

CHARACTERIZATION AND ENERGY ANALYSIS OF
FIBER REINFORCED POLYMER COMPOSITES
BY ACOUSTIC EMISSION ANALYSIS

by

Michael Francis Schuster

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Mechanical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

October 2014

©COPYRIGHT

by

Michael Francis Schuster

2014

All Rights Reserved

ACKNOWLEDGEMENTS

I would like to acknowledge all Montana State University Composites Research Group members for their assistance with my education, composites manufacturing and testing assistance. My family; especially Ms. Shanna Hopson for her unwavering support, encouragement and patience as I pursue my academic endeavors. Finally, Dr. David Miller for sparking my interest in experimental research, asking the right questions and providing an education of unquestionable excellence. To these and many others I offer my utmost gratitude.

TABLE OF CONTENTS

1. INTRODUCTION TO STUDY	1
2. BACKGROUND.....	5
Composite Materials.....	5
Fiber Reinforced Polymer Composites	6
Fiber Reinforced Polymer Composite Manufacturing.....	8
Composite Damage and Failure Mechanisms.....	9
Strain Energy	15
Effects of Defects.....	18
Acoustic Emission	20
Elastic Wave Theory	23
Basic AE Waveform Metrics	27
AE Timing Parameters.....	29
Acoustic Emission Locating	32
Time Domain Data.....	35
Frequency Domain Data	38
Thesis Goals	46
3. EXPERIMENTAL PROCEDURES	47
Test Coupon Manufacture	47
Mechanical Test Setup	52
Acoustic Emission Setup.....	53
Test Process	55
4. RESULTS.....	59
Fabric Characterization Results.....	59
[90] _n Static Characterization Results.....	60
[0] _n Static Test Characterization Results.....	67
[90/0] _s Static Characterization Results	75
[±45] ₄ Static Characterization Results	81
Load – Unload – Reload Characterization Results	85
Strain Energy Correlation.....	91
Total Accumulated Energy.....	100
5. CONCLUSIONS.....	105
Future Work	107
REFERENCES CITED.....	110

TABLE OF CONTENTS - CONTINUED

APPENDICES	115
APPENDIX A: Plate and Coupon Data	116
APPENDIX B: Manufacturing Data	162
APPENDIX C: AEWIn Software Settings	179

LIST OF FIGURES

Figure	Page
1: Cost Per MegaWatt Hour of Various Energy Sources [2].....	1
2: Commercial Wind Turbine Size Comparison.....	2
3: SEM Cross Section of an FRP Composite.....	8
4: VARTM Manufacturing Process	9
5: Matrix Cracking in Composite Micro-Structure.....	11
6: Fiber/Matrix Debond	12
7: Fiber/Matrix Pullout	13
8: Delamination.....	14
9: Fiber Break	15
10: Stress-Strain Curve and Dissipated Energy	16
11: Out-of-Plane Wave	19
12: In-Plane Wave.....	19
13: Traditional Piezoelectric Acoustic Emission Sensor	23
14: Lamb Waves for AE Applications.....	26
15: Basic AE Signal Features	28
16: Representative AE Waveform	40
17: Representative FFT Transform.....	40
18: Previously Determined Damage Mechanism to P-FRQ Correlation.....	44
19: VARTM Manufactured Glass Plate.....	52
20: WDI-AST Frequency vs Sensitivity Calibration Sheet	54

LIST OF FIGURES CONTINUED

Figure	Page
21: Various Failed Coupons from Left to Right: [0] _n Carbon-D and Glass-B, [90/0] _s Glass-A, [90] _n Glass-A and [45] ₄ Glass-C	60
22: Hit Peak Frequency for [90] ₄ Glass-A, AE Not Removed.....	61
23: Hit Peak Frequency for [90] ₂ Glass-B, AE Not Removed.....	61
24: Hit Peak Frequency for [90] ₂ Carbon-D, AE Not Removed.....	62
25: Average Frequency Content for Static [90] _n Coupons.....	64
26: Absolute Energy for [90] ₄ Glass-A	66
27: Absolute Energy for [90] ₂ Glass-B	66
28: Hit Peak Frequency for [0] ₄ Glass-A, AE Removed 2.2%	68
29: Hit Peak Frequency for [0] ₂ Glass-B, AE Removed 1.9%	69
30: Hit Peak Frequency for [0] ₂ Carbon-D, AE Not Removed.....	70
31: Average Frequency Content for Static [0] _n Coupons.....	71
32: Absolute Energy for [0] ₄ Glass-A, AE Removed 2.2%.....	72
33: Absolute Energy for [0] ₂ Glass-B, AE Removed 1.8%	73
34: Absolute Energy for [0] ₂ Carbon-D, AE Not Removed	74
35: Hit Peak Frequency for [90/0] _s Glass-A, AE Removed 2.2%.....	76
36: Hit Peak Frequency for [90/0] _s Glass-B, AE Removed 2.2%.....	77
37: Hit Peak Frequency for [90/0] _s Carbon-D, AE Removed 1.2%.....	78
38: Average Frequency Content for Static [90/0] _s Coupons	79
39: Absolute Energy for [90/0] _s Glass-A, AE Removed 2.2%	80

LIST OF FIGURES CONTINUED

Figure	Page
40: Absolute Energy for [90/0]s Glass-B, AE Removed 2.2%.....	81
41: Absolute Energy for [90/0]s Carbon-D, AE Removed 1.2%	81
42: Hit Peak Frequency for [+/-45]4 Glass-C, AE Not Removed	82
43: Average Frequency Content for Static Glass-C Coupons	83
44: Absolute Energy for [+/-45]4 Glass-C, AE Not Removed.....	84
45: P-FRQ to Absolute Energy Comparison	85
46: Hit Peak Frequency for LUR [90/0]s Carbon-D, AE Removed	86
47: Absolute Energy for LUR [90/0]s Carbon-D, AE Removed.....	86
48: Hit Peak Frequency for LUR [0]n Glass-B, AE Removed.....	88
49: Absolute Energy for LUR [0]n Glass-B, AE Removed.....	89
50: Hit Peak Frequency for LUR [90]n Glass-A, AE Not Removed.....	90
51: Absolute Energy for LUR [90]n Glass-B, AE Not Removed.....	91
52: Stress-Strain Curves for Several Cycles of LUR.....	92
53: Energy Method Comparison for Glass-A	93
54: Energy Method Comparison for Glass-B	94
55: Energy Method Comparison for Carbon-D	94
56: Energy Correlation Constant for Glass-A.....	97
57: Energy Correlation Constant for Glass-B.....	98
58: Energy Correlation Constant for Carbon-D.....	98
59: Total Absolute Energy Accumulated for [0]n Coupons	100

LIST OF FIGURES CONTINUED

Figure	Page
60: Total Absolute Energy Accumulated for [90] _n Coupons	101
61: Total Absolute Energy Accumulated for [90/0] _s and [+/-45] ₄ Coupons	102

LIST OF TABLES

Table	Page
1: Summarized Peak Frequency Bin Ranges	46
2: Fabric Architecture and Designation	48
3: Acoustic Emission Test Matrix.....	50
4: Measured Coupon Wave Velocites.....	57

ABSTRACT

Fabric reinforced polymer matrix composites are an integral structural material used in wind turbine blades. Wind turbines are expected to experience growth both in physical size and utilization as the focus of power generation shifts towards utilizing renewable sources more efficiently. Even current generation blades are experiencing reliability concerns. These factors are now driving improvements in design and manufacture of wind turbine blades. With this, progress in characterizing the mechanical behavior of materials is necessary. Composite materials possess unique damage mechanisms due to their constituent materials and these require further study.

Composite materials were manufactured into four layups from four fabrics and an epoxy matrix. Acoustic emission sensors were applied in a linear locating arrangement to capture elastic waves from damage mechanisms during a tensile test. Data critical to this work that was extracted from the elastic waveforms include peak frequency and absolute energy. A static loading scenario was used to characterize the materials and their damage progression while an LUR loading scenario was used to correlate absolute energy to dissipated strain energy.

Results of the material characterization found that a greater range of frequencies, thus damage mechanisms, were observed for increasingly complex fabric architectures. The observed frequency and energy data provided valuable information on the interaction of the various constituent materials. Attempts at obtaining an accurate and consistent correlation value were not successful with the LUR tests. However, total accumulated energy emerged as a consistent metric of equal value between static and LUR tests that shows promise of being an indicator of coupon damage state.

Acoustic emission was found to provide a unique analysis that can identify and characterize damage and fabric composition in composite materials. The frequency content provides a consistent method of identifying damage mechanisms between varying materials. Correlating acoustic energy to strain energy dissipated appears to be more complex than is developed here but the concept does hold merit and requires further study. An applicable database of AE characteristics of the materials was created that will be of great use for future more complex sub-structure component testing.

1. INTRODUCTION TO STUDY

The demands for energy in the United States are continually increasing. With the decrease in use of older power generation technologies, there has been a significant push for renewable sources of energy to be utilized. Cases vary state by state but for example, the state of Montana has required a minimum of 15% of total power generation to come from a renewable source by 2015 and currently generates 6% from wind [1]. Leading the renewable market in many categories is wind energy, as seen in Figure 1. Wind power generation has been identified as one of the most affordable power generation technologies overall and it currently amasses the largest percentage of generation in the renewable category as well as the largest growth [2]. It is the cheapest option for companies and governing bodies looking to invest in renewable energy.

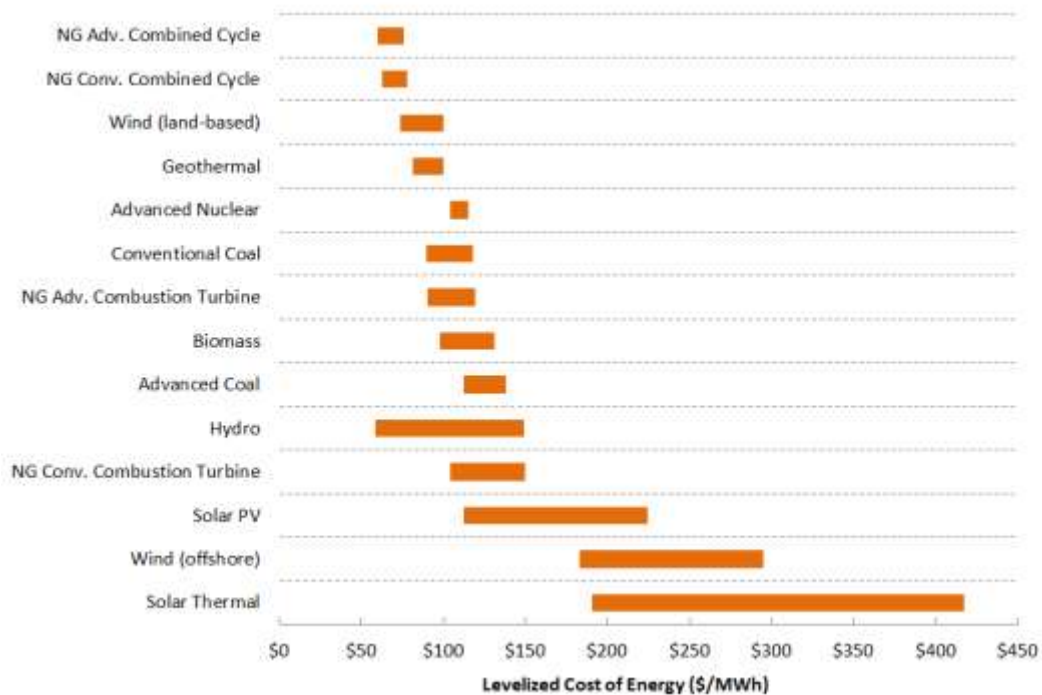


Figure 1: Cost Per MegaWatt Hour of Various Energy Sources [2]

However, for wider acceptance and use of wind energy, the cost of design, development, operations and maintenance must be reduced. To further the progress of the wind industry the US Department of Energy has allocated significant funding and attention to a number of National Labs, members of industry and research programs to the progress of wind energy. Paramount to the reduction in several of the cost categories is the improvement in turbine blade design and manufacturing. The overall trend in wind energy is to make turbine towers taller with longer blades. The increased size and height increases efficiency and allows the blades to enter airflow that is more consistent and away from the ground effects. Currently manufactured turbine sizes can be seen below in Figure 2. The motivations and directions of the industry dictate that stronger and more efficient materials and structures are required.

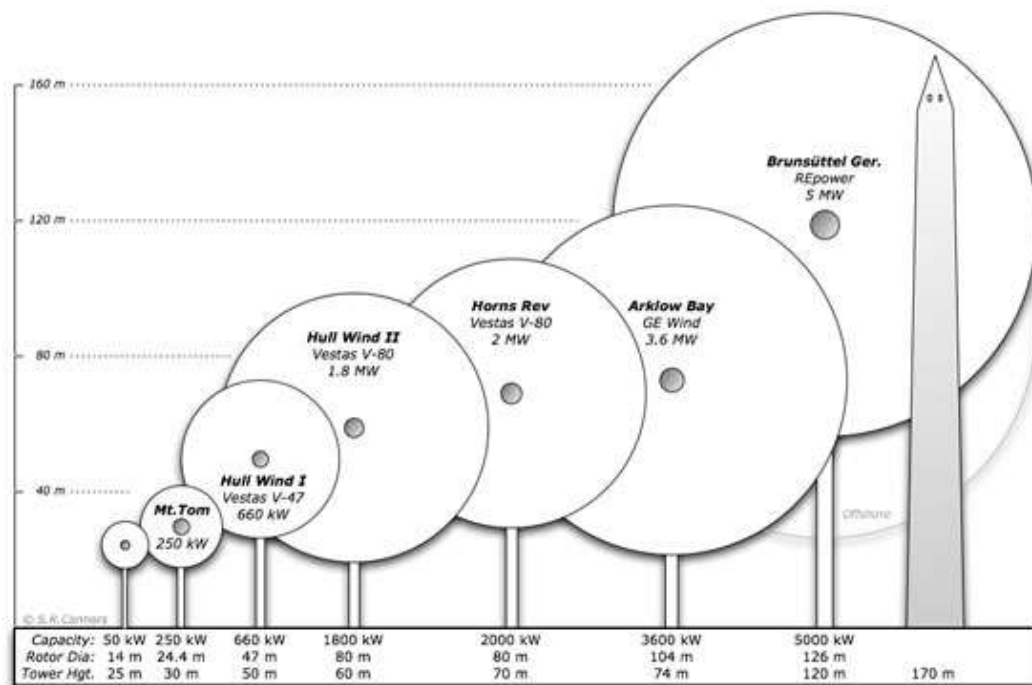


Figure 2: Commercial Wind Turbine Size Comparison¹

¹ <http://www2.technologyreview.com/player/06/05/09Bullis/1.aspx>

The major structural support in wind turbine blades is composed of carbon and glass fiber reinforced polymer matrix composites. These materials allow for inexpensive construction, complex aerodynamic geometry and the ability to finely tune the strength and stiffness of the blade. Composite materials in general are seeing an explosion of growth and use in many industries and product markets from aerospace, to automotive, to general consumer products. However, these types of composite materials are complex with numerous material interactions that result in difficulty understanding their overall mechanical behavior, failure modes and lifetimes.

As part of this continual improvement process, Montana State University has played an integral role in materials and structures development. The MSU Composites Research Group has been tasked with several projects including understanding effects of defects, material fatigue analysis, sub-structure component testing and environmental effects; all of which is focused around composite materials. The research work planned, executed and discussed within this paper extends the body of knowledge surrounding the damage, failure and lifetime of composite materials specific to the wind industry. Increasing the understanding of the mechanisms behind material failure will improve design and implementation of these materials in wind structures.

This research will explore the behaviors of these composite materials through the real-time application of non-destructive analysis to a destructive, mechanical test. Non-destructive testing (NDT) and non-destructive inspection (NDI) cover many technologies that are finding new applications in academic settings and already see wide acceptance in industry. These technologies allow the user to analyze the material in question without

altering the overall behavior or structure of the material. Among these is a technology termed acoustic emission. Acoustic emission is an appealing analysis method because it has the ability to locate and differentiate damage in composite materials based on the elastic waveform emitted from the damage that occurs while a material is being destructively tested. This technology has been applied from a small coupon scales to entire sub-scale wind turbine blades and has proven to be an effective method of gaining unique knowledge about the material system in question.

2. BACKGROUND

Composite Materials

A composite material can be broadly defined as any material containing multiple constituent materials wherein the final material has properties representative of the whole and not of the individual constituents [3]. Engineered composites are often a stiff fiber or particle reinforcement surrounded by a matrix of supporting material. Particles or short fibers can be randomly placed within the matrix or can be very uniform and straight. Composite materials represent an expansive selection of many materials. They have been used for centuries as building materials in different natural forms such as wood, composed of fiber and core, adobe (straw and mud) to concrete (aggregate and slurry). The list of composite materials also comprises modern materials such as metal-matrix composites, carbon nanotube composites and ceramic composites.

Composite materials present a great benefit in that they can be engineered to have specific properties in a specific direction as the engineer chooses simply by altering the orientations or ratios of the constituents. Parts can be designed to fail in one direction while maintaining a structurally whole part or have increased stiffness under certain loading conditions and because of this intrinsic ability, composite parts can be lighter, cheaper and more efficient. These properties make composites an ideal material choice for wind turbine blades. The focus of this work is a class of composite materials called fiber reinforced polymer matrix composites, specifically glass (GFRP) and carbon (CFRP) fiber reinforced composites.

Fiber Reinforced Polymer Composites

Composites that are used in the wind turbine industry for blade structures fall under the category of fiber reinforced polymer composites. The fibers consist of glass or carbon that are manufactured into a fabric that can be rolled out, cut, stacked and layered in the desired orientation. Fabrics can also be formed from chopped or random strand mats that result in isotropic properties, i.e. the same in all direction. Unidirectional fabrics consist of tows, bundles of continuous straight fibers, laid parallel to each other and are often stitched together. A bi-axial (biax) fabric integrates parallel fibers in two major directions while a tri-axial (triax) utilizes three within the same fabric. Randomly oriented mats, chopped fiber or individual tows can also be stitched onto unidirectional fabric for support; these are often referred to as backing. Fabric weaves feature tows of fiber woven together in various patterns at a particular angle to each other to create a loosely bound fabric. Weaves create the characteristic look and sheen of high end components and are primarily used for damage resistance, appearance and environmental protection. Some manufactured products feature different types of fabrics such as Kevlar and carbon integrated together to produce specific material properties. When multiple fabrics are stacked together and manufactured to form a contiguous material the final material is a laminate and each layer of fabric is called a ply.

When specifying the composition of a composite laminate, a widely accepted notation is followed where angles are specified in brackets for each ply that represent the primary direction of the fibers. For example, $[0]_n$ specifies that the primary fibers run in the 0° direction with respect to the loading direction while the “n” indicates that there are n numbers of repeated plies in this direction. Likewise, $[90]_n$ signifies that n numbers of

plies are oriented perpendicular to the loading direction at 90° and $[90/0]_s$ indicates that plies are oriented at 90° and 0° and this is then mirrored about itself to produce a four ply symmetric (as indicated by the “s”) laminate. This standard notation allows for engineers and technicians to quickly determine the laminate composition.

The matrix for FRP composites can be one of several different polymers. Polymers are classed as either thermoset or thermoplastic polymer. Thermosets are easier to work with for composite materials, requiring lower cure temperatures and simpler production but result in brittle behavior once cured. Thermoplastics behave plastically once cured but are more difficult to work with and manufacture. Popular thermosets include vinylester, polyester and epoxy while polyurethane and PEEK are popular thermoplastics. Epoxy is the most widely used resin system for wind energy and aerospace applications because of its improved mechanical properties over the other thermosets. Not surprisingly then, it is the most expensive of the thermosets. It also has the greatest difficulty bonding to glass fibers. The SEM image below in Figure 3 is an example of a complex, multi-ply laminate. Fibers can be seen running parallel and perpendicular to the cross section. The lower portion of the image contains a fabric weave with fibers of small diameter while areas without visible fibers are resin rich. Also present are regions of porosity and some large voids; the most common though ultimately undesirable defect created in the manufacturing process of composite materials.

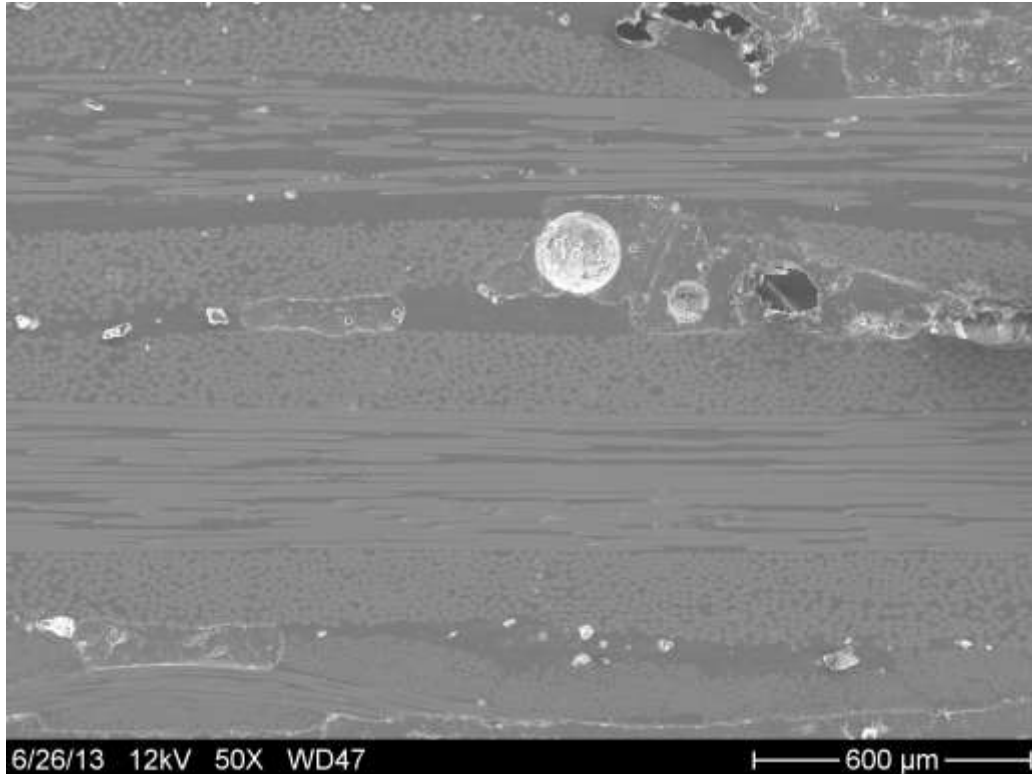


Figure 3: SEM Cross Section of an FRP Composite²

Fiber Reinforced Polymer Composite Manufacturing

There are a number of manufacturing methods that can be applied to fiber reinforced polymer matrix composites. These methods vary greatly in overhead equipment costs, materials used and intensity of required manual labor. Several processes include pulltrusion, filament winding, automated prepreg layup, resin transfer molding (RTM), vacuum assisted resin transfer molding (VARTM) and hand layup. Wind turbine manufacturing utilizes some automated processes as well as a significant amount of manual labor with a VARTM process. Blades are generally manufactured in an open mold VARTM process to create a clamshell style assembly where the two

² Montana State University Composites Research Group

finished halves are adhered together with an inner supporting spar running down a portion of the blade. Consequently, the VARTM process is primarily used at MSU to create thin plates, thick laminates, sandwich structures, spar cap type structures and other complex geometries. The VARTM method consists stacking peel ply, fabrics at the desired orientations, more peel ply and flow media on a hard mold surface. A flexible vacuum bag is then sealed to the mold. Injection and vacuum ports for the resin infusion are either machined into the mold or cut into the vacuum bag during layup. A vacuum is applied to the laminate through the vacuum port which compresses the fibers and reduces the free space in the fabric stack. After a majority of the air has been removed, the properly proportioned and mixed resin is pulled into the laminate and allowed to saturate the fibers. The resin is allowed to cure and often a post-cure is performed at elevated temperatures as well. The schematic in Figure 4 details the material stacking sequence for the VARTM process.

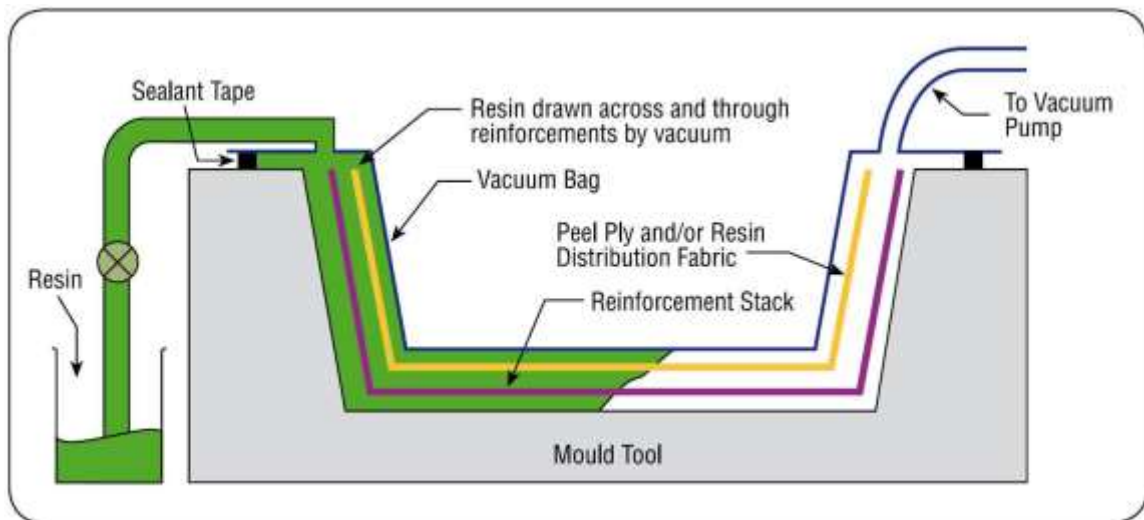


Figure 4: VARTM Manufacturing Process³

³ <http://www.gurit.com/files/documents/vac-consv2pdf.pdf>

Composite Damage and Failure Mechanisms

Composite materials have classifications for modes of damage and failure that are unique and critical to this work. The uniqueness stems from the fact that the fibers and matrix have vastly different properties in different directions within a laminate. The polymer matrix has low strength and low stiffness but isotropic properties that transfer loads and stresses to surrounding material effectively. The fiber reinforcement, however, has high strength, high stiffness but is ineffective as the sole structural material. An individual, unsupported fiber will behave much like a rope and will not support loading other than axial. The discontinuities of stiffness and strength at the fiber/matrix interface lead to several of these damage mechanisms while the constituents lend their own individual mechanisms. A composite part may experience a single type or multiple types of damage leading up to failure. The types of damage that manifest within the laminate depend on the materials present, their orientations and how the laminate is loaded. If one instance of damage occurs, it does imply total failure. In fact, this work hinges on the reality that much of this damage can occur unnoticed by human senses but nevertheless alters the physical state of the material. If enough damage is accumulated of a single type or some combination of types, the part will fail. It is these complex interactions and damage mechanisms that occur in a non-homogenous, fully orthotropic material system that complicates failure criteria and lifetime estimates and requires greater understanding.

Matrix cracking is often the first damage type to occur and can lead to failure in a weakly supported material in the loading direction. Cracks can initiate from a defect in the material, material interface or some other sharp radius at the edge or center of the

laminate. Once initiated, these cracks will grow through the resin matrix perpendicular to the stress acting on the starter crack. This damage mechanism occurs as a result of the low strength and brittle behavior of thermosetting polymer resins like epoxy. If there is no stiffness or support in an adjacent ply perpendicular to the crack, such as from fibers in the loading direction, matrix cracking can fail the part once the crack reaches a critical length. Otherwise, the load that was carried in the matrix is shed to the surrounding material. A schematic of matrix cracking and the overall composite laminate micro-structure can be seen in Figure 5.

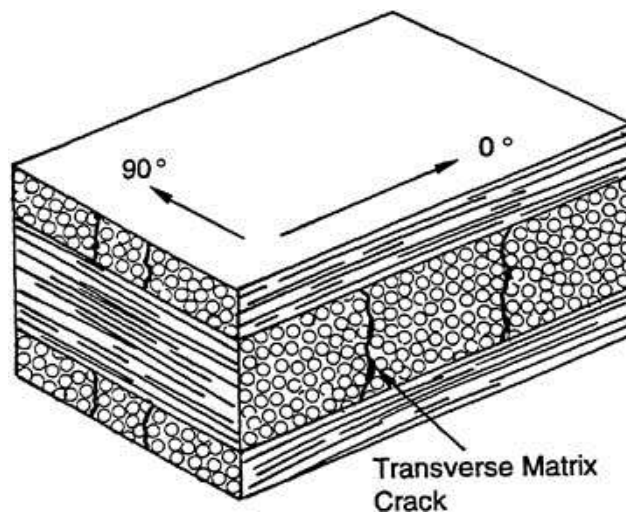


Figure 5: Matrix Cracking in Composite Micro-Structure⁴

Fiber pullout and fiber debond are two similar damage mechanisms in which the interface between fiber and impregnated resin loses cohesiveness. The interface between the two dissimilar materials separates and a loss of stiffness occurs. Several researchers within the acoustic emission field refer to both types with the overall characterization of

⁴ National Research Council

interphase failure yet there are differences. Fiber pullout occurs as a result of excessive shear stress at the interface. The fibers can pull out or slip through the matrix along the fiber's axis. Fiber debond occurs when the stress is greater than the strength at the fiber/matrix interface and the two materials separate at the radius of the fiber. Fiber debond is a precursor to fiber pullout but it may occur independently. These damage mechanisms are difficult to identify and usually require microscopic methods post failure. These mechanisms can point towards a poor choice of materials as some fiber/matrix combinations are more cohesive than others. Interphase and matrix failures have been identified as resulting in lower fracture energy, thus, they often occur at lower stresses and strains in a statically loaded material [4]. Coupon failure due specifically to these modes is rare but may occur because surrounding material is unable to effectively carry the load. The SEM images in Figure 6 and Figure 7 are the result of fiber/matrix debond and fiber pullout.

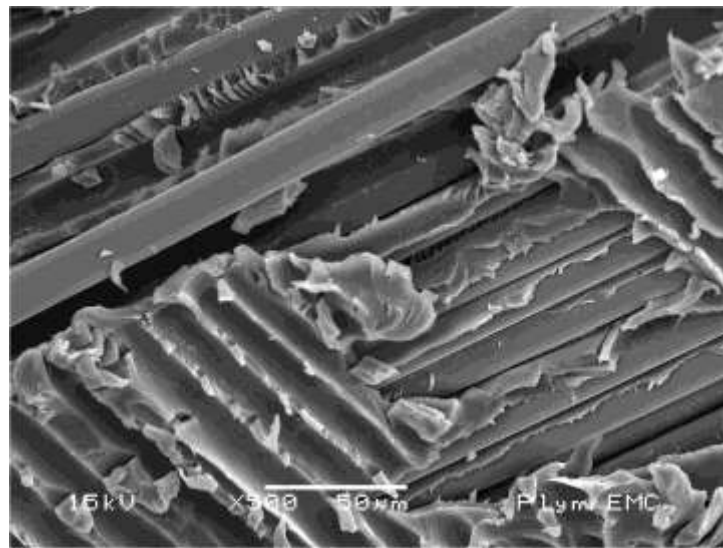


Figure 6: Fiber/Matrix Debond⁵

⁵ John Summerscales, University of Plymouth School of Engineering

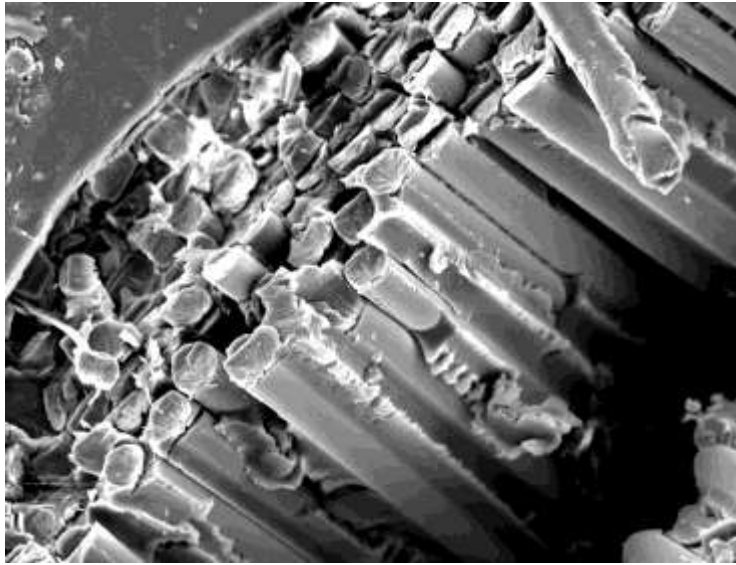


Figure 7: Fiber/Matrix Pullout⁶

Delamination is a significant failure mode that is characterized by separation of adjacent laminate plies of composite material, this can be seen in Figure 8. Delamination can be caused by numerous loading scenarios but is most prevalent in bending as is experienced in an aircraft wing or wind turbine blade. As the plies peel away from each other, they lose flexural stiffness and the matrix can no longer distribute load to neighboring plies. Depending on the loading scenario the composite may be unable to carry the load that is required and fail. In terms of micro-mechanical damage, delamination is a combination of matrix cracking and interphase failure induced by various loading scenarios. For this reason, delamination will not be explicitly investigated in this research.

⁶ John Summerscales, University of Plymouth School of Engineering

Figure 8: Delamination⁷

Fiber failure often constitutes the final, catastrophic failure of a composite part when loading a laminate in the direction of primary fiber content. Since fibers are the stiffest constituents in a polymer matrix composite, they carry the majority of the load. As the fibers are loaded, strains increase until they reach the strain limit of the fibers and fracture occurs. Fiber failure is often accompanied by interphase failures as well [5]. Fiber fracture is primarily observed in unidirectional materials under tensile load though numerous other scenarios may cause this damage. As individual fibers become damaged and fail this load must be shed to other fibers and plies that are available. Often, this will cause the resulting fibers to fail due to the significant increase in load combined with the reduction in total load carrying area. This pattern of load shedding and resulting failure is termed cascading failure and will result in final failure of a simply supported laminate. Fiber failure as shown in Figure 9 is quite obvious due to the significant amount of energy that is released when fibers break with quite catastrophic results whether it is in a laboratory or in the field.

⁷ Amy L. Stratton, Rutgers University College of Engineering

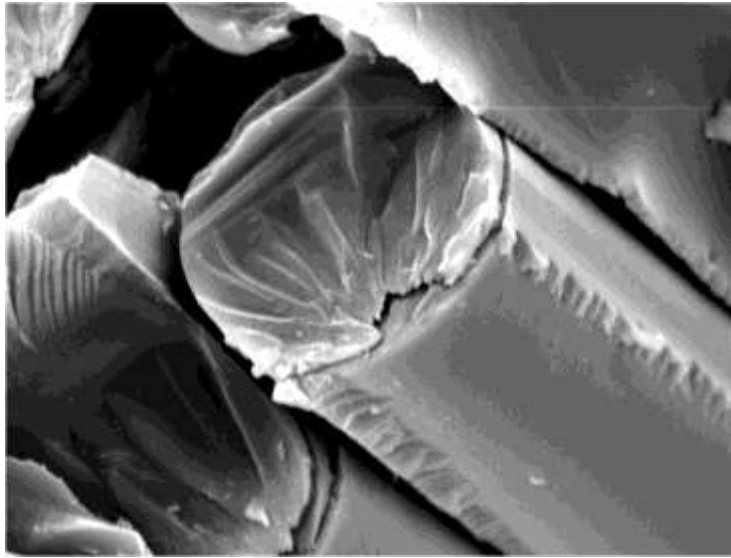


Figure 9: Fiber Break⁸

Strain Energy

Energy is the basis for many concepts, theories and derivations in the engineering world as well as paramount to the everyday physical world. We generally define energy as something that has the ability to do work. Energy can be broadly defined to fall into either a kinetic or potential form. Kinetic energy is energy in motion that is doing work while expending energy. Potential energy is energy stored by some medium that can be released to do work. Energy is defined to be in a system, which is chosen based on the system in question. Energy within this arbitrary system can be added, removed or converted to another medium depending on the conditions and properties of this system, however, it must always be conserved. If the system is taken to be a composite coupon in a mechanical test machine, as force is applied to the coupon it deforms, energy is added into the system and stored as an elastic spring force. The spring force, in this context, is

⁸ John Summerscales, University of Plymouth School of Engineering

termed strain energy and is a measure of the potential energy put into a material as it is being stretched or strained. For an idealized mechanical test this energy storage process is well represented visually. Below in Figure 10 is a traditional stress-strain curve created during a uni-axial tensile test and is applicable to many materials.

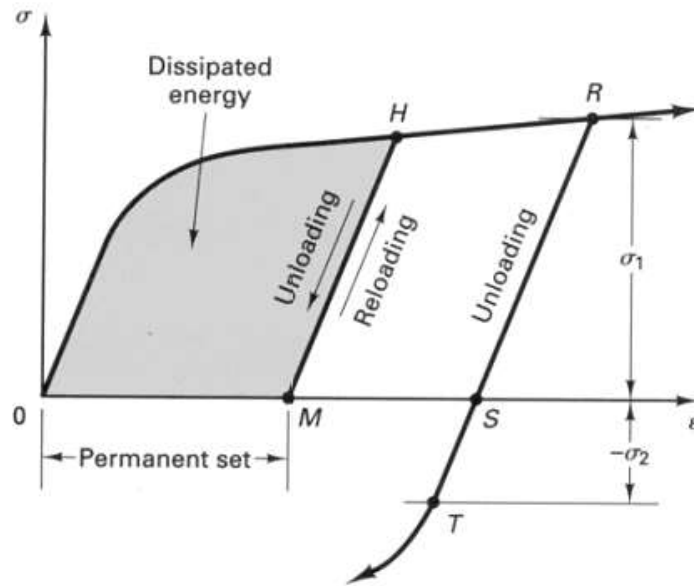


Figure 10: Stress-Strain Curve and Dissipated Energy⁹

If a small axial load is placed on a coupon, the stress and strain increase at a linear relationship to each other as defined by the laminate's elastic modulus. Consequently, a straight line is created on this stress-strain diagram. The integral of that line represents the amount of strain energy put in to the material and is determined by Equation 1.

$$u = \int_0^{\epsilon_{ij}} \sigma_{ij} d\epsilon_{ij} \quad (1)$$

⁹ <http://emweb.unl.edu/>

The units are Joules per meter cubed and this is classically called strain energy density. Taking the measuring volume into account results in the strain energy contained within that volume in Joules. If the applied load is released, both the stress and strain would return to zero in the easiest manner, a straight line in the diagram, and ideally, the entirety of potential energy would be conserved and recovered similar to a spring being released. However, this assumes no damage. If during this same test, a load is reached that produces stresses large enough to cause damage by one of the mechanisms discussed above, the linear stress-strain relationship breaks down and becomes non-linear as energy is released from the coupon via the damage mechanism. Following the conservation of energy, the damage mechanisms convert the energy from strain energy to one of the other numerous dissipative mediums such as the creation of new surfaces, elastic stress waves or frictional heating. The curve will flatten as a greater strain is required to reach the next increment of stress. Upon unload, the stress and strain return to zero in a straight line path, however, the strain does not reach zero and there is an area between the two curves represented by the shaded area in the diagram above. If the same strain energy integral is performed on the load and unload curves and the two results subtracted from each other we are left with the section of area between the two curves; the strain energy dissipated. In fiber reinforced polymer matrix composites, each instance of damage will release energy that if summed together with all other damage events in all other energy mediums, should equate the total energy dissipated as seen in the stress-strain curves. This concept has not been shown for composite materials at this time though advances have been made in relating singular dissipative energy forms for a single well-defined crack path. These

efforts will be discussed below in relation to acoustic emissions. Thousands of instances of damage potentially occur in a uni-axial test and acoustic emission analysis may prove to be one of the few methods to provide a measure of released energy per instance of damage.

Effects of Defects

The blades of most small and utility scale wind turbines are manufactured by a labor intensive VARTM layup process. As with any manual process, there is an inherent chance of defects entering the part throughout various stages of manufacturing. These defects have been identified as causing premature failure or required maintenance in utility scale blades. Montana State University has been a major partner in the Department of Energy Blade Reliability Collaborative (BRC) with Sandia National Labs which works to further the progress of all aspects of wind turbine blade design, analysis, manufacture and maintenance. The effects of defects are not of explicit concern for this study but they do motivate the goals of the research and are worth mentioning here.

Riddle has characterized the major flaws that are present in as-manufactured blades [6]. These defects were identified as out-of-plane waves (Figure 11), in-plane waves (Figure 12) and porosity. The waves can be a result of careless handling of the fabrics, excess material or poor layup of the material in the mold. Porosity is caused by poor vacuum during resin infusion, excess air in the resin or unintentional injection of air into the laminate that creates pockets or voids within the hardened laminate. These defects creates stress concentrations, crack tips and weak material due to miss-aligned fibers and ultimately affects the structural integrity of the part. Some amount of these

defects is acceptable though not desirable and they could result in an entire part being scrapped if severe enough.

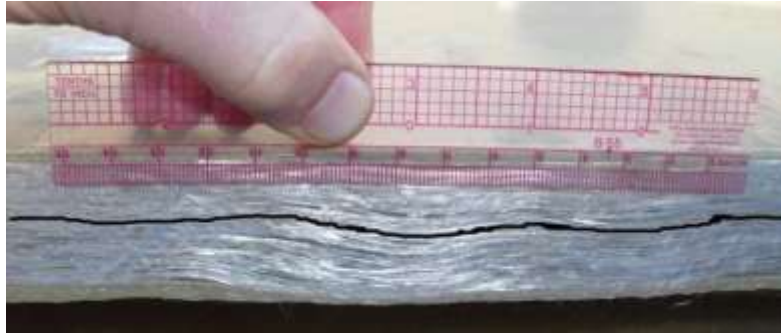


Figure 11: Out-of-Plane Wave¹⁰

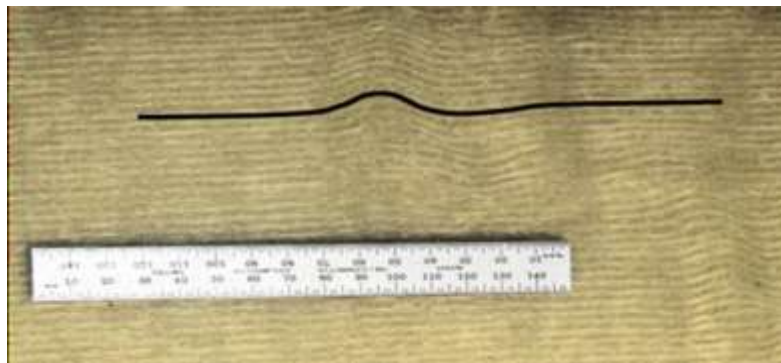


Figure 12: In-Plane Wave¹⁰

Nelson has put forth a great amount of work to understand how these inherent defects affect the strength, stiffness and failure of a composite laminate [7]. Advanced modeling techniques as well as a vast matrix of coupon testing has supplied knockdown factors for the material properties under static loads; fatigue loading is currently being investigated as well. This data was used to predict the static and fatigue failure conditions of a 9m mock-up blade. However, to expand the coupon data directly to a

¹⁰ Montana State University Composites Research Group

scale blade test requires significant estimation and conservative material properties. To bridge the two ends of the testing spectrum, tests of major sub-structure components such as the spar, end caps and root sections are required. Testing sub-structure components will provide information on flaws in a less idealized test than a coupon test resulting in less estimation and more accurate knockdown factors when applied to scale blade tests.

MSU is investing in this hierarchical approach to testing to help advance manufacturing and design of blades and materials. A multi-axial fatigue load frame is in development that can apply a bending and torsional load. Currently the frame is capable of three and four point bending tests on components up to 2.5m long and roughly 20cm square. Cantilever bending tests will also be possible in the near future. Other current research includes design and analysis of manufacturing parameters for a representative sub-structure test article and integrating the previously characterized flaws into the representative sub-structure. Key to fully understanding and characterizing flaws is a way of knowing when, how and why they occur. A method of locating and characterizing the type of damage occurring during a test would clearly be beneficial to any scale of composite structures testing. As new analysis techniques are applied to materials, such as acoustic emission, the work often begins at the smaller scales. The work discussed in this paper will focus on coupon sized materials with significant motivation towards application on larger sub-scale structures.

Acoustic Emission

It is known that flaws and damage in composite materials alter the strength and stiffness of coupons as well as larger scale components. The defects can also alter the

damage mechanisms and thus the failure modes from those seen in an ideal structure. Once test articles become more complex, such as in a sub-structure or blade test, these changes become much more difficult to observe. Damage detection can be of varying difficulty and utility depending on the variety of damage, location, material and at what stage of the material's lifetime it is analyzed. Detection methods are classed as either being destructive or non-destructive. Destructive testing means that the material will no longer be able to perform its original function or retain its original properties after testing. In an industrial setting, particular parts may be sampled and mechanically tested to failure or cut into and visually inspected. Non-destructive test (NDT) methods leave the material intact; ideal if the part is to be used in a final assembly and is popular in many industries including the wind turbine industry. These various methods allow one to see inside the material and depending on the particular method, damage will manifest itself in various ways.

Digital image correlation (DIC) has proven useful for mapping the surface strain field of a test article and can identify defects by regions of higher strain, however, processing takes place after the completion of a test thus limiting the real-time information that can be gathered. The resolution decreases when larger areas are imaged so knowledge of the flaw and failure location must be known beforehand. Other imaging techniques such as CT scanning and ultrasonic inspection prove difficult to perform on a large scale or during a test though they are quite effective at characterizing known flaws or inspecting production parts. Thermal imaging has provides a real-time technique of locating damage however it suffers from the same image related detriments as DIC.

Acoustic emission (AE) is a method that can be applied during a test to monitor individual damage events in real-time. The strength of acoustic emission is in its flexibility of application and its ability to directly sense the release of energy from damage. The National Renewable Energy Laboratory (NREL), National Wind Technology Center (NWTC) has performed many of these analysis techniques on full scale or scale wind turbine blades in an effort to identify the strengths and weaknesses of the various sensing techniques [8].

By itself, acoustic emission is a non-destructive evaluation method but it can be used during a destructive, mechanical test to provide real-time information on the damage as it is occurring. This method has great applicability to composite material mechanical testing. As composites strain, damage will occur and release transient elastic stress waves that propagate through the material. An AE system utilizes sensors that can detect these waves, turn them into a representative electrical signal and then process this data into various identifying metrics. AE systems have been increasing in use for composite material testing because they have the capability to detect when, where and how damage is occurring within the laminate; something that has always been difficult in materials and has shown great benefits to the growing composites related industries and research.

Acoustic emission sensors consist of a sensitive piezo-electric crystal mounted behind a wear plate that transmits the elastic wave from the material to the crystal (Figure 13). Piezo-electrics output a small voltage proportional to the deflection it experiences. The piezo crystal dictates the level and type of response from a given input. Wideband sensors produce a relatively constant voltage output regardless of the input frequency. To

achieve a wideband response, multiple crystals and damping of the crystals may be performed, however, this leads to decreased sensitivity over the useable frequency spectrum. The sensitivity of an acoustic sensor can be increased by using a tuned piezo that prefers a specific resonant frequency, often with a very limited response in other frequency ranges. The material phenomena that is being monitored directs the choice of sensor type, size or resonance, of which there are many commercial options. With all types of sensors, the analog voltage is very small and must be amplified by a pre-amplifier that is able to drive the signal through longer lengths of signal cable. The data acquisition system can then record the electrical waves via a high bitrate A/D converter and then software can extract the desired information. Although acoustic emission methods are not new, the computing power of packaged commercial systems has increased and allows for more real-time calculations. This data is dependent on the structure of the elastic waveform emitted from the material mechanisms in question.

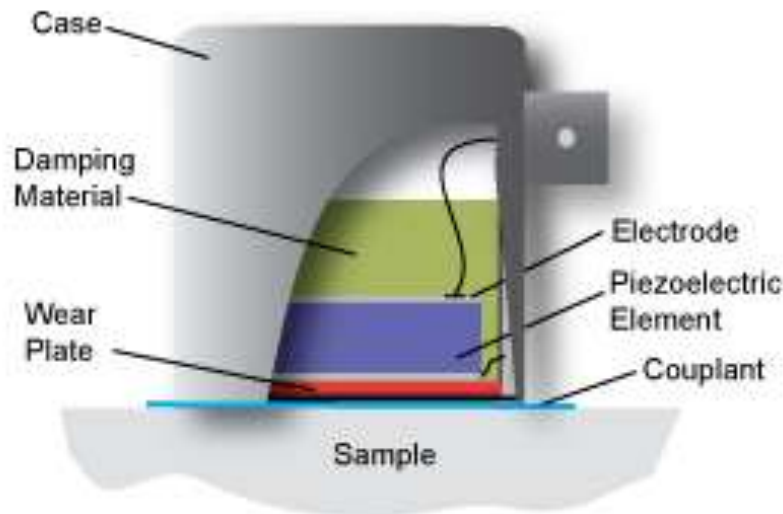


Figure 13: Traditional Piezoelectric Acoustic Emission Sensor¹¹

¹¹ <https://www.nde-ed.org>

Elastic Wave Theory

The acoustic emission analysis technique is built upon elastic wave theory and a solid grasp of the theory precedes successful implementation of the technology. Elastic wave theory specifies that stress imparted in a material behaves as a wave and can be described analytically by the traditional wave equation. Within elastic wave theory there are many theories to describe wave motion such as longitudinal and shear waves in a free volume and Rayleigh waves on surfaces. The wave equation was classically decomposed into components applicable to plate geometry by Lamb in 1917 [9]. The solution of the wave equation for Lamb waves allows for numerous orders of solutions, however it is the zero-order modes that are most important in application. The zero-order Lamb wave components are defined as the symmetric (s_0) and anti-symmetric (a_0) Lamb wave modes or more commonly known as the extensional and flexural wave modes. The boundary conditions for the wave equation allow for simultaneous solution of these two modes thus allowing for both modes to be excited independently and at different magnitudes depending on the source of the elastic wave. Lamb waves are a surface phenomenon that can be applied for thin, plate-like materials such as composite laminates. The wave shapes given by plate theory indicate that extensional waves contract and extend material symmetrically about the mid-plane of the plate in the direction of propagation and flexural waves displace asymmetrically out of plane of the plate, i.e. perpendicular to the direction of propagation.

The analytic solution of the wave equation by Lamb does have some deficiencies when applied to composite materials. The original solution was for an isotropic and homogenous material and composites certainly do not fit these qualifications. The

original solution also employs an assumption of elastic media and boundary conditions of an infinite plate. However, composite plies are composed of various fabrics and orientations in a multi-layer laminate that result in varying properties through the thickness of the laminate. The multiple constituent materials also result in a non-homogeneous microstructure as well as anisotropy. Experimental studies of composite material usually employ some form of test coupon with finite boundaries, thus deviating further from theory. Waves reflect off surfaces of significant material mismatch which includes the edges of the plate as well as the matrix/fiber interfaces. This consequently induces directionality in the emission and causes overlapping of the extensional and flexural wave modes [10]. To address these discrepancies between theory and application, work has progressed using plate assumptions and full 3D elasticity models that account for the complications in anisotropic layered media [11].

While exact solutions are necessary to fully understand the elastic waveform propagation in composite materials, they are unnecessary for wave velocity estimations. A composite laminate analysis can be performed that generates overall laminate properties including fully orthotropic moduli if desired. This analysis assumes a macroscopically homogenous material and is especially applicable to Lamb waves when the wavelength of the elastic wave is large with respect to the plate thickness. This allows for simplifications in the governing equations while still describing the wave propagation in sufficient detail. From the laminate analysis (which is described in full detail in Barbero [3]) the primary tensile and bending stiffness coefficients can be used for the modulus in the extensional and flexural equations wave speed equations,

$$c_e = \sqrt{\frac{A_{11}}{\rho h}} \quad (2)$$

$$c_f = \sqrt[4]{\frac{D_{11}}{\rho h}} * \sqrt{\omega} \quad (3)$$

where ρ is the material density, h is the thickness and ω is the frequency of the wave [12]. Of interesting note here is that the extensional wave is assumed non-dispersive; the speed is not dependent on the frequency. This is an allowable assumption at the low frequencies encountered in AE applications, however, the flexural wave is dispersive. The extensional wave speed is also much higher than the flexural wave. The wave modes as generally seen in an AE analysis can be seen below in Figure 14.

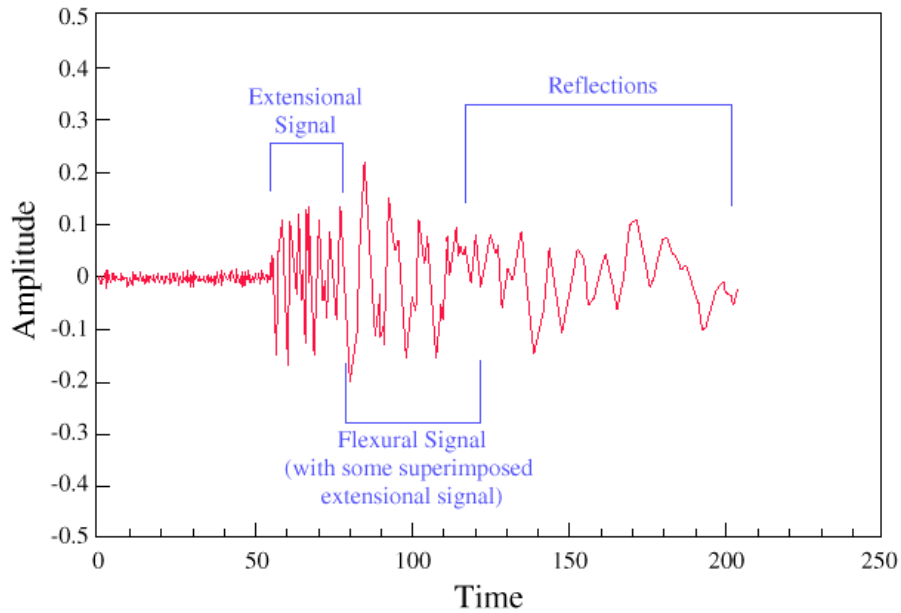


Figure 14: Lamb Waves for AE Applications¹²

¹² Gregory N. Morscher, NASA Lewis Research Centre

Gorman demonstrated the principles behind Figure 14 and the above equations and compared the behavior of the two wave types specifically for acoustic emission purposes. Since the extensional wave has a higher velocity and is non-dispersive, he concluded it should be used for AE, however the signal is often much smaller as detected by the sensor because of the wave's in-plane propagation as well as its lower energy behavior [13]. There are methods that can be utilized to decompose a combined extensional/flexural waveform, however these add significant post-processing time and custom numerical scripts [14]. Instead, for this work, traditional AE software parameters that help shape the type of waveform captured will be used to control the waveform acquisition. However, one must fully recognize that some superposition and overlapping of the two wave modes will occur and that some flexural waves will be triggered on by the AE system which will in turn affect the accuracy of associated waveform metrics.

Basic AE Waveform Metrics

The data that most current AE systems collect can be grouped into several general categories. These categories differ by what parameters are necessary for the calculations involved in obtaining the data. These categories consist of time domain based data, frequency domain based data and location based data. With the AE system used in this study, all data can be collected in real time. For most commercial systems, an AE signal is detected by setting a decibel level threshold on the sensor voltage input. As soon as the AE signal crosses this threshold, the system begins recording the signal as a discrete "hit" until the signal level no longer rises above the threshold. The AE signal is converted

from the raw voltage from the sensor to a decibel (dB) value using Equation 4, where V is the voltage from the sensor and Gain is the preamplifier gain of the system in decibels.

$$dB = 20 \log(V) - Gain \quad (4)$$

The maximum decibel level of the hit is called the amplitude. The time until the hit reaches the amplitude is the rise time. The duration is how long in time the hit has been above the threshold and the counts are how many times the AE signal crosses the threshold throughout the duration. Since the system is always recording data, there is always a voltage being recorded that is sensitive to noise. If the threshold is set too low, the system will record background noise as an AE event, too high and actual events may be missed. The basic AE signal can be seen below in Figure 15.

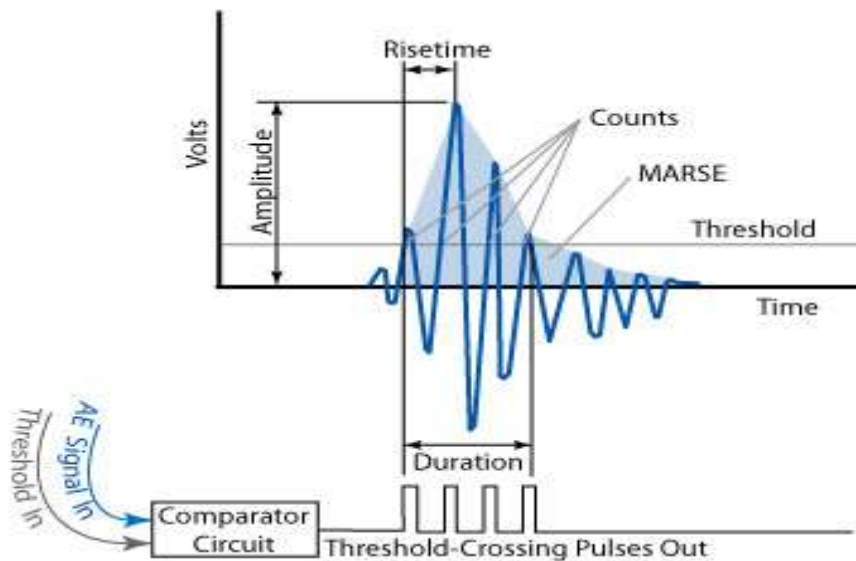


Figure 15: Basic AE Signal Features¹³

¹³ <http://www.ndt-ed.org/>

Much of the early acoustic emission research relied solely on the decibel level to draw conclusions. It has also been an ongoing goal to differentiate and correlate specific AE waveform types to composite damage mechanisms. In an often referenced paper, Barre and Bezeggagh characterized the bonding between glass fiber and thermoplastic resin and concluded that lower amplitude hits correspond to matrix cracks, mid-level hits to pullout/debond and high dB hits to fiber fracture [15]. However, all waveforms attenuate over a distance thus lowering the amplitudes of the signals, with high frequency waves attenuating quicker. Other work clearly indicates that a wide array of amplitudes may result from matrix cracking and that amplitude is heavily dependent on thickness [10, 16]. Amplitude increases with thickness of material and suggests that damage mechanism identification using amplitude is not ideal. The utility of amplitude as a damage identifier is a great point of contention within AE research.

Nevertheless, the combination of the above basic waveform metrics are important data points that can be used to quantitatively describe AE waveforms. They can also be used to set software filters on the incoming waveform. For example, and to reference the earlier discussion on the difficulty of differentiating between extensional and flexural waves, a software filter on rise time could be set to remove hits with long rise times i.e. a flexural wave. Attempting this type of filtering does require intimate knowledge of the expected waveforms so that important waveform information is not lost.

AE Timing Parameters

Special attention should be given to the four timing parameters used by acoustic emission systems. These parameters control what is considered to be a part of a

waveform and the spacing between successive waveforms. Successful implementation of these parameters often requires trial and error because the best values will vary depending on material, type of acoustic signals and other various factors. In the interest of ensuring that future users of the AE system at MSU fully grasp the effects of these parameters, they will be covered here. Tuning the parameters to obtain the most accurate waveform involves simulating or testing a similar material with a representative impulse, observing the waveforms to see what is captured and adjusting the timing values. Careful selection of timing values will improve the accuracy of all AE metrics.

For successful implementation of the timing parameters, it is critical to conceptually develop what is desired to be captured in terms of an AE waveform. Significant portions of the flexural wave can be collected or one can attempt to limit the length of the waveform to avoid that component all together. Or, it may be desired to capture a very long waveform without the system triggering on another waveform. The max duration parameter specifies the maximum amount of time that can constitute an AE hit. Values lower than the 99ms default value are only applied with very reflective and resonant materials for which shorter times are specified to end the hit. For composite applications this value will rarely come into effect due to the short signals and acoustically damping nature of the material, therefore the setting for this in milliseconds is of no great concern for composites. The following three parameters give sufficient control over recorded hits in composite materials. Hit definition time (HDT) is the maximum amount of time allowed between subsequent threshold crossings. If the threshold is not crossed in the specified time span, the hit is ended and the processing

begins. Because waveforms in composite materials attenuate significantly, there is not a lot of “ringing” to the waveform and the high frequency hits are short in duration.

Longer settings here will capture a longer waveform and more reflections from waves.

Therefore, this is set to the lower end of the spectrum of possible values for composites.

Hit lockout time (HLT) defines how much time passes in between subsequent hits. This

parameter begins timing immediately after the HDT has defined the end of the hit and

effectively blocks any incoming signals from being recorded as hits. Shorter times will

allow more hits to be collected but then stored hits may also include reflections from

previous hits. Longer times will prevent this but may also cause critical hits to miss

being recorded. This is also set to the lower end of the spectrum of values for the same

reasons that govern the HDT. Peak definition time (PDT) is perhaps the least utilized

parameter but can be used to give greater control over the mode of waveform collected.

This parameter defines the maximum amount of time allowed to pass before the peak

amplitude of the AE hit is observed. Returning to the prior wave mode discussions,

extensional waves have a higher frequency and shorter duration. Flexural waves have a

lower frequency and longer duration thus flexural waves require a longer time to reach

their peak amplitude. Higher values of PDT will allow hits with the longer rise times of

flexural waves whereas shorter times will only allow extensional waves. This is of

course, purely conceptual where in reality the reflections, interaction of modes and

distance to the sensor make selecting one value of PDT difficult and rarely attempted for

the absolute level of control available in theory. The PDT parameter is generally set

equal to the HDT value. Examples of the effects of these values can be found in the MISTRAS handbook [17].

Shorter times of HDT, HLT and PDT can be used due to composite materials' non-resonant nature in comparison to metals and because of the short duration of damage signals. As there are no standard values that are required for these parameters, different researchers have utilized various values for similar setups. Although carbon coupons will have a slightly higher wave speed, using identical timing parameters for carbon and glass test materials should not affect test results because the elastic waves created by damage are similar. Some specific examples of values include: Zarouchas, who used 30, 150, 300 microseconds for PDT, HDT and HLT [18], Huguet used 40, 80 and 300 microseconds [19], Santulli used 30, 300 and 600 and 80, 300 and 1000 microseconds were used by Sause for a DCB setup. Due to the great effect that these three timing parameters can have on results, it is pertinent to consistently apply and report these values along with other critical threshold and amplification settings.

Acoustic Emission Locating

One of the premier uses for acoustic emission is determining the source location of emissions. It is also one of the most useful pieces of information in a practical application and has seen a good amount of work dedicated to devising improved methods of event locating. A location calculation with an AE system allows for the precise triangulation of where an event took place. An event in AE terms means that independent hits have been triggered on separate AE sensors in an array of sensors and the software has determined that the hits have come from one source spatially and

temporally. The most basic method for determining location is time of flight difference between the sensors. Similar to the way earthquakes are detected, the difference in time between when each sensor records a hit will allow for an accurate position if the speed of sound in the material is known. The more sensors that are used, the more accurate the event locating becomes. For coupon based testing, a linear setup utilizes only two sensors and therefore only gives location in one dimension on a line between the sensors. Multiple sensors can be used on larger structures to produce two and three dimensional locating of emissions. Prosser performed experiments on biaxial graphite and epoxy coupons and determined that traditional linear locating methods determined the location of transverse cracks with an average of 3.2 mm error for a sensor gage length of 152 mm [16]. However, if an AE sensor happens to miss the initial extensional wave or triggers on the slower flexural wave traditional time of flight locating schemes can have error in excess of 50% [12].

