Low-velocity impact damage detection using coda waves on CFRP laminates

Subal Sharma

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Low-velocity impact damage detection using coda waves on CFRP laminates

by

Subal Sharma

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Aerospace Engineering

Program of Study Committee:
Vinay Dayal, Major Professor
Leifur Leifsson
Scott Chumbley

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2021

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ABSTRACT

Coda waves have been shown to be sensitive to lab-controlled defects such as very small holes in fibrous composite material. In the real world, damages are subtler and more irregular. The main objective of this work is to investigate coda wave sensitivity to low-velocity impact damages. The emphasis is to detect the presence of barely visible impact damage using ultrasonic waves. The estimation of the size of the damage is not the objective. This incipient damage state can grow into bigger flaws over the structure life and hence is the objective of interest. Five differential features, previously used in similar work, have been utilized to detect realistic impact damages on carbon fiber composites. Quasi-isotropic composite laminates were subjected to low-velocity impact energy ranging from 2J to 4.5J. Not all differential features have shown promising results, but some features could detect the presence of damage. It is observed that ply orientation can be a deterministic factor for indicating damages. The size and shape of the impact damage have been characterized using ultrasonic c-scans. Results indicate that coda waves are sensitive to small impact damages.
CHAPTER 1. INTRODUCTION

In the era of smart devices, smart structures, smart vehicle technology is moving forward with motivation to create smart material. The world is moving to a technology where objects can communicate their health condition to the user. Non-destructive testing is becoming an integral & critical part of the engineering system. However, inspections usually are time-consuming, complex to analyze results, and expensive. To address these drawbacks, researchers have been improving inspection methods. Structural health monitoring (SHM) is booming in the research area. Researchers have tried to analyze signals from SHM to extract health information, localizing critical areas for repair or detailed inspection for damage characterization. Some researchers approached the issue by changing or improving the inspection methods. The presented study aims to provide Coda waves capability to detect impact damage of low velocity on carbon fiber reinforced polymer (CFRP). Scheduled inspections miss out on damages or manufacturing defects present in the non-critical area of a structure. Defects often miss out on fibrous composites, which critically reduces the designed composite mechanical advantages. These issues motivate this work to address quick inspections, even in the non-critical areas, before thorough inspection on critical areas.

Composites have an increased requirement in many industries. The aerospace sector is switching to composites for their superior advantage over metals. Composite usage has increased from 2% in 1978 to about 50% presently. Boeing 787 aircraft claims composite usage of 50% by weight, shown in Figure 1-1. Environmental effects and CO₂ emissions are also a major factor for the aerospace industry to switch for composite material. International Civil Aviation Organization (ICAO) declared a CO₂ emission cap in 2009 to provide carbon-neutral growth, starting in 2020 (Wood et al., 2019). Composites attract engineers for their various advantages
like, light-weight, specific strength and stiffness, fatigue & corrosion resistance, tailored directional strength, easy to achieve complex geometries, and low dielectric conductivity (Mangalgiri, 1999). However, all advantages aside, composites at the same time have weak interfaces, presence of manufacturing flaws, and are highly susceptible to impact damages.

![Boeing 787 material usage diagram](image)

**Figure 1-1: Boeing 787 material usage diagram**

One type of damage that occurs in composites is barely visible impact damages (BVID). These can be defined as impact damages that are not visible with naked eyes. They mainly occur due to impact by runway debris, hail-strike, bird-strike, and tool drops. The damages with high velocity impact leave visible damage on the surface, whereas in the case of low-velocity impact, damage usually occurs inside the laminate, which is not visible to the eyes. This becomes critical because it can reduce compression strength up to 60% (Mangalgiri, 1999). High-velocity impacts cause energy to dissipate over a small area. In contrast, low-velocity impact relatively has a longer contact time, causing dispersion of energy away from the point of contact (Ali et al., 2020). This causes delamination in the internal structure of the laminate. Delamination occurs in the ply interface where matrix fail induces interlaminar cracks. Therefore, BVID is not visible on the surface yet, composite strength may decrease substantially.
The non-destructive testing method is used to inspect such damages. But inspecting larger areas is not an easy and quick task. Usually, NDT inspections are carried out on critical areas like joints, leading edge of aircraft wings, etc. It is possible that BVIDs may go undetected during a scheduled inspection. Presently, damage tolerance for most civilian aircraft is regulated by Federal Aviation Administration (FAA). FAA sets a limit on damages and divided them into five categories. BVID falls under category 1, which is included with the manufacturing defects. According to FAA, BVID must be above the ultimate load with specified lifetimes testing (U.S. Department of Transportation. Federal Aviation Administration & Federal Aviation Administration, 2012). Figure 1-2 outlines the damage tolerance for various categories of damage. Category 1 includes those damages which go undetected by scheduled inspection and allowable manufacturing defects. Including design tolerances of such defects with composite inherent damage tolerance thresholds make designers over design components (Livings, 2017).

![Figure 1-2: Schematic of damage tolerance for designing composite material by FAA](image)

Composite damage characterization and detection are complex since failure can occur in the matrix, fibers, fiber-matrix interface, or interlaminar region and under tensile or compressive
Various NDT techniques on composites need the damage or defect to be directly in the path of inspection. These techniques indicate the change in parameters to the inspector, indicating damage.

