ABSTRACT

PAWAR, SACHIN SAMPATRAO. Identification of Impact Damage in Composite Laminates through Integrated Pulsed Phase Thermography and Embedded Thermal Sensors. (Under the direction of Dr. Kara J. Peters).

This dissertation develops a methodology to identify impact damage in aerospace composite laminates using integrated pulsed phase thermography and fiber Bragg grating (FBG) sensors. Initially, a two-dimensional woven, carbon fiber epoxy laminate is used to calibrate the defect depth with blind frequency for the particular material system using pulsed phase thermography (PPT). The calibration specimen contains simulated defects in the form of polymer foam inclusions. The calibrated depth vs. blind frequency relation is then applied to specimens with barely visible impact damage due to low velocity impacts. The results demonstrate that the use of the polymer insert simulated defects, in contrast to drilled holes or inserts with higher thermal contrast, provides thermal phase shifts similar to that observed in the impacted specimens. Despite the differences between the simulated and impact damage (e.g. the irregular boundaries and thin nature of the delaminations), the minimum depth of delamination from the impacted surface and the extent of damage on the rear surface of the specimen calculated from the PPT images are shown to correspond well with those of visual observations.

The next group of laminated composite specimens are fabricated with embedded FBG sensors to test the ability of the combined inspection method using pulsed phase thermography and FBG sensors to identify impact damage severity. Initially three sets of specimens containing a single FBG sensor at the mid-plane, along with data from previous studies, are used to optimize the distance of low velocity impact damage from the FBG sensor and also to optimize the FBG interrogator data acquisition rate. The results from these
specimens show a wide scatter in the FBG sensor temperature measurements during cooling. Also, due to its low conductivity, specimen took long time to cool, increasing the inspection time. Therefore for the final specimen the FBG sensor data acquisition is performed in the heating transient. The final specimen contains three FBG sensors, embedded at different depths and is used to quantify the initiation and through the thickness progression of impact damage of varying severities. Pulsed phase thermography is used for the global assessment of the impact damage, meaning to quantify the absolute damage size and also to quantify the damage severity in terms of the phase contrast between damaged and pristine specimen areas. The results demonstrate the higher sensitivity of the internal FBG temperature sensors than that of the PPT during damage initiation. The PPT images were able to capture the later during damage progression. Visual inspection, microscopic images and PPT results are used to compare the damage modes and severity at different depths detected by the FBG sensors. A damage assessment model is then formulated based on the results of combined inspection method.
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Identification of Impact Damage in Composite Laminates through Integrated Pulsed Phase Thermography and Embedded Thermal Sensors

by
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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DEDICATION

This work is dedicated to my parents, my brothers, parents in law, my wife and my friends.
Sachin Sampatrao Pawar obtained his Bachelor of Engineering in Mechanical Engineering from Shivaji University, India in 2001. He worked as a Lecturer in Mechanical Engineering Department of Bharati Vidyapeeth College of Engineering (BVCOE) and received his Master of Engineering (M.E.) specializing in CAD/CAM/CAE from Bharati Vidyapeeth University (BVU) in 2006. In January 2009, he joined Aerospace Engineering department at North Carolina State University to start his current PhD program. Before that he worked as an Assistant Professor in Mechanical Engineering Department of BVCOE. He pursued a Doctor of Philosophy degree under the direction of Dr. Kara Peters, concentrating on Pulsed Phase Thermography and fiber optic sensors.
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Chapter 1  Introduction

1.1 Motivation

Unlike traditional engineering materials such as metals or plastics, composite materials present unique challenges for design, manufacturing and most importantly inspection as they can fail in a variety of modes [1]. In addition, these potential modes are distributed and interacting in nature [2]. Additional challenges for damage detection in composites include their inhomogeneity, anisotropy and varying material properties based on the chosen matrix, fibers and manufacturing processes. The property of anisotropy leads to their material property orientation dependence as well as stiffness mismatching between adjacent laminae with different fiber angles (both extensional and bending stiffness) which makes such composites susceptible to delamination. The property of non-homogeneity is responsible for the location dependence of material properties. Material property mismatching between the fiber and the matrix can create matrix cracking when the material is subjected to a load [2]. Additional factors which makes damage detection further difficult includes the different thermal properties of the constituents and subsurface occurrence of damage. Also as compared to metals, the failure mechanism and failure modes in composite materials are less well understood. Unlike metals, impact damage in composites often begins on the non-impacted surface or as an internal delamination.
Due to ductile nature of metals, a large amount of impact energy may be absorbed through plastic deformation. On the other hand, due to the brittle nature of composites, they absorb energy through elastic deformation and through multiple damage mechanisms [1]. As composite materials are used in important structures such as airplanes, marine vehicles and civil infrastructure, it is necessary to develop reliable damage detection techniques that accurately detect their predicted failure modes [3].

Various non-destructive testing methods such as visual inspection, ultrasonic inspection, X-ray techniques, strain gauge methods, eddy-current methods, vibration based methods, optical fiber methods, and thermography are widely used as inspection techniques for composite structures [3]. Each of these techniques has its own advantages and disadvantages. For example, visual inspection is simple and the least expensive but not always effective; as damage in composites occur below the surface which is not easy to detect by the unassisted eye. Visual inspections also cannot determine the damage mechanism and severity. Ultrasonic and X-ray imaging techniques require large and costly equipment, although both methods gives highly accurate results. Strain gauge methods are also simple to implement and the results can be easily interpreted. But a single gauge can cover only a small area, thus for large structures systems this will increase the complexity because of the many lead wires required. Eddy-current methods work well for metallic materials but are not suitable for composites because of insulative properties of epoxy matrix [3]. Thus a single, available technique is not capable of detecting all forms of damage modes and damage severity in composite materials. Therefore the best approach is to apply two or
more techniques and fuse the damage detection to enhance the data reliability [4,5].

### 1.2 Scope of Research

Different non-destructive testing techniques have been applied in the literature and in practice to inspect aircraft components [3,5]. Special attention is given to low velocity impact damage, also called barely visible impact damage (BVID), as such damage is potentially harmful and can remain undetected in visual inspections [6]. BVID is caused by a variety of incidences including dropped tools, stones on the runway, minor collisions on the ground, or bird strikes. This type of damage is barely visible as a scratch or dent on the impacted surface, but the opposite surface can be severely damaged. Hence this type of damage is sometimes called “blind-side impact damage”. Another important point from the inspection point of view is that the opposite side is not accessible in real life components [7]. Thus damage in composites due to low velocity impacts may go unnoticed as it begins as internal delamination or on the non-impacted side as discussed earlier [1].

More recently, infrared (IR) thermography has shown significant promise for NDE of aircraft composites due to the fact that a large section of the structure can be imaged simultaneously without the need for a specialized environment, drastically reducing the required imaging time [6,8]. One estimate reaches a time saving of 1000 hours for the complete inspection a Boeing 737 fuselage [9]. As the average airline spends 12-20% of its total operating expenses on maintenance and inspection, this reduction in required imaging time can have a major financial impact on the industry [10]. The idea of this research project
is to develop a reliable structural inspection system specifically for laminated composite material systems subjected to low-velocity impacts, which will combine such two or more techniques to enhance the data reliability.

**RESEARCH OBJECTIVES**

The main objective of this research is to:

Apply and verify a combined inspection system of embedded fiber Bragg grating temperature sensors and Pulsed Phase Thermography imaging for through the thickness identification of low velocity impact damage in composite laminates.

To accomplish this task, a series of specific objectives were defined:

- To quantify the damage depth resolution in composite laminates using Pulsed Phase Thermography for a standardized specimen with inclusions representing realistic phase contrast ranges and derive a calibration method for future imaging;
- Apply the calibration method to Pulsed Phase Thermography imaging of BVID in a laminated composite material system and derive an algorithm to reconstruct through the thickness delamination images;
- Measure the response of temperature sensors (fiber Bragg gratings), embedded in a composite laminate with BVID, to a controlled thermal pulse as a function of damage state;
• Correlate these temperature measurements to visual observations and Pulsed Phase Thermography images of the same damage state for verification of damage identification results.
• Characterize damage size and severity with a combined inspection method for low velocity impact damage.

1.3 Thesis Outline

The achievement of each of these objectives will be presented in detail in this dissertation. This dissertation is organized as follows: Chapter 1 presents a brief introduction to this research, which includes the motivation, scope of research and an overview of the project objectives. Chapter 2 reviews the fundamental concepts of non-destructive testing approaches based on thermography in general, and Pulsed Phase Thermography in particular. This chapter also describes the thermal sensitivity and response of Fiber Bragg Grating sensors. Chapter 3 describes the fabrication of composite laminated specimens with simulated damage through polymer foam inserts, specimens with low-velocity impact damage and specimens with embedded sensors for the combined inspection method. This chapter also describes the associated testing procedures. Chapter 4 presents the Pulsed Phase Thermography imaging results and the calculation of the depth information for each simulated foam insert defect to calibrate the damage depth resolution of the Pulsed Phase Thermography system. We then apply this depth calculation to laminates with varying levels of impact-induced damage to reconstruct the through the thickness extent of delamination.
Chapter 5 describes previous studies of thermal damage detection of aerospace composites and presents results of the combined inspection method. This chapter also validates the results of the combined inspection method with microscopic images and visual inspections of the laminate after impact. Finally, Chapter 6 presents conclusions drawn from this research and recommendations for future work.
Chapter 2  Background

This chapter reviews non-destructive testing approaches based on thermography and presents the fundamental concepts of the particular technique used in this dissertation.

2.1 Thermography

The primary full field, Non Destructive Evaluation (NDE) approach used in this research is Pulsed Phase Thermography, which is a specific type of infrared thermography. Before going into a detailed explanation of the procedure for Pulsed Phase Thermography, the general concepts of thermography and its types are briefly reviewed.

Infrared thermography is based on the principle that heat flow in any material is altered by the presence of flaws or defects. Hence a localized temperature difference is caused due to the change in heat flow in the material, which in turn produces different thermal patterns on the surface of the material. The study of such thermal patterns to find the anomalies in the material is known as thermography. The thermal patterns or maps collected by using infrared thermal imaging equipment are called thermograms, which are used to assess the integrity of materials and processes [11].

Thermography has been used widely in the NDE of structures in civil engineering such as bridges and buildings, for example to detect cracks in concrete [12] and defects in concrete structures strengthened with FRP composites [13]. It has also been applied in the aerospace industry for detecting various types of defects such as voids, disbands and barely
visible impact damage (BVID) in composite airframes [14]. The thermal signals used for inspecting defects by thermography are diffusive in nature therefore there is drop in detectability of subsurface defects which is nonlinear with depth. For this reason thermography is best suited for NDE of thin structures such as those found widely in the aerospace industry [15].

We can divide thermography approaches into two classifications. The first is passive thermography in which the material to be tested is naturally at a different temperature than the ambient temperature, while the second one is active thermography where we have to heat or cool the material to be inspected in order to induce the required thermal contrast [16]. A survey of active and passive thermography techniques are listed in figure 2.1. Although there are many types of active thermography (as in figure 2.1) depending on the type of external stimulus applied, here we are only interested in types of thermography where the external excitation is an optical one.

2.1.1 Pulse Thermography

In Pulse Thermography the material to be inspected is heated with a thermal pulse using a high power source such as xenon lamps and then allowed to cool so that the heat pulse diffuses into the material. The duration of the pulse varies from microseconds to some seconds depending on the thermal properties and thickness of the material being inspected. This process creates a thermal wavefront propagation through the material as shown in figure 2.2. If the material has a localized defect, the defective area will create a higher thermal impedance to the wavefront propagation, reducing the diffusion rate as compared to that of
the non-defective material area [17]. This reduction in diffusion rate at the defect causes heat entrapment just over the defect. Hence this defect appears as a hot spot or cold spot in a thermal image captured by thermal camera, depending on the direction from which the material is imaged [16].

Figure 2.1 Classification of thermography techniques depending upon excitation source.
In pulse thermography, as shown in figure 2.2, the thermal image is captured when the material is cooling. At time $t_1$, this wavefront passes through flaw 1 which is nearer to surface than flaw 2. Hence, the diffusion rate at flaw 1 is reduced causing heat entrapment over the flaw. At time $t_2$, the second flaw is encountered which again reduces the diffusion rate. There is time delay between the emergences of the two reflected wavefronts on the surface of the sample which can be used to identify the depth of each flaw [6].

![Wavefront propagation and damage detection in pulse thermography](image)

Figure 2.2 Wavefront propagation and damage detection in pulse thermography [23].

