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Damage Characterization Using Thermography of Composite Plates Subjected to Low Velocity Impact Loads

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Abstract

Composites are prone to delamination damage when impacted by low velocity projectiles because of the poor through-thickness strength. So, some of the problems with composites are their poor impact damage resistance, low post-impact mechanical properties and the difficulties to inspect the impacted area using nondestructive means. Damage characterization of composite materials requires a logical scientific methodology and a wide knowledge of polymeric materials and additionally a direct field experience. Effort is being taken to locate the most solid Non-Destructive Testing "NDT" strategy for characterization of damage in composite materials. In this work, impact response of composite laminates was experimentally studied with drop-tower to determine the energy absorption. Three types of composites were used: carbon fiber, glass fiber and mixed fiber composite laminates. In addition, these composites were characterized visually and using thermography to quantify their post impact damage. It was found with the 3D temperature distribution that there is a strong correlation between the measured temperatures at the impact region with the quantification of the damage using thermal imaging with advanced mid-wave camera.

Keywords: Composite; Glass fiber; Carbon fiber; Impact damage; Non-destructive; Thermography

Introduction

Composite materials have become an attractive alternative for traditional metals with widespread in structural and low pressure piping applications. They are light in weight with great strength capability. However, composite may fail due to the following factors including but not limited to: manufacturing issues, damage during installation, unexpected service conditions, product misuse, out-of-customer specifications, incorrect design and other material issues. The term damage is commonly used in different ways in the field of composite to describe lack of adhesive, dis-bonding of the fiber from its matrix, delamination or breakage of the fiber. Any damages specially for fiberglass pipeline that transport crude oil may lead to oil leaks, contamination, which can result in productivity losses, environmental damages and even fatality. Figure 1 shows example of composite pipe failures due to impact and joint overstressing.

Most of the service failures in composite materials systems are due to the presence of porosity during manufacturing, damages happen to the pipes by mistakes during handling and transportation, damages made during the constructing of the pipeline in the field or damages during the service life of the fiberglass pipe when it is in production. In other word, defects occurring in composite structures can be classified as: manufacturing defects or in-service defects. Currently in fiberglass manufacturer communities as well as with field piping inspector on oil and gas industries, they are relaying either in hydrostatic testing which requires pipeline outage or in the visual inspection by naked eye, looking for magnification, or active lighting/shadowing techniques. Impact of the composites can be most of the time considered as invisible (or barely visible) at the impact surface. Acoustic non-destructive testing (NDT) is also used for composite inspection using hammer where the inspector tapped over a large area while the inspector listens for a change in the echo frequency, a manifestation of localized surface dis-bonding. However, deeply buried defects are both invisible to the human eye and inaudible to the human ear. So, the fluctuation in inspection quality owing to the human factors of inspector skill and experience, and the difficulty in providing quantitative results, mean that the use of these techniques alone is no longer sufficient to provide the level of evaluation needed for engineering certification.

For this reasons, there is essential needs for an inspection method that can be used in the field which needs to be nondestructive and easy to use with high quality results. One of the major limiting factors for most of the existing methods they the lack of quantitative and qualitative non-destructive means. Sometime two or more techniques shall be used together to get the results. Many attempts have been made to measure those types of damages in composite structures. These attempts include x-ray, microwave and thermal imaging. The last technique can be used only on fiberglass if thermal gradients are introduced. The concept of temperature production using flash or continuous heating of the fiberglass that need to be inspected has been tried while capturing the infrared thermal imaging. Low temperatures are normally observed in the fiberglass region that experienced crack damage due to impact that leads to the dis-bonding of the plies where pocket of air is generated in the vicinity of the impacted area that makes the heat flow takes longer time to pass through the fiberglass than the solid part of the fiberglass that does not have damage. The development of localized low temperatures, in the course of impacted area and breakage and delamination of the fiber, might be considered a believable mechanism of fiberglass damage. The role of the delamination is to act as a thermal resistance to the heat diffusion in series with the global resistance of the sample, such as a thin air layer. This structural

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Figure 1: Different failure modes in composite pipes can be occurred due to several factors.

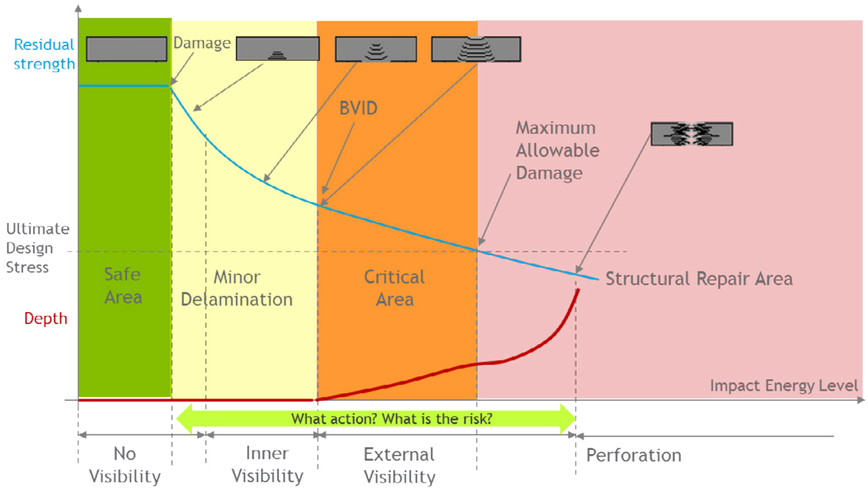


Figure 2: Decision-making workflow (risk based maintenance).

in-homogeneities in the fiberglass lead to more time for the heat to pass through. The infrared thermography proves its success, as seen later by the conducted experiments, to identify the star cracking of the fiber glass while quantification of the damage still needs more research to correlate the temperature profile with the thickness damage in the fiberglass. The idea of relating damage in the fiberglass to intrinsic dissipation of heat by measuring the temperature seems to be highly relevant field of nondestructive testing for fiberglass pipes specially in the industrial applications where these sections of pipe cannot be taken immediately out of service or in case of the evaluation of the fiberglass pipe integrity along its life during the production.

