ABAQUS combine/avg functions

As a result, one average curve is displayed, per Figure 48. These steps were repeated to determine the *FEA Stress* and *FEA Strain* values in Tables 14 and 15 in Section VII.

Figure 48 – Average strain (in/in) plotted as a function of time (sec)

VII. Results Discussion

The following data represents the FEA to analytical, and FEA to tensile test results. It should be noted from the beginning that slippage was indeed an issue with several of the specimens during test, therefore, several of the runs were discarded from each set's averages. A point load of 1000lbf was studied for each case.

Cross-ply

Figure 49 displays all cross-ply, 1/8" hole tensile test runs to failure. Tension orientation is along the length of the specimen (y-axis).

Figure 49 - Cross-ply, centered 1/8" hole, tensile test results at failure

Reference Table 14 for the tensile test results for the cross-ply, centered 1/8" hole specimen at 1000lbf point load. Run 2 was identified as anomalous and removed from the average. The analytical strain value was determined to be 0.00120in/in, FEA strain: 0.00117in/in

Table 14 - Cross-ply, centered 1/8" hole, tensile test results at 1000lbf

	Point Stress (psi)	Point Strain (in/in)
Run 1	8809	0.00122
Run 2	8810	0.00089
Run 3	8810	0.00110
Run 4	8802	0.00112
Run 5	8801	0.00118
AVERAGE		0.00115

Figure 50 compares FEA strain against the test and analytical strain at 1000lbf. The slightly steeper graph produced by the test results may be a product of a slight slip, however, at a minimum strain value of 0.0011in/in (after discarding Run 2's 0.00089in/in), a ten-thousandths of an inch deviation from predicted, this may be a resultant of tolerance stacks. Strain error rate of FEA to analytical: 3%; strain error rate of FEA to test: 1%.

Figure 50 - Cross-ply, centered 1/8" hole, FEA compared with test and analytical at 1000lbf

Figure 51 shows all cross-ply, centered 1/4" hole tensile test runs to failure.

Figure 51 - Cross-ply, centered 1/4" hole, tensile test results to failure

Reference Table 15 for tensile test results at 1000lbf point load for the cross-ply, centered 1/4" specimens under tensile loading. Runs 2 and 4 were removed from determining the average strain value for the 1/4"

cross-ply. The analytical strain value was determined to be 0.0014in/in,
FEA strain: 0.00136in/in.

Table 15 - Cross-ply, centered 1/4" hole, tensile test results at
1000lbf

	Point Stress (psi)	Point Strain (in/in)
Run 1	10260	0.0013
Run 2	10264	0.0012
Run 3	10270	0.0015
Run 4	10277	0.0012
Run 5	10264	0.0014
AVERAGE		0.0014

Figure 52 graphically delineates the differences of the expected analytical stress/strain curve with that of the average strain at 1000lbf. FEA to analytical strain error: 3%; FEA to test strain error: 10%. It's good to note here that the test-to-analytical error was also higher than the average at 9%. This may be due to the natural variables introduced from performing a tensile test, such as strain gauge application methods and strain gauge/load cell tolerance stacks.

Figure 52 - Cross-ply, centered 1/4" hole, FEA compared with test and analytical at 1000lbf

Quasi-isotropic

Reference Figure 53 for tensile test results for the quasi-isotropic, centered 1/8" hole specimen to failure.

It should be noted that two of the five quasi-isotropic specimens, Runs 2 and 4, behaved like a classical homogenous material, with a linear elastic region, a distinct yield point, and a sloping plastic region until fracture. The remaining three specimens resulted in less distinguished elastic-to-plastic transitions, but fractured within the expected range of strain.

Additional testing may be required to fully understand the differences in the exhibited stress/strain curves—it is most likely that the tab design/configuration, combined with the improper grips/tooling, contributed to slippage until the 70,000psi range, causing the Instron to reduce its load rate from 0.05in/min. Due to this, one would have noticed

minimal strain and growing stress until the 0.002in/in range, where the Instron would have reduced its load rate, reducing the act of slipping, allowing the material to strain until failure.

Figure 53 - Quasi-isotropic, centered 1/8" hole, tensile test results
at failure

Table 16 delineates the tensile test results at 1000lbf point load. Runs 2 and 4 were removed from determining the average strain. The analytical strain was predicted to be 0.00170in/in, FEA strain: 0.00175in/in

Table 16 - Quasi-isotropic, centered 1/8" hole, tensile test results at
1000lbf

	Point Stress (psi)	Point Strain (in/in)
Run 1	11675	0.0016
Run 2	11669	0.0003
Run 3	11668	0.0018
Run 4	11670	0.0003
Run 5	11662	0.0019
AVERAGE		0.0018

Figure 54 graphically delineates the differences of the expected analytical stress/strain curve with that of the quasi-isotropic 1/8" plate at 1000lbf. The FEA to analytical strain error was calculated to be 3%; FEA to test strain error was also calculated to be 3%.