Ultrasonic testing is no doubt a highly reliable method to do non-destructive testing. However, it is time-consuming and a tedious job. Scanning generally is carried out on failure-prone critical joints, surfaces, welded areas, etc. Damages that may be existing in non-scanned areas, can easily go undetected. The incident of the United Airlines flight 232 crash teaches us the importance of defect detection. On July 19, 1989, United Airlines flight 232 crashes during an impossible landing at Sioux City, Iowa killing 112 out of 296 passengers and crew on board. The aftermath of the crash conducted by the National Transportation Safety Board (NTSB) concluded that the initial cause was a manufacturing defect of titanium alloy fan disk missed during NDT inspection performed by General Electric Aircraft Engines. Fatigue failure occurred in the fan disk defect due to stress experienced during full thrust engine power conditions. The crack further led to damaging the hydraulic system of the aircraft and eventually failing both engines. This catastrophic incident could have been prevented if NDT inspections were performed accurately.

Another incident relating to the undetected manufacturing flaw on a high-speed train wheel in Germany crashed into a road bridge on June 3, 1998. In this accident, 101 people were killed, with 88 severely injured, and considered the worst rail disaster in Germany's history. On one wheel, a fatigue crack was formed at low-stress levels. The crack propagated as the train was running at a high speed of 250 kmph. The final fracture split the wheel off after the crack propagated until 80% of the cross-section. The weaker spot could have been detected if non-destructive testing were carried out on regular service checks.
Figure 1-3: (a) Train disaster of Eschede, and (b) United flight 232 crash

Ultrasonic guided waves travel farther than bulk waves, and upon interaction with the damage, they generate mechanical vibrations. Limitations to guided waves were that damage must be in the propagation path of the transducer, and individual modes and echoes need identification and interpretation (Michaels, 2008).

Coda waves (also called diffuse waves) overcome the limitations of guided waves. They are easy to generate, and wave modes are not required to be specified (Michaels & Michaels, 2005)(Lu, 2007). Coda waves are highly sensitive to changes due to the presence of defects and flaws. In fact, damage need not to be in the direct path of coda waves. However, this advantage is also disadvantageous because environmental effects interfere with information from the testing specimen (Livings, 2017). Coda wave is defined by many researchers (Snieder et al., 2006), (Anugonda et al., 2001), (Egle, 1981) as late-arriving elastic waves with multiple scatter from defects and boundaries which superimpose at the receiver with no discernable wave modes. Coda waves have been questioned due to their undefinable properties, whereas traditional waves ultrasonic inspection relied on classical properties, which are defined mathematically. Livings (2017) describes a coda wave as an ensemble sum of waves superimposed on the receiver after multiple scatters and time delays.

Coda waves have been used to compare two signals at two discrete times and decipher the change between the two times. These differential features compare the recorded signal in the
time-domain and spectral-domain (Michaels & Michaels, 2005). The analysis from signal differencing in time-domain, spectral-domain, and local temporal coherence shows a good correlation in detecting and characterizing damage. The extension of this work included carbon fiber reinforced polymer (CFRP) with a focus to detect changes caused by small drilled in composites (Livings, 2017).

The goal is set to further expand the research by investigating low-velocity impact damage detection in CFRP in the presented work. The methodology is to use differencing parameters to analyze recorded signals subjected to varying impact damages. Impact damages imitate BVIDs on composite laminates. This research aims to warn NDT inspectors about the presence of benign defects or damages to localize inspection areas. Usual NDT scheduled inspection requires dismantling aircraft, which increases the cost and is time-consuming. An initial quick inspection of the whole aircraft with minimum equipment required can help in addressing structural health. Once the damage presence is indicated, sophisticated NDT methods can be utilized to perform a thorough inspection in damage localization and damage growth.

In the following chapters, an outline of this work, experiments, and results are explained. In chapter 2, the ultrasonic background is discussed. Furthermore, details of the equipment used are addressed. Next, barely visible impact damage is defined with its most common causes. Its effects on composite strength and the need for identification are explained. In the next section, the development of coda waves is discussed, coda wave definition is explained, and the scope and objectives of this presented work are addressed. Finally, all five differential features used are described, and how they were used in work has been discussed.

Chapter 3 describes the methodology of the experimental work performed. First, the experimental plan of the research work is described. Then sample preparation is explained.
Terminologies used to identify different types of samples are stated. Following that, the scanning procedure for the experiment is described. Both coda wave scanning, and ultrasonic scanning are discussed, along with instrument specifics used in the experiment. Next, the impact testing procedure is explained. Equipment, machine, and instruments used are stated. The experimental details are presented and discussed. Finally, image processing needed for this analysis is discussed.

Chapter 4 addresses result from the experiments. The presented research work provides observational results. First, damage characterization is established. Ultrasonic scanning is discussed with characteristics of the damage observed. Following that, five differential features results are discussed. The differential features and their relation to the damage identification are discussed. Finally, results are concluded at the end of the chapter with the differencing parameter capabilities.

Chapter 5 concludes the presented work along with a direction for possible future work.
CHAPTER 2. BACKGROUND AND THEORY

Introduction

In this chapter, first, some ultrasonic testing background is provided in 2.1. A brief ultrasonic procedure is provided, and a discussion of understanding ultrasonic working is described. Details for the instruments and equipment used in the experiment are addressed. Non-destructive testing significance is established with a brief history. In section 2.2, barely visible impact damages are defined. Their significance for detection in composites is described. The most common cause of their occurrence is reported, along some methods to detect them have been discussed. In section 2.3, the origin of the coda wave and the definition are established. Furthermore, their advantages are discussed along with some applications used in previous work by researchers. Finally, section 2.4 describes the five differencing parameters used in the experiment to compare the signals. The terminology used for identifying signals is presented, along each differential feature background is explained.