Accurate location data is predicated upon an accurate wave velocity which as discussed above, is complicated by the microstructure and behavior of composite materials. As the wave velocity equations are dependent upon moduli, any changes in moduli will affect location data. It is clear then that if defects are present or damage occurs within the laminate, this will affect the speed of sound and wave propagation. When damage occurs, surfaces are created for the waves to reflect off of as well as an overall reduction in modulus and therefore a reduction in wave velocity. Severely damaged material can potentially block waves from reaching the sensors at all. The change in moduli associated with increasing damage was interestingly utilized by Aggelis

to measure the damage state of a tensile coupon by using a dedicated pulsing sensor and two receiving sensors to monitor the change in extensional wave velocity throughout the test [20].y Acoustic emission can accurately locate initial defect areas experiencing damage but as a result of damage effects, time-of-flight location data from events later in the test may suffer; especially on large and complex structures where multiple damage sites may exist.

There have been a number of methods that have attempted to improve upon the classic time-of-flight approach to locating. The locating errors that are the result of the discrepancy between flexural and extensional wave behaviors have warranted these advanced methods. A two-step picker method was successfully utilized by Sedlak in thin composite plates [21]. The propagation differences of the two wave modes was shown to be beneficial by Surgeon as shown by the modal analysis technique that requires only one sensor for accurate source locating [14]. Once research moves away from thin, simple plates, locating becomes more of an issue. Baxter used an advanced method called “DeltaT Locating” on a geometrically complex aerospace part with success [22]. Multiple regression methods with multiple locating schemes are possible in current commercial software although not applicable in linear locating. Alternate methods such as these have improved location results but have not found widespread utilization. More advanced locating methods require post-processing and with the software used in a linear setup, locating is relatively straightforward. In the interest of having real-time results with data centrally collected and displayed through the AE system, no advanced locating methods were utilized in this research. Basic time-of-flight methods of locating can still

be used on complex structures if attention is given to sensor positioning and if the effects of complex geometry are accounted for as shown by Zarouchas. The research therein applied basic locating methods to wind turbine sub-structures with success [23]. For the present coupon work, location information will be used primarily to ensure proper operation of the sensors. Because the entire coupon experiences damage, location data covers the entire length of the coupon and does not provide much in terms of enlightening data. The accuracy of locating will be checked where possible but the primary benefit will come when more complex structures are being analyzed that will emit AE at particular locations where the damage is concentrated.

Time Domain Data

Time domain based acoustic emission data constitutes the bulk of the analyzed data for early AE work. Time domain based data can be directly measured or derived from the voltage waveform. Either way, the value is dependent upon the time over which the waveform is collected. Time domain data includes all of the previously mentioned basic waveform metrics but the most critical time based value for this study is absolute energy. Energy is an inherently important concept when characterizing and understanding material deformation, fracture and properties. Having a definable value of energy from an acoustic emission event provides a versatile tool and piece of data to construct a full interpretation of the state of the material being tested. There are two similar methods for determining an energy value that are popular in acoustic emission studies. The first is referred to simply as energy or PAC-energy for the system used herein. This value is derived from the integral of the rectified voltage signal over the

duration of the AE hit. In practice, the software takes the amplitude of the signal and multiplies it by the duration and converts this to counts by normalizing at 100 kHz/volt. While this is a good measure of how strong a signal is, it does not give a very good physical representation of the hit, nor is it a true value of energy due to having units of “counts”. A measure that is seeing greater utilization is the absolute energy or MARSE. Described as a “true” energy measure of the hit, its units are attoJoules (10E-18 J). This value is derived from the integral of the squared voltage signal (Vs) divided by the reference resistance (Rs) over the duration of the AE waveform where t_f and t_i denote the waveform duration time limits (Equation 5).

$$AbsEnergy = \sum_{t_i}^{t_f} \frac{V_s^2}{R_s} \times 10^{-6} \quad (5)$$

This calculation is only active when the voltage signal is above the threshold and is normalized to a 1 MHz sample rate. It provides a value that represents the area under the waveform voltage signal and should be relatable to theoretical energy. However, calling this a true measure of the energy of the hit is still erroneous for several reasons. The value is dependent upon the voltage signal returned from the sensor. It has already been shown that thickness affects the amplitude and therefor the voltage, making absolute energy a thickness dependent value. There is a large selection of commercially available sensor types with varying sensitivities, with minor differences present between identical models. The sensitivity also changes over the frequency response range of the sensor. If different sensor types observe the same AE hit, they may output vastly different absolute

energies. To be a true measure of the energy of a damage event, this also assumes that all energy released from the event reaches the sensors when in fact, we know this to be impossible. When a damage event occurs, the elastic wave propagates in multiple directions, not just towards the sensor. What is directed at the sensor also attenuates. Energy is also released from the damage event in the form of heat, frictional work and noise at a frequency level humans can hear. With these effects combined, absolute energy is certainly not the true absolute value of energy released during a particular damage event. The MISTRAS software has the ability to make up for the effects of attenuation but this only corrects for one type of energy lost among several. The attenuation correction is primarily beneficial to larger structures where the effects of attenuation are greater. For sub and scale structures, the amount of attenuation is actually used to correctly space and position sensors. With the size of coupons anticipated for this research, attenuation should be minimal and was confirmed to be so in preliminary tests.

Although alternate forms of energy detract from the energy transmitted to the AE sensors, the absolute energy measure has shown correlation to other well established energy measures. With energy loss from directionality being relatively constant for a linear setup, attenuation accounted for and other losses minor or constant, the absolute energy reported from the AE system has been shown to be proportional to the physical release of energy due to damage. Monitoring AE energy has been applied to metallic and composite materials with the goal being to directly determine crack length and fatigue life from the AE absolute energy. Roberts provided a methodology to calculate crack length and stress intensity factor from absolute energy [24]. This approach was improved

by others by using a Bayesian model to incorporate uncertainty into a probabilistic model [25, 26]. Compact tension and double cantilever beam type tests have worked well because there is only one theoretical crack path to release energy but for a tensile composite coupon with numerous damage sites, modes and crack paths, this is a fundamentally more challenging problem. Tensile coupon tests remain the most basic mechanical test performed on a material and produce the most commonly used material properties. Instead of analyzing one discrete crack in the material, a broader approach must be taken. Bouchak completed work on static and fatigue loaded tensile coupons and has found that the AE energy provided good measure of the accumulation of damage [27]. However, specific thresholds or failure criteria were not developed as comparisons to other damage inspection techniques were the foci. Therefore, a portion of this study will look into the absolute energy released by a coupon during both static loading and a load-unload-reload scenario in attempts to further progress towards failure criteria based on acoustic emission. Strain energy dissipated will also be correlated to the AE energy specifically during multi-cycle loading. If a direct correlation to dissipated energy in a composite material can be made with AE, the absolute energy parameter becomes much more effective and universal in terms of damage parameters, failure criteria and life estimates for a composite material.

Frequency Domain Data

Frequency domain data from acoustic events have shown to be a promising method of non-destructive, real-time damage characterization of composite materials. The waveform of an AE hit is a complex construction of various frequencies that have

been altered from their initial form by reflections, attenuation, wave speed variations and interference. As is the case in many types of waveform analysis, there is important information within this seemingly convoluted waveform. A Fourier Transform can be performed to convert the AE waveform from a time based representation to a frequency domain based form. This is accomplished in real-time on board the AE system as a Fast Fourier Transform (FFT) and provides a valuable analysis technique for composite material applications.

Frequency related data relevant to this study include the frequency centroid (C-FRQ), peak frequency (P-FRQ) and a technique termed partial powers. Figure 16 below contains an actual AE waveform; this is the voltage signal representation of the elastic wave captured by the sensor. As can be seen in the figure, the waveform is a conglomeration of many frequencies. Figure 17 is then the same waveform after the FFT has been performed. Now in the frequency domain, the relative decomposition of frequencies present in the original waveform can be seen. Frequencies that contribute more to the final waveform have a larger magnitude in the frequency domain. Identifying features for this waveform include a large peak around 50 kHz, several minor sub-peaks, no identifying peaks above 150 kHz and no activity above 325 kHz.

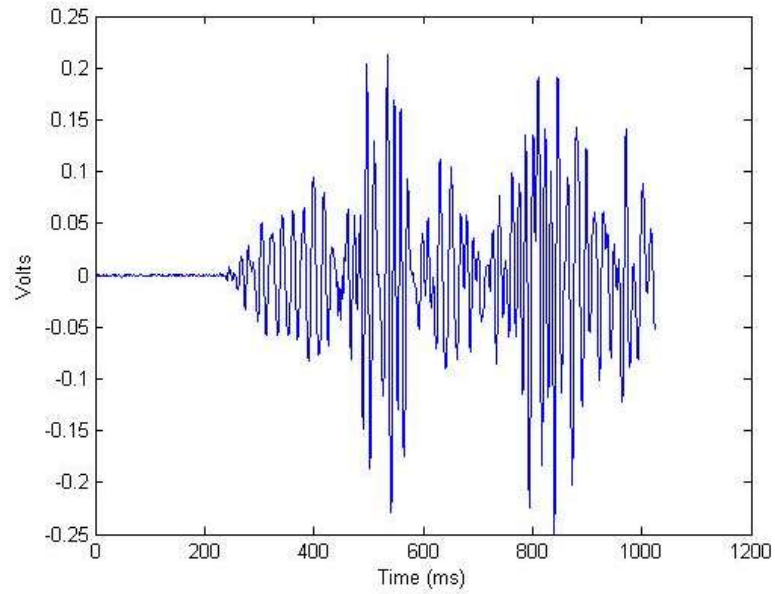


Figure 16: Representative AE Waveform

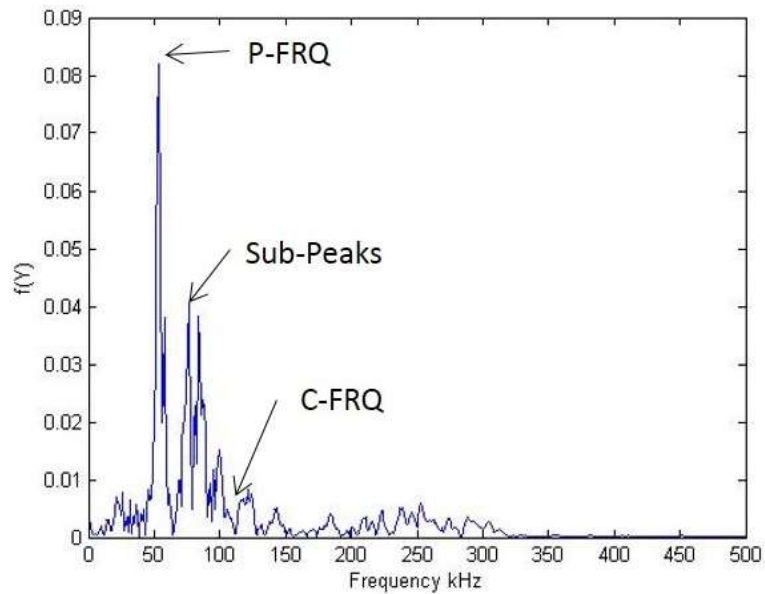


Figure 17: Representative FFT Transform

The frequency centroid is the first moment of inertia of the waveform, a magnitude weighted value of the average frequency and is calculated by Equation 6. The frequency centroid gives a good indication of where the frequency content is centered

over the entire collection of frequencies. The peak frequency (P-FRQ) is the frequency at which the peak magnitude in the power spectrum occurs. In a relatively simple waveform such as is shown in Figure 17, the centroid and peak will return very similar values. In more complex or overlapped signals there could be significant secondary peaks at a range of frequencies that will shift the centroid. Only the highest peak will be reported by peak frequency but the frequency centroid will give an indication of the frequency content that is not centered on the peak.

$$C - FRQ = \frac{\sum(magnitude * frequency)}{\sum(magnitude)} \quad (6)$$

A more in-depth analysis of an AE waveform can be performed with partial powers. This technique can give a comprehensive look at what regions of frequency the frequency content is falling within. Partial powers analysis is accomplished by splitting the frequency scale into several bins. The amount and span of bins are controlled by the user and are dependent upon the application. The calculation reports the total magnitude of power contained within each frequency bin of the transformed waveform, relative to the total power and is report as a percent.

The frequency domain metrics gained attention quickly as acoustic emission and computing technology improved. Early composite material based research found that peak frequency content over the course of a mechanical test fell into well-defined “bands” of activity. Research efforts then focused on correlating peak frequency to some physical phenomenon occurring in the material. Results of this work found that the various primary frequencies are released by the physical micro-mechanical damage

mechanisms. Generally these characterizations have used a singular material to manufacture simple baseline coupons which attempt to excite an individual damage mechanism. Single fiber or tow coupons as well as neat resin coupons have been added to many test regimens to round out the baseline frequency signatures. As these frequency characterizations of damage are critical to this work, a summary of these studies is given below.

In an early paper in 1988, Suzuki observed damage mechanism to peak frequency correlations for matrix cracking at 30 -150 kHz, interphase failures 180 -290 kHz and fiber breaks 300 – 400 kHz in glass and polyester composites [28]. A comprehensive work completed by deGroot in 1995 showed identification of frequency bands using unidirectional coupons at 0°, 10° and 90° orientations, lap shear, DCB, neat resin and single fiber coupons of carbon and epoxy [29]. Concluded in this oft referenced work is that matrix failures emit a band of peak frequency around 100 kHz, fiber pullout 180 – 240 kHz, fiber/matrix debond 240 – 300 kHz and fiber failures above 300 kHz. A summary and comparison of earlier results is also provided in that work. Ramirez-Jimenez built upon this work with carbon fiber using SEM images to microscopically confirm damage mechanisms in more complex laminates [30]. Using a thermoplastic resin, it was concluded that 100 kHz peak frequency signals are due to fiber/matrix debonding, 200 - 300 kHz due to fiber slippage and pullout and fiber breaks above 400 kHz. Single carbon fibers in the longitudinal and transverse direction as well as neat resin coupons of epoxy were used by Ni to identify narrow ranges of AE activity for matrix cracking, fiber/matrix failure and fiber failure at peak frequencies of 20, 180 and

450 kHz, respectively [31]. Bohse determined that matrix cracks emit frequencies ranging from 100 – 350 kHz, fiber breaks from 350 – 700 kHz and fiber/matrix debonding frequencies lie in the middle of those two ranges. Various combinations of thermoset and thermoplastic resins as well as carbon and glass fibers were used to draw those conclusions [32]. Bohse also discusses the source of the different frequencies being the varying viscoelastic relaxation times near the source of AE. The relaxation time is dependent on modulus and therefore results in lower frequencies for the lower modulus matrix damage and higher for fiber breaks. This was earlier identified by Giordano in single fiber tests correlated to numerical simulations [33]. Through these reviewed works, others that have utilized their work [34-39] and further sources referenced within these, numerous loading schemes and materials have been tested specifically for the purposes of determining and confirming the correlations between peak frequency of emission and damage mechanism. Contained within Figure 18 below is a summary of the five independently researched results for damage mechanism to peak frequency correlation that were briefly discussed above. This figure should be used for general reference only since the details of the results are not accounted for. For example, while some researchers have recognized that there are separate fiber pullout and fiber/matrix debond frequencies, some have been able to successfully correlate each damage type while others have not. Others only recognize a grouped “interphase” damage mechanism. However, it can be seen that the frequency ranges generally align for similar damage mechanisms between the various investigators.

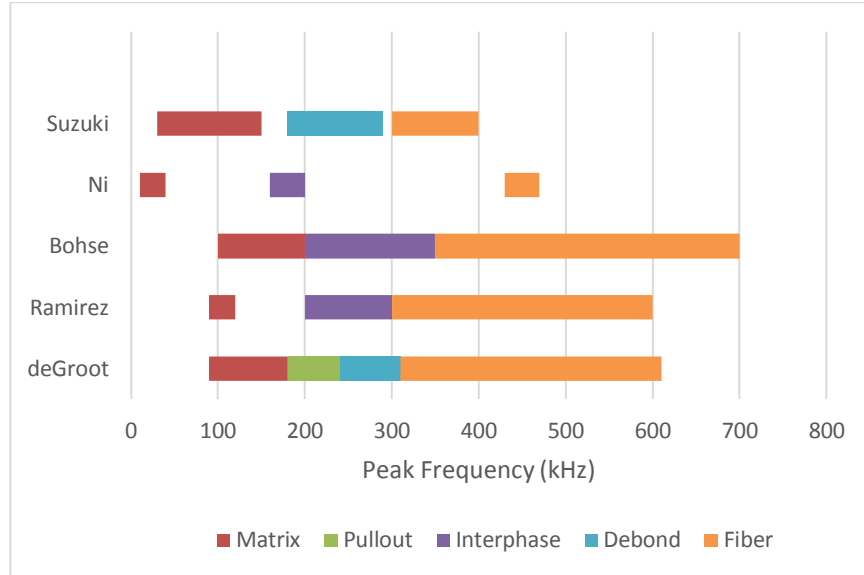


Figure 18: Independently Determined Damage Mechanism to P-FRQ Correlations

More complex methods of frequency content analysis have garnered significant attention as well. These include techniques such as discrete wavelet transformation such as that performed by Skal'skii [40] that have been applied along with multivariate clustering techniques to generate classifications of AE signals comparable to P-FRQ characterizations [41]. These methods take into account the overall shape and structure of the waveform to correlate damage mechanisms. Another interesting alternative frequency calculation was recently done by Kempf that utilized P-FRQ and C-FRQ in combination as well as partial powers to generate characterizations [42]. A K-means algorithm and Kohonen's self-organizing map function as a form of neural network and are also popular methods of processing AE events [43]. The downfall to these advanced techniques is that they require significant post-processing of the AE data. While this can be accomplished with relative ease, it does not give real-time information if using commercial AE software. It is desired to generate the dataset in a real-time method on

board the AE system for immediate interpretation of the status and health of the test article.

Due to the plethora of available sources on baseline characterizations, the present research will not attempt to reproduce these same efforts but instead expand to characterization of material systems and the progression frequency content leading up to final failure. The previous peak frequency characterizations were taken into account along with preliminary test data and specific transducer sensitivities to construct the following frequency ranges to be applied to the current research. Low frequency hits in the range of 50-120kHz will be considered matrix cracking, 120-200 kHz as fiber pullout, 200 - 300 kHz as fiber/matrix debonding and 300 kHz and above as fiber breakage. It is expected that peak frequency results will return narrow frequency bands of activity but the wide ranges specified above will allow for any potential frequency differences between the materials. Similar ranges were used by Waller [44] and Sause [37] utilized these ranges as partial powers ranges to help identify AE events in a double cantilever bending test. However, instead of binning the frequency spectrum of singular waveforms as is done with partial powers, for this work, the peak frequencies throughout the course of an entire test will be binned and analyzed. These bins are denoted F1, F2, F3 and F4 and are tabulated in Table 1. The analysis will take into account various material architectures and layups while utilizing the previously discussed baseline frequency spectra. Comparisons and differences between material types will be explored and presented. Performing this analysis will further the understanding of how these fabric materials fail, investigate the effects of fabric architecture and provide a dataset with

which future tests can be analyzed for damage mechanisms. Eventually, this information will aid in development of analysis techniques for more complex structure testing when material type and damage location are not as evident as they are with a coupon test.

Peak Frequency Bin Ranges		
Bin	P-FRQ Range	Identified Mechanism
F1	50-120kHz	Matrix Cracking
F2	120-200kHz	Fiber slip/pullout
F3	200-300kHz	Fiber/Matrix Debond
F4	300kHz +	Fiber Break

Table 1: Summarized Peak Frequency Bin Ranges

Thesis Goals

The volume of work done on frequency analysis is indicative of the ability of AE to represent the damage occurring in a composite material as it is strained. The numerous failure modes in composites are well understood and predictable but acoustic emission gives researchers the ability to show exactly when, where and what type of damage is occurring from real-time data. The background above lays the groundwork and motivations for the study presented herein. Frequency spectrum and energy data from the acoustic emissions will be used to characterize the damage progression and failure modes of several GFRP and CFRP materials specific to the wind turbine industry in static tests. Energy will also be used in a load – unload – reload scenario to correlate acoustic emission to the dissipation of energy in the coupon. The acoustic energy will be analyzed to identify a damage parameter that could be used to better understand and experimentally determine the damage state and remaining life of the composite material.

3. EXPERIMENTAL PROCEDURES

Test Coupon Manufacture

Montana State University possess a vast database of static and fatigue properties for glass and carbon fiber reinforced plastic materials commonly used in the wind turbine industry. Materials chosen for analysis in this study represent a small set of these materials but provide significant architectural differences that not only represent some of the most common products used in the industry but should also provide for a wide range of damage mechanisms. Four materials were chosen for study including three E-glass fabrics and one carbon fabric. PPG-Devold L1200/G50-E07 represents a mature glass fabric that is commonly used for major structural sections of blades with an areal weight of 1250 g/m². It is composed of 91% unidirectional 0° tows of Hybon 2026, 4% 90° backing strands, 4% random strand mat and stitched together with polyester yarn composing 1% of the total fabric weight. This material was chosen for its wide use and relatively complex construction that may yield a more complex acoustic emission over the course of a test. Vectorply E-LT-5500 is a high density, structural fabric (1875 g/m²) that has been utilized in a wide array of analyses performed at MSU. It is composed of 92% 0° unidirectional tows, 6% 90° backing tows and the final 2% is polyester stitching. This material was chosen because it has a simpler architecture than the L1200 yet is a denser, thicker fabric. The tows on this material are physically much stiffer and less drapeable than the L1200 fabric. Density and thickness should not alter the AE characterization but the way in which the fabric is constructed may affect the damage mechanisms observed. Vectorply E-BX-0900 is a low density $\pm 45^\circ$ double bias fabric at

334 g/m². Double bias materials such as this are used to give strength in off-axis directions, increase damage resistance and create a more integrated part. It is composed of equal amounts of unidirectional tows in each bias with 11% of the total areal weight being polyester stitching. The polyester stitching is expected to provide some mechanical support in the 0° direction of this fabric. This material will provide unique damage and failure among the other materials since there will be no fiber in the loading direction and will rely on the fiber/matrix interface for its minimal strength. This material type often exhibits significant non-linearity and large strains. Finally, Vectorply C-LA 2012 unidirectional carbon with an areal weight of 710 g/m² will be used. This fabric is primarily 0° fiber with an A-glass veil backing and polyester stitching. The exact percentages of the constituents are unknown as it is a fabric under development and no data sheet is available. Having both carbon and glass fabric will provide for contrasting results due to strength limits, matrix/fiber bonding characteristics, fiber diameters and resulting damage mechanisms. A summary of these selected fabrics can be seen below in Table 2 and will be designated Glass-A,B,C and Carbon-D for the remainder of this paper. Full material data sheets are in Appendix B. The LT5500 and L1200 materials' mechanical properties have been thoroughly studied by MSU and appear in the MSU/DOE Materials Database as materials D and H, respectively [45].

Manufacturer	Product	Desig.	Fiber	GSM	0°	90°	±45°	Mat	Stitch
PPG-Devold LLC	L1200/G50	Glass-A	Glass	1261	91	4	0	4	1
Vectorply	E-LT-5500	Glass-B	Glass	1875	92	6	0	0	2
Vectorply	E-BX-0900	Glass-C	Glass	334	0	0	89	0	11
Vectorply	CLA-2012	Carbon-D	Carbon	710	?	0	0	?	?

Table 2: Fabric Architecture and Designation

A number of layups were selected to give the best representation of AE behavior for the chosen materials. Each of the particular layups will induce a primary mode of failure that is expected and well understood. By applying acoustic emission to these basic layups it will be possible to look into the various fabrics' micromechanical damage leading up to final failure and how it changes throughout the course of a test. This damage progression can then be compared and quantified between the fabrics. Coupons with the fibers oriented perpendicular (90°) to the loading direction, $[90]_n$, produce transverse failures as matrix cracks or fiber/matrix debonding. This layup type should reveal some characteristics of the fiber/matrix interface as well as the influence of backing strands and random strand mats on the damage mechanisms and fabric characterization in a weakly supported material. Coupons with fibers oriented in the direction of loading (0°), $[0]_n$, fail by fiber pullout and breakage. This coupon type will reach high stresses and strains that will undoubtedly cause damage in the supporting matrix and fiber materials, the amount of which though, is unknown between the materials. The Glass-C fabric will be manufactured and tested in its natural $\pm 45^\circ$ orientation, denoted $[\pm 45]_4$. This layup should not introduce any new damage mechanisms but the final failure is much different in a low load, high strain as well as off-axis configuration. The slightly more complex laminates composed of both 0° and 90° plies in a symmetric layup of $[90/0]_s$ provide a chance to observe and characterize the damage progression without failing the coupon at the onset of matrix cracking. This layup should provide for consistent emission for the most direct comparison between the three primarily unidirectional materials.

A total of seven laminate plates were manufactured as the $[90]_n$ and $[0]_n$ coupons could be cut from the same plate. A quieter, electrical screw actuated load frame was to be used for these tests to allow for lower AE thresholds and less noise in the data. Therefore, the test coupon dimensions and layups had to be designed to fail within a 100 kN load limit. Four plies were used for all coupons because the greater thickness simplifies coupon preparation and extensometer attachment. However, some $[0]_n$ coupons would not reach the required strain to failure at the minimum coupon width which was dictated by the AE sensor diameter. For these fabrics, the number of plies was reduced to two. The test matrix can be seen below in Table 3.

Acoustic Emission Test Matrix				
Static & LUR	Materials			
	Glass-A	Glass-B	Glass-C	Carbon-D
Layup	$[0]_4$	$[0]_2$	$[\pm 45]_4$	$[0]_2$
	$[90]_4$	$[90]_2$		$[90]_2$
	$[90/0]_s$	$[90/0]_s$		$[90/0]_s$
Total	60			

Table 3: Acoustic Emission Test Matrix

Manufacturing of the test coupons was performed at MSU using the VARTM method described above. The matrix for these laminates was a two-part Momentive epoxy developed for the wind industry. The resin used was Epikote™ RIMR 135 and the hardener was Epicure™ RIMH 1366. The resin system was mixed at ratios following

manufacturer's recommendations of 100:30±2 parts resin to hardener by weight for 10 minutes followed by degassing in a vacuum chamber for 10 minutes. Vacuum was applied to the laminates at 80 kPa for 15 minutes and then the ports were sealed off to check for leaks in the vacuum bag. The vacuum was then reapplied and the degassed resin allowed to flow into the laminate through tubing connected to the inlet port. After the infusion was complete, laminates were cured at room temperature for 48 hours and post-cured in an oven at 70 °C for 8 hours. Manufacturing sheets can be found in Appendix B.

Following successful plate manufacturing, coupons were cut to 300mm long by 30mm wide with a diamond saw. Thickness was dependent on the particular fabric and architecture used. Coupon edges were sanded with P80 grit sandpaper to remove stray fibers and to minimize edge micro-cracks created during cutting. Loading grip tabs of G10 fiberglass material were applied with 3M DP460 two-part epoxy adhesive and clamped for 24 hours. The [90]_n coupons were not tabbed. The AE sensors were placed on the mold side of the coupons during testing and the exact locations were sanded with P180 grit sandpaper to give a smooth contact surface. Sensor positioning marks were drawn on each of the coupons to aid in alignment during the test process. Over 80 coupons were prepared using this process; 60 to be tested and extra coupons for each variant of test. An example of a manufactured plate that is marked for cutting can be seen in Figure 19 and images of the other plates can be seen in Appendix B.

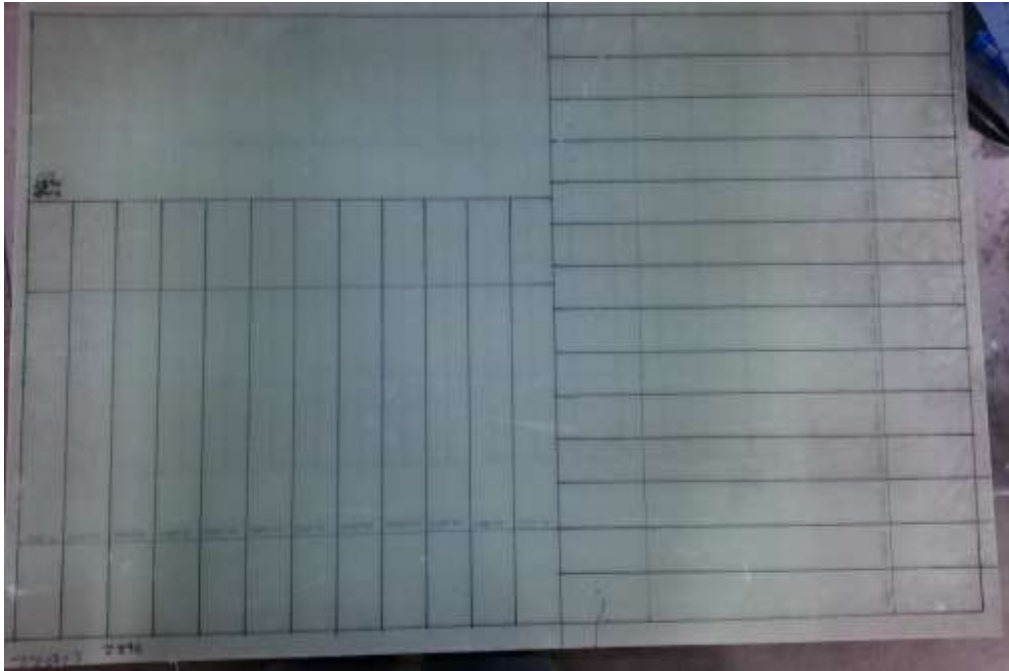


Figure 19: VARTM Manufactured Glass Plate

Mechanical Test Setup

Coupon layups and dimensions were chosen specifically so that all materials could be tested to final failure in an Instron 8502 electro-mechanical test frame with a 100 kN maximum load. All mechanical tests were completed in environmental conditions of 23°C and 20% - 40% humidity. A full round of quasi-static, monotonic testing was first completed with three coupons per each material and layup to develop the acoustic emission material characterization. The statics tests were executed with a single ramp waveform in position control at rates of 1.5mm/min for [0]_n and [90/0]_s tests, 0.25mm/min for [90]_n tests and 6.35mm/min for [±45]₄ tests. An Instron 2620-824 extensometer with a gage section of 12.7mm and a range of +/-40% strain was used to

collect strain data. The strain data and load data from the 100 kN load cell were input to the acoustic emission system via parametric inputs to correlate directly to AE events.

Load – unload – reload tests were performed following the static tests. Three coupons were tested for all materials and layups as well. Loads were increased statically at increments equal to 10% of the average static failure load for each cycle. The LUR testing was executed in load control utilizing a dual ramp waveform where the load step was manually entered following completion of the previous load step. Load rates consisted of 890 N/s for [0]_n and [90/0]_s coupons, 45 N/s for [90]_n coupons and 90 N/s for the double bias [± 45]₄ coupons. After testing one of each coupon type in the LUR scenario, minimal or very similar AE activity was observed in the first few cycles and the loading levels were adjusted to 20% load steps up to the 60% cycle followed by 10% load steps until failure. This adjusted loading scenario is hereafter referred to as the "modified" loading scenario.

Acoustic Emission Setup

Acoustic emission analysis was accomplished through the use of a MISTRAS PCI-8 Micro-II SAMOS system. Two WDI-AST sensors with integral 40 dB pre-amps were used for coupon tests and had an operating range of 50 kHz to 1000 kHz. The triggering and acquisition system collected waveforms at 3 MS/s with 128k of pre-trigger data and a total waveform length of 1024k. The on-board frequency filter was set to allow frequencies between 20 kHz and 400 kHz. The upper frequency limit was dependent upon the PCI board, which in this case was limited to 400 kHz while the lower limit was chosen based on the fact that the WDI-AST sensors provide minimal returns

below 50 kHz. The calibration sheet showing the sensitivity response for a WDI sensor is shown in Figure 20. The PDT, HDT, HLT and max duration were set to 50, 100, 300 microseconds and 99 milliseconds respectively. A software filter was applied to energy to filter out hits with AE PAC-energy lower than 1 count. This was done to help eliminate reflections, noise and erroneous hits that were observed below this level during preliminary tests.

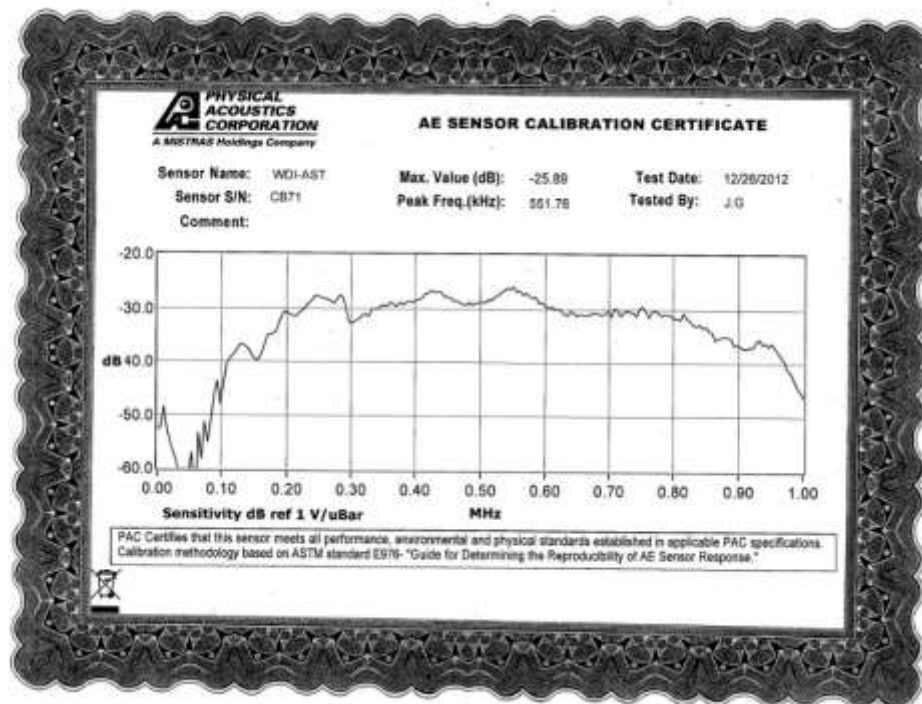


Figure 20: WDI-AST Frequency vs Sensitivity Calibration Sheet

The two WDI sensors were applied to the coupons in a linear arrangement 130mm apart. The linear setup as opposed to a single sensor configuration allowed for a DeltaT filter to be applied that could filter events based on the time of flight difference of the individual hits. By setting limits on the allowable time of flight (Dt), events were limited to within a linear span of distance that corresponds to the specified Dt limits

multiplied by the input velocity given. The Dt limits were set to 85% of the total wave transmission time between sensors. This effectively limited acceptable AE events to between the closest physical edges of the two WDI sensors.

The AE system was set to acquire parametric data at 50ms intervals in the AEWIn software and plots set to update at 5s intervals or 500 AE data points, whichever came first. If the plot update speed was set to update on every point, parametric data would be dropped from memory and fail to plot when high rates of AE activity occurred. Plots that were closely monitored during static tests included absolute energy and peak frequency versus strain or position scatter plots as well as accumulated absolute energy and parametric data line plots. For LUR tests, absolute energy and peak frequency were monitored against time instead of strain to provide a comprehensive and clear picture of AE activity during the tests. Four separate data files were manually saved at the completion of each test. Conveniently auto-generated report and statistics files were saved as well as an ASCII file of parametric data via the utilities menu. A text file of individual AE events was generated with the data replay function by checking the export to file option in the replay menu. These text files were then processed with a combination of Microsoft Excel and custom MATLAB scripts. Screenshots of all software options can be seen in Appendix C.

Test Process

The following test process remained standard and repeatable throughout all static and LUR tests. The coupon was mounted in the hydraulic grips through the use of a special tool designed to accurately place all coupons in the center of the upper and lower

grips. The grips were then closed while the coupon held in place. Approximately 3.5 – 7MPa of grip pressure was applied to low load coupons and 14MPa applied to high load coupons. The AE sensors were then applied to the coupon with a small dab of high vacuum grease as a couplant and by aligning the sensor between the positioning marks. The sensors were firmly pressed onto the coupon surface and then moved in a small circular motion to ensure that there were no air pockets trapped in the grease. Small, low force quick clamps were applied to the centers of the sensor housing to provide just enough resistance to keep the sensors from moving while also maintaining square contact between the wear plate and coupon. The clamps were tightened as much as they would allow thus giving a consistent clamp force for all tests. The clamps were marked as having a 90 N clamp force. Results could vary if higher, lower or unbalanced clamp forces were applied and for that reason, screw clamps were avoided. The load was zeroed on the load frame to remove any built up forces created during coupon mounting. The AE automatic sensor test was then run to check for proper sensor attachment, wave velocities and Dt times. If the Dt values varied by more than 10% between the two reported values, the offending sensor was re-mounted and the AST was repeated. The reported wave velocity was checked against theoretical velocities calculated for major discrepancies using Equation 2. A rounded value for velocity was entered into the location settings. A table of wave velocities experimentally measured with the AST function and applied in the software is shown below in Table 4. These velocities were kept consistent for each of the three tests of similar coupons even if there were small variations in the individually reported velocities.

Coupon Wave Velocities (m/s)					
Static & LUR		Materials			
		Glass-A	Glass-B	Glass-C	Carbon-D
Layup	[0]n	4700	4500	NA	6600
	[90]n	2800	2700	NA	1800
	[90/0]s	3700	3700	NA	4300
	[±45]4	NA	NA	2300	NA

Table 4: Measured Coupon Wave Velocites

Following the software adjustments, a standard pencil lead break test, or Hsu Test was performed at several locations along the length of the coupon [46]. This simply involves breaking a portion of mechanical pencil lead on the coupon while acquiring data and observing the result to determine if the AE returns are of satisfactory nature. Specifically for these tests, accurate positioning of the PLB and Dt values within the limits set according to the AST results were of chief concern and provided sufficient metrics to judge the quality of sensor attachment. More accurate and consistent calibration waveforms could be produced by breaking the lead on the edge of the coupon thus producing an extensional wave in contrast to a true Hsu-Nielsen source which produces a larger flexural wave [12]. Interestingly, there was considerable error between theoretical and AST reported velocities for the two ply carbon coupons which became evident during the PLB test. This is thought to be caused by the very thin laminate affecting the propagation of the large amplitude AST produced waveforms, which are not exactly representative of waveforms observed in composite AE applications. Wave velocities were increased towards the theoretical value until satisfactory event locating was achieved during the PLB test.

After setup and calibration of the AE system was completed, the extensometer was attached to the coupon with rubber bands. The proper load levels, load control rates or position control rates were set on the Instron controller and the strain balanced. The AE system was then set to acquire data and the test started. The extensometer was removed at 1.2% strain on the [0]_n carbon coupons in static testing and after the completion of the 90% load cycle for LUR tests. This was done to protect the extensometer from explosive failure often seen in carbon 0° coupons around 1.5% strain. Unfortunately, the acoustic emission sensors had to be removed prior to final failure of any "high load" coupons as well. High load coupons included all [0]_n and all [90/0]_s coupons for both glass and carbon. Although the primary final failure mechanism of these coupons occurred in-plane, there was often some out of plane component in the subsequent release of energy. The large out of plane component generates a very high amplitude flexural wave that if near an AE sensor, irreversibly damaged it. Therefore, AE sensors were removed at a strain level less than the anticipated failure strain for static tests. According to the MSU/DOE Materials Database, Glass-A and B fail at an average of 2.6% strain in similar manufacture and layup. While, again, the Carbon-D was assumed to fail at an average of 1.5% strain. The sensors were also removed at the completion of the 90% load cycle for LUR tests of the [0]_n and [90/0]_s layups.

4. RESULTS

The primary motivations behind the work that has been researched, discussed and set up above was 1) the characterization of acoustic emissions of several commonly used materials and layups in the wind turbine industry to not only provide future users with a dataset of material emissions but also enhance the understanding of the damage progression and mechanisms of these materials and 2) relate the energy emitted by acoustic sources to strain energy dissipated in order to develop a physical basis for the acoustic emission produced and 3) determine if the AE energy can be a viable measure of a material's damage state. The results of these ambitions are discussed below.

Fabric Characterization Results

Following will be an in-depth analysis of several methods used to characterize the damage progression of tensile tested composite coupons analyzed with acoustic emission instrumentation. Specifically monitored metrics are peak frequency, absolute energy and events over the course of a test. The energy of individual events as well as the accumulation rate will be taken into consideration for the test progression as well. These metrics be analyzed for all variants of static tests as well as representative tests of each layup type for the LUR dataset. Comparisons between materials and test types will be made and overall trends observed. Various failed coupons after testing can be seen below in Figure 21.



Figure 21: Various Failed Coupons from Left to Right: $[0]_n$ Carbon-D and Glass-B, $[90/0]_s$ Glass-A, $[90]_n$ Glass-A and $[45]_4$ Glass-C

$[90]_n$ Static Characterization Results

There are many AE metrics available for analysis within the dataset produced by these experiments but peak frequency has shown to be a powerful piece of data because it can differentiate composite damage mechanisms. The following plots are representative of the peak frequency of events for $[90]_n$ static tests for each of the three primarily unidirectional materials. Plots for all coupons not specifically mentioned in the text are located in Appendix A. Data from the first hit sensor is plotted because it is regarded as the more accurate data point compared to the second hit sensor which is always further away, though marginally so for the small coupons used for these experiments. Lines

marking the boundaries of the frequency bins are drawn on the plots of Glass A and B for reference. Similar lines could be drawn on all other peak frequency figures but have been omitted for clarity. Captions also denote when, or if, AE instrumentation was removed for the protection of the sensors.

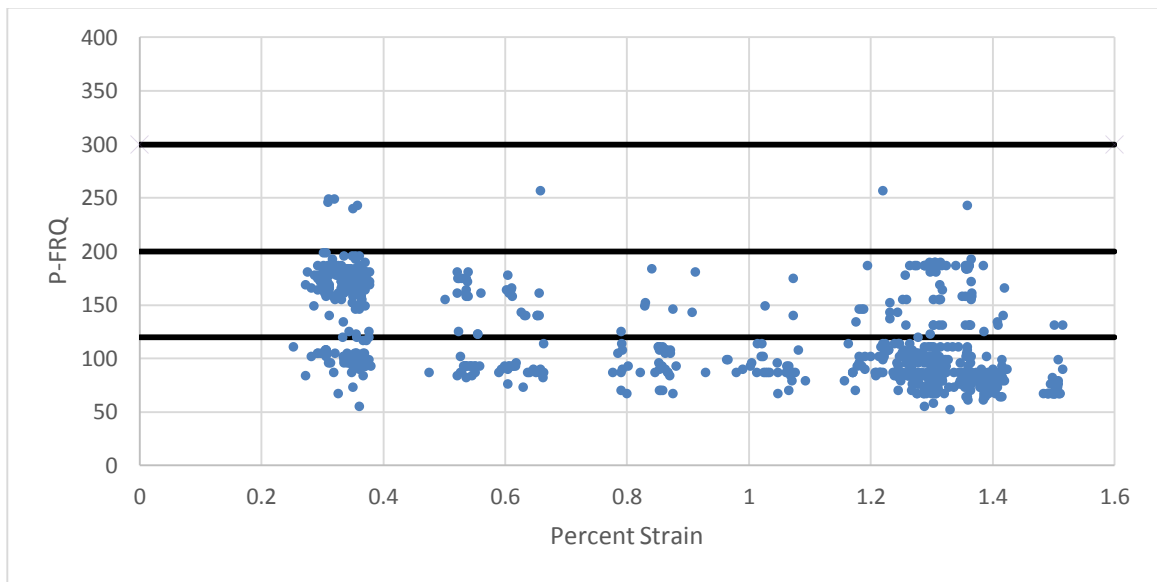


Figure 22: Hit Peak Frequency for [90]4 Glass-A, AE Not Removed

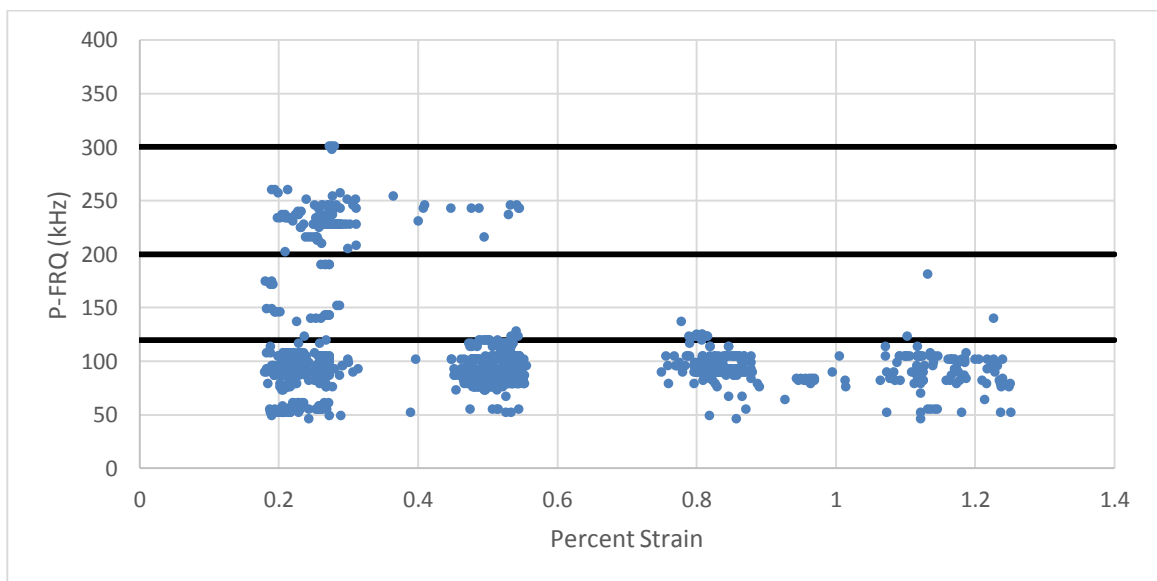


Figure 23: Hit Peak Frequency for [90]2 Glass-B, AE Not Removed

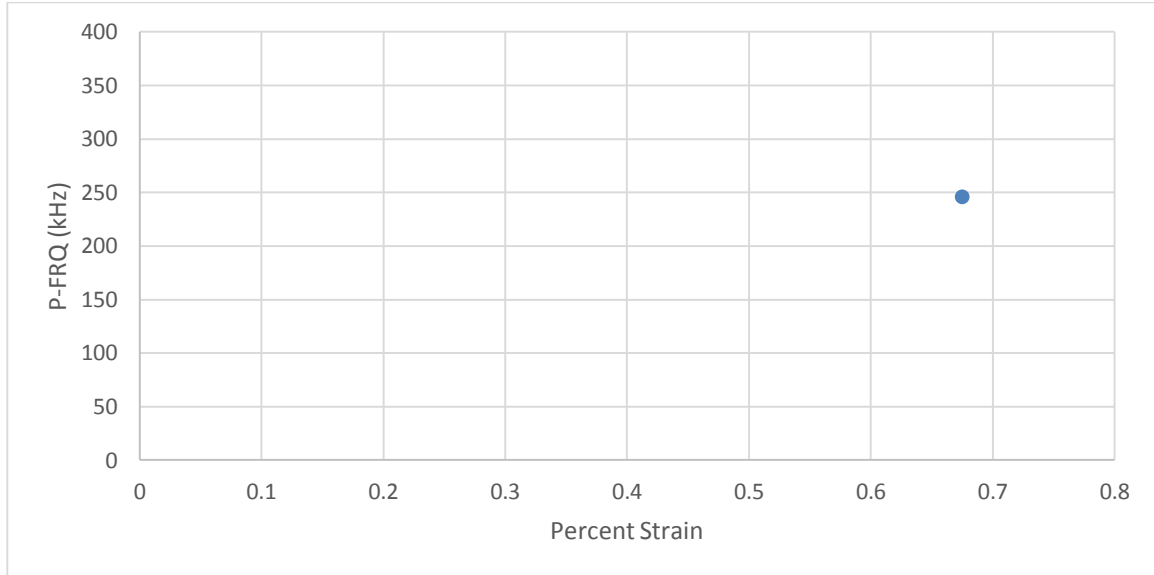


Figure 24: Hit Peak Frequency for [90]2 Carbon-D, AE Not Removed

Figure 22, Figure 23 and Figure 24 above show the progression of hit peak frequency as the coupons are strained to failure with the primary fabric tows at 90° to the loading direction. Results were consistent among identical coupons and some variation in emission can be seen between the different materials. The most noticeable difference is the complete lack of hits for the Carbon-D seen in Figure 24. One AE event was produced and only one physical transverse crack was visually apparent during each test of this variant. While damage locating abilities were not of explicit concern for these experiments, the software was able to accurately locate the one crack that occurred in this coupon type to within 2mm of the physical crack location for the 130mm gage section. The location data also showed a resolution of approximately 1mm on average, however, this is strongly dependent on the wave speed and sample rate. The carbon could be clearly defined as a quiet material and the fact that this first hit is at 0.68% strain indicates that the fabric system is quite resistant to damage but not tolerant once the

damage is present. Recall that there were no transverse backing strands in this truly unidirectional fabric, only a glass veil, so this behavior is expected. The frequency was higher than expected at 250 kHz, indicating a simple matrix crack was not the mode of failure as anticipated. Upon inspecting coupons for this test type, the final failures were often within a fabric tow, not a resin rich area, and individual debonded fibers could be seen bridging across the crack opening. This behavior would indicate a fiber/matrix debond for this single hit which matches the identified frequency range.

The two primarily unidirectional glass materials in Figure 22 and Figure 23 show much different behavior than Carbon-D due to the backing strands in the fabrics. The large gaps in AE activity indicate jumps in strain and are a result of matrix cracks opening at discrete locations along the length of the coupon and affecting the strain sensed by the extensometer. However, the coupons are able to survive many transverse cracks because the backing strands provide some strength. A great majority of the transverse damage occurs at a peak frequency band concentrated around 90 kHz. Glass-A emitted a noticeable cluster of mid-range frequencies around 180 kHz at the initiation of transverse cracking whereas Glass-B had similar activity but at a range 50 kHz higher than Glass-A. In both cases, these mid-level frequencies are prevalent at the initiation of transverse failure and activity in this range drops afterwards. As the backing strands strain, the transversely cracked surfaces separate, the surrounding matrix cracks and leads to continued low frequency signals. The backing strands can be seen as faint white lines running perpendicular to the transverse cracks in the failed coupon in Figure 21.

The frequency content over the course of several static tests was discussed above and it was noted early in that discussion that results were consistent among each of the three tests of identical coupon type. In finding a way to judge the consistency of the peak frequencies emitted and observe overall frequency content among the varying fabric types, histograms were generated for each material with bins consisting of the four ranges of peak frequency that correspond to physical damage mechanisms identified in the background research (see Table 1). Because the coupons were composed of basic layups that give well-defined modes of failure, there is a general notion of what frequency bins should have the greatest percentages for each coupon type, i.e. [90]_n coupons should show a higher percentage in the F1 bin due to primarily matrix cracking damage and [0]_n coupons should show high activity in the F4 bin for fiber breaks. This is certainly the case for the [90]_n coupons shown in Figure 25.

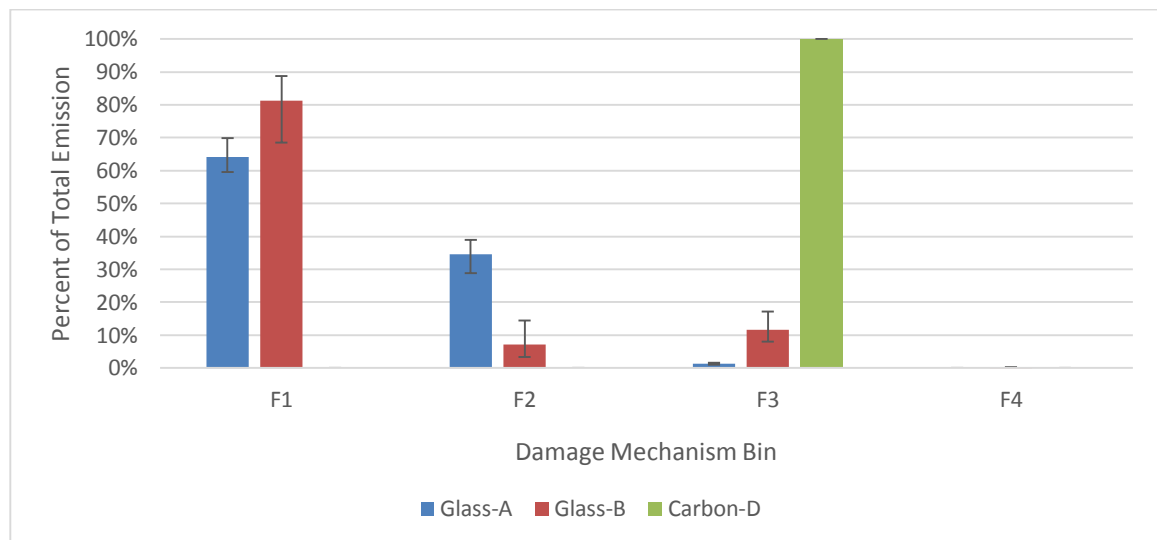


Figure 25: Average Frequency Content for Static [90]_n Coupons

Matrix crack type signals in the F1 bin account for 65% of the total AE events on average for Glass-A and a full 80% for Glass-B. However, 30% of the events are identified as fiber pullout type emissions in bin F2 for Glass-A. Some additional frequencies were expected but this amount was more significant than anticipated and suggests a large amount of damage due to the supporting glass material. From what is known about the fabric architecture, either the random strand mat fibers or backing strands must contribute to these mid-frequency interphase damage events. Glass-B showed a noticeable shift in the mid-level frequencies in the F3 bin in the plots of test progression but these are not a significant percentage of the total frequency content at only 10% on average. The one event for Carbon-D always fell within the F3 bin, indicating a fiber/matrix debond. It would be expected then that this content would appear in all material types but Glass-A shows a very minimal amount. It is unclear at this time if there is a significant increase in pullout type damage rather than debonding events in Glass-A or if there is a shift in frequency of the debond type events. All three of these materials show no events in the fiber break bin, F4.

Figure 26 and Figure 27 below are from the same tests for Glass-A and Glass-B as above but represent the acoustic absolute energy released during the tests. Individual points represent the absolute energy reported for an event while the line represents the accumulation of hit energy on both sensors throughout the test. The energy is reported in attoJoules ($J \times 10^{-18}$), an incredibly small value that lends itself well to plotting in log scale. However, this style of plot over-emphasizes the accumulated energy of early hits

and does not fully represent the energy of later hits. Accumulated energy will sometimes increase with decreasing strain because of the discontinuous jumps in strain noted earlier.

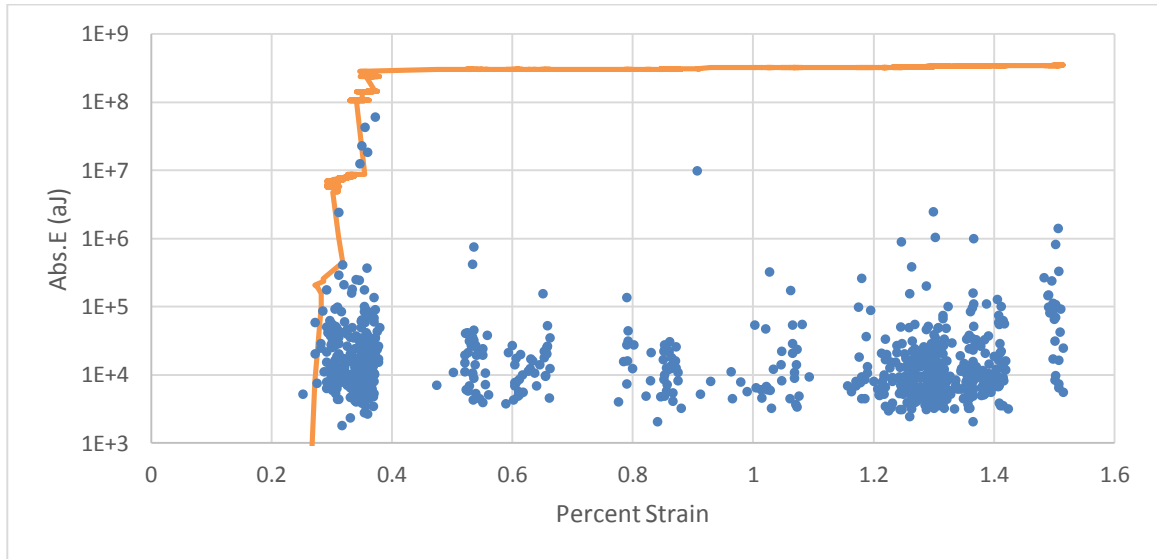


Figure 26: Absolute Energy for [90]4 Glass-A, AE Not Removed

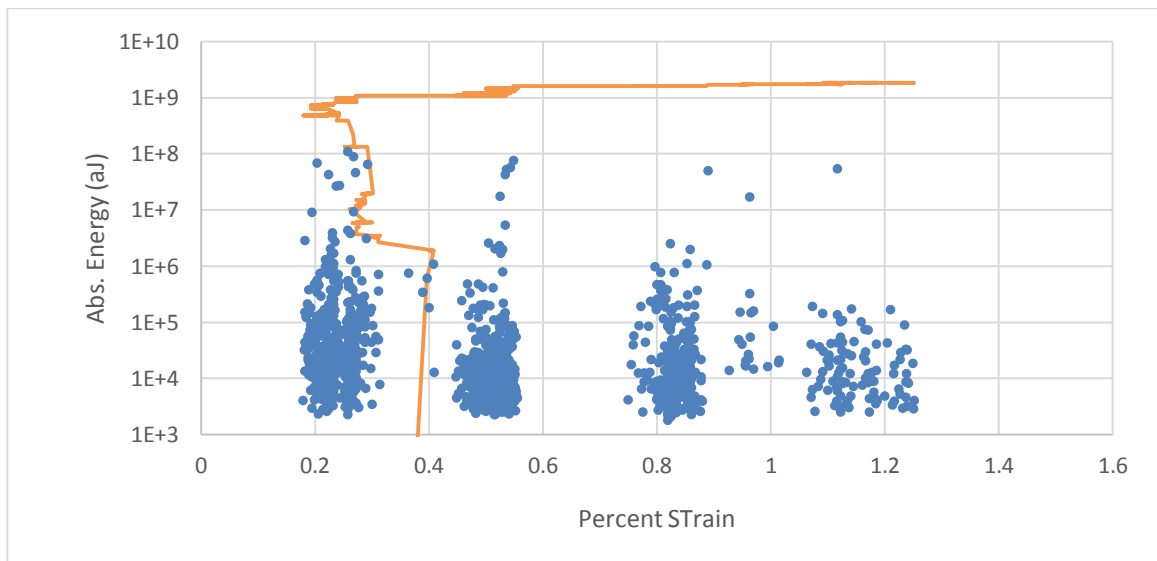


Figure 27: Absolute Energy for [90]2 Glass-B, AE Not Removed

Both of the glass unidirectional materials released numerous high energy hits as soon as transverse failures began at 0.3% strain for Glass-A and 0.2% strain for Glass-B.

The events then leveled off in accumulation rate and magnitude after transverse cracks propagated through all crack paths and the backing strands began to carry the majority of the load. In these materials, the final failure is a result of the backing strands failing, which should produce a fiber break type signal of large magnitude but final failures were not captured most likely due to the heavily damaged and cracked condition of the coupon. The cracks do not provide enough continuous material for the elastic waves to propagate without drastic attenuation of high frequency waveforms. A plot of the energy for the Carbon-D material provides little more information as there was only the one event with absolute energy of 2.07×10^7 attoJoules.

What can be gathered from these tests is that [90]n tests are dominated by low and mid-frequency events. Damage is accumulated very quickly due to large transverse cracks releasing large amounts of energy directed towards the sensors. A lack of high energy events are seen later on in the test when there are backing strands to support the load carrying capabilities of the coupon. At this later stage, minor cracking and debonding occurs around the fiber before final failure. Both unidirectional glass materials produce similar failures but the shift in the frequency is unaccounted for. Possibilities for this shift include a shift in frequency of identical mechanisms or different mechanisms occurring in the two materials. Preliminary conclusions for Carbon-D cannot be made at this time due to the limited events.

[0]n Static Test Characterization Results

Glass and carbon fiber coupons tested with the fibers running in the direction of loading can carry significantly higher loads and reach much higher strains to failure than

the [90]_n coupons. They also exhibit different modes of final failure although similar damage mechanisms are present leading up to final failure. The progression of damage is markedly different though. In Figure 28 for Glass-A, no acoustic emission events are even detected until 0.8% strain. Even then, activity is sparse until 1.5% strain, the failure strain of this material's [90]_n coupons. The majority of AE peak frequency is concentrated around three bands; 90 kHz, 180 kHz and 280 kHz. The lower two bands are located at the same frequency as seen in the [90]_n tests. For this material, no one mechanism dominates in terms of number of events throughout the test progression and significant activity is observed in each F1, F2 and F3 frequency bin at all strain levels. Some activity is observed at high frequencies, generally reserved for fiber breaks, at higher strains. Events were also registered at high strains with P-FRQ above 400 kHz, the reported frequency limit of the PCI-8 AE system.

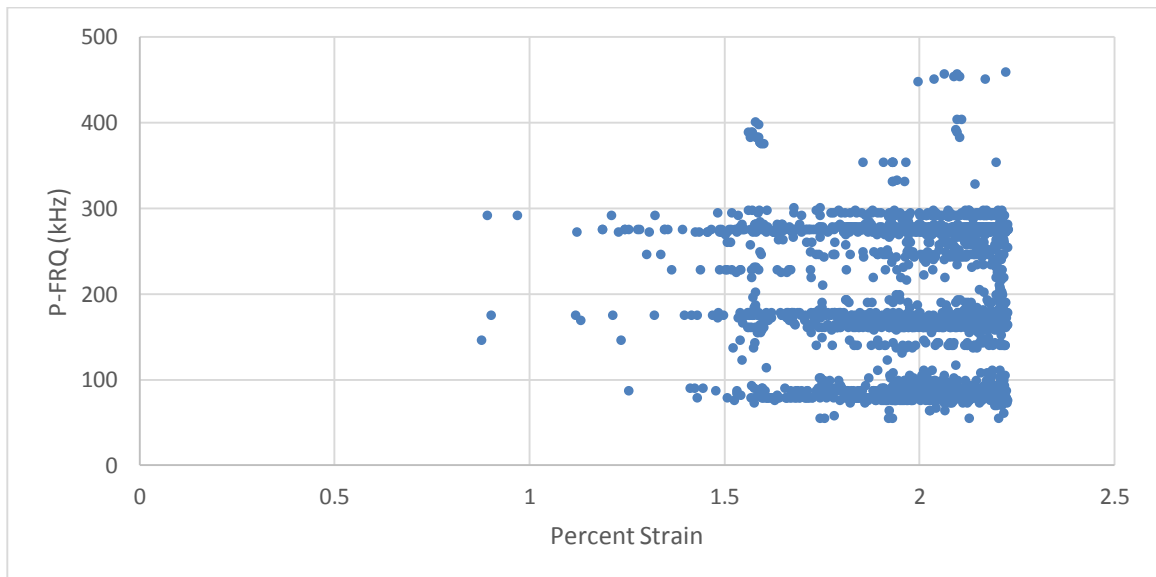


Figure 28: Hit Peak Frequency for [0]₄ Glass-A, AE Removed 2.2%

The plot for peak frequency of the Glass-B material in Figure 29 contains similar frequency bands as Glass-A, although the bands are less consistent and span a wider range of frequency. Bands are seen at 90 kHz, 220 kHz and 280 kHz. Similar to the [90]_n tests, the mid-level band of frequency is shifted up compared to Glass-A. Significant activity for this material began around 0.7% strain with an increase in activity until sensor removal at 1.9% strain. Some high frequency hits at 400 kHz are seen above 1.7% strain, indicating the start of minor fiber failure. Glass-B failed at 2.2% strain on average, which was lower than anticipated and resulted in damage to the AE sensors during the first test of this material. It is suspected that a slight fiber misalignment during coupon manufacture is the cause of the lower strength and strain to failure.