So, Damage characterization of composite materials requires a logical scientific methodology and a wide knowledge of polymeric materials and additionally a direct field experience. Effort is being taken to locate the most solid NDT strategy for characterization of damage in composite materials. The cutting edge NDT systems for composite materials are as per the following: visual examination; optical techniques; eddy current; ultrasonic testing (UT) laser ultrasonic; acoustic emission (AE); vibration investigation; radiography; thermography [1]. Some defects can be seen by visual inspection. However, localized impacts typically lead to the phenomenon of barely-visible impact damage (BVID) in which the high lateral stiffness of the laminate causes the uppermost ply to return to its undamaged position, transferring the impact energy through the thickness in a pyramidal fashion (Figure 2). The vast majority of non-destructive examination work was either limited to structures of thickness 5–10 mm, or dealt exclusively with near-surface flaws. A thick-section composite can be defined per the Composite Materials Handbook [2] as having the geometry, material constituents, lamination scheme, processing and service loading that will exhibit three-dimensional states of stress, resulting in failures that cannot be accurately predicted using 2-D finite-element models.

Infrared thermography is a convenient technique for producing heat images from the invisible radiant energy emitted from stationary or moving objects at any distance and without surface contact or in any way influencing the actual surface temperature of the objects viewed. The scanning infrared camera has been used to visualize the surface-temperature field on fiberglass-epoxy composite samples during fatigue tests [3]. Rique AM et al. [4] studied the voids presented in bonded joints in order to minimize failures due to low adhesion of the joints in the industry field. One of the main parameters to be characterized is the porosity of the glue where he used high energy X-ray micro tomography and the results showed its potential effective in recognizing and quantifying directly in 3D all the defects regions presented at glass fiber-epoxy adhesive joints. The quantity of energy W (W m^{-2} micro meter), emitted as infrared radiation, is a function of the temperature and emissivity of the specimen. The higher the temperature the more important is the emitted energy. Differences of radiated energy correspond to differences of temperature. Guillaumat et al. [5] found that the rapid estimation of the damage of a composite plate is possible with thermal methods. Such methods have been improved with the use of high performance based on focal plane array of quantum detectors (Jade III from CEDIP) and suitable processing methods.

Ibrahim [6] critically reviewed and assessed the reported advances in the non-destructive Testing (NDT) of thick-section composites (structures of thickness above 15 mm are considered thick for the purposes of his review), and he identified future research opportunities to overcome the limitations of existing technologies. Kleiner et al. [7] reviewed the state-of-the-art of inspection techniques and technologies towards condition assessment of water distribution and transmission mains. They showed the potential to apply an inspection technology to different pipe materials where they reported that thermographic testing does not work with concrete and composite structures. Luong [8] illustrated the relevant use of infrared thermography as a nondestructive, real-time and non-contact technique to observe the physical processes of damage, fatigue and failure on metallic specimens. Anthony et al. [9] presented a contactless, non-intrusive method for measurement of the steady-state core temperature in a heat generating solid body. A theoretical heat transfer model for a heat-generating cylinder is developed to show that the steady state core temperature of the cylinder can be measured using appropriate integrals of the measured spatial temperature distribution on the cylinder surface. Astarita et al. [10] reviewed the basic concepts that govern this innovative measurement technique together with some particular aspects linked to its use. They discussed deferent operating methods together with their implementations. They also analyzed the capability of infrared thermography to deal with several simple, or complex, fluid flow configurations. We can notice that the thermographic testing does not work with glass fiber pipes as it is. This is the reason why we have introduced the heat source in our experiment to generate thermal gradient before we started capturing the images. Lega et al. [11] introduced first results of a Thermal Pattern and Thermal Tracking approach that can be used to identify different phenomena and several pollutants. Musto et al. [12] developed and validated a mathematical model of experimental setup to measure object surface temperature by means IR thermo-camera. This mathematical model was used to quantify the temperature measurement error in the dual-color technique. A novel correlation to estimate temperature measurement error was provided.

In heat transfer field of study, there are increased interests are directed to ways of handling composite materials, where the ability to conduct heat is very directional. Much of the work in conduction analysis is now accomplished by use of sophisticated computer codes. These tools have given the heat transfer analyst the capability of solving problems in nonhomogeneous media, with very complicated geometries, and with very involved boundary conditions [13]. Active thermography methods are utilized for different non-destructive examination such as evaluation of abnormalities in metallic and composite components. It is considered as a rising technology for the characterization of polymer composite materials. It is relevant to the crack detection, impact damage and fatigue failure cases. Thermography likewise seems to be the capable technique with the end goal of fiber content assessment. Thermographic testing works by heating the material and measuring the heat as it is scattered from the sample utilizing an infrared camera [14]. Nevertheless, for composite materials, external source of heat is required to generate differences in the temperature between the defective and non-defective parts of the equipment [15]. Three methods can be used for heat wave NDT in thermograph camera testing: flash pulse, phase pulse "stepped heating", lock-in thermography and vibro-thermography. In phase pulse and lock-in thermography, halogen lamps are required where the flash xenon lamp is used as a heat wave in pulse thermography and it is mainly used for small surface analysis. There are a number of variants to thermography techniques, the most common forms are by producing thermal excitation via a pulsed or continuous lamps (using either flash Xenon or Halogen lamps. These methods can be used for heat wave NDT in thermograph camera testing. Pulse Thermography is best to be used for small surface analysis. Phase pulse thermography adopt using long pulse (from 1 to 5 seconds) in order to generate the required thermal gradients needed for image capturing. Lock-in thermography use periodic heating with different frequencies. Subsequently, the object's cooling/heating characteristics are monitored by an infrared camera and these characteristics are then interpreted to discern object properties [16]. The detection of the damage on composite structure can be on-line using reflection mode or off line using transmission mode (mainly for failure analysis purposes in case of off-line mode). Varied active thermographic testing methods, which use a heat source to obtain the desired thermal contrast, have been developed for different applications. All the testing systems that are commercially available as summarized by Kleiner [7]. In the event that the material containing such flaws is subjected to a uniform heating on one surface, the heat flow move through its thickness is uneven as a result of local changes of thermal conductivity [17]. Zones with distinctive absorption and radiation rates. Infrared waves act like visible light as they can be reflected, absorbed, and refracted. So, heat flux passing through a composite structure gives a uniform temperature on the surface assuming that there is no flaw or delaminated region of the fibers. At the point when a flaw or de-bonding site is available, the flow of heat flux is interrupted on and temperature decrease is detected on the surface. Distinctive thermal techniques exist considering the way the heating. For instance, lock-in thermography and pulse thermography have been used to recognize corrosion, cracks, delamination, and voids of surfaces [1].