Figure 54 - Quasi-isotropic, centered 1/8" hole, FEA compared with test and analytical at 1000lbf

Reference Figure 55 for tensile test results for the quasi-isotropic, centered 1/4" hole specimen to failure. Similarly to the 1/8" hole set of quasi-isotropic specimens, the 1/4" set experienced a similar trend where three of the five runs exhibited a more distinguished yield point.

Again, it is assumed slippage had caused the Instron to reduce its load rate from 0.05in/min. Due to this, less strain was experienced than expected until reaching roughly 0.002in/in, until the Instron reduced its load rate, reducing the act of slipping, allowing the material to strain until failure.

Figure 55 - Quasi-isotropic, centered 1/4" hole, tensile test results
at failure

Table 17 delineates the tensile test results at 1000lbf point load.
Runs 2, 3, and 5 were discarded.

Table 17 - Quasi-isotropic, centered 1/4" hole, tensile test results at
1000lbf

	Point Stress (psi)	Point Strain (in/in)
Run 1	13617	0.00203
Run 2	13609	0.00022
Run 3	13607	0.00020
Run 4	13610	0.00212
Run 5	13606	0.00025
AVERAGE		0.00208

Figure 56 graphically delineates the differences of the expected analytical stress/strain curve at 1000lbf. With slippage apparent for Runs 2, 3, and 5, the resulting curve is an average of Runs 1 and 4, resulting in a 1% FEA to analytical strain error and a 3% FEA to test error.

Figure 56 - Quasi-isotropic, Centered 1/4" hole, FEA compared with test and analytical at 1000lbf

Figures 57 and 58 portray failure mode examples for the cross-ply and quasi-isotropic substrates, respectively.

Figure 57 - Cross-ply failure mode example

Figure 58 - Quasi-isotropic failure mode example

For the purposes of this thesis, a global seed size of 0.020, or on the order of magnitude of 30,000 nodes per substrate, was identified as the ideal number of nodes for analysis; "ideal" defined as the node count that provides the most accurate results in the most reasonable time, and importantly, completion of FEA. If the exhibited error rates in this thesis is deemed unacceptable, it is possible to revisit these analyses with a higher node count to try to reduce the error rates between FEA and analytical, or FEA and test.

Additionally, 0.020 may not be the ideal node count for specimens of different materials, different layups, geometries, hole configurations, imperfections, loading, boundary conditions, etc. As an example, for the homogenous baseline, a global seed size of 1 was analyzed, but only after an analysis time of 144 minutes at a global seed size of 0.020, which still failed to produce a result. Perhaps an equation can be derived, that per given cross-sectional area, a certain order-of-magnitude of global seed size should be used as a starting point; it would be prudent for the engineer to then toggle between several mesh configurations, prior to running the actual analysis, to understand what node count would be optimum for the structure at hand.

Figure 59 juxtaposes the strain results from the FEA, tensile tests, and the analytical calculations. Figure 60 juxtaposes the respective stress results.

Figure 59 - Juxtaposition of analytical strain with tensile and FEA strain at 1000lbf

Figure 60 - Juxtaposition of analytical stress with tensile and FEA stress at 1000lbf

With the known slippage issues throughout the tensile tests, discarding the known anomalous results helped align the tensile test results more closely with the predicted values from the analytical.

As previously mentioned, variability in the FEA results could be attributed to which nodes had been selected in determining the FEA average, however, both FEA stress and strain values trended closely with the predicted analytical values, averaging a 6% error in stress and a 2% error in strain. This would be expected given that stress and strain are correlated by E , therefore, one would expect their respective error ranges to be similar; reference Table 18.

Table 18 - FEA results compared with analytical

	FEA Stress (psi)	Analytical Stress (psi)	Error (%)	FEA Strain (in/in)	Analytical Strain (in/in)	Error (%)
1/8" Cross-Ply	8022	8791	10%	0.0012	0.0012	3%
1/4" Cross-Ply	9398	10256	9%	0.0014	0.0014	3%
1/8" Quasi-Isotropic	12054	11662	-3%	0.0018	0.0017	-3%
1/4" Quasi-Isotropic	13902	13605	-2%	0.0020	0.0020	-1%
Avg:			6%	Avg: 2%		

Table 19 delineates a FEA-to-tensile test comparison. The FEA-to-tensile test stresses experienced a 6% error, and the FEA-to-adjusted tensile strains averaged an error of 4%.

Table 19 - FEA results compared with tensile test

	FEA Stress (psi)	Tensile Stress (psi)	Error (%)	FEA Strain (in/in)	Tensile Strain (in/in)	Error (%)
1/8" Cross-Ply	8022	8806	10%	0.0012	0.0012	-1%
1/4" Cross-Ply	9398	10267	9%	0.0014	0.0015	10%
1/8" Quasi-Isotropic	12054	11668	-3%	0.0018	0.0018	3%
1/4" Quasi-Isotropic	13902	13613	-2%	0.0020	0.0021	3%
Avg:			6%	Avg: 4%		

Table 20 delineates a tensile test-to-analytical comparison. The tensile test and analytical stresses were nearly identical at 0.10% error, and the adjusted tensile strains averaged an error of 6%.