2.1 Ultrasonic

Ultrasonic testing uses high-frequency sound waves to detect subsurface discontinuities, defects, or flaws. Such a method does not require cutting the material or component; hence it falls under the category of non-destructive methods. Ultrasonic waves pass through the material, and a receiver captures returning sound waves, and the signal is interpreted. The material, flaws, or cracks absorb some waves. Further analysis indicates the presence of defects. Ultrasonic has been used in the manufacturing, aerospace, automotive, and medical industries.

Sergei Y. Sokolov first used ultrasonics for flaw detection in metals in 1928. Dr. Floyd Firestone in 1940 presented a practical ultrasonic testing method. He described his device as
capable of detecting inhomogeneities of metals. In 1962, radio engineer James F. McNulty explained more about ultrasonic testing. He described how ultrasound is generated using a piezoelectric transducer when subjected to electrical pulses of ultrasonic frequency. These were some initial works in the ultrasonic NDT.

Since 1960's, ultrasonic testing has evolved. Early instruments were bulky because they had vacuum tubes and had high energy consumption. In 1984, Panametrics, a company manufacturing NDT equipment, introduced a digital flaw detector. Current technology in ultrasound has improved the calibration, precise measurements, and data retention. NDT devices have also become component specific. Automation has also been introduced in inspections. Olympus Automated Train Wheel Inspection System (WIS), FOCUS PX, Rotating Tube Inspection System (RTIS) are some latest technologies.

Ultrasonic setups include a transducer, a receiver, pulse generator, oscilloscope, and a computer. The fundamental working of ultrasonic is simple. Pulser produces desired ultrasonic frequency electrical pulse. The transducer converts that electrical impulse to sound waves using material like piezoelectric crystals. When the wave first contacts the material, it reflects due to density change. But some waves pass through the material. This first reflected energy is indicated as an initial pulse on the device, like an oscilloscope. Furthermore, when there is no flaw in the path of propagating waves, waves get reflected from the back wall surface, again due to density change. However, when there is a discontinuity in the path, waves are partially reflected by the flaw, and some energy is absorbed. This gives a small spike between the initial pulse and back wall pulse, indicating a flaw in the material as seen in Figure 2-1.
It is also important to note that crack orientation becomes an important factor for detection and flaw characterization. If the crack length is parallel to the propagating wave, there will not be much reflection. For this reason, researchers have developed ways to transmit waves at various angles instead of transmitting normal to the plane. Waves not only reflect but also refract when transmitted at an angle to the continuity.

2.2 Barely Visible Impact Damage (BVID)

Composite materials have shown various advantages over metallic materials in terms of high specific strength, high stiffness, immunity to corrosion, lightweight, etc. However, composites are prone to various defects, which affect their residual strength drastically (Jones et al., 1987). Impact damages cause most of the delamination defect, which may go undetected. They are significant to engineers because these undetected damages can cause the structure's life span to reduce significantly. Besides, other causes such as dropped tools are the most common cause of damages during maintenance of structures or vehicles. As it may sound not so critical, damages often go undetected due to very low visibility of indented damage on the surface. Yet, significant delamination may exist underneath. Thus, such damages are known as Barely Visible Impact Damages (BVID).
Other causes of BVID are due to bird strikes, hail strikes, flying debris on the runway, and unintentional bumps due to service equipment. With low-velocity impact energies, the time of contact is longer and therefore disperse the energy away from the point of contact (Ali et al., 2020). This compression travels the thickness of the laminate, and it is reflected from the back surface, converts to a tensile wave. This tensile wave causes delamination in the laminates.

Compression After Impact (CAI) strength has been used to account for residual strength in composites subjected to BVIDs. Figure 2-2 shows the effect of damage on compression after impact strength (Ali et al., 2020).

![CAI strength vs Impact energy](image)

**Figure 2-2:** (a) CAI strength vs Impact energy, (b) damages under the cyclic impact

It was observed that matrix cracks, delamination, and fiber break are evident upon cyclic low-velocity impact loading. This occurs at lower energy levels than the critical threshold energy (Ali et al., 2020). Critical threshold energy exists where delamination is evident merely after one impact. BVID detection has been approached in many ways. In a study, Fiber Bragg Grating (FGB) was used to investigate the presence of BVID, detection range, and address detection limits subjected to environmental conditions (Goossens et al., 2021). Another study tried to approach BVID detection with a comparative study using surface mounted and embedded PZT
transducers. It was found that surface-attached transducers were default technology instead of embedding (Dziendzikowski et al., 2016).