The blends of different materials and staking sequences exhibited in a composite material can make it hard to figure out composite's thermal and physical properties. Utilizing Infrared thermography, scientists have discovered quantitative solutions for deciding certain properties of composite materials, for example, thermal diffusivity and thermal expansion. These parts are prone to impact damage, delamination, fiber dis-bonding, inclusions, porosity and water ingress. Impact damage is a hard issue to figure out by inspection in composite structures, since there might possibly be any noticeable surface damage present depending upon the energy of the impact. Localized delamination can be found in the impacted area and obviously appear on a thermography images. As each surface has different level of absorption and emitting power, emissivity is the material property used to evaluate this distinction. Most composites luckily have a high emissivity value, which is one of the reasons that thermography yields great results in composite testing. Unpainted carbon fiber composites have high emissivity values, ranging from 0.90-0.97 [14].

The thermography is still be used as a laboratory technique for investigating damage and occurring in composite structures. For investigation purposes, active thermography procedures were used in this work where outer heating source utilized for creating temperature difference between the defect and defect-free areas. We applied a uniform heat source on one surface of the material and recorded the transient temperature contours on the other surface by high resolution infrared thermography camera. The heat source can be as direct as high temperature water packs, hot air-dryers or lights [17]. Reflection mode, where camera and heating source are on the same side, is utilized when there is no way to get access to the opposite side of the component that should be examined [15]. Using thermography with heating/cooling source as NDT allows the engineers to do periodic inspection of in-service pipe without extensive disassembly or special facilities where image results are easily archived. It can be used to identify deep cracks, delamination in large structures and voids in multi-ply structures.

Researchers along with engineers in the field are looking for rapid test for predicting the impact resistance of the fiberglass pipes. This is found by using the infrared thermographic technique to quantitatively evaluate the change of temperature at the impacted location after exposing the specimen to few minutes of continuous heat in form of light. Using the framework of this concept for heat dissipation needs further investigations where this paper touch bases on the use of the infrared thermography for identification of cracks due to impact on 19 different design of composite plates. The temperature gradient where measured on the impacted fiber glass plates as a starting point of the research for future plan to extend the outcome and the procedure for fiberglass pipes that are used in hydrocarbon high pressure applications. In practice, the impacted composite plates (129 mm × 129 mm) were subject to continues heat source from one side (a total of 4 halogen lamps where each has 500 watts) until a constant temperature gradient was reached, and then the infrared images were taken from the other side. For the current work, lights were used as a heating source from one side of the plate while the capturing of the images done in the opposite side. The future aim of this study is to find a way to make it as a field technique that is easy and portable for inspection as nondestructive tool for fiberglass pipes specifically in hydrocarbon application. This technique can be used during the fiberglass pipes and fitting manufacturing to reveal any manufacturing defects including porosity or lack of resin or fiber discontinuities.

Materials and Specimens Manufacturing

The materials in this study consist of carbon, glass and mixed fiber-reinforced laminates which were designed and manufactured based on previous author's work [18-20] to enhance the impact resistance on composite using numerical and Finite Element modeling which help them to identify best composite designs which recently manufactured and experimentally tested to study their impact responses [21]. Different ply thickness and resin types were also considered. Table 1 summarizes the detailed information for these 19-symmetric laminated composite plates that were impact tested. These composites were characterized by different stacking sequences. The amount of fiber and resin for each specimen was also considered with different ratio as shown in Table 1. Note that C stands for carbon-fiber, G stands for glass-fiber and M stands for mixed-fiber. For matrix material, three types of resins were used which are epoxy, phenolic (PH) and polyester (PL). The final size of each test specimen is 129 mm × 129 mm.

Low Velocity Impact Testing Procedure

The low velocity impact tests were performed by a drop tower "INSTRON Dynatup 9250G". The equipment consists of striker holder which accommodates additional weights, striker and hemispherical impactor. The impact machine was equipped with a hemispherical impactor head with diameter of 1 inch. Weights are added to alter the energy of the impact. For all impact tests in this study, the mass of the impactor was 9.2 kg with constant impact energy level of 20 J and corresponding to an impact velocity of 2.06 m/s. The impact velocity is measured by a photocell device that is placed in the path of the striker before the impactor strikes the composite plates. The force-time history is measured from the point of initial contact with the plate until the impactor travels through the composite plate thickness. The energy is calculated from the integration of the force-time signal. The force-time history and energy-time were recorded by the data acquisition system. For impact conditions in which the striker recovered from the composite plate, multiple impacts may occur causing excessive damage, which is not desirable. To avoid such repeated impacts, two rebound arrestors are located on both sides of the composite plate. The arrestors are pneumatically actuated rebound, and spring up and separate the impactor from the composite plate after the first impact. Figure 3 shows the schematic picture of the drop weight machine.

The composite plates to be impacted was positioned under the drop tower using an in-house manufactured specimen fixture where the exposed composite area within the fixture is 129 mm × 129 mm.