For the discarded test runs: the larger strain errors were attributed to slipping, as at any given value of stress, the correlating strain values were consistently lower than expected. With a consistently lower strain value at a given stress, a higher slope, or E, results, which could potentially question the original set of material properties, however, with the peculiarity in how the responses trended, it is most probable that slippage was experienced with the cross and quasi substrates due to factors such as tab design/configuration and tooling grip errors.

It is interesting to note, the analytical-to-tensile-test stress values were more closely aligned than the analytical-to-tensile test strain values. This could be very well due to the natural variables introduced when conducting a tensile test, from strain gauge application methods to tolerance stacks from load cells (~5% error) and strain gauge

readings (~5%); it would not be improbable these factors could have contributed to the ten-thousandths to hundred-thousandths of an inch differences.

Table 20 - Tensile results compared with analytical

	Analytical Stress (psi)	Tensile Stress (psi)	Error (%)	Analytical Strain (in/in)	Tensile Strain (in/in)	Error (%)
1/8" Cross-Ply	8791	8806	0.17%	0.0012	0.0012	-4%
1/4" Cross-Ply	10256	10267	0.11%	0.0014	0.0015	9%
1/8" Quasi-Isotropic	11662	11668	0.05%	0.0017	0.0018	6%
1/4" Quasi-Isotropic	13605	13613	0.06%	0.0020	0.0021	4%
Avg:			0.10%	Avg:		
						6%

As verification, another set of stress/strain values were analyzed at a point load of 3000lbf; Figure 61 compares the tensile test and FEA results with the analytical. The FEA-to-tensile strain averaged an error of 5% and the FEA-to-analytical strain averaged an error of 1%.

Figure 61 - Juxtaposition of analytical stain with tensile and FEA strain at 3000lbf

VIII. Closing Discussion

Conclusion

The objective of this thesis was to determine whether the advancements in numerical methods have progressed enough such that its results could be accurate enough to deem experimental testing redundant in validating structural design. Based on the conducted research, certain numerical methods, such as the shell element numerical approximations through ABAQUS, coupled with sufficient mesh designs, have historically shown strong correlations between numerical and experimental test results, as was validated through the results of this thesis.

Additionally, the investigation of variables to test design, such as varied ply orientations and hole configurations, further provided validation that error rates between numerical and experimental results remained unaffected, regardless of ply orientations or hole configurations. With FEA-to-analytical strains averaging an error of 2%, FEA-to-tensile strains averaging an error of 4%, and strain values accurate up to ten-thousandths and hundred-thousandths of an in/in, Table 21 further summarizes the average FEA-to-analytical and average FEA-to-average-tensile-test strain values at 1000lbf point load; Table 22 summarizes the correlating stress values, showing a 6% error for both FEA-to-analytical and FEA-to-experimental test results. With design margins and factors of safety incorporated into every design as an industry standard, the acceptability of these error rates could depend on how those margins are already being leveraged in the design, particularly for mission critical components, though margins are generally sufficient to be able to cover the error rates in analysis.

Additionally, it has been observed through this thesis that a denser, more intricate mesh design could provide a greater level of accuracy for numerical solutions, which proves the notion that if lower

error rates were necessitated, continued research with a more powerful processor should be able to provide the granularity and accuracy in output that would further minimize error rates between FEA and experimental and FEA and analytical results.

Table 21 – FEA-to-analytical and FEA-to-tensile test strain, with correlating error rates

	FEA Strain (in/in)	Analytical Strain (in/in)	Error (%)	Tensile Strain (in/in)	Error (%)
1/8" Cross-Ply	0.0012	0.0012	-3%	0.0012	1%
1/4" Cross-Ply	0.0014	0.0014	-2%	0.0015	-9%
1/8" Quasi-Isotropic	0.0018	0.0017	3%	0.0018	-3%
1/4" Quasi-Isotropic	0.0020	0.0020	1%	0.0021	-3%
Avg:			2%	Avg:	4%

Table 22 – FEA-to-analytical and FEA-to-tensile test stress, with correlating error rates

	FEA Stress (psi)	Analytical Stress (psi)	Error (%)	Tensile Stress (psi)	Error (%)
1/8" Cross-Ply	8022	8791	-9%	8806	-9%
1/4" Cross-Ply	9398	10256	-8%	10267	-8%
1/8" Quasi-Isotropic	12054	11662	3%	11668	3%
1/4" Quasi-Isotropic	13902	13605	2%	13613	2%
Avg:			6%	Avg:	6%

The lessons-learned from the conducted research were successfully folded into the design and approach of this thesis: a point load was examined (1000lbf and 3000lbf) by combining the shell element model approach through ABAQUS, as discussed in Wang's research, with the ply-

stack sequence study from Hallett's and Haque's research, resulting in numerical results with error rates under 10%.