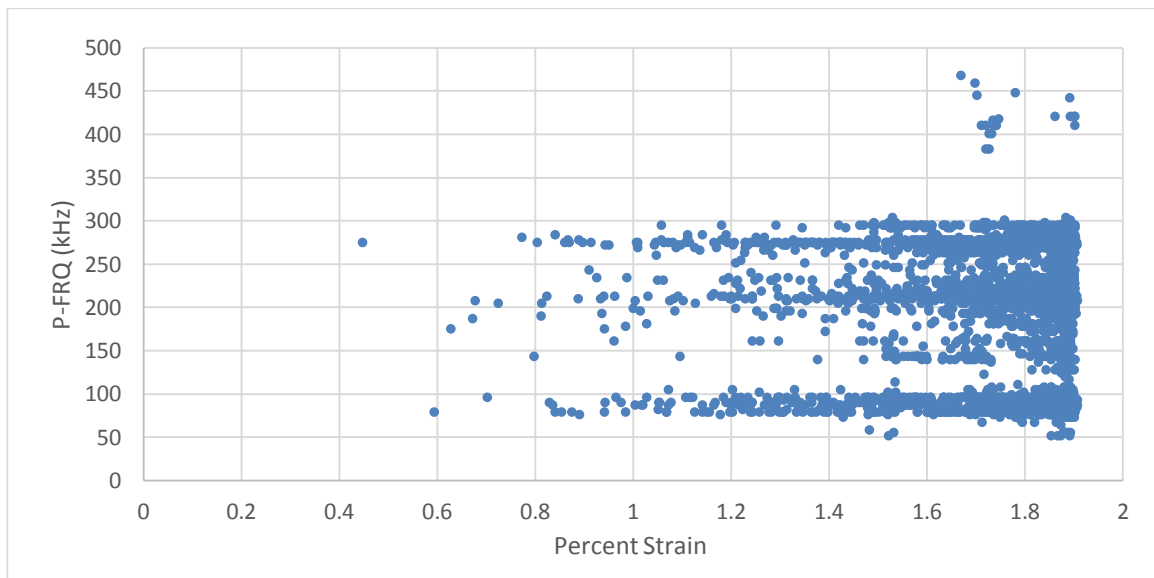


Figure 29: Hit Peak Frequency for [0]2 Glass-B, AE Removed 1.9%

Figure 30 for material Carbon-D is interesting in that the three bands previously seen in glass [0]_n tests have been replaced by only two bands; one remaining at 90 kHz and the second occupying the entire region between 200 kHz and 300 kHz. Significant

AE activity did not begin until 0.8% strain, similar to the other materials and suggests that the early activity is dependent on the matrix and less so the fibers. Also of note with the carbon is that the strain achieved was quite high at 1.7 percent. For the particular test shown here, AE activity was recorded to final failure as this test was completed before sensors became damaged and the protective measure of removing sensors put in place. Very few AE events were observed at high frequencies above 300 kHz even until final failure. This supports the belief that significant AE activity and information is not lost when the sensors are removed prior to final failure as was done in the majority of tests completed. The few tests that were completed with sensors remaining in place up to failure did not exhibit significant changes in activity until the precise moment of failure.

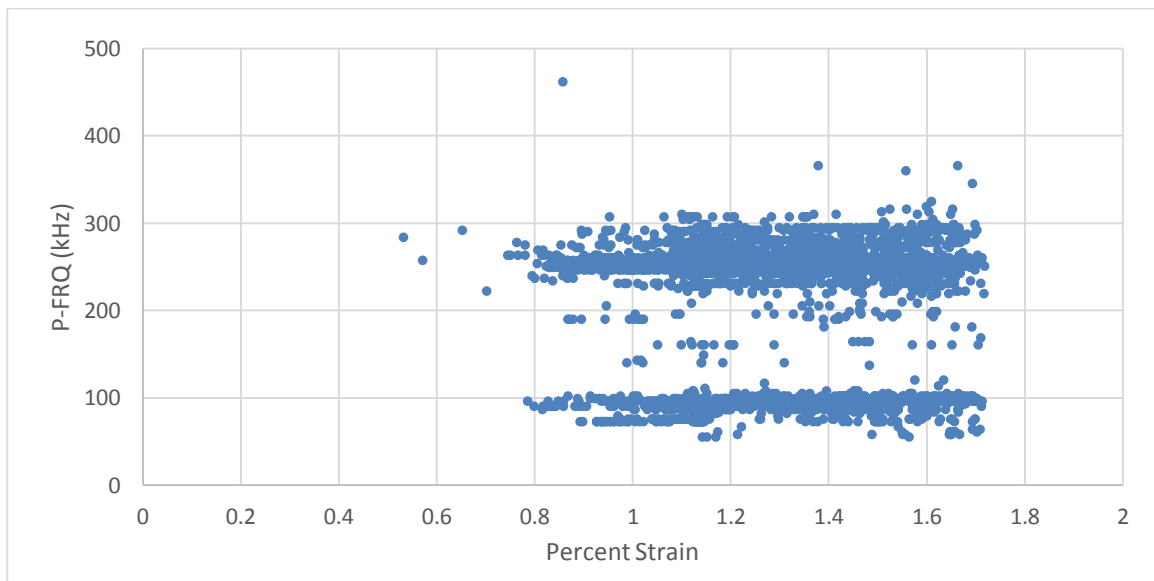


Figure 30: Hit Peak Frequency for [0]2 Carbon-D, AE Not Removed

Overall, the [0]_n coupons had a wider spread of frequency than the [90]_n coupons and the histogram in Figure 31 reflects this with significant frequency content in multiple bins. For all materials, 30% of the events fall into the F1 damage mechanism, matrix

cracking. It was surprising to find this much low frequency content but according to a traditional laminate ply failure analysis, the matrix in the transverse direction will be the initial though not critical failure in a 0° coupon test. Significant matrix damage was visually observed in all $[0]_n$ failed coupons. For the F2 bin, Glass-A sees a significant contribution of another 30% of its hits from the fiber pullout mechanism. Glass-B shows a small 10% contribution and Carbon-D shows a negligible amount. Glass-B and Carbon-D show greater contribution of nearly 65% to the total percentage of events from the fiber/matrix debond mechanism. For a coupon where fiber breaks were expected there is a lack of events in the F4 bin. Many researchers have indicated that fiber breaks occur at frequencies higher than the PCI-8 AE system can record as well as the fact that AE was not recorded to final failure leads to very few fiber break type events.

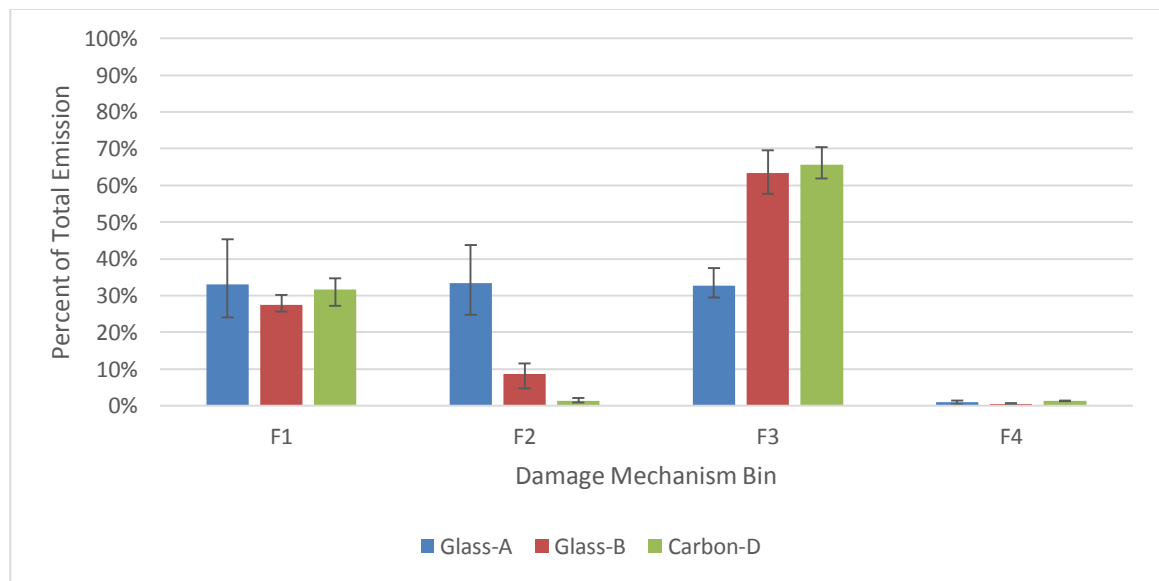


Figure 31: Average Frequency Content for Static $[0]_n$ Coupons

The following three figures describe the AE absolute energy activity during the $[0]_n$ coupon tests. Events occurring before 1.5% strain for Glass-A have minimal energy

and only one event registered above $1\text{E}7$ aJ for the entire test in Figure 32. This is a stark contrast to the Glass-A [90]_n tests that had numerous hits above $1\text{E}8$ attoJoules. It would appear then that matrix cracking in the transverse direction is responsible for the highest energy hits. Although matrix cracking is prevalent in these tests, the cracks run parallel to the load between the fabric tows and do not contain the same level of energy when the waveform reaches the sensors. The energy accumulation for a [0]_n test is more gradual as a result. The plot for Glass-B in Figure 33 shows a similar trend with AE absolute energy not significantly increasing until 1.5 percent. However, with this material, there was a significant amount of very low energy level activity though this may be due in some part to fiber tows on the edge of the coupon that split off at lower strains. “Knees” or changes in slope of the energy accumulation can be identified at around 1.5% strain for both glass materials which previous research has shown to indicate a change in phase of the damage progression of the material.

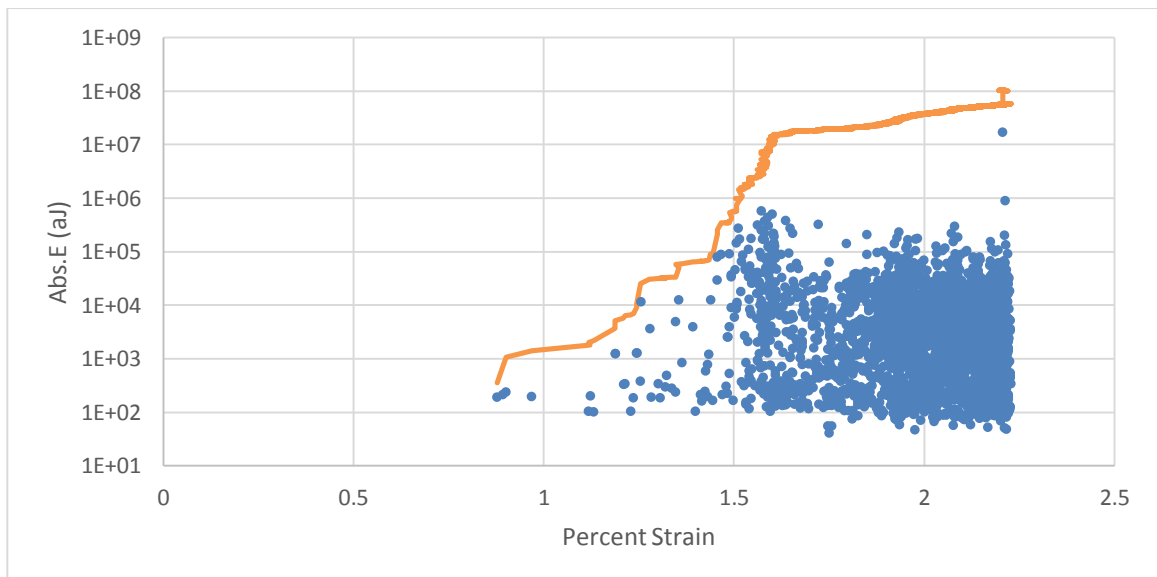


Figure 32: Absolute Energy for [0]₄ Glass-A, AE Removed 2.2%

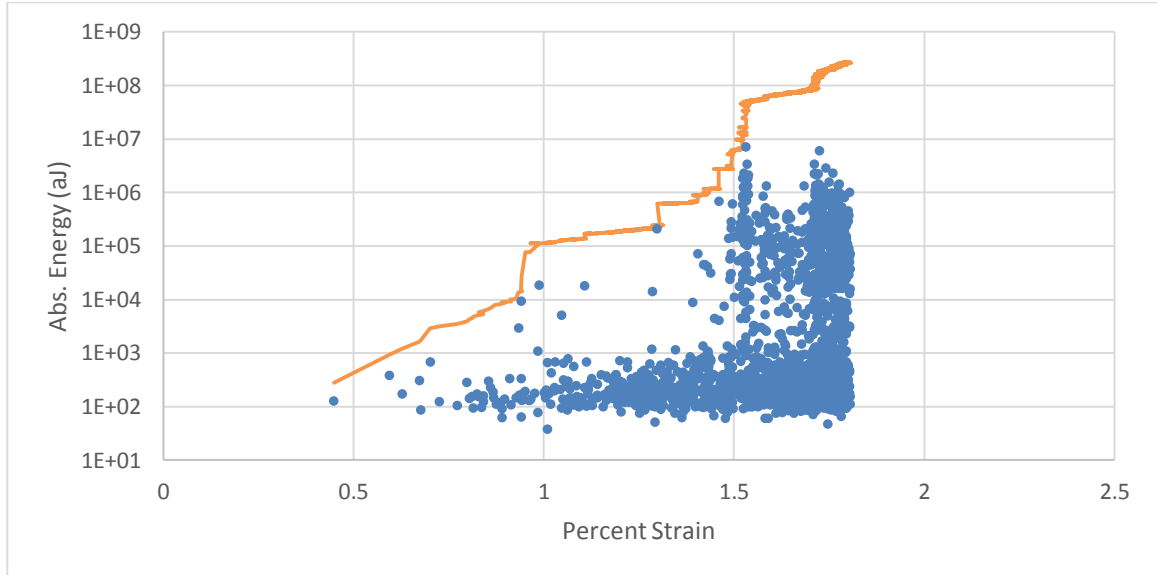


Figure 33: Absolute Energy for [0]2 Glass-B, AE Removed 1.8%

The plot for Carbon-D in Figure 34 shows a steady increase in accumulated energy starting at 0.7% strain with a large increase at 1.1% strain. After this point, there are several high energy events that were uncharacteristic of this layup but that were consistently observed in this fabric. Again, this was one of a very few tests to final failure and it shows a decrease in highly energetic events up to failure. The coupon is still intact at this point and the waveforms are not affected by the significant transverse cracks seen in the [90]_n coupons. The respective strains for sensor removal all reached a point of consistent activity and energy accumulation such as was seen here after 1.2% strain. Data for all of the following analyses were trimmed to the same value of percent strain when sensors were removed.

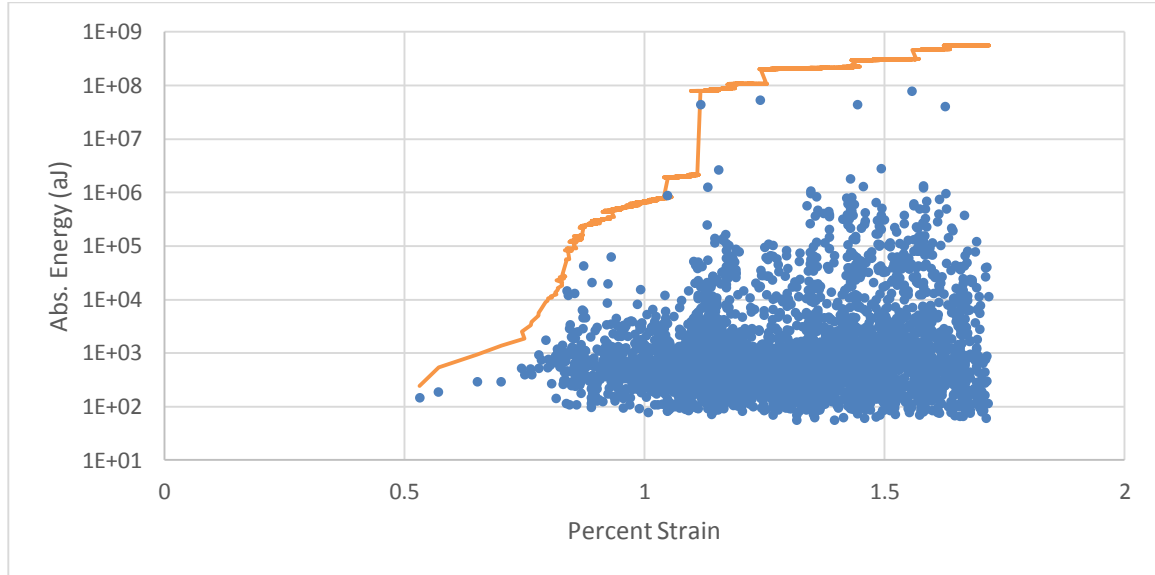


Figure 34: Absolute Energy for [0]2 Carbon-D, AE Not Removed

In summary, [0]_n coupons reach much higher strains before significant AE activity commences compared to the [90]_n tests. Initial activity is a combination of debond and matrix crack type events of low energy. The frequency bands for Glass-A and Glass-B are similar though the same shift in mid-levels frequencies between the two was observed. Carbon-D exhibited a deviation in behavior from the glass materials that is, as of yet, unexplainable. In terms of fabric architecture, the major difference is the lack of backing material in the Carbon-D material. However, carbon fiber is a fundamentally different material with a smaller fiber diameter and higher modulus than a glass fiber. Therefore, it is unsure at this time if the significant difference in frequency distribution is a result of the lack of backing strands, altered damage mechanisms due to the fiber/matrix bond characteristics or from a completely different fiber material. Frequency content is consistent throughout the test progression other than the emergence of the few high frequency events at high strains. It is suspected that there are numerous

other events at high frequencies that this AE system cannot collect. The majority of absolute energy data points are less than those for the same materials' [90]_n tests suggesting that transverse matrix cracking leads to a waveform with greater absolute energy even though they occur at lower strains.

[90/0]_s Static Characterization Results

The [90/0]_s layup provided for a way to reach high strains to progressively fail the transverse matrix of the outer 90° plies without completely failing the coupon. Because they contain 90° and 0° plies, there should be characteristics of both sets of test data from the frequency and energy results. The plot of peak frequency distribution for Glass-A (Figure 35) shows consistent P-FRQ emission throughout the entire test. Bands of peak frequency are present from both the [90]_n tests and [0]_n tests and are located at 90 kHz, 180 kHz and 270 kHz; an interesting harmonic effect that has not been noted nor explained by any past research analyzed by this author. Events initiated at low strains of 0.2% in all frequency bins and an increase in the number of hits is seen at 1.3% strain and after 2% strain. The F3 bin activity is concentrated towards the beginning of the test when the transverse failures are primarily occurring. Very few high frequency hits were observed.

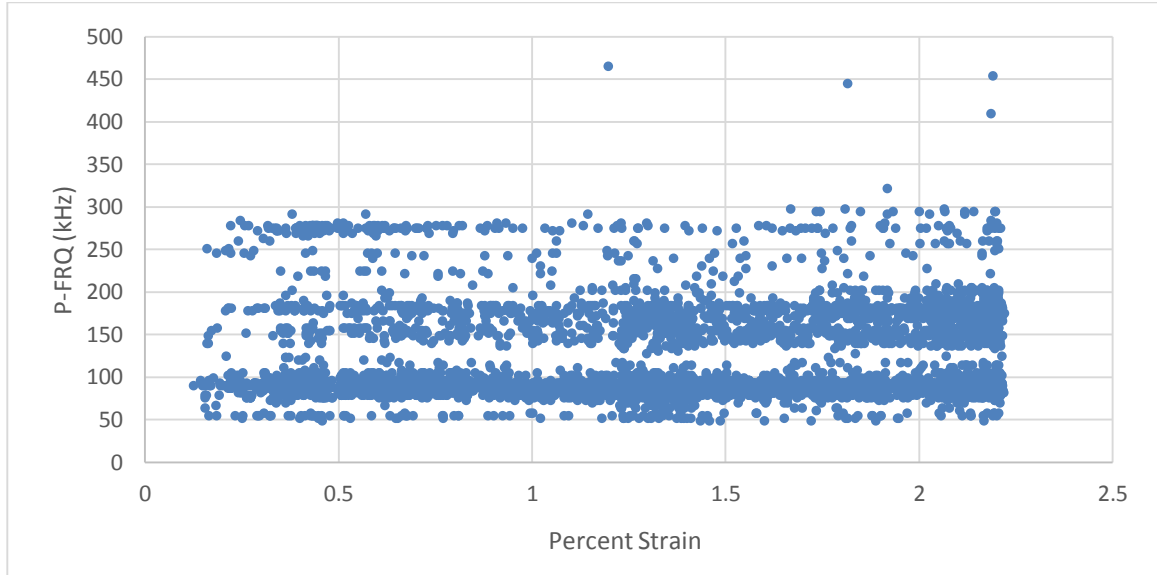


Figure 35: Hit Peak Frequency for [90/0]s Glass-A, AE Removed 2.2%

The biax coupon for Glass-B in Figure 36 exhibited an overall quieter AE progression compared to Glass-A with hits at the mid to higher frequency bands noticeably absent compared to the [0]_n Glass-B tests. Bands of peak frequency occur at 90 kHz, 140 kHz and sporadically at 250 kHz. A simple superposition of [0]_n and [90]_n test results does not appear to be sufficient to describe this result. The 140 kHz band had not been previously observed for this material and significantly more activity had occurred higher than 200 kHz. It is unclear what could cause this discrepancy but results were consistent for all three tests of this material. Similar to Glass-A, F3 bin events were more prevalent at low strains starting at 0.2% strain but then little activity until 2% strain. Very few fiber break type events were recorded for Glass-B as well.

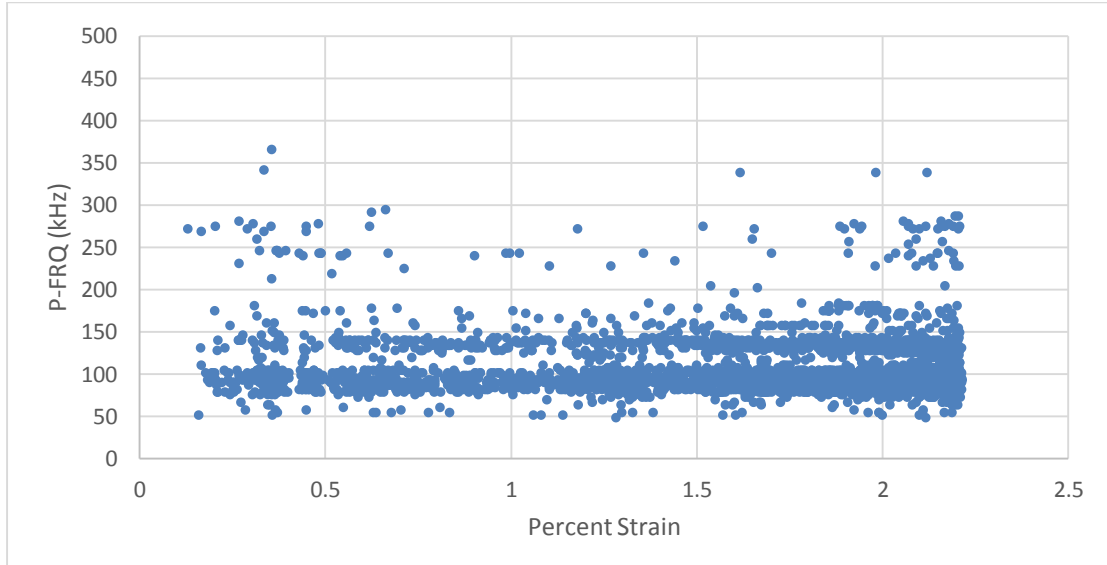


Figure 36: Hit Peak Frequency for [90/0]_s Glass-B, AE Removed 2.2%

The Carbon-D fabric does not contain backing strands and where it had only been able to withstand one transverse failure in earlier tests, it could experience many transverse failures with supporting 0° plies. The band of frequency content around 180kHz that was conspicuously absent in the [0]_n tests is now present in Figure 37 with bands appearing at 90 kHz, 160 kHz and 250 kHz. It was previously considered that the absence of that band could be due to the nature of carbon fiber itself but since it is present for this layup it instead indicates that the absence of frequency content compared to the glass fabrics was due to the absence of the particular damage mechanism. The interaction between the 90° and 0° plies in the biax coupons produces a fiber pullout damage mechanism similar to the interaction between unidirectional tows and backing materials seen in the glass fabrics. The strain at which significant AE activity begins is again much higher than the glass materials as was seen in the previous [90]_n tests. Once AE activity did begin, it occurred in the F1, F2 and F3 frequency bins consistently.

Similar to the glass materials, very little activity was observed in the F4 bin before the sensors were removed at 1.2% strain.

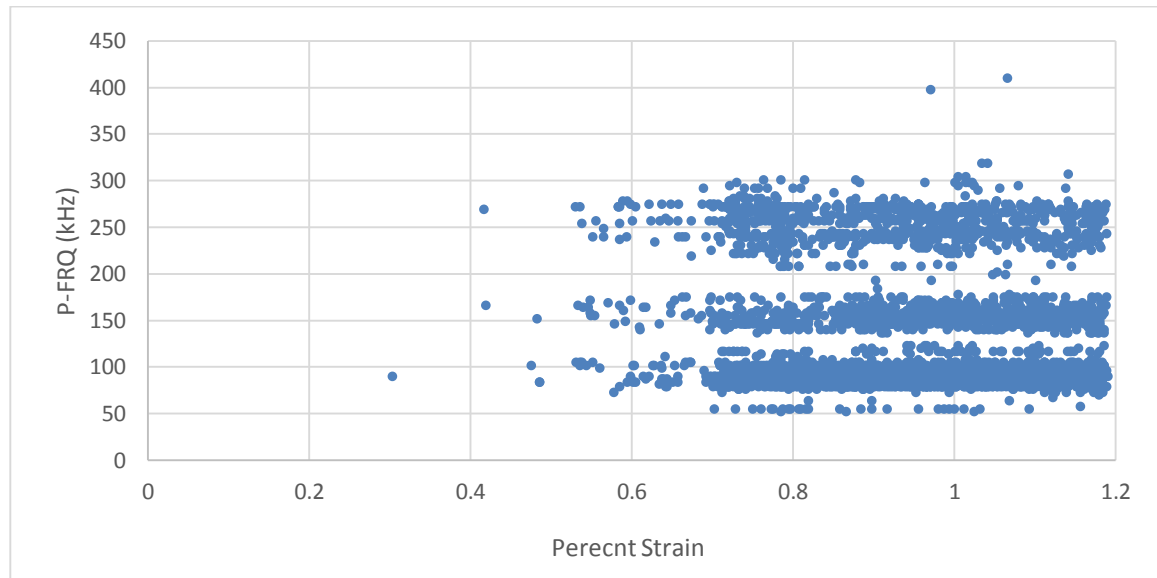


Figure 37: Hit Peak Frequency for [90/0]s Carbon-D, AE Removed 1.2%

The [90/0]s coupons show similar characteristics between fabrics in average frequency content. With this layup, all materials effectively had the same biaxial fabric architecture that forced similar damage mechanisms. This is most critical to the Carbon-D material which could only withstand one transverse crack in its [90]_n layup but was able to withstand many more in the biaxial configuration. As can be seen in Figure 38, all materials show primarily matrix based damage mechanisms up to the point of sensor removal with between 57% and 77% of the total frequency content. These tests exhibit both high energy transverse matrix cracks and low energy matrix cracks that occur between the 0° fabric tows. The Carbon-D laminate showed a significant increase in matrix crack events from the earlier [90]_n tests and is shown in the P-FRQ content. All materials show some activity in the F2 bin but Glass-A shows the largest amount as it has

done for all other layups. A lesser amount of activity is seen in the F3 fiber/matrix debond bin than before but these [90/0]s coupons also produced more events than the other basic layups. However, the Carbon-D fabric again shows an affinity for the debond damage mechanism. A negligible amount of events was found in the F4 bin for all of these materials. The results for the [90/0]s layups show an increasingly similar damage progression and peak frequency content. While this increases the difficulty in differentiating the materials it also shows that peak frequency content, and therefore damage mechanism differences, are due primarily to architectural differences of the fabrics. However, underlying trends and variations in the frequency emission from the baseline [0]n and [90]n tests carry over to these more complex layups.

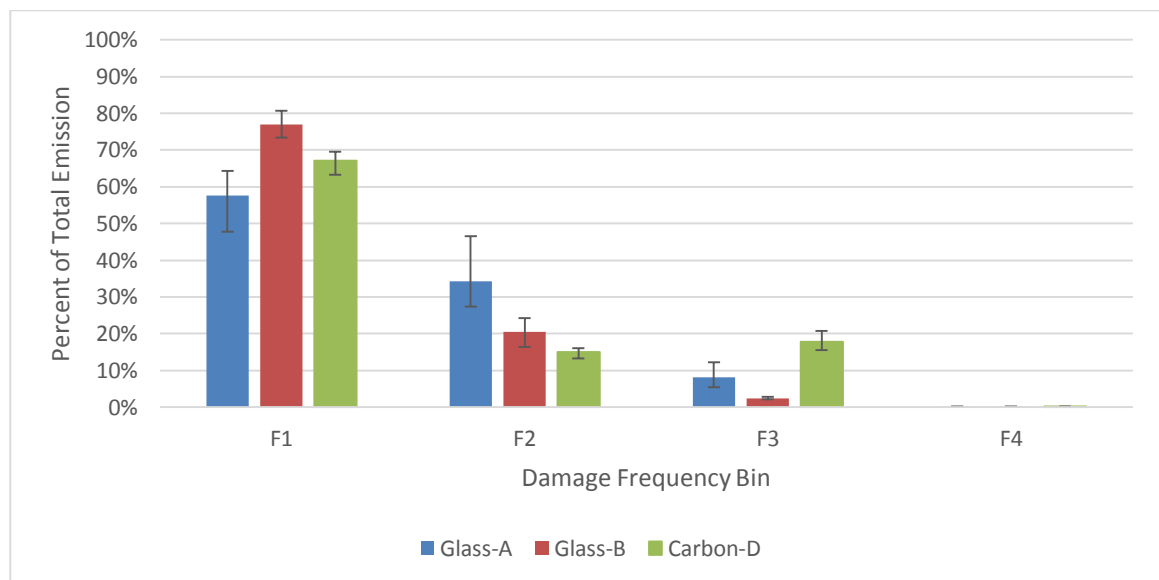


Figure 38: Average Frequency Content for Static [90/0]s Coupons

Plots for absolute energy emission and accumulation for the [90/0]s layup can be seen below in Figure 39, Figure 40 and Figure 41. The similarity among the materials for this layup seen in the frequency results continues for the energy results as well. Early

high energy hits that rapidly accumulated damage give way to consistent activity with more modest gains in accumulated energy. This is the expected behavior if a superposition of results from $[90]_n$ and $[0]_n$ tests is followed. Early matrix cracking that releases high energy continues as the inner 0° plies support the coupon. As the test progresses to higher strains, this gives way to an increase in hits per second but each of much smaller magnitude and the energy accumulates slower but at a steady pace. This creates a significant knee in the energy accumulation as the coupon transitions from large transverse matrix cracks to smaller magnitude cracks and interphase failures. Both glass materials shows very similar behaviors. The Carbon-D plot in Figure 41 contains high energy hits above $1E8$ aJ throughout the entire test. There is also a large delineation in the energy levels of the carbon events with the majority of events registering energy levels below $1E6$ attoJoules.

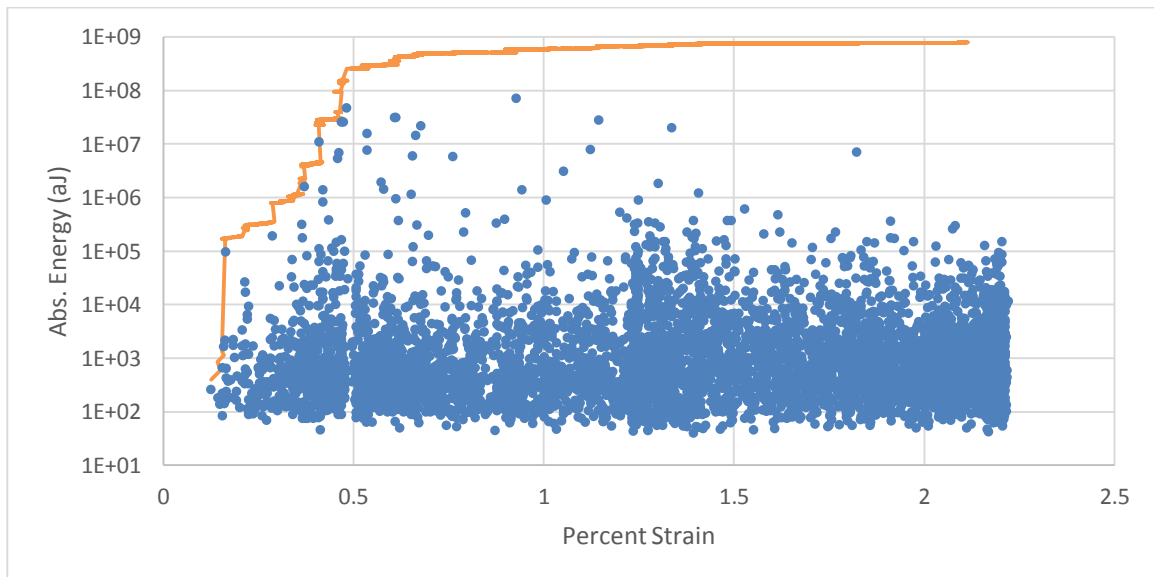


Figure 39: Absolute Energy for $[90/0]_s$ Glass-A, AE Removed 2.2%

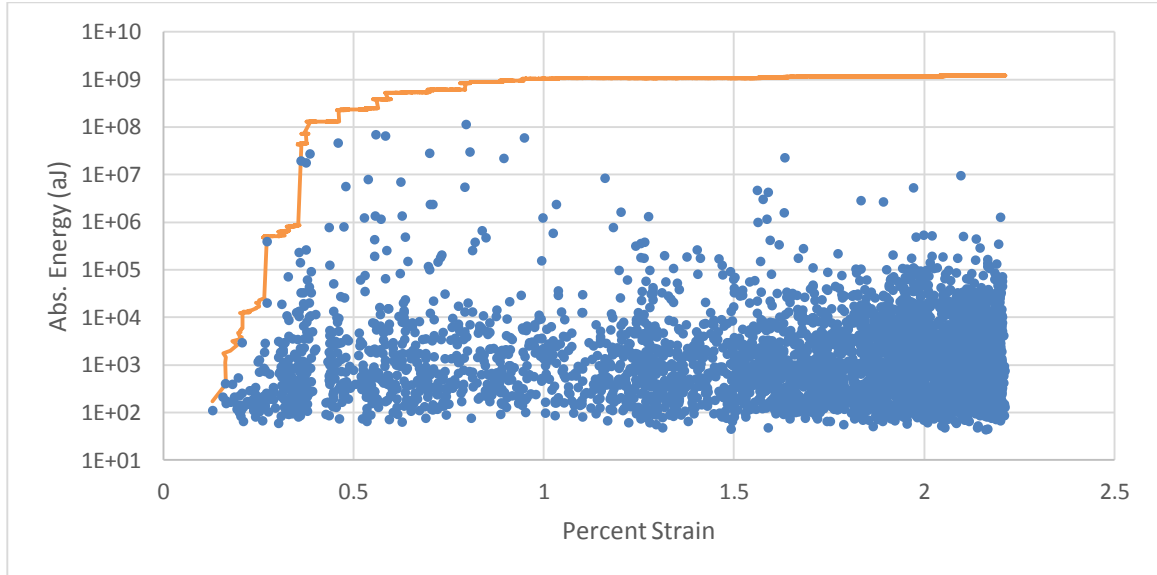


Figure 40: Absolute Energy for [90/0]s Glass-B, AE Removed 2.2%

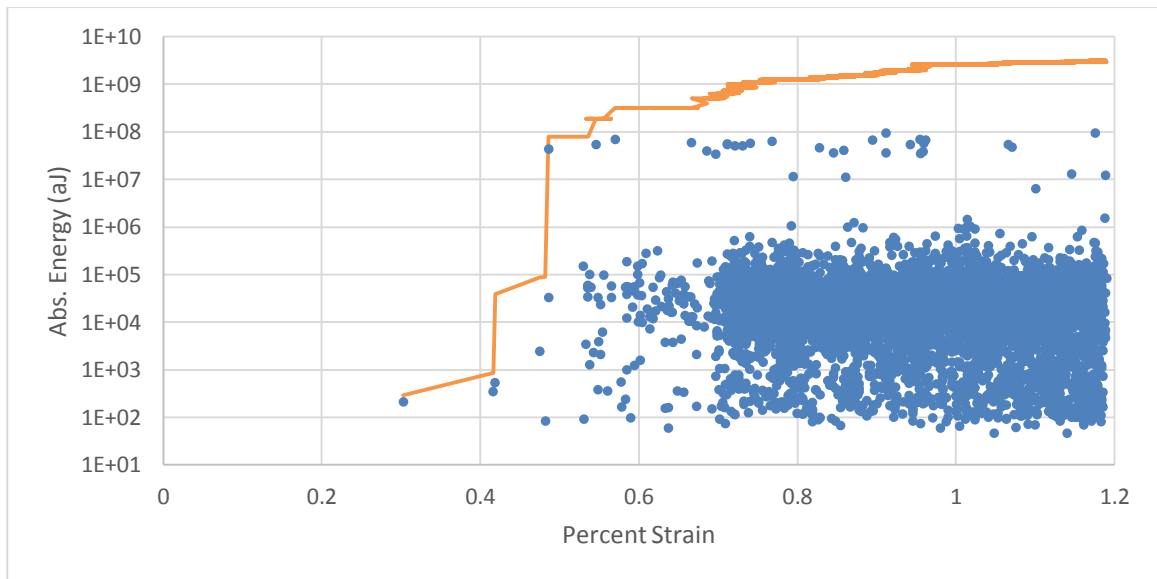


Figure 41: Absolute Energy for [90/0]s Carbon-D, AE Removed 1.2%

[±45]4 Static Characterization Results

A discussion of the characterization results for the Glass-C double bias fabric was left for last as the $\pm 45^\circ$ fiber orientation differentiates significantly from other layups in material behavior and acoustic emissions, as seen below in Figure 42. Foremost, the

strain to failure is much higher for this material at above 20% percent. This high strain allows for many more hits over the course of the test, however, consistent events do not begin until 3.7% strain. Two major bands of peak frequency are seen at 90 kHz and 270 kHz, the matrix failure and fiber/matrix debond bins, with a number of higher and mid-level frequency events that become more prevalent at higher strains (Figure 43). The P-FRQ results match the behavior seen in the failed coupon in Figure 21. In this layup, each individual fiber of glass is quite short as they run from one edge of the coupon to the other and cannot carry significant load. Matrix cracks and debonds run at 45° to the loading direction and the coupon goes from somewhat transparent to completely opaque due to the number of cracks paths as it strains. Some fiber breaks and fiber pullout events were observed visually and in the AE as the coupon necks and tears apart.

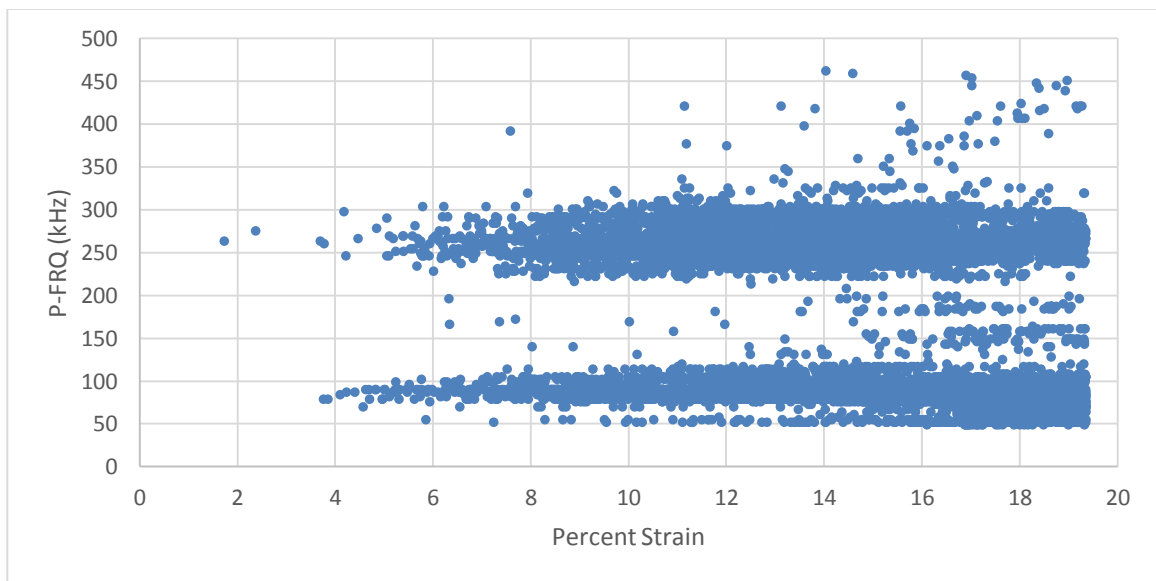


Figure 42: Hit Peak Frequency for [+/-45]4 Glass-C, AE Not Removed

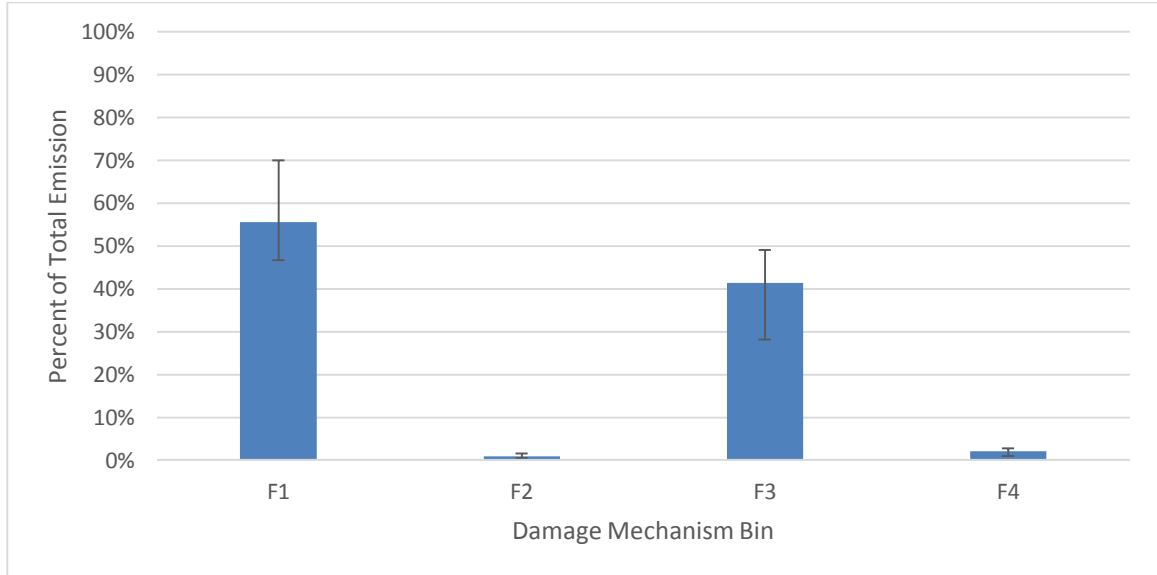


Figure 43: Average Frequency Content for Static Glass-C Coupons

From the energy plot in Figure 44, it can be seen that hits are of low energy for Glass-C and the rate of accumulation of absolute energy is very consistent. This material and layup could be tested to final failure without concern of damaging the sensors so it can be seen in the energy plot that there is an increase of higher energy events immediately before failure. Though still quite small compared to transverse matrix cracks, these events are of significant magnitude for this material. It is interesting to note that the value for total accumulated energy for this Glass-C static test and the Carbon-D [90]_n test discussed above are exactly the same even though the number of hits for this Glass-C test was above ten thousand and the carbon test produced one event.

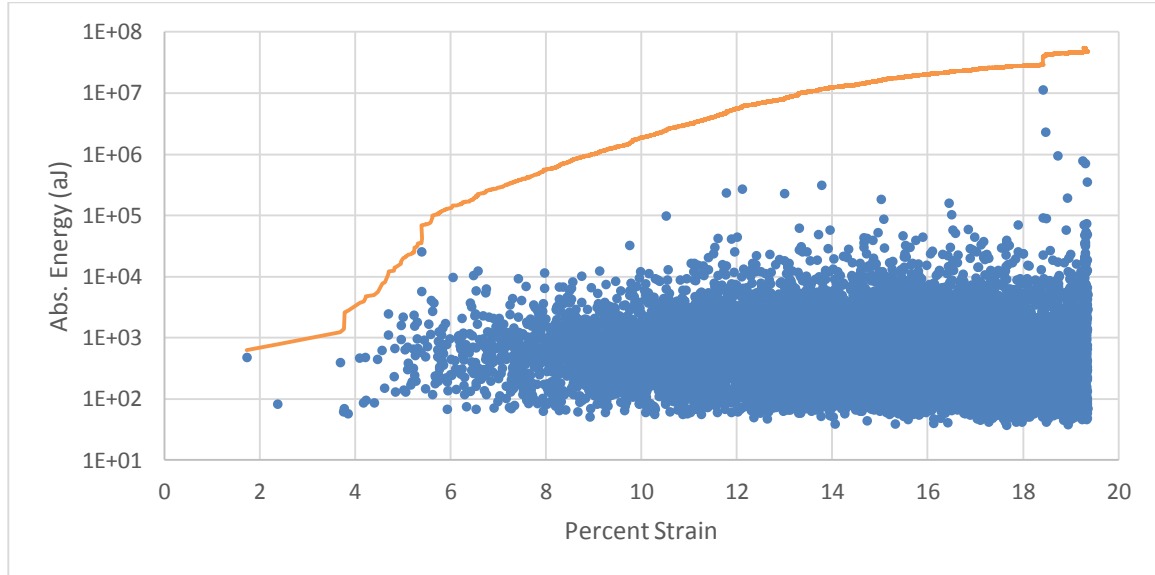


Figure 44: Absolute Energy for $[+/-45]_4$ Glass-C, AE Not Removed

Through all of these discussions, the comment has been made that the highest absolute energy hits observed correspond to transverse matrix cracks. It was not a goal of this work to characterize emissions based on energy due to the effects of geometry on amplitude which in turn will affect the energy value. Nevertheless one might be curious how the peak frequency relates to the absolute energy. The plot below is from a static test of Glass-A material in a $[90/0]_s$ layup, which was discussed earlier in Figure 35 and Figure 39. Hits were recorded in each of the frequency bins during this test. What it shows is that a high energy hit can most likely be attributed to a low frequency hit but not all low frequency hits are of higher energy. The 90 kHz range attributed to matrix cracking contains by far the most energy and there were several very high energy releases. Through the experiments for this research, these have been correlated to early, through thickness transverse matrix cracks while numerous other low energy matrix

cracks occur continuously. Other damage mechanisms are undefinable based on the energy released and are hardly removed from the zero axis on this non-log scale plot.

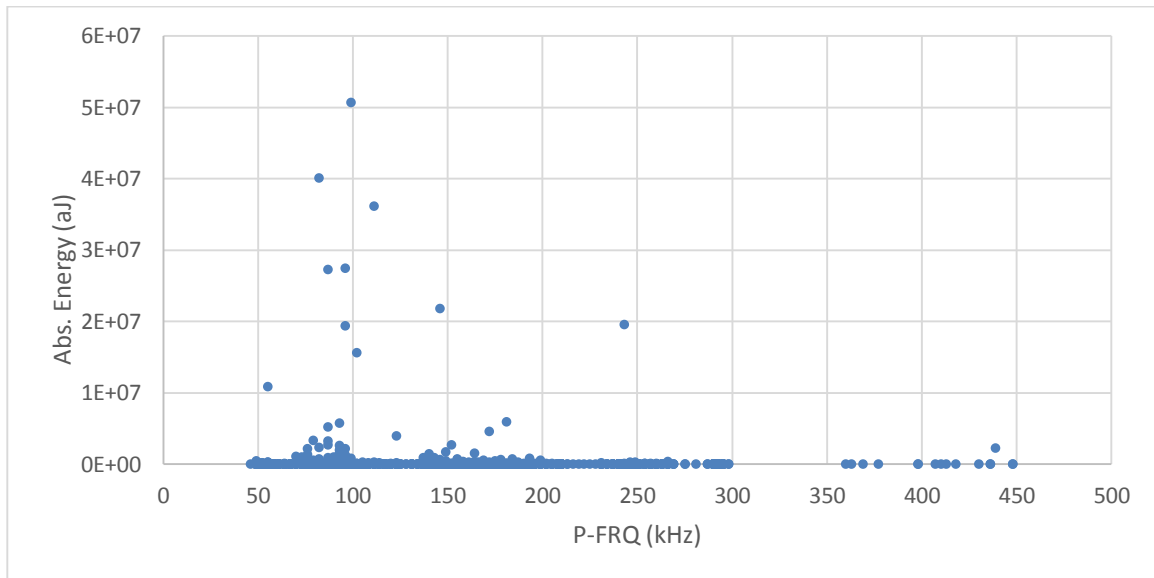


Figure 45: P-FRQ to Absolute Energy Comparison

Load – Unload – Reload Characterization Results

The LUR tests were performed following the completion of all static tests and used the average load at failure for each of the static coupon types to construct the respective load levels. As was mentioned in the experimental process, the initial 10% load steps were modified to 20% load steps for the first three cycles followed by 10% to failure. These load cycles incrementally increased up to the 100% cycle, the average static failure load, and further if necessary to fail the coupon.

The progression of the frequency and energy parameters discussed above for static tests remained much the same for LUR tests and a selection of results from each test type will be analyzed below. Additional plots for all coupons are located in Appendix A. In the plots below, the strain data with respect to time has been overlaid on

the acoustic emission data and the individual loading cycles over time can be clearly seen. The strain data will often contain more errors compared to the load data but provides a more direct comparison to static test data. A plot of the peak frequency of a [90/0]s coupon of Carbon-D is shown in Figure 46 while Figure 47 shows the absolute energy from the same coupon test. This particular test utilized modified load levels.

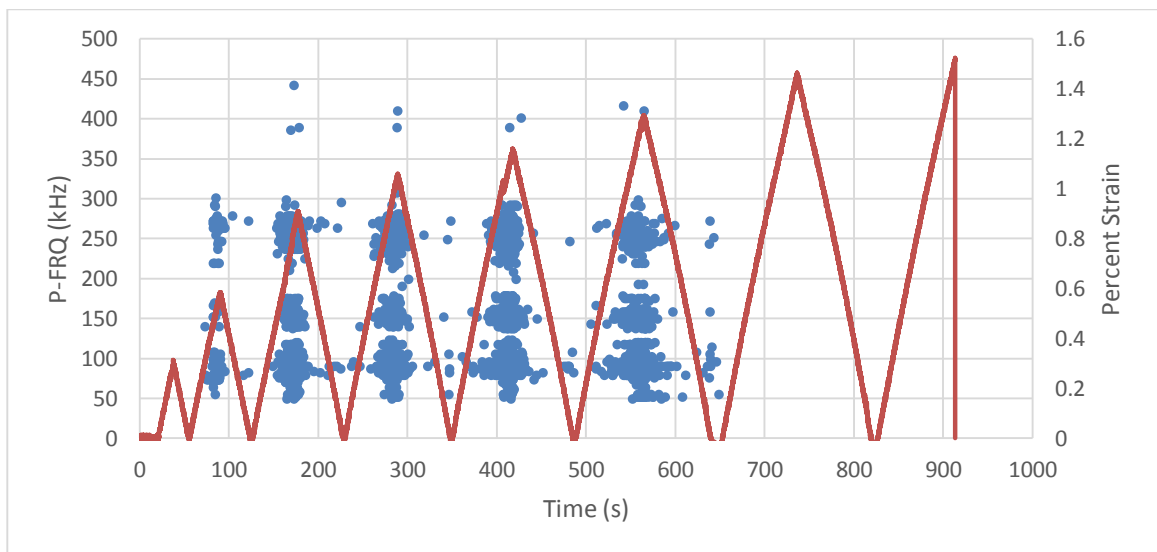


Figure 46: Hit Peak Frequency for LUR [90/0]s Carbon-D, AE Removed

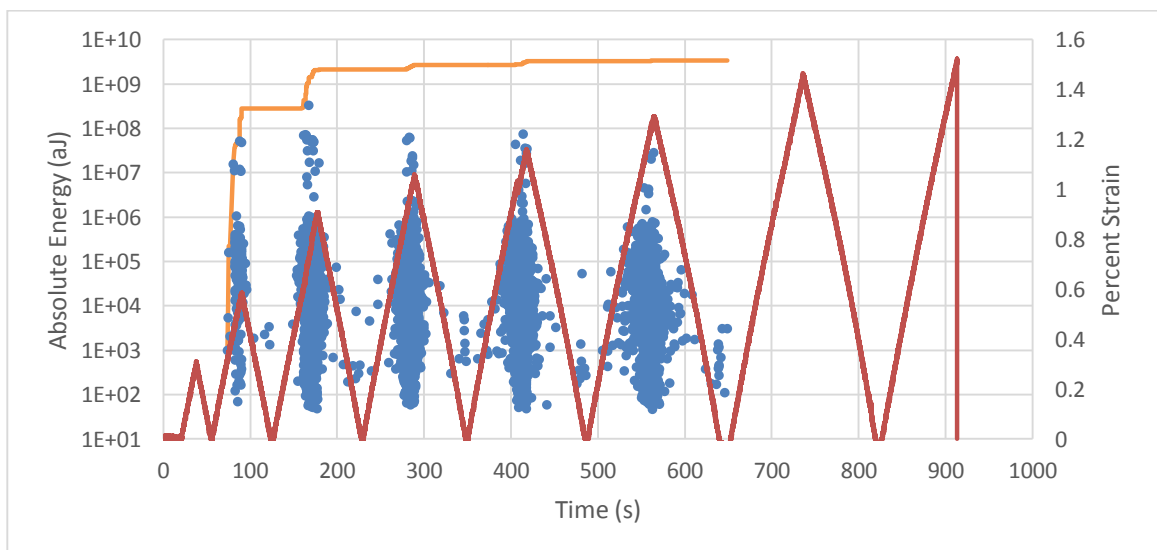


Figure 47: Absolute Energy for LUR [90/0]s Carbon-D, AE Removed

Acoustic emission events did not begin until the 20% load cycle for the Carbon-D material. There is also a lack of any AE data after the 90% load cycle, but this is of course due to sensor removal as discussed in the experimental procedures. The test was continued past sensor removal and the coupon finally fails in the 110% load cycle. While failure at a higher load level is not surprising since the 100% load cycle is just an average of several failure loads, many coupons did reach the 120% load cycle. This apparent strengthening of the coupon appears to be an effect of the load – unload – reload type test. Whether the higher load levels reached are a result of statistical spread or an effect of the LUR test is not critical to the results and the progression of AE events remained much the same.

The consistency of damage mechanisms between test types is apparent when comparing the static to LUR frequency progression. The bands of peak frequency for the [90/0]_s Carbon-D coupon are exactly the same when compared to static plots from above. The 40% load level sees the onset of AE activity with peak frequencies observed in all bins but F4. These highest frequencies are observed in later load cycles starting at 0.9% strain, the same strain as when these high frequency hits began in the static tests. The LUR absolute energy progresses similar to the monotonic tests as well. Significant, high energy events are seen in the early cycles when transverse matrix cracking is prevalent. These high energy events give way to greater numbers of events but of less energy in later cycles. The similarity seen here between monotonic and LUR test results are analogous to the other materials' [90/0]_s coupons. The similarity of peak frequency is

expected because both loading scenarios are a quasi-static process that should produce the same damage mechanisms.

Frequency and energy characterization results were also very similar between a material's [0]_n monotonic and LUR tests. Figure 48 and Figure 49 show the results for a Glass-B LUR coupon. The tests of this layup can be characterized by low frequency, low energy hits in the first few cycles. After more cycles, higher frequency as well as higher energy hits increase in occurrence, though these may not be the same events. The absolute energy accumulation did not significantly increase until the 70% load cycle which correlates to the nearly 1.5% strain at which energy was accumulated in the static tests of Glass-B coupons (Figure 33). In association with the higher energy events occurring in the [0]_n layup, the highest frequency fiber break type events also begin.

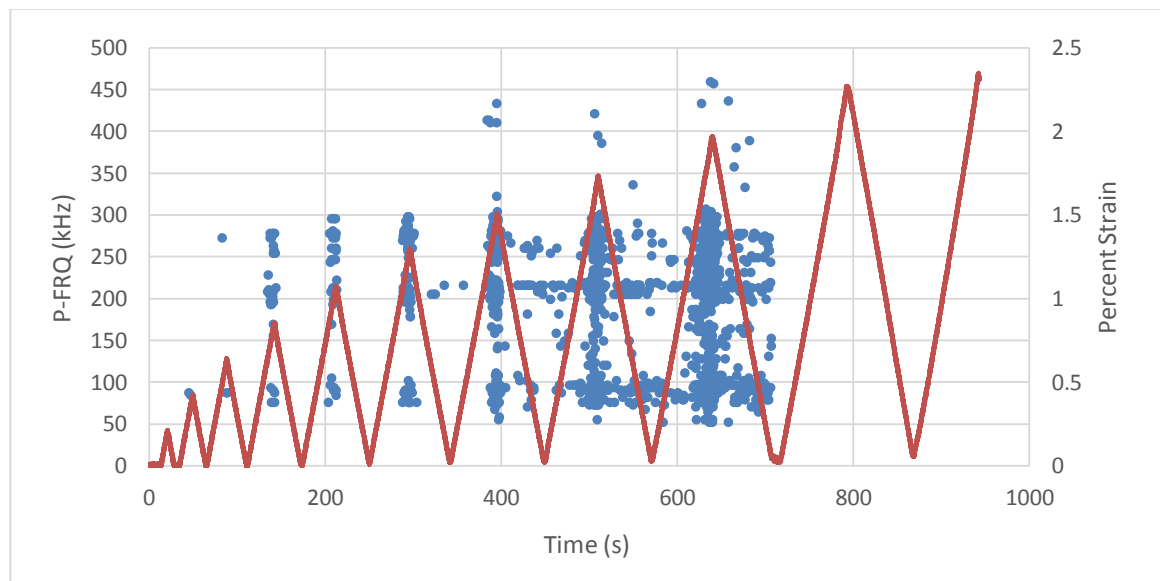


Figure 48: Hit Peak Frequency for LUR [0]_n Glass-B, AE Removed

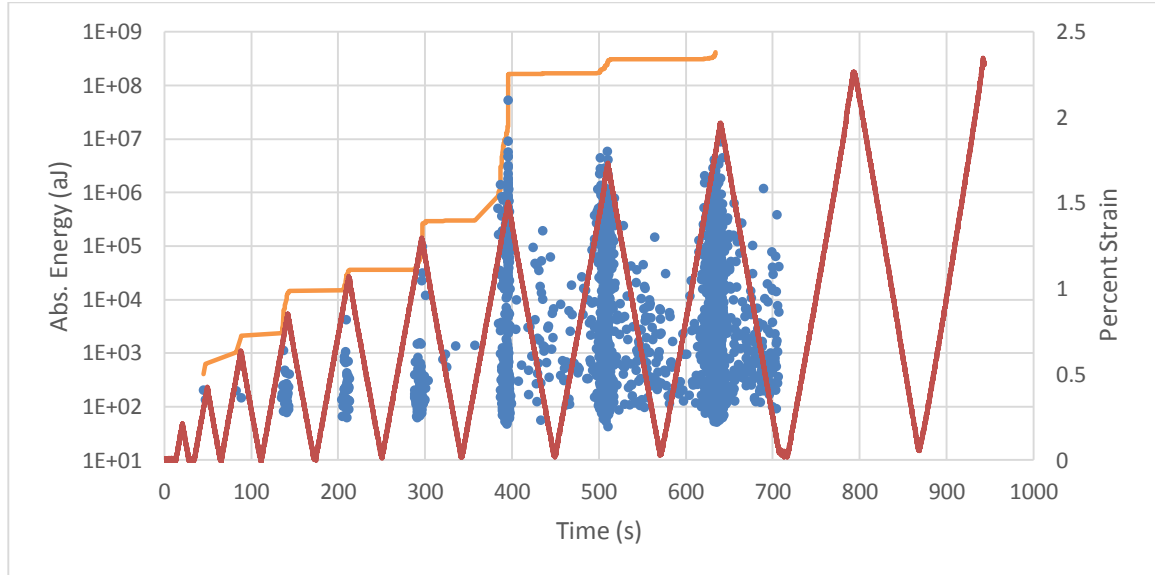


Figure 49: Absolute Energy for LUR [0]n Glass-B, AE Removed

The [0]n test seen in Figure 48 and Figure 49 displays the issue of noise upon unload that was present in many of the LUR tests. As the load is reduced on the coupon after reaching the peak cycle load, surfaces that were separated come back together, fibers rub against each other and even additional minor damage all have the potential to emit elastic waves that are picked up by the AE system but are not desired. Interestingly for this test, the noise was constrained to narrow bands of frequency that can be seen bridging actual AE activity at the peak loads. The noise was not always this identifiable and to add to the issue, some critical damage could occur upon unload, though very near the peak cycle load. From the energy plot, this noise occurs within the low to middle level hit absolute energy. Though no single noise event is significant, the accuracy of the acoustic characterizations and analysis suffers as more noise events accumulate.

The [90]n LUR tests are summarized by very little emission until at least the 50% load cycle followed by low frequency events and several of very high energy. Finally, a

decrease in high energy hits is seen in the last few cycles. For the particular test of Glass-B in Figure 50 and Figure 51, significant activity did not begin until the 80% load level. Events were initially seen in all peak frequency ranges and then focused in the lowest frequencies during the later load cycles. This again matches the static results and indicates that more complex damage is occurring than just matrix cracks. During the 90% load cycle, a transverse matrix crack opened in between the extensometer arms and with little remaining stiffness in that direction, a large strain is recorded. Absolute energy results also held good comparison to static data in that there was a large, initial increase in energy followed by “wearing-in” of the damage and less significant uptakes in accumulated energy as the cracked surfaces separate and the backing strands carry the load. The cycle in which final failure occurred often exhibited a wider range of frequencies than the other cycles but still no events were recorded as fiber breaks above 300 kHz peak frequency.