When the square thermal pulse reaches the material surface from the lamps, the wavefront propagation is given by Fourier's diffusion equation in three dimensions as
\[
\n\n\frac{\nabla^2 T}{\alpha} - \frac{1}{\alpha} \frac{\partial T}{\partial t} = 0
\]

(2.1)

If the above equation is simplified by assuming a Dirac pulse applied to a semi-infinite isotropic solid, it can be reduced to the one dimensional solution is given by Carslaw and Jaeger [18] as

\[
T(z,t) = T_0 + \frac{Q}{e^{\sqrt{\pi t}}} \exp \left( -\frac{z^2}{4\alpha t} \right)
\]

(2.2)

where, \(T_0\) is initial surface temperature, \(Q\) is the heat absorbed by the surface, \(t\) is time, \(z\) is the through the thickness coordinate, \(\alpha\) is the material thermal diffusivity and

\[
e = \sqrt{k \rho C_p}
\]

(2.3)

is the thermal effusivity. In this equation \(k\) is the thermal conductivity, \(\rho\) is the mass density and \(C_p\) is the specific heat capacity of the material.

The surface temperature (at \(z = 0\)) is given as

\[
T(0,t) = T_0 + \frac{Q}{e^{\sqrt{\pi t}}}
\]

(2.4)

Thus the surface temperature, which is recorded by a thermal camera during the cooling transient, is different between the non-defective area and damaged area due to the difference in thermal effusivity at these areas as indicated by equation 2.4. Thermal effusivity, which is
a measure of material’s ability to exchange heat with its surroundings, is 230 to 681 times
greater for Carbon-Fiber-Reinforced Polymer (CFRP) than for air [19]. Thus a pristine area
of CFRP material acts as a better heat sink than air (which can be viewed as a representative
defective area in CFRP such as due to a void). Thus hot spot or cold spot creation at the
defect location depends on the relative thermal properties of both the material and the defect

The observation time, $t_{\text{obs}}$, during which there is measurable thermal contrast
between a pristine region and defect region and the loss of contrast, $C_c$, are given as [11],

$$t_{\text{obs}} \approx \frac{z^2}{\alpha}$$

(2.5)

$$C_c \approx \frac{1}{z^3}$$

(2.6)

The required observation time or acquisition period should be estimated to be at least [21]

$$t_{\text{obs}} \approx \frac{2L^2}{\pi \alpha}$$

(2.7)

where $L$ is the thickness of the specimen to be inspected. These two equations indicate the
limitations of Pulse thermography that detectable defects are shallow in nature and that the
contrast weakens as the depth increases. The observed contrast is also function of defect size,
the initial temperature rise and the thermal properties of the material which are not included
in equation 2.6.

The two possible observation directions in pulse thermography are:

(a) Reflection: Here the thermal camera and heat source are located on same side of the material to be inspected. This method is used for detection of defects nearer to the heat source (see figure 2.3).

Figure 2.3 Experimental arrangements for in-reflection Pulse Thermography.
(b) Transmission: Here the thermal camera and heat source are located on each side of the material to be inspected. This method is used for detection of defects closer to the rear surface (see figure 2.4). If the rear surface is not accessible, this approach is not feasible. For the defect depth estimation, the transmission approach cannot be used as the travel time for the thermal wavefront through the material thickness is the same, irrespective of the defect depth [16].

Figure 2.4 Experimental arrangements for in-transmission Pulse Thermography.
2.1.2 Lock-in Thermography

Lock-in thermography was first developed by Carlomagno and Berardi [22] and later further investigated by many researchers [14]. In lock-in thermography, the material to be inspected is heated with a modulated heating source (rather than pulsed heat source as in pulse thermography) such as halogen lamps. The heating source is modulated at a fixed frequency $\omega$ until a thermal steady state is achieved (in contrast to pulse thermography), as shown in figure 2.5.

The incident heat is absorbed at the surface of the material, creating a thermal wave at the surface of the object. This absorbed thermal wave propagates inside the material and is reflected by the flaws, where the physical heat propagation parameters are changing. The interference of incoming and reflected waves from a flaw creates a harmonic, oscillating radiation pattern on the surface of the material, which is detected by the infrared camera. Hence, areas on the object surface above flaws exhibit a different phase with respect to undamaged area as shown in figure 2.6. The lock-in thermography system and software then computes the amplitude and phase information to identify areas with flaws [15].

In Lock-in Thermography, the phase angle refers to the phase difference between a sinusoidally modulated incident thermal wave and the resulting thermal wave reflected from the subsurface defects [15]. Here the temperature field is continuously monitored during the modulated heating with a thermal camera. Fourier analysis is then performed on the time varying measurement for each pixel to get the amplitude image and the phase image [14].
A second, easier, method to calculate phase and amplitude at each pixel is to synchronize the modulation frequency, $\omega$, with the image capture (with a lock-in amplifier). Four signal values are obtained (say $S_1$, $S_2$, $S_3$, and $S_4$) per period in every pixel of the image. These signal values will differ by a phase values of $90^\circ$ and are used to calculate the local amplitude, $A$, and phase, $\varphi$, through [23],

$$A = \sqrt{(S_3 - S_1)^2 + (S_4 - S_2)^2}$$

(2.8)
\[
\varphi = \arctan \left( \frac{S_3 - S_1}{S_4 - S_2} \right) \quad (2.9)
\]

The phase image is of prime importance because it is least affected by noise parameters such as non-uniform heating and emissivity variations. All the data containing thermal pulse amplitude variations goes into the amplitude of the Fourier spectrum. The only noise component that affects the phase calculation is transverse heat transfer due to non-uniformity of the illumination source (but this is generally not significant). An added advantage is that maximum depth penetration of the phase is approximately twice the depth penetration of the amplitude [11].

The one dimensional solution for diffusive periodic wave propagation through a semi-infinite isotropic solid is given by [20],

\[
T(z,t) = T_0 \exp \left( -\frac{z}{\mu} \right) \cos \left( \frac{2\pi z}{\lambda} - \omega t \right) \quad (2.10)
\]

where, \(T_0\) is the initial surface temperature, \(\omega\) is the modulation frequency, \(\lambda = 2\pi \mu\) is the thermal wavelength and \(\mu\) is the diffusion length given by

\[
\mu = \sqrt{\frac{2\alpha}{\omega}} = \sqrt{\frac{2k}{\omega \rho C_p}} = \sqrt{\frac{\alpha}{\pi f_b}} \quad (2.11)
\]

Thus to calculate the diffusion length, we require thermal diffusivity \(\alpha\) of material being inspected and the frequency \(f_b\) (the blind frequency) at which the defect becomes visible. For the amplitude image, the depth range is given by above equation, whereas for phase image
the maximum depth corresponds to $2\mu$ [24]. From the equation 2.10 we can see that the penetration depth is inversely proportional to the square root of frequency, which means that low modulation frequencies will probe deeper. Hence we have to carry out a number of experiments for different frequencies, each corresponding to a different depth, starting with higher frequencies for surface defects. This procedure is typically repeated until the entire thickness of the material is probed or the minimum available frequency is reached [23]. From equation 2.9, the phase $\phi$ at a depth $z$ is given by,

$$\phi = \frac{2\pi z}{\lambda} = \frac{z}{\mu}$$  

(2.12)
2.1.3 Pulsed Phase Thermography

Pulsed Phase Thermography, which was first introduced in 1996 [25], is a mathematical link between Pulsed Thermography and Lock-in Thermography. Through the superposition principle, the square pulse thermal input in Pulsed thermography can be approximated by the sum of sine waves with frequencies ranging from zero to infinity [26]. Thus a transformation algorithm such as the Fourier Transform can be used to extract a certain number of thermal waves (each having different frequencies) from the thermal pulse [19]. In Pulsed Phase Thermography, the positive features of Pulsed Thermography and Lock-in Thermography are combined while several of the noise sources are omitted. In Pulse Thermography, the data acquisition is fast but various factors such as non-uniform heating and environmental reflections affect the thermal image; whereas in Lock-in Thermography the phase image is not affected by these problems but requires a number of experiments for defect detection at various depths [19]. Thus in Pulsed Phase Thermography the data is acquired as in Pulse Thermography (with the benefit of time savings) and the phase image is obtained as in Lock-in Thermography. The added advantage in Pulsed Phase Thermography is that several frequencies are available in a single experiment.

The experimental setup for Pulsed Phase Thermography is same as that of Pulsed Thermography. A sequence of images are recorded during the cooling transient and using one dimensional Fourier transform on each pixel of this sequence, the various frequencies are extracted as will be explained in section 2.2.2.
2.1.4 Fourier Transform and Discrete Fourier Transform

The Fourier Transform or Continuous Fourier Transform (CFT) is a reversible, linear transform which can be derived by representing the complex Fourier integral as a sum of exponential functions. For any function \( f(x) \), the Fourier Transform can be denoted as \( F(s) \), where the product of \( x \) and \( s \) is dimensionless. Often \( x \) is a measure of time \( t \) (i.e. time domain signal) and \( s \) corresponds to inverse time or frequency (i.e. frequency domain signal). Hence the CFT of any time domain function \( f(t) \) can be written as [27],

\[
F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-2\pi i \omega t} \, dt
\]  

(2.13)

The continuous Fourier transform converts a time-domain signal of infinite duration into a continuous spectrum composed of an infinite number of sinusoids. In real life, we deal with signals that are discretely sampled, usually at constant intervals, and that are of finite duration or are periodic. For such data, only a finite number of sinusoids are needed and the Discrete Fourier Transform (DFT) is appropriate. The DFT of any time domain function \( f(t) \) can be written as [25],

\[
F(n) = \frac{1}{N} \sum_{n=0}^{N-1} f(k \Delta t) \exp \left( \frac{-2i\pi nk \Delta t}{N} \right)
\]

(2.14)

where \( k \) is the frequency increment \((k = 0, 1, \ldots, N-1)\) and \( \Delta t \) is the sampling interval.

The Discrete Fourier Transform is used for approximating the Fourier coefficients, partial sums of Fourier series and Fourier transforms, however, computing it directly from
the definition is often too slow to be practical. Hence, for effectively implementing this tool, one requires efficient computing techniques for carrying out a large number of calculations. This is where Fast Fourier Transform, FFT, can be applied. The FFT is not a transform, but an efficient algorithm for computing DFTs [28]. The FFT algorithm is available in commercial software packages such as Matlab to greatly reduce the computing time.

2.2 Thermal Data Analysis and Parameters in Pulsed Phase Thermography

The various procedures involved in Pulsed Phase Thermography, starting from data acquisition to calculating phase and amplitude images, are discussed in depth in this section.

2.2.1 Data Acquisition

In Pulsed Phase Thermography, like in Pulse Thermography, an inspected specimen is stimulated with a heat pulse from flash lamps, usually from some milliseconds to a few minutes depending on the thermal properties of the material to be inspected and the power of the flash lamps. The thermal wave propagates in the material as described in section 2.1. The IR camera continuously monitors the temperature evolution on the surface of the material and records the thermograms at regular intervals. A typical heating and cooling graph is shown in figure 2.7. At the starting time \( t_s \), i.e. the time before the heat wave reaches the surface of the material being inspected; we get an image called the cold image. Although the cold image can be used for eliminating the spurious reflections due to emissivity variations (which is good for thermal data visualization and quantification), it is not useful when
working with phase delay images [19]. Shortly after the application of the heat pulse, some saturated thermograms are acquired, which are temperature saturated and hence typically out of the camera calibration scale. The number of acquired saturated thermograms depends on the sampling frequency and the thermal properties of the material being inspected. The cooling transient for the material being inspected is the period from the Early Recorded Thermograph (ERT) to the Last Recorded Thermograph (LRT) in between which a number of thermograms are recorded. These thermograms constitute the “thermogram sequence”.

Figure 2.7 Thermograms acquisition in Pulsed Phase Thermography [19].
The thermogram is a 2D matrix consisting of temperature values, which can be arranged into a 3D matrix for the thermogram sequence, \( T \) (row, column, time). Row and column indices denote the position of each individual image pixel \( T(r, c) \), while its value corresponds to the temperature at that referred point. The time index \( t \) determines an individual thermogram order in the thermogram sequence. Thus, the matrix \( T(r, c, t) \) is a 3D temperature function of the spatial coordinates and observation time of the equivalent thermogram.

![Diagram of 3D temperature matrix and thermal decay profile](image)

**Figure 2.8** Formation of 3D temperature matrix and (below) thermal decay profile for non-defective pixel (co-ordinates \((r,c)\)) of material being inspected.
2.2.2 Thermal Data Analysis

The fundamental data processing in Pulsed Phase Thermography is to analyze the temporal evolution of the surface of the material being inspected in the frequency domain.

The required frequency spectrum is available in the square thermal pulse as discussed in section 2.1.3 and as shown in figure 2.9.

![Diagram showing Pulse Thermography and Pulsed Phase Thermography with Fourier Transform](image)

Figure 2.9 Extraction of various frequencies in Pulsed Phase Thermography using FT [19].