No.	Sample No.	Materials Type	Glue Type (Resin)	Percentage of Fiber	Percentage of Epoxy	No. of Layers	Stacking Sequence	Measured thickness (mm)
1	C1	Carbon	Epoxy	42.48	57.52	16	[90/-60/-30/0/90/-60/-30/0]s	3.3
2	C2	Carbon	Epoxy	43.59	56.41	16	[90/0/45/-45/90/0/45/-45]s	3.8
3	C3	Carbon	Epoxy	45.49	54.51	20	[45/-45/90/0/45/-45/90/0/45/-45]s	4.7
4	C4	Carbon	Epoxy	45.74	54.26	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5.5
5	C4 PH	Carbon	Phenolic	45.74	54.26	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5.15
6	C4 PL	Carbon	Polyester	45.74	54.26	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5.5
7	C5	Carbon	Epoxy	47.68	52.32	28	[45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]s	6.4
8	C6	Carbon	Epoxy	47.58	52.42	32	[90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]s	7.4
9	C7	Carbon	Epoxy	45.52	54.48	28	[-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.6
10	C8	Carbon	Epoxy	50.00	50.00	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	7.3
11	G1	Glass	Epoxy	50.04	49.96	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	4.9
12	G1 PH	Glass	Phenolic	50.04	49.96	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5
13	G1 PL	Glass	Polyester	50.04	49.96	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	4.7
14	G4	Glass	Epoxy	52.51	47.49	24	[90/-60/-30/0/90/-60/-30/0/90/-60/-30/0]s	5.1
15	G5	Glass	Epoxy	58.79	41.21	36	[-30/-45/45/30/-30/-45/45/30/-30/-45/45/30/-30/-45/45/30/-30/-45]s	7.1
16	G6	Glass	Epoxy	66.60	33.40	36	[45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]s	7.4
17	M1	Mixed Carbon-Glass (2 C in the Middle)	Epoxy	62.50	37.50	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.5
18	M2	Mixed Carbon-Glass (2 C in the Bottom)	Epoxy	62.53	37.47	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.7
19	M3	Mixed Carbon-Glass (2 C in the Top)	Epoxy	64.51	35.49	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.7

Table 1: Composite Laminates' Properties.

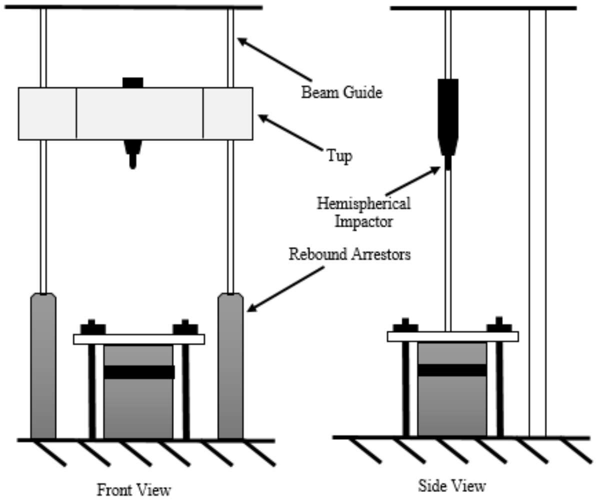


Figure 3: Schematic of drop weight machine.

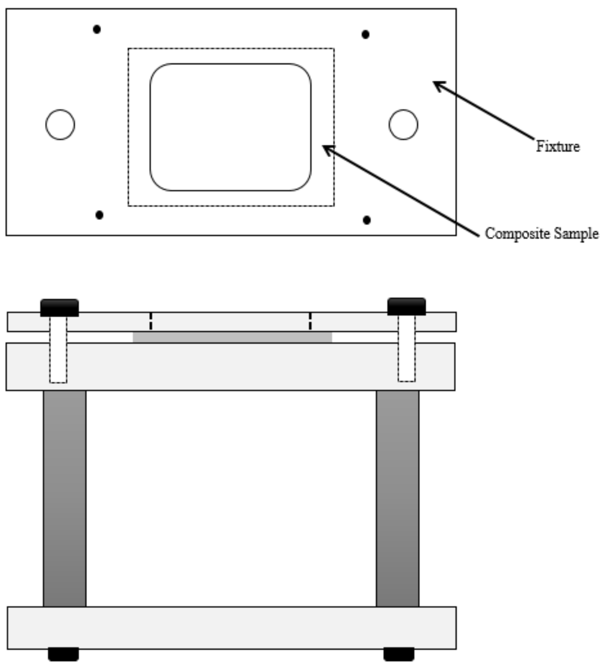


Figure 4: Schematic view of the fixture and sample location within the fixture.

The composite plates were clamped along all edges. Clamping force is provided by steel plates on the top and bottom edges as shown in the schematic drawing (Figure 4). The clamping force is applied by tightening 2 bolts at edge of the fixture.

Impact Testing Results

As per the procedure described above a total of 19 composite design were impacted using INSTRON Dynatup 9250G drop tower in order to determine the amount of impact energy lost in damage during the impact process for each of the defined cases per Table 1. Table 2 summarizes the measured load, deflection and absorbed energies for all composite samples where carbon-fiber composite sample C2 exhibits the highest absorbed energy.

The results from the impact testing experimental work show that the carbon-fiber/epoxy composite plate has better impact resistance compared to glass-fiber/epoxy composite plates due to the higher measured strength and the fracture energies of the carbon-fiber/epoxy. C1 has the highest measured absorbed energy then C2, C3, C4 PH, C4, C5, C4 PL, C7 while C6 has the lowest absorbed energy. It worth mentioning that there almost negligible differences in the measured absorbed energy for C5, C4 PL and C7. It was found that G1 PH has the highest measured absorbed energy then G1 PL, G4, G1, G6 while G5 has the lowest absorbed energy. It was expected that the composite plates with glass fiber as the reinforcement material will behave in a similar fashion as the carbon fiber based plates. However, we noticed that the effect of thickness of individual layers show that the increase in thickness results in the increase in the absorbed energy and the effect of thickness is most profound on the impact performance of the composite plate. In addition, a higher energy absorption is clearly seen in [45/-45/90/0]s composite plates than other composite plates' stacking sequences. For mixed composite combination M1, M2 and M3, the glass fiber composite with 2 carbon fiber plies on the bottom has the highest value of the absorbed energy in compression with the same plate with carbon fiber plies on the middle or in the top. However, the difference is not that pronounced. An interesting result was obtained for absorbed energy-time. It was found that the plate with phenolic resin gives the highest absorbed energy when it is compared with the epoxy and polyester resin for both glass and carbon composite plates.