### 2.3 Coda Waves

Coda waves were first used in seismology studies. Researchers became fascinated due to coda wave sensitivity to the details. The term "Coda wave" was first coined by Aki to refer to seismic waves tail end. One way to describe coda waves is backscattering waves from heterogeneities randomly distributed away from the source wave's direct path (Aki & Chouet, 1975). Coda waves attracted many researchers and have been implemented non-destructive inspections. Diffuse ultrasonic field, also known as Coda wave, is a hot topic for structural health monitoring (SHM). The ultrasonic source is excited to get diffuse fields. Unlike typically used ballistic or coherent waves, which have identifiable wave modes, coda wave modes are not discernable. Aki described them as late-arriving elastic waves without discernable modes (Aki & Chouet, 1975). Coda wave's sensitivity to small changes and defects is widely accepted (Michaels & Michaels, 2005), (Snieder et al., 2002), (Planès & Larose, 2013). In the early 1980s, Egle and Weaver gave the theory of diffuse ultrasonic waves in solid media (Egle, 1981).

Coda waves superimpose multiple wave modes at the transducer after multiple reflections from small changes or defects. This interaction of multiple reflections and interaction with small changes or defects accumulates in coda waves. Coda waves do not depend on the geometry and can form in any material. They become more complex in carbon fiber composites due to their heterogeneous nature.

Michaels and Michaels first compared the signals from diffuse ultrasonic waves three ways (Michaels & Michaels, 2005). They made the comparison of two signals, where the first signal was recorded when there was no flaw in the specimen and the second when a deliberate
flaw was added. Michaels & Lu quantified small damages correlating with changes in coda waves (Michaels & Michaels, 2005) (Lu, 2007). They developed five differential features for damage characterization in aluminum specimens. It was found differential features provided better diffuse field change for damage presence. Later, composite laminates were quantified based on Michaels work, where small drilled through-holes were investigated using coda waves (Livings, 2017). It was found that coda waves could be used to detect small, drilled holes presence in CFRP laminates.

2.4 Differential Features

A good way to detect and characterize damage when individual wave modes cannot be identified is to quantify ultrasonic signal change. The differential feature is a differencing parameter between two signals. The two signals are recorded and analyzed using differencing parameters for detecting the change. The parameters can differentiate fabrication variations in the laminate from changes due to intentionally introduced impact damages.

In the presented work, $h_0(t)$ is referred to as a baseline signal in the time domain. Baseline signal is signal recorded before impact damage is introduced in laminates. When impact damage is introduced, the signal is called a measured signal and represented as $h_1(t)$, with a fixed signal length $T$ for either signal. $\tilde{h}$ is the normalized value of signal. Signals have sampling period $T_s$ such that $h_i(n)$ corresponds to the sample at time $t = nT_s$ and the total number of samples is $N$, where $T = N T_s$. All differential features compare the measured signal with the baseline signal. These are now described as follows.
2.4.1 Residual Temporal Energy

Residual temporal energy is a simple baseline signal subtraction to measure how closely the shapes of signals match. First, the measured signal is scaled to unity by factor \( \alpha \) to minimize the mean square error between signals. Then it is subtracted from the normalized measure signal. This way, the difference becomes an amplitude-independent measure. Equations are as following:

\[
\tilde{h}(n) = \frac{h_1(n)}{\sqrt{\sum_{n=0}^{N-1} h_0^2(n)}}
\]

\[
\alpha = \frac{\sum_{n=0}^{N-1} \tilde{h}(n)h_0(n)}{\sum_{n=0}^{N-1} h_0^2(n)}
\]

\[
E_{\text{temp}} = \sum_{n=n_1}^{n_2} (\tilde{h}(n) - \alpha h_0(n))^2
\]

Residual temporal energy \( E_{\text{temp}} \) is then calculated by summing up squared difference values of signals specified over a time window from \( n_1 \) to \( n_2 \).

2.4.2 Residual Spectral Energy

Residual spectral energy is a time-frequency representation for nonstationary signals to scrutinize signal difference. It measures the scattered energy change caused by defects. The spectrogram of signals is computed by short-time Fourier transform (STFT). Both signal spectrogram is normalized to unity, and then baseline signal is subtracted from the measured signal. Tukey window \( w(n) \) function is used with 12.5% taper at both ends, where function length is \( M<N \) and \( k \) is the frequency index from \( 0 \leq k < M \).
\[ H_i[n, k] = \sum_{m=0}^{M-1} h_i[m] w[m-n] e^{-j2\pi km/M} \] (4)

\[ D[n, k] = \frac{|H_1[n, k]|}{\sqrt{\sum_{n=n_1}^{n_2} \sum_{k=k_1}^{k_2} H_1[\hat{n}, \hat{k}] H_1^*[\hat{n}, \hat{k}]}} - \frac{|H_0[n, k]|}{\sqrt{\sum_{n=n_1}^{n_2} \sum_{k=k_1}^{k_2} H_0[\hat{n}, \hat{k}] H_0^*[\hat{n}, \hat{k}]}} \] (5)

\[ E_{spec} = \sum_{n=n_1}^{n_2} \sum_{k=k_1}^{k_2} D^2[n, k] \] (6)

Similar to temporal energy, the baseline signal is first normalized and then subtracted from the measured signal. Finally, the square of the difference in spectral range over frequency window computes residual spectral energy.