A transformation algorithm such as the Fourier Transform (or in the case of discrete data the digital Fourier Transform, DFT) is used to extract specific frequency thermal waves.
from the measured reflected thermal wave (at each pixel in the captured thermogram) [11],

\[ F(n) = \frac{1}{N} \sum_{k=0}^{N-1} T(k \Delta t) \exp\left(-\frac{2\pi i nk \Delta t}{N}\right) = \text{Re}(n) + i \text{Im}(n) \]  \hspace{1cm} (2.15)

where \( k \) is image index, \( T(k \Delta t) \) is the temporal evolution for each pixel, and \( \text{Re} \) and \( \text{Im} \) are the real and imaginary parts of the Fourier transform respectively [11]. The amplitude and phase of the reflected wave at each pixel are calculated from the imaginary and real parts of the DFT as [23]

\[ A(n) = \sqrt{\text{Re}^2(n) + \text{Im}^2(n)} \]  \hspace{1cm} (2.16)

\[ \phi(n) = \arctan \left[ \frac{\text{Im}(n)}{\text{Re}(n)} \right] \]  \hspace{1cm} (2.17)

As the phase information calculated from reflected thermal wave is not as influenced by noise sources such as non-uniform heating, surface variations and environmental conditions, only the phase information will be considered in this study. It will be seen later that choosing the frequency window over which to perform the DFT, will window the imaging depth resolved through the phase information. Therefore we will calculate and present the phase information from the DFT for a range of frequencies \( f_k \) with

\[ f_k = \frac{k}{N \Delta t} = \frac{k}{w(t)} \]  \hspace{1cm} (2.18)
and the maximum \( f_k = 1/(2\Delta t) \), where \( w(t) \) is the truncation window.

### 2.2.3 Sampling Theorem and Band Limitedness

Shannon’s sampling theorem states that, a continuous function can be fully recovered from the sampled data, if a sampling frequency “\( f_s \)” used, that is at least twice the maximum available frequency (called the Nyquist frequency \( f_c \)) [27],

\[
f_s \geq 2f_c
\]  

(2.19)

The condition for the sampling theorem to apply is that the function to be sampled, \( f \), should be “band-limited”; that is, its Fourier transform is nonzero over a finite range of the transform variable. In other words,

\[
F(f) = 0 \quad \text{for} \quad |f| \geq f_c
\]  

(2.20)

However, real signals, like the thermal decay profiles in pulse thermography, are never band limited. Sampling non-band-limited functions introduces aliasing, which can be minimized to acceptable levels by complying with Shannon’s sampling theorem.

In pulse phase thermography, we have to sample and truncate the data as shown in figure 2.8. The truncation window size is given by \( w(t) = N\Delta t \) [29]. Hence, the sampling process requires establishing values for any two of the following three parameters: the truncation window size \( w(t) \), the total number of points to be sampled \( N \), and the spacing between sampled points \( \Delta t \). Once these time domain parameters are selected, the various sampling and truncation parameters in frequency domain can be selected by table 2.1 [19].
2.2.4 Acquisition Parameters

In Pulsed Phase Thermography, the first two acquisition parameters that need to be determined are the frame rate, $f_s$, and the acquisition time, $t_{acq}$, as described in section 2.2.3. The maximum storage capacity of the IR system limits these two parameters as $N_{max} = f_s t_{acq}$. The selection of the frame rate depends on thermal properties of the specimen.

For high conductivity materials, the thermal variations occur rapidly, and hence they require faster frame rate (than that for low conductivity materials) to avoid loss of thermal information. As thermal variations decay more rapidly in high conductivity materials, they require lower acquisition time than low conductivity materials. The general guideline about acquisition is that the thermal acquisition should begin before thermal wave reaches any defect inside material to be inspected and it should end after the thermal contrast becomes negligible. Ideally, the Last Registered Thermograph (LRT) is nearly at the room temperature (i.e. the temperature of the cold image). However, for low conductivity materials, it could take a long time to reach this temperature and in practice, acquisition is truncated when the thermal contrast between defective and non-defective area diminishes [19].
Table 1 Sampling and truncation parameters in Time and Frequency domains [19].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time Domain</th>
<th>Frequency Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>$\Delta t$</td>
<td>$\Delta f = 1/w(t)$</td>
</tr>
<tr>
<td>Truncation window</td>
<td>$w(t) = N.\Delta t$</td>
<td>$f_{\text{max}} = f_c = 1/(2.\Delta t)$</td>
</tr>
<tr>
<td>Sampled points</td>
<td>$N$</td>
<td>$N/2$</td>
</tr>
<tr>
<td>Single element value</td>
<td>$t_n = n.\Delta t$</td>
<td>$f_n = n/(N.\Delta t)$</td>
</tr>
<tr>
<td>Minimum value</td>
<td>$t_1 = \Delta t$</td>
<td>$f_1 = 1/(N.\Delta t)$</td>
</tr>
<tr>
<td>Maximum value</td>
<td>$t_n = t_0 + w(t)$</td>
<td>$f_n = f_{\text{max}} = f_c = 1/(2.\Delta t)$</td>
</tr>
</tbody>
</table>
2.2.5 Depth Calculation by Pulsed Phase Thermography

The depth at which a particular defect occurs can be determined from the thermal transient through the diffusion length of the thermal wave at different frequencies, similar to the method used in lock-in thermography [30]. The depth of the defect, \( z \), can be determined from

\[
z = C \sqrt{\frac{\alpha}{\pi f_b}} = C \mu
\]  \hspace{1cm} (2.21)

where \( \alpha \) is the diffusivity of the material (in the non-defective area), \( f_b \) is the blind frequency (i.e. the maximum frequency at which the defect is visible in the thermal transient) and \( \mu \) is the diffusion length. The diffusion length is the maximum depth at which subsurface structure affects the surface temperature. The coefficient \( C \) depends upon the specimen configuration and the defect type and is typically calibrated through a linear regression fit of \( z \) to \( \mu \) for a given specimen type. Practically, determining the blind frequency of a given defect requires the optimization of the sampling and truncation parameters [30]. Additionally, by defining the blind frequency for a particular defect based on a mathematical representation of the phase contrast between non-defective and defective regions, the defect depth can be estimated without the need for user interpretation of the thermal images [30]. This approach will be applied in this study.
2.3 Fiber Bragg Gratings Sensors

Fiber Bragg Gratings (FBGs) have been widely applied in civil, mechanical and aerospace engineering as strain, temperature, pressure and vibration sensors [31]. FBG sensors are small, lightweight, flexible, non-conductive, non-corrosive and immune to electromagnetic interference. Additionally they can be embedded into composite laminates for subsurface measurements. These sensors can therefore be integrated into “fly-by-light” concepts for future generations of aircraft. In an optical fiber light is guided through the core, which is made of germanium-doped silica. The core is surrounded by a cladding region whose index of refraction is slightly lower than the core [31]. In many applications, there is also a coating on the optical fiber which protects the sensor from harsh environmental conditions.

A FBG sensor consists of a small segment (usually around 10 mm) of optical fiber where a periodic modulation of the core index of refraction is formed. This is typically done by exposing the core to an interference pattern of intense UV light (at approximately 245 nm). When broadband light is passed through the FBG, the optical back reflected spectrum of such Bragg grating comprises a very narrow peak. This strong back reflection occurs at a particular wavelength called the Bragg Wavelength, $\lambda_B$, which is related to the effective core refractive index, $n_{\text{eff}}$, and the period of index modulation or grating period, $\Lambda$, [31]:

$$\lambda_B = 2n_{\text{eff}} \Lambda$$  \hspace{1cm} (2.22)
The Bragg wavelength shifts with changes in either $n_{\text{eff}}$ or $\Lambda$ (see figure 2.10). The change in these two parameters is sensitive to temperature, strain and pressure, and hence the wavelength change can be used to determine the strain, temperature or pressure to which the optical fiber is subjected, as shown in fig. 2.10.

Although the application of these FBG sensors to temperature measurements in various fields are found widely in literature [32,33], only a few references are found for thermal flaw detection in composites [34]. When a thermal load is applied to the FBG, the Bragg wavelength changes, $\Delta \lambda_B$, due to a material property change, $\Delta n_{\text{eff}}$, and an expansion
or contraction of the optical fiber in the axial direction which changes the grating period, $\Delta \Lambda$

Near room temperature this change is a linear function of applied temperature, $\Delta T$. We can therefore write

$$\Delta \lambda_B = 2 \Delta n_{\text{eff}} \lambda + 2 \Delta \Lambda n_{\text{eff}}$$

(2.23)

and

$$\frac{\Delta \lambda_B}{\lambda_B} = \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} + \frac{\Delta \Lambda}{\Lambda}$$

(2.24)

The change in grating period, $\Delta \Lambda$, is directly related to the thermally induced axial strain,

$$\Delta \Lambda = \alpha \Delta T$$

(2.25)

where $\alpha$ is the thermal expansion coefficient of fused silica ($\alpha = 8.0 \times 10^{-7} \, ^\circ\text{C}^{-1}$) [35]. The material property change, $\Delta n_{\text{eff}}$, has two contributions: the temperature induced change in the index of refraction and the strain induced change in the index of refraction due to the thermally induced strain. The first effect will be written as

$$\Delta n_{\text{eff}} = \xi \Delta T$$

(2.26)

where $\xi$ is the thermo-optic coefficient of fused silica ($\xi = 7.3 \times 10^{-6} \, ^\circ\text{C}^{-1}$) [35]. The portion due to the thermally induced strain will be written as
\[ \Delta n_{\text{eff}} = -p_e \varepsilon = -p_e \alpha_s \Delta T \]  

(2.27)

The coefficient \( p_e \) is the photo-elastic coefficient for the optical fiber. A typical value is \( p_e = 0.26 \) [36]. Combining equations (2.24) through (2.27), we can write the total shift in Bragg wavelength due to the applied temperature change \( \Delta T \),

\[ \frac{\Delta \lambda_B}{\lambda_B} = \left[ \alpha_s (1 - p_e) + \xi \right] \Delta T = \eta_{\text{free}} \Delta T \]  

(2.28)

Equation (2.28) is therefore predicts the thermal response of a fiber Bragg grating when it is free. For the case of a FBG sensor embedded in a host material (such as the composite laminate) the FBG is forced to expand with the host material, therefore the thermal expansion coefficient is no longer \( \alpha_s \), but rather \( \alpha_h \), the thermal expansion coefficient of the host material. The thermal response of the fiber Bragg grating then becomes,

\[ \frac{\Delta \lambda_B}{\lambda_B} = \left[ \alpha_h (1 - p_e) + \xi \right] \Delta T = \eta_{\text{embedded}} \Delta T \]  

(2.29)

This equation assumes that the FBG does not change the deformation of the host material. A typical value for the thermal expansion coefficient of graphite fiber reinforced epoxy is \( \alpha_h = 3.4 \times 10^{-6} \, {^\circ}\text{C}^{-1} \) [35]. Using the specific coefficients for silica and graphite fiber reinforced epoxy, \( \eta_{\text{free}} = 7.89 \times 10^{-6} \, {^\circ}\text{C}^{-1} \) and \( \eta_{\text{embedded}} = 9.82 \times 10^{-6} \, {^\circ}\text{C}^{-1} \). The fractional change in the thermal response coefficient, \( \eta \), between the embedded and free optical fiber conditions is
This difference is important when calculating the applied temperature from the measured Bragg wavelength shift of the FBG sensor, when it is embedded in a material with damage. Prior to damage the optical fiber can be considered fully constrained by the composite laminate and the coefficient $\eta_{\text{embedded}}$ used to calculate the applied temperature. However when damage to the composite laminate is present at the location of the optical fiber, the actual physical constraint on the optical fiber will be somewhere in between that of the embedded fiber (perfect bond) and the free fiber (no bond) and

$$\eta_{\text{embedded}} \leq \eta \leq \eta_{\text{free}}$$  \hspace{1cm} (2.31)

From a measurement perspective, this means the sensor gauge factor is dependent on the damage which is to be detected and therefore is unknown. However, in this work, two measurement techniques will be applied simultaneously; therefore the Pulsed Phase Thermography results will be used to determine the gauge factor for the embedded FBG sensors. This topic will be discussed in Chapter 4.

The damage detection in composites by using FBG sensors is based on the principle that the flaws inside the composite alter the heat flow inside the specimen because of changes in the thermal conductivity of the composite and hence damage can be detected by measuring local temperatures in the sample being inspected [37].
Chapter 3  Experimental Methods

Consistent with the goals of this project, as outlined in Chapter 1, three sets of experiments were performed:

**Calibration of the PPT setup and its resolution for the detection of voids in carbon fiber-epoxy laminated specimens:** For these experiments, laminated carbon-fiber epoxy laminated plates were fabricated with embedded polymer foam inserts, following the ASTM standard for thermal imaging. These specimens will be referred to as specimen type 1. PPT imaging of these specimens quantified the diameter to depth ratio and expected phase contrast for the detection of voids for the PPT setup at NCSU. The data also provided a calibration of the diffusion length as a function of defect depth that would be applied in the second set of experiments.