Thermography Experimental Testing

Damage characterization for composite plates using high end resolution infrared camera was conducted in this study for 19 different composite plate designs. The source can be used in different positions as illustrated in Figure 5. However, external excitation (heat) source in transmission mode was adopted in this study where the back side of the sample was subjected to the heating source and the images were taken from the front of the sample.

The experiment is based a transient heat transfer method using heating source. As illustrated in Figure 5. The non-destructive testing by infrared thermography camera utilizing an in-house developed testing station was performed to measure the maximum and minimum

Sample No.	No. of Layers	Stacking Sequence	Measured thickness (mm)	Peak Load (kN)	Deflection at Peak Load (mm)	Absorbed energy (J)
C1	16	[90/-60/-30/0/90/-60/-30/0]s	3.3	4.48	4.97	15.68
C2	16	[90/0/45/-45/90/0/45/-45]s	3.8	4.10	4.69	16.27
C3	20	[45/-45/90/0/45/-45/90/0/45/-45]s	4.7	5.83	4.67	14.25
C4	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5.5	7.66	3.42	12.75
C4 PH	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5.15	5.62	6.63	13.78
C4 PL	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5.5	8.34	4.16	11.18
C5	28	[45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]s	6.4	9.57	3.03	12.89
C6	32	[90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]s	7.4	11.25	2.68	10.69
C7	28	[-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.6	9.45	3.18	12.62
C8	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	7.3	11.44	2.73	14.16
G1	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	4.9	7.59	4.90	9.01
G1 PH	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	5	5.53	7.47	13.20
G1 PL	24	[90/0/45/-45/90/0/45/-45/90/0/45/-45]s	4.7	7.57	4.97	9.49
G4	24	[90/-60/-30/0/90/-60/-30/0/90/-60/-30/0]s	5.1	7.45	4.76	10.22
G5	36	[-30/-45/45/30/-30/-45/45/30/-30/-45/45/30/-30/-45/45/30/-30/-45]s	7.1	10.09	3.24	9.46
G6	36	[45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]s	7.4	9.66	3.19	11.08
M1	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.5	9.66	3.19	11.08
M2	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.7	8.74	3.53	11.51
M3	32	[60/45/-45/-60/60/45/-45/-60/60/45/-45/-60/60/45/-45/-60]s	6.7	8.91	3.47	11.28

Table 2: Low velocity impact properties of composite samples.

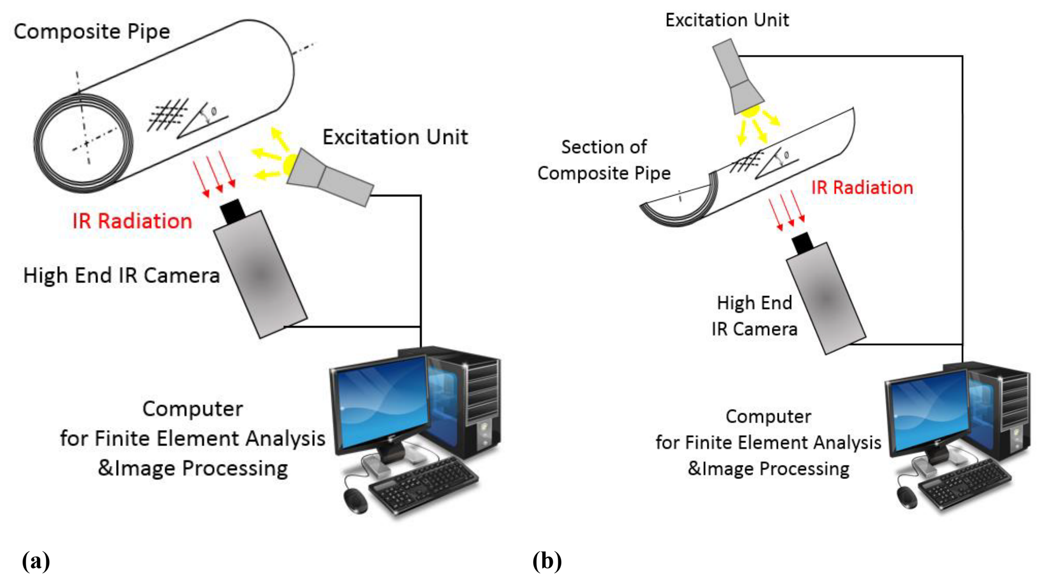


Figure 5: Experimental set-up for a) Reflection Mode and b) Transmission Mode.

temperature on the one side of heated surface for each of the 19 composite impacted specimens. Each composite sample was prepared with different configuration (thickness, stacking sequence and fiber and resin type, etc.). The results achieved were analyzed and compared for each composite and correlated with the results of the impact testing were the absorbed energy for each sample is measured. Each composite plate specimen was prepared with different design (thickness, stacking sequence and fiber type and resin type). The achieved outcomes were examined and compared for every composite plate design and correlated with the impact testing results shown in the previous sections. The most vital issue, which was considered when utilizing the active thermography as in all cases, was to acquire a high precision and repeatability of all measurements. So, for each case and to provide a uniform heating conditions we make sure to have a stable specimen mounting as shown in Figure 6 with constant distance between heating source and specimen. The experimental apparatus is mainly constituted of aluminum box, halogen lamps used as heating system and thermal imaging camera. Thermal insulation is placed around the plate to limit capturing only the heat that passes through the plate. To minimize the other light interference, the light of the room, where the experiment is conducted, are switched off. The acquisition of the data is done manually. The composite specimens are located on the front of the aluminum box. The composite rectangular specimen is heated from one side and the thermal image of the heated plate is taking from a camera located 0.4 meter from the plate. The specimen was vertically mounted (parallel to the heat source) in a rectangular opening of the in-house made aluminum box where each sample is exposed to three halogen lamps (500 Watts each). All heated plates reach steady state after 10 minutes. So, the measurement time for best resolution is set to be 10 minutes in all of the 19 composite plates. So, precise heating time for each sample was considered for all measurements. The image for each sample were taken from both sides, the front side were the plate impacted with 20 Joule using low velocity impact testing and the back side of the sample. The emissivity for the composite was assumed to be 0.9.