### 2.4.3 Loss of Coherence

Loss of coherence is a cross-correlation measure in the time-domain and not spectral coherence. It is the measure of shape change between two signals. When normalization of the signal is done, it makes this feature amplitude independent for measuring damage. It measures the time delay between the two signals, where time delay (\( \tau \)) is the delay corresponding to the maximum correlation. After normalizing the signals, peak coherence (\( \gamma \)) is calculated, which is the maximum correlation coefficient for each time window. To yield loss of coherence, mean peak coherence is subtracted from maximum peak coherence for each time window.

\[ \hat{R}_{01}[\tau, t] = h_0[t]. h_1^T[t - \tau] \] (7)
\[
\hat{y}_{01}[\tau, t] = \frac{\hat{R}_{01}[\tau, t]}{\sqrt{\hat{R}_{00}[0, t]\hat{R}_{11}[0, t]}}
\]

\[
LoCh = \max[\max_\tau(\hat{y}_{01}[\tau, t])] - \text{mean}[\max_\tau(\hat{y}_{01}[\tau, t])] \tag{9}
\]

### 2.4.4 Loss of Correlation

Loss of correlation measures the overall match in waveform shape between two signals. Loss of coherence is computed in terms of the mean value of the signal (\(\mu\)), sampling period (\(\Delta t\)), and standard deviation (\(\sigma\)). The amount of temporal change between baseline and measured signal loss of correlation given by Eq. 11.

\[
\rho_{01} = \frac{\Delta t}{\sigma_0 \sigma_1} \{(h_0[n] - \mu_0) \cdot (h_1[n] - \mu_1)^T\} \tag{10}
\]

\[
LoCh = 1 - \rho_{01} \tag{11}
\]

### 2.4.5 Differential Curve Length

Differential curve length measures the change in the complexity of the signal. Both baseline and measured signal is first normalized, and then subtraction is done. It is given as:

\[
DCL = \sum_{n=0}^{N-1} |(\tilde{h}_1[n] - \tilde{h}_0[n]) - (\tilde{h}_1[n-1] - \tilde{h}_0[n-1])| \tag{12}
\]

### 2.5 Transducer selection

In this work, we refer to two types of non-destructive investigations. The first is the conventional C-scan. A well-defined pulse of ultrasound is used, and here the criteria of use are (a) the signal should not get absorbed in composites, and (b) the pulse width is narrow enough so
that it is discernable on reflection. It is determined that a 5 MHz transducer is best for this investigation. Very clear damage images can be generated at this frequency. The second NDE is the subject of this research, viz, Coda Waves. It was observed from experiments that a 1 MHz transducer produced a strong signal which would produce a diffuse field for measurable defect detection.
CHAPTER 3. EXPERIMENTS

3.1 Experimental Plan

First, all laminates were prepared using unidirectional CFRP prepreg, and samples of size 6" x 4" in were cut using a water jet. This was to ensure that the sample preparation does not introduce any fabrication damage. Next, they were all scanned with coda waves. Each sample was scanned ten times, where the transducers were removed and placed on the samples after each scan. Furthermore, ultrasonic scans were recorded for each undamaged sample. The samples were then subject to the impact test. These two steps were taken to establish the baseline for the undamaged samples. We prepared two sets of samples. For the first set of samples, impact energy was increased in steps of 0.5 J in the range of 2 J to 4.5 J energy. In the second set of samples, only 3 J of the impact energy was used to do damage. The purpose of the second set of samples is to measure the variability in our measurements. Samples were prepared in various batches, and an attempt was made to maintain the same manufacturing conditions. The natural variability of composites is a reality, and the second set of samples provide a measure of variability. Ultrasonic through transmission scan is performed on the damaged samples to get a measure of the damaged area. Finally, a coda wave is now used to record the effect of the damage on coda waves.

3.2 Samples Preparation

Carbon fiber reinforced polymer (CFRP, Toray P235W-19 (Torayca 3900-series) prepreg) was used to prepare the composite laminate samples. The samples were prepared with quasi-isotropic ply orientation, with stacking sequence given as [0°\/-45°\/+45°\/90°]s. The thickness of each sample was about 2.5 mm (16 plies \* 0.15 mm). The samples had a dimension
of 6” x 4” inches. All samples have the same stacking sequence, but the two sets have the outer ply of 0° along the length of the laminate, and in the second, the 0° is along the width of the samples.

Laminates were sealed in a vacuum bag. This bagging is essential for curing laminates. A release film was the first layer put on laminate and is in direct contact with the laminate. This makes sure that other layers over it do not stick to the laminate during the curing process. Over a release film was a bleeder. Bleeder helped in sucking out air trapped in the laminate during the fabrication process. It also helps in removing the harmful gases that might release during the curing process. Finally, a high-temperature bag film and is sealed with a high-temperature resistant sealant tape (Dam Tape). A copper tube is also sandwiched in the bag, which was connected to the vacuum outlet. Figure 3-1 represents the schematic of bagging.

![Bagging schematic of a laminate](image)

**Figure 3-1:** Bagging schematic of a laminate

Wabash Genesis G30H-ASTM Test Sample Molding press was used for laminate preparation, an autoclave style molding press, as shown in Figure 3-2.
After the sample was prepared, it was put in the press for curing at the required temperature and pressure. Figure 3-3 shows the pressure and temperature cycle each laminate goes through.

Figure 3-2: Hot Press for laminate preparation

Figure 3-3: Pressure and Temperature cycle for curing laminates
3.3 Scans

The sequence of testing is as follows after the samples were prepared:

(i) Coda wave investigation to establish baseline signal
(ii) Ultrasonic scan to establish the basic laminate condition
(iii) Impact test
(iv) Ultrasonic scan to record the damage state
(v) Coda wave investigation to record the wave change due to damage

The details of the test are as follows:

Figure 3-4 represents the flowchart for collecting the data. First, six samples of each 0° and 90° laminates were prepared. Further, each sample was scanned with an ultrasonic scanner and coda waves before the impact test. Signal recorded before the impact test was taken as baseline signal or un-damaged signal. For signal reproducibility, each laminate was scanned ten times. After impact testing, all the samples were scanned again with an ultrasonic scanner and coda wave. These signals were treated as measured signals or damaged signals. Again, each laminate was scanned ten times to get reproducibility.