**Through the thickness imaging of low-velocity impact induced damage in the same material system:** For these experiments, similar laminated carbon-fiber epoxy laminated plates were fabricated, without the embedded polymer foam inserts. These specimens will be referred to as specimen type 2 and were later impacted at various low-velocity impact energies. The PPT setup was then applied to perform through the thickness imaging of the impact induced damage and compared to micrograph images of sample specimens.
Enhancement of through the thickness imaging through the fusion of PPT data with that of internal discrete temperature sensors: For these experiments the same laminated carbon-fiber epoxy plates were fabricated, however with embedded FBG sensors at various depths in the laminate. These specimens will be referred to as specimen type 3. Three specimens were prepared with a single embedded FBG sensor, but at different distances from the center of impact, from which the FBG response to the thermal loading pulse was measured in both the heating and cooling periods. From this data the optimal FBG location and data acquisition parameters were defined. Afterwards, a single specimen with three embedded FBG sensors at the same in-plane location, but different depths, was fabricated. This specimen was applied for the combined PPT and internal temperature sensor imaging of low-velocity impact damage.

This chapter describes the preparation methods for each of the laminated composite samples used in the experiments, the use of low velocity impacts to create realistic damage modes in some samples, and the experimental setup for the pulsed phase IR thermography and FBG sensor interrogation. The results of each these experiments are presented in Chapters 4 and 5.
3.1 Sample Preparation

Three different types of laminated, 2x2 twill woven carbon-fiber epoxy composite plates were fabricated. The first type (specimen type 1) included Rohacell foam inserts introduced between different pre-preg layers to simulate manufacturing defects. These specimens were used to optimize the sensitivity of the pulsed phase IR thermography setup for the carbon fiber laminates to be tested. The specimens were also used to calibrate the minimum defect size to depth ratio that could be detected. The second type (specimen type 2) was used to investigate the sensitivity of the pulsed phase IR thermography to BVID in the laminates and its ability to reconstruct depth information. The third type (specimen type 3) was used to evaluate the combined inspection technique using both pulsed phase IR thermography and embedded FBG sensors for the detection of barely visible impact damage.

All specimens were prepared from 12 layers of 2x2 twill weave carbon fiber-epoxy pre-preg (Advanced Composites LTM22/CF0300). A single 2mil thickness Mylar release film and four separate pieces of polyester peel-ply fabric were used to prevent adhesion of the sample to the mold surface. The dimensions of the specimens were 115 mm x 115 mm, except for the specimen type 1 for which the dimensions were 125 mm x 125 mm. All specimens were assembled and vacuum bagged prior to curing in a hot-press. The samples were cured following a stepped temperature profile of 15 min at 50 °C, 15 min at 65 °C and 180 min at 80 °C, followed by 30 min without heating. A constant pressure of 690 kPa was maintained throughout the temperature cycle. Afterwards, the assembly was removed from the hot-press and allowed to cool to room temperature.
3.1.1 Calibration Specimens (Specimen Type 1)

The specimens of type 1 were used to test the infrared imaging response to inclusions and were thus prepared with controlled Rohacell polymer foam inclusions embedded during the laminate layup process. These inclusions are representative of voids created during the manufacturing process [38]. The motivation for using the polymer foam inserts in this work was to replicate the effects of barely visible impact damage (within a single interface between laminae) as closely as possible while controlling the damage size. Previous researchers have applied Teflon inserts, Nylon bagging film, Rohacell inserts, Kapton inserts, flat bottom holes and aluminum shims to simulate internal defects [38,39,40]. The difference in heat absorption rate between the polymer foam and the carbon-fiber epoxy pre-preg is close to that between an air void and the pre-preg material. Simulated defects using flat bottom holes, Teflon inserts and aluminum shims present much larger phase shifts in contrast to the surrounding composite material and are therefore not representative of impact induced damage [41].

The Rohacell foam (of thickness 3.0 mm) sheets were cut into squares of 1.5 cm x 1.5 cm, 1.0 cm x 1.0 cm and 0.5 cm x 0.5 cm and inserted at various locations and depths in the laminate, following ASTM standard E2582-07 (with the exception that the largest size defects were not spaced sufficiently far apart from one another). One sheet of each size was embedded between the 1st and 2nd layers, one between the 2nd and 3rd layers, one between the 3rd and 4th layers, one between the 4th and 5th layers, one between the 5th and 6th layers and one between the 6th and 7th layers (i.e. at the midplane), as shown in figure 3.1.
The laminate was then placed under pressure and heated as described above. The total thickness of the samples was 2.60 mm, 0.25mm greater than samples without the foam inserts. The individual foam sheets were therefore partially crushed during the laminate fabrication and the surrounding laminate layers deformed around them. Once cured, the
samples were spray painted with Black Rustoleum Flat Protective Enamel to increase the emissivity of samples for more accurate thermal imaging.

3.1.2 Through the Thickness Imaging Specimens (Specimen Type 2)

The specimens of type 2 were used to test the sensitivity of the pulsed phase thermography technique to impact damage. For these specimens, the laminates were fabricated as described above (without foam inserts). Four different specimens (ID1, ID2, ID3, and ID4) were fabricated to simulate impact damage at different impact energies. The dimensions of specimen type 2 are shown in Figure 3.2. The resulting laminate thickness was 2.35 mm.

Figure 3.2 Dimensions of specimen types 2 (not to scale).
3.1.3 Combined Imaging Method Specimens (Specimen Type 3)

The specimens of type 3 were used to test the sensitivity of both the infrared imaging and FBG sensors to impact damage. To fabricate the specimen with a single FBG sensor (as shown in figure 3.3), the lower 6 lamina were removed from their plastic and release backing and stacked in place in the center of the peel-ply square aligned with one another. The sensor fiber was then placed on top of the lower layers at 0° orientation to the carbon fiber and 16 mm or 12 mm offset from the center of the sample, with the center of the FBG aligned with the impact point. To maintain sensor alignment, the ends of the fiber were taped to the workbench, holding the fiber taut. The remaining 6 layers of pre-preg were then assembled on top of the lower layers and sensor fiber. Figure 3.5 shows a specimen of type 3 during vacuum bagging. To provide protection for the fiber from excess epoxy resin during the curing process, a small ball of plumber’s putty was placed around the fiber on either side of the sample (see figure 3.5). The curing cycle and the rest of the fabrication procedure was the same as that of first and second set of specimens. Three specimens were prepared as shown in figure 3.3.

The final specimen in this category was prepared with 3 FBG sensors embedded between 6th and 7th layer, between 8th and 9th layer and between 10th and 11th layer respectively as shown in figure 3.4. All FBG sensors were embedded at the same planar location at a distance of 12 mm from the center of impact.
3.2 Low-velocity Impact Testing

The second and third sets of specimen were subjected to a low-velocity impact using the instrumented drop tower impactor shown in figure 3.6. The impactor consists of a 19 mm diameter hemispherical steel impacting probe. The entire crosshead and impactor mass was 5.5 kg. The specimens were mounted between two 76 mm diameter steel clamping rings with a layer of 1.5 mm neoprene film on each side to distribute the clamping pressure evenly over the clamped area. The crosshead was manually arrested during the rebound following impact with the specimen to prevent secondary strikes. The impact energy was manually adjusted by
changing the release height of the crosshead. The precise impact energy for each strike was determined from a magneto-restrictive position sensor mounted to the crosshead. The average change in the position vs. time was calculated for 100 data points prior to the impact. The impact energy was then calculated as

\[ E = mv^2 \]  

(3.1)

where \( m \) is the mass of the crosshead and \( v \) is the impact velocity.

Figure 3.4 Dimensions of specimen type 3 with multiple embedded FBG sensors (not to scale).
Figure 3.5 Photograph of Specimen type 3 during vacuum bagging.

Figure 3.6 Instrumented drop tower impactor.
3.3 Pulsed Phase IR Thermography

The experimental setup for the Pulsed Phase infrared thermography (in reflection) of the specimens is shown in figure 3.7. All specimens used in this study were laminated flat plates; therefore a specimen mounting system was designed using machined aluminum rails. The mounting system allows adjustment of the infrared camera perpendicular to the specimen plane and movement of the specimen within its own plane. The specimen was held in place in the frame by a Rohacell plate to reduce heat transfer from the specimen to the aluminum rails. Infrared images were captured with a Cedip Titanium 560MWIR focal plane array camera, which operates in the mid-wavelength spectral range (1.5-5.1 µm). This camera has a InSb detector array producing images with a resolution of 640 x 512 pixels and has a thermal sensitivity of less than 20 mK at a temperatures of 25 °C. The maximum frame rate is 100 Hz.

Generally in Pulse Thermography, high power xenon lamps with heating duration of few milliseconds [16] are used for high thermal conductivity materials. However, good results can be obtained for low conductivity (i.e. slow thermal response) materials, such as CFRP, using modest power Halogen lamps in a long pulse mode [39]. Hence, here halogen lamps were preferred over xenon lamps for all the experiments. The specimens were heated by two halogen lamps each of 1700 W of capacity for 7 seconds and then allowed to cool. The image acquisition was manually started just before the cooling began. The function generator (Tektronix AFG3021B) sent a square wave pulse to the IR power module (IR
Power control 330 US) to activate the heat lamps. The pulse had an amplitude of 5 V corresponding to a single halogen lamp output of 850 W. The lamps were placed at an angle of 30° to the sample so that the sample could be relatively uniformly heated. The distance between halogen lamps and the specimen was chosen to be 0.5 m following trials to ensure that non-uniformities in the applied heating were minimized as far as possible. The specimens were imaged from the front of specimen and the images were captured from the infrared camera using a PC and Altair software. The image data files were then saved and imported into Matlab for further processing. The total data set from the thermal camera was first processed to remove the heating period and then was processed using the open access Matlab based IR VIEW [42] to calculate the phase and amplitude images.
Figure 3.7 Experimental setup for Pulsed Phase IR Thermography. (a) Schematic of system. (b) photograph of lab system including: (1) specimen; (2) specimen mounting system; (3) halogen lamp; (4) IR Camera; (5) camera mounting system; (6) function generator; (7) IR power controller; (8) FBG interrogator
3.4 FBG Sensor Data Collection

For the final set of experiments, data was collected simultaneously from both the IR camera and the embedded FBG sensors during and after heating of the specimen with the flash lamps. A schematic of the introduction of the FBG interrogator into the IR Pulsed Phase Thermography setup is shown in figure 3.8. The same flash lamp heating and IR camera procedure as described was followed. Data recording by the IR camera and the FBG optical interrogator (Micron Optics sm130) was manually started just before the start of the pulse heating. Micron Optics Enlight software was used to capture the FBG sensor peak wavelength data as a function of time. Peak wavelength data acquisition rates varied from 1 – 20 Hz among the different experiments. Individual reflected spectra from the FBG were also collected after each impact to check for spectral distortion. The IR camera images and FBG sensor data were later manually synchronized for each experiment based on the FBG heating response. Window averaging filtering was also applied to remove noise in the FBG sensor data, as described in Chapter 5.
Figure 3.8 Schematic diagram of experimental setup for simultaneous IR imaging and FBG sensor interrogation.
Chapter 4  Pulsed Phase Thermography Results and Discussion

4.1 Thermal Response of Carbon Fiber-Epoxy Composite Laminates

Typical pulse durations in pulse thermography vary from a few milliseconds to several seconds depending upon the thermo-physical properties of the material being inspected and the properties of the defect. In general the pulse duration is chosen to balance the two competing requirements of maximizing thermal energy to maximize the thermal response of the material (while remaining below thermal material damage) and minimizing the thermal pulse duration to maximize the temperature contrast between defective and non-defection areas [11]. For the 2D woven carbon composite specimen used in this study, the pulse duration was varied between several trials, from which 7 s was selected to produce the best defect image. This pulse duration was then used for all experiments described in this paper.

The measured thermal response of two pixels from impact damage specimen ID1 to a square pulse of 7 s is shown in figure 4.1. The thermal response was measured after the specimen was impacted. As carbon fiber – epoxy is a low conductivity material, the specimen required a long time to reach the room temperature, approximately 15 minutes, and the full measurement time is not plotted in figure 4.1(b). From figure 4.1(b), we observe that the observation time, $t_{obs}$, defined as the time from the beginning of cooling transient until
there is no thermal contrast between a non-defective and defective area, was approximately 12 s. We can compare this observation time to that predicted based on the time required for an incident thermal wave to reflect from the back surface of the specimen to the front surface [11],

\[ t_{\text{obs}} = \frac{z^2}{\alpha} \]  

(4.1)

Using the laminate thickness of 2.35 mm and an approximate value of \( \alpha = 0.42 \) mm\(^2\)/s for carbon-fiber epoxy [43] yields \( t_{\text{obs}} = 13.1 \) s, close to that measured experimentally.

In later experiments, the full thermal data acquisition time was set to 60 s, including a portion of the heating time. The truncation window, \( w(t) \), was then extracted from the thermal images during post-processing to fall within this observation time.