FLIR IR camera (Model: GF 309) [22] and FLIR IR Research software were used for thermal imaging to study the surface temperature distribution. The camera is based on a matrix of 320 × 240 Indium Antimonide (InSb) detector, convenient for the detection of 3.8-4.05 µm IR wavelength which has exceptionally sensitive detector. The FLIR GF309 is intended for high temperature industrial furnace applications. These infrared cameras are ideal for monitoring a wide range of heaters, furnaces and boilers, especially in the oil, gas, petrochemical and utility industries. Table 3 demonstrates the FLIR GF309 specification. The FLIR GF309 can detect temperatures from -40°C to +1,500°C. The high performance of the camera is particularly related to the noise level, which is as detectable temperature variation <15 mK. The IR camera was calibrated for the composite surface emissivity to be 0.9. IR camera viewing angle was set to be directly in front of the composite plate.

Visual Measurements

Visual inspection for composite plates is the first line of investigation and it is the easiest system to use by eye or microscope for two-dimensional mapping along the surface. Using such technique,

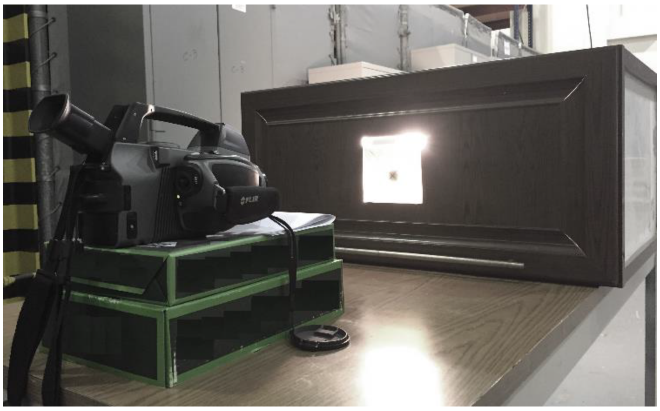


Figure 6: View of the thermography camera system.

Detector Type	Cooled Indium Antimonide (InSb) detector
Spectral Response	3.8-4.05 µm
Resolution	320 × 240 (this means 76,800 pixels or using 76,800 infrared thermometers at the same time)
Total Pixels	76,800
Thermal Sensitivity	<15 mK @ +30°C (+86°F)
Accuracy	±1°C (±1.8°F) for temperature range 0°C to +100°C (+32°F to +212°F) or ±2% of reading for temperature range >+100°C (>+212°F)
Temperature Range	-40°C to 1,500°C (-40°F to 2,732°F)
Emissivity correction	Variable from 0.01 to 1.0 or selected from editable materials list
Zoom	1-8× continuous digital
Focus	Auto & Manual
Color LCD	4.3”; 800 × 480 Pixels
Adjustable Viewfinder	Tiltable OLED, 800 × 480 pixels
Video Camera w/Lamp	3.2 MP

Table 3: FLIR309 Imaging Specifications [22].

you can visually detect: surface damage (abrasions, cuts, and dents), blisters, porosity and delamination. Using ASTM D7136 / D7136M [23], a relationship can be established between impact energy and the preferred damage parameter. To facilitate the measurement, transparent paper (129 MM × 129 mm) with a net (Figure 7) has been used to precisely measure the damage extent on the surface of all glass fiber samples. This mapped transparent paper are placed on both side of the composite samples and the diameter of the damage are measured.

Delamination, crack or indentation are normally the observed damage forms (More light area than the rest of the plat). Figure 8 and Table 4 illustrates the measurements of the damage extension relative to the composite specimen size. It is also showing the surface damage on the front and back sides of the plates. It was found that glass fiber sample with phenolic epoxy "G1 PH" experienced the lowest damage on booth surfaces (front and back). Glass Fiber plate G5 has the lowest damage when it is compare with other glass epoxy plates. We can correlate the extent of the damage with the measured absorbed energy where we can conclude that the higher absorbed energy shows less damage as in the case of G4.

Active Thermography Testing Results

After the impact tests for 19 samples using 20J by drop-weight method where the details of the sample design and recorded absorbed energy are shown in previous sections, thermal images were captured using active thermography testing setup described previously (Table 5). Table 6 shows the results for all samples from both sides along with the absorbed energy values measured using low velocity impact testing. More than 100 thermal images were taken by the active thermography testing however just a choice of them are presented here because of the confinement on space. Results for all measured temperatures from both sides along with the measured absorbed energy values are reported in Table 2. The damages on those samples have been clearly seen after exposing each sample to the halogen lamp for 10 minutes. The minimum surface temperature of all samples was exactly at the impacted region in the center of the plates for all cases. Infrared thermography readily detects the occurrence the propagation of crack failure as can be seen in Table 6. This can be further investigated to establish an inspection technique to quantify the damage in fiberglass plates so the remaining solid thickness of the section can be quantified.