Compared to Wang's 1.5% error in peak stress prediction between FEA and test, the results of this thesis's error for stress at a 1000lbf point load was calculated to be 3%. However, with the sensitivity analysis conducted in this thesis to study how mesh densities affect stress/strain results, it can be concluded with full confidence that this 3% error could be minimized with a greater node count.

In comparison to Hallett's experiment, utilizing the shell element model through ABAQUS as discussed in Wang's study, proved to be a much more accurate numerical method as predicted: a 10% error from Hallett's study compared to a 6% error in stress for this thesis.

Bringing Haque's study into the fold, the 6% error rate from this thesis was a vast improvement from the 29% error from Haque's, which also provided an insight different from Haque's conclusion: lay-up sequences are, indeed, significant, and notch configurations do, indeed, have an effect on local stresses—and subsequently, stress concentrations, even at smaller hole sizes (hole-diameter-to-specimen width ratios: 0.2–0.3, as quoted by Haque's study).

Although a sub-6% error rate across all experiments conducted in this thesis can be seen as a success, the following section identifies some adjustments that could be made to further investigate the nuances of composite behavior and properties, while minimizing error rates.

Future Work

Future work could involve an FEA, analytical, and tensile test study focused specifically on stress concentrations based on growing hole sizes (diameter-to-width ratios ranging from 0.05 to 0.5), utilizing several types of pre-preg, and maintaining the varied ply sequences, at a node count per specimen on the order of magnitude of 100,000s of nodes; this

would essentially combine Wang's, Hallett's, and Haque's studies with the thesis conducted here, at a higher granularity in FEA. This should provide a tighter correlation between FEA, test, and analytical, resulting in error rates more consistently within the 1.5% seen in Wang's research.

Furthermore, other load types, such as compression and bending, may also provide further insight into how these materials behave under loading, thus furthering the discussion of whether testing could one day be completely replaced by numerical analysis for validating structural design.

Finally, some of the higher error-rate case studies presented in the *Previous Works* section of this thesis could be recreated using analytical and numerical models that are known to have more accurate predictions, such as CLPT and the shell element numerical approximation method.

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Appendix

Classical Laminated Plate Theory Equations

$$\mathbf{Q}_{ij} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \quad (\text{Eq. 1})$$

$$Q_{11} = \frac{E_{11}^2}{(E_{11} - \nu_{12} \cdot E_{22})} \quad (\text{Eq. 2})$$

$$Q_{12} = \frac{\nu_{12} E_{11} E_{22}}{E_{11} - \nu_{12}^2 E_{22}} \quad (\text{Eq. 3})$$

$$Q_{22} = \frac{E_{11} E_{22}}{E_{11} - \nu_{12}^2 E_{22}} \quad (\text{Eq. 4})$$

$$Q_{66} = G_{12} \quad (\text{Eq. 5})$$

$$\overline{Q_{11}} = Q_{11} \cos(\theta)^4 + 2(Q_{12} + 2Q_{66}) \cos(\theta)^2 \cdot \sin(\theta)^2 + Q_{22} \sin(\theta)^4 \quad (\text{Eq. 6})$$

$$\overline{Q_{12}} = \overline{Q_{21}} = Q_{12}(\cos(\theta)^4 + \sin(\theta)^4) + (Q_{11} + Q_{22} - 4Q_{66}) \cos(\theta)^2 \sin(\theta)^2 \quad (\text{Eq. 7})$$

$$\overline{Q_{16}} = \overline{Q_{61}} = (Q_{11} - Q_{12} - 2Q_{66}) \cos(\theta)^3 \sin(\theta) - (Q_{22} - Q_{12} - 2Q_{66}) \cos(\theta) \sin(\theta)^3 \quad (\text{Eq. 8})$$

$$\overline{Q_{22}} = Q_{11} \sin(\theta)^4 + 2(Q_{12} + 2Q_{66}) \cos(\theta)^2 \sin(\theta)^2 + Q_{22} \cos(\theta)^4 \quad (\text{Eq. 9})$$

$$\overline{Q_{26}} = \overline{Q_{62}} = (Q_{11} - Q_{12} - 2Q_{66}) \cos(\theta) \sin(\theta)^3 - (Q_{22} - Q_{12} - 2Q_{66}) \cos(\theta)^3 \sin(\theta) \quad (\text{Eq. 10})$$

$$\overline{Q_{66}} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) \cos(\theta)^2 \sin(\theta)^2 + Q_{66}(\cos(\theta)^4 + \sin(\theta)^4) \quad (\text{Eq. 11})$$

$$\overline{\mathbf{Q}}_{ij} = \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix} \quad (\text{Eq. 12})$$

Creating an FEA Model in ABAQUS

Step 1: Creating a Part

Starting Abaqus, under menu heading *Create Model Database*, click *With Standard/Explicit Model*.