For the camera frame rate of 60 Hz, for above experiment, \( \Delta t = 0.0166 \) s and \( w(t) = 12 \) s yields a total number of images \( N = 720 \). To reduce the data processing, 1 image was selected out of 10 images reducing the number to \( N = 73 \) images. Thus the sequence of 73 images with \( \Delta t = 0.166 \) s produces a minimum frequency of 0.083 Hz for the Pulsed Phase Thermography procedure.

### 4.2 Calibration of PPT with Simulated Defects

As discussed earlier, specimen set 1 was used to find the sensitivity of the PPT setup for two dimensional carbon fiber–epoxy woven laminates and to calibrate the depth to blind
frequency for this material which is widely used in aerospace industry. The sensitivity (also known as aspect ratio) of thermography systems is defined as the defect diameter to depth ratio required for a given defect to be detectable (defined in ASTM standard E2582-07). This sensitivity is different for different materials and is dependent on material properties and hence usually determined by using simulated defects such as Teflon inserts, Nylon bagging film, Rohacell inserts, flat bottom holes etc. [44]. Rohacell foam inserts were used as discussed in 3.1, to simulate defects in aerospace composites which is caused due to inclusions, air bubbles and disbonds etc.

4.2.1 Simulated Defect Detection

The composite laminate was first imaged such that the inclusions were embedded in between layers 1-7 with respect to the front of the surface. The measured thermogram and temperature decay curve for a pixel in a defective and non-defective area of the specimen are shown in figure 4.2. (a) and (b) respectively. The absolute contrast, defined as the temperature difference between the pixel in the non-defective and defective areas, is also plotted in figure 4.2(b). The pulse thermography image with the maximum absolute thermal contrast was captured 1 s after the beginning of the cooling transient and is shown in figure 4.2(a). The available observation time for this specimen was approximately 10 seconds (up to point a in figure 4.2(b)). Not all defects are clearly visible in figure 4.2(a); in particular the defects between layers 5 and 6 and those between 6 and 7 are difficult to distinguish. Additionally, non-uniform heating of the specimen from the left to the right of the image is also apparent.
Figure 4.1 (a) Single pulse thermography image of specimen ID1 showing defective and non-defective areas. (b) Thermal response of pixels 1 and 2 from (a) and truncation window selection.
For PPT processing, we selected a maximum truncation window of 7.4 s, i.e. the time at which the absolute contrast was negligible, shown as point b in figure 4.2(b). The acquisition frame rate was 60 Hz, from which 1 out of every 10 images was subsampled, producing $\Delta t = 0.166$ s, reducing the total number of available images to 45. The minimum frequency available for this truncation window was 0.133 Hz. The phase image calculated using this frequency range is shown in figure 4.3, where all defects are clearly visible. Contrasting figure 4.3 and 4.2(a) shows the imaging improvement obtained by the use of phase information. The deepest defects (those in the top row) are not visible in the maximum contrast pulse thermography image of 4.2(a), however they are clearly visible in the phase image.

We next demonstrate the importance of the selected frequency window on the imaging quality of defects at different depths. Keeping the sampling interval constant, we varied the minimum frequency available by varying the truncation window length (or $N$). The resulting phase images for four different truncation windows are shown in figure 4.4. As the minimum frequency decreased the depth of the defects that can be imaged also increased. There is also a windowing behavior, as the defects with the maximum phase shift also propagated further into the laminate as the minimum frequency is decreased. The phase images of figure 4.4 show that there is an optimum choice of sampling parameters (i.e. $\Delta t$, $w(t)$) for each inspection depth. However, caution should be taken in using these phase images to determine the depth of a particular defect. The minimum frequency at which a defect is “visible” in the phase images (the blind frequency) is influenced by the method of
data presentation and user interpretation. A quantitative calibration of the blind frequency will be performed in the following section.

The specimen was then reversed in the mounting fixture such that the inclusions were embedded in between layers 7-12. In this manner, all depths of inclusions could be studied with the same specimen. The best pulse thermography image giving a maximum thermal contrast is shown in figure 4.5.

For PPT processing, the camera rate was reduced to 10 Hz to allow a longer truncation window. Sufficient absolute contrast was obtained over \( w(t) = 8 \) s. Further subsampling of 1 out of 2 images, reduced the total number of images to 41, with a sampling rate of \( \Delta t = 0.2 \) s. Thus the minimum frequency available for phase images was 0.125 Hz. The phase image obtained using this minimum frequency is shown in figure 4.6, where all defects of size 225 mm\(^2\) and 100 mm\(^2\) size were visible. The deepest defect of size 25 mm\(^2\) was not visible. In contrast, almost none of the defects are visible in the pulse thermography image of figure 4.5. Finally, the detectable diameter to depth ratio for the PPT measurements can be estimated based on the deepest defect of 25 mm\(^2\) that was detected (at a depth of 2.38 mm). The sensitivity of the PPT setup for these laminates is therefore approximately equal to 5 mm / 2.38 mm = 2.1, comparable with other PPT systems reported in the literature.

### 4.2.2 Depth Resolution of Simulated Defects

The final step, prior to imaging impact damage, is to calibrate the blind frequency as a function of defect depth for the given specimens and experimental setup. In other words, we need to calibrate the coefficient \( C \) in Eq. (2.21) for the given specimens. However, since
\( \alpha \) for the material systems is not known exactly, we instead calibrate the coefficient
\[ C' = C \sqrt{\alpha} \] (since \( \alpha \) is the same for all specimens). We will then write,
\[ z = C' \mu' = C' \sqrt{\frac{1}{\pi f_b}} \] (4.2)

where \( \mu' \) is the modified diffusion length.

Following the procedure of Ibarra-Castanedo et al. [30], the blind frequency for a given defect is estimated by plotted the phase shift vs. frequency curve for a pixel in the defective area and a pixel outside the defective area. By fitting a line to the upper frequency region, we estimate the frequency at which the two curves diverge. This process is shown in figure 4.7 for the 225 mm\(^2\) size defects (when imaged from the front of the specimen as in figure 4.3). The linear fit provides a reasonable estimation of \( f_b \) in the presence of noisy data. The blind frequency for each of the defects in figure 4.3 was thus calculated. For the deepest defects, this calibration procedure did not work well, as shown in figure 4.7 (f). The maximum frequency at which the defective and non-defective area produced phase contrast was not in the linear region of the curves. Therefore, only five defects of each size were used for the calibration.
Figure 4.2 (a) Pulse thermography image of specimen type 1 at maximum absolute thermal contrast. Defects increase in depth from bottom to top of image; (b) temperature decay for pixels in defective and non-defective areas of (a) and absolute thermal contrast. Time begins at the start of the cooling transient.
Figure 4.3 Phase image of specimen type 1 showing simulated defects at different depths in layers 1-7.

The blind frequency calculation for the 100 mm\(^2\) and 25 mm\(^2\) are shown figure 4.8 and figure 4.9 respectively. For each defect, a pixel at the center of the defect was used for the calculation of blind frequency. As the phase contrast is not uniform over the defective area, the choice of pixel can alter the calculation slightly. Pixels further from the center of the defective region are influenced by the boundary values near the defect. González et al [45] used an average phase shift over the defective region. Our goal is to calibrate the blind frequency as a function of depth for later, through the thickness imaging of impact damage. As impact damage does not present a clearly defined boundary, the use of a single pixel is more appropriate in this work.
The modified diffusion length, $\mu'$, was then calculated for each defect from the blind frequency. The known defect depth is plotted against the calculated modified diffusion length for each defect in figure 4.10. We observe that the relationship is approximately linear as predicted by Eq. (4.2). A linear fit to the data for each defect size is also plotted in figure 4.9. There is an effect of the defect size on the slope of the curve, consistent with previous observations of thermal imaging of flat bottom holes in steel plates [15]. Gonzales et al [45] normalized the parameters based on the thermal diffusivities in the through-the-thickness and the transverse directions to adjust the calculated depth as a function of blind frequency. As the damage size will not be known a-priori for the impact damage, we cannot apply a similar normalization to these results. However, the largest defect size in figure 4.10 is nine times larger than the smallest defect size, this dependence on defect size is not strong (the slope increased by 17.7% between the smallest and largest defects). We will therefore neglect the size influence in the calibration, as other noise factors will produce higher uncertainties.
Figure 4.4 Phase image from specimen type 1 for minimum frequency of a) 0.6 Hz ($N = 10$, $w = 1.66$ s); b) 0.4 Hz ($N = 15$, $w = 2.49$ s); c) 0.3 Hz ($N = 20$, $w = 3.32$ s); d) 0.17 Hz ($N = 35$, $w = 5.81$ s).
Figure 4.5 Pulse thermography image of specimen of type 1 imaged from back side to detect inclusions in layers 7-12.

Figure 4.6 Phase image of specimen type 1 showing simulated defects at different depths in layers 7-12.
Figure 4.7 Estimation of blind frequency $f_b$ by using phase profiles of defects of size 225 mm$^2$ at depths of (a) 0.2 mm, (b) 0.44 mm, (c) 0.68 mm, (d) 0.92 mm, (e) 1.16 mm and (f) 1.4 mm
Figure 4.8 Estimation of blind frequency $f_b$ by using phase profiles of defects of size 100 mm$^2$ at depths of (a) 0.2 mm, (b) 0.44 mm, (c) 0.68 mm, (d) 0.92 mm, (e) 1.16 mm and (f) 1.4 mm
Figure 4.9 Estimation of blind frequency $f_b$ by using phase profiles of defects of size 25 mm$^2$ at depths of (a) 0.2 mm, (b) 0.44 mm, (c) 0.68 mm, (d) 0.92 mm, (e) 1.16 mm and (f) 1.4 mm
We therefore calibrated the depth as a function of modified diffusion length for all defect sizes using a linear least squares regression. Figure 4.11 shows the resulting calibration, along with the 95% prediction and confidence intervals. The correlation coefficient for this linear fit over all data was $R = 0.981$. The resulting calibration curve was

$$z = 5.624 \left( \text{mm} / s^{1/2} \right) \mu' - 1.43 \text{ mm}$$

(4.3)

The constant term in Eq. (4.3) is a function of the distance from the surface of the specimen to the camera and may be influenced by replacing specimens in the support frame or indentations in the specimen surface. In later experiments, we will eliminate the constant term by referencing the depth measurements to the surface of the specimen.

Figure 4.10 Linear calibration of depth $z$ versus modified diffusion length $\mu'$ for three different defects sizes.
4.3 Imaging of Impact Damage

After calibrating the PPT setup with simulated defects, simulating voids created during manufacturing, the focus of this section is on impact damage, more specifically low velocity impact damage. Various authors differ over the exact definition of low velocity impact damage and over the transition from low velocity impact damage to high velocity impact damage. Cantwell and Morton [5], in their review of the impact resistance of composite materials reported the value of low velocity impact damage as a damage up to an impact velocity of 10 m/s, considering the test techniques used for simulating the damage.
Abrate [46] in his review of impact damage on laminated composite reported the value for low velocity impact damage to be less than 100 m/s. A more appropriate approach, suggested by Joshi and Sun [47] and Liu and Malvern [2], was adopted here for the impact tests. This approach classifies impact damage according to the prevalent damage modes. High velocity is characterized by fiber breakage due to penetration and low velocity is characterized by matrix cracking and delamination. Specimen set 2 consisted of four different specimens (ID1, ID2, ID3, and ID4), which were used for simulating impact damage at different impact velocities of 1.75 m/s, 1.4 m/s, 1.1 m/s and 0.9 m/s respectively. These impact velocities correspond to impact energies of 8.4 J, 5.4 J, 3.3 J, and 2.2 J. Initial tests were conducted with higher impact velocities and gradually the impact velocity was reduced until the impacted surface (which will be the only surface accessible for inspection in real life cases) shows a visible dent. For all the specimens in specimen set 2, pulse thermography images were taken from the same side as that of the impact, as for the real life case where we have access to inspect the impacted side only, e.g. the inspection of fuselages.

4.3.1 Detection of Impact Damage

Two major challenges distinguish imaging through the thickness of laminates subjected to impact induced damage as compared to imaging of inclusions or holes. The first is that shadowing of damage occurs due to the conical shape of the damage region (from the front to rear surface). This same shadowing is a common problem for imaging applications, however as we want to measure the extent of damage through the thickness of
the composite, this is not a serious issue for imaging of barely visible impact damage. The second challenge is that the thermal contrast between the defective and non-defective regions due to barely visible impact damage is much lower than that of inclusions used in standardized ASTM testing (even in the phase information). The reason for this lower contrast is threefold:

- impact damage is typically not as thick and do not have as different thermal diffusion properties as the inclusions used in standardized ASTM testing;
- impact damage boundaries are not necessary parallel to the thermal wave propagation direction;
- impact damage boundaries are not as sharp as the inclusion edges.