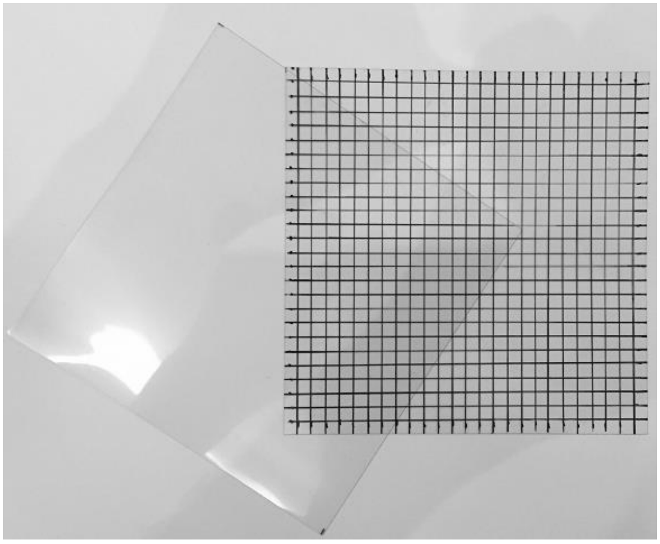
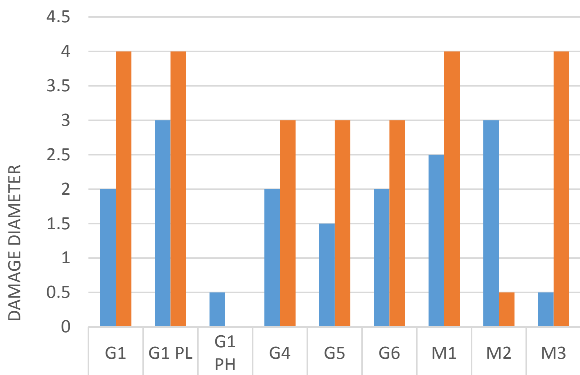


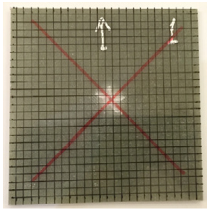
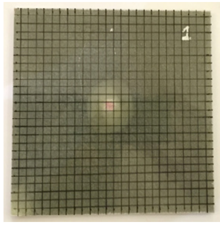
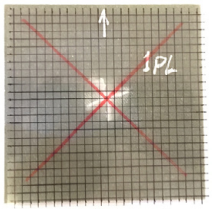
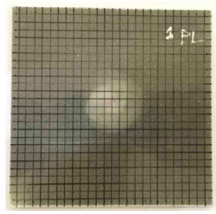
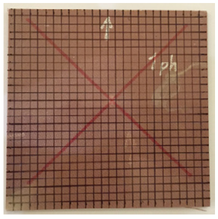
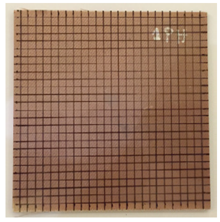
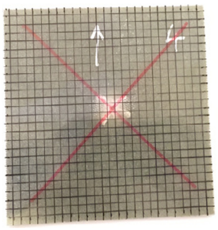
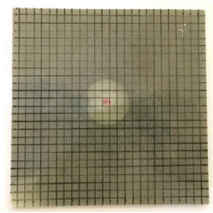
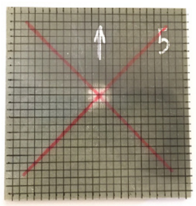
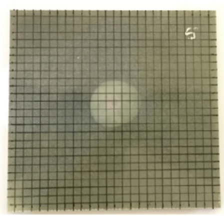
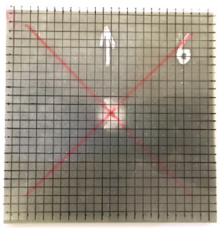
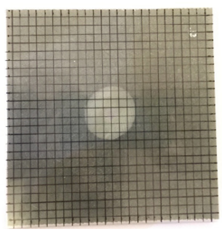
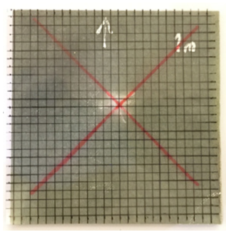
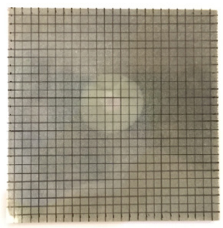
Figure 7: Transparent paper used for damage measurement.



	G1	G1 PL	G1 PH	G4	G5	G6	M1	M2	M3
Front Damage Diameter	2	3	0.5	2	1.5	2	2.5	3	0.5
Back Damage Diameter	4	4	0	3	3	3	4	0.5	4

Figure 8: Summary of the damage measurement for glass and mixed fiber samples.

Citation: Al-Athel KS, Alomari AS, Arif AFM, AlSulaiman FA, Malik MH (2019) Damage Characterization Using Thermography of Composite Plates Subjected to Low Velocity Impact Loads. J Material Sci Eng 8: 530.

	Front		Back	
	Damage Diameter (cm)	Photo	Damage Diameter (cm)	Photo
G1	2		4	
G1 PL	3		4	
G1 PH	0.5		0	
G4	2		3	
G5	1.5		3	
G6	2		3	
M1	2.5		4	

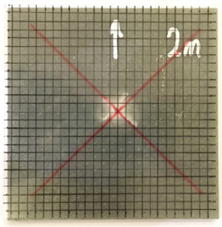
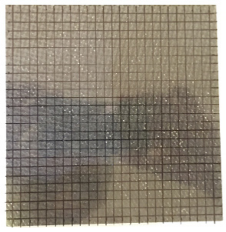
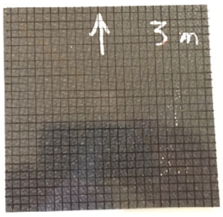
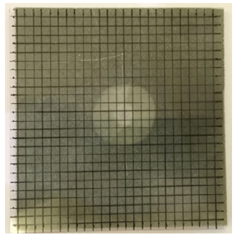
	Front		Back	
	Damage Diameter (cm)	Photo	Damage Diameter (cm)	Photo
M2	3		0.5	
M3	0.5		4	

Table 4: Visual damage measurements.