- Sketch & Extrude

Start by creating a part. Click on the *Create Part* icon; by default, the options should be set to the following:

- Modeling Space: 3D
- Type: Deformable
- Base Feature: Shape: Solid
- Base Feature: Shape: Type: Extrusion
- Approximate Size: 200

Click: *Continue*

From here, the entire upper left module becomes a tool bar to sketch the specimen profile. Generally, one may start with the *Create Isolated Point* or the *Create Lines: Connected* buttons. When the sketch is complete, click *Done* at the bottom of the screen, and extrude the sketch to the appropriate depth.

- Partition

Modeled specimens can be partitioned to improve FEA solver performance; with more complicated geometries, and depending on which mesh type the user is utilizing—hexahedral or tetrahedral, partitioning of a part breaks down the complicated geometries to ensure the mesh design is being applied to every part of the specimen. To do this, hold down the *Partition Cell: Define Cutting Plane* button, select *Partition Cell: Extrude/Sweep Edges*, identify on the model where the partitions should be made, and finally, which direction each respective sweep should be made:

- Create Reference Point

Like any other analysis, a reference point will need to be established. Hold down the *Create Datum Point: Enter Coordinates* icon, and move the cursor over to the *Create Datum Point: Midway Between 2 Points* icon. This will display all datum points. Click on the two middle datum points along the top edges of the specimen, and an unfilled point will appear between them. Go to the *Tools* dropdown menu, click on the *Reference Point* selection, and click on the newly appeared, unfilled datum point to establish it as the specimen's Reference Point. An "x" with "RP" will appear over the point when completed successfully.

- Establish Material Properties

Under the *Module* dropdown, select *Property*. This will update the main left module to selections those that would manage options related to the properties of the part. From here, click on the *Create Material* icon: at the prompt, determine a name and

description for the material to be defined (defaults to "Material-1"), click on the *Mechanical* dropdown, select *Elasticity*, *Elastic*, and subsequently complete the *Young's Modulus* and *Poisson's Ratio* data fields. The *Type* selection should remain as *Isotropic* for this instance.

- Assign Material Properties to Defined Sections

Click on the *Create Section* icon. Again, determine a name for the section to be created—default is “Section-1”. For the homogenous baseline, *Category: Solid, Type: Homogenous* will be used. Click *Continue*. For the *Edit Section* popup, *Material-1* should be defaulted in the dropdown; click *Ok* to continue.

Click on the *Assign Section* icon; select the entire specimen with the cursor. When the entire specimen's frame is selected red, ensure the "Create set" box is unchecked at the bottom of the screen, and click *Done*. An *Edit Section Assignment* popup will appear; click *Ok* to proceed. The model will now have turned a blue-green.

Step 2: Defining the Test Parameters

- Creating an Instance

Under the *Module* dropdown, select *Assembly*. Do not be alarmed if the part disappears. Find and click on the *Create Instance* icon. On the ensuing popup, select *Create instances from: Parts*; verify “Part-1” is selected; confirm the Instance Type is *Dependent (mesh on part)*; click *Ok* to continue.

- Defining Steps

Under the *Module* dropdown, select *Step*. Find and click on the *Create Step* icon. Confirm Procedure type is *General > Static, General*; click *Continue*. An *Edit Step* popup will appear. Under the *Basic* tab, enter a description as desired, define the time period as 1 (default); leave *Nlgeom* in the *Off* state; do not apply any automatic

stabilization. Under the *Incrementation* tab: Type: *Automatic*; Maximum number of increments: *100*, Increment size: Initial: *0.1*, Minimum: *1E-005*; Maximum: *1*; click *Ok* to continue.

- Defining Constraints

Under the *Module* dropdown, select *Interaction*. Select the *Create Constraint* icon to get started. Name the constraint characteristics as desired (default: "Constraint-1"), and select the Type to be *Coupling*. Selecting *Continue* will initiate a request to define the constraint control point; select the *Reference Point* here, click *Done*; for the constraint region type, select: *Node Region*; for selecting points for the surface nodes, navigate up to the dropdown menu in the upper menu, and change *Enable Selection* from *All* to *Cells*. Clicking on the cell regions to constrain will turn the wireframe of that section magenta. Clicking *Done* will prompt the *Edit Constraints* popup. From here, define the constraints to be *Kinematic* and constrain all degrees of freedom. Click *Ok*.

- Defining Boundary Conditions

Under the *Module* dropdown, select *Load*, and then the *Create Boundary Condition* icon. Name the boundary condition accordingly, and select the following: Step: *Step-1* (or equivalently named); Category: *Mechanical*; Types for Selected Step: *Symmetry/Antisymmetry/Encastre*. Click *Continue*. *Enable Selection* may need to be changed from *All* to *Cells* once again. Select the region to apply the Boundary Condition on the model, click *Done*, and then *Encastre*. Click *Ok*, and then proceed to create a secondary Boundary Condition to limit the *Displacement/Rotation* of the specimen. The same settings will apply until the Edit Boundary Condition popup, where the following axes should be selected to lock: U1, U3, U4, UR1, UR2, and UR3. Click *Ok* to finalize the second set of Boundary Conditions.