For example, Brown et al [41] measured a thermal contrast for impact damage of only 10% that of flat bottom holes in the same specimen and lock-in thermography configuration. For this study, we specifically chose to calibrate the PPT configuration with polymer foam inserts to reduce the large thermal property difference, however the effectiveness of the calibration will be determined from the imaging results.

We now apply the depth calibration based on the previous 1D thermal propagation assumption and compare the PPT imaging results with those from optical microscopy of the specimens. Figure 4.12 shows the specimen impacted at the highest velocity, 1.75 m/s. The thermal image at maximum contrast is shown in figure 4.12(a), while the PPT image using the maximum frequency range \( w(t) = 5.6 \text{s}, N = 35, \Delta t = 0.16 \text{s} \) is shown in figure 4.12 (b). The minimum frequency available in this window was 0.17 Hz. Both methods clearly detect
the presence of impact damage. Figure 4.12 (c) and (e) show the front and back surfaces of the specimen, with the domain of visible damage delineated with a white line. Closer views of these surfaces are shown in figure 4.12 (d) and (f). The visible damage on the front and rear surfaces is typical of low velocity impacts in laminated composites [48]. The front surface shows localized indentation at the location of the impact. The front surface damage is not symmetric due to the orthotropic properties of the material system. The rear surface shows a more extensive damage region, with cracks parallel to the two principal material directions. During impact, bending of the laminate creates high tensile stress on the rear surface, which leads to cracking, followed by extensive delamination. The resulting damage area has the rhombus shape observed in figure 4.12 (e). Internally in the laminate, the damage region within a lamina (or in-between laminae) is expected to decrease in size from the rear to the front surface [5].

Similar images for each of the other three specimens of type 2 are shown in figure 4.13 -4.15. We observe that the pulse thermography was not able to detect the impact damage for the specimens impacted at either 1.10 m/s (3.3 J) or 0.9 m/s (2.2 J). PPT was not able to detect damage for the specimen impacted at 0.9 m/s. Therefore, we demonstrated damage detection in the 2D woven material system for a minimum impact energy of 3.3 J using PPT. The extent of damage is directly related to impact energy in low-velocity impact testing of composite laminates [48].
Figure 4.12 Post-impact images of specimen impacted at 1.75 m/s: (a) pulse thermography image at highest contrast; (b) PPT phase image over full frequency range; (c) photograph of impacted surface; (d) local view of damage region on impacted surface; (e) photograph of rear surface; (f) local view of damage region on rear surface.
Figure 4.13 Post-impact images of specimen impacted at 1.40 m/s: (a) pulse thermography image at highest contrast; (b) PPT phase image over full frequency range; (c) photograph of impacted surface; (d) local view of damage region on impacted surface; (e) photograph of rear surface; (f) local view of damage region on rear surface.
Figure 4.14 Post-impact images of specimen impacted at 1.10 m/s: (a) pulse thermography image at highest contrast; (b) PPT phase image over full frequency range; (c) photograph of impacted surface; (d) local view of damage region on impacted surface; (e) photograph of rear surface; (f) local view of damage region on rear surface
Figure 4.15 Post-impact images of specimen impacted at 0.9 m/s: (a) pulse thermography image at highest contrast; (b) PPT phase image over full frequency range; (c) photograph of impacted surface; (d) local view of damage region on impacted surface; (e) photograph of rear surface; (f) local view of damage region on rear surface.
4.3.2 Depth Resolution of Impact Damage

For through the thickness imaging, we will consider the first specimen (impacted at 1.75 m/s) since the damage region is the largest. The area enclosed by the rhombus region in figure 4.12 (e) and the circular area in figure 4.12 (c) are approximately 175 mm² and 64 mm² respectively. For comparison, the rear surface damage area calculated from the PPT image (the region with sufficient visible phase contrast) is 180 mm², very close to that estimated from the photograph of the rear surface. Therefore PPT imaging provides an excellent measurement of the extent of low-velocity impact damage in this composite laminate material system. In contrast, the pulse thermography image underestimated the extent of damage. This is primarily due to the lower thermal contrast between the damaged and undamaged regions in the amplitude information as compared to the phase information.

We next consider the extent of damage at different depths through the laminate. Figure 4.16 shows the obtained phase image for this specimen for different frequency ranges. The detected damage in each frequency range is the damage regions present between the front surface of the specimen and the diffusion depth associated with each minimum frequency. To confirm the assumption that the impact damage increases from the front to the rear surface of the specimen, the extent of damage does increase as the minimum frequency is reduced in the phase images of figure 4.16. The damage regions of figure 4.16 can therefore be considered as the damage region at the diffusion depth associated with each minimum frequency.
Figure 4.16  PPT phase images for specimen impacted at 1.75 m/s with minimum frequencies of (a) 1.2 Hz, (b) 0.6 Hz, (c) 0.4 Hz, (d) 0.3 Hz, (e) 0.2 Hz, and (f) 0.17 Hz.
Figure 4.17 Sub-region including detected damage from PPT phase image for specimen impacted at 1.75 m/s using full frequency range (one pixel corresponds to approximately 0.2 x 0.2 mm).

A second important observation is that the phase contrast across the specimen (i.e. the maximum phase contrast between damaged and undamaged regions) in figure 4.16 (f) is approximately 0.18 rads. The maximum phase contrast in the imaged polymer foam inserts (from figure 4.3) was 0.25 rads. Therefore the impact damage phase contrast was 72% of the calibration specimen. This is much higher than the 10% reported previously for flat-bottom holes [41] and gives confidence in the validity of the previous calibration data when applied to barely visible impact damage.
The next step is to calculate the blind frequency at different pixels in order to calculate the depths of each phase image. We did not calculate the blind frequency at all pixels due to the computational effort involved. Figure 4.17 shows a selected portion of the phase image of figure 4.16 (f) (with the maximum frequency range) which was used for this calculation. The blind frequencies at the five points labeled in figure 4.17 were calculated following the same procedure as for the calibration specimen. Figure 4.18 plots the phase and phase contrast (as compared to a pixel in a non-defective region) for these five points, as a function of minimum frequency, obtained from the phase images. We observe a higher level of noise in these plots at higher frequencies. This noise is typical of experimental PPT data and can be reduced by curve fitting of the phase vs. frequency plots [30]. From these plots, the blind frequency was estimated to be 3.8 Hz, 2.7 Hz, 1.8 Hz, 1.2 Hz and 0.8 Hz at points 1, 2, 3, 4 and 5 respectively. From these blind frequency values, the modified diffusion length and the predicted depth were calculated using Eqs. (4.2) and (4.3). In order to apply this depth prediction to other pixels in the damage region, a linear fit of the phase value (from figure 4.17) to the predicted depth for each of the five points was calculated. There is not a theoretical justification for a linear fit between the two parameters, however this linear fit had a correlation coefficient of $R^2 = 0.985$ for this data, therefore it was considerable a reasonable method to fit data. Unlike the depth calibration of Eq. (4.3), however, this fit is specific for this image and does not transfer to data from other specimens. Using this linear fit, the depth at each pixel within the damage region was calculated for the image of figure 4.17. Finally, the constant term in Eq. (4.3) was adjusted
such that the maximum depth was the rear surface of the specimen. A contour plot of the calculated damage region as a function of depth is shown in figure 4.19 (a). The plotted contours were chosen to be at each inter-laminar boundary. The minimum depth in the damage region calculated was 0.32 mm, located within the second lamina from the front surface. We observe that the damage envelope has the predicted conical form.

Figure 4.18 Phase and phase contrast plots calculated for five pixels highlighted in Fig. 4.17.
Figure 4.19  (a) 3 D impact damage progression using PPT (one pixel corresponds to approximately 0.2 x 0.2 mm) and (b) microscopic image of cross section of impacted specimen.
To compare the minimum depth calculated with the PPT images, the specimen was sectioned with a wet blade through the center of the specimen. Figure 4.19 (b) shows the sectioned specimen, imaged through a microscope with magnification 50x. The width of this image is 5.75 mm (equivalent to approximately 19 pixels in figure 4.19 (a)), therefore the image lies in the region of minimum damage depth.

Visible types of damage are highlighted on the image, including fiber rupture and tow splitting near the rear surface and delamination, occurring at many locations through the thickness. It is the presence of delamination which we expect the imaging to detect, due to the large aspect ratio perpendicular to the direction of the thermal wave propagation. In contrast, the optical cross-sectional imaging is more sensitive to damages occurring in the through-the-thickness plane. A similar distinction has been observed for ultrasonic imaging of barely visible impact damage [49]. Additionally, the minimum defect depth of 0.32 mm predicted from the PPT imaging is also marked by the dashed line in figure 4.19 (b). We observe that this predicted depth corresponds well the visually observed delamination in the microscopy image.

A few other points in through the thickness imaging of the specimen for barely visible impact damage can be drawn from the microscopy image. To begin, the importance of adjusting the constant term in the depth calibration of Eq. (4.3) by fixing the maximum depth of observed damage to the rear surface of the specimen is highlighted by the post-impact residual bending of the specimen. Localized bending of individual laminae, such as due to the peeling of the rear surface after fracture of the rear lamina, will not be
compensated. However, global curvature of the lamina after impact can create a significant error in the depth measurement without compensation. Secondly, the minimum measured depth of 0.32 mm, or any specific depth, does not correspond to an individual lamina or inter-lamina boundary due to the woven geometry of the laminate, clearly visible in figure 4.19 (b). This non-planar geometry is especially evident in the surface profile of the specimen (the surface visible here was in the contact region of the impactor). Care should therefore be taken when interpreting the PPT through the thickness profiling, specifically when correlating the measured damage regions to detailed numerical models of the composite behavior. Again, this non-planar geometry highlights the deficiency of the assumed one-dimensional thermal wave propagation, however good quality estimates of the extent of damage were obtained using this assumption.
Chapter 5  Combined Inspection Method Results and Discussion

This chapter presents the results of the combined inspection method for the imaging of internal damage in composite laminates due to low-velocity impacts. Both the discrete, internal temperature sensors (in this case fiber Bragg gratings) and the Pulse Phase Thermography imaging results are captured due to the same pulse heating input. In this chapter, the results of both sensing systems are described and compared to the presumed damage states identified through visual inspection of the laminate front face, rear face, and sectioned samples.

5.1  Previous Studies of Damage Assessment of Composites through Internal Temperature Sensors

Two research groups have experimentally measured the response of thermal point sensors to identify internal damage in a laminated composite structure [34,37]. In the case of Stewart et al. [37], the sensors were embedded in the composite material, whereas Wu et al. [34] mounted the sensors on the rear face of the laminate (opposite to the heated surface). In both applications, the fundamental damage detection concept was that a thermal wave entering the composite material is partially absorbed by internal delaminations, delaying the
thermal wave propagation. By measuring the time response of a controlled input thermal wave at the sensor location, regions with and without delaminations can be differentiated. This same concept will be applied for the current study. These methods are primarily sensitive to damage in the form of delamination, as compared to matrix cracking or other damage modes. This high sensitivity is due to the fact that delaminations propagate perpendicular to the direction of the thermal wave propagation and can present a significant thickness in the direction of the thermal wave propagation, increasing the interaction time between the thermal wave and the defect. This sensitivity is consistent with the Pulse Phase Thermography results described in the previous chapter.

It is important that we discuss these two previous studies in detail, because the response of the thermal sensor is highly dependent on the form of the internal damage and the relative location of the sensor to the damage. The goal of research by Wu et al. [34] at NASA Langley was to replace the need for thermography imaging of aerospace structures entirely by surface mounting FBG temperature sensors on the rear face of the laminated structure. These are the same sensors used in this dissertation. For practical applications, the rear face would be the surface farthest from the impact and would not be visible for inspection. The goal of the temperature sensors was to identify the depth and extent of delaminations within the composite structure. In their experiments, the thermal response of the FBG sensors was consistent with the results from thermographic techniques. There was also a good agreement between the response of the FBG sensors and predicted simulation results based on the quadrupole method, except during later stages in cooling (presumably
due to uneven heating of the specimen). For the estimation of the delamination depth, the FBG sensor information concurred with the thermography results for shallow defects, but presented significant errors for deeper delaminations.

The goal of research by Stewart et al. [37] at UCLA was to use embedded, extrinsic Fabry-Perot interferometer (EFPI) sensors, rather than thermography, to perform in-situ measurements of the severity of simulated impact damage in laminated composites. Again, the specimens were heated with a controlled thermal pulse. The EFPI sensor has a slightly different configuration that the FBG sensor, however the rough embedment procedure, size and measurement principle are the same. They concluded that the fiber optic sensors were not only able to detect damage, but also could differentiate between damage severities more readily than traditional C-scan imaging. At the same time, there was a higher amount of noise in the thermal sensor data than that of Wu et al. [34] due to the fact that the sensors were embedded in the material system. In addition, some measurements of the sensor response did not follow the same trend as those at lower or higher levels of damage. These two sensor response features are inherent for embedded sensors (as will be supported by the results of the dissertation), and could be considered a trade-off in that embedded temperature sensors decrease measurement certainty but increase measurement sensitivity.