Sample No.	No. of Layers	Absorbed energy (J)	Max Front Temp (C)	Min Front Temp (C)	Max Back Temp (C)	Min Back Temp (C)	ΔT Front (C)	ΔT Back (C)
C1	16	15.68	85.8	80.8	86.5	76.9	5	9.6
C2	16	16.27	82.5	76.8	86.5	79.7	5.7	6.8
C3	20	14.25	87.1	83.1	82.6	76.8	4	5.8
C4	24	12.75	81.5	77.7	83.8	78.8	3.8	5
C4 PH	24	13.78	81.5	76.2	79.5	75.4	5.3	4.1
C4 PL	24	11.18	79	75.4	83.8	77.9	3.6	5.9
C5	28	12.89	84.4	81.2	84.4	78.9	3.2	5.5
C6	32	10.69	80.2	77.3	80.2	76.8	2.9	3.4
C7	28	12.62	79.9	76.5	85.5	79.7	3.4	5.8
C8	32	14.16	78.5	73.6	85.7	81.4	4.9	4.3
G1	24	9.01	81.7	76	75.9	66.5	5.7	9.4
G1 PH	24	13.2	64.1	60.5	66.6	64.8	3.6	1.8
G1 PL	24	9.49	81.1	73.1	81.5	73.1	8	8.4
G4	24	10.22	81.1	75.7	78	68.1	5.4	9.9
G5	36	9.46	76.7	71.9	79.4	76.1	4.8	3.3
G6	36	11.08	82	77.4	82.9	79.9	4.6	3
M1	32	11.08	77.1	70.6	78.9	75.3	6.5	3.6
M2	32	11.51	82.6	77.6	78.5	74.2	5	4.3
M3	32	11.28	79.3	74.5	83.9	81.3	4.8	2.6

Table 5: Active thermography results.

Based on the finding after interpreting the thermal images, it was found that this effect could become noticeable if the fiberglass is significantly impacted where clear cracks within the thickness of the composite structure can be seen as a star cracking while the visual inspection as can be seen in However, the detected temperature rise, resulting from the used heat source, must be correctly discriminated by particular testing setup and environmental conditions to avoid any interference of lights that may affect the images captured by the IR camera. This is the main difficulty when interpreting the thermal images obtained from experiments under usual conditions. Heat source is one of the challenges that need to be carefully identified and fixed from the distance of the source to the composite structure to the amount of the heat for the lamps used in the testing and the level of heating; either continuous for very specific time or as flash. The distance of from the heat source to the composite structure under investigation as well as the distance from the structure to the infrared camera should be optimized. The other challenges in this type of test is identifying the emissivity of the structure where normally 0.9 is used during the setup of the camera for composite structure as it is regarded as wood and rocks. Since the composite materials made out of at least two type of materials, the variances in thermal conductivity may arise because of local in-homogeneities or flaws in the fiberglass. Where an unsteady state exists, the thermal behavior is governed not only by its thermal conductivity but also by its heat capacity. The ratio of these two properties is termed the thermal diffusivity e=K/C which becomes the governing parameter in such a state. A high value of the thermal diffusivity implies a capability for rapid and considerable changes in temperature. It is important to bear in mind that two materials may have very dissimilar thermal conductivities but, at the same time, they may have very similar diffusivities.

One of the main interests of this thermal imaging analysis is the 3D observation of the damaged zone. Where the depth of the damage can be identified by correlating the measured temperature at the impacted

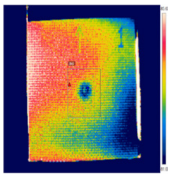
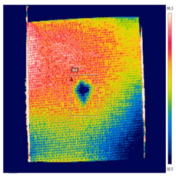
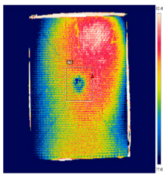
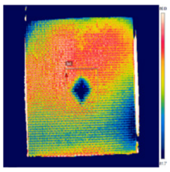
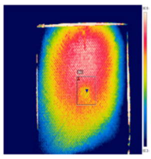
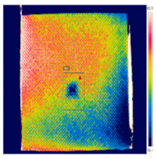
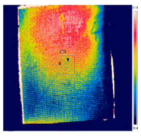
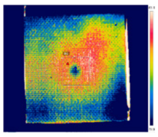
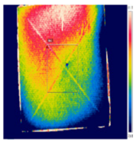
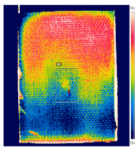
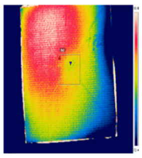
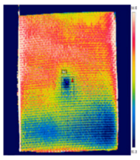
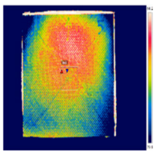
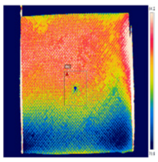
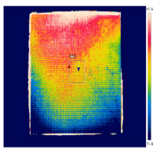
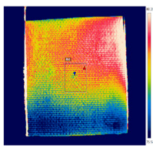
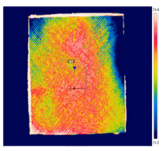
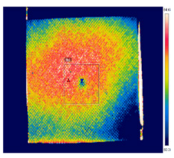
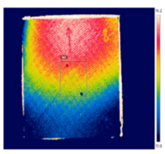
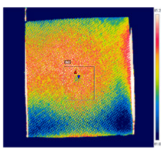
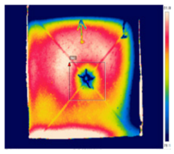
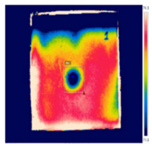
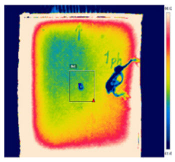
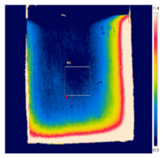
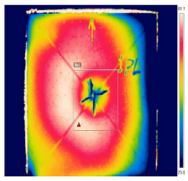
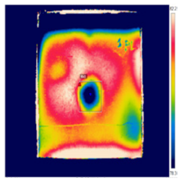
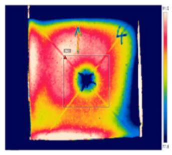
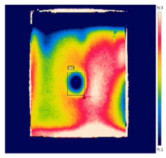
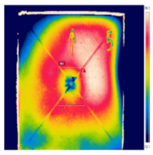
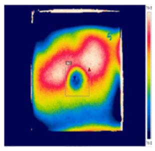
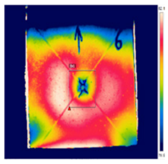