Figure 3-4: Flow chart of collecting data
Coda wave experimental setup: Samples were scanned with coda waves before the impact test. This was done to compare the signals before and after the impact test. Each sample was scanned ten times. For the repeatability of the tests, the transducer and receiver were removed and placed again before recording another signal. A fixture was used to place the transducers as repeatable as possible, as shown in Figure 3-5. Two Olympus V103, 1 MHz, and 0.5" in diameter were used in this investigation. Panametrics 5052PR pulser/receiver was used for recording signals with 360 V spike excitation and 40 dB of gain. The pulser/receiver signal was displayed on Tektronix MDO3022 Oscilloscope having 200 MHz bandwidth. The digital output from the oscilloscope was collected and saved in a computer for further data processing.

Figure 3-5: Coda wave transducer/receiver setup with fixtures

In the case of coda waves, two transducers were used to collect data. Transducer and receiver were 1 MHz, 0.5-inch diameter, flat transducers. They were semi-permanently attached to the sample using Crystal Bond 555 wax. Figure 3-6 shows the schematic of the scanning process. A pulser/receiver, Panametrics 5052 PR, generates a pulse and sends it to a transducer. The receiver collects the signal and passes it to an ultrasonic preamp, which adds +40 dB gain. Signal information is then visualized in an oscilloscope, Tektronix MDO 3022. Data is then collected and saved from the oscilloscope using a computer. Data is 100,000 points in length.
Ultrasonic scan setup: Ultrasonic scan was then performed on the samples. The purpose is to ascertain their initial condition of the samples before they are subjected to impact testing and damage. A Panametrics 5077PR pulser/receiver by Olympus was used for 100 V spike excitation. Model 5077PR was considered ideal for maximizing response in scattering material, such as CFRP. Pulse-echo mode was used with Panametrics V309 transducer of 5 MHz, 0.5" in diameter, and 2" in focal length. Model 5077PR provided a superior signal-to-noise ratio when using transducers of 10 MHz or lower\(^1\). A -0.6 dB of constant gain was used as an ultrasonic preamp. Sample and transducer were immersed in the water as a coupling medium. Inspection Ware software was used to get the output of the signal. Resolution of the scan was set to 0.04 in, voltage maximum-minimum set to ±0.25 V, and back wall signal was recorded for experiments. The images of scans were taken for further image processing to calculate the area of the damage after the impact test.

\(^1\) http://telab.vuse.vanderbilt.edu/docs/specs/Olympus-5072PR.pdf
3.4 Impact Test Setup

A low-velocity impact test was carried out on samples to imitate the damage. Instron Dynatup, an 8200 series impact testing machine, was used to carry out the test. It has the capacity to create 136J (100 ft-lbs.) of energy, and the weight can be varied up to 259 kg (570 lbs.). In this experiment, a weight of 3.91 kg (8.62 lbs) was used for producing impact damage, with a hemispherical tup of diameter 0.5 inches. With the kinetic energy Eq. 13, the impact velocity was estimated for the desired impact energy. The height of the weight was adjusted to match the velocity required for the energy. The impactor was captured after the first impact to ensure that the weight just hit the sample once. The setup for the impact test is described below in Figure 3-8.

\[ E = \frac{1}{2} m v^2 \]  \hspace{1cm} (13)

\( E \) is the impact energy, \( m \) is the mass, and \( v \) is the velocity with which the impactor hits the laminate. Table 3-1 shows the velocity for each impact energy. Once the height was adjusted, the sample was positioned in the sample slot, and position grips were used to keep them in place,
shown in Figure 3-8. Finally, weight was dropped using the release button. It was made sure that the tup hits the sample just once at the center.

Figure 3-8: INSTRON Dynatup Impact Testing Machine
<table>
<thead>
<tr>
<th>S.No.</th>
<th>Impact Energy (J)</th>
<th>90° Laminate v (m/s)</th>
<th>0° Laminate v (m/s)</th>
<th>v (theoretical) (m/s)</th>
<th>v (statistical) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1.06</td>
<td>1.09</td>
<td>1.01</td>
<td>1.08</td>
</tr>
<tr>
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<td>2.5</td>
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<td>1.34</td>
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<td>1.34</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1.43</td>
<td>1.43</td>
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</tr>
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<td>4.5</td>
<td>1.51</td>
<td>1.51</td>
<td>1.52</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Table 3-1: Velocity for each impact energy for 0° & 90° laminates

3.5 Image Processing

Ultrasonic C-scans were used for damage characterization. The image processing method was used to measure the actual damage area due to impact energy. Since coda waves themselves cannot provide this information, C-scan was used to measure the damaged area and then related to coda waves.