Finally, one of the major differences between the current and these previous studies, is the method damage was induced in the composite laminate, and therefore the response of the thermal sensor to the damage. To simulate damage to the composite material, Wu et al. [34] embedded inserts between the laminate plies. Therefore the damage was well-
controlled, strictly between laminate plies and without external cracking or spalling. Stewart et al. [37] applied an increasing static indentation to the front surface of the laminate to simulate low velocity impact damage. Quasi-static indentation has been applied by several researchers to simulate low velocity impact damage [50-53], however the quality of this simulation depends on multiple variables such as the specimen thickness, impactor shape and size, stacking sequence and support span [54-56]. A general conclusion is that static indentation well represents low velocity impact damage for relatively stiff composite laminate specimens [53]. The stiffness here is defined as the inverse of the ratio of the support span to the laminate thickness. Nettles and Douglas [53] defined two extremes of laminates: flexible laminates with span to thickness ratio > 150 and stiff laminates with span to thickness ratios < 25. The difference in the response of stiff and flexible specimens to low velocity impact damage is shown in figure 5.1. For the stiff (thicker) laminates, damage usually initiates at the upper surface of the laminate whereas initial failure in flexible (thinner) laminate occurs in the lower plies directly under the point of impact and they fail in a flexure when perforation threshold is reached [57].

The samples used in the current experiments have a span to thickness ratio of approximately 40, which we will refer to as a medium stiff laminate, so we can expect to observe damage modes combining those of the two cases proposed in figure 5.1(c). These post-impact damage modes have been observed extensively in similar laminates by the authors [58]. We will see that for this case, the sensor response is strongly affected by the damage modes both above and below the sensor location, critically changing the response of
the sensor as a function of damage propagation. Such mid-range cases of laminate stiffness are important for a wide variety of applications including imaging low velocity impact damage in composite airframe structures and measuring through the thickness temperature profiles in structurally integrated thermal protection material systems.

![Figure 5.1 Schematic of damage initiation in stiff and flexible laminates due to low velocity impact damage.](image)

Figure 5.1 Schematic of damage initiation in stiff and flexible laminates due to low velocity impact damage.
5.2 Experimental Procedure

From the previous experiments on specimens of type 2, it was shown that for impact velocity of 1.1 m/s, damage was barely visible with Pulsed Phase Thermography. Therefore the specimens in this experiment were impacted multiple times at this same velocity, 1.1 m/s (3.3 J impact energy). The goal of these experiments was to evaluate the response of the embedded thermal sensors to the step function thermal pulse applied in pulse phase thermography for varying degrees of impact induced damage. The numbers of strikes required to induce particular damage states varied slightly between the composite specimens. A total of twelve impacts were applied to each specimen, after which point no further change in the laminate response was observed. The specimens were not impacted until penetration because the goal of the study is to identify barely visible impact damage at low levels. After each strike, the specimen was removed from the impact tower and fixed in the support for Pulsed Phase Thermography imaging. A square pulse thermal input was then applied to the specimen using the flash lamps for a duration of 7 seconds. This thermal input pulse was previously optimized for imaging of the CFRP laminates. During the thermal pulse and the cooling phase after the thermal pulse, data was collected with both the IR thermal camera (for later pulse phase processing) and the FBG sensors.

Three specimens were used to find the optimum distance of low velocity impact damage from the FBG sensor. Stewart et al. [59] showed that 20 mm size Teflon simulated delaminations could be detected at a distance up to 17 mm using embedded extrinsic Fabry-
Perot interferometer (EFPI) thermal damage detection sensors. In one of the sample used in the current experiments, FBG sensor was used at 16 mm away from impact damage sensor; which detected the damage, but was unable to differentiate between damage severities. Hence for further experiments, the FBG sensor was placed 12 mm from the center of impact center. For the last specimen, multiplexed FBG sensors were placed at the midplane, between the 8th and 9th plies and between the 10 and 11th plies, as shown in figure 3.4. For convenience, these sensors are named as sensor 6, sensor 8 and sensor 10 respectively for further discussion. The wavelengths of these FBG sensors were 1570 nm, 1574 nm and 1578 nm respectively before embedding them in specimen.

5.3 Thermal Response of FBG Sensor for Non-defective Specimen

Figure 5.2 shows the temperature measured by a FBG sensor embedded at the midplane of a laminate specimen during and after the thermal pulse heating. The temperature was calculated form the measured Bragg wavelength shift using equation 2.29 and the value of η for the fully embedded sensor, η = 9.82 x 10^6 °C. This particular FBG sensor had a Bragg wavelength of \( \lambda_B = 1550.1 \) nm. Wavelength shift data was collected at 1 Hz. We observe that the sensor experienced a rapid heating period, followed by a slow cooling period once the thermal pulse was completed. More than 10 minutes were required to cool the FBG sensor to room temperature, due to the low conductivity of the CFRP. The maximum temperature rise measured by the FBG sensor was approximately 4.6 °C, corresponding to a wavelength shift of 0.07 nm.
Figure 5.2  Response of embedded FBG sensor during heating and cooling periods. An exponential fit to the cooling data is also plotted.

A second observation that can be made from figure 5.2 is the wide scatter in the temperature measurements (as a result of the wide scatter in the wavelength shift measurements from the FBG sensor). This scatter is created by the small total wavelength shifts experienced by the FBG during the thermal pulse. The wavelength resolution of the sm130 interrogator, 0.002 nm, can be seen in the data of figure 5.2. The data noise level in the cooling period appears to be much large than that in the heating period, however this is simply due to the fact that the rate of change of temperature is much less relative to the data acquisition rate in the cooling period. If either the heating or cooling temperature period
data is used, a fit to the data would be required to reduce the effects of the scatter. To minimize the inspection time required, for all further experiments FBG sensor data acquisition was performed during the heating period and the data collection time reduced to 7 seconds. The data acquisition rate was also increased to 20 Hz to better resolve the temperature changes during the heating period.

Figure 5.3 Response of embedded FBG sensor measured during two independent trials. An exponential fit to the cooling data for each trial is also plotted.

The repeatability of the FBG sensor response was also tested. Figure 5.3 shows the measurement of temperature for the same specimen as the data of figure 5.2, collected
during two different thermal pulse loads on the specimen. A curve fit to the cooling period data is also plotted for each set. The two curves had a rate of decay equal to $5.61 \times 10^{-3}$ s$^{-1}$ and $5.87 \times 10^{-3}$ s$^{-1}$ respectively, a 4.5% difference. These data demonstrate the high repeatability of the FBG sensor response, even in the presence of the large data scatter.

### 5.4 Response of Multiplexed FBG Sensors to Multiple Impacts

Once the FBG data acquisition parameters had been determined, a specimen with three embedded FBG sensors was impacted multiple times, with combined PPT imaging and FBG data collection after each strike. The FBG sensors were embedded between the sixth and seventh ply (at the laminate midplane), between the eighth and ninth ply, and between the tenth and eleventh ply, all at the same in-plane location. These sensors will be referred to as sensor 6, sensor 8, and sensor 10 respectively for the rest of the discussion. The Bragg wavelength of each sensor prior to embedment was approximately 1570 nm, 1574 nm, and 1578 nm respectively. The FBG sensors were therefore serially multiplexed for synchronized response measurements with respect to time. The first ply was the impacted surface (front face), and all PPT imaging was also performed in reflection on the front face. The scanning rate of the FBG interrogator was increased to 20 Hz to obtain a more accurate description of the response during the heating period. As the three sensors were all embedded in the same specimen they represent measurements relative to the same damage state. Previous studies by the authors [60] on similar specimens had shown that FBG sensors embedded greater or equal to 16 mm from the impact location were not sensitive to the low-
velocity impact damage. This was consistent with Stewart et al. [59], who determined that embedded Fabry-Perot interferometer sensors could detect static indentation damage up to a distance of 17 mm. Therefore, the FBGs in this specimen were embedded at 12 mm from the impact location. Embedding them closer to the impact location would increase their sensitivity to the induced damage, but also increase the risk of premature sensor failure during an impact. The specimen was subjected to twelve impacts, however significant changes in the front or back face visible damage was not observed after the fourth strike. This observation was consistent with the response of the FBG sensors, therefore we will only focus on results from the first four strikes in the following discussion. In particular we are interested in the ability of the combined internal temperature sensor and pulsed phase thermography inspection method to detect the onset of damage.

5.4.1 Visual Observations

Figures 5.4 and 5.5 provide photographs of the visible damage after each strike on the back and front faces respectively. The development of damage follows that predicted for the medium stiffness laminate of Fig. 5.1(c). Cracking was visible on the back surface after the second strike along the principal material directions. With the third strike the cracks grew significantly, while separation of the laminate into the pyramidal shape occurred after the fourth strike. This protrusion of the back face is due to extensive delamination in the last few plies, which deform during bending as the laminate is impacted. Residual deformation of these layers prevents them from returning to the original planar shape after the bending was released. Matrix cracks were also visible on the front face after the second strike and
increased in size with the third and fourth strikes. It is expected that delaminations also occurred near the front face of the laminate, as seen in Fig. 5.6, however these were not independently verified after each strike, as this would require sectioning the specimen.

For comparison, an identical specimen (however without embedded FBG sensors) was sectioned after a few low-velocity impact events. A microscopy image of the region surrounding the impact location is shown in Fig. 5.6. This image indicates the types of damage experienced by such a laminate, although the exact extent of each type would vary.
between specimens. The embedment depth of each of the three FBG sensors is also shown in Fig. 5.6. In this figure we see the presence of some delamination in the upper half of the laminate (particularly in the first interlaminar interface below the impacted face). Delamination is considerably more extensive in the lower (or rear) half of the laminate. The lower last few plies show extensive delamination and residual bending. Finally we can observe the presence of complete through cracking of the lower two plies (which is the cracking visible on the rear surface photographs in figure 5.4.).

Figure 5.5 View of impact damage on front face after strike (a) 1; (b) 2; (c) 3; (d) 4.
5.4.2 Pulsed Phase Thermography Imaging

Figures 5.16(a)-(d) show the phase images obtained by pulsed phase thermography after each of the first four strikes. These images were calculated using minimum frequency of 0.19 Hz ($N = 35, \omega = 5.81$ s) to obtain the maximum phase contrast between damaged and undamaged areas. These phase images show the formation of delamination after the strike 1. The delamination appeared to grow slightly with the three other strikes, however there was not a significant change in the delamination area. Comparing these results with the previous visual observations, it is most likely that delamination formed directly under the impactor after strike 1. Delamination then formed and grew near the back face with the additional strikes, however this was not visible in the PPT images due to shadowing by the
delamination near the front face. According to the images in figures 5.14 and 5.16, the delamination region did not reach the FBG sensor location after strike 4. This result indicates that the delamination region at the FBG sensor location, if present, was not sufficiently large to be observed with the PPT imaging resolution or visual observations of the rear surface. This fact will be critical later, when comparing the early damage capabilities of the PPT and embedded FBG temperature sensors.

Figure 5.7 FBG temperature measurements obtained from pristine specimen.
5.4.3 FBG Thermal Sensor Response

Figure 5.7 shows the measured temperature responses of the three FBG sensors during and after heating of the non-defective specimen. A moving window average of nine data points was applied to smooth the original peak wavelength data. The temperature response of each sensor was calculated using \( \eta \) for the undamaged material and the particular Bragg wavelength of each sensor. As these three FBG sensors were serially multiplexed, they permit a comparison of the temperature shift of each sensor within the same loading case; which can then be used to estimate the local temperature change and consequently damage severity at different depths. The temperature measurements are plotted for 12 seconds which includes 2 seconds of data at room temperature, 7 seconds of data during the pulse heating period and 3 seconds of data collected during cooling of the specimen.

Sensor 6 measured a maximum temperature change of approximately 4.5 °C, comparable with the previous specimen (for which the FBG was also embedded at the midplane). Sensor 8 measured a maximum temperature change of approximately 4 °C, lower than that of sensor 6, as expected. The behavior of sensor 10 did not follow the same trend as the other sensors.