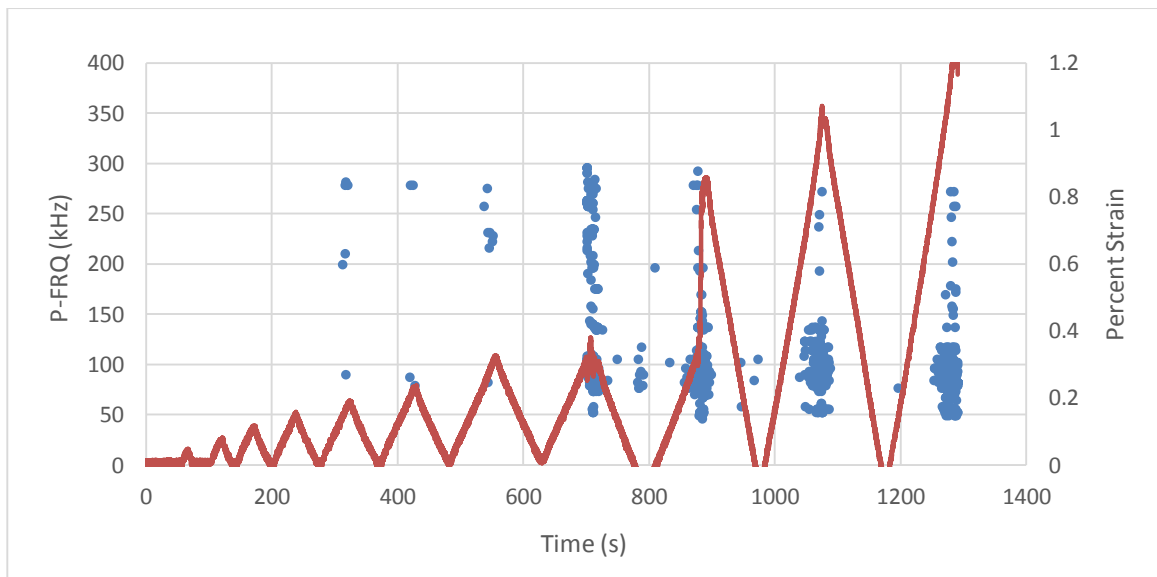


Figure 50: Hit Peak Frequency for LUR [90]_n Glass-A, AE Not Removed

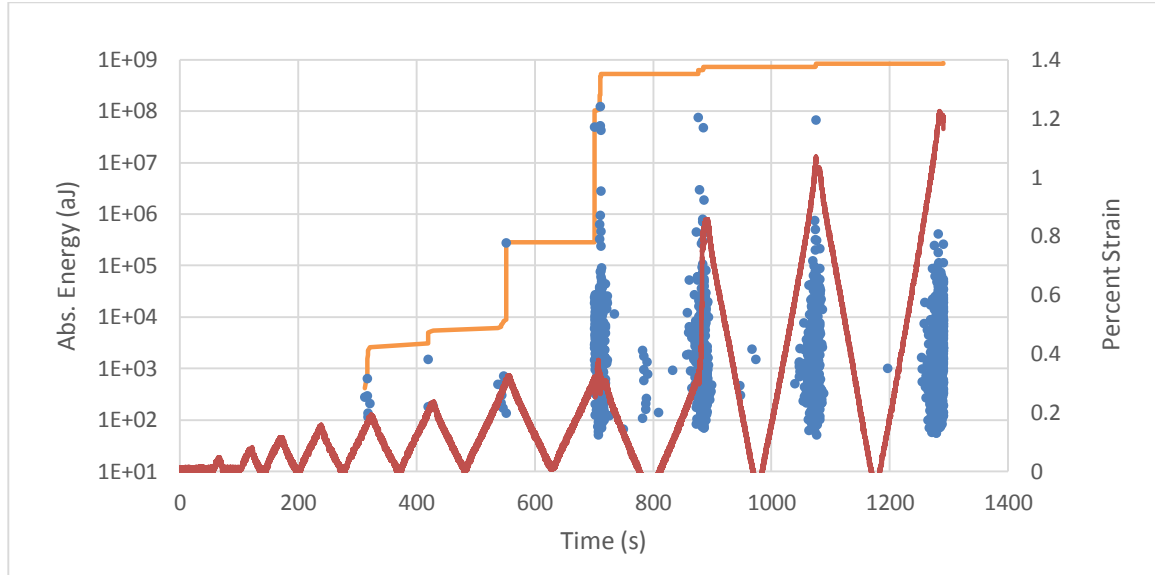


Figure 51: Absolute Energy for LUR [90]_n Glass-B, AE Not Removed

Strain Energy Correlation

The primary motivation behind performing the LUR tests was to understand the relationship between strain energy dissipated and AE absolute energy. The result of correlating these two concepts is discussed below. Figure 52 shows the stress-strain curves through several load and unload cycles of one LUR test of [90/0]_s Glass-A. As the load increases, damage can be seen occurring when the stress-strain curve begins to have a slight non-linear curvature near the peak of each cycle. For this particular test, over 200 individual AE events were recorded for the 60% load cycle and are plotted as circles. Where the AE events are concentrated, more curvature is apparent in the stress-strain curve. Upon unloading, the load returns to zero and the strain decreases linearly. What is visible in the curves is a sliver of area in-between the load and unload portions of the stress-strain curve. This sliver of area represents the dissipated strain energy as discussed in the background and this area, normalized to the coupon volume, was

compared to the AE absolute energy occurring from zero load to the peak load of that cycle. The AE activity recorded was limited to the same volume applied to the strain energy through use of the DeltaT filter. Some noise is evident at low strains though the majority of activity is intensely concentrated at the upper portion of the load cycle where new damage is occurring. Gorman observed similar effects as these in an LUR loading scenario for Felicity Ratio analysis though unloading hysteresis was much greater in the Carbon-Carbon composites [47].

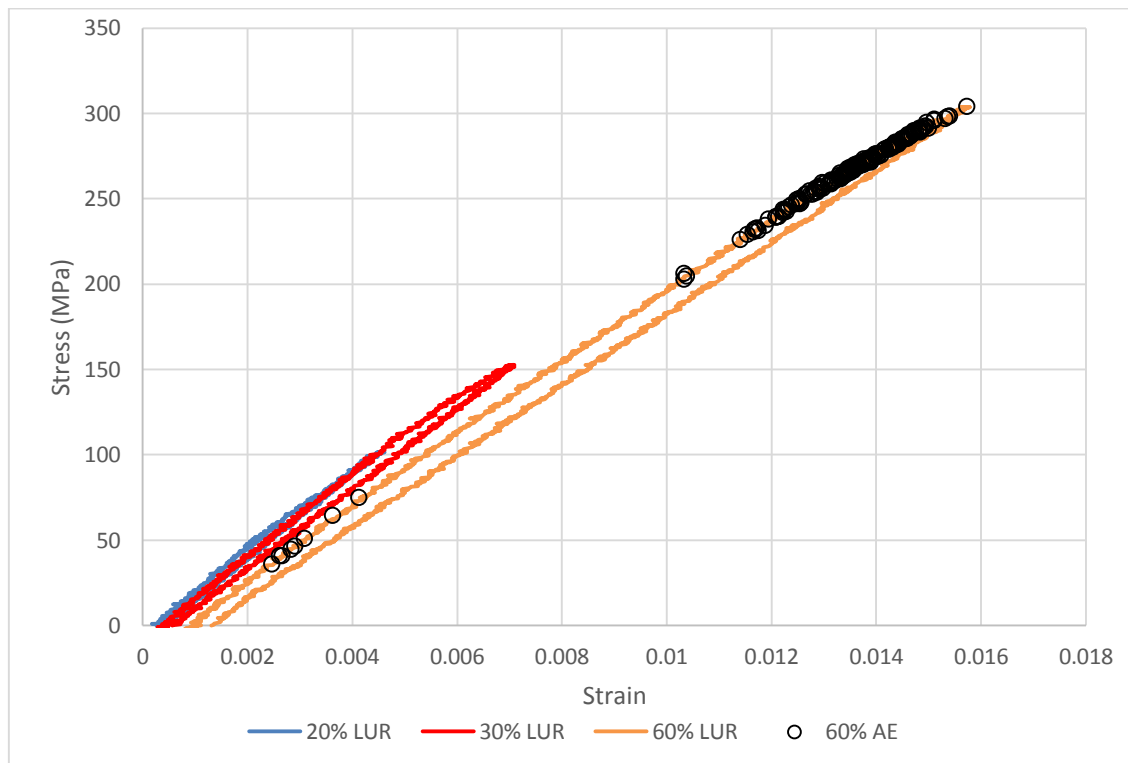


Figure 52: Stress-Strain Curves for Several Cycles of LUR

The [90/0]_s coupons provided the most consistent energy progression so they were the sole layup that the energy correlation analysis was performed upon. Accurate load and strain data is required for the calculations of strain energy and extensometer

slips and discrete crack jumps do not provide data of sufficient quality for the trapezoidal integration of the stress – strain curves. The three plots below in Figure 53, Figure 54 and Figure 55 mark the trends between the calculated strain energy dissipated and AE absolute energy measured for each load cycle and material. Each of the three tests performed on each material are included and marked with different colors. Dotted lines and squares points denote the accumulated AE absolute energy for each cycle and solid lines and circles mark the dissipated strain energy for each cycle. Load cycles are marked on the x-axis. The scales for the two energy methods are orders of magnitude different from each other but as discussed earlier, AE will certainly not capture the total energy released in a damage event.

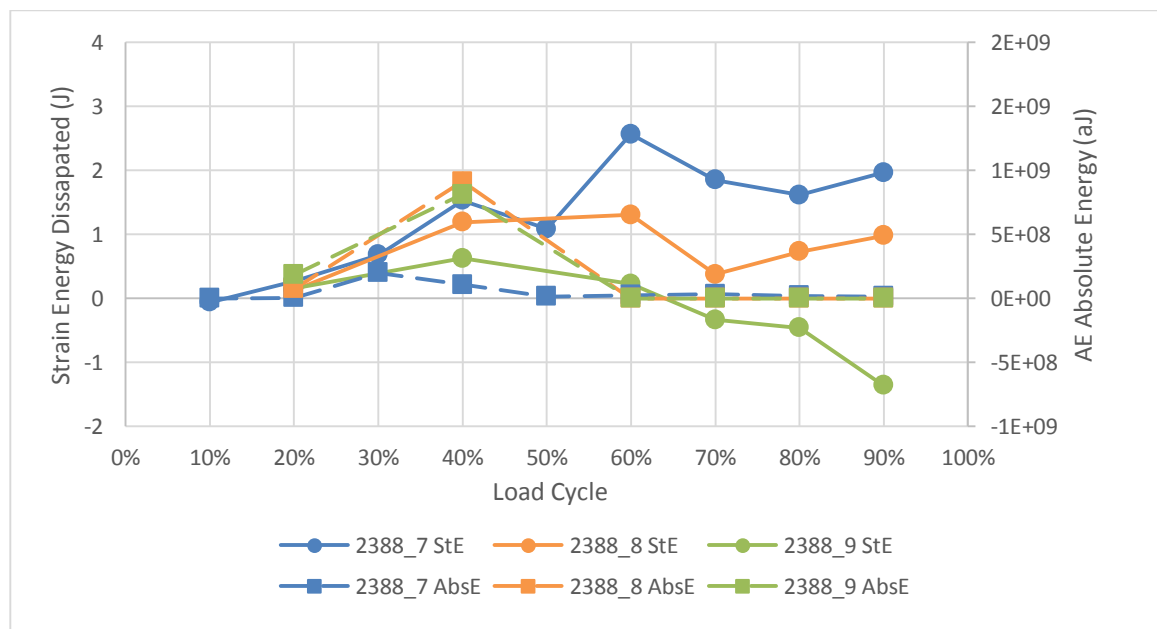


Figure 53: Energy Method Comparison for Glass-A

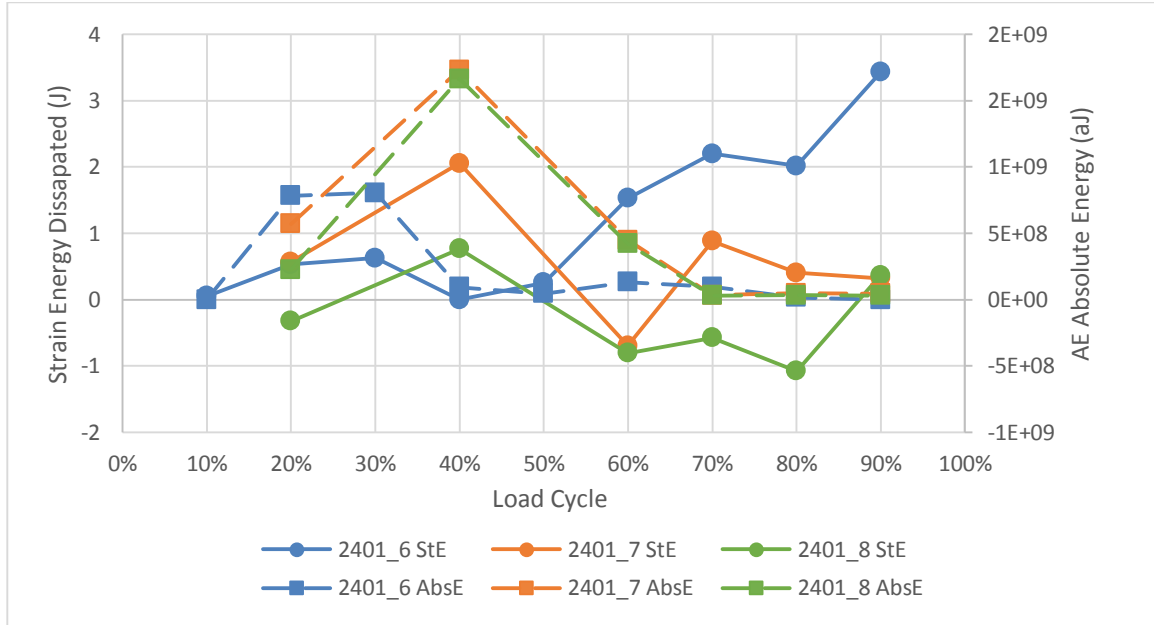


Figure 54: Energy Method Comparison for Glass-B

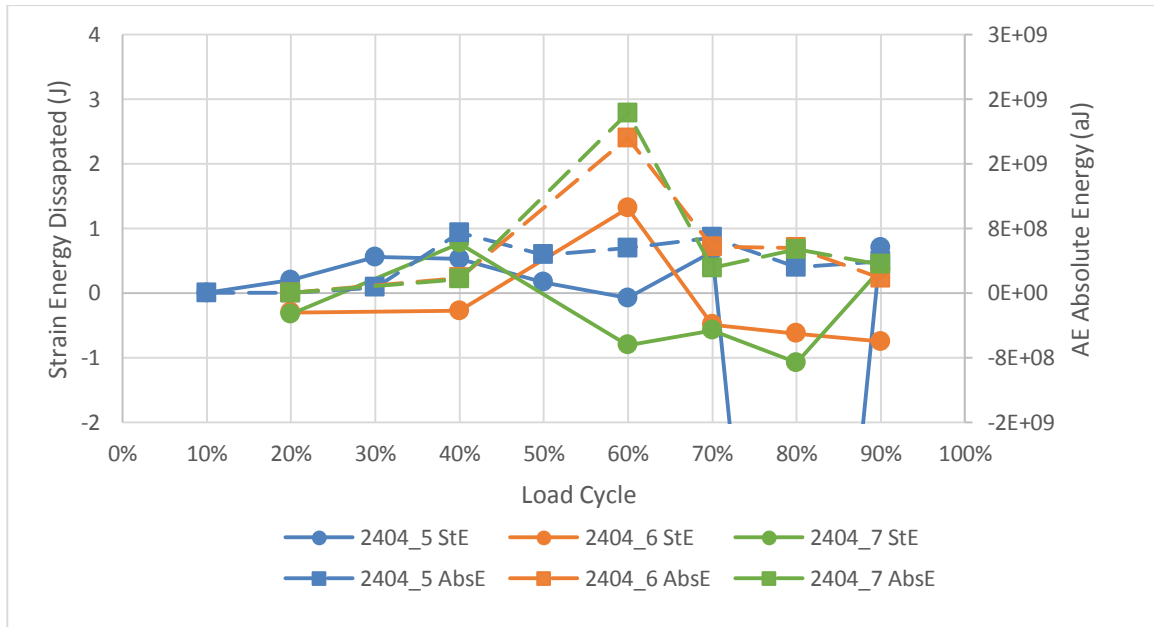


Figure 55: Energy Method Comparison for Carbon-D

If the relationships between the two energy values held perfectly, an increase in strain energy dissipated would be directly proportional to AE absolute energy emitted

during that cycle. In some load cycles, this does hold true. Peaks of highest absolute energy occur in the 40% load cycles for glass and 60% load cycle for carbon and are often met with a similar large increase in strain energy dissipated in that same cycle. After the peak, absolute energy often decreases rapidly with much lower values for the remaining load cycles. Similarly, the strain energy dissipated often decreases after this peak and then conservatively increases to the end of the test. However, in other cases such as the 60% cycle for Carbon-D coupon 2404_7, values diverge from each other; absolute energy increases and strain energy dissipated decreases. Differences in results can clearly be seen between the two load level schemes with the lowest numbered coupon corresponding to the 10% load levels and the two higher numbered coupons using the modified load levels. The modified load levels will group more AE into one load level thus resulting in larger peaks of absolute energy. Theoretically, this should also result in larger peaks for strain energy dissipated and the relationship should hold.

Noteworthy issues also arise in the above plots when the strain energy dissipated returns a negative value. This can happen when minimal strain energy is dissipated and the scatter in the load and strain data creates a small, negative value. Second, as is more noticeable for carbon, is that 0° fibers will often undergo straightening under high strains. This requires some damage to occur in order to make way in the matrix for the carbon fibers to adjust and align. This behavior is called stress stiffening and will actually steepen the stress strain curve and thus produce a negative value of dissipated energy. Finally, any jumps or errors in the extensometer data will produce jumps in the stress-strain plots and could result in erratically small or large values for strain energy

dissipated. Efforts were made to adjust the extensometer data where possible although not all slips could be reconciled without compromising the integrity of the data. This issue is the main cause of the erratic value in the 80% load cycle of Carbon-D coupon 2404_5 for example. Following the plots of the trends observed in both values, the correlation of strain energy dissipated to AE absolute energy for each load cycle is presented below for all materials. The correlation values were calculated using Equation 7 which simply relates the two values in a ratio. The log operator was applied to reduce the order and produce a more applicable value.

$$AE_{cc} = \log \frac{\text{Strain Energy}}{\text{AE Absolute Energy}} \quad (7)$$

Correlations for Glass-A in Figure 56 are by far the best results obtained, both in terms of correlation values between load cycles of the same test and between the three coupon tests. Recall that the 30% and 50% load cycles were not utilized by the latter two coupons that used the modified load levels so no correlation is present for those cycles. The plot shows that the absolute energy correlation constant is generally lower for earlier cycles and increases throughout the test. The values vary more between individual coupons, however, it is consistent between load cycles, suggesting that some type of normalization with respect to the behavior of each coupon may be possible. The exact coupon volume is already accounted for in the strain energy calculation and other efforts to normalize have not proved successful. Again, if correlations reported the same value for each load cycle, that would indicate a direct correlation between AE energy and

actual energy dissipated. As such, the Glass-A results do certainly show a possibility of a modified correlation value.

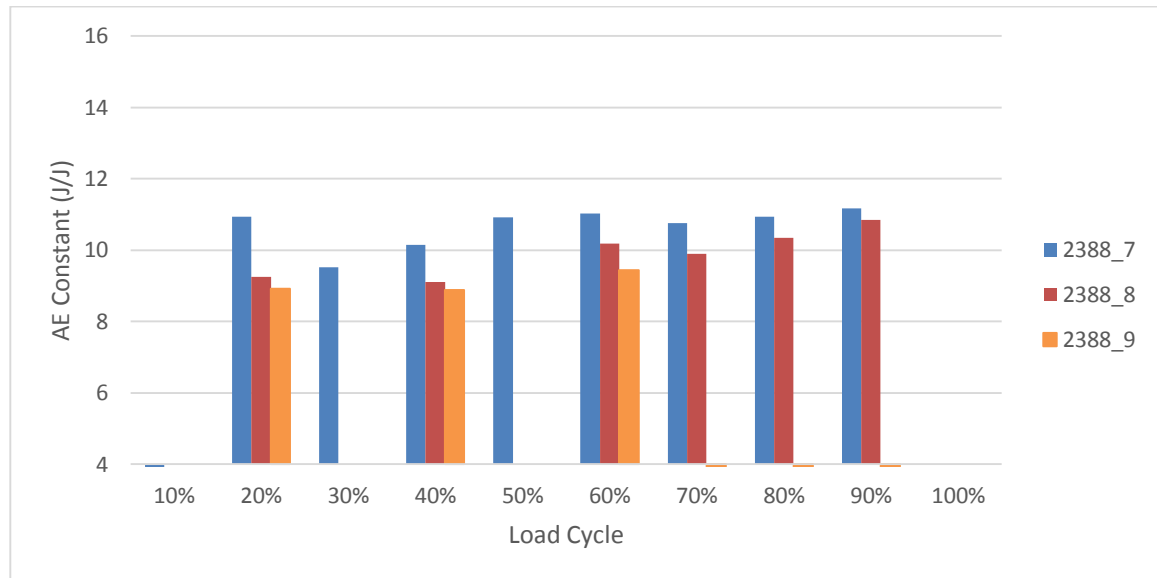


Figure 56: Energy Correlation Constant for Glass-A

Glass-B and more so Carbon-D correlations in Figure 57 and Figure 58 fall victim to negative strain energy dissipation values and require more data points to draw better conclusions. Due to the log operator, negative energy correlation values cannot be computed. Where results are present for multiple coupons, results show moderately good correlation among the individual coupons and even between load cycles in some cases. If 20% load steps were used for the entire test more data points may be filled in because a greater amount of damage would occur per cycle and strain energy dissipated would not be so prohibitively small that the parametric data returns a negative value. Any future attempts at this type of analysis may prove difficult with carbon due to the stress stiffening effect on the modulus but the glass results do show some potential.

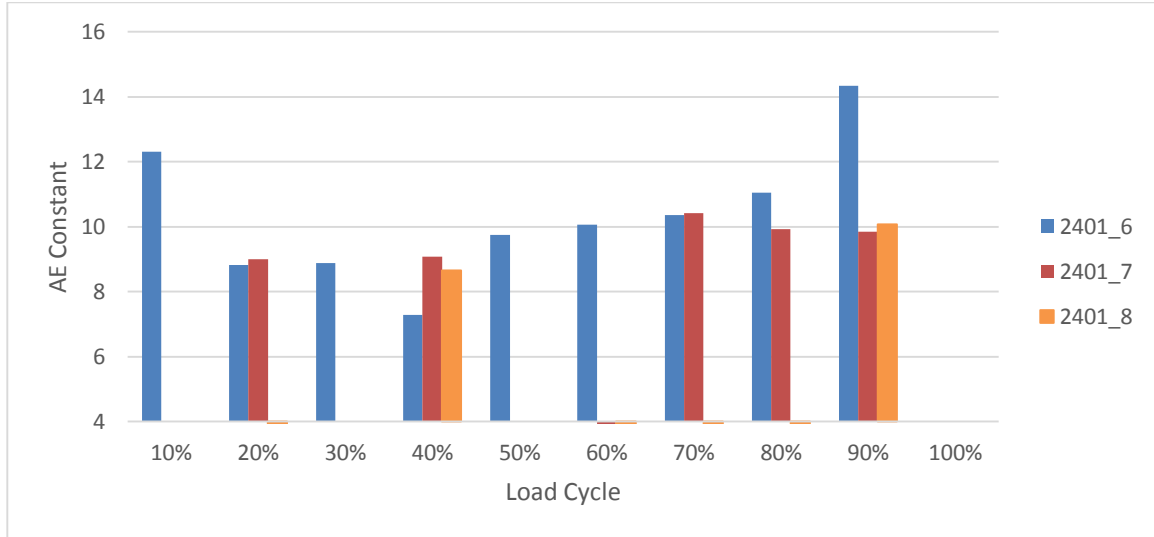


Figure 57: Energy Correlation Constant for Glass-B

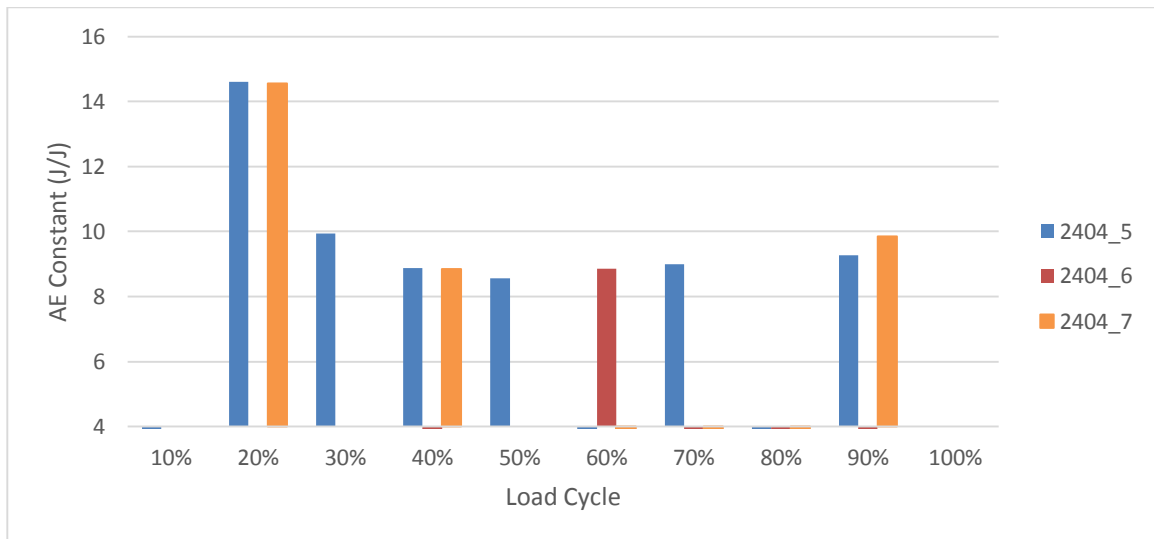


Figure 58: Energy Correlation Constant for Carbon-D

These correlation results also show that the first load cycle with AE data often shows an erratically large correlation value. This is due to the small number of high energy, matrix crack type events that do not greatly affect the overall coupon damage state. This highlights an issue with the present method that factors into the poor correlation values. Specifically for the [90/0]_s layup discussed here, matrix failure does

not drastically change the stiffness of the coupon but does contribute significantly to the acoustic energy. The 0° fibers will still carry a majority of the load as the stiffest material constituent and when these fail, the damage mechanisms are of smaller absolute energy but contribute more to the final failure of the coupon. Transverse matrix cracks do absorb a great portion of strain energy and release the most AE absolute energy as detected by the AE sensors but alter the overall coupon stiffness the least, thus resulting in smaller dissipated energy values. It is proposed that some scaling be applied to each event's absolute energy dependent on the damage event in relation to the criticality of the type of damage to the coupon.

Equation 7 was used to produce the correlations values above but it had been independently devised and implemented in a similar form. Minak coined the term Sentry Function for this equation and its purpose was to monitor the damage state of a composite coupon similar to the goals of this work [48]. However, the application of the equation was different in that the correlation was a function of strain; the value was generated at every point of stress-strain data collected. This was used to assess the continuously changing relationship of strain energy to absolute energy during a static test. Also, the energy of concern was not dissipated energy but the total strain energy within the coupon so that drops in strain energy aligned with spikes in AE energy. This method provided an interesting analysis for a static test but appears to be too intensive for continuously running fatigue tests. Further, the fact that the dissipated energy is monitored in this work and correlated to acoustic emission, which senses dissipated energy, seems to be a more direct application to theory.

Total Accumulated Energy

In the preceding discussion of test progression results, the individual fabrics were characterized both in terms of per hit and accumulated absolute energy as well as peak frequency. While the above initial efforts to relate the absolute energy emission back to dissipated strain energy were not met with complete success, absolute energy was found to have merit as a repeatable, definable test metric that can indicate the damage state of the composite coupon. The total accumulated absolute energy was averaged for each set of static tests and the results found to be quite consistent among each coupon variant. Furthermore, when these results are compared to the total accumulated absolute energy for the LUR test regimen of the same coupon, the two values compare remarkably well as seen in Figure 59, Figure 60 and Figure 61.

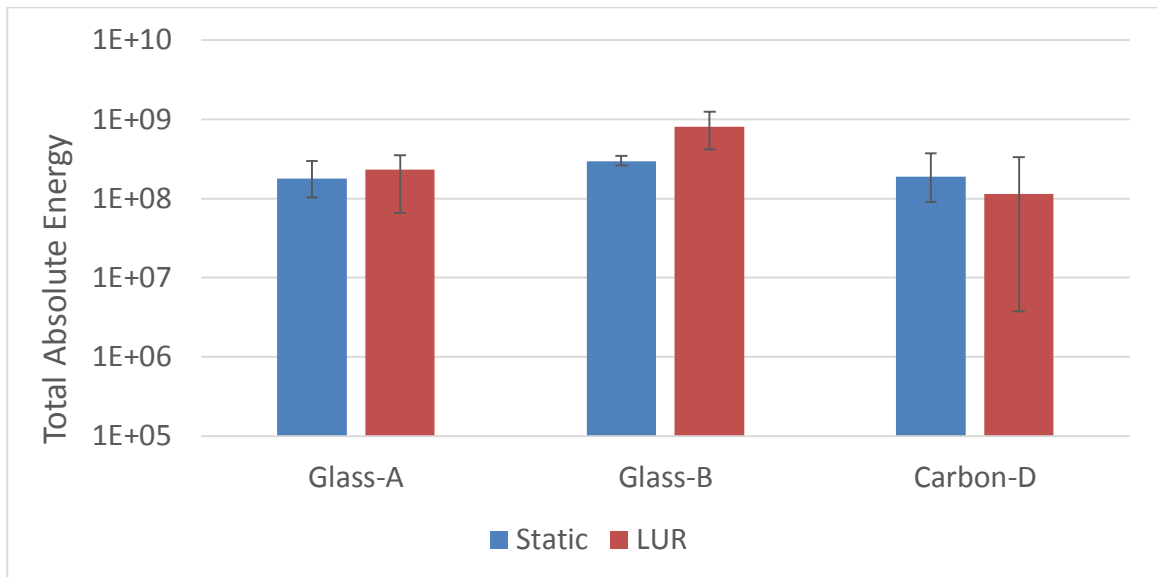


Figure 59: Total Absolute Energy Accumulated for [0]n Coupons

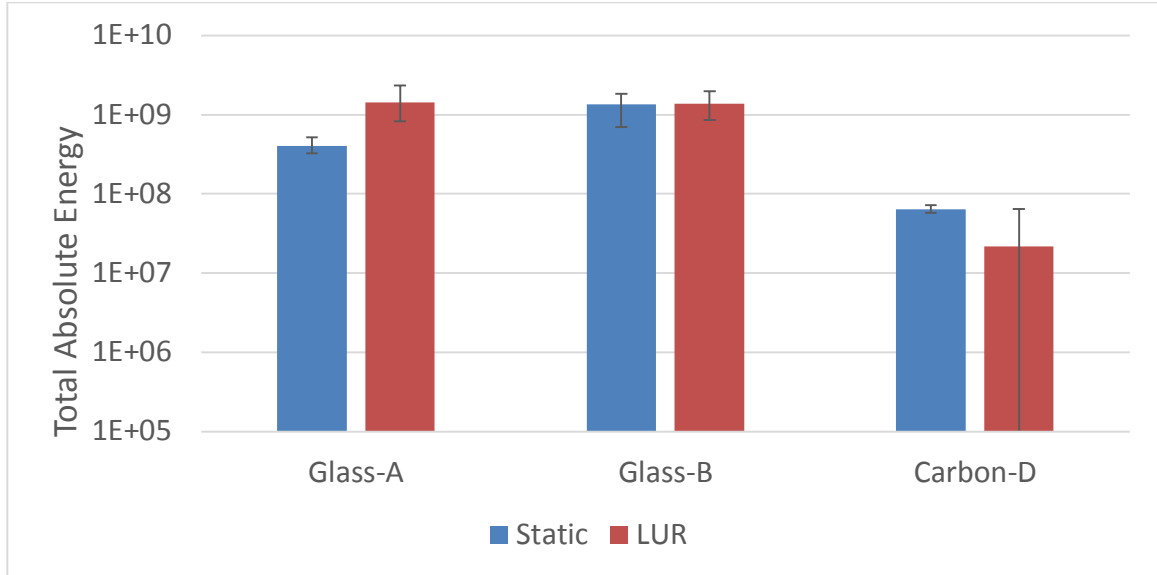


Figure 60: Total Absolute Energy Accumulated for [90]n Coupons

The comparisons for [0]n and [90]n laminates in Figure 59 and Figure 60 show significant correlation though the error is high in a few cases. The error in the LUR [90]n Carbon-D data is extreme but is explainable by the fact that the final failure AE data point was thought to be captured but the DeltaT software filter blocked the hit data because the one event occurred outside the gage section. Thus the one and only data point for several of these tests was not captured. What was captured was an erroneous, low energy reflection from the primary failure. A Carbon-D LUR [0]n coupon also failed significantly early, giving a large error and damaging a sensor in the process. Total accumulation values for the LUR tests are generally higher than the static values due to the noise upon unloading that was shown in the progression results above. The LUR AE events were limited to the same maximum strain observed in the monotonic tests and all AE data points, including noise events, below that strain were included.

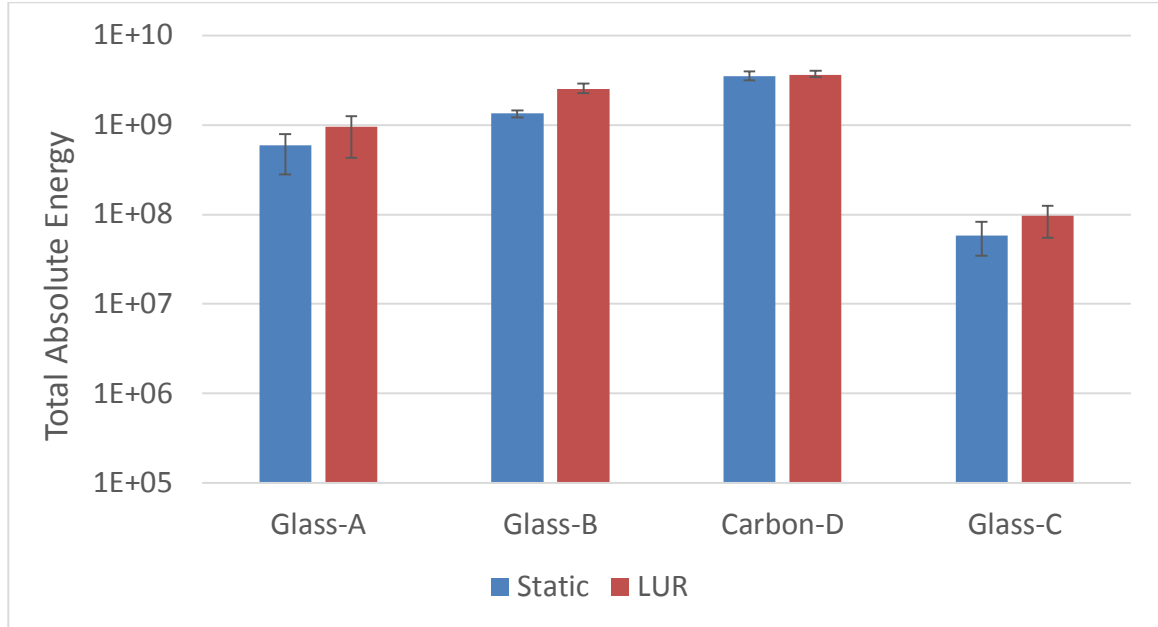


Figure 61: Total Absolute Energy Accumulated for [90/0]_s and [+/-45]₄ Coupons

The biax coupons in Figure 61 show an excellent and consistent correlation. The amount of absolute energy accumulated is most nearly a constant; independent of loading scheme. A load – unload – reload test is still a quasi-static form of mechanical testing so failure should follow the same pattern as for the statically tested coupons – and the test characterization results indicated this. Yet these results show that the number of cycles and various load steps applied to the coupons do not alter how much absolute energy is released and detected by AE sensors. The values given in the figure above are a quasi-static critical threshold of AE energy that in future testing can indicate the remaining health of the coupon and could be further extended to indicate the degradation of material properties as a state variable. Even though the sensors were removed at set values of strain for [0]_n and [90/0]_s layups, this was above the strain level that these materials

would experience when integrated into production parts and the accumulation remained consistent up to the arbitrary strain threshold applied for sensor removal.

In comparison between the four materials tested, there are some trends in total accumulated energy that differentiate the materials. The double bias Glass-C fabric had by far the lowest energy accumulated on average. This is due to the orientation of the damage mechanisms at 45° , the type of damage mechanisms releasing lower energy waves and the uniformly damaged material may have increased attenuation of the waveforms. For the other glass materials, Glass-B released more energy on average than Glass-A. In part, this is due to Glass-B being a thicker material but it is also a denser material that released more energy per event than Glass-A. Carbon-D showed the least energy of the primarily unidirectional materials during the $[0]_n$ and $[90]_n$ coupon tests. The combination of being a thinner fabric as well as acoustically quieter behavior with significantly fewer events ensured a reduction in total energy. During the $[90/0]_s$ tests though, it emitted the largest number of events of the three materials as well as the most energy since many more transverse failures were possible than during the $[90]_n$ tests. Plots of total numbers of events can be seen in Appendix A.

The $[90/0]_s$ laminates provided the most consistent results because of the well-defined and activated damage mechanisms. The combination of weak outer plies backed by stiff and strong fibers means that transverse cracks formed in all resin rich areas rather than the single crack that failed the Carbon-D material. The moderate error on both the static and LUR results for Glass-A is thought to be caused by the random strand mat and increased number of transverse strands that provided a less consistent amount of

microscopic damage sites and therefore released energy. That very error would appear to be consistent between the two loading scenarios suggesting that the statistical spread of data is due to the material itself and not test methods. The difference between the Carbon-D loading scenarios is minimal and this is attributed to the material being acoustically quieter in general and the reduced strain to failure that results in transverse cracks being physically separated less than with the glass coupons. Less separation leads to fewer noise events occurring due to fiber bridges closing and friction of cracked surfaces. Visually, transverse cracks and separation that was visible in glass coupons were not discernible for carbon coupons. It is expected that if the amount of noise upon unloading could be reduced, then the greater amount of AE absolute energy seen in the LUR tests would be reduced thus bringing the static and LUR total accumulated absolute energy values even closer.

5. CONCLUSIONS

Acoustic emission analysis has proven to be a valuable instrumentation tool to extract unique, real-time information from a mechanical test of fabric reinforced polymer matrix composites. Strains to damage initiation and changes in damage state were identified in each of the fabric types through the use of peak frequency and absolute energy data. The correlations between peak frequency and four primary composite damage micro-mechanisms determined by other researchers were in agreement with the characterizations performed for this research. Significant activity was observed outside of the frequency range of the expected mode of failure and complex fabrics emitted more events of these other damage types. Thus giving invaluable insight into the micro-mechanical damage processes that occur throughout the progression of a test and effect the strength and damage tolerance of the various fabrics. Interphase failures exhibited noticeable shifts in peak frequency between fabrics. Fiber breaks may also show a shift in peak frequency though limited data was collected in this frequency range. Consistent results were achieved with the biax coupons yet the results were similar between materials due to the complex layup forcing similar damage mechanisms.

This material characterization will aid in analysis of future coupon work with these materials and will help to identify damage mechanisms for complex sub-structures during test. Because the peak frequency is a direct representation of the damage, various modes and critical modes of damage can be identified in situations where it is impossible to visually observe the damage. The characterizations and progression of damage identified for these materials will also aid validation of damage initiation and progressive

damage modeling. These ideal material characterizations can also be compared to defective materials to further quantify the effect of defects. This ability will increase the information gathered per test, thus reducing iterations, test time and cost.

Correlating the absolute energy to a classically defined energy measure is not without merit although efforts herein were inconclusive. Ultimately, a simple ratio was not sufficient to describe the relationship between strain energy dissipated per cycle and AE absolute energy emitted per cycle. The results suggest that to improve the correlation value, a method of normalization among individual coupons is needed. In addition, a damage mechanism dependent scaling factor should be applied to each AE event's absolute energy value. Previous research has shown that this type of correlation is possible although much of this work was done on single, well-defined crack paths. Relating classic theory that is able to describe the state of a material to an experimental value will increase the applicability and relevance of AE and it demands further attention.

In the interest of developing an AE test metric that could potentially lead to failure criteria, state variables and lifetime estimates, the accumulated absolute energy was found to be a promising candidate. The absolute energy accumulated was consistent not only between tests of the same layup and material but was also consistent between monotonic and multi-cycle loading regimes. This indicates that for a particular material system, the total accumulated energy can be considered to be a constant value. This constant could be applied as a criterion such that specified levels of accumulated energy can trigger actions such as removing sensors or manually checking the condition of the test article. Though the rate of accumulation is far from linear, the changes in

accumulation rate do indicate various stages of damage progression. An effective method of monitoring the damage state of the test article can be applied when knowledge of the rate of accumulation and values of total accumulation are taken into account.

Through the process of developing the above results and conclusions, an analysis technique new to Montana State University Composites Research Group was explored and developed for future use. Over 80 individual coupon tests were completed for the data presented within this paper as well as numerous preliminary tests that explored the multitude of software and hardware settings for best practices. A full dataset of four commonly used materials is now available for comparison and future analysis as well. This data will progress the application and analysis techniques of acoustic emission to sub-structure and effects of defects related mechanical testing. This work has developed the data and process necessary to locate, identify and quantify the effect of damage to the test article health.

Future Work

Based on the research performed on composite materials utilizing acoustic emission analysis discussed in this paper, there are two branches of future work to be investigated further. These two paths could be developed in parallel or independently and will ideally re-converge in practice once both methodologies are further investigated and understood.

The first direction for future acoustic emission work is integrating the system into sub-structure testing. Applying the sensors and methods to a sub-structure test was a major contributor to the motivation of the coupon based testing. This research was a

necessary stepping stone for applying complex acoustic emission techniques to complex structures but on a much higher level, it developed critical data sets, analysis methods and advanced material characterizations necessary for these structures. The material characterization performed for this research will be able to aid in identifying damage mechanisms, damage state and possibly identify within which material damage is occurring during the test. The characterizations will be especially useful because the same materials experimented on here will be used in the eventual MSU designed sub-structure test article.

Complications to the currently performed test process arise from the size of the test article (waveform degradation, sensor configuration), the complex load introduction schemes and fatigue loading conditions (noise and software setup). The data collected and monitored on these sub-structure tests will be of greatest utility when combined with accurate position information, which was not critical for this research and only briefly mentioned. The location data is necessary to compartmentalize the data so that it can represent the material degradation of a localized failure. Both linear and 2D locating schemes could potentially be applied, each with their own benefits and drawbacks. The software even includes an anisotropic option for the speed of sound differences experienced in composites. Sensor configurations vary between the two schemes and the accuracy and applicability of each need to be identified. Despite these complications the material characterizations and accumulated energy analysis can be directly applied if similar material configurations are used. Early sub-structure testing at Montana State University has revealed unpredictable and poorly constrain modes of failure.

Understanding when, where and how damage progresses with the level of fidelity that acoustic emission provides will significantly improve the design, analysis and testing of these larger, more complex test articles.

The second major direction to continue this work is in extending and improving the analysis using AE absolute energy. The consistent total accumulated energy between monotonic and LUR tests indicate that it is an accurate way to monitor the damage state of the material and should be formally developed. Extending the comparison to fatigue loaded coupons should be investigated to determine if the same or a similar consistency exists. If so, this would present a powerful method of real-time experimental lifetime and strength reduction estimations during a fatigue test. Efforts should also be continued in identifying a means of correlating acoustic energy to dissipated strain energy. Due to the successes in correlating AE energy to well defined crack propagation in research referenced in the background, more advanced normalization and scaling schemes should be attempted. If the absolute energy emitted by a coupon before reaching the end of its life is as consistent as this work suggests, the governing mechanisms must play a role in this as well. Combining the constant value of accumulated energy as reported here with a physical correlation is an exciting proposition that solicits future investigation. As mentioned above, the particular type of damage occurring may be the largest factor to take into account for successful correlation. While these recommendations for future work certainly complicate the application and execution of acoustic emission analysis, the research and results found within this work provides the impetus for such work to be investigated.

REFERENCES CITED

- [1] AWEA. Montana Wind Energy. 2014.
- [2] Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013. Energy Information Administration; 2013.
- [3] Barbero E. Introduction to Composite Materials Design. 2nd ed: Boca Raton: CRC; 2011.
- [4] Cantwell WJ, Morton J. THE SIGNIFICANCE OF DAMAGE AND DEFECTS AND THEIR DETECTION IN COMPOSITE-MATERIALS - A REVIEW. Journal of Strain Analysis for Engineering Design. 1992;27:29-42.
- [5] Kim BW, Nairn JA. Observations of fiber fracture and interfacial debonding phenomena using the fragmentation test in single fiber composites. Journal of Composite Materials. 2002;36:1825-58.
- [6] Riddle T, Cairns DS, Nelson J. Effects of Defects Part A: Stochastic Finite Element Modeling of Wind Turbine Blades with Manufacturing Defects for Reliability Estimation. 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference: American Institute of Aeronautics and Astronautics; 2013.
- [7] Nelson J, Cairns DS, Riddle T. Effects of Defects: Part B?A Comparison of Progressive Damage Modeling of Fiberglass/Epoxy Composite Structures with Manufacturing Induced Flaws. 32nd ASME Wind Energy Symposium: American Institute of Aeronautics and Astronautics; 2014.
- [8] Rumsey MA, Paquette JA. Structural health monitoring of wind turbine blades - art. no. 69330E. Conference on Smart Sensor, Phenomena, Technology, Networks, and Systems. San Diego, CA2008. p. E9330-E.
- [9] Lamb H. On waves in an elastic plate. Proceedings of the Royal Society of London Series a-Containing Papers of a Mathematical and Physical Character. 1917;93:114-28.
- [10] Scholey JJ, Wilcox PD, Wisnom MR, Friswell MI. Quantitative experimental measurements of matrix cracking and delamination using acoustic emission. Composites Part a-Applied Science and Manufacturing. 2010;41:612-23.
- [11] Wang L, Yuan FG. Group velocity and characteristic wave curves of Lamb waves in composites: Modeling and experiments. Composites Science and Technology. 2007;67:1370-84.
- [12] Gorman MR. PLATE WAVE ACOUSTIC-EMISSION. Journal of the Acoustical Society of America. 1991;90:358-64.
- [13] Prosser WH, Seale MD, Smith BT. Time-frequency analysis of the dispersion of Lamb modes. The Journal of the Acoustical Society of America. 1999;105:2669-76.

- [14] Surgeon M, Wevers M. Modal analysis of acoustic emission signals from CFRP laminates. *Ndt & E International*. 1999;32:311-22.
- [15] Barre S, Benzeggagh ML. ON THE USE OF ACOUSTIC-EMISSION TO INVESTIGATE DAMAGE MECHANISMS IN GLASS-FIBER-REINFORCED POLYPROPYLENE. *Composites Science and Technology*. 1994;52:369-76.
- [16] Prosser WH, Jackson KE, Kellas S, Smith BT, McKeon J, Friedman A. ADVANCED WAVE-FORM-BASED ACOUSTIC-EMISSION DETECTION OF MATRIX CRACKING IN COMPOSITES. *Materials Evaluation*. 1995;53:1052-8.
- [17] SAMOS AE System User's Manual Rev 3. MISTRAS Group, Inc.; 2011.
- [18] Zarouchas D, van Hemelrijck D. Mechanical characterization and damage assessment of thick adhesives for wind turbine blades using acoustic emission and digital image correlation techniques. *Journal of Adhesion Science and Technology*. 2014;28:1500-16.
- [19] Huguet S, Godin N, Gaertner R, Salmon L, Villard D. Use of acoustic emission to identify damage modes in glass fibre reinforced polyester. *Composites Science and Technology*. 2002;62:1433-44.
- [20] Aggelis DG, Barkoula NM, Matikas TE, Paipetis AS. Acoustic structural health monitoring of composite materials: Damage identification and evaluation in cross ply laminates using acoustic emission and ultrasonics. *Composites Science and Technology*. 2012;72:1127-33.
- [21] Sedlak P, Hirose Y, Enoki M. Acoustic emission localization in thin multi-layer plates using first-arrival determination. *Mechanical Systems and Signal Processing*. 2013;36:636-49.
- [22] Baxter MG, Pullin R, Holford KM, Evans SL. Delta T source location for acoustic emission. *Mechanical Systems and Signal Processing*. 2007;21:1512-20.
- [23] Zarouchas DS, Van Hemelrijck D. Monitoring the Structural Integrity of Wind Turbine Blades Subcomponents using Advanced Signal Processing Techniques. *Structural Health Monitoring 2013, Vols 1 and 2*. 2013:2448-55.
- [24] Roberts TM, Talebzadeh M. Acoustic emission monitoring of fatigue crack propagation. *Journal of Constructional Steel Research*. 2003;59:695-712.
- [25] Zarate BA, Caicedo JM, Yu JG, Ziehl P. Probabilistic Prognosis of Fatigue Crack Growth Using Acoustic Emission Data. *Journal of Engineering Mechanics*. 2012;138:1101-11.

- [26] Dassios KG, Kordatos EZ, Aggelis DG, Matikas TE. Crack Growth Monitoring in Ceramic Matrix Composites by Combined Infrared Thermography and Acoustic Emission. *Journal of the American Ceramic Society*. 2014;97:251-7.
- [27] Bourchak M, Farrow IR, Bond IP, Rowland CW, Menan F. Acoustic emission energy as a fatigue damage parameter for CFRP composites. *International Journal of Fatigue*. 2007;29:457-70.
- [28] Suzuki M, Nakanishi H, Iwamoto M, Jinen E. Application of Static Fracture Mechanisms to Fatigue Fracture Behavior of Class A-SMC Composite. *Proc 4th Japan-US Conf on Composite Materials* 1988. p. pp. 297-306.
- [29] deGroot PJ, Wijnen PAM, Janssen RBF. Real-time frequency determination of acoustic emission for different fracture mechanisms in carbon epoxy composites. *Composites Science and Technology*. 1995;55:405-12.
- [30] Ramirez-Jimenez CR, Papadakis N, Reynolds N, Gan TH, Purnell P, Pharaoh M. Identification of failure modes in glass/polypropylene composites by means of the primary frequency content of the acoustic emission event. *Composites Science and Technology*. 2004;64:1819-27.
- [31] Ni QQ, Kurashiki K, Iwamoto M. AE technique for identification of micro failure modes in CFRP composites. *Materials Science Research International*. 2001;7:67-71.
- [32] Bohse J. Acoustic emission characteristics of micro-failure processes in polymer blends and composites. *Composites Science and Technology*. 2000;60:1213-26.
- [33] Giordano M, Condelli L, Nicolais L. Acoustic emission wave propagation in a viscoelastic plate. *Composites Science and Technology*. 1999;59:1735-43.
- [34] Gutkin R, Green CJ, Vangrattanachai S, Pinho ST, Robinson P, Curtis PT. On acoustic emission for failure investigation in CFRP: Pattern recognition and peak frequency analyses. *Mechanical Systems and Signal Processing*. 2011;25:1393-407.
- [35] Arumugam V, Kumar CS, Santulli C, Sarasini E, Stanley AJ. A Global Method for the Identification of Failure Modes in Fiberglass Using Acoustic Emission. *Journal of Testing and Evaluation*. 2011;39:954-66.
- [36] Loutas TH, Kostopoulios V, Ramirez-Jimenez C, Pharaoh M. Damage evolution in center-holed glass/polyester composites under quasi-static loading using time/frequency analysis of acoustic emission monitored waveforms. *Composites Science and Technology*. 2006;66:1366-75.
- [37] Sause MGR, Muller T, Horoschenkoff A, Horn S. Quantification of failure mechanisms in mode-I loading of fiber reinforced plastics utilizing acoustic emission analysis. *Composites Science and Technology*. 2012;72:167-74.

- [38] Yousefi J, Ahmadi M, Shahri MN, Oskouei AR, Moghadas FJ. Damage Categorization of Glass/Epoxy Composite Material Under Mode II Delamination Using Acoustic Emission Data: A Clustering Approach to Elucidate Wavelet Transformation Analysis. *Arabian Journal for Science and Engineering*. 2014;39:1325-35.
- [39] Ni QQ, Iwamoto M. Wavelet transform of acoustic emission signals in failure of model composites. *Engineering Fracture Mechanics*. 2002;69:717-28.
- [40] Skal'skii VR, Stankevich EM, Matviiv YY. A study of the features of the macrofracturing of composite materials. *Russian Journal of Nondestructive Testing*. 2013;49:562-71.
- [41] Marec A, Thomas JH, El Guerjouma R. Damage characterization of polymer-based composite materials: Multivariable analysis and wavelet transform for clustering acoustic emission data. *Mechanical Systems and Signal Processing*. 2008;22:1441-64.
- [42] Kempf M, Skrabala O, Altstaedt V. Acoustic emission analysis for characterisation of damage mechanisms in fibre reinforced thermosetting polyurethane and epoxy. *Composites Part B-Engineering*. 2014;56:477-83.
- [43] Godin N, Huguet S, Gaertner R. Integration of the Kohonen's self-organising map and k-means algorithm for the segmentation of the AE data collected during tensile tests on cross-ply composites. *Ndt & E International*. 2005;38:299-309.
- [44] Waller JM, Nichols CT, Wentzel DJ, Saulsberry RL. USE OF MODAL ACOUSTIC EMISSION TO MONITOR DAMAGE PROGRESSION IN CARBON FIBER/EPOXY COMPOSITES. 37th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE). San Diego, CA: Amer Inst Physics; 2010. p. 919-26.
- [45] Mandell JF, Samborsky DD. SNL/MSU/DOE Composite Materials Fatigue Database Version 23.0. 2014.
- [46] Hsu NN, Breckenridge FR. CHARACTERIZATION AND CALIBRATION OF ACOUSTIC-EMISSION SENSORS. *Materials Evaluation*. 1981;39:60-8.
- [47] Gorman MR. ACOUSTIC-EMISSION IN 2-D CARBON-CARBON COUPONS IN TENSION. *Journal of Composite Materials*. 1991;25:703-14.
- [48] Minak G, Zucchelli A. Damage Evaluation and Residual Strength Prediction of CFRP Laminates by Means of Acoustic Emission Techniques. In: Durand LP, editor. *Composite Materials Research Progress*: Nova Science Pub Inc; 2008. p. 307.

APPENDICES

APPENDIX A

PLATE AND COUPON DATA

Acoustic Emission Plate Layups					
Plates:	Plate #	Material	Layup	Warp (in)	Weft (in)
1	2390	PPG1250	[0]4	30	20
2	2395	ELT5500	[0]2	30	20
3	2393	BX0900-10	[45's]4	20	20
4	2399	CLA2012	[0]2	30	20
5	2388	PPG1250	[90/0]s	20	20
6	2401	ELT5500	[90/0]s	20	20
7	2404	CLA2012	[90/0]s	20	20

All data available on the locally accessible MSU CRG server.