Damage sample C-scan was analyzed to accurately assess the damaged area, as shown in Figure 3-9. It was observed from the C-scans that the damage was in the blue color scale of the image. Collected images were indexed images, so at first, images were converted to RGB images. From RGB images, blue scale image was separated and subjected to image processing further. In Figure 3-9, other blue highlighted areas are also visible on damaged sample. These all were laminate fabrication flaws.
Figure 3-9: Undamaged and damaged C-scan at (a) 4.5J on 0° laminate, (b) 4.5J on 90° laminate

Since the impact test was done at the center of the laminates, it was clear that the rest of the other colors were either noise or fabrication flaws present in the laminates. In Figure 3-9, the images on the left look completely different, but the images are of the same samples. When subtracting the damaged sample scan from the undamaged sample scan, the impact damage comes out clearly.

In Figure 3-10, image difference is presented for 0° and 90° laminate at 4.5J impact energy. The contrast of the images was adjusted to identify damage at the center clearly and is presented. Damaged areas are clearly standing out from the noise and fabrication flaws.
However, to avoid noise interference with actual damage, a blue color scale of the image was used for assessing the damage. The flow chart of steps used for image processing is presented in Figure 3-11.

![Figure 3-10: Subtraction of damaged & undamaged images at 4.5J for (a) 0°, and (b) 90° laminates](image)

After separating the blue color scale of the RGB image, an intensity level was required to convert images to a binary image. This was required to calculate the pixel area. The intensity level was set such that pixels below that intensity turn black and above which pixels turn white. Four different intensity levels were tried for conversion. The average area was calculated from different intensities and used. Since impact damage was at the center, a cropping window was used to separate noise that still was present in the laminate other than at the center. This cropping window was consistent throughout all the samples. Finally, the cropped image was used to calculate the number of pixels. These pixels were then multiplied with the area of each pixel in $mm^2$ to get the final size of damage.
The damaged area boundary was superimposed on the original blue color scale of the damaged laminate to verify the intensity level accuracy, shown in Figure 3-12. Magenta color boundary represents damage area captured with different cut-off intensities. Cut-off intensities used for laminates damage area calculation were 0.9, 0.85, 0.75, and 0.5.

Figure 3-12: Cut-off intensity levels (a) 0.3, and (b) 0.9 superimposed on 90° laminate at 4.5J
CHAPTER 4. RESULTS

Introduction

In this section, we will present the results of the experiments. First, damage characterization will be elaborated. This will give an understanding of how damage varies with an increase in impact energy. After that, each differential feature results will be compared for both 0° and 90° laminates. Finally, results for coda wave damage detection will be summarized based on differential features.

4.1 Damage Characterization using Ultrasonic Scans

From the C-scans, it was observed that the damage orientation was along with the outermost ply orientation. Figure 4-1 shows a comparison for 0° and 90° laminates.

(a)  
(b)

Figure 4-1: C-scans of damaged area for (a) 0°, and (b) 90° laminates both at 4.5J impact
Damage tries to propagate horizontally in 0° laminate while damage propagates vertically in 90° laminate. This happens because the fibers dominate the energy propagation. Energy from impact spreads away from the impactor initial point of contact. More impact energy is absorbed by fibers in the transverse direction. Thus, matrix failure and delamination propagate along fibers.

Damage area is observed increasing from 2J to 4.5J impact energy as shown in Table 4-1 and Figure 4-2. A normalized damage area is plotted against impact energy. A horizontal dashed line represents no damage state.

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>90° Laminate</th>
<th>0° Laminate</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Damaged Area (mm²)</td>
<td>Average Damaged Area (mm²)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.05</td>
<td>0.47</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1.02</td>
<td>1.22</td>
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<td>1.48</td>
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</tr>
<tr>
<td>4</td>
<td>2.26</td>
<td>1.22</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>2.53</td>
<td>1.56</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>2.75</td>
<td>2.73</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 4-1: Damaged area calculated from ultrasonic scans
Damage area from 2J to 4.5J showed an increasing characteristic. The linear fit is assumed for the small energy of 2J to 4.5J for both 0° and 90° laminates.

The composite laminates can vary in thickness, plies orientation, and surface roughness, which can result in changes in mechanical properties. To address this issue, another set of five samples were prepared. These laminates were impacted with 3J of energy. The standard deviation for all the damaged areas of these laminates was calculated. This gave us the error bound for the estimation of damage area variation. The purpose of the ultrasonic scan was to characterize the damage. From the ultrasonic scans, it was evident damage was increasing with the increase in impact energy.

### 4.2 Residual Temporal Energy (RTE) sensitivity to impact damage

Figure 4-3 shows the results of residual temporal energy. Residual temporal energy error bounds captured the reference line, which indicated RTE change for the damaged signal was not
much different than RTE undamaged signal. Hence RTE is not able to differentiate various damage levels.

![Graphs of Residual Temporal Energy for (a) 0° laminates, and (b) 90° laminates](image)

Figure 4-3: Residual Temporal Energy for (a) 0° laminates, and (b) 90° laminates

It should be kept in mind that the transducer was removed from the samples for each energy which has increased the error bound on the measurement.

### 4.3 Residual Spectral Energy (RSE) sensitivity to damage

Residual Spectral Energy calculates the scattered energy change caused by the defects or flaws in the laminate. This measures how closely the shapes of signals match. In Figure 4-4, the RSE is plotted against the impact energy. The change is not definite until 3.5J of energy. When the damage is below 3.5J, the RSE cannot differentiate between damage status, but when the damage increases to about 3.5J, a definite trend is observed. The change also shows an increasing trend as the impact of energy increases. Figure 4-4 shows the relation between the impact energy and the damaged area. Thus, residual spectral energy indicates the presence of an area greater than 2.25 mm² for 90° laminates, and 1.22 mm² for 0° laminates.
The results are similar for both $0^\circ$ and $90^\circ$ laminates. Thus, residual spectral energy was not much affected by fiber orientation and transducer positioning. This makes residual spectral energy a good differential feature for low-velocity impact damage detection and damage characterization.