Multiple thermal loading cycles applied to the specimen prior to impact loading provided insight into this sensor behavior. While the response of sensor 6 and 8 remained the same, the temperature response of sensor 10 changed after the third heating cycle. The data shown in Fig. 5.7 are for this third thermal loading cycle. Further thermal loading
cycles were applied, for which the response of sensor 10 did not change. It was suspected that the resin had not fully cured around sensor 10 or that it was near the location of a void, such that the repeated thermal cycles changed the residual strain state near sensor 10. Once stabilized the response of sensor 10 was still different that of the other two sensors. For the first few seconds of heating the FBG sensor reported a decrease in Bragg wavelength instead of a Bragg wavelength increase. As this sensor was closest to the back face of the specimen, it may have been strongly influenced by the thermal boundary conditions on the back of the specimen. The fact that there was an apparent temperature drop was most likely induced by a compressive strain, not drop in temperature. As it was assumed that the only strain component in Eq. (2.29) was the thermally induced strain, the possibility of residual compressive strains on the sensor was not permitted.
Figure 5.8 shows temperature shift for all three sensors during the thermal loading applied after strike 1. For further discussion, the terms rise and peak will be used to describe the rate of shift in temperature during the 7 seconds of heating and the approximately constant temperature after heating for 3 seconds respectively, as shown in figure 5.8. The data for each sensor showed a higher peak temperature shift than that obtained during thermal loading of the non-defective specimen (also plotted in figure 5.8). This change in peak temperature shift indicates that damage existed within the specimen. This measured temperature rise is due to fact that internal delaminations resisted the heat flow which caused heat accumulation over the sensor. A schematic of the damage progression in the
specimen (as reconstructed from the FBG temperature measurements, the visual observations and the PPT images) is shown in figure 5.13. Sensor 6 experienced a lower temperature shift after strike 1 than sensor 8 and sensor 10. The wavelength rise for sensor 6 was less because, as explained in figure 5.13(a), for flexible and mid-stiffness laminates damage on the front face consisted of a dent, micro-cracks and minor delaminations. The onset of major delamination was initiated in the internal plies near the rear surface of the specimen. This is consistent with the microscopic image of typical low velocity impact damage as shown in figure 5.6. Sensor 8 and sensor 10 also measured a higher temperature rise because they are more influenced by the thicker delaminations close to the rear surface as well as the delamination near the front surface.

The temperature trends in figure 5.8 are similar to those in the graph in figure 4.1(a) obtained by using thermography, the only difference being the magnitude of the temperature change. The phase image obtained by PPT for this specimen (figure 5.16(a)) after the first strike shows a small region of delamination. The effectiveness of the PPT technique depends upon the contrast created by the defect in the material under examination. In the case of carbon fiber composites, the thermal conductivity in the plane of the laminate is approximately nine times higher than that in the through-thickness direction. As a result of this low transverse thermal diffusivity, defects or damage zones located at near the back of a thick composite are difficult to detect with PPT at low damage levels, whereas internal detection method like embedded FBG temperature sensors are more sensitive to local conditions. This data shows the potential advantage of a combined inspection technique in
which the limitations in damage detection by one method is overcome by data from other method. This advantage will be explored for the further strikes.

Figure 5.9 Temperature response of sensor 6 after first four strikes.

Figure 5.9 shows a plot of $\Delta T$ versus time measured from sensor 6 during thermal loading after the first four strikes. The shift in temperature during heating (the rise) and after heating (the peak) further increased after the second and third strike. This was probably due to heat entrapment in matrix cracks in the upper layers starting under the edges of the impact zone and may include some minor delaminations near the surface and up to the midplane formed during the second and third strikes. Although the minor delaminations formations
near the top surface was not validated (as there were no microscopic section images after the second and third strikes), matrix cracks were visible under the edges of the impact zone (as shown in figure 5.10(a)) after the second strike and grew after the third and fourth strike. In contrast, the shift in temperature during heating (the rise) detected by sensor 6 decreased after the fourth strike. This was due to heat loss from the back surface which had visible spalling after the fourth strike and bending cracks as shown in figure 5.10(b).

Figure 5.10 (a) Zoomed view at front face damage showing matrix cracks and (b) zoomed view at back face damage showing bending cracks.

The wavelength shift response for sensor 8 and sensor 10 showed an increase in temperature change after the first strike and then a decrease in the same parameter after the second strike. This can be explained by figure 5.4 (a) and (b) which shows the back surface damage. For the first strike, there was no exterior damage in the form of bending cracks and hence the heat remained for longer time near the rear surface. From the second strike bending cracks started forming and hence heat loss from those cracks competed with the
resistance effect due to delaminations. The closer the FBG sensor was located to the rear surface, the larger the heat loss. After the third strike, the temperature rise for sensor 8 and sensor 10 was more than the second strike due to an increase in resistance to heat flow due to increasing delamination progressing from the rear surface. But this temperature rise was less than the temperature rise after the first strike due to the heat loss effect. It was not clear why the response from sensor 8 showed an increase in temperature after the fourth strike, which was not consistent with the other sensor responses.

Figure 5.11 Temperature response of sensor 8 after first four strikes.

The assumed damage progression, constructed from the FBG sensors measurements, the visual observations and microscopic section images are summarized in figure 5.13.
Finally, individual reflected spectra collected from all three FBG sensors after the fourth strike is shown in figure 5.15. These spectra are included to show that the FBG reflection spectra each remained a well-defined spectral peak, and therefore there was no error in the peak wavelength measurements due to spectral distortion.

![Figure 5.12 Temperature response of sensor 10 after first four strikes.](image)

These FBG sensor measurements reveal the complexity of the thermal response of an embedded temperature sensor, even when the thermal input is a repeatable, controlled input. For these experiments, the complexity was due to the presence of delaminations both in front of and behind the FBG sensors (in the direction of heat flow) and the eventual cracking on the rear surface of the laminate which led to increased heat flow from the rear
surface. As result, the temperature measurements do not reveal a monotonic response with increasing levels of damage. However, using expected damage states due to low-velocity impact, as well as visual information and information from PPT, the progression of damage can be constructed for such a laminate, as shown in figure 5.13. A key to the development of this sketch was the presence of temperature sensors at different depths within the laminate, from which the relative affects of damage at the front and rear surfaces could be estimated.

Figure 5.13 Sketch explaining probable damage progression between the strikes. Red lines indicate depth of embedded FBG sensors.
A second insight gained from these experiments is that the sensitivity of the internal temperature sensors was much higher than that of the PPT imaging for small levels of damage. As the number of strikes was increased, a consistent trend in the FBG sensor responses was not observed. For this reason, the FBG sensor information was highly useful in the early strikes, and less useful for later strikes. In contrast, the PPT imaging data was highly useful for the later strikes (when the damage regions had reached a critical size) and less useful for the earlier strikes. The benefits of each method therefore complement each other in terms of non-destructive inspection of composite laminates to low-velocity impact damage.

Figure 5.14 Global view of impact damage at front face (left) and at back face (right).

Finally, the conversion of the peak wavelength measurements of the FBG sensors to temperature in the previous figures was based on the sensitivity factor of the fully embedded sensor, \( \eta_{\text{embedded}} = 9.82 \times 10^{-6} \, ^\circ\text{C}^{-1} \), as described in Chapter 2. One of the original goals of
this research effort was to use the PPT images to determine the sensitivity factor of the FBG sensor to temperature as a function of the damage state, $\eta_{\text{free}} < \eta < \eta_{\text{embedded}}$. However, the resolution of the PPT images was not sufficient to detect the presence of delamination immediately surrounding the FBG sensor, at least in the low damage levels of interest. Therefore, while it is not likely that the sensitivity factor was near $\eta_{\text{free}}$, there is still uncertainty in the temperature value. To examine the importance of this uncertainty, figure 5.17 plots the temperature range calculated from the wavelength shift of each sensor (equations (2.28) and (2.29)) in the sensitivity range $\eta_{\text{free}} < \eta < \eta_{\text{embedded}}$. From this figure it is clear that even with the uncertainty it is still separate the response of the sensors during the rise period, however there is considerable overlap between sensor 6 and sensor 8 at the maximum temperature change after the heating period. However, the PPT image resolution was not sufficient to resolve this uncertainty.

Figure 5.15 FBG reflection spectra measured after fourth strike.
Figure 5.16 Pulse Phase Thermography images of composite laminate after strike: (a) 1; (b) 2; (c) 3; (d) 4; (e) 8; (f) 12. Color scale shows phase contrast. The same scale is used for the images (a)-(d) to show increasing phase contrast with strike number. Note that images (e) and (f) have different scales, with significantly increased magnitudes.
Figure 5.17 Temperature response of embedded FBG sensors after strike 4. Upper and lower bounds plot temperature calculated using $\eta = \eta_{\text{free}} = 7.89 \times 10^{-6} \text{°C}^{-1}$ and $\eta = \eta_{\text{embedded}} = 9.82 \times 10^{-6} \text{°C}^{-1}$ respectively. Center line plots temperature calculated using $\eta = 0.5 (\eta_{\text{free}} + \eta_{\text{embedded}})$.

5.5 Damage Assessment Model by using Combined Inspection Method

A proposed methodology for damage assessment in a composite structure by using the combined inspection method is shown in the flow chart in figure 5.18. Thermal data would be collected during the cooling transient for a suspected damaged specimen, which would initially be processed by using PPT. Pulsed Phase Thermography provides a used as global damage inspection approach, which scans whole specimen to rapidly detect damage. If damage is prominently visible then repair of component is required. If damage is barely visible or suspicious, then the local damage inspection approach using the FBG sensors would be applied. For this, FBG data from damaged specimen is collected during heating
and cooling and compared with FBG data from pristine specimen. If FBG data demonstrated a rise in temperature shift, then damage is confirmed and repair initiated. This FBG data also would also be used to show the severity of damage.
Figure 5.18 Combined inspection method- damage assessment model.
Chapter 6  Conclusions

This study showed the potential for combined inspection techniques in composite laminates to low velocity impact damage of varying damage severity by using integrated pulsed phase thermography and embedded FBG sensors. Three different types of specimens were used for detection and characterization of in-service as well as manufacturing type of defects in aerospace composites by using combined inspection method. By qualitatively examining the responses of pulsed phase thermography and embedded FBG sensors, a complete picture of impact damage progression can be created.

Conclusions to be drawn from analyzing the results using pulsed phase thermography and FBG sensors are the following:

- The sensitivity (aspect ratio) for 2x2 twill woven carbon-fiber epoxy composite was demonstrated with the current Pulsed Phase Thermography system for inclusion detection. While the sensitivity which was demonstrated to be 2.1 for single specimen with Rohacell inserts, it is expected that similar behaviors would be observed for complicated geometries structural components made up of same material. Also the purpose of using these to replicate the delamination mode of damage in case of impact damage is validated later on.

- The calibration of defect depth to blind frequency for given specimens and experimental setup was done by using linear least squares regression, which worked
well (with correlation coefficient of $R^2 = 0.98$) except some deeper defects. The size dependence was not that strong on blind frequency calculations.

- The use of Rohacell foam inserts for calibration purpose was justified as it is used to characterize delamination depth in case of impact damage. Rohacell foam inserts were highly porous in nature and would contain mostly air; hence their thermal conductivity was varied with temperature in same manner as that of air. Other inserts would create different phase contrast because of their different thermal properties and hence were not used to simulate impact damage.

- Pulsed phase thermography showed an excellent measurement of low velocity impact damage as compared to pulse thermography. For a given specimen size, an impact damage of minimum impact energy of 3.3 J was detected with current Pulsed Phase Thermography system for given material. Also, imaging with depth resolution of damage progression was successfully demonstrated for the first time for low velocity impact damage, using Pulsed Phase Thermography. This was validated by visual inspection and microscopic images of impact damage.

- The results of preliminary testing of the combined inspection method showed a wide scatter in temperature measurements during the cooling transient due to the lower data acquisition rate (1 Hz) of the FBG interrogator as compared to rate of change of temperature of specimen. This was consistent with the results from previous literature studies and highlighted the need to increase the data acquisition rate in further specimens. Even in the presence of large data scatter, the FBG sensor response
showed a high repeatability. The difference in a decay rate was negligible (< 5%) during two different thermal loading cases.

- The preliminary testing data also highlighted the need to optimize the location of the FBG sensor from the damage location. Considering the compromise between sensitivity to the induced damage and the risk of premature sensor failure during an impact, the distance of the FBG sensor from the impact location was optimized.

- The final specimen in combined inspection method showed more accurate response during the heating period because of increase in scanning rate of FBG interrogator to 20 Hz. This specimen also showed synchronized FBG sensor response measurements with respect to time because of serially multiplexed FBGs.

- Measuring the temperature shift using the FBG sensors during the transient heating period and fusing this data with the phase contrast calculated during the cooling period provided quantitative information on the initiation and progression of impact damage. The FBG sensors were found to be more sensitive than the PPT during damage initiation, while the PPT results were highly useful during damage progression. The spalling due to bending cracks, which is common in mid-stiff laminates, resulted in a heat loss from back surface and made limited the capability of the damage severity detection by the FBG sensors during the last stages of damage progression. This was counter-balanced by the PPT results which detected an increased damage severity in terms of the increased phase contrast during damage progression.
• A combined damage assessment model was formulated based on these results for the global-local inspection approach.

• To further investigate the validity of the estimated damage progression by FBG sensor, numerical simulations of the heat flow through the laminate should be performed to predict the resulting FBG temperature response for several representative cases.
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