- Defining the Test Load

The Test Load is defined by *category*—mechanical, acoustic, thermal, etc., and *type*—concentrated force, pressure, gravity, etc. The manner in how a load is distributed is defined by the *Amplitude*

settings, where a user is able to dictate at which frequency and profile a load may be introduced to a specimen.

With the *Module* set to “Load”, select the *Load Manager* icon.

At the prompt, *Create a load*, defining it as a *Mechanical*, *Concentrated force*.

Select a point, or a set of points, on the FEM for the load to be applied.

At the *Edit Load* prompt, define a uniformly distributed load at a magnitude of choice, and define the *Amplitude* as a tabular ramp. By default, the Amplitude will be named *Amp-1*.

Define the ramping characteristic frequencies.

From the dropdown, select the newly created *Amp-1*.

- Mesh

Properly setting up the Mesh is one of the most important steps to FEA. With the *Module* set to *Mesh* and *Object* set to *Part: [part name]*, click on the *Global Seeds* icon.

The *Approximate global size* determines the number of elements utilized in the finite element calculations; the greater the *Approximate global size*, the less number of nodes; the smaller the *Approximate global size*, the more nodes—the more nodes, theoretically, more accuracy in results. The initial global size was set to 10.

Curvature control determines the shape of each element: the smaller the *Maximum deviation factor*, the more quadrilateral each respective node will be. The initial *curvature control* was set to 0.1 (default).

When completed, ensuring the *Object* is selected as *Part* > [Name of Part], click *Yes* when prompted *Ok to Mesh Part?* The model will now turn blue with the meshed nodes visible.

- **Submit for Test**

Set the *Module* dropdown to *Job*. Select *Job Manager* > *Create...*, a popup will appear. Name the job (defaults to "Job-1"), select *Source: Model: Model-1* (or equivalent), add a description as necessary, and click *Ok*. Back on the *Job Manager* screen, highlight *Job-1* and click *Submit*. The model is now being analyzed. Once the job is complete, click *Results* to review the finite element analysis.

Finite Element Models

Cross-ply, 1/8" Hole

Cross-ply, 1/4" Hole

Quasi-isotropic, 1/8" Hole

Quasi-isotropic, 1/4" Hole

Previous Works Summary

Author(s)	Year	Title	Study Type(s)	Objective
Abisset, E., Daghia, F., Ladeveze, P.	2011	On the Validation of a Damage Mesomodel for Laminated Composites by Means of Open-hole Tensile Tests on Quasi-isotropic Laminates	Numerical, Experimental	Predicting evolution of damage in composite structures until failure using a damage mesomodel developed at LMT-Cachan; open-hole tensile tests on quasi-isotropic laminates to validate models using two different material parameter sets
Achard, V., Bouvet, C., Castanie, B.	2014	Discrete Ply Modeling of Open Hole Tensile Tests	Numerical, Experimental	The robustness and accuracy of Discrete Ply Modeling (DPM) is show-cased, comparing with experimental results four different stacking sequences with well-predicted failure scenarios and patterns, however, DPM requires very high computational cost.
Arslan, H.M., Kaltakci, M.Y., Yerli, H.R.	2009	Effect of Circular Holes on Cross-ply Laminated Composite Plates	Numerical	An analysis of fiber-reinforced, laminated composite plates with circular holes is conducted, showing stress concentrations around a hole for layers having different fiber orientations, different material pairs with different E1/E2 ratios, and "first-ply failure"—using, Tsai-Hill failure criterion to find minimum bearing circumferential stresses and where they occur as a function of fiber orientation angle.
Atas, A., Arslan, N., Sen, F.	2008	Failure Analysis of Laminated Composite Plates with Two Parallel Pin-Loaded Holes	Numerical, Experimental	This study focuses on the failure loads and failure modes of laminated woven-glass-polyester composite plates with two parallel circular holes subjected to traction forces by two rigid pins by varying plate-width-to-hole diameter ratios and different ply orientations.
Chen, B.Y., Tay, T.E., Baiz, P.M.	2013	Numerical Analysis of Size Effects on Open-Hole Tensile Composite Laminates	Numerical, Experimental	Tensile strength prediction of open-hole laminates using cohesive zone model accounting for thickness dependence of translaminar fracture toughness; studying two failure modes: pull-out and delamination
Dan-Jumbo, E., Keller, R., Chan, W.S.	2009	Strength of Composite Laminate with Multiple Holes	Experimental	A study was conducted to determine the effects of hole pattern arrangements on the structural strength of composite laminates; this data can lead to better understanding the effects of various damage scenarios and the corresponding repairs needed to meet design requirements
Ercin, G.H., Camanho, P.P., Xavier, J.	2013	Size Effects on the Tensile and Compressive Failure of Notched Composite Laminates	Analytical, Experimental (Digital Image Correlation)	The effects of hole size on strength of composite laminates in tension and compression are presented for two layups and two loading conditions; it is shown that finite fracture mechanics model is the most accurate method.
Falco, O., Mayugo, J.A., Lopes, C.S.	2014	Variable-stiffness Composite Panels: Defect Tolerance Under In-plane Tensile Loading	Micrographic Analysis, Experimental	Investigating the effects of fiber angle discontinuities in un-notched and open-hole tensile strength laminates; results reveal 'ply staggering' and '0% gap coverage' as effective combination in reducing influence of defects
Gan, K.W., Wisnom, M.R., Hallett, S.R.	2013	Effect of High Through-Thickness Compressive Stress on Fibre Direction Tensile Strength of Carbon/Epoxy Composite Laminates	Numerical, Experimental	Carbon/epoxy laminates experiencing through-thickness compressive stresses were experimentally investigated for fiber-direction tensile strength, and compared with the predictions of a numerical model. Results indicate a linear decrease in fiber-direction strength with the mean, through-thickness stress.
Hallett, S.R., Green, B.G., Giang, W.G.	2009	The Open Hole Tensile Test: A Challenge for Virtual Testing of Composites	Numerical	A finite element-based numerical analysis technique has been developed and applied to predict failure modes, trends, and strengths when looking at sub-critical damage in the form of intra-ply splits, inter-ply delaminations, and fiber failure in open hole tensile strength studies of composite materials