4.4 Loss of Coherence (Loch) sensitivity of damage

Loss of coherence for the two classes of samples is presented in Figure 4-5. Results show that the $0^\circ$ laminate does not show any sensitivity to Loch. On the other hand, $90^\circ$ laminates showed damage detection. Even though the Loch is sensitive to damage in $90^\circ$ laminates but is not sensitive to the damage area.
Figure 4-5: Loss of Coherence against impact energy for (a) 0°, and (b) 90° laminates

The delay in time is caused due to the presence of defects or flaws in the laminate. Although, the damage characteristic is not definite. Thus, loss of coherence has shown low-velocity impact damage, but damage size characterization is not definite.

The delay time (in loss of coherence) for each laminate was plotted against the impact energy, as shown in Figure 4-6. The lag is noted at the point when the baseline signal and measured signal match exactly. The lag is between the second signal with respect to the first. However, the change falls under the reference line. This means that change was visible, but it was not clear if the change was due to damage or existing fabrication variability in the laminates.
Figure 4-6: Lag of signals indicating damage presence with increasing impact energy for (a) $0^\circ$, and (b) $90^\circ$ laminates

4.5 Loss of Correlation (Locor) sensitivity to damage

Figure 4-7 shows the results of the loss of correlation as a function of impact energy. When capturing the overall match in waveform shape, loss of correlation could not distinguish clearly between undamaged and damaged signal. This indicates that Locor of coda waves is not sensitive to changes in the laminate due to impact damage.

Figure 4-7: Loss of Correlation for (a) $0^\circ$, and (b) $90^\circ$ laminates
The changes are very small and not enough for this differential feature to distinguish from the undamaged signal.

4.6 Differential Curve Length (DCL) sensitivity to damage

Figure 4-8 presents the differential curve length as a function of impact energy. Differential curve length can be used to understand the relation of change due to damage concerning impact energy. Differential curve length can be used to get the information about the non-linearity relation; however, as seen in Figure 4-8, no change is seen. DCL is totally insensitive to the small level of damage; in other words, there is no complexity in the signal.

![Figure 4-8: Differential Curve Length for (a) 0°, and (b) 90° laminates](image)

4.7 Conclusion

Coda wave signals were evaluated using five differential features. Not all differencing parameters showed damage detection. Among all the differential features, residual spectral energy showed the best damage detection and damage characterization. Damage was seen increasing with respect to an increase in impact energy. Loss of coherence also showed the
presence of damages. However, the fiber orientation of laminate does affect the detection capability. The change observed was weak as well. Differential curve length indicates that the relation between damage area and impact energy was linear over the range of damage inflicted in the study. Loss of correlation and residual temporal energy do not indicate any definite damage detection.
CHAPTER 5. CONCLUSION & FUTURE WORK

5.1 Conclusion

The work presented here has used the coda waves for the detection of low-velocity, barely visible damage in composite laminates. An energy level of 2J to 4.5J was used to impact damage the samples. Ultrasonic C-scan was used to characterize and measure the growth of damage as the impact energy increases. Ultrasonic was easily able to discern the small damage size. The sensitivity of coda waves to the small barely visible impact damage was investigated and is the central objective of the work. In the study, five differential features were used to process changes from undamaged and damaged samples of carbon fiber reinforced polymer (CFRP). Not all differential features show the damage presence in CFRP. Residual Spectral Energy (RSE) indicated damage presence above 3.5J impact energy. The damage increase was also indicated when impact energy increased. Although, differential curve length (DCL) indicated a linear relationship between impact energy and damage. It was also seen that RSE results were very similar for both 0° & 90° laminates. This means RSE does not depend on fiber orientation and transducer positioning. Thus, making Residual Spectral Energy versatile to detect damage on CFRP. Loss of coherence presented a weak detection in 90° laminates. The change is visible yet, not strong enough to differentiate from the undamaged signal. Residual temporal energy and loss of correlation, on the other hand, were not able to detect low-velocity impact damages. From a previous study, it was seen that residual spectral energy and loss of coherence show the best detection of small drilled through holes. These differential features behaved differently in the case of low-velocity impact damages detection. This work, along with the previously published work, indicates that residual spectral energy is a strong candidate for damage detection in composites.
Actual damage characterization was confirmed with ultrasonic tests. To acquire the damaged area, image processing was utilized. This gave damage characteristic with the increase in impact energy.

5.2 Future Work

From the presented work, it was seen residual spectral energy low-velocity damage detection capability. Exploring RSE sensitivity to change with respect to low-velocity impact damage should be considered. The laminate thickness should be considered for changes in RSE capability. Loss of coherence response to higher impact damages needs to be explored. Impact energy and damage relation for higher velocity impact damages also need to be evaluated. It must be determined if the relationship remains linear at high-velocity impact.

Fiber orientation, laminate thickness, and transducer spacing should be considered for understanding damage characterization due to low-velocity impact damage using coda waves on carbon fiber reinforced polymer.
REFERENCES