Plate #	Coupon Layup	Coupon Thick	Coupon Width	Load Scheme	Failure Load	Wave Velocity	Failure Strain	Total Energy	Total Events
Coupon #	[90/0]s	mm	mm	STATIC	kN	mm/s	%	aJ	#

2388	Layup	Thick	Width	Scheme	Load	Velocity	Strain	Energy	Events
1	[90/0]s	3.52	30.00	STATIC	52.2	NA			
2	[90/0]s	3.36	28.95	STATIC	52.3	3677884	2.423	7.49E+08	7995
3	[90/0]s	3.44	29.61	STATIC	51.1	3743892	2.206	7.85E+08	4738
4	[90/0]s	3.45	29.46	STATIC	52.6	3660370	2.482	2.80E+08	5043
5	[90/0]s	3.37	29.85	LUR					
6	[90/0]s	3.45	28.72	LUR					
7	[90/0]s	3.45	29.29	LUR	50.1	3655960	2.595	4.30E+08	2893
8	[90/0]s	3.45	29.68	LUR	56.1	3683777	2.367	1.19E+09	3997
9	[90/0]s	3.42	29.40	LUR	53.9		2.07	1.26E+09	4339
10	[90/0]s	3.43	29.89	EXTRA					
11	[90/0]s	3.42	29.75	EXTRA					
12	[90/0]s	3.53	28.60	EXTRA					
13	[90/0]s	3.46	30.76	EXTRA					

2390	Layup	Thick	Width	Scheme	Load	Velocity	Strain	Energy	Events
1	[0]4	3.46	29.73	STATIC	89.16	4702947	UNK	1.37E+08	2601
2	[0]4	3.53	30.50	STATIC	89.14	4571713	UNK	7.62E+06	635
3	[0]4	3.41	29.47	STATIC	84.83	4599216	UNK	2.97E+08	6057
4	[0]4	3.44	29.50	STATIC	89.12	4491623	2.30	1.03E+08	2758
5	[0]4	3.39	29.42	LUR	#REF!	NA	NA	NA	NA
6	[0]4	3.40	28.57	LUR	85.78	4553571	UNK	2.79E+08	4019
7	[0]4	3.44	31.07	LUR	94.35	4571785	UNK	6.63E+07	2018
8	[0]4	3.46	28.22	LUR	85.89		UNK	3.50E+08	3932
9	[0]4	3.39	29.95	EXTRA					
10	[0]4	3.46	29.88	EXTRA					
11	[0]4	3.35	29.49	EXTRA					
12	[0]4	3.39	29.09	EXTRA					
13	[0]4	3.43	29.77	EXTRA					
14	[0]4	3.47	28.57	EXTRA					
15	[90]4	3.33	29.41	STATIC	NA	NA	NA	NA	NA
16	[90]4	3.50	30.20	STATIC	4.92	2854495	0.38	4.38E+08	613
17	[90]4	3.52	28.98	STATIC		2845499			
18	[90]4	3.48	29.54	STATIC	4.85	2765076	0.59	3.25E+08	637
19	[90]4	3.52	29.75	LUR	5.54	2522916	1.20	8.24E+08	1065
20	[90]4	3.41	29.48	LUR	5.47	2819478	1.14	1.08E+09	2186
21	[90]4	3.53	30.08	LUR	5.84	2847394	UNK	2.34E+09	4798
22	[90]4	3.41	29.70	STATIC		2749169			
23	[90]4	3.22	29.33	NA	NA	NA	NA	NA	NA
24	[90]4	3.46	29.20	STATIC	4.85	2879661	0.65	6.53E+08	673
25	[90]4	3.46	29.57	STATIC	5.74	2861595	1.21	5.21E+08	639
26	[90]4	3.56	29.96	STATIC	5.54	2840364	1.53	3.52E+08	840

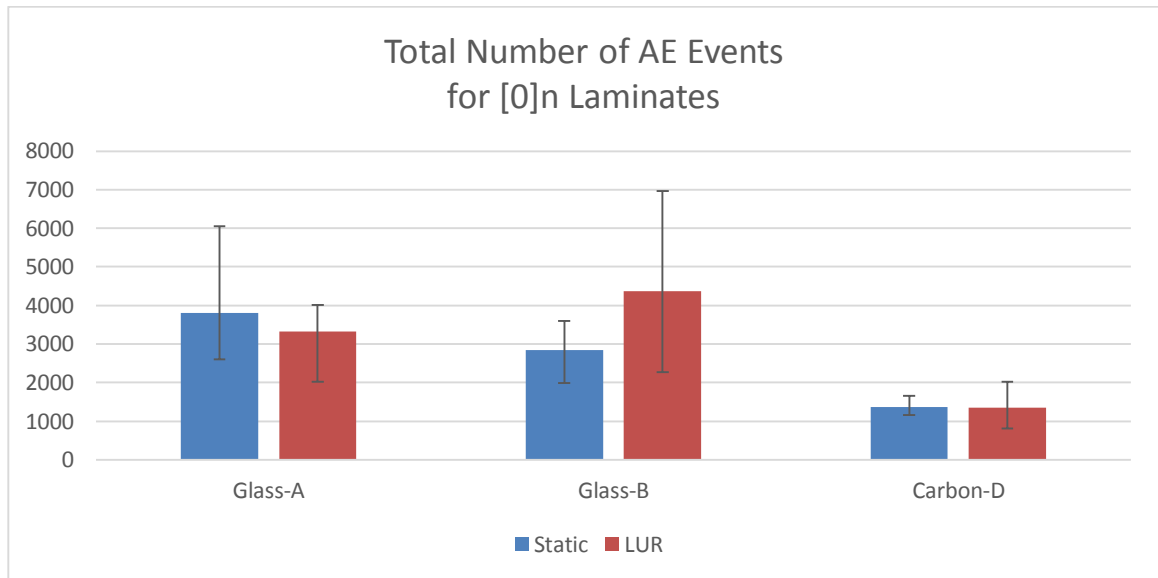
2393	Layup	Thick	Width	Scheme	Load	Velocity	Strain	Energy	Events
1	[45's]4	1.64	29.45	STATIC	3.59	2233031	12		
2	[45's]4	1.55	28.87	STATIC	4.5	2596167	17	6.26E+06	2646
3	[45's]4	1.6	29.67	STATIC	4.93	2193660	21	3.48E+07	10083
4	[45's]4	1.64	29.55	STATIC	4.99	2362433	19	5.50E+07	12514
5	[45's]4	1.63	29.63	LUR	5.44	2460763	21	5.48E+07	11978
6	[45's]4	1.61	28.73	LUR	5.15	2305851	20	1.12E+08	12688
7	[45's]4	1.59	30.08	LUR	5.42	2270349	18	1.25E+08	10863
8	[45's]4	1.63	28.73	LUR	4.89	2470744	23	8.34E+07	19088
9	[45's]4	1.55	30.45	EXTRA					
10	[45's]4	1.61	29.13	EXTRA					
11	[45's]4	1.61	30.05	EXTRA					
12	[45's]4	1.63	28.72	EXTRA					
13	[45's]4	1.62	29.91	EXTRA					
14	[45's]4	1.61	28.57	EXTRA					
15	[45's]4	1.7	30.15	EXTRA					

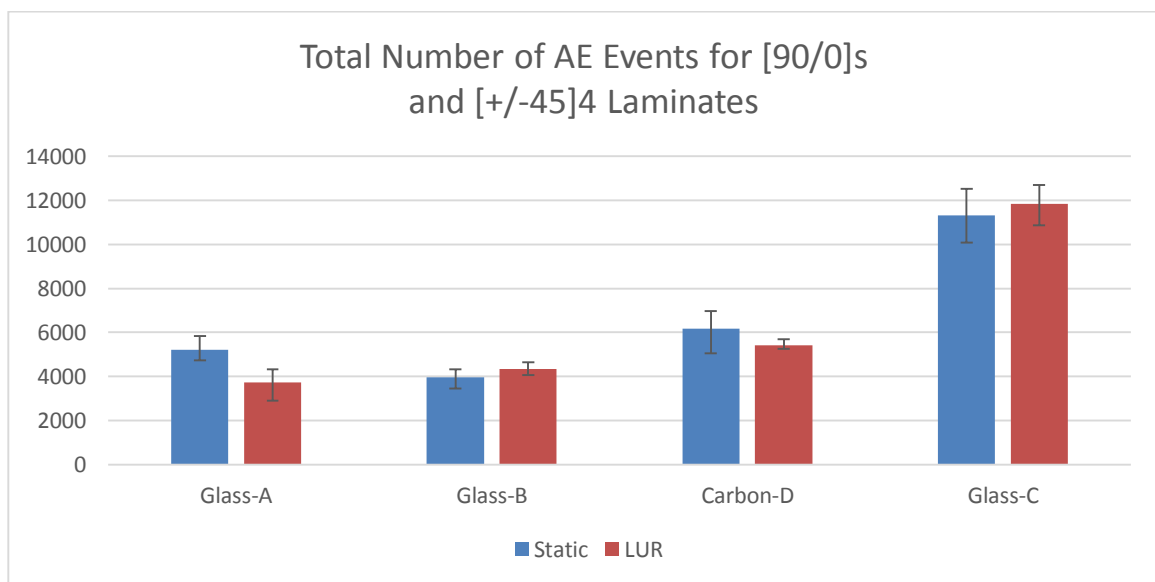
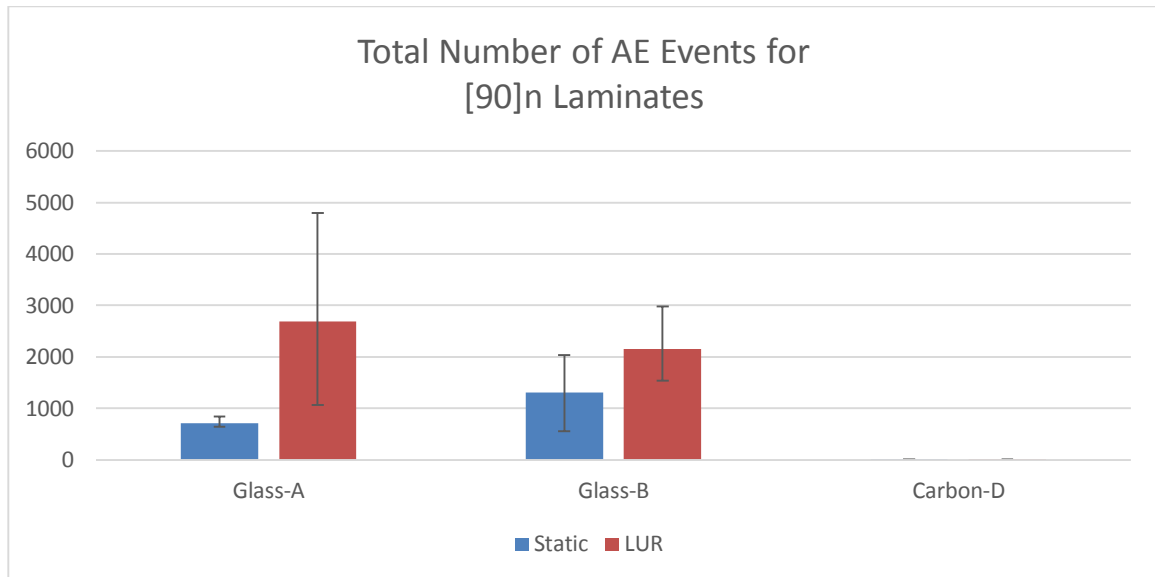
2395	Layup	Thick	Width	Scheme	Load	Velocity	Strain	Energy	Events
1	[0]4	2.63	28.79	STATIC	63.5	4553710	2.096	2.62E+08	2960
2	[0]4	2.61	29.37	STATIC	65.3	4433805	UNK	2.68E+08	1983
3	[0]4	2.62	30.13	STATIC	72.1	4544572	UNK	3.49E+08	3594
4	[0]4			BAD					
5	[0]4			BAD					
6	[0]4			BAD					
7	[0]4			BAD					
8	[0]4	2.66	31.27	STATIC					
9	[0]4	2.53	29.91	LUR	67.1	4571713	2.3475	4.16E+08	2264
10	[0]4	2.63	29.63	LUR	67.0	4487907	UNK	7.63E+08	3884
11	[0]4	2.58	29.92	LUR	66.3	4512268	UNK	1.25E+09	6960
12	[0]4	2.6	29.51	LUR					
13	[90]4	2.62	29.3	STATIC	3.9	2446739	0.7288	1.49E+09	555
14	[90]4	2.64	31.37	STATIC	4.4	2748490	1.2549	1.83E+09	1330
15	[90]4	2.63	29.42	STATIC	3.7	2712765	0.4334	7.30E+08	323
16	[90]4	2.65	28.06	STATIC	4.5	2843905	1.9446	6.94E+08	2034
17	[90]4	2.64	29.15	LUR	4.2	2631382	2.1229	1.77E+09	1945
18	[90]4	2.55	28.85	LUR	4.9	2690596	1.2256	8.56E+08	1939
19	[90]4	2.63	28.96	LUR	4.2	2798797	UNK	1.30E+09	2985
20	[90]4	2.6	29.83	LUR	4.2	2691129	UNK	1.96E+09	1540

2399	Layup	Thick	Width	Scheme	Load	Velocity	Strain	Energy	Events
1	[0]2	1.97	30.07	TENSILE	81.0	6934104	1.72	1.06E+08	1321
2	[0]2	1.91	29.2	TENSILE	58.4	6447443	UNK	3.75E+08	1651
3	[0]2	1.95	29.68	TENSILE	59.8		UNK	9.14E+07	1153
4	[0]2	1.95	29.35	TENSILE	66.3	6305706	UNK	2.18E+05	242
5	[0]2	1.89	28.76	LUR	69.0	6507735	UNK	3.75E+06	812
6	[0]2	1.89	29.32	LUR	74.3	6203427	UNK	6.67E+06	1203
7	[0]2	1.95	29.23	LUR	64.1	6609101	UNK	3.34E+08	2028
8	[0]2	1.94	29.92	LUR					
9	[0]2	1.91	29.96	EXTRA					
10	[0]2	1.82	29.63	EXTRA					
11	[0]2	1.9	29.52	EXTRA					
12	[0]2	1.95	29.15	EXTRA					
13	[0]2	1.91	29.39	EXTRA					
14	[0]2	1.96	30.74	EXTRA					
15	[90]2	1.88	28.53	TENSILE	2.1	1871946	0.69	5.71E+07	1
16	[90]2	1.98	28.44	TENSILE	2.1	1813086	0.69		
17	[90]2	1.93	28.41	TENSILE	2.2	1874999	0.73	7.15E+07	1
18	[90]2	1.98	32.15	BAD					
19	[90]2			BAD					
20	[90]2	1.88	29.81	LUR	2.1	1837527	0.62	1.21E+03	
21	[90]2	1.97	30.63	LUR	2.5	1949404	0.71	6.48E+07	4
22	[90]2	1.88	29.19	LUR	2.4	2030974	0.84	4.48E+02	
23	[90]2	1.94	28.94	LUR	2.1	2045513	0.69	6.30E+03	10
24	[90]2	1.92	29.67	TENSILE	2.1	1999280	0.69		
25	[90]2	1.92	30.21	TENSILE	1.8	1946010	0.54		
26	[90]2	1.93	29.76	TENSILE	2.1	1797314	0.59	9.95E+02	3
27	[90]2	1.85	29.98	TENSILE	1.9	1925388	0.59	6.20E+07	1

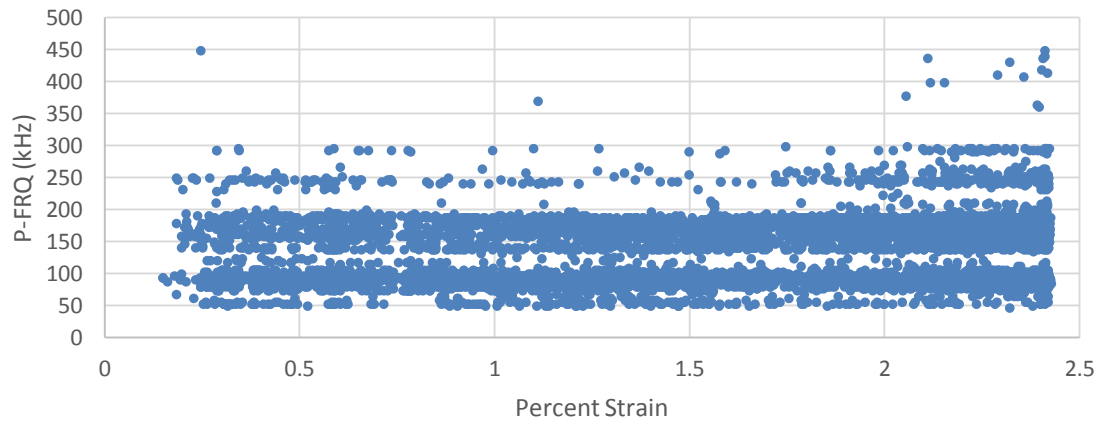
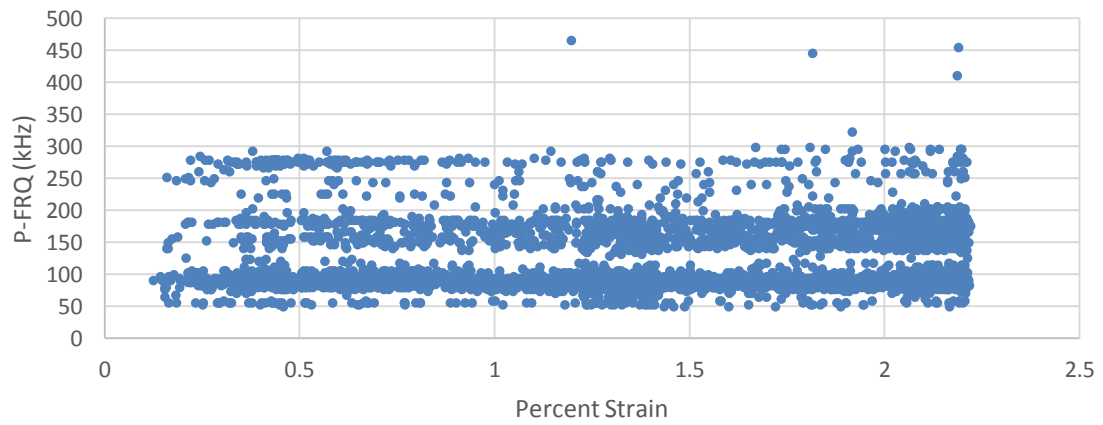
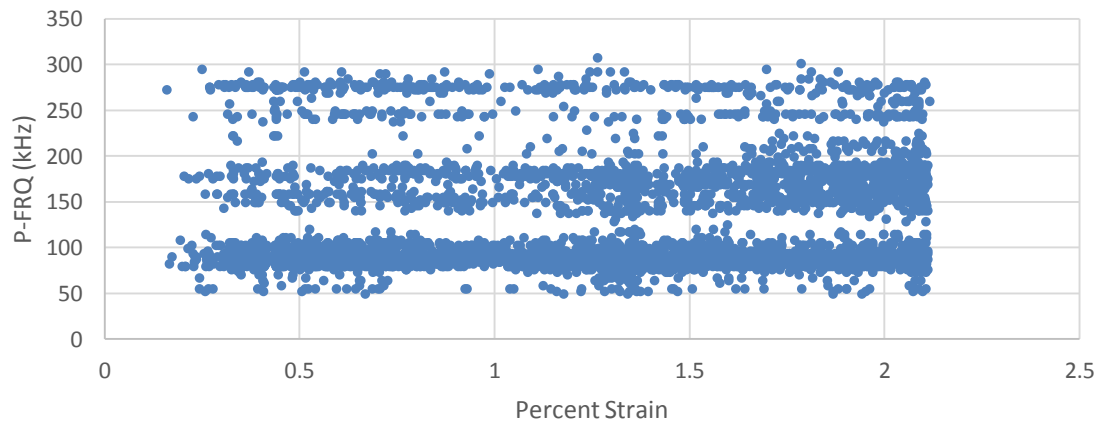
2401	Layup	Thick	Width	Scheme	Load	Velocity	Strain	Energy	Events
1	[90/0]s	5.00	29.13	STATIC	80.1	NA		NA	NA
2	[90/0]s	5.07	28.91	STATIC	75.3	3569215	2.29	1.22E+09	4332
3	[90/0]s	5.09	29.87	STATIC	85.4	3602905	2.50	1.35E+09	3463
4	[90/0]s	5.07	29.14	STATIC	NA	NA	NA	NA	NA
5	[90/0]s	5.00	29.83	STATIC	82.2	3608526	2.14	1.44E+09	3525
6	[90/0]s	4.98	29.64	LUR	88.9	3597178	2.85	2.25E+09	4300
7	[90/0]s	5.08	28.78	LUR	82.6	3541666	2.60	2.92E+09	4647
8	[90/0]s	5.03	29.43	LUR	88.6	3683797	2.60	2.45E+09	4071
9	[0/90]s	5.06	29.21	EXTRA					
10	[0/90]s	4.97	29.97	EXTRA					

2404	Layup	Thick	Width	Scheme	Load	Velocity	Strain	Energy	Events
1	[90/0]S	3.74	29.46	STATIC	70.5	NA		NA	NA
2	[90/0]S	3.71	28.95	STATIC	74.6	4281954	UNK	3.44E+09	6473
3	[90/0]S	3.77	30.21	STATIC	77.6	4249999	UNK	3.98E+09	6958
4	[90/0]S	3.69	29.46	STATIC	80.9	4290846	UNK	3.16E+09	5064
5	[90/0]S	3.4	29.6	LUR	74.7	4257889	1.36	3.43E+09	5269
6	[90/0]S	3.78	29.27	LUR	78.9	4346590	1.52	3.42E+09	5326
7	[90/0]S	3.73	29.96	LUR	73.6	4289754	1.39	4.03E+09	5692
8	[90/0]S	3.77	29.94	LUR					
9	[90/0]S	3.63	29.06	EXTRA					
10	[90/0]S	3.7	30.79	EXTRA					

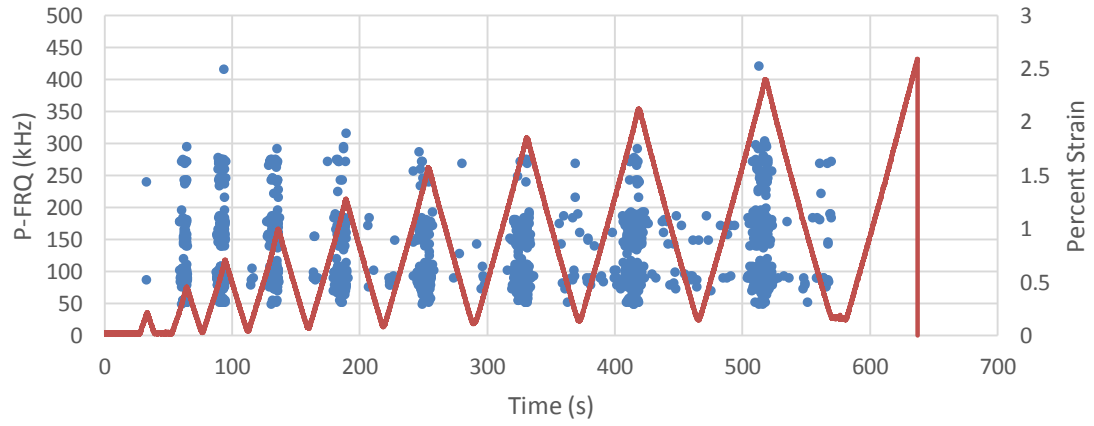




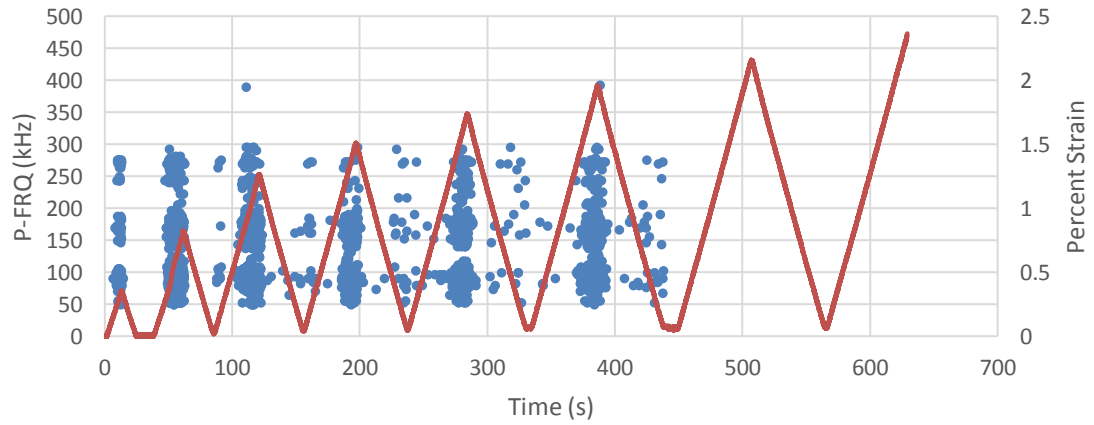
Hit Peak Frequency, 2388_2; Sensors Not Removed

Hit Peak Frequency, 2388_4; Sensors Removed 2.2% ϵ Hit Peak Frequency, 2388_4; Sensors Removed 2.1% ϵ 

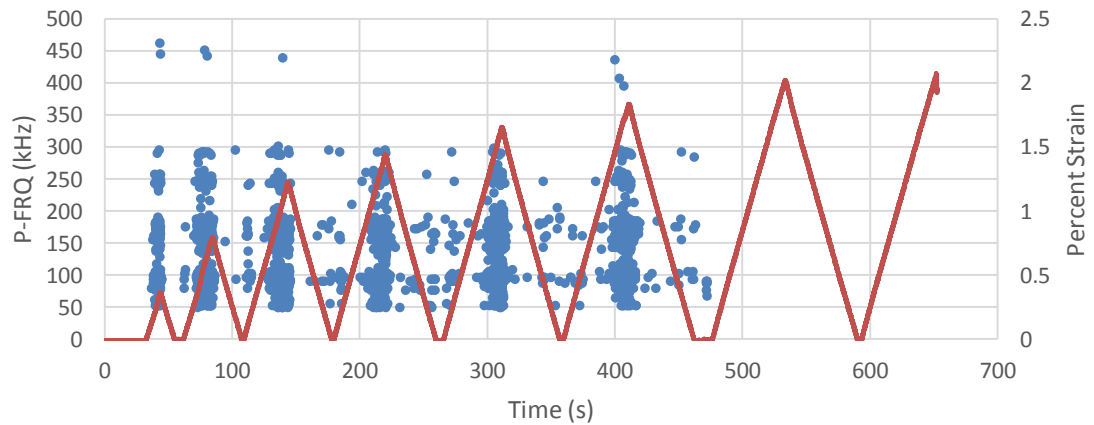
Hit Peak Frequency, 2388_7; Sensors Removed 90% LUR

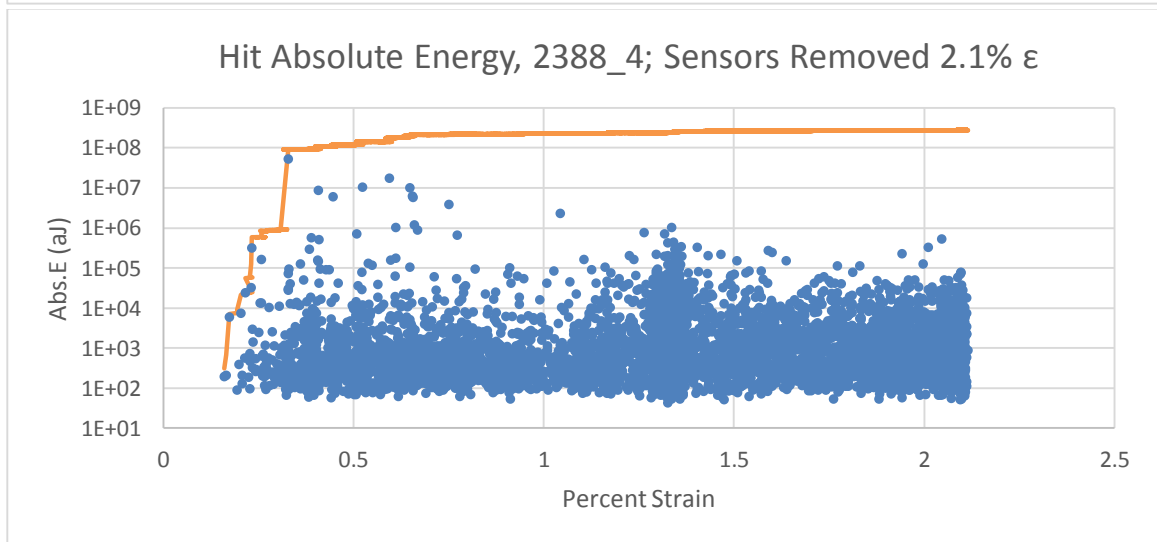
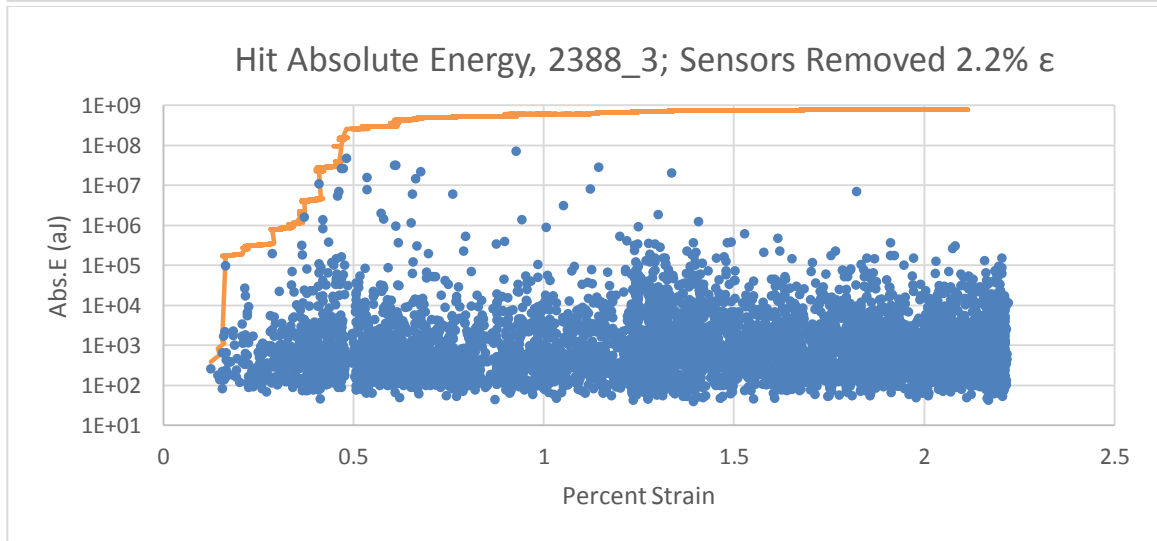
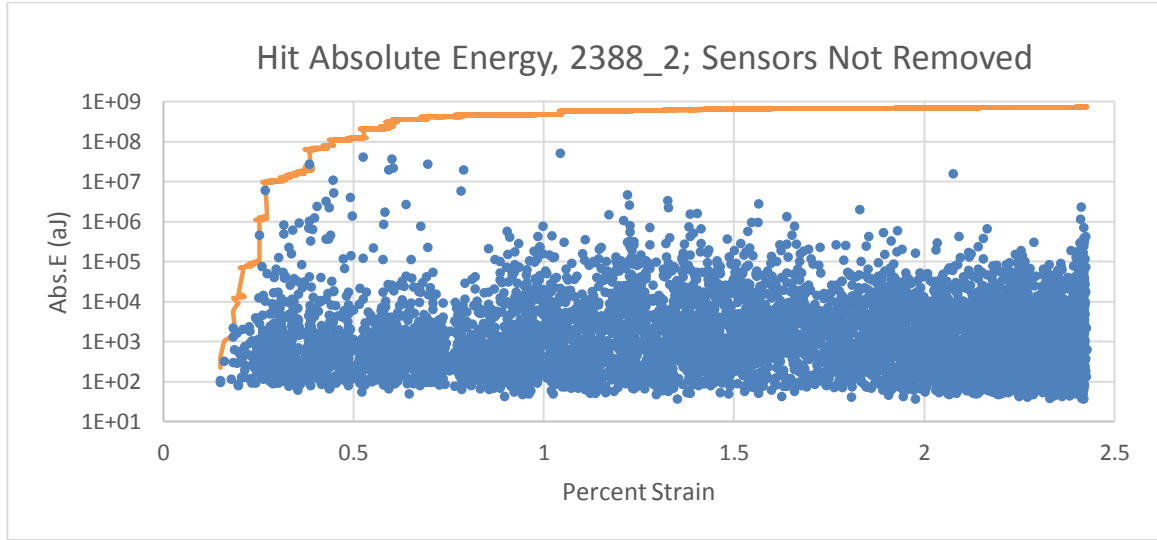


Hit Peak Frequency, 2388_8; Sensors Removed 90% LUR

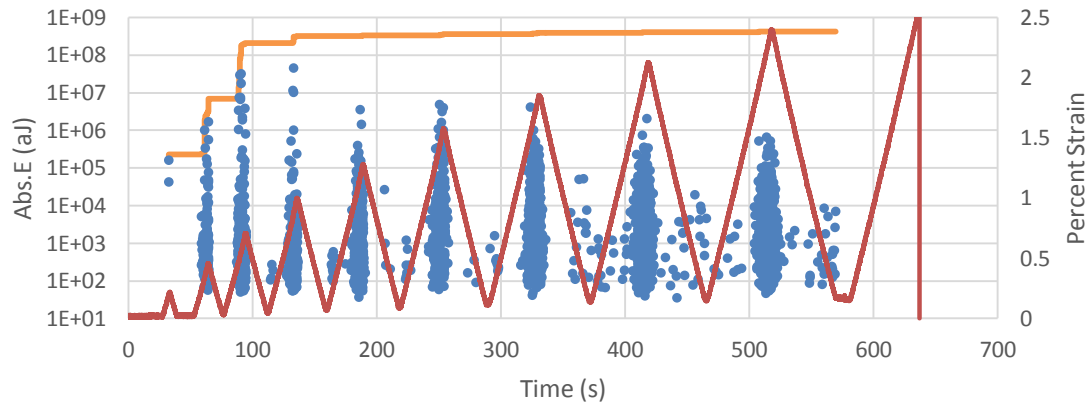


Hit Peak Frequency, 2388_9; Sensors Removed 90% LUR

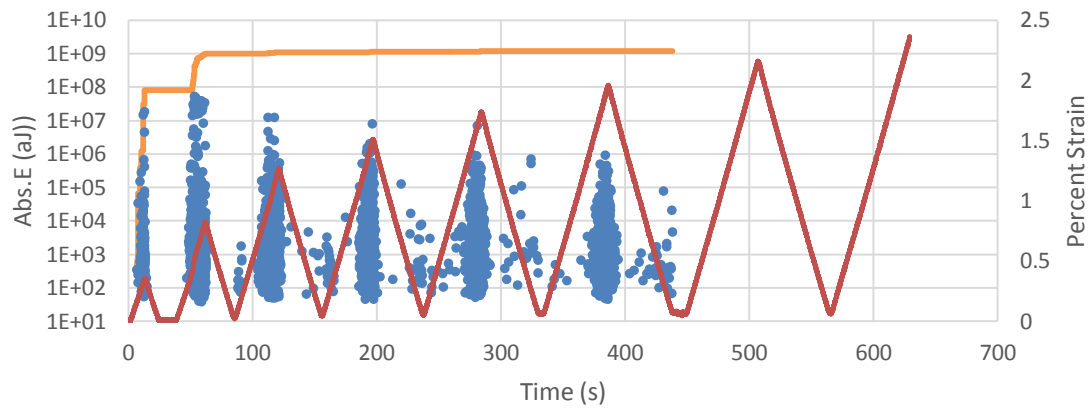




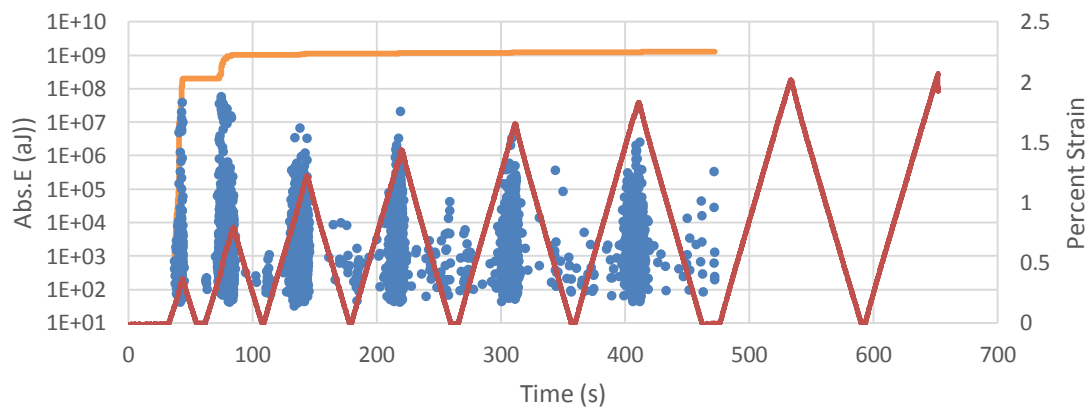
Hit Absolute Energy, 2388_7; Sensors Removed 90% LUR

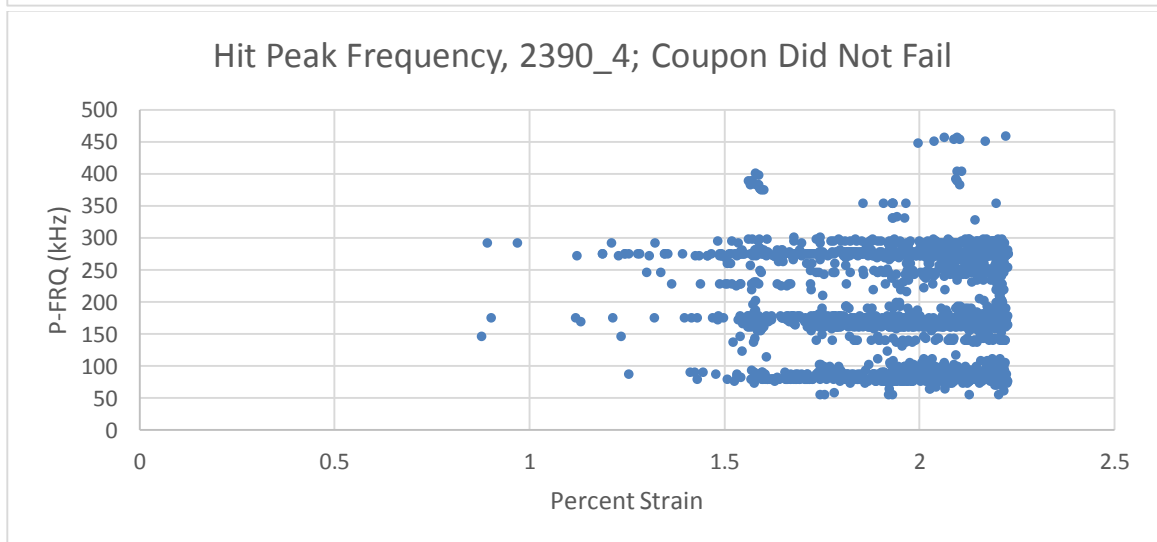
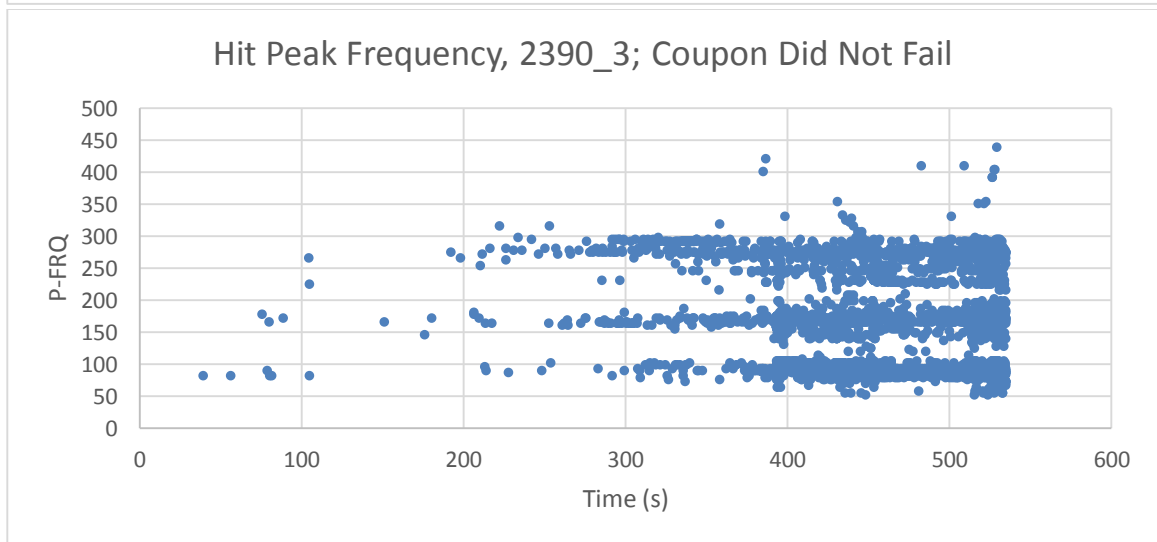
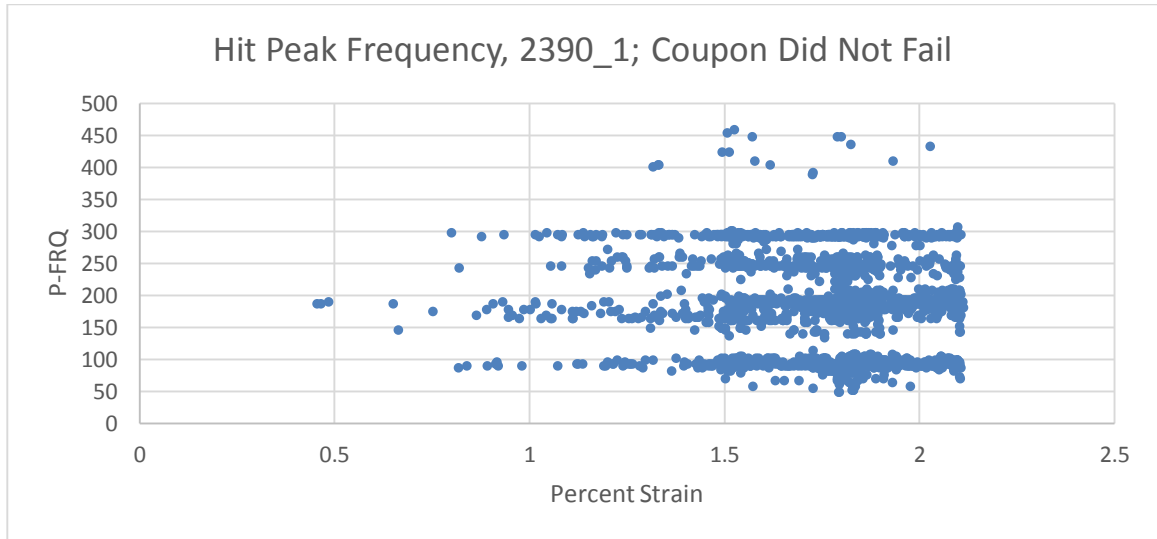


Hit Absolute Energy, 2388_8; Sensors Removed 90% LUR

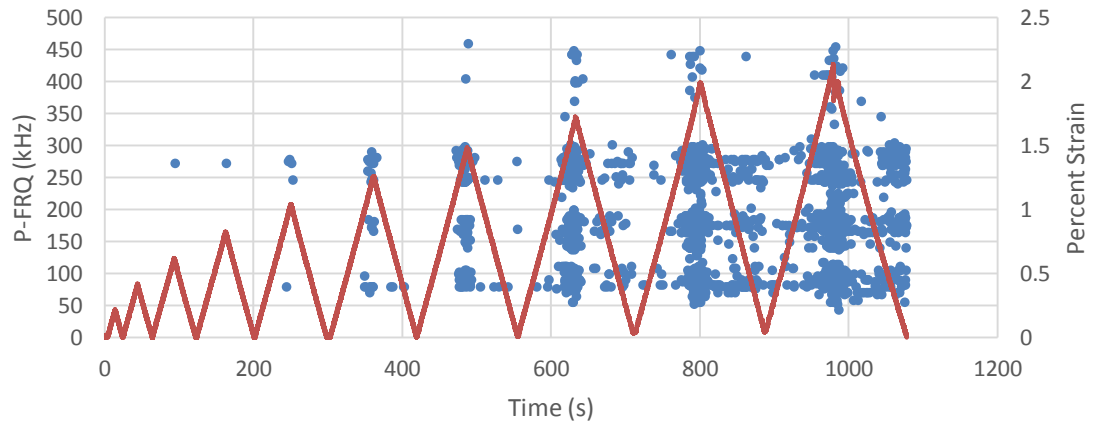


Hit Absolute Energy, 2388_9; Sensors Removed 90% LUR

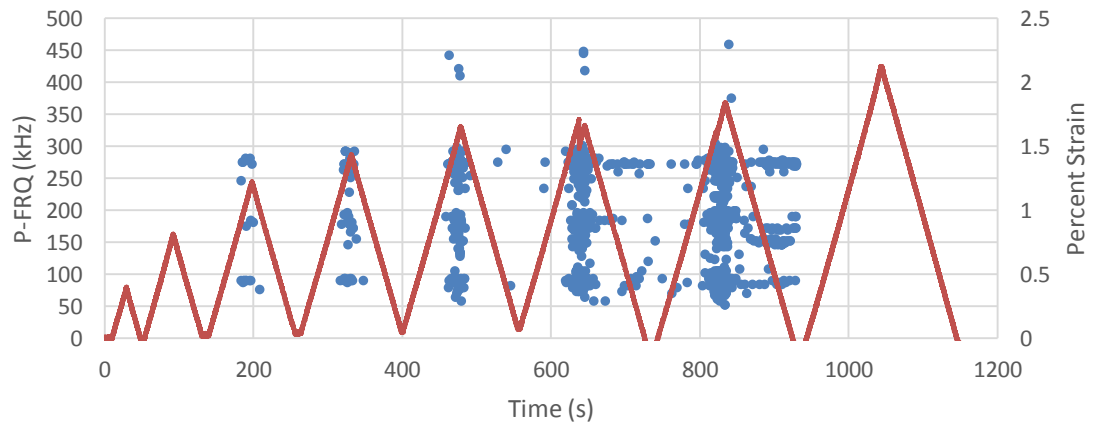




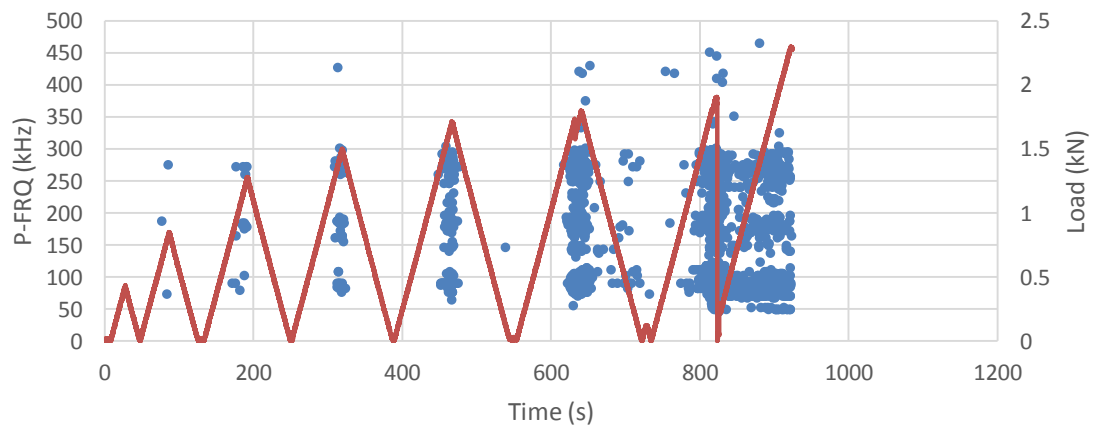
Hit Peak Frequency, 2390_6; Coupon Did Not Fail

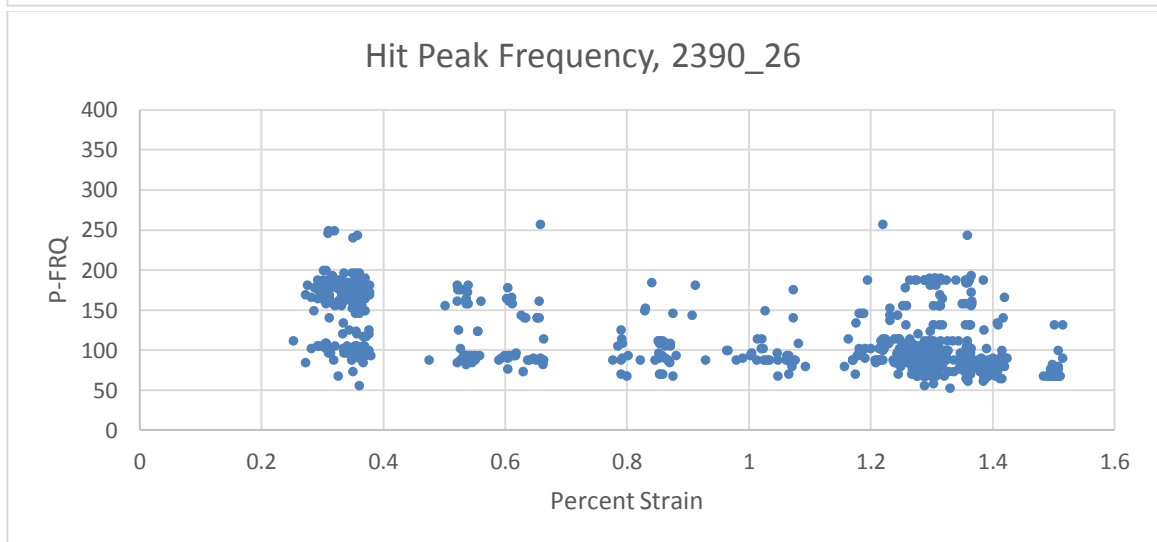
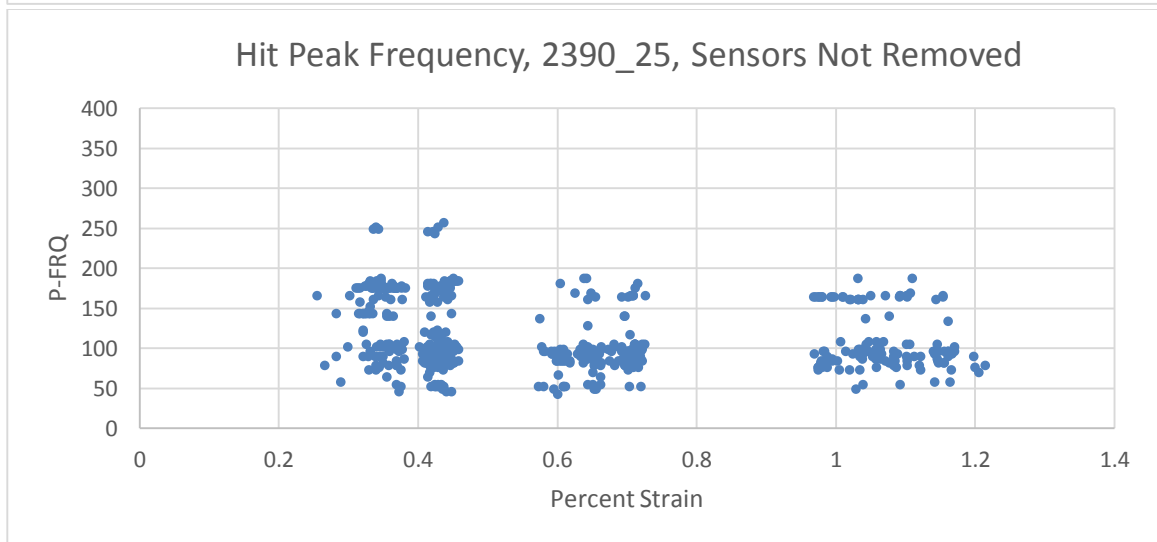
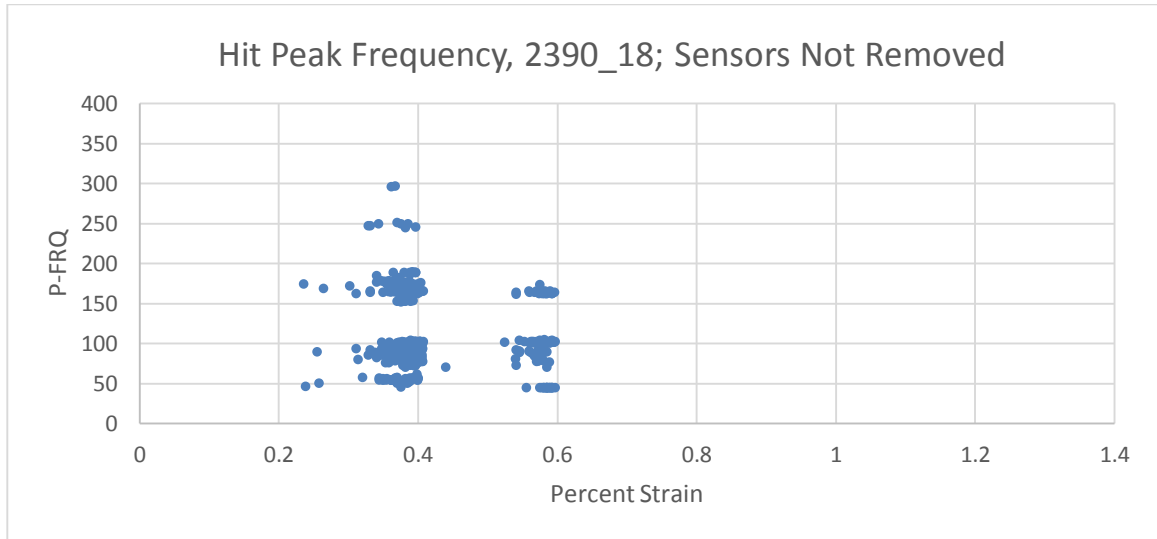


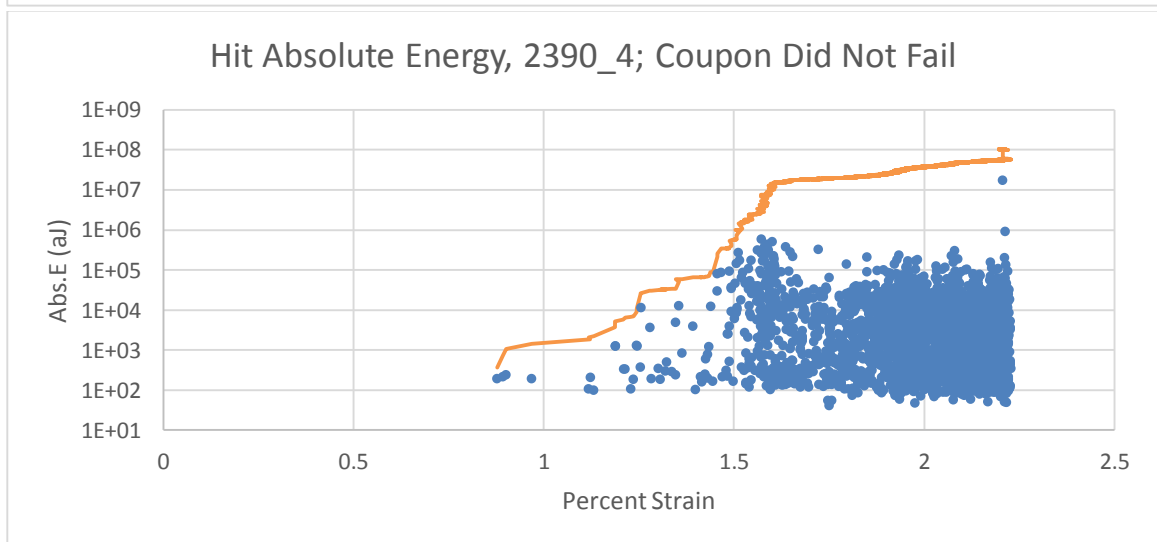
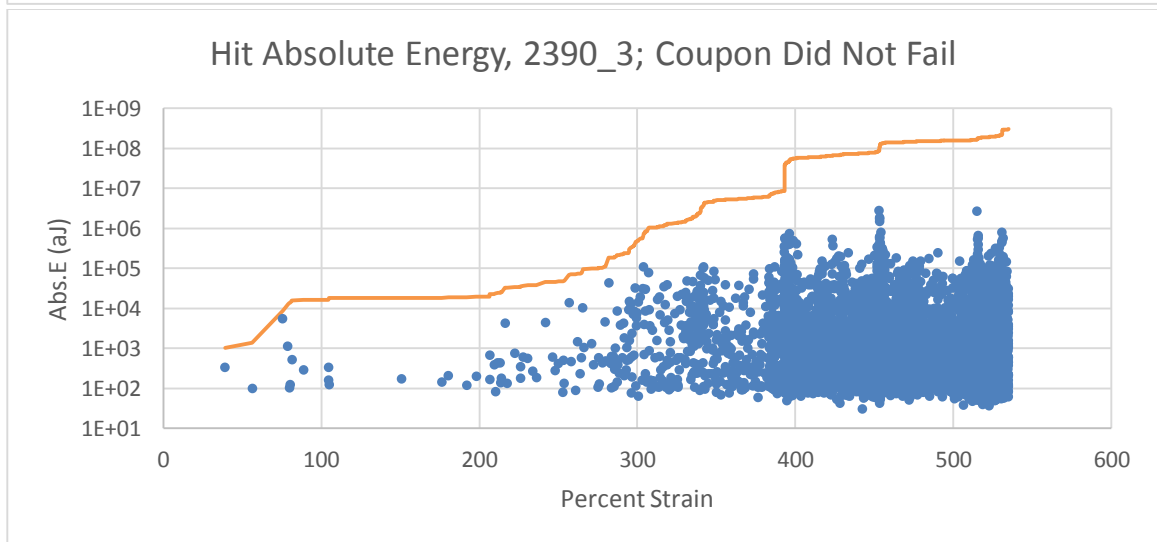
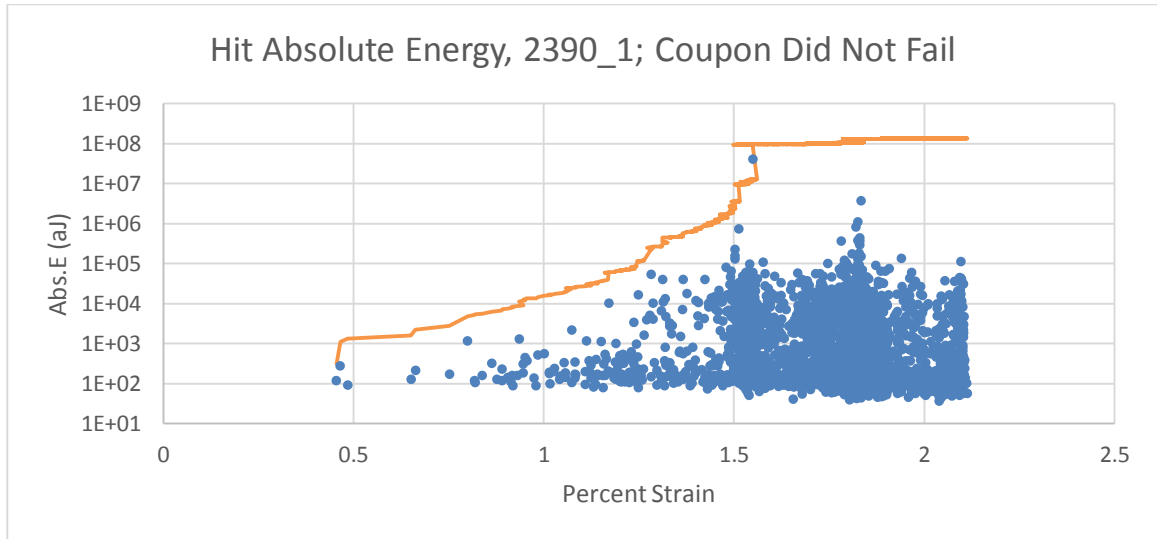
Hit Peak Frequency, 2390_7; Coupon Did Not Fail



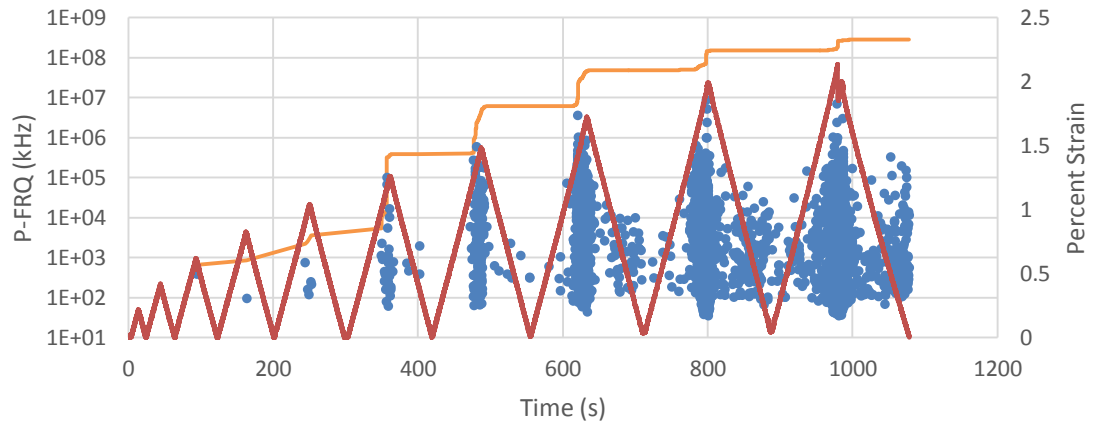
Hit Peak Frequency, 2390_8; Coupon Did Not Fail



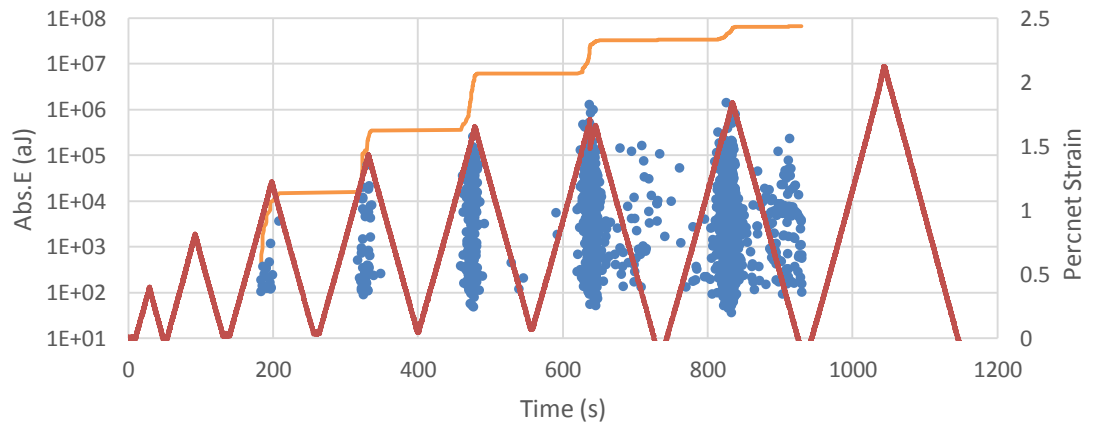




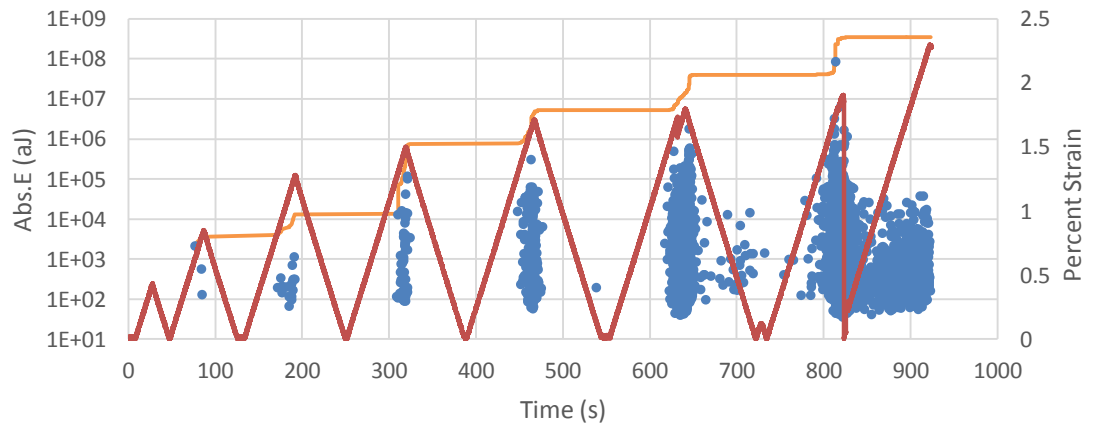
Hit Absolute Energy, 2390_6; Coupon Did Not Fail



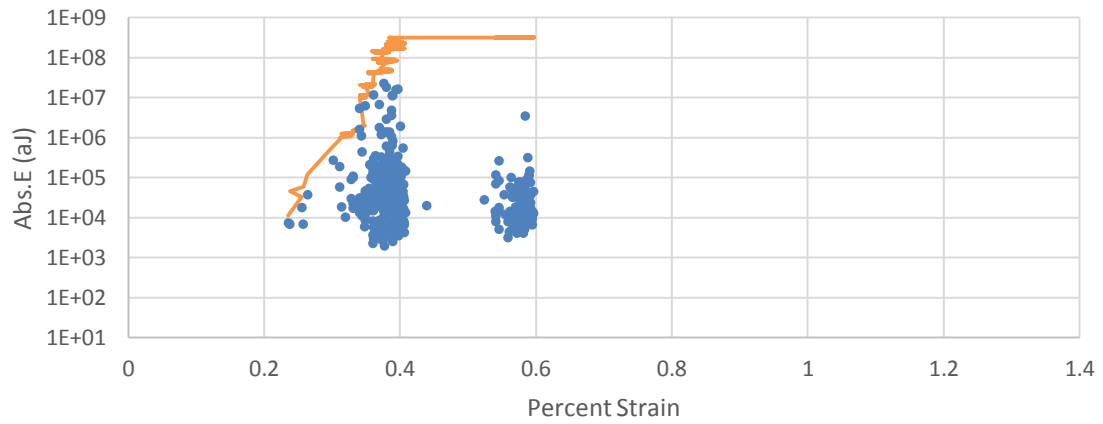
Hit Absolute Energy, 2390_7; Coupon Did Not Fail



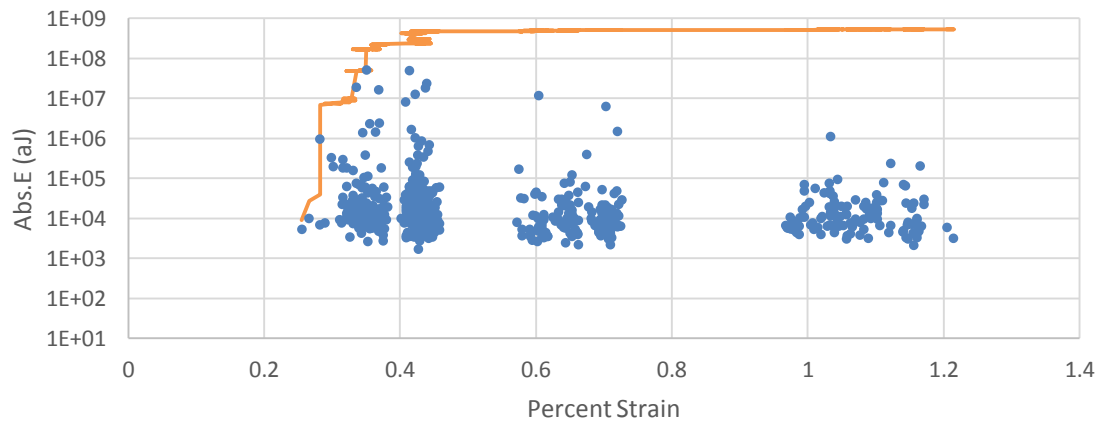
Hit Absolute Energy, 2390_8; Coupon Did Not Fail



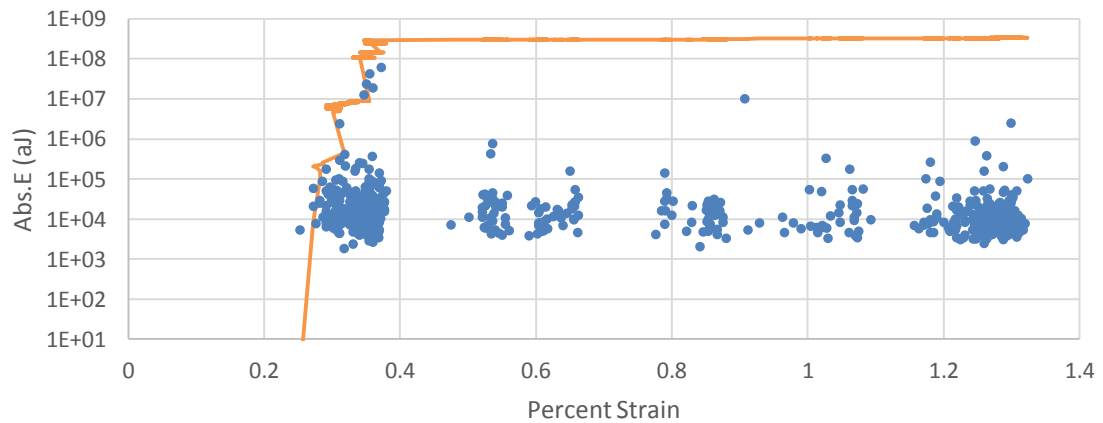
Hit Absolute Energy, 2390_18; Sensors Not Removed