Author(s)	Year	Title	Study Type(s)	Objective
Hallett, S.R., Jiang, W.G., Wisnom, M.R.	[2007]	The Effect of Stacking Sequence on Thickness Scaling of Tests on Open Hole Tensile Composite Specimens	Numerical, Experimental	Ply stacking sequences had been varied on open-hole tensile strength of composite laminates to identify how the sequences affected the strength; modeled numerically, tested experimentally
Haque, A., Ahmed, L., Ramasetty, A.	[2005]	Stress Concentrations and Notch Sensitivity in Woven Ceramic Matrix Composites Containing a Circular Hole--An Experimental, Analytical, and Finite Element Study	Analytical, Numerical, Experimental	Woven ceramic matrix composites were studied analytically, numerically, and experimentally for stress concentrations, while also testing for notch sensitivity based on hole sizes
Hatta, H., Denk, L., Watanabe, T.	[2004]	Fracture Behavior of Carbon-Carbon Composites with Cross-ply Lamination	Numerical, Experimental	Tensile fracture behavior and failure modes of carbon-carbon composites were examined using double end-notched specimens
Hermann, T.M., Locke, J.E.	[2005]	Failure Analysis of Anisotropic Composites Utilizing Commercial FEA Software	Numerical, Experimental	Analysis of anisotropic composite plates in tension and compression; experimental compared with Max Strain, Max Stress, and Tsai-Wu failure estimations
Hu, F.Z., Soutis, C., Edge, E.C.	[2007]	Interlaminar Stresses in Composite Laminates with a Circular Hole	Analytical, Numerical	An analytical model developed by Ko and Lin used to evaluate interlaminar stress distributions around a circular hole in symmetric composite laminate plates under in-plane tensile loading is compared with a 3D numerical FEA results to determine its accuracy.
Iarve, E.V., Mollenhauer, D., Kim, R.	[2005]	Theoretical and Experimental Investigation of Stress Redistribution in Open Hole Composite Laminates Due to Damage Accumulation	Numerical, Material Property Degradation, Experimental	Comparing two methods for the prediction of stress redistribution due to subcritical damage accumulation near open holes in composite laminates: FEA with method of material property degradation, and a three-dimensional ply-level modeling method; both methods compared with experimental results for correlation
Liu, G., Tang, K.	[2015]	Study on Stress Concentration in Notched Cross-ply Laminates Under Tensile Loading	Numerical	A detailed study on the analysis of stress concentrations in notched, unidirectional fiber-reinforced composites is performed, focusing on longitudinal splitting at notch tips along the fiber direction, the inability to apply the widely-used material property degradation method to accurately redistribute the local stresses at notch tips, and the notch blunting effect is investigated by modeling longitudinal splitting; by introducing intra- and inter-ply damage modes, the failure of a double-notched cross-ply laminate is predicted and compared with experimental results from open literature
Morais, A.B.	[2000]	Open-Hole Tensile Strength of Quasi-Isotropic Laminates	Numerical, Experimental	A mixed 2D/3D FEA approach was used to compare with experimental data available in references, avoiding material-dependent empirical parameters, and focusing on size-dependency of layers' longitudinal tensile strengths.
Moure, M.M., Otero, F., Garcia-Castillo, S.K.	[2015]	Damage Evolution in Open-Hole Laminated Composite Plates Subjected to In-plane Loads	Numerical, Experimental	The Discrete Damage model, which estimates matrix damage and fiber failure, is tested for accuracy by comparing its numerical results with experimental results taken from scientific literature, which entail different materials, laminate stacking sequences, and specimen geometries for notched and un-notched laminates subjected to in-plane loads.
Pierron, F., Green, B., Wisnom, M.R.	[2007]	Full-field Assessment of the Damage Process of Laminated Composite Open-Hole Tensile Specimens	Numerical, Experimental	Assessing composite open-hole tensile specimens using full-field strain measurements, deriving strains from displacements, and investigating two methods to do so: local differentiation and polynomial fitting
Rahmani H., Najafi, S.H.M., Saffarzadeh-Matin, S.	[2013]	Mechanical Properties of Carbon Fiber/Epoxy Composites: Effects of Number of Plies, Fiber Contents, and Angle-ply Layers	Experimental	This work studied the effects of three variable parameters: fiber content, number of plies, and layer orientations, on the mechanical properties of composites; experimental results were juxtaposed to compare how each parameter contributed to the overall mechanical properties of each permutation; scanning electron microscopy (SEM) was used to analyze failed specimens