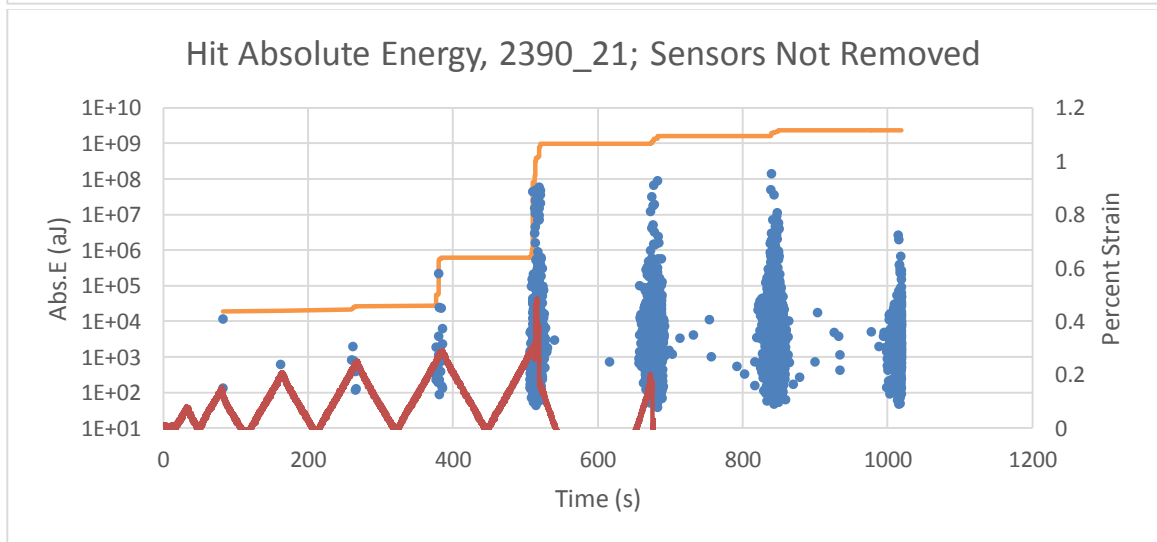
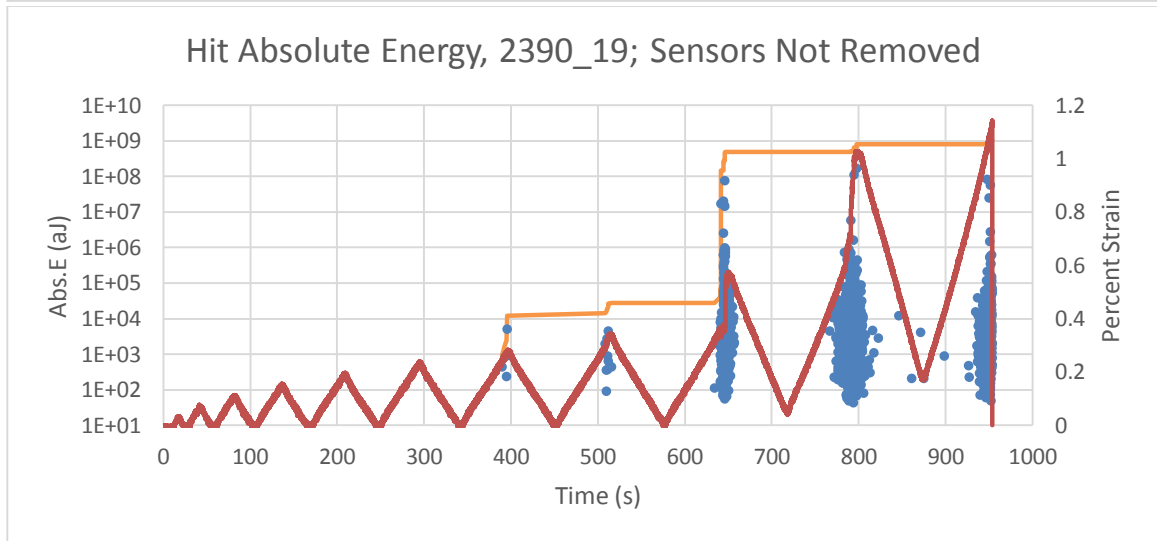
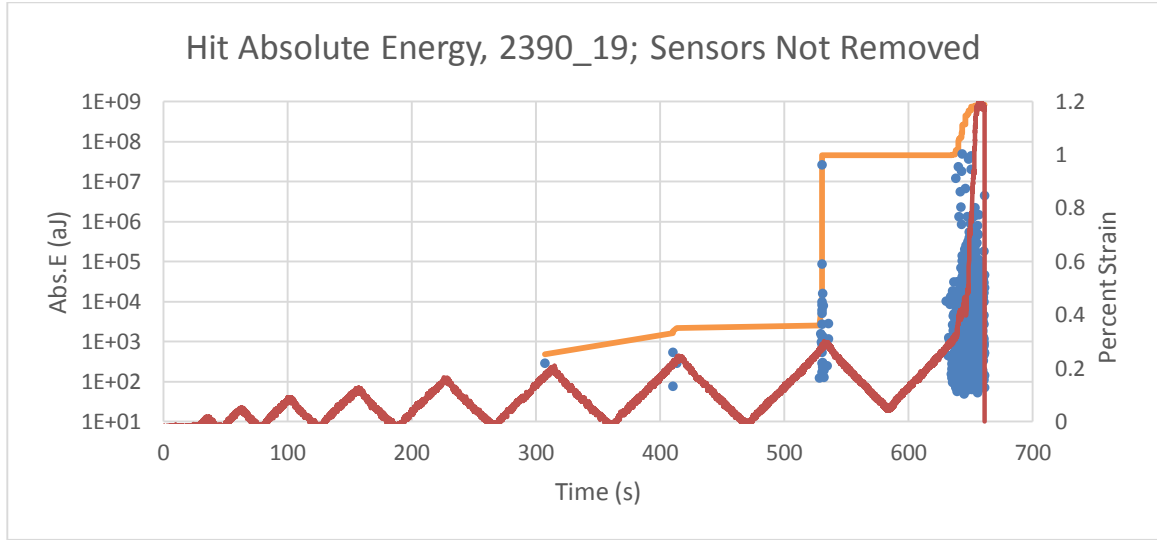


Hit Absolute Energy, 2390_25; Sensors Not Removed

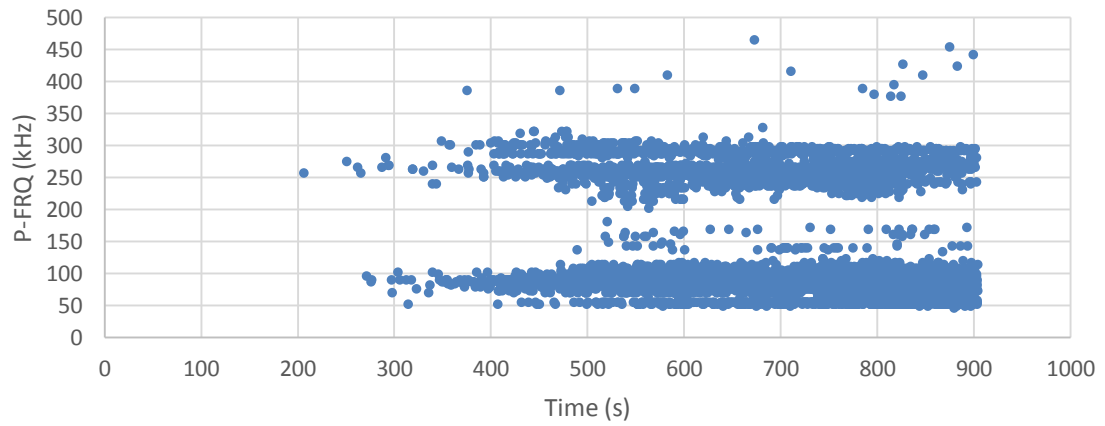


Hit Absolute Energy, 2390_26; Sensors Not Removed

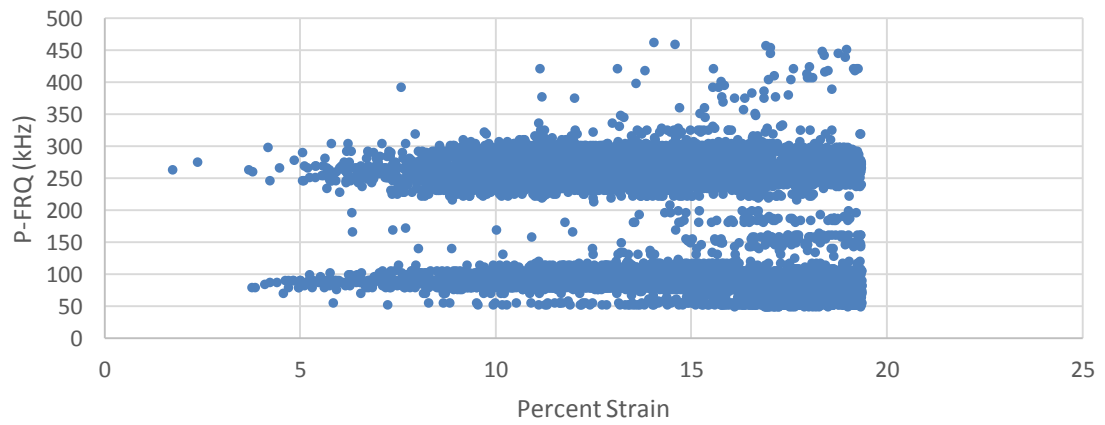




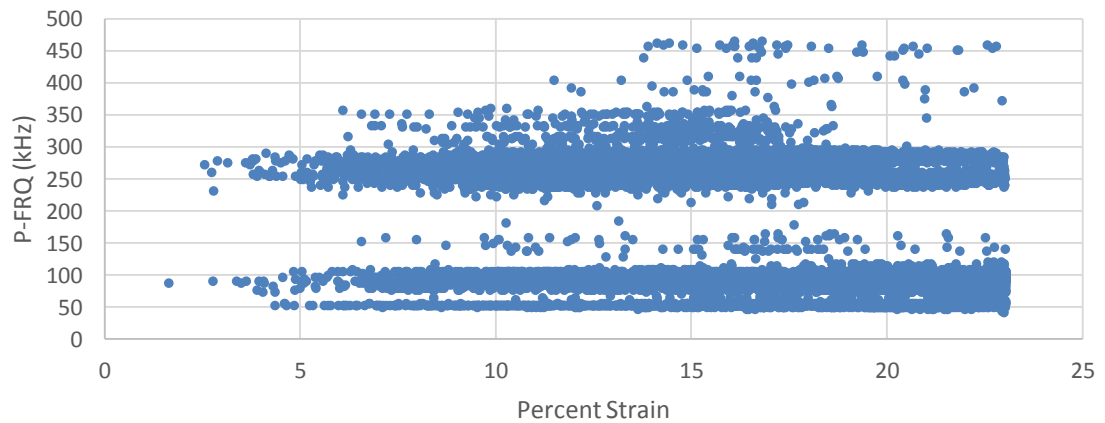
Hit Peak Frequency, 2393_3; Sensors Not Removed



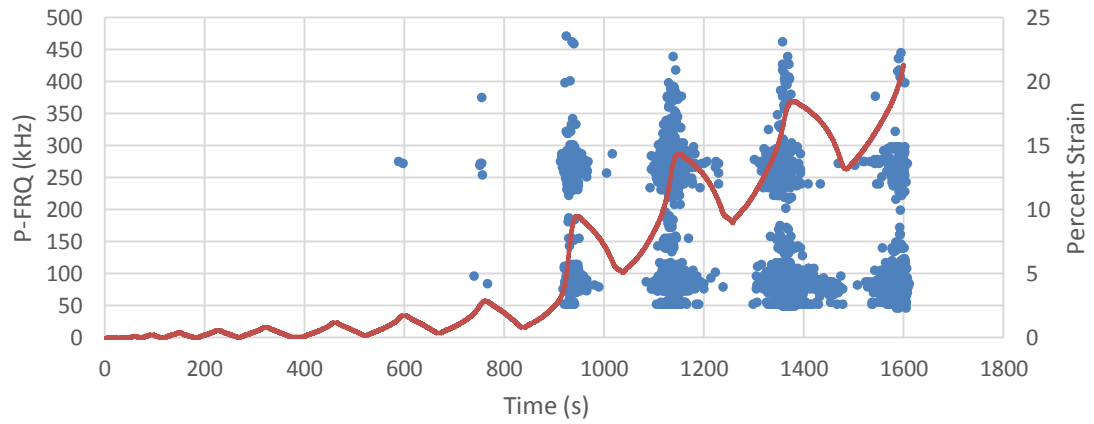
Hit Peak Frequency, 2393_4; Sensors Not Removed



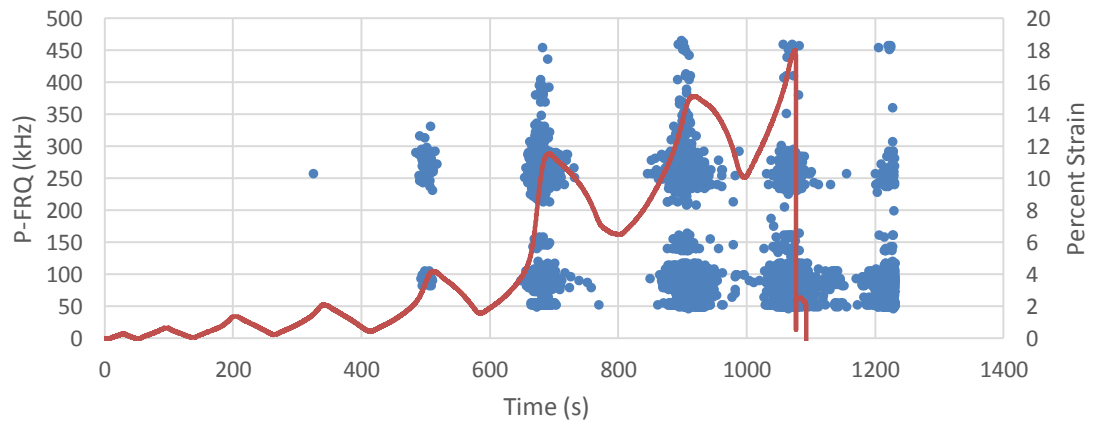
Hit Peak Frequency, 2393_8; Sensors Not Removed



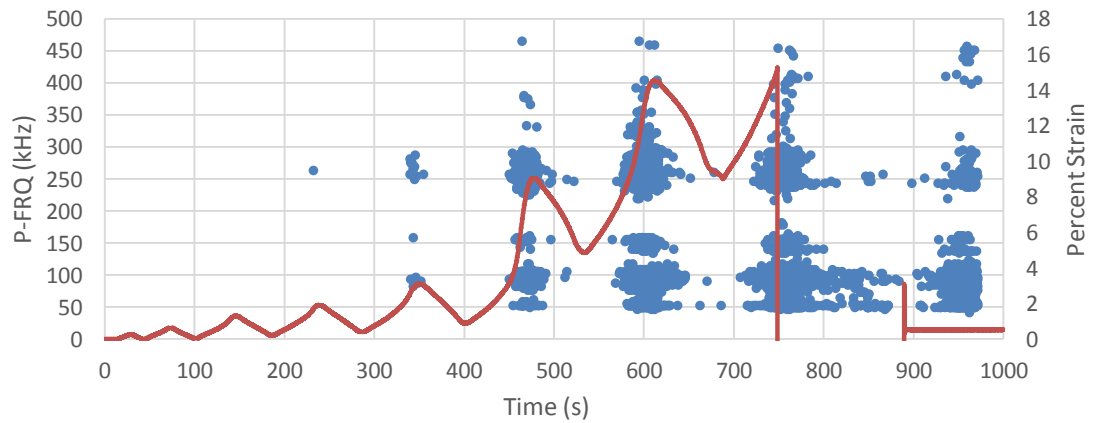
Hit Peak Frequency, 2393_5; Sensors Not Removed



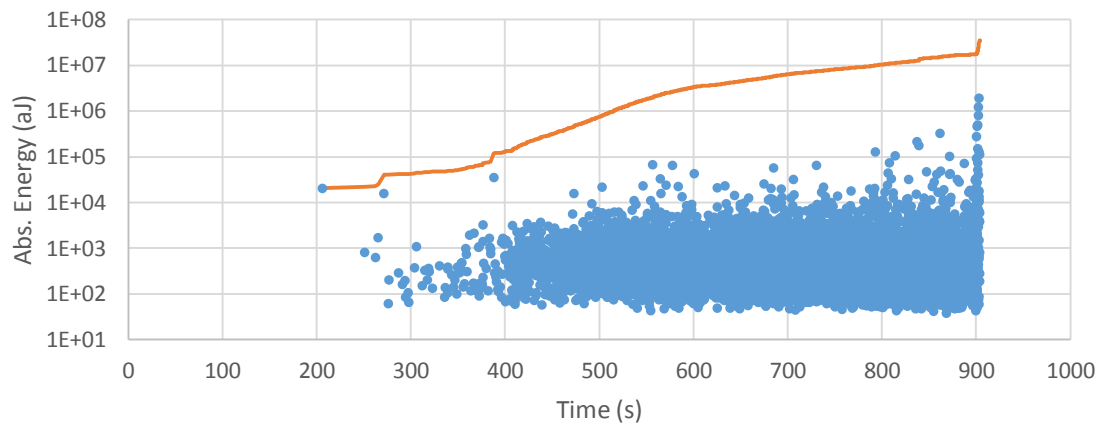
Hit Peak Frequency, 2393_6; Sensors Not Removed



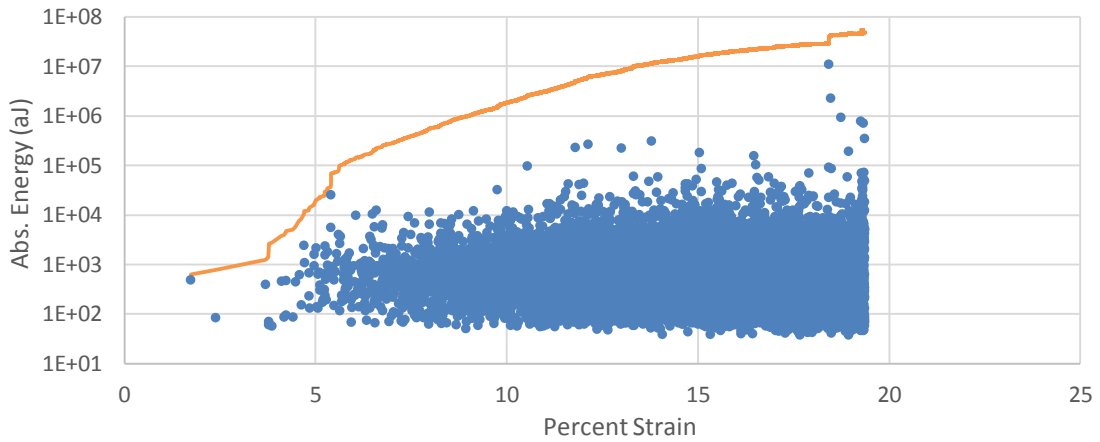
Hit Peak Frequency, 2393_7; Sensors Not Removed



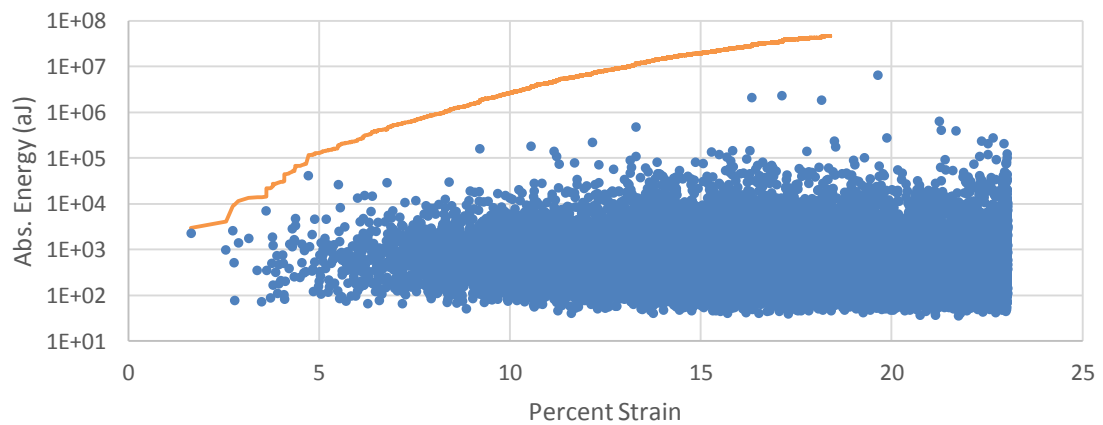
Hit Absolute Energy, 2393_3; Sensors Not Removed



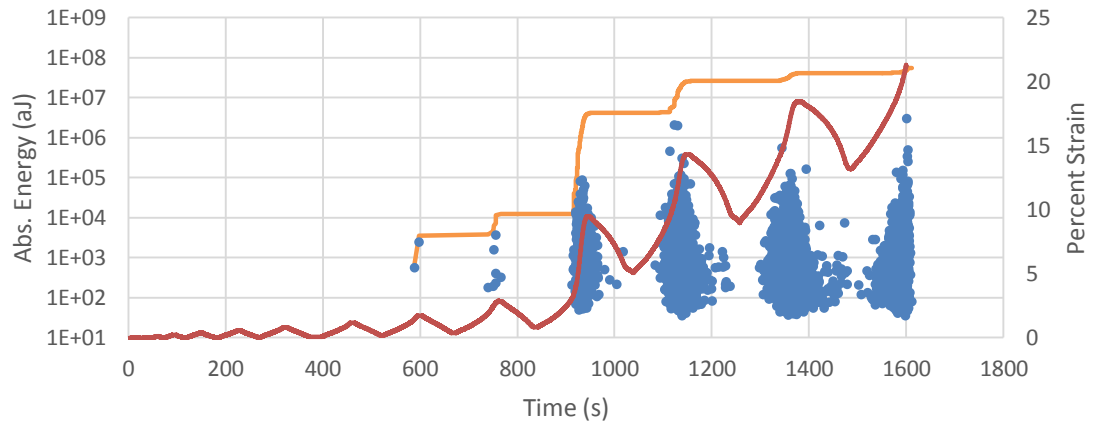
Hit Absolute Energy, 2393_4; Sensors Not Removed



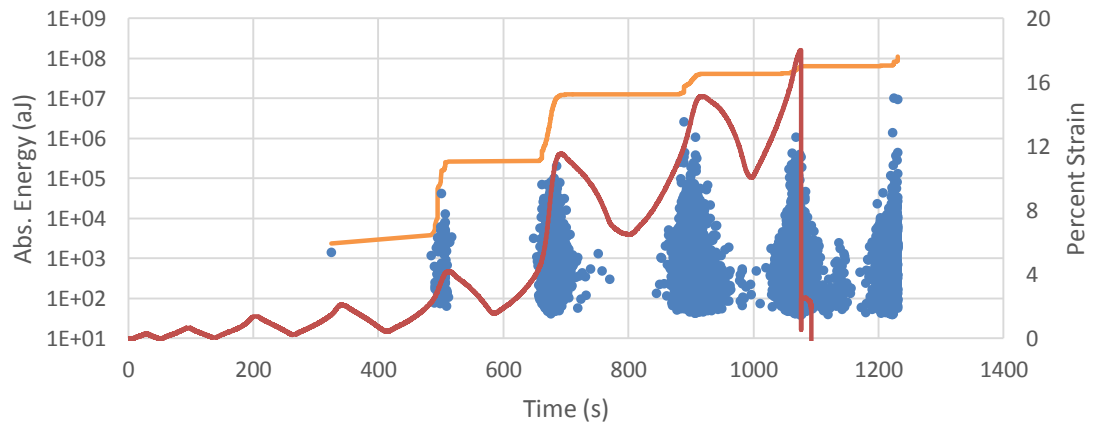
Hit Absolute Energy, 2393_8; Sensors Not Removed



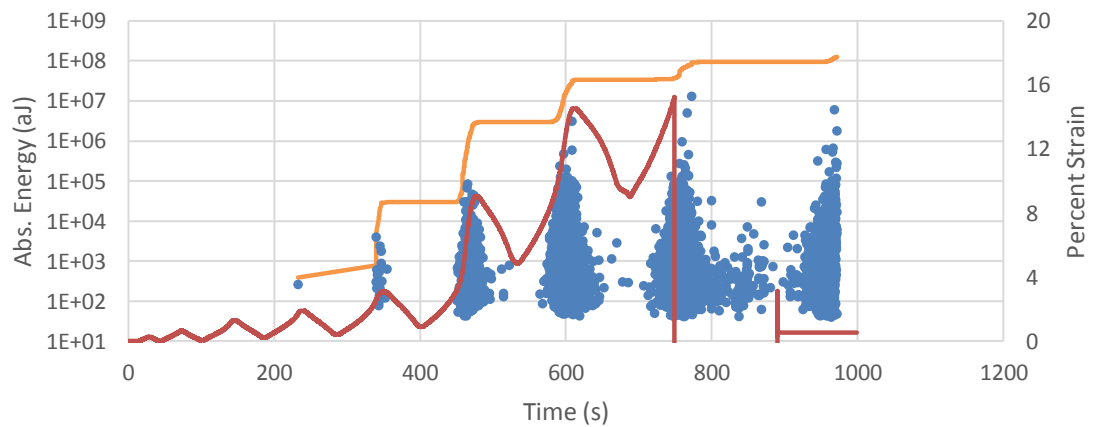
Hit Absolute Energy, 2393_5; Sensors Not Removed



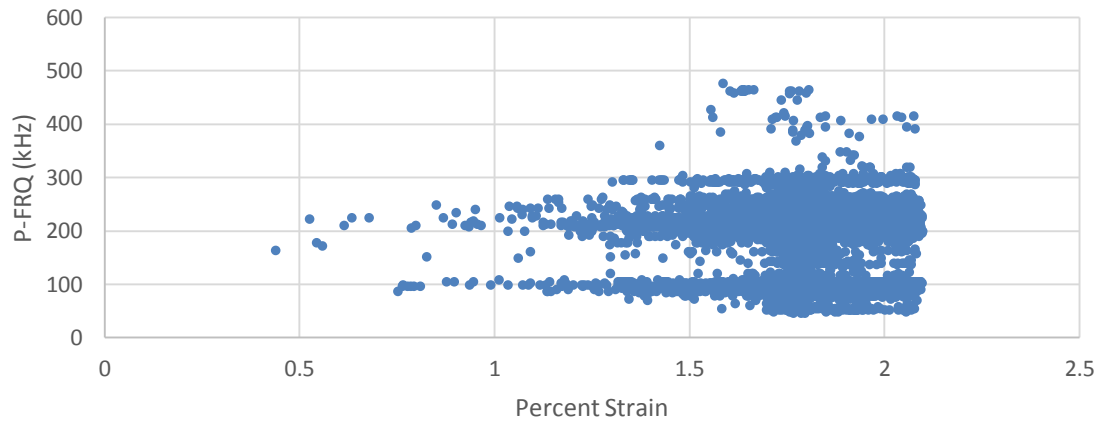
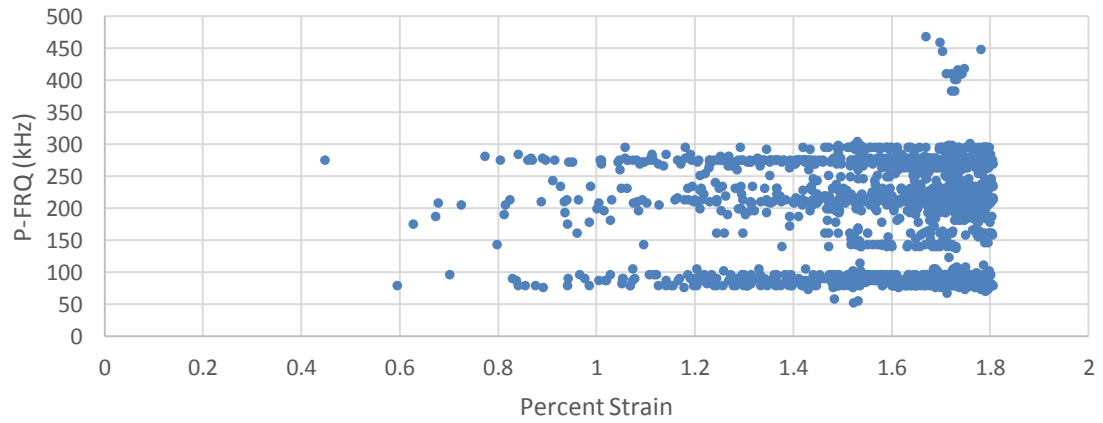
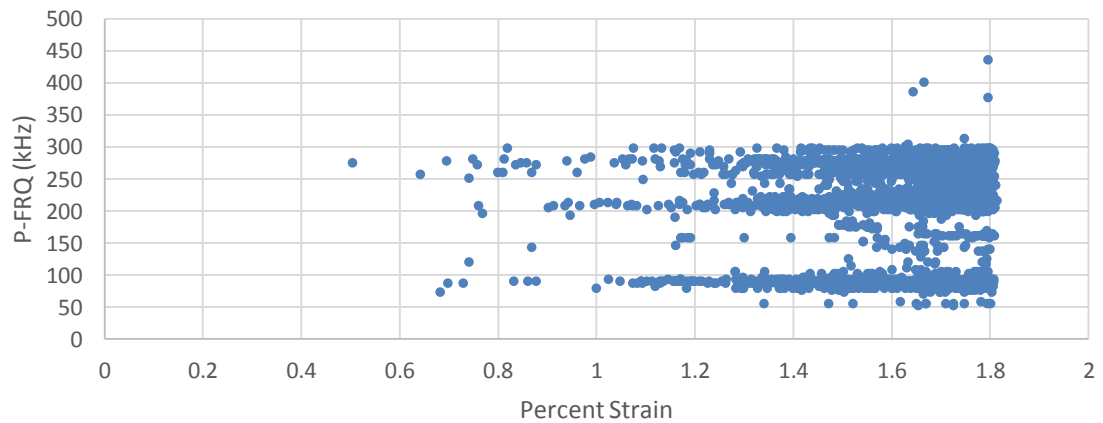
Hit Absolute Energy, 2393_6; Sensors Not Removed

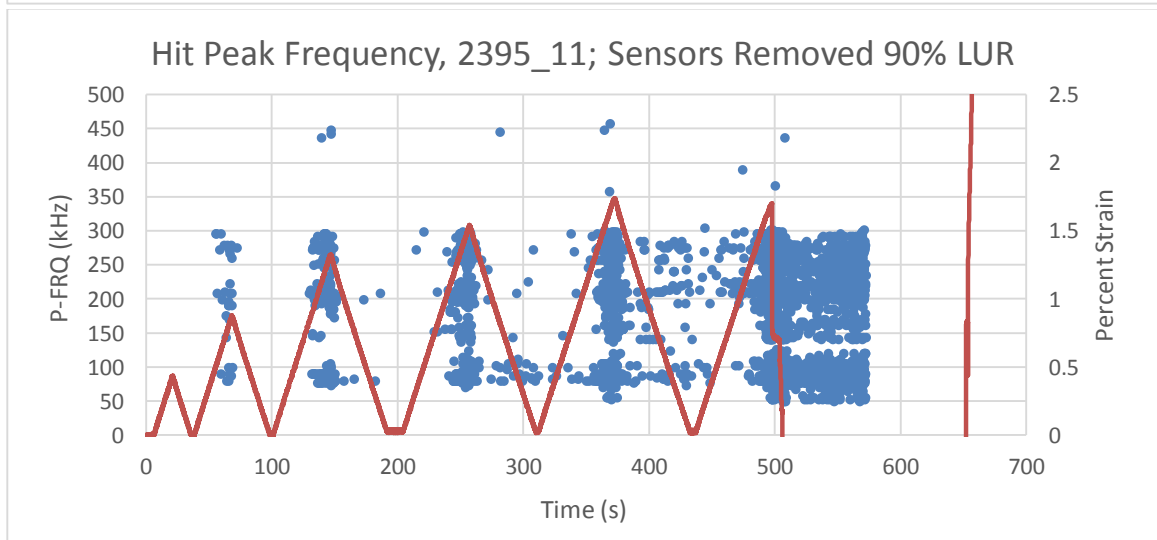
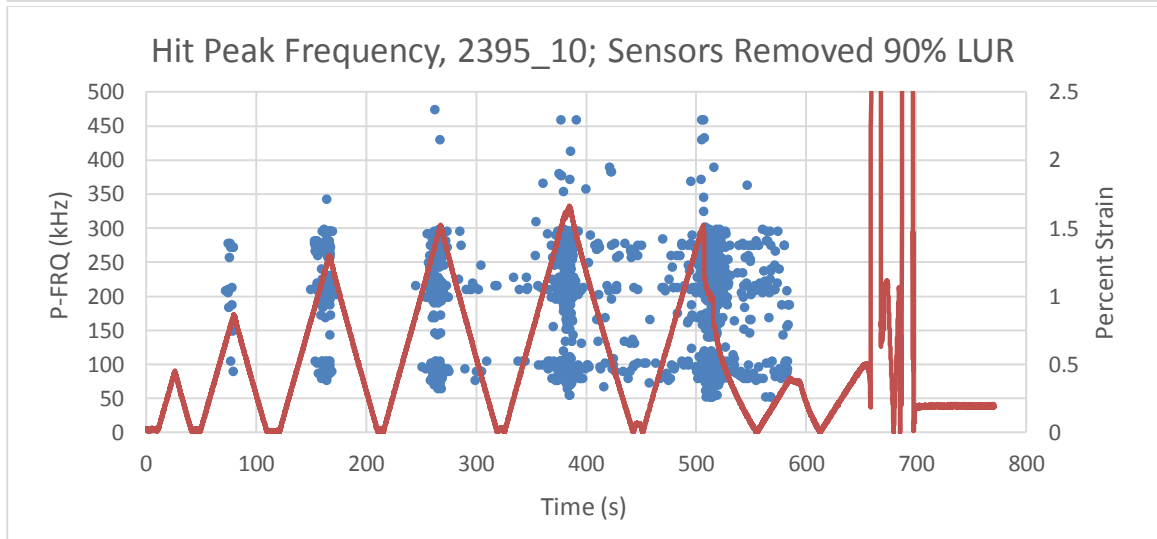
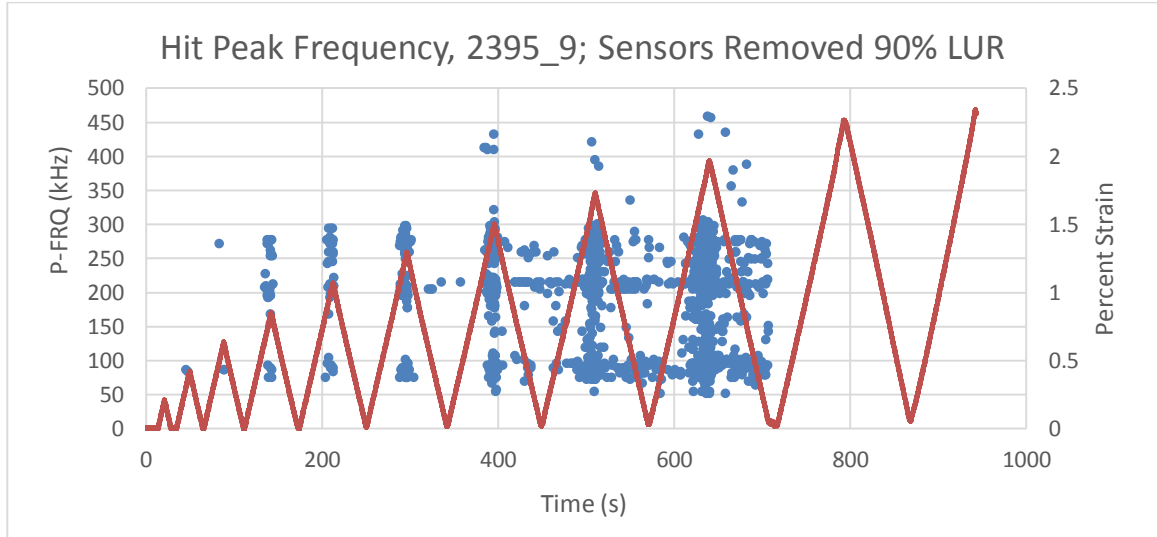


Hit Absolute Energy, 2393_7; Sensors Not Removed

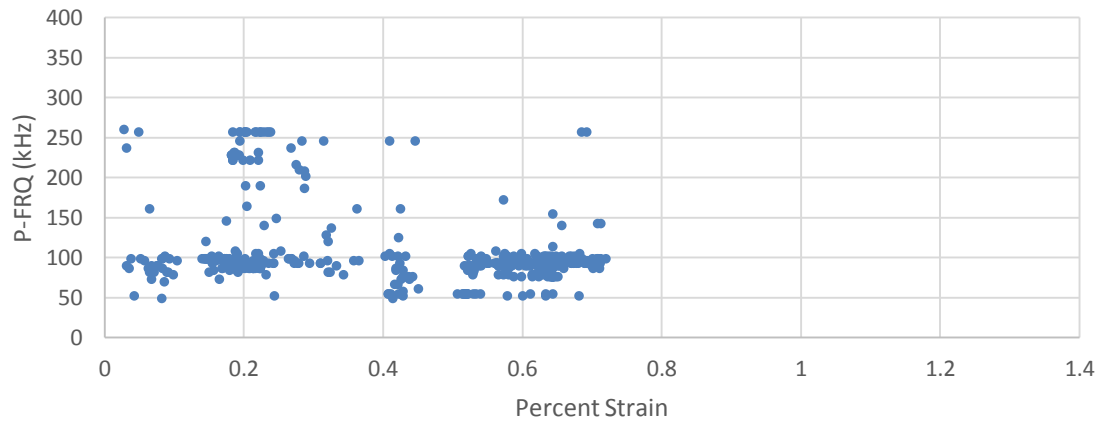


Hit Peak Frequency, 2395_1; Sensors Not Removed

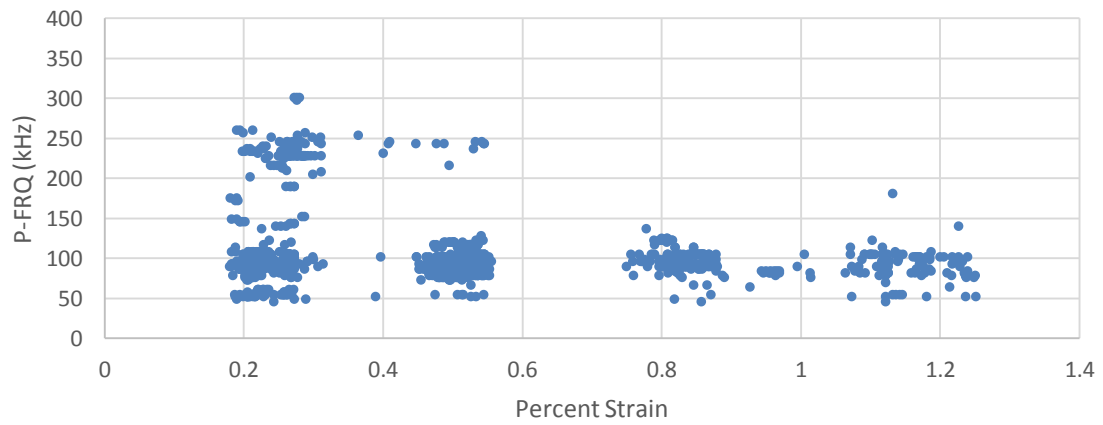
Hit Peak Frequency, 2395_2; Sensors Removed 1.8% ϵ Hit Peak Frequency, 2395_3; Sensors Removed 1.8% ϵ 



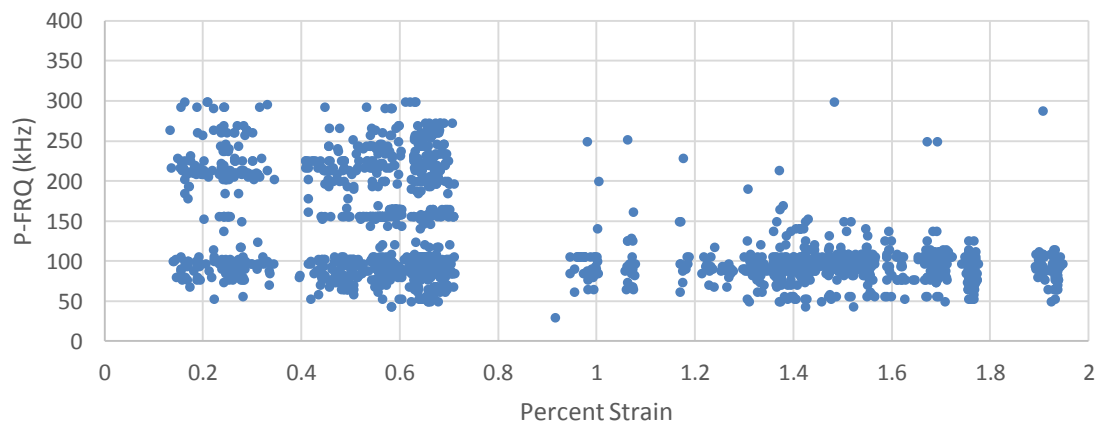
Hit Peak Frequency, 2395_13; Sensors Not Removed

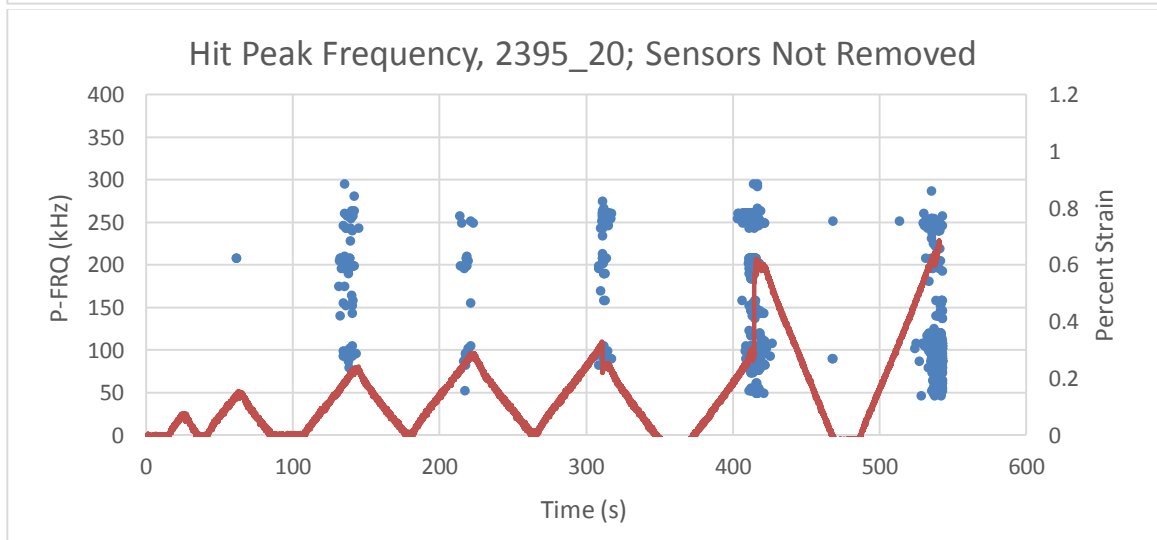
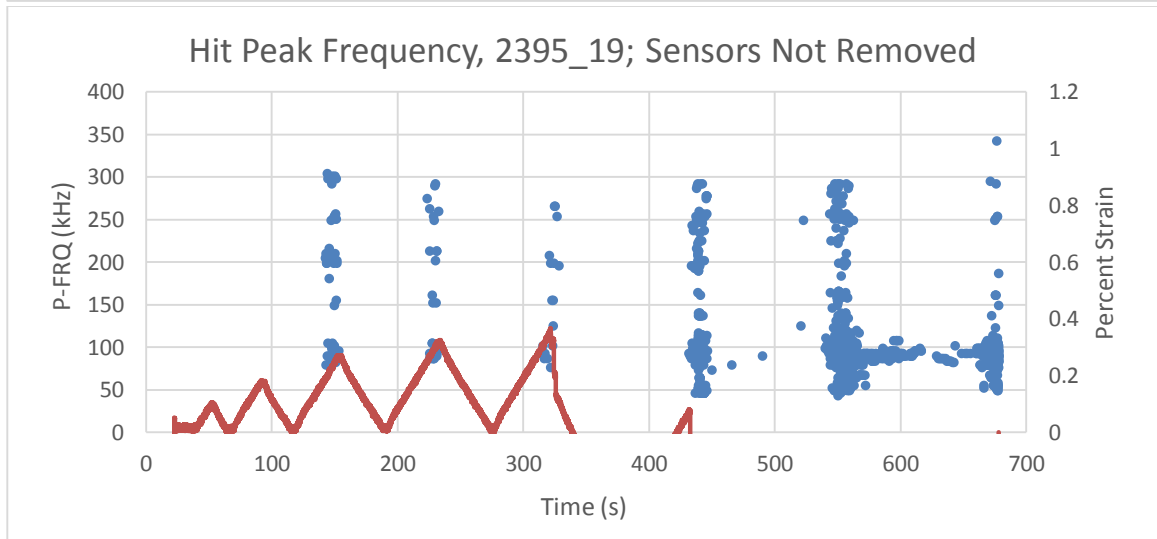
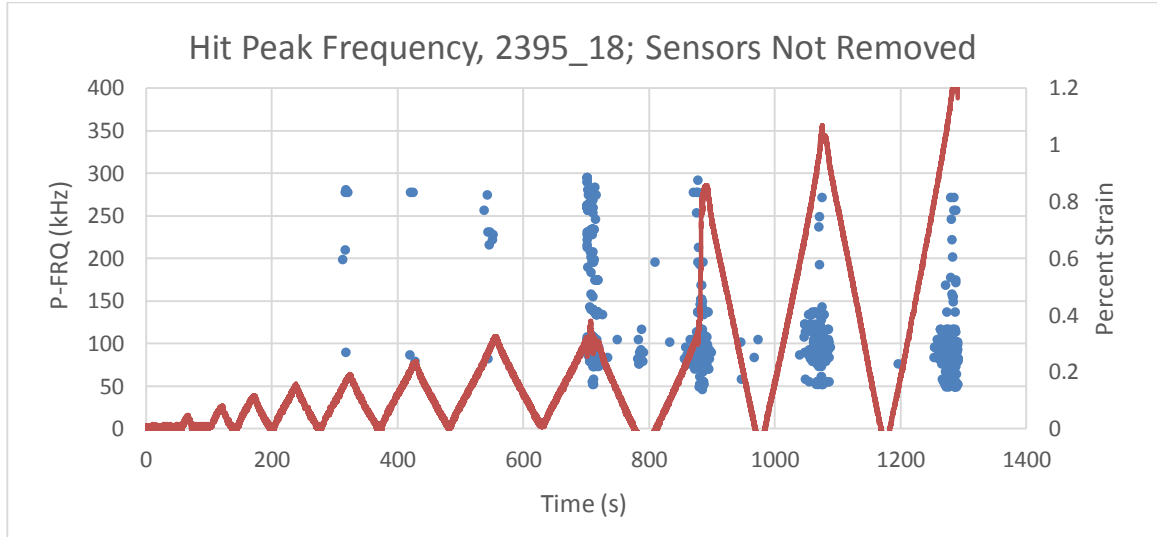


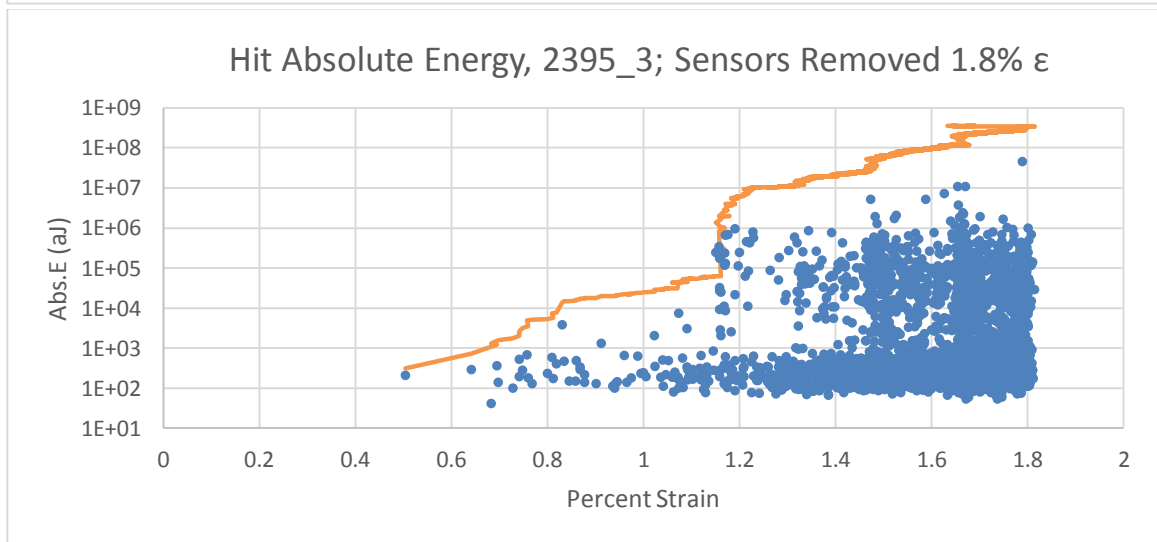
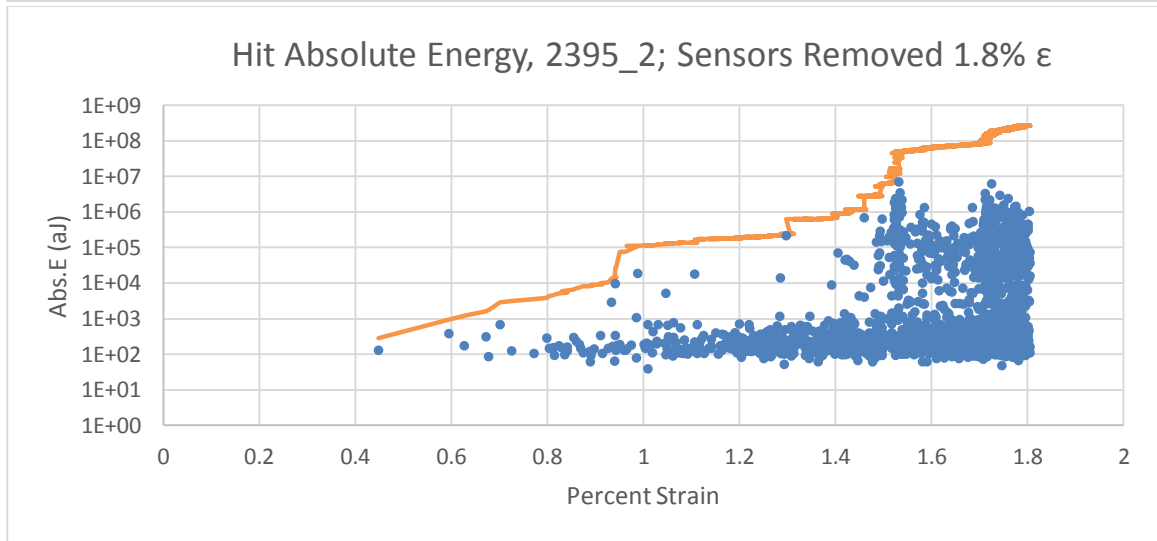
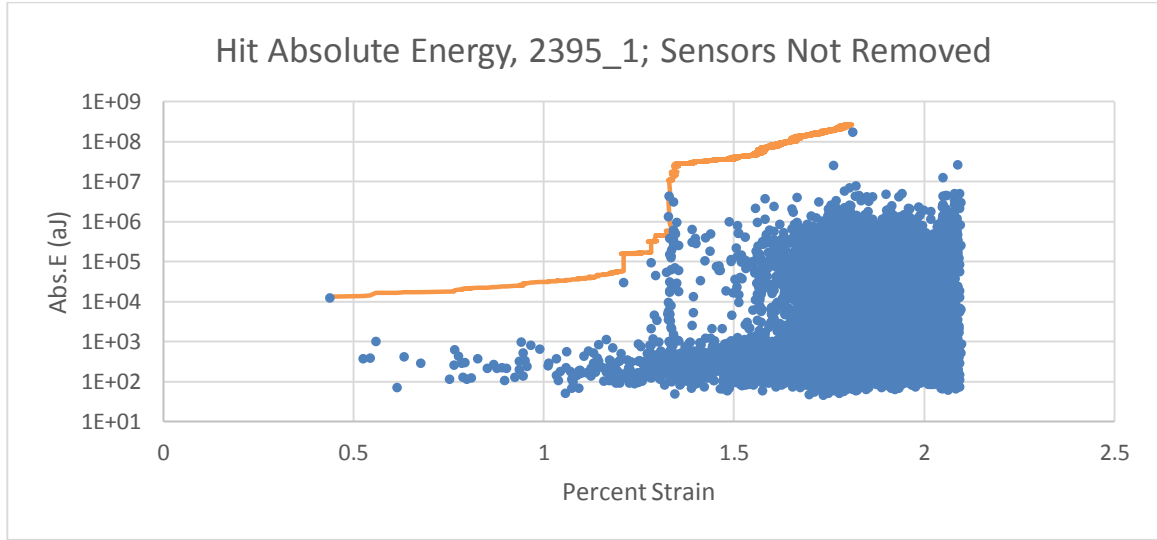
Hit Peak Frequency, 2395_14; Sensors Not Removed



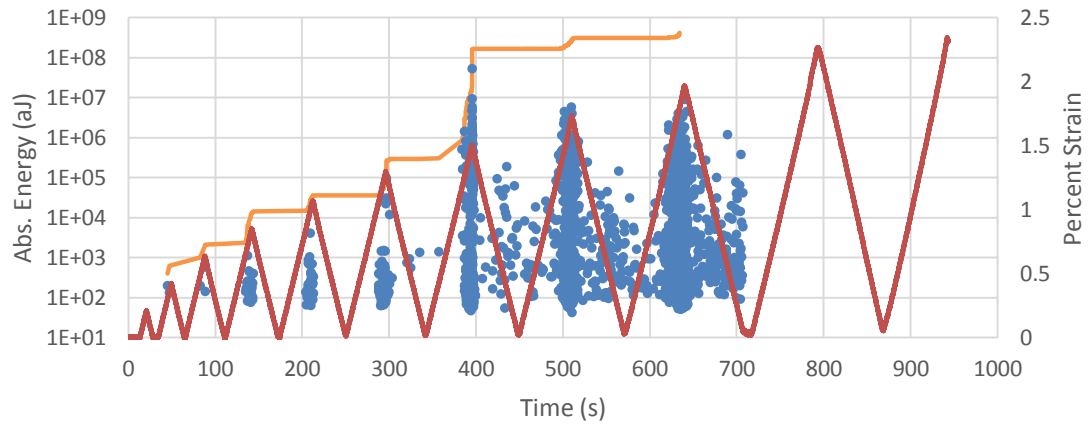
Hit Peak Frequency, 2395_16; Sensors Not Removed



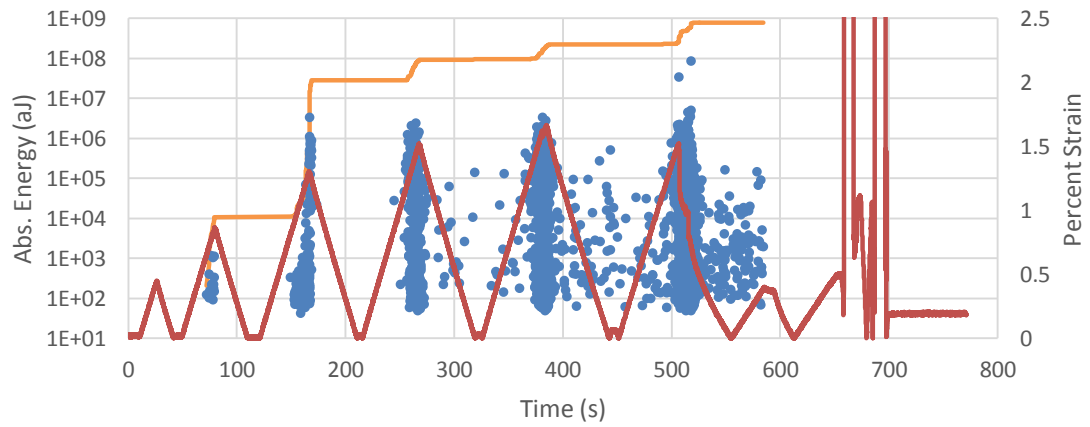




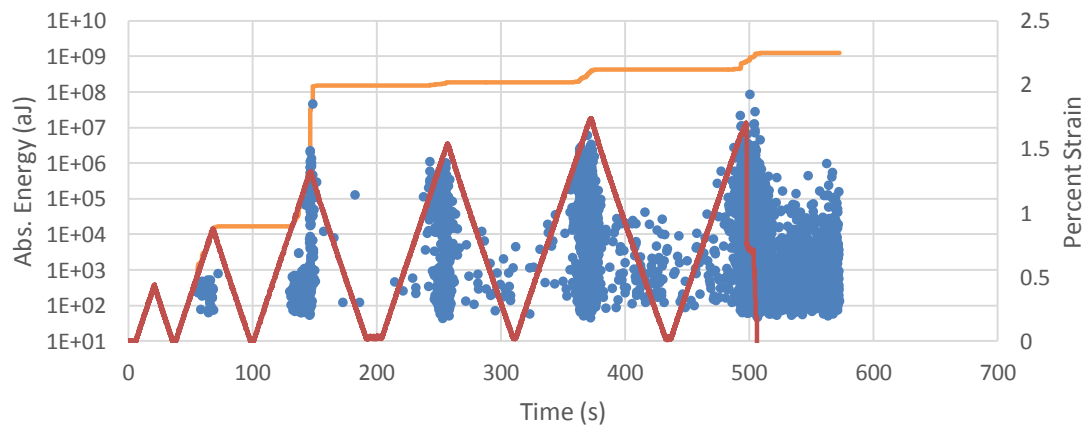
Hit Absolute Energy, 2395_9; Sensors Removed 90% LUR



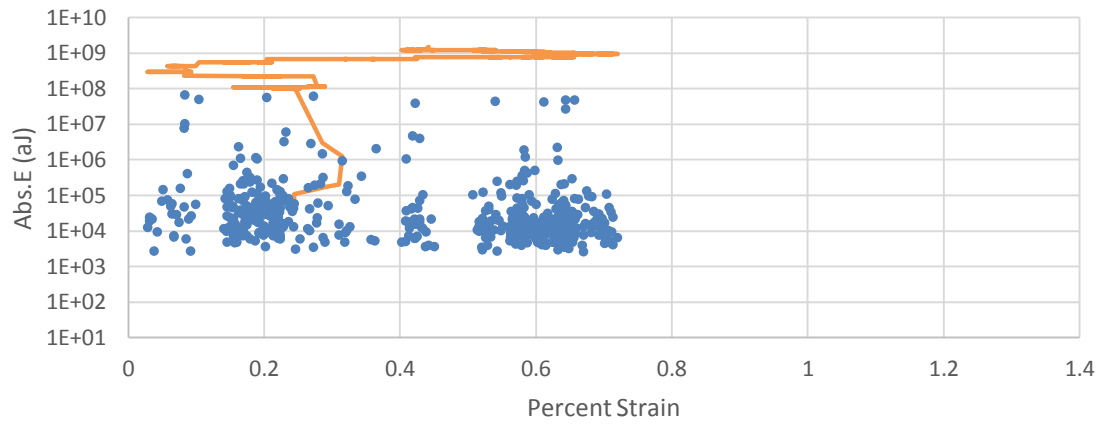
Hit Absolute Energy, 2395_10; Sensors Removed 90% LUR



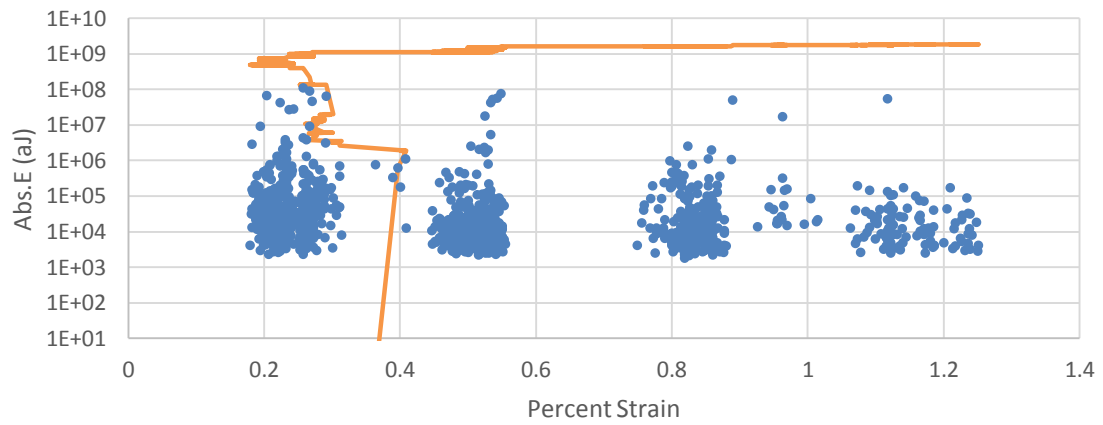
Hit Absolute Energy, 2395_11; Sensors Removed 90% LUR



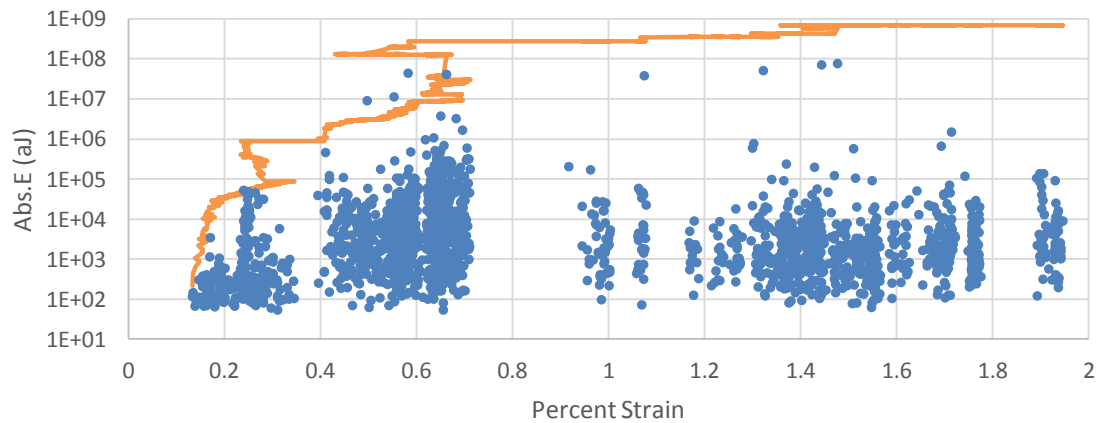
Hit Absolute Energy, 2395_13; Sensors Not Removed

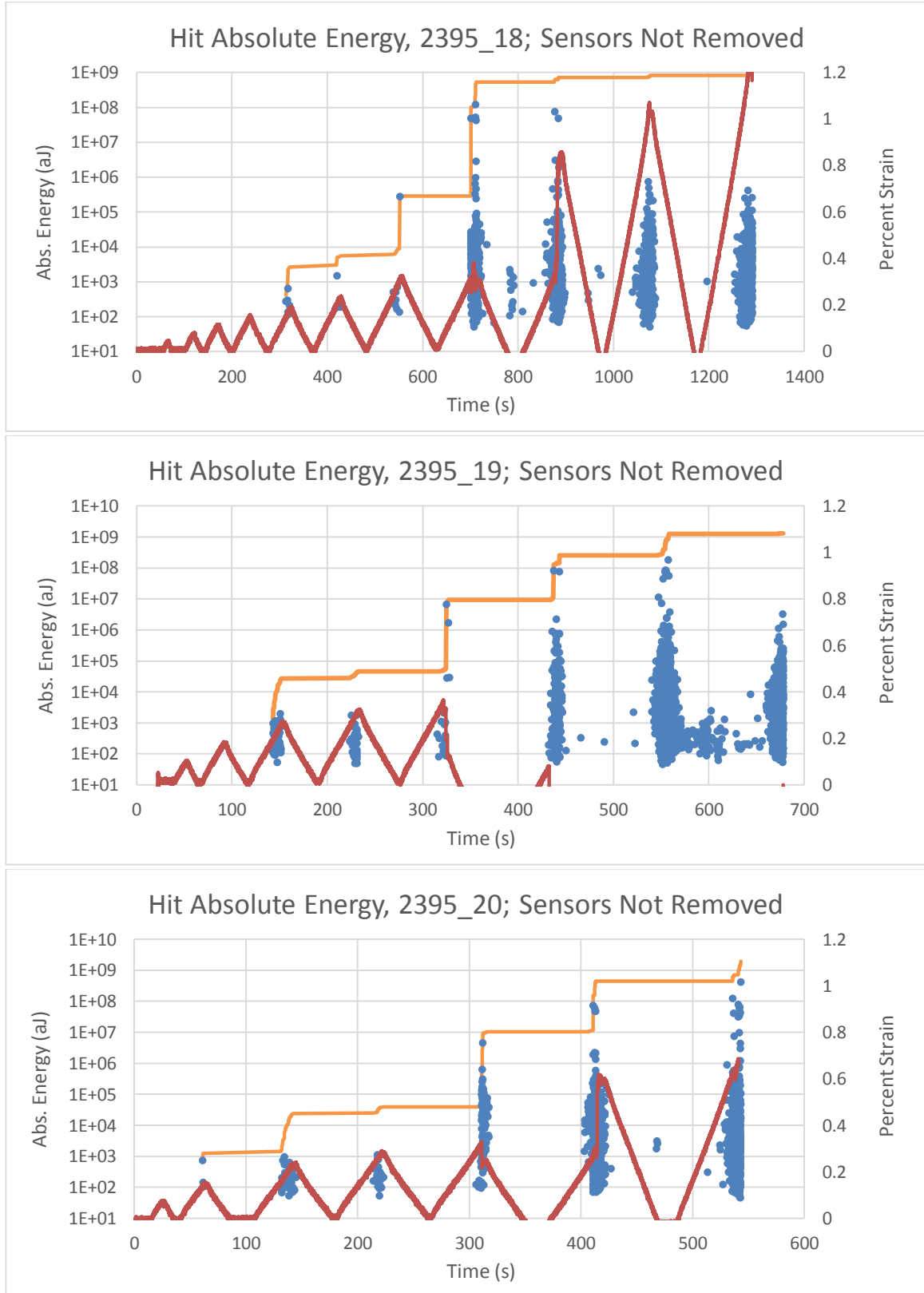


Hit Absolute Energy, 2395_14; Sensors Not Removed

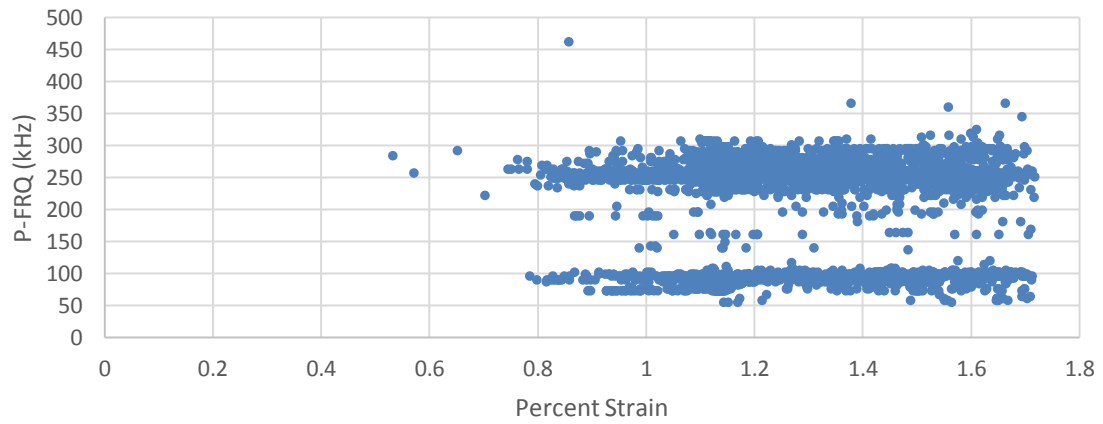
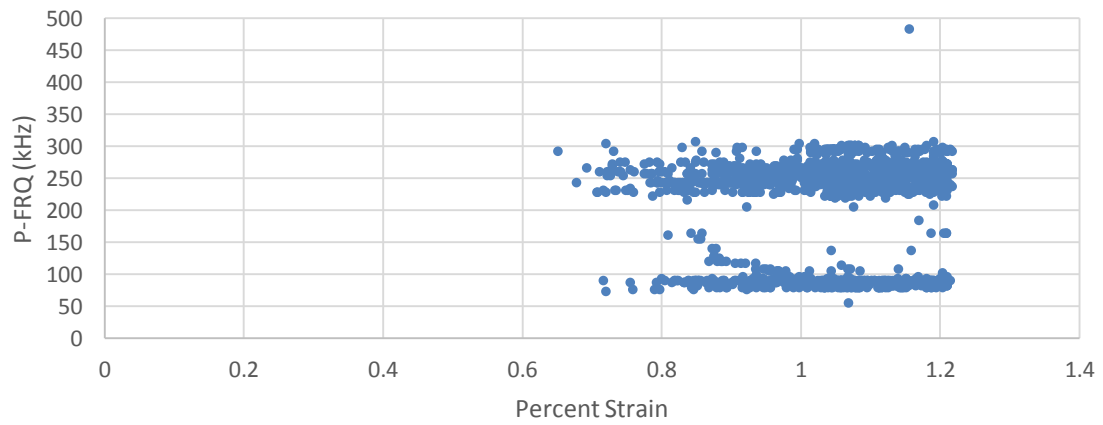
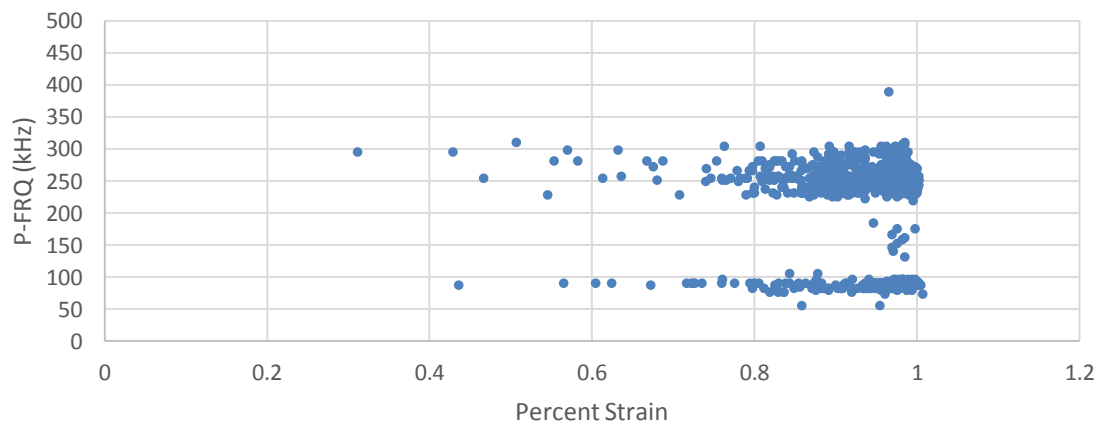


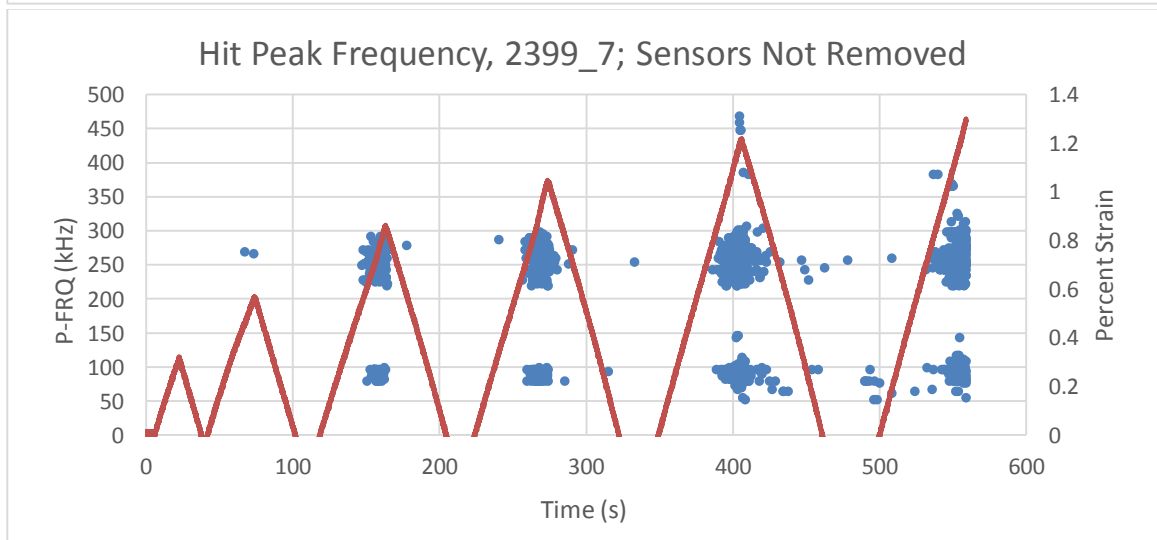
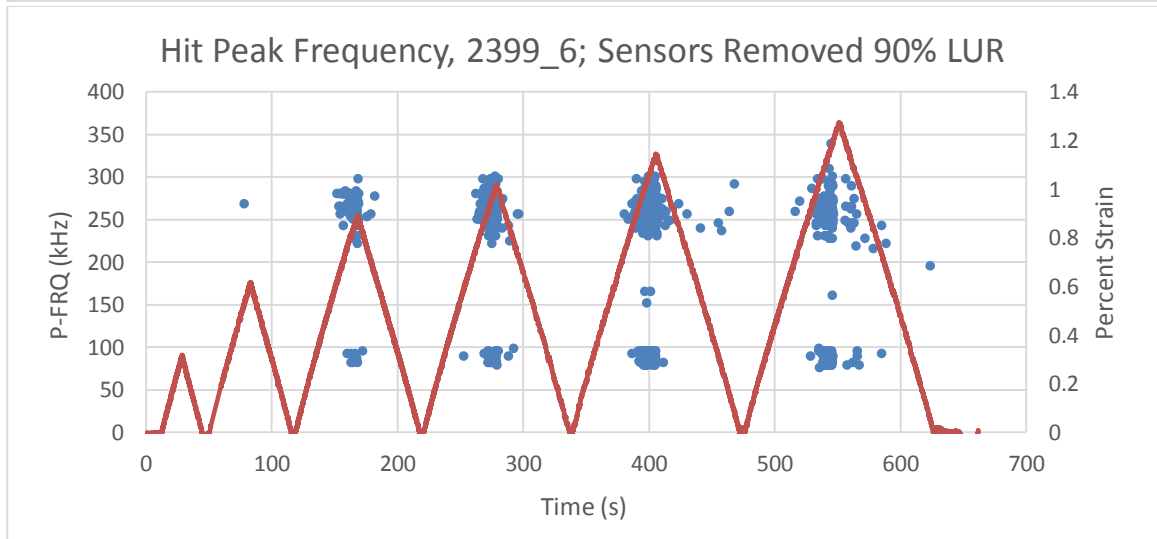
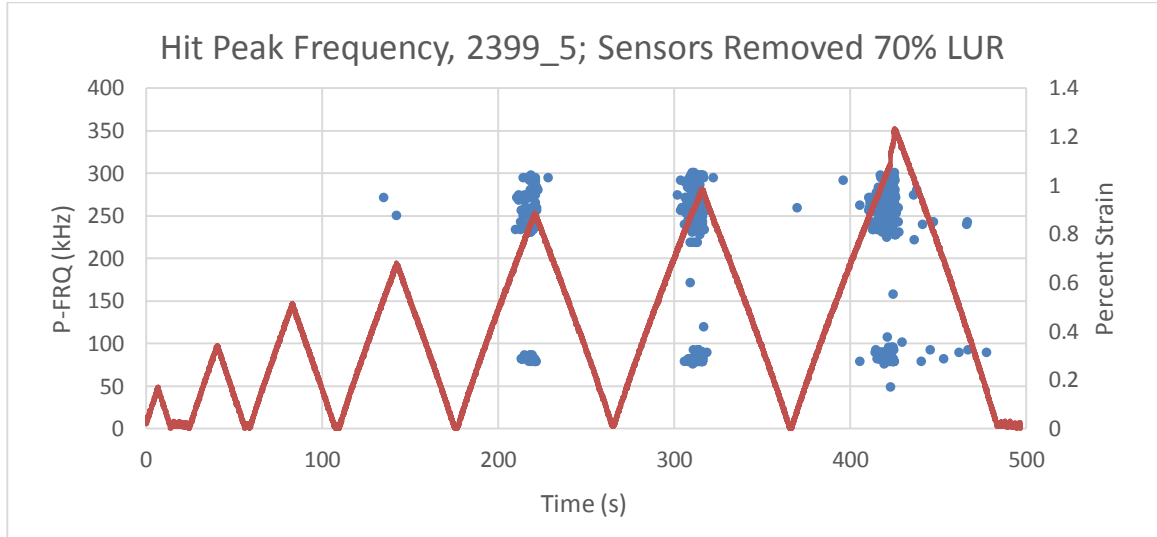
Hit Absolute Energy, 2395_16; Sensors Not Removed



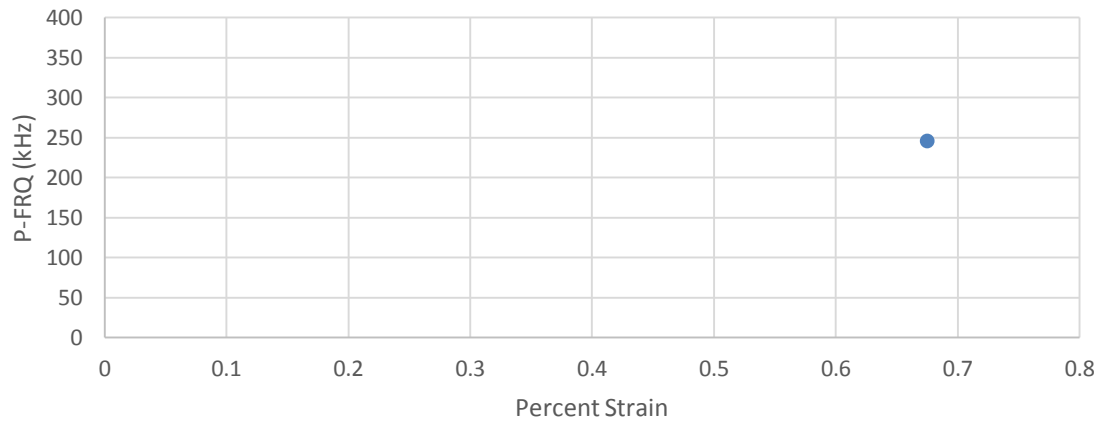


Hit Peak Frequency, 2399_1; Sensors Not Removed

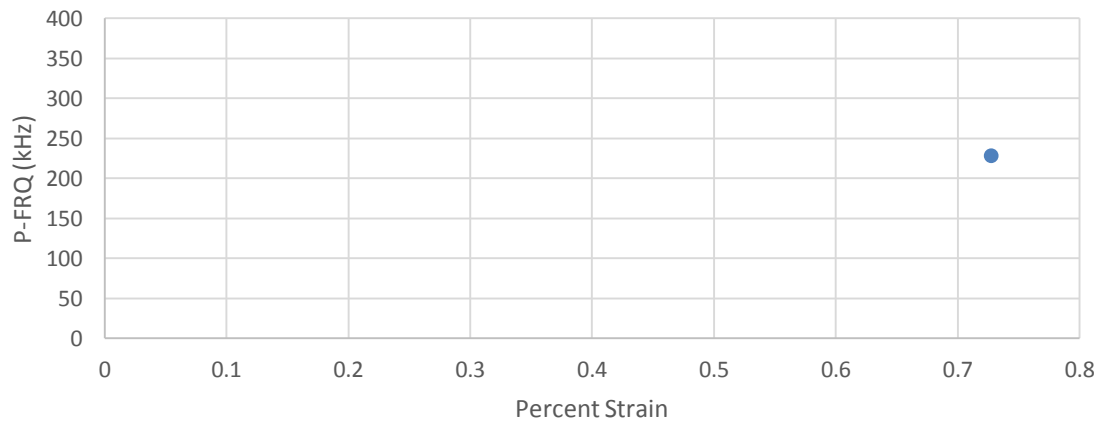
Hit Peak Frequency, 2399_2; Sensors Removed 1.2% ϵ Hit Peak Frequency, 2399_3; Sensors Removed $\approx 1.2\% \epsilon$ 



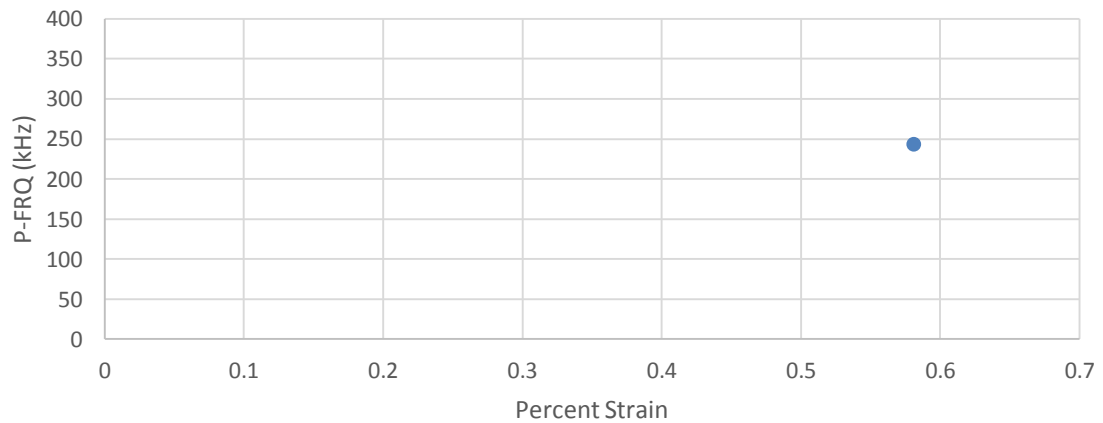
Hit Peak Frequency, 2399_15; Sensors Not Removed

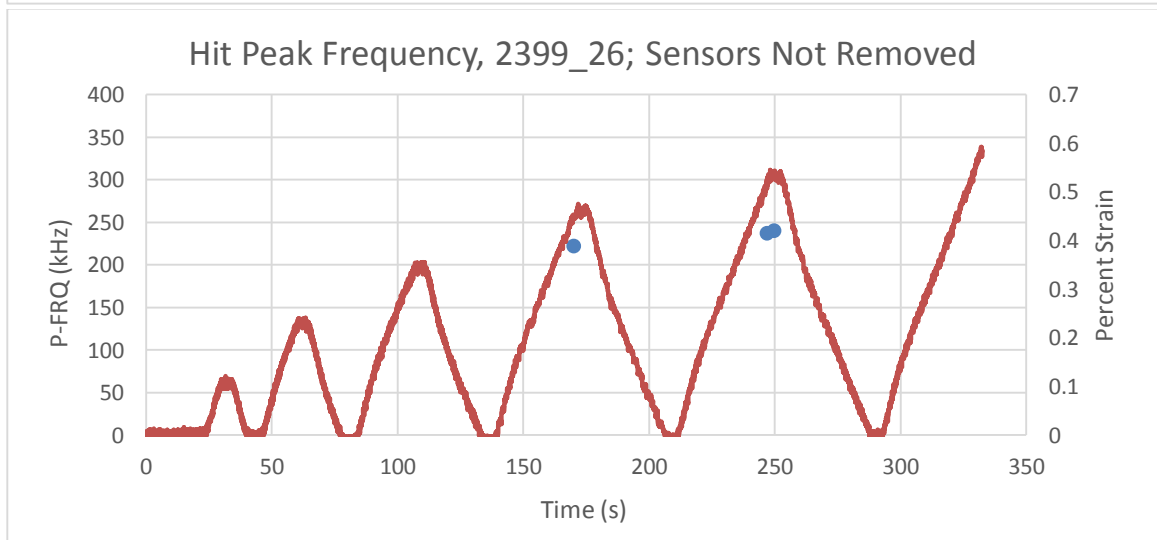
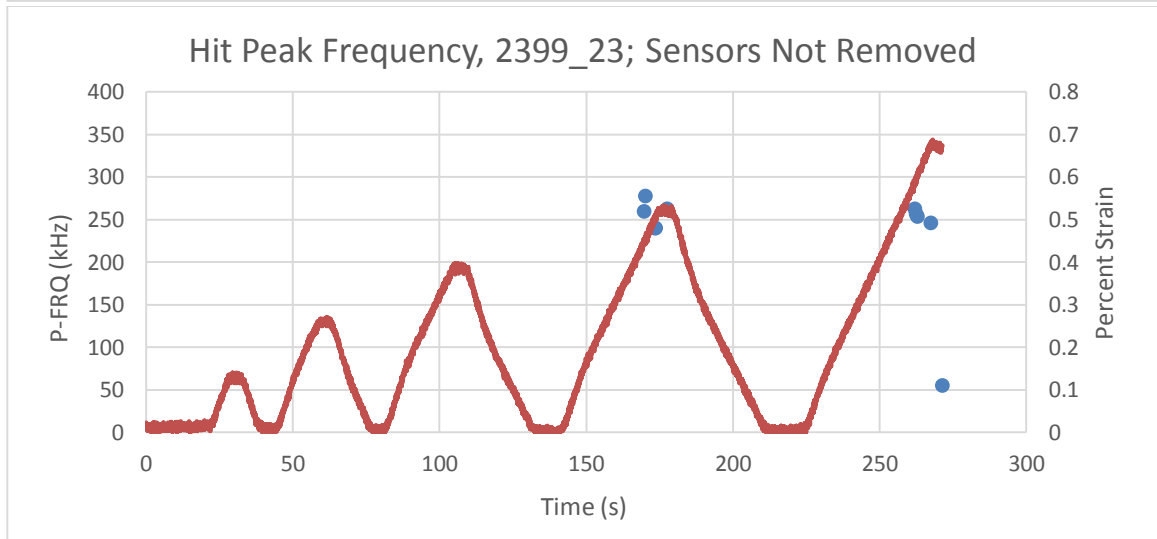
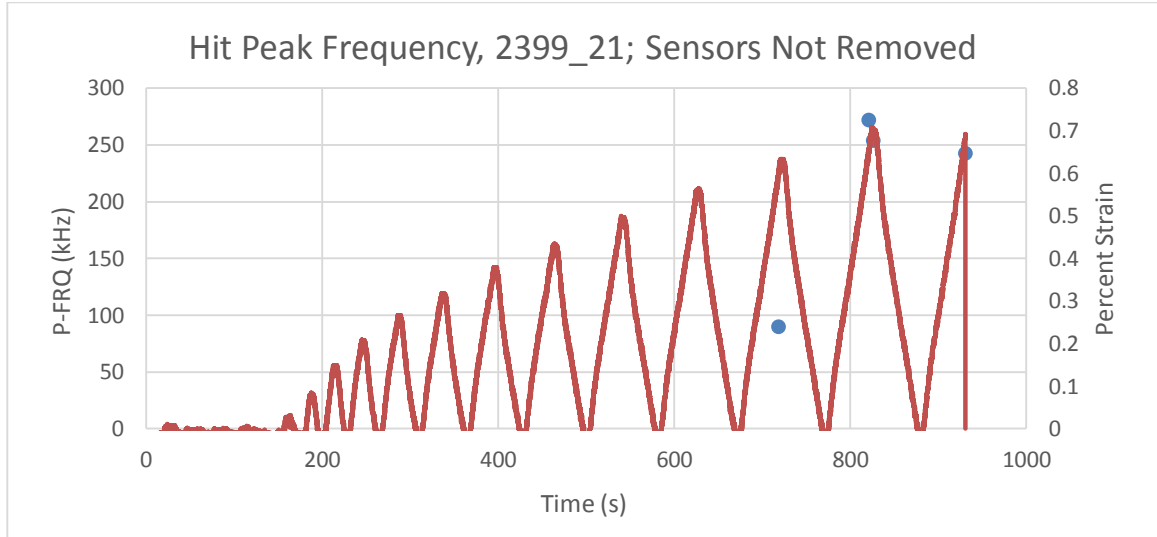


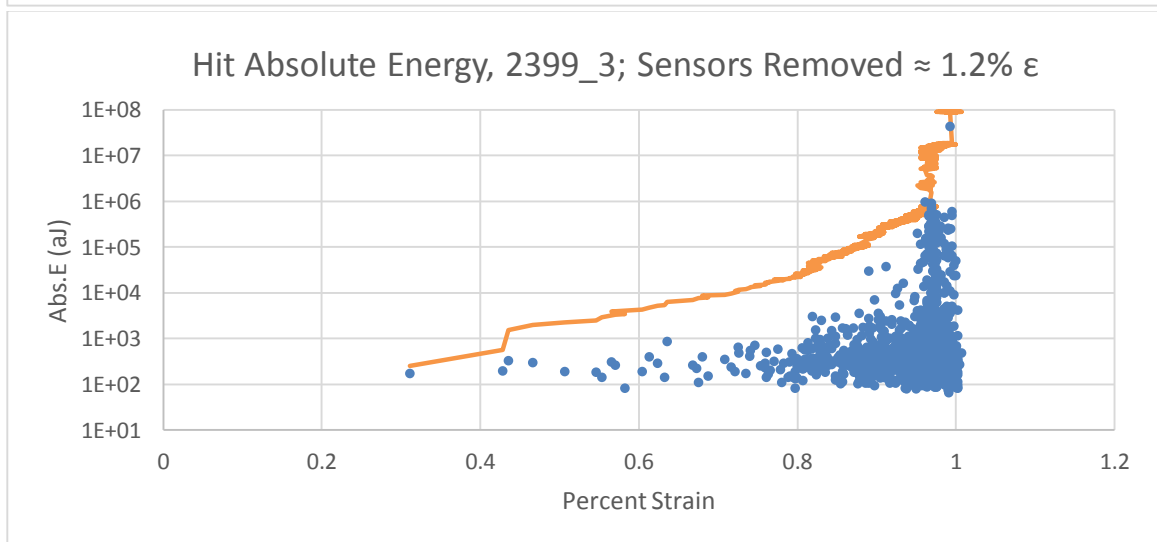
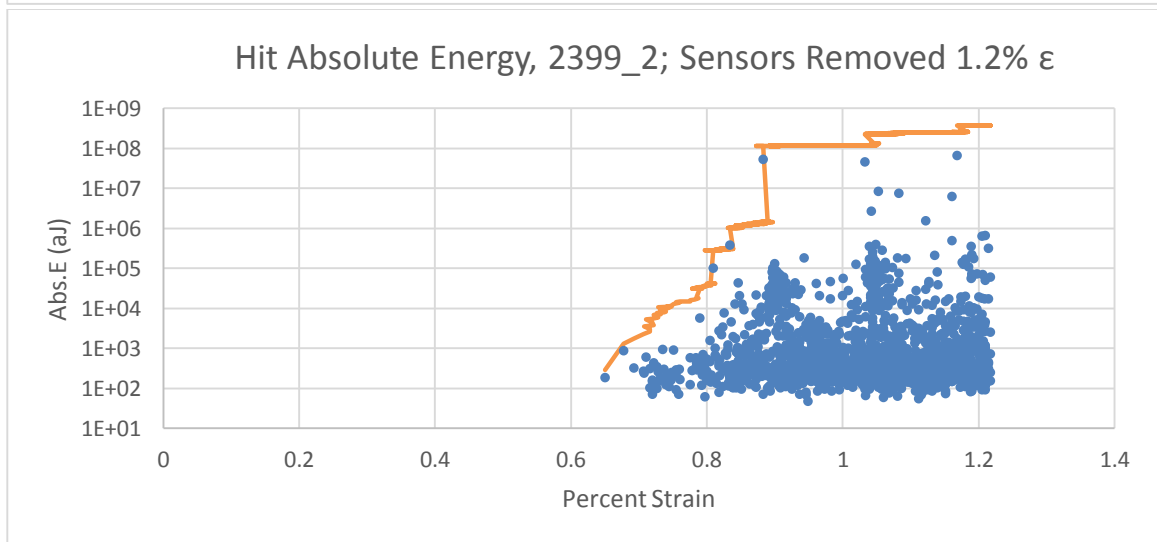
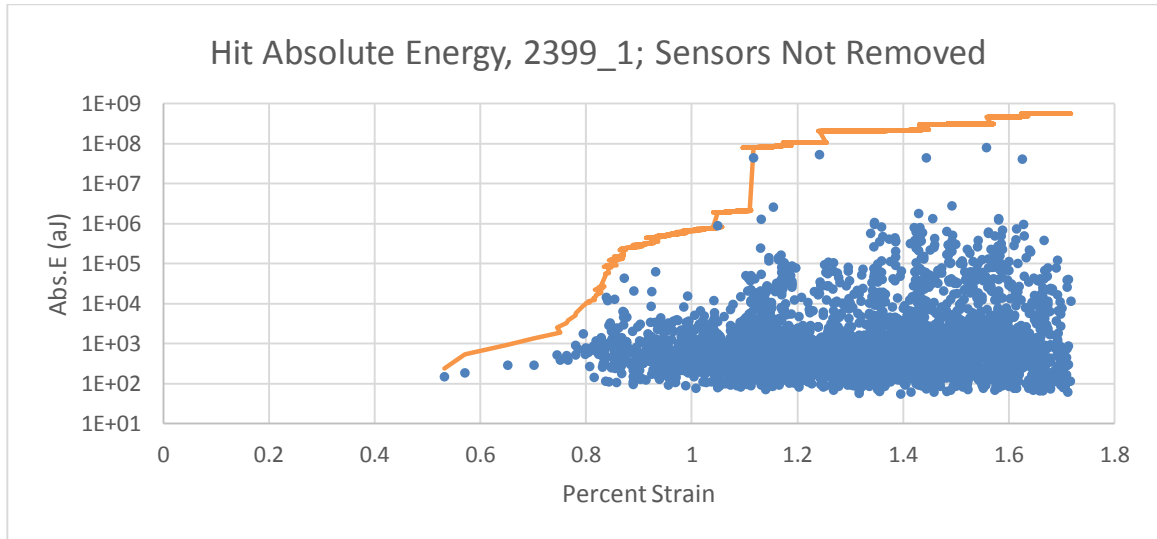
Hit Peak Frequency, 2399_17; Sensors Not Removed



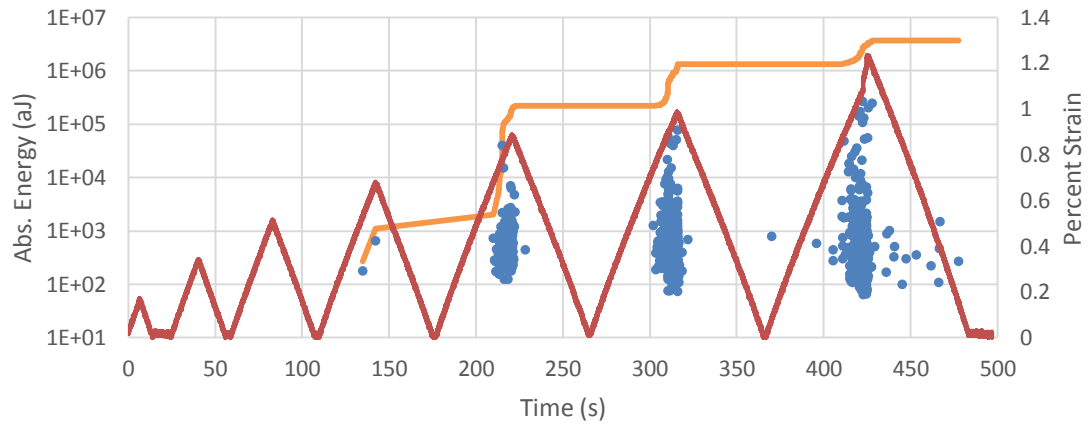
Hit Peak Frequency, 2399_27; Sensors Not Removed



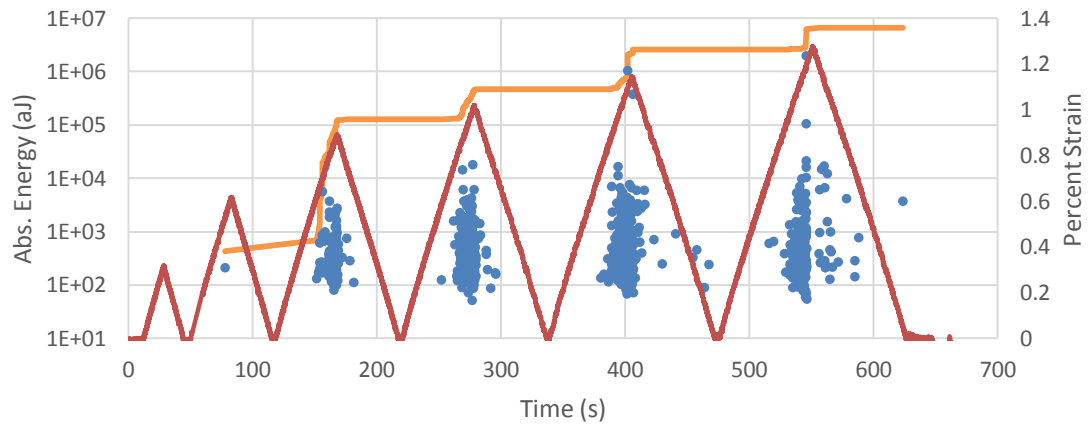




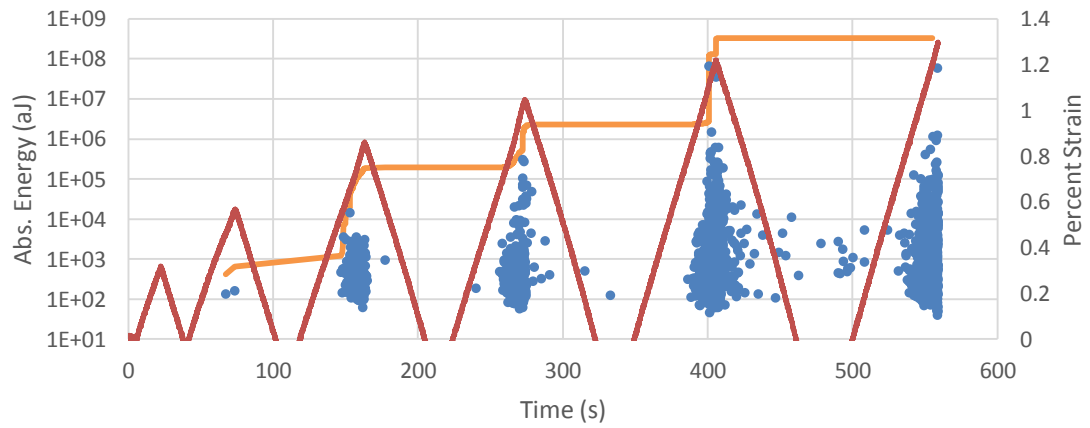
Hit Absolute Energy, 2399_5; Sensors Removed 70% LUR



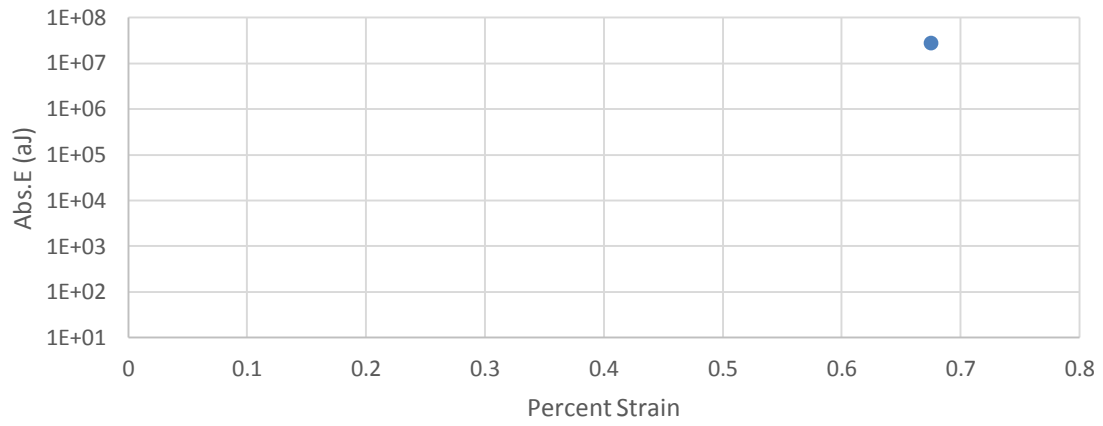
Hit Absolute Energy, 2399_6; Sensors Removed 90% LUR



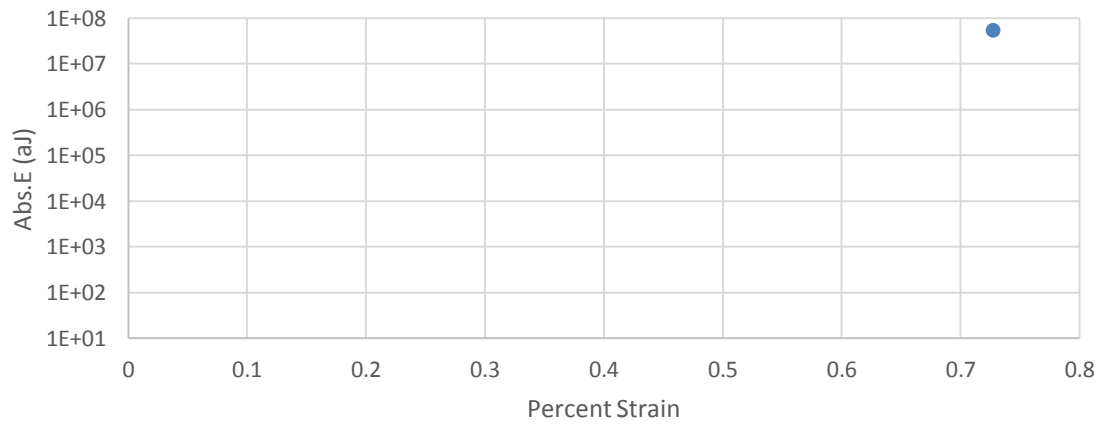
Hit Absolute Energy, 2399_7; Sensors Not Removed



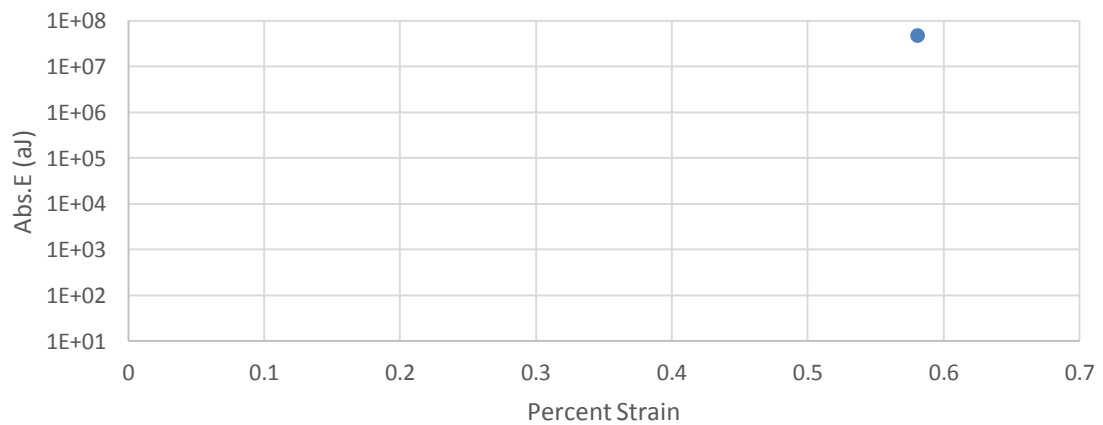
Hit Absolute Energy, 2399_15; Sensors Not Removed



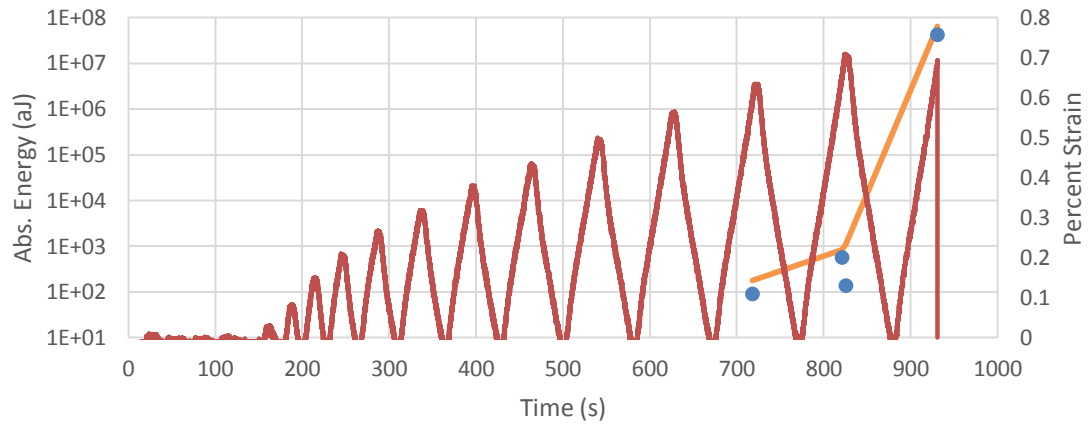
Hit Peak Frequency, 2399_17; Sensors Not Removed



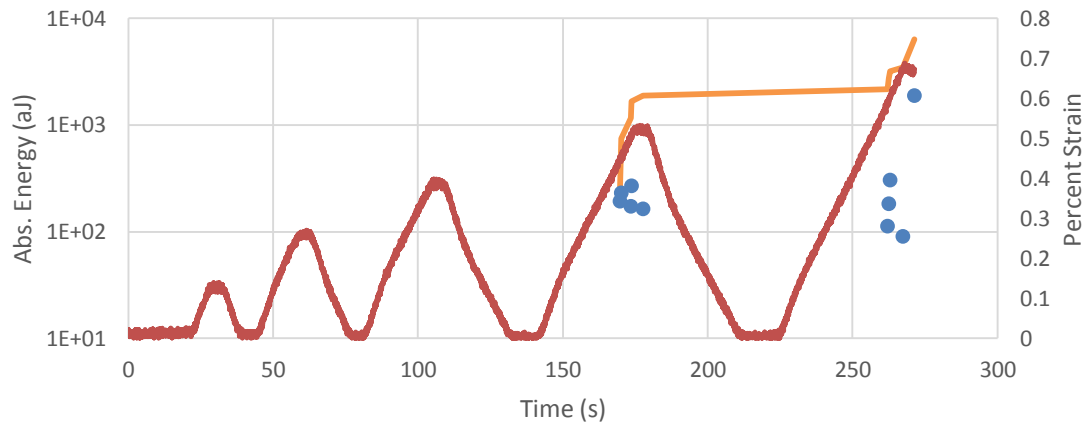
Hit Absolute Energy, 2399_27; Sensors Not Removed



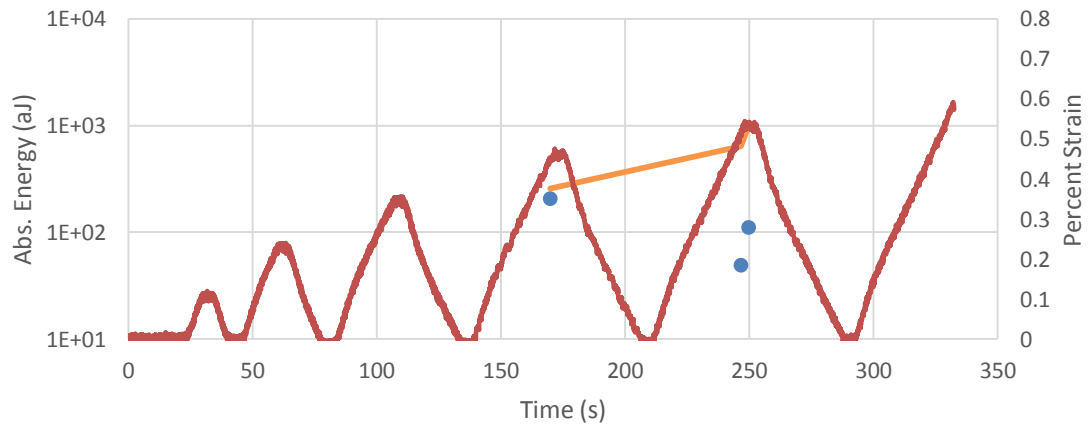
Hit Absolute Energy, 2399_21; Sensors Not Removed

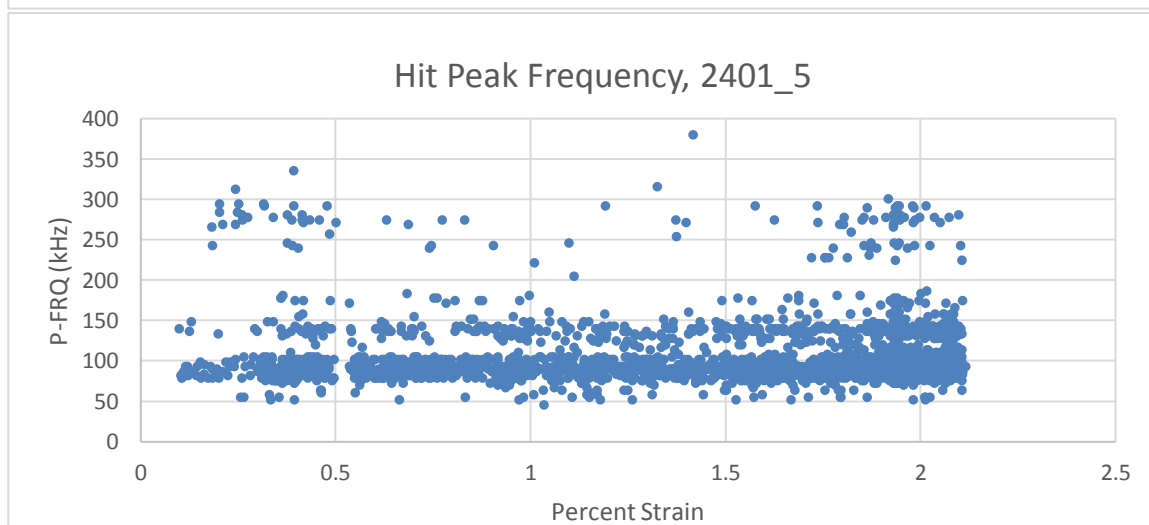
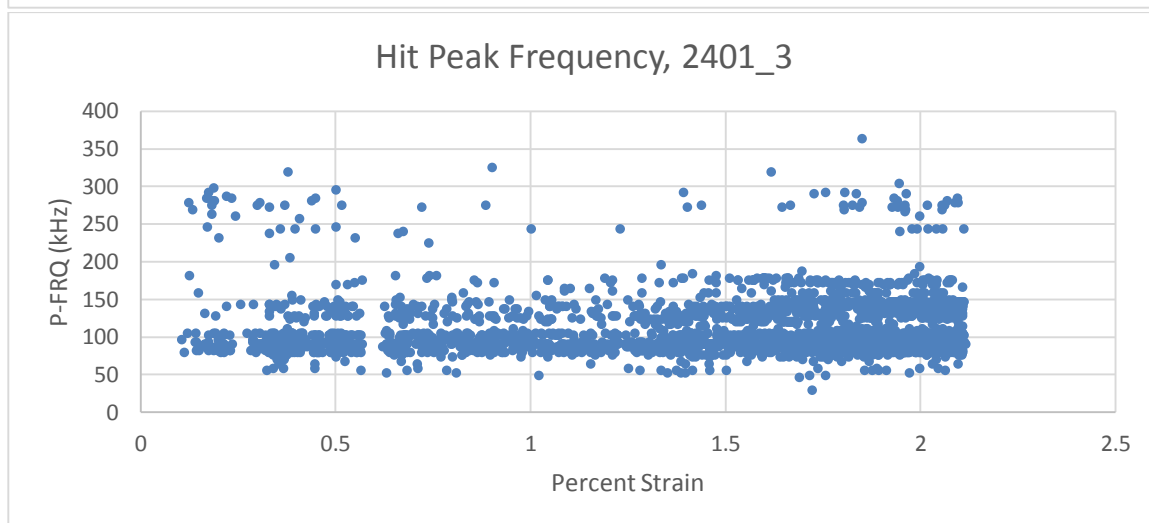
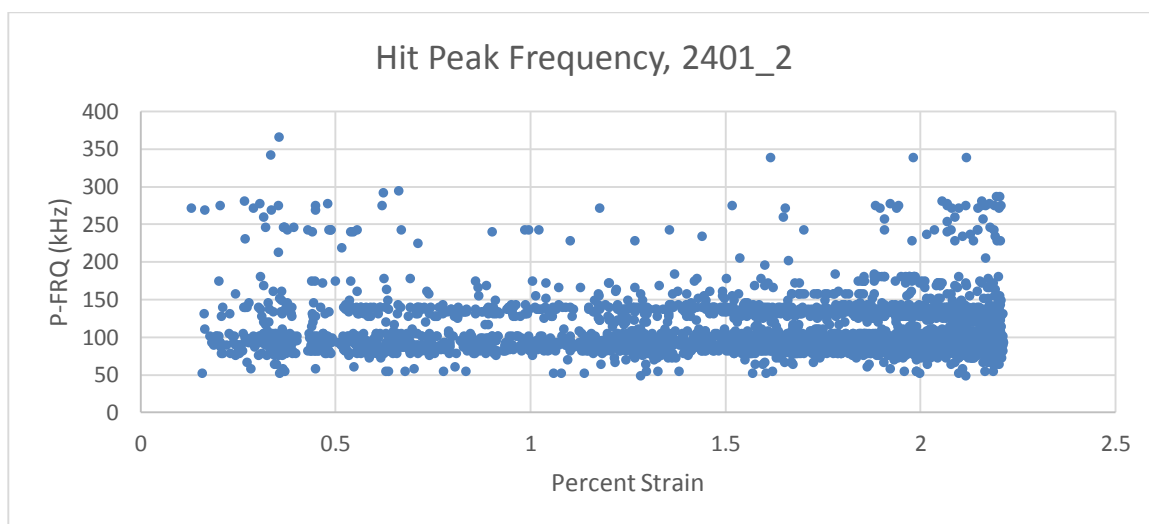


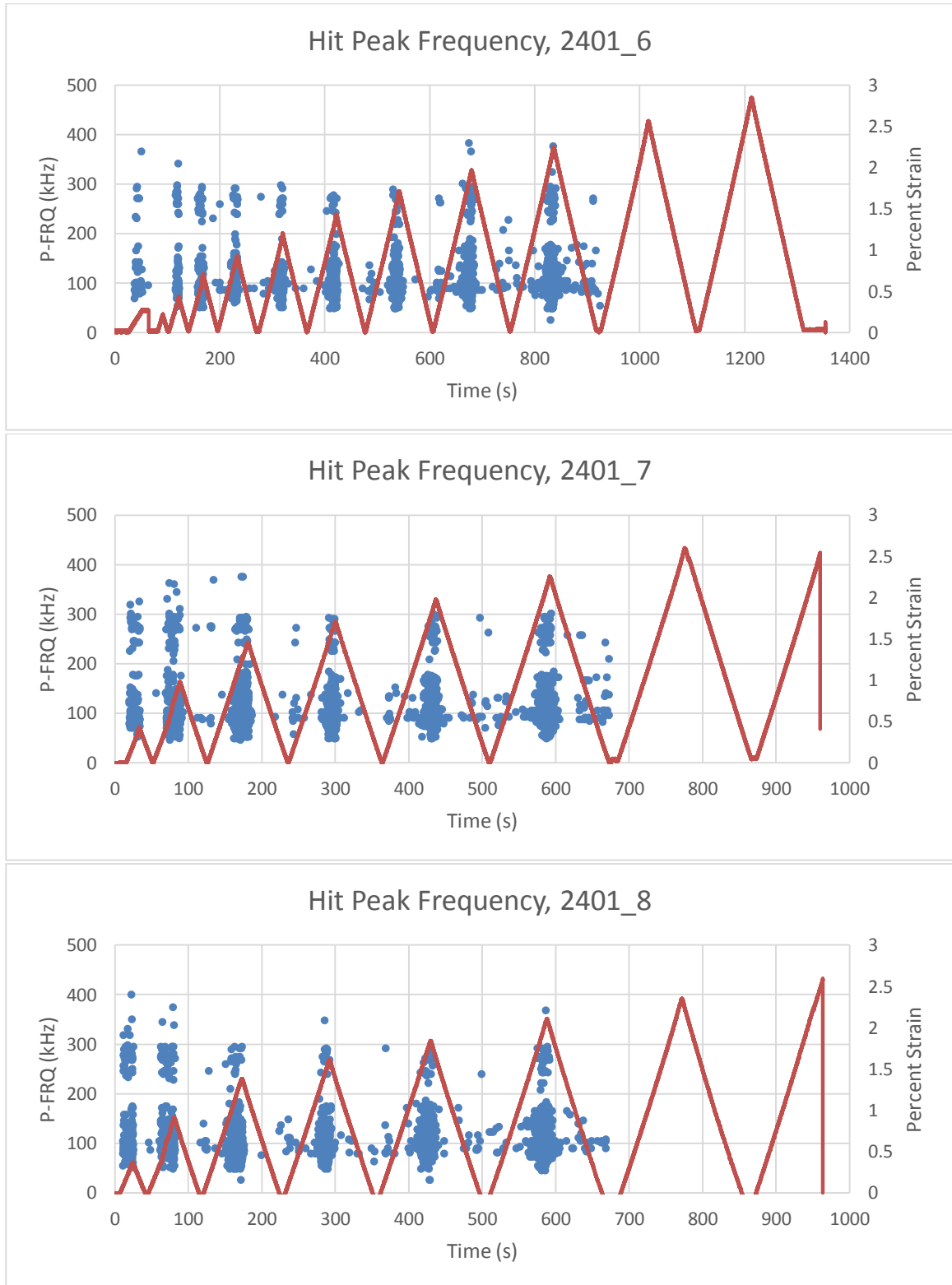
Hit Absolute Energy, 2399_23; Sensors Not Removed

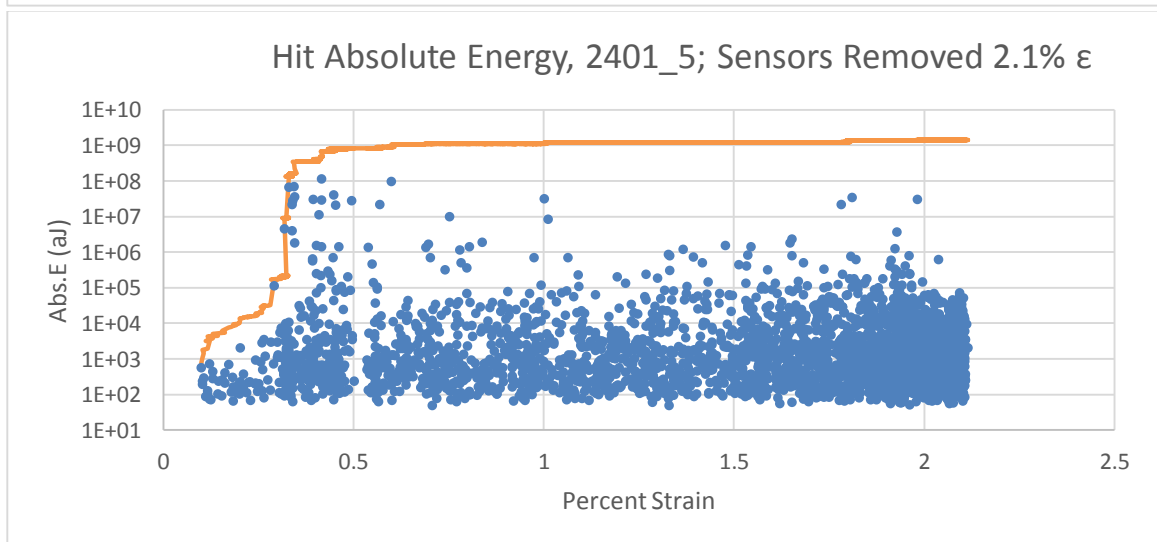
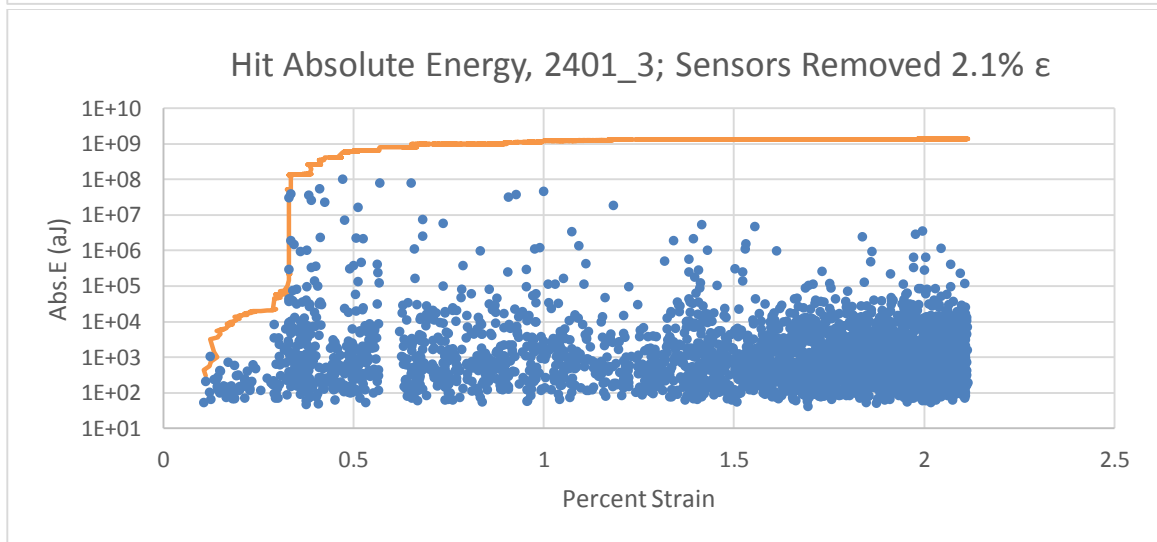
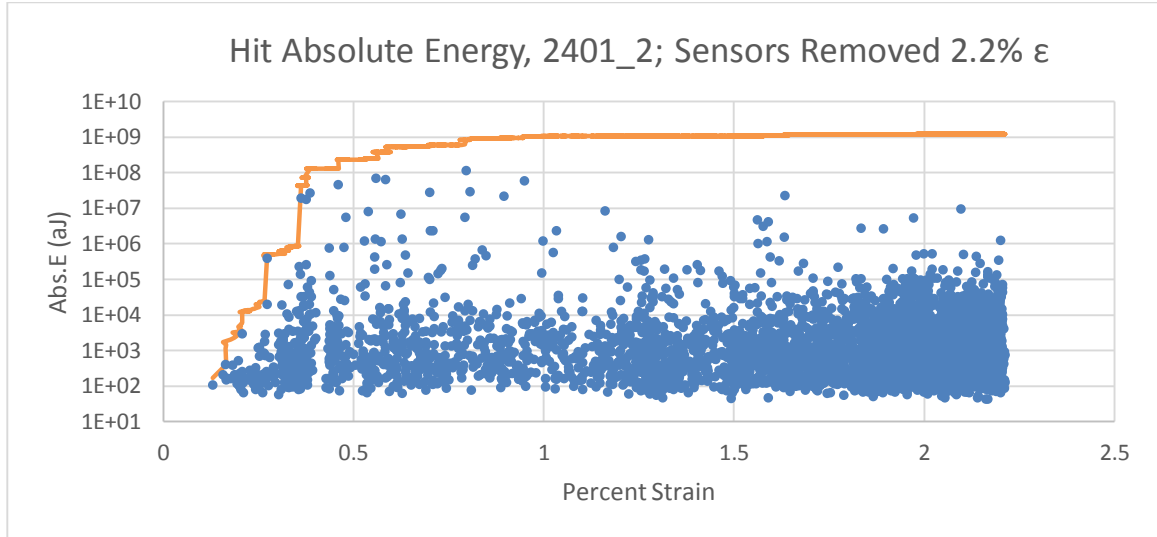


Hit Absolute Energy, 2399_26; Sensors Not Removed

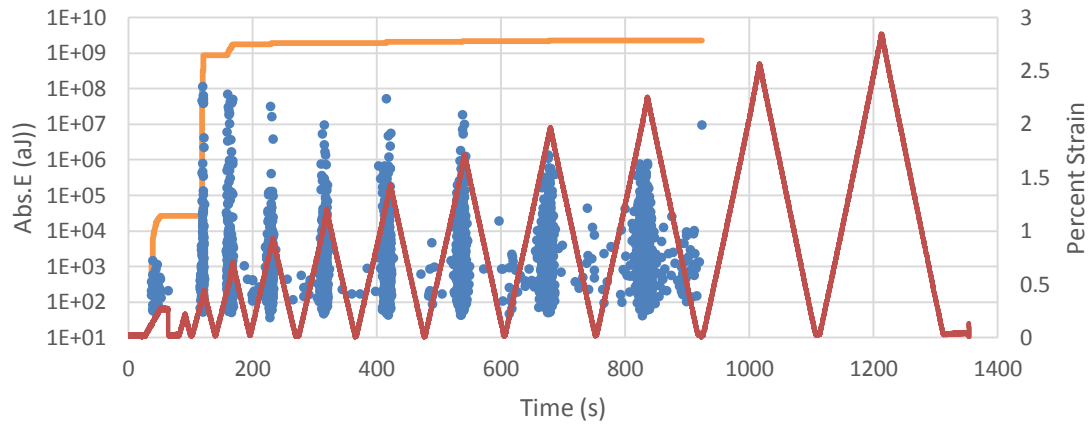




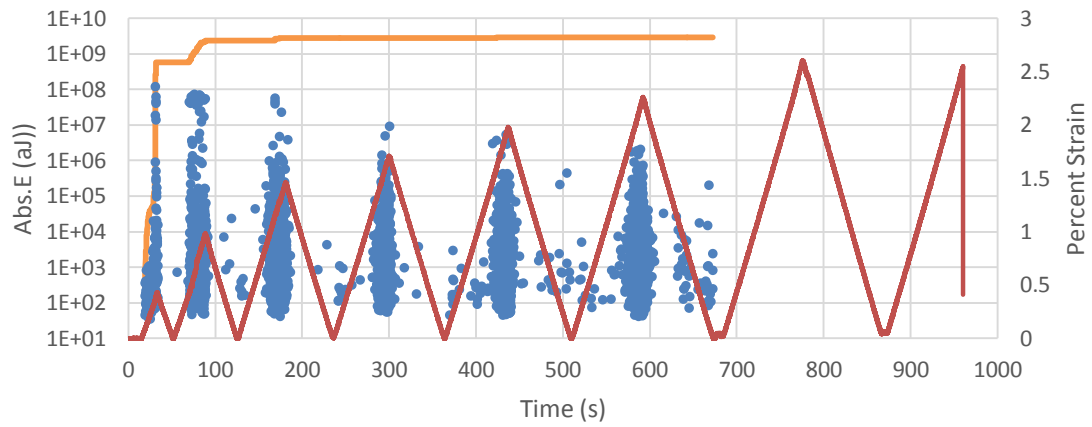




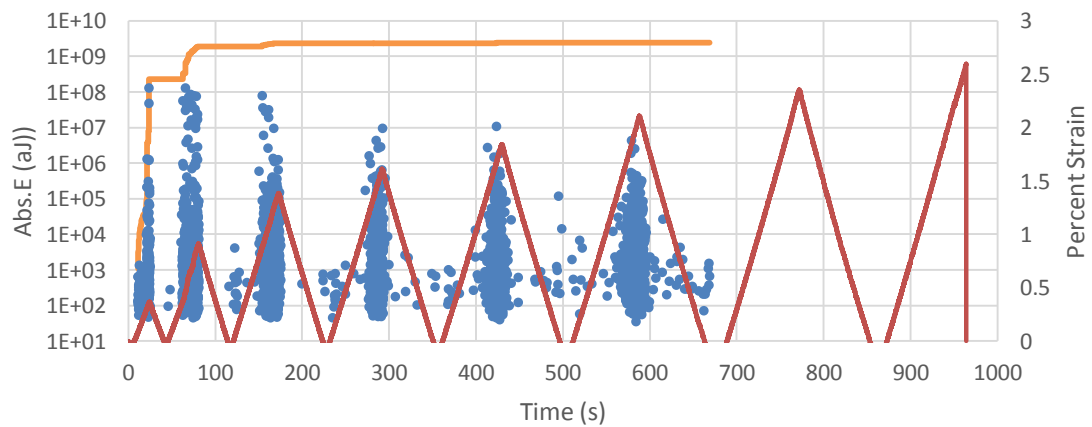
Hit Absolute Energy, 2401_6; Sensors Removed 90% LUR

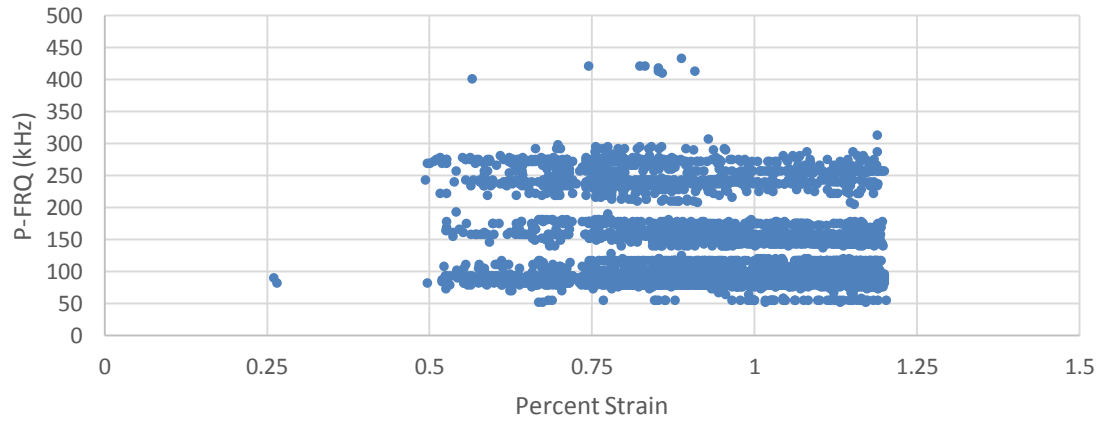
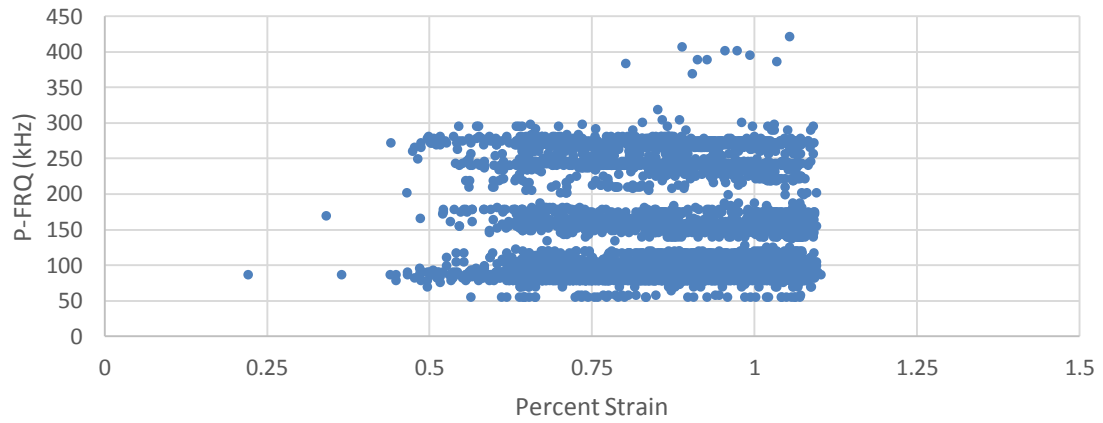
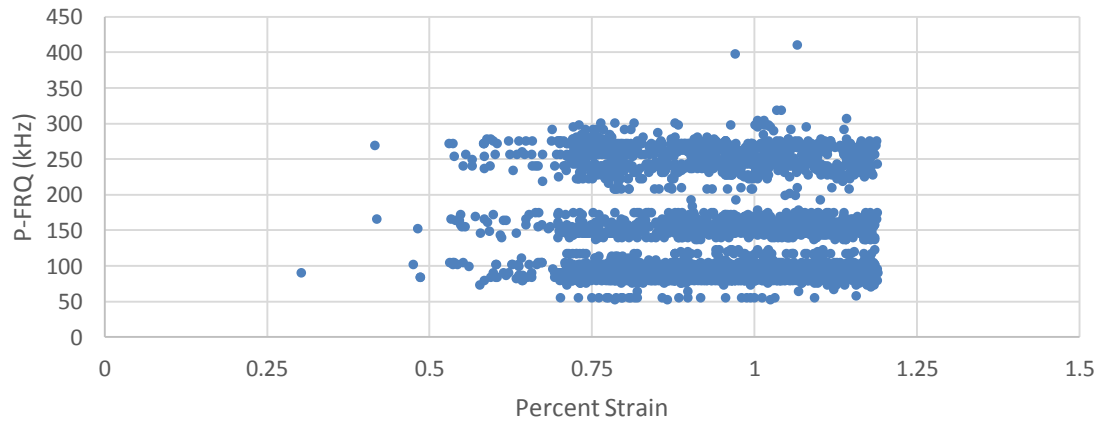


Hit Absolute Energy, 2401_7; Sensors Removed 90% LUR

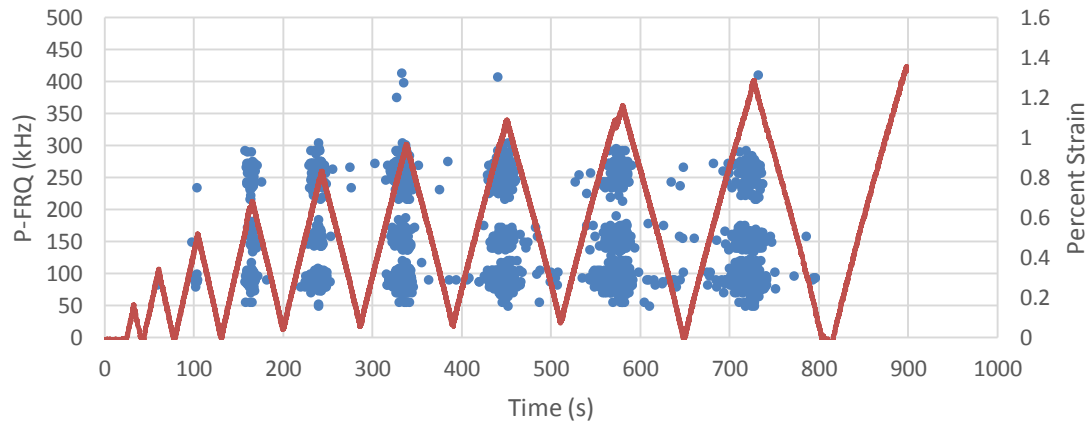


Hit Absolute Energy, 2401_8; Sensors Removed 90% LUR

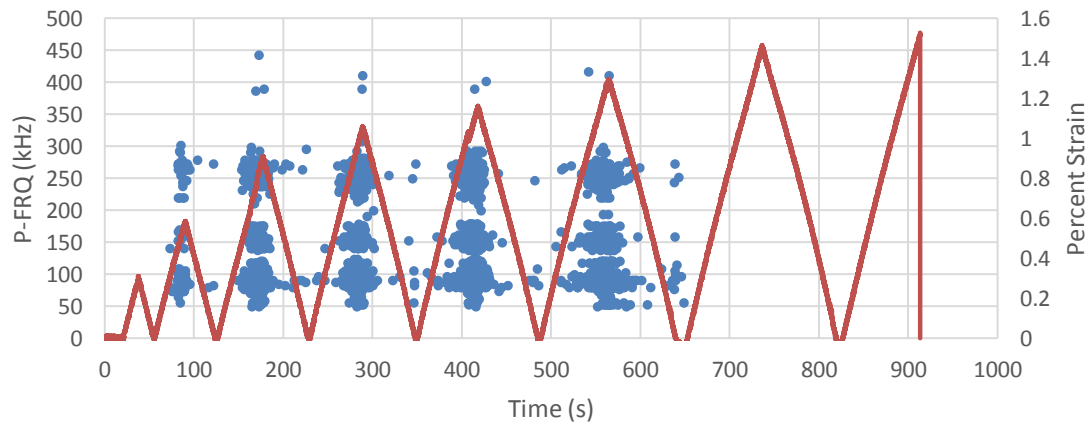


Hit Peak Frequency, 2404_2; Sensors Removed 1.2% ϵ Hit Peak Frequency, 2404_3; Sensors Removed 1.1% ϵ Hit Peak Frequency, 2404_4; Sensors Removed 1.2% ϵ 

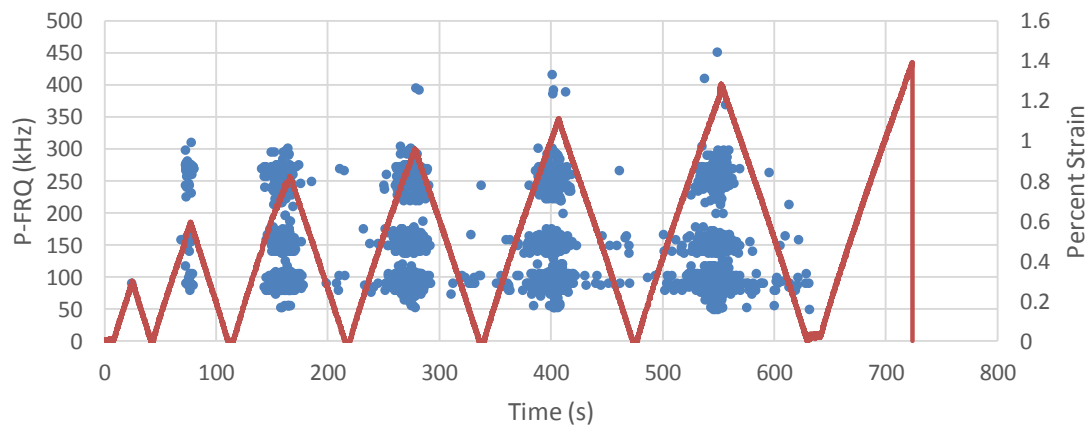
Hit Peak Frequency, 2404_5; Sensors Removed 90% LUR

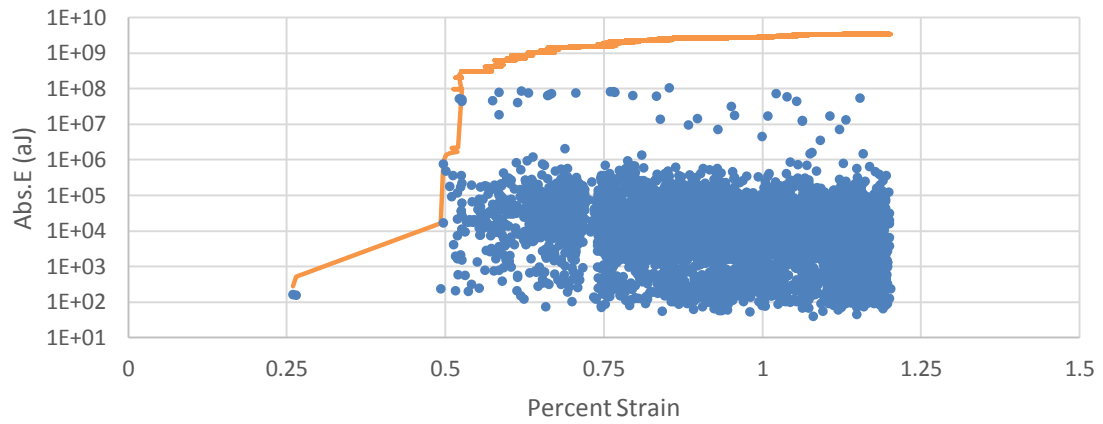
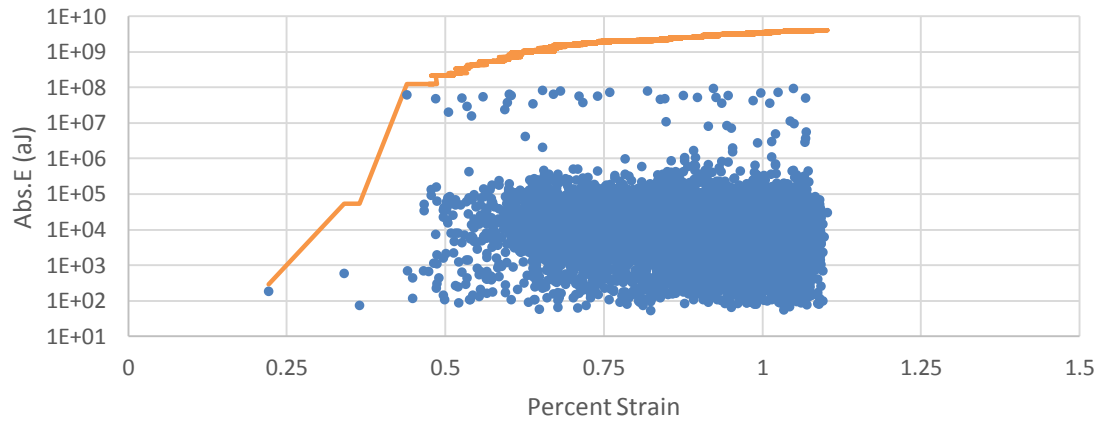
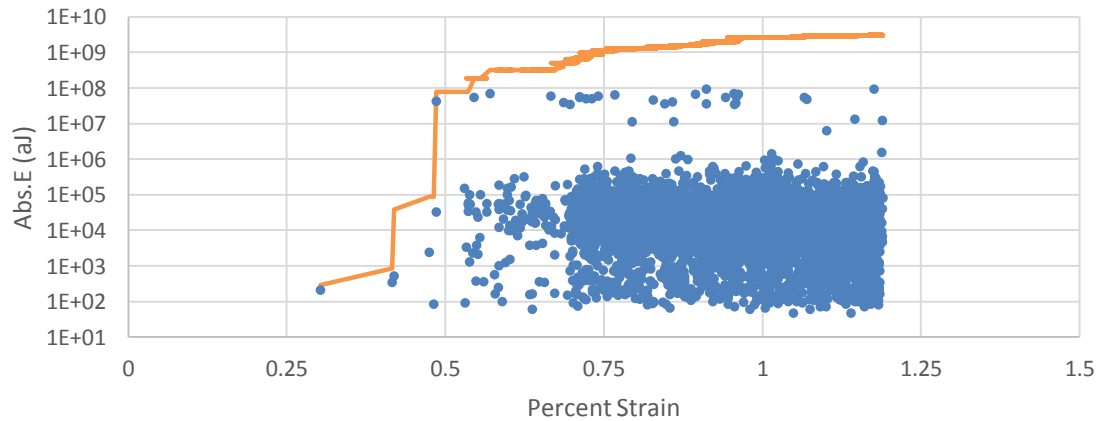


Hit Peak Frequency, 2404_6; Sensors Removed 90% LUR

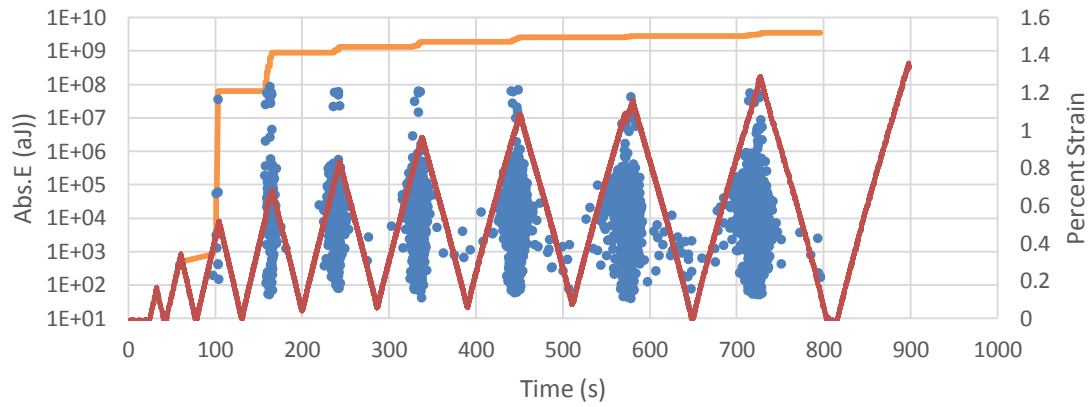


Hit Peak Frequency, 2404_7; Sensors Removed 90% LUR

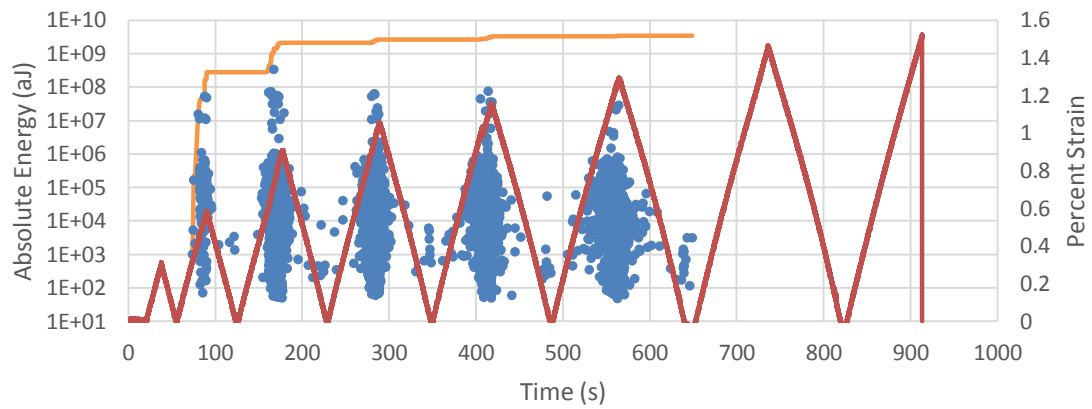


Hit Absolute Energy, 2404_2; Sensors Removed 1.2% ϵ Hit Absolute Energy, 2404_3; Sensors Removed 1.1% ϵ Hit Absolute Energy, 2404_4; Sensors Removed 1.2% ϵ 

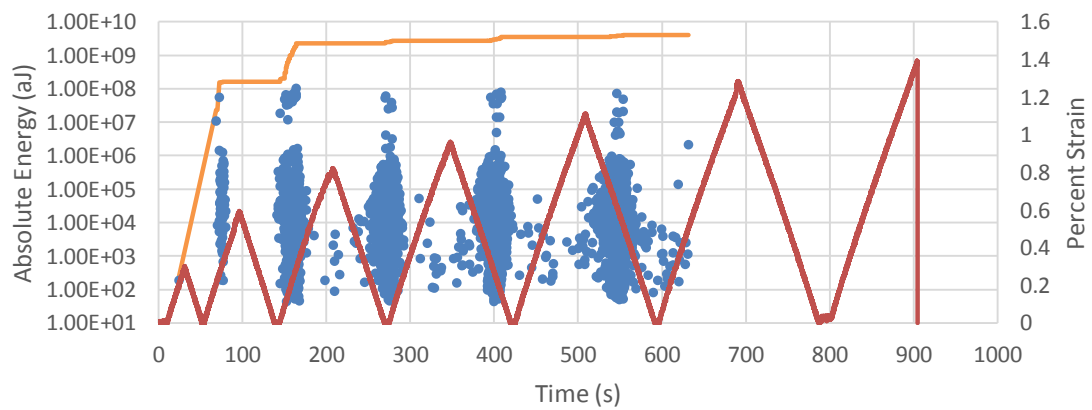
Hit Absolute Energy, 2404_5; Sensors Removed 90% LUR



Hit Absolute Energy, 2404_6; Sensors Removed 90% LUR



Hit Absolute Energy, 2404_7; Sensors Removed 90% LUR



APPENDIX B

MANUFACTURING AND MATERIAL INFO

Laminate Global Number	2388
Laminate Project Descript	AE Plate #5
Technician:	Michael Schuster
Date:	5/29/2014
Layup (top to bottom):	[(90/B)/(0/B)/(B/0)/(B/90)]
Fabric Type #1:	PPG 1250 UD 2026
Fabric Type #2:	
Fabric Type #3:	
Resin System:	Hexion Epikote MGS® RIMR 135, RIMH 1366
Resin Quantity; ml, g:	Totals: 1037.84ml/ 1138.21g Part A: 761.35ml/ 875.55g Part B: 276.49ml/ 262.66g
Process:	Vacuum Bag
Vacuum Pressure (V.P.):	25.2
Peel Ply (P.P.):	Airtech Release Ply Super F (Polyester)
Flow Media (F.M.):	Airtech Greenflow 75
Initial Cure Temperature:	25°C (77°F) -- 48 hrs
Post Cure Temp:	70°C (158°F) -- 8 hrs -- Oven
Plate Size:	20in x 20in
Mix and Degas:	Mixed for 10 min @ 220 RPM; degassed for 10 min @ 25.2 in Hg
Caul Plate:	No
Notes:	REDO: 5/30/14 A:875.88g B:262.66g 214RPM Waited 30min under no vacuum to leak check. Transverse fibers have difficulty filling out, some porosity.

Laminate Global Number	2390
Laminate Project Descript	AE Plate #1
Technician:	Michael Schuster
Date:	6/3/2014
Layup (top to bottom):	[(0/B)/(0/B)/(B/0)/(B/0)]
Fabric Type #1:	PPG 1250 UD 2026
Fabric Type #2:	
Fabric Type #3:	
Resin System:	Hexion Epikote MGS® RIMR 135, RIMH 1366
Resin Quantity; ml, g:	Totals: 1335.61ml/ 1464.78g Part A: 979.79ml/ 1126.76g Part B: 355.82ml/ 338.03g
Process:	Vacuum Bag
Vacuum Pressure (V.P.):	25.2
Peel Ply (P.P.):	Airtech Release Ply Super F (Polyester)
Flow Media (F.M.):	Airtech Greenflow 75
Initial Cure Temperature:	25°C (77°F) -- 48 hrs
Post Cure Temp:	70°C (158°F) -- 8 hrs -- Oven
Plate Size:	29in x 20in
Mix and Degas:	Mixed for 10 min @ 220 RPM; degassed for 10 min @ 25.2 in Hg
Caul Plate:	No
Notes:	A: 1126.9g B: 338.1g Good vacuum, injection.

Laminate Global Number	2393
Laminate Project Descript	AE Plate #3
Technician:	Michael Schuster
Date:	6/4/2014
Layup (top to bottom):	[[+/-45)/(+/-45)/(+/-45)/(+/-45)]
Fabric Type #1:	Vectorply E-BX 0900-10
Fabric Type #2:	
Fabric Type #3:	
Resin System:	Hexion Epikote MGS® RIMR 135, RIMH 1366
Resin Quantity; ml, g:	Totals: 842.96ml/ 924.49g Part A: 618.39ml/ 711.14g Part B: 224.57ml/ 213.34g
Process:	Vacuum Bag
Vacuum Pressure (V.P.):	25.2
Peel Ply (P.P.):	Airtech Release Ply Super F (Polyester)
Flow Media (F.M.):	Airtech Greenflow 75
Initial Cure Temperature:	25°C (77°F) -- 48 hrs
Post Cure Temp:	70°C (158°F) -- 8 hrs -- Oven
Plate Size:	20in x 20in
Mix and Degas:	Mixed for 10 min @ 220 RPM; degassed for 10 min @ 25.2 in Hg
Caul Plate:	No
Notes:	A: 711.10g B: 213.45g Very good, quick injection. Very thin laminate.

Laminate Global Number	2395
Laminate Project Descript	AE Plate #2
Technician:	Michael Schuster
Date:	6/6/2014
Layup (top to bottom):	[(O/B)/(B/O)]
Fabric Type #1:	Vectorply E-LT5500-10
Fabric Type #2:	
Fabric Type #3:	
Resin System:	Hexion Epikote MGS® RIMR 135, RIMH 1366
Resin Quantity; ml, g:	Totals: 1216.98ml/ 1334.69g Part A: 892.77ml/ 1026.68g Part B: 324.22ml/ 308.01g
Process:	Vacuum Bag
Vacuum Pressure (V.P.):	25.2
Peel Ply (P.P.):	Airtech Release Ply Super F (Polyester)
Flow Media (F.M.):	Airtech Greenflow 75
Initial Cure Temperature:	25°C (77°F) -- 48 hrs
Post Cure Temp:	70°C (158°F) -- 8 hrs -- Oven
Plate Size:	30in x 20in
Mix and Degas:	Mixed for 10 min @ 220 RPM; degassed for 10 min @ 25.2 in Hg
Caul Plate:	No
Notes:	Increase in reaction time and deeper blue color noticed in new hardener. Part A has been from same resin rec'd Spring 2014. Part B Lot: LL3C0045. 1 Glass fiber leak under tacky-tape.

Laminate Global Number	2399
Laminate Project Descript	AE Plate #4
Technician:	Michael Schuster
Date:	6/11/2014
Layup (top to bottom):	[(O/B)/(B/O)]
Fabric Type #1:	Vectorply CLA 2012
Fabric Type #2:	
Fabric Type #3:	
Resin System:	Hexion Epikote MGS® RIMR 135, RIMH 1366
Resin Quantity, ml, g:	Totals: 1123.88ml/ 1232.58g Part A: 824.47ml/ 948.14g Part B: 299.41ml/ 284.44g
Process:	Vacuum Bag
Vacuum Pressure (V.P.):	25.2
Peel Ply (P.P.):	Airtech Release Ply Super F (Polyester)
Flow Media (F.M.):	Airtech Greenflow 75
Initial Cure Temperature:	25°C (77°F) -- 48 hrs
Post Cure Temp:	70°C (158°F) -- 8 hrs -- Oven
Plate Size:	30in x 20in
Mix and Degas:	Mixed for 10 min @ 220 RPM; degassed for 10 min @ 25.2 in Hg
Caul Plate:	No
Notes:	A: 948.64g B: 288.44g LOT: LL3C0045 Good shoot, moderate bubbling in vacuum port but no leak noticeable.

Laminate Global Number	2401
Laminate Project Descript	AE Plate #6 REDO
Technician:	Michael Schuster
Date:	6/12/2014
Layup (top to bottom):	[(0/B)/(90/B)/(B/90)/(B/0)]
Fabric Type #1:	Vectorply E-LT5500-10
Fabric Type #2:	
Fabric Type #3:	
Resin System:	Hexion Epikote MGS® RIMR 135, RIMH 1366
Resin Quantity, ml, g:	Totals: 1229.79ml/ 1348.74g Part A: 902.17ml/ 1037.49g Part B: 327.63ml/ 311.25g
Process:	Vacuum Bag
Vacuum Pressure (V.P.):	25.2
Peel Ply (P.P.):	Airtech Release Ply Super F (Polyester)
Flow Media (F.M.):	Airtech Greenflow 75
Initial Cure Temperature:	25°C (77°F) -- 48 hrs
Post Cure Temp:	70°C (158°F) -- 8 hrs -- Oven
Plate Size:	20in x 20in
Mix and Degas:	Mixed for 10 min @ 220 RPM; degassed for 10 min @ 25.2 in Hg
Caul Plate:	No
Notes:	A: 1038.2g B: 313.0g LOT: L260125, new part B very blue.

Laminate Global Number	2404
Laminate Project Descript	AE Plate #8
Technician:	Michael Schuster
Date:	6/18/2014
Layup (top to bottom):	[(0/B)/(90/B)/(B/90)/(B/0)]
Fabric Type #1:	Vectorply CLA 2012
Fabric Type #2:	
Fabric Type #3:	
Resin System:	Hexion Epikote MGS® RIMR 135, RIMH 1366
Resin Quantity, ml, g:	Totals: 1105.66ml/ 1212.6g Part A: 811.1ml/ 932.77g Part B: 294.56ml/ 279.83g
Process:	Vacuum Bag
Vacuum Pressure (V.P.):	25.2
Peel Ply (P.P.):	Airtech Release Ply Super F (Polyester)
Flow Media (F.M.):	Airtech Greenflow 75
Initial Cure Temperature:	25°C (77°F) -- 48 hrs
Post Cure Temp:	70°C (158°F) -- 8 hrs -- Oven
Plate Size:	20in x 20in
Mix and Degas:	Mixed for 10 min @ 220 RPM; degassed for 10 min @ 25.2 in Hg
Caul Plate:	No
Notes:	A:933.3g B:279.79g LOT:LL200125 Lots of small bubbles in flow media during injection, formed large bubbles in flow media after cure. Poor degassing? Laminate ok.

2558 4145

2558
4145

Plate 2388: Laminate and Coupon Markup

[illegible]

Plate 2390: Laminate and Coupon Markup

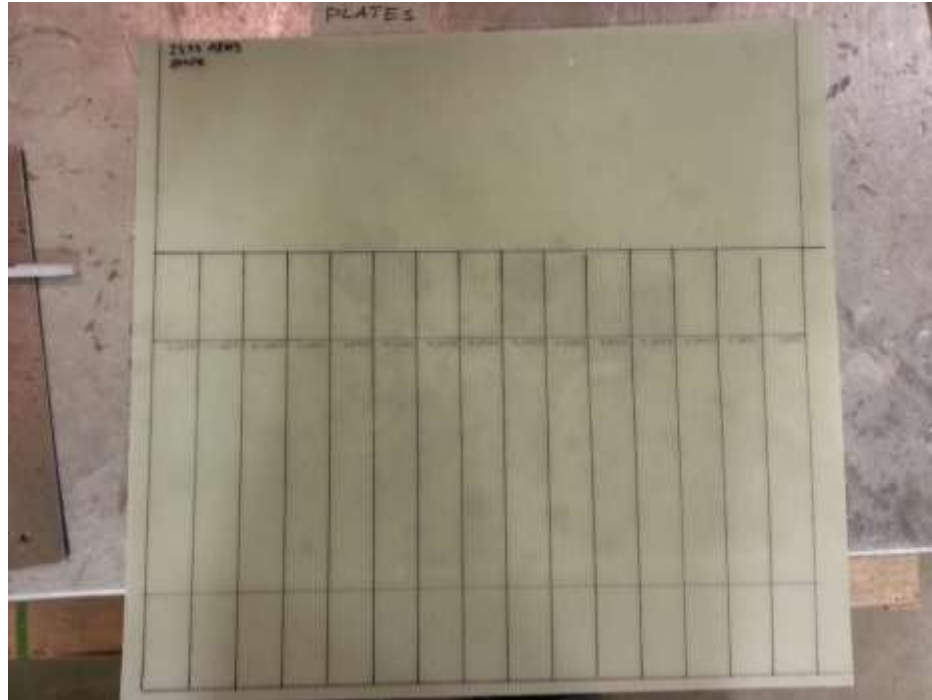


Plate 2393: Laminated and Coupon Markup

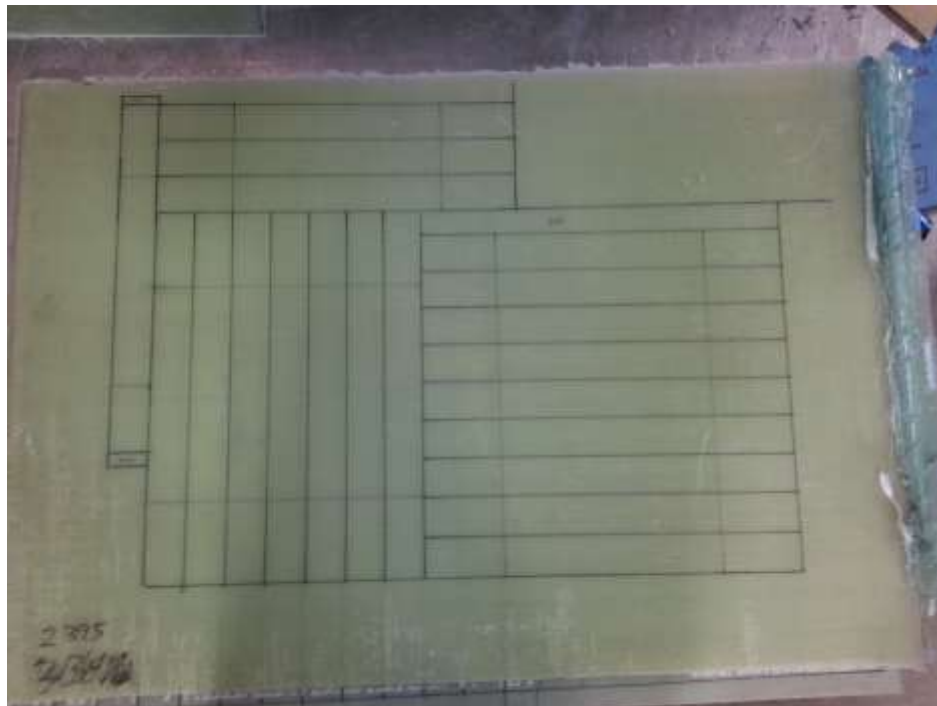


Plate 2395: Laminated and Coupon Markup

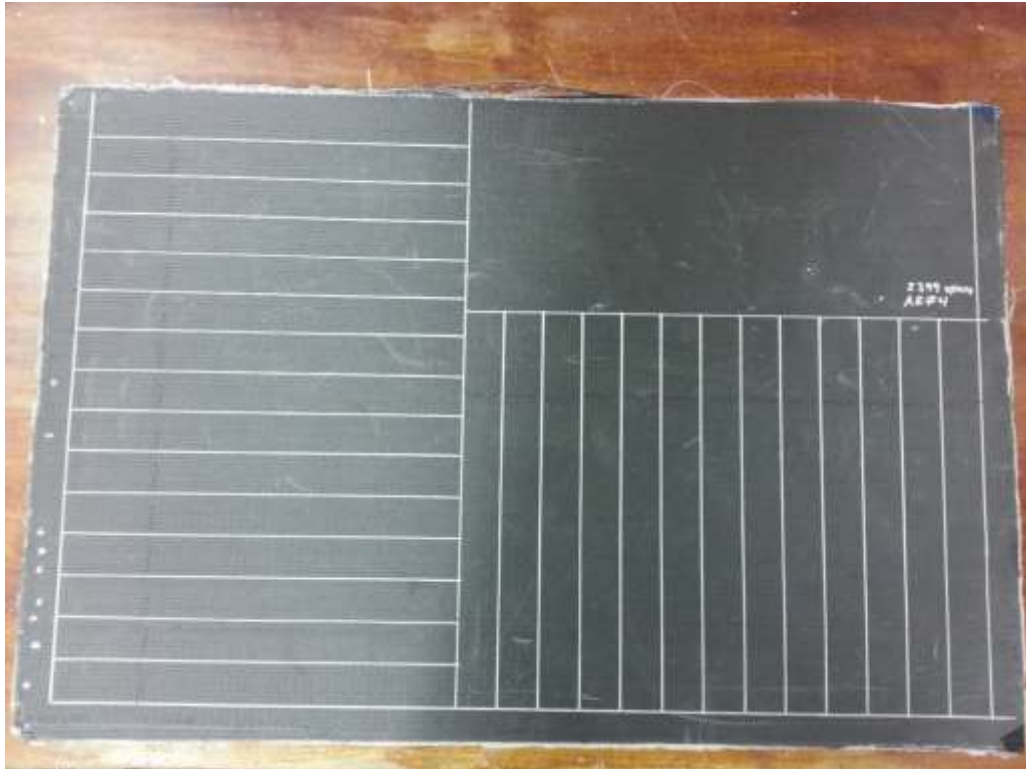


Plate 2399: Laminate and Coupon Markup



Plate 2401: Laminate and Coupon Markup

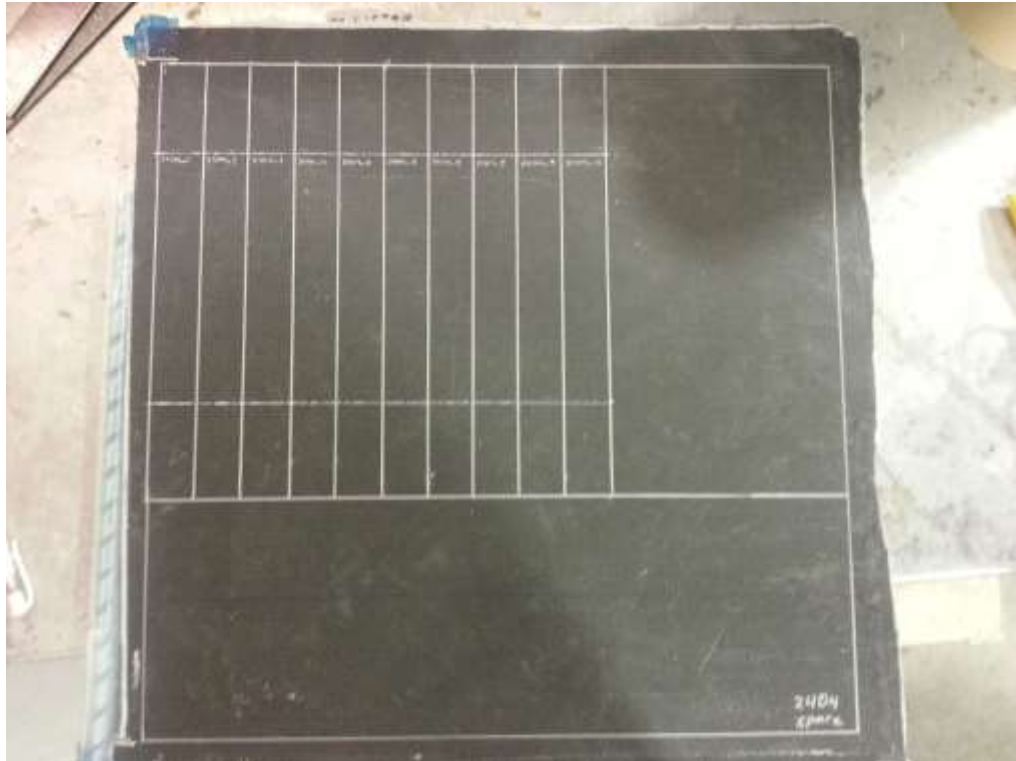


Plate 2404: Laminate and Coupon Markup

SPECIFICATION**Product:** L 1200/G50-E07

Rev.data:

Layers

Layer	Material 1								Area Weight [g/m²]
	Tex	Material Type							
0°	2400	E-Glass							1152
90°	200	E-Glass							52
CS	2400	E-Glass							50
Stitch	7.6	Polyester/							7
Nominal area weight:									1251
Theoretical width (mm):									3280 mm
Average area weight:									1250

Resin Compatibility *

UP, EP, VE

Processing and Control

Binding/ Stitch Information		Quality Assurance / Test		
Stitch type:	Tricot	Weight:	ISO 4605	
Stitch length:	5mm / Stitch	Loss of Ignition:	ISO 1867	
Space between needles:	3.57mm	Moisture content:	ISO 3344	
Pilot yarn colour:	Violet			

Logistics

Roll length:	180m	Tube size:	76mm
Roll width:	Various widths	Pallet size:	120x130
Roll weight:		Rolls per pallet:	
Roll direction:	Matt facing roll	Stacking:	Pyramide
Max fringe length:	± 10mm		

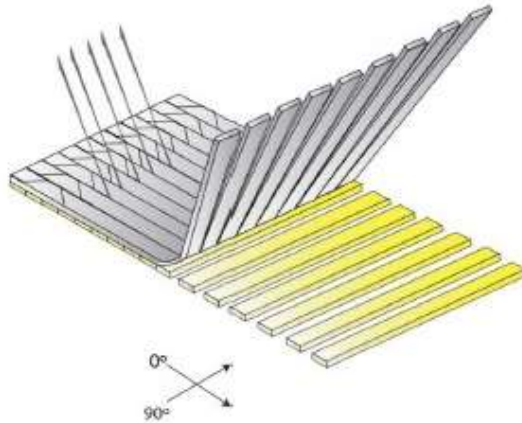
Devold AMT Acceptance Criteria

1. Area weight should be within ±3% of average value
2. Fibre orientation should be within ±2° of nominal value
3. There should be no dirt or oil spots
4. Gap wider than 5mm will be considered as a defect (measured 90° on roving)
5. No damage on outer roving or stitch yarn due to cutting edges

* UP: Polyester; EP: Epoxy; VE: Vinyl ester; ac: Anhydride cure

** CpE: Counts per ends, yarns/cm

Comment
0° k/glk 90° ±45°



E-LT 5500

Fiber Type: E-Glass
Architecture: 0/90 Biaxial
Dry Thickness: 0.060 in. / 1.52 mm
Total Weight: 54.33 oz/sq.yd / 1842 g/sq.m

Roll Specifications			Fiber Architecture Data	
Roll Width:	Roll Weight:	Roll Length:	0 ° :	50.97 oz/sq.yd / 1728 g/sq.m
50 in / 1270 mm	269 lb / 122 kg	56 yd / 51 m	45 ° :	n/a
			90 ° :	3.36 oz/sq.yd / 114 g/sq.m
			-45 ° :	n/a
			Chopped Mat :	n/a

1: Packaging: box or bag.
2: Weights do not include polyester stitching.

Laminated Properties

0 °

0 °

Laminate Weight		
(lb/sq.ft)	E-LT 5500 Resin Infused	E-LT 5500 Open Mold
Fiber	0.38	0.38
Resin	0.16	0.31
Total	0.54	0.69

Physical Properties		
	E-LT 5500 Resin Infused	E-LT 5500 Open Mold
Density (g/cc)	1.90	1.69
Fiber Content (% by Wt.)	70%	55%
Thickness (in)	0.054	0.078

Laminate Moduli		
(MSI)	E-LT 5500 Resin Infused	E-LT 5500 Open Mold
Ex	6.57	4.76
Ey	2.44	1.69
Gxy	0.66	0.47
Ex,flex.	6.24	4.53
Ey,flex.	2.32	1.61
Ultimate Stress		
(KSI)	E-LT 5500 Resin Infused	E-LT 5500 Open Mold
Long. Ten.	120	87
Long. Comp.	81	59
Trans. Ten.	47	32
Trans. Comp.	32	22
In-Plane Shear	13	9
Long. Flex.	115	83
Trans. Flex.	44	31
In-Plane Stiffness, "EA"		
10 ³ lb/in	E-LT 5500 Resin Infused	E-LT 5500 Open Mold
(EA)x	358	372
(EA)y	133	132
(GA)xy	36	37
Ultimate In-Plane Load		
lb/in	E-LT 5500 Resin Infused	E-LT 5500 Open Mold
Long. Ten.	6,558	6,810
Long. Comp.	4,439	4,609
Trans. Ten.	2,538	2,516
Trans. Comp.	1,718	1,703
In-Plane Shear	716	733

Notes:

- 1: Resin Infused laminate made with a poly / vinyl ester resin blend.
- 2: Open mold laminate made with poly / vinyl ester resin blend.
- 3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.



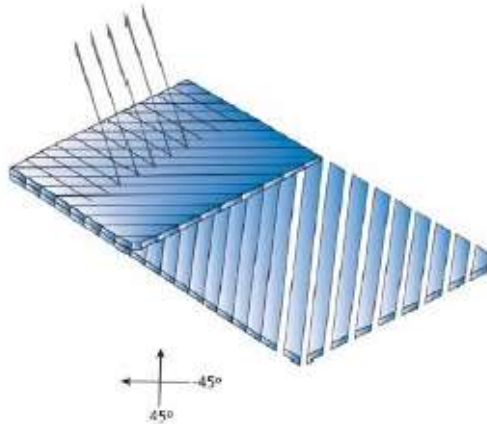
3500 Lakewood Dr. Phenix City, AL 36867 tel. 334 291 7704 fax. 334 291 7743

REV: 5/3/2011

Disclaimer:

As a service to customers, Vectorply Corporation ("VP") may provide computer-generated predictions of the physical performance of a product using a reinforcement fabric produced by VP in combination with other materials or systems.

VP makes no warranty whatsoever as to the accuracy of any such predicted physical performance, and customer acknowledges that customer is solely responsible for determining the performance and fitness for a particular use of any product produced by customer utilizing a fabric or material produced or manufactured by VP. Specifications of reinforcements may change without notice.



E-BX 0900

Fiber Type: E-Glass
 Architecture: 45/-45 Double Bias
 Dry Thickness: 0.012 in. / 0.30 mm
 Total Weight: 9.86 oz/sq.yd / 334 g/sq.m

Roll Specifications			Fiber Architecture Data
Roll Width:	Roll Weight:	Roll Length:	0 ° : n/a
50 in / 1270 mm	194 lb / 88 kg	210 yd / 192 m	45 ° : 4.93 oz/sq.yd / 167 g/sq.m
			90 ° : n/a
			-45 ° : 4.93 oz/sq.yd / 167 g/sq.m
			Chopped Mat : n/a

1: Packaging: box or bag.

2: Weights do not include polyester stitching.

Laminated Properties

45 °

45 °

Laminate Weight (lb/sq.ft)	E-BX 0900 Resin Infused	E-BX 0900 Open Mold
Fiber	0.07	0.07
Resin	0.03	0.06
Total	0.10	0.12

Physical Properties

	E-BX 0900 Resin Infused	E-BX 0900 Open Mold
Density (g/cc)	1.90	1.69
Fiber Content (% by Wt.)	70%	55%
Thickness (in)	0.010	0.014

Laminate Moduli		
(MSI)	E-BX 0900 Resin Infused	E-BX 0900 Open Mold
Ex	3.91	2.82
Ey	3.91	2.82
Gxy	0.93	0.64
Ex,flex.	3.71	2.68
Ey,flex.	3.71	2.68

Ultimate Stress		
(KSI)	E-BX 0900 Resin Infused	E-BX 0900 Open Mold
Long. Ten.	74	53
Long. Comp.	74	53
Trans. Ten.	74	53
Trans. Comp.	74	53
In-Plane Shear	19	13
Long. Flex.	88	64
Trans. Flex.	88	64

In-Plane Stiffness, "EA"		
10 ^{^3} lb/in	E-BX 0900 Resin Infused	E-BX 0900 Open Mold
(EA)x	39	40
(EA)y	39	40
(GA)xy	9	9

Ultimate In-Plane Load		
lb/in	E-BX 0900 Resin Infused	E-BX 0900 Open Mold
Long. Ten.	732	757
Long. Comp.	732	757
Trans. Ten.	732	757
Trans. Comp.	732	757
In-Plane Shear	185	180

Notes:

- 1: Resin infused laminate made with a poly / vinyl ester resin blend.
- 2: Open mold laminate made with poly / vinyl ester resin blend.
- 3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.



3500 Lakewood Dr. Phenix City, AL 36867 tel. 334 291 7704 fax. 334 291 7743

REV: 5/3/2011

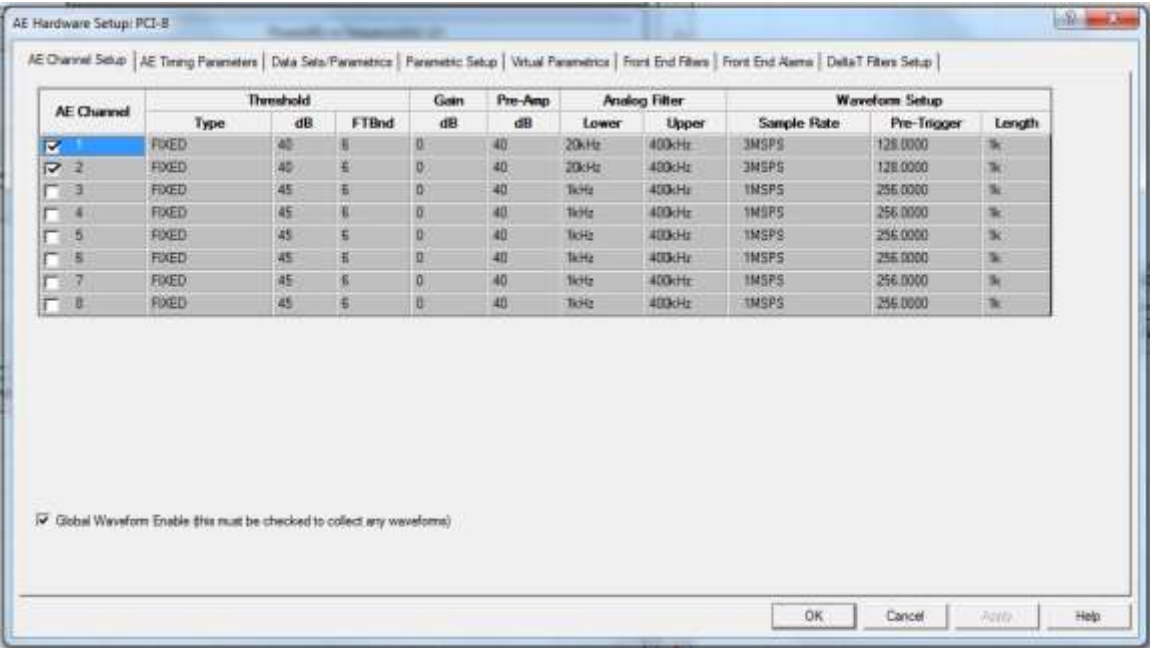
Disclaimer:

As a service to customers, Vectorply Corporation ("VP") may provide computer-generated predictions of the physical performance of a product using a reinforcement fabric produced by VP in combination with other materials or systems.

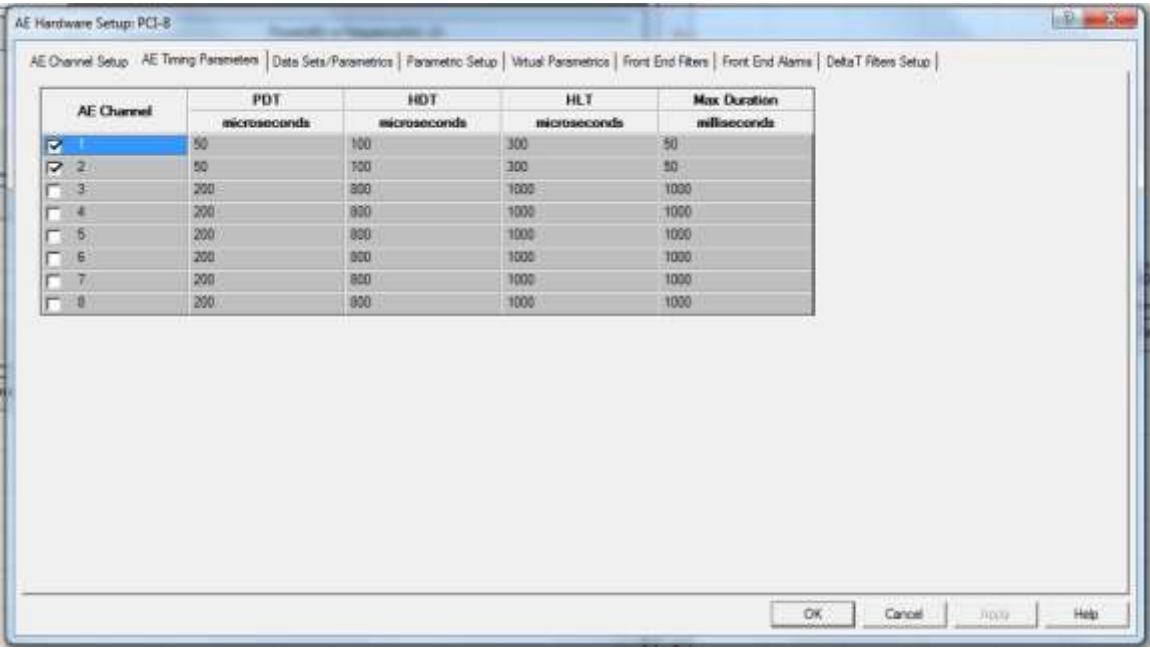
VP makes no warranty whatsoever as to the accuracy of any such predicted physical performance, and customer acknowledges that customer is solely responsible for determining the performance and fitness for a particular use of any product produced by customer utilizing a fabric or material produced or manufactured by VP. Specifications of reinforcements may change without notice.

APPENDIX C

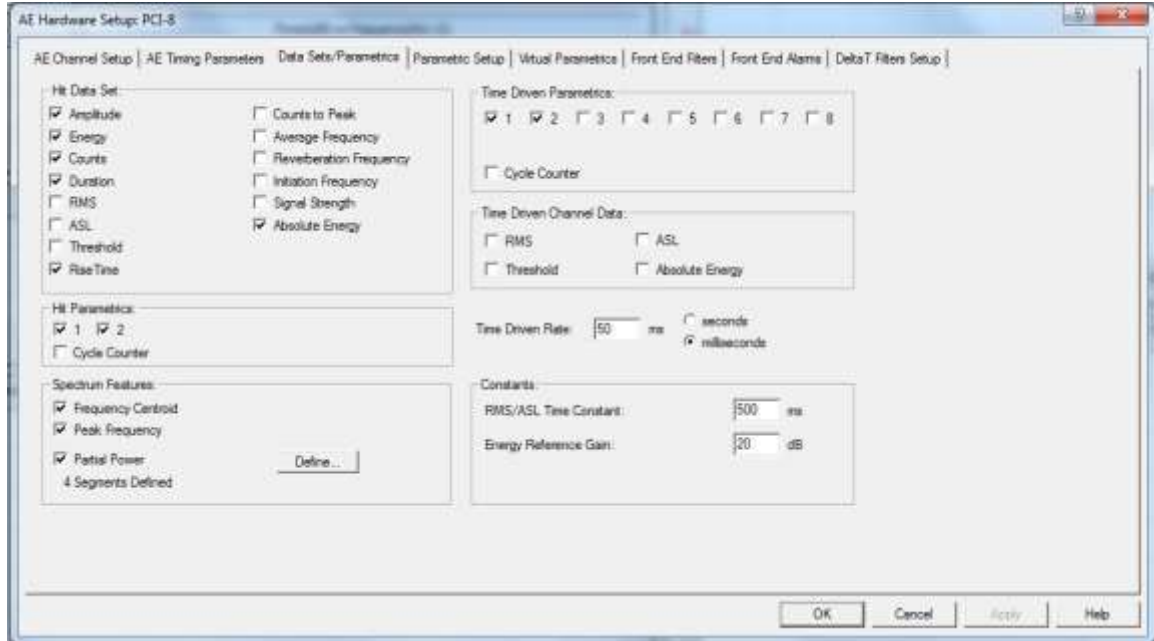
AEWIN SOFTWARE SETTINGS



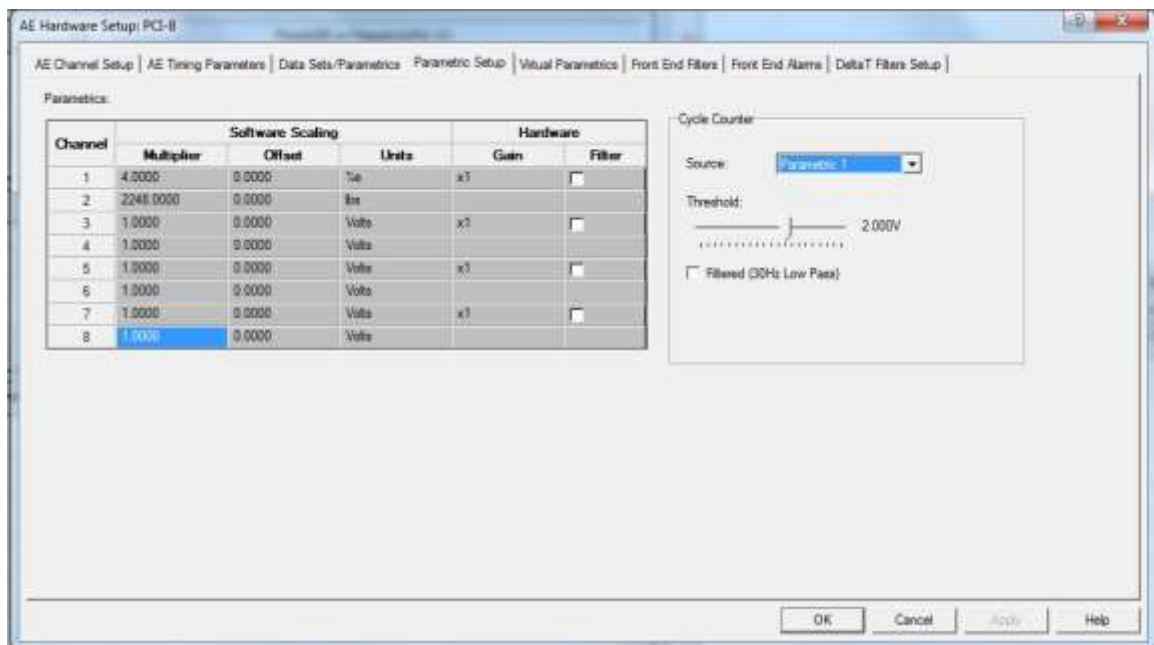
AEWin Software Setup: AE Channel Setup



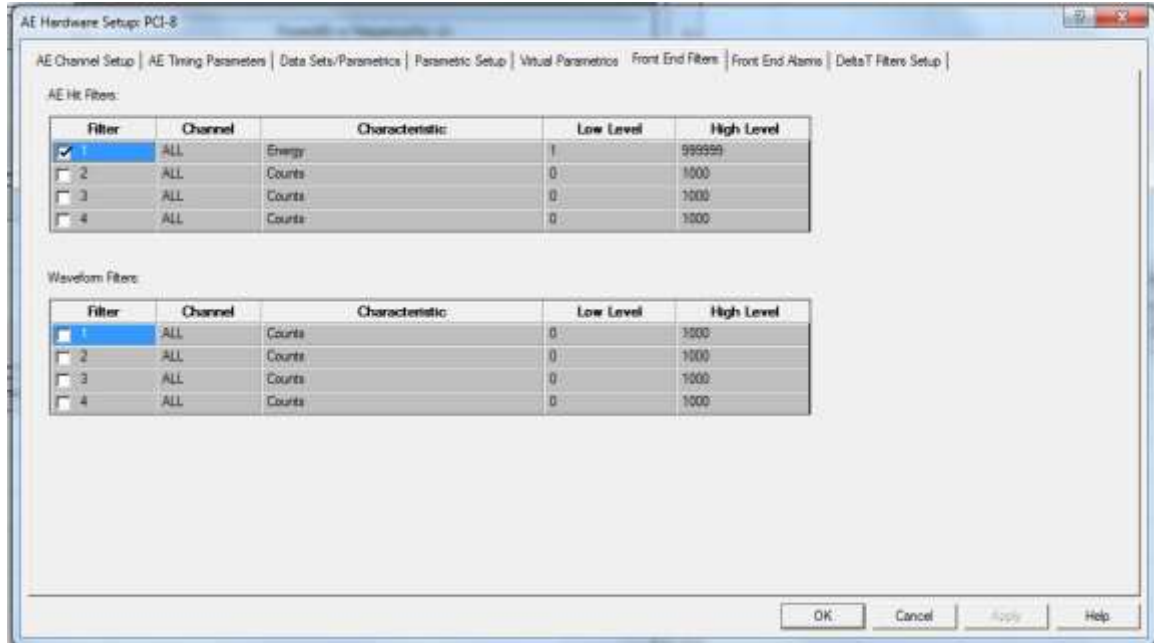
AEWin Software Setup: AE Timing Parameters



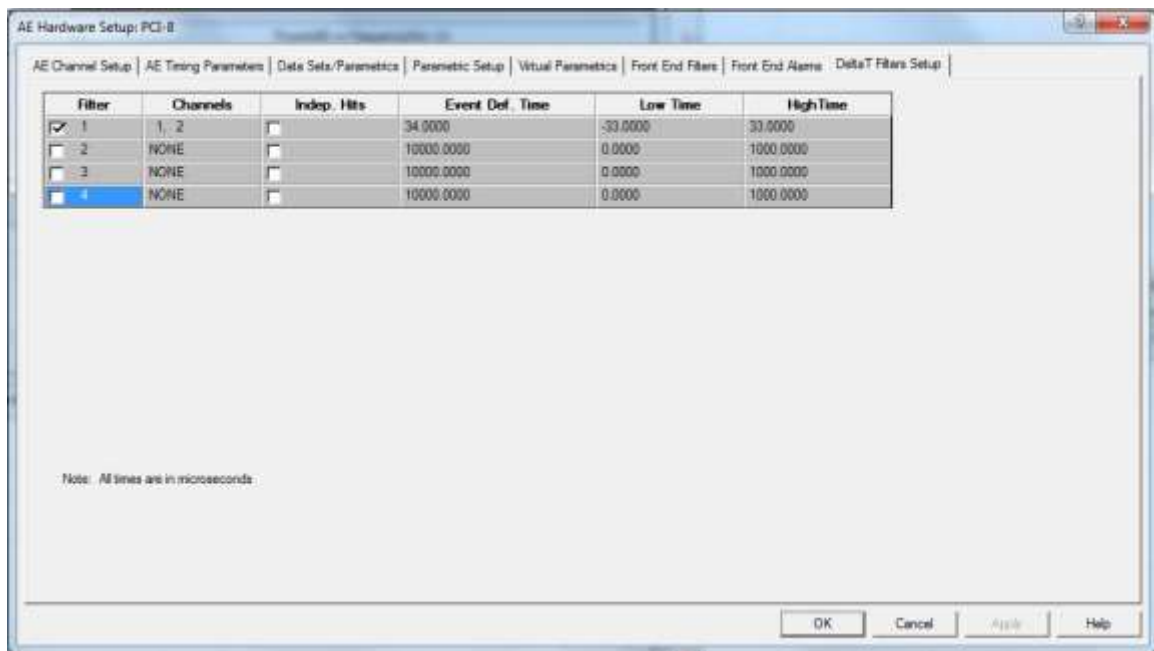
AEWin Software Setup: Data Sets/Parametrics



AEWin Software Setup: Parametric Setup



AEWin Software Setup: Front End Filters



AEWin Software Setup: DeltaT Filters Setup

Location Setup

General | Timing | Options

Group #	Show All Points	Location Type	Wave Velocity (DU/Sec)	Event Definition Value (DU)	Event Lockout Value (DU)	Overall Value (DU)	Timing Strategies	Hits/Event		Max Iterations
								Min	Max	
☒ 1	☐	Linear	2400000.00	140.0000	0.0000	30.0000	Primary	2	2	0
☐ 2	☐	Linear	2400000.00	140.0000	0.0000	30.0000	Primary	2	2	0
☐ 3	☐	Linear	2400000.00	140.0000	0.0000	30.0000	Primary	2	2	0
☐ 4	☐	Linear	2400000.00	140.0000	0.0000	30.0000	Primary	2	2	0
☐ 5	☐	Linear	2400000.00	140.0000	0.0000	30.0000	Primary	2	2	0
☐ 6	☐	Linear	2400000.00	140.0000	0.0000	30.0000	Primary	2	2	0
☒ 7	☐	Linear	2400000.00	140.0000	0.0000	30.0000	Primary	2	2	0

Guard Sensors... Material... Attenuation... Distance Units (DU)... Millimeters Location View... OK Cancel

AEWin Software Location Setup: General

AE Sensor Placement

X 147.8 [Millimeters] Y 32.0 [Millimeters]

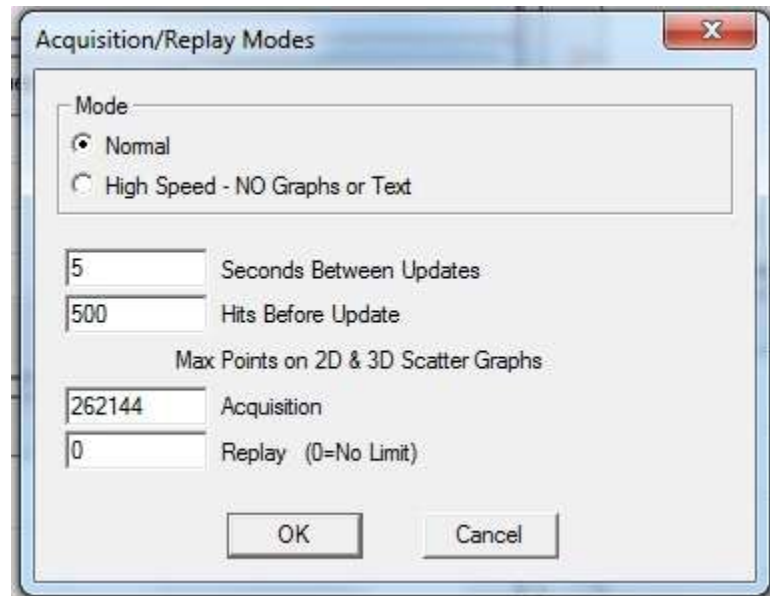
Sensors | Welds | Nozzles

Channel	X	Y
1	25.150	15.000
2	152.650	15.000

Group # 1 Structure Plate Dimensions Import Graphic OK Cancel

Graphic ☒ 3D View ☐ Grid ☒ Welds ☐ Nozzles ☐ Sensors ☒ Attenuation ☐ Lock Sensors ☒

AEWin Software Location Setup: Location View



AEWin Software Acquisition/Replay Mode Settings