Author(s)	Year	Title	Study Type(s)	Objective
Sakai, K., Nassar, S.	(2016)	Failure Analysis of Composite-Based Lightweight Multimaterial Joints in Tensile-Shear Tests After Cyclic Heat at High-Relative Humidity	Experimental	Failure analysis of tensile-shear tested bonded composite-based single lap joints (SLJs) have been subjected to two different levels of cyclic environmental loading; scanning electron microscope (SEM) and energy dispersive spectrometry (EDS) utilized to investigate root cause failure of fractured surfaces that gives an insight into the effects of cyclic heat on static load transfer capacity (LTC). SEM and EDS show that failure modes shift from interfacial adhesive failure to fiber tear for joints that have been exposed to cyclic heat with and without high relative humidity as compared to ambient conditions General solutions for determining stress intensity factors for cracks emanating from circular holes in laminated composite infinite plates subjected to arbitrary loading, with layers of arbitrary fiber orientations, stacking sequences, focusing on effects of crack orientation, loading pattern, and fiber orientations for orthotropic and isotropic plates. A new method for calculating calibration factors for measuring residual stresses in different material systems is presented by simulating the process of hole drilling using FEA; different material types, varying layout modeled
Sharma, D.S., Ukadgaonker, V.G.	(2008)	Stress Intensity Factors for Cracks Emanating from a Circular Hole in Laminated Composite Infinite Plate Under Different Loading Conditions	Numerical	Drilling-induced damage acts as an inhibitor as holes act as stress concentration sites for failure under loading; this research studies the influence of drilling-induced damage on the residual tensile strength of uni-directional composite laminates and proposes a mathematical model correlating residual strength with drilling parameters Un-notched and notched quasi-isotropic laminate coupons were tested in tension and compression, in search for an accurate method of numerical modeling to compare with test results; it was found that using a linear analysis with a properly defined secant shear modulus gave an accurate prediction, however, at least one measured value of notched strength is still required for calibration to use this approach Evaluation of tensile strength properties of woven carbon fiber reinforced polymer (CFRP) composite laminates at cryogenic temperatures using open-hole specimens using quasi-isotropic woven CFRP laminates and microscopic examinations of failed specimens; FEA and experimental results were compared for accuracy The accuracy of Cohesive Zone model is tested for predicting composite strength, comparing numerical results with experimental for notched twill weave composite specimens that displayed different stress gradients.
Shokrieh, M.M., Ghasemi, A.R.	(2006)	Simulation of Central Hole Drilling Process for Measurement of Residual Stresses in Isotropic, Orthotropic, and Laminated Composite Plates	Numerical	A thermoplastic angle-ply laminate with a hole is studied through a FEA model, focusing on the relationship between interlaminar stresses and fiber orientations and how they may contribute to the locations of delamination
Singh, I., Bhatnagar, N.	(2005)	Drilling-induced Damage in Uni-Directional Glass Fiber Reinforced Plastic (UD-GFRP) Composite Laminates	Analytical, Numerical	Predicting stresses at curved free boundaries of laminated composite plates with in-plane loading using a single-layer higher-order model; compared with current numerical methods, FEA solutions
Wang, J., Callus, P.J., Bannister, M.K.	(2004)	Experimental and Numerical Investigation of the Tension and Compression Strength of Un-notched and Notched Quasi-isotropic Laminates	Numerical, Experimental	
Watanabe, S., Shindo, Y., Takeda, T.	(2011)	Evaluation of Tensile Strength of Woven Carbon/Epoxy Composite Laminates at Cryogenic Temperatures Using the Open Hole Specimens	Numerical, Experimental	
Xu, W., Thorsson, S., Waas, A.	(2015)	Experimental and Numerical Study on Cross-ply Woven Textile Composite with Notches and Cracks	Numerical, Experimental	
Yan, X., Ding, S., Tong, J.W.	(2009)	Numerical Elastic-Plastic Simulation of Interlaminar Stresses in a Notched Angle-ply Thermoplastic Composite Laminate	Numerical	
Zhen, W., Chen, W.	(2009)	Stress Analysis of Laminated Composite Plates with a Circular Hole According to a Single-layer Higher-order Model	Numerical (Single-layer higher-order model, FEA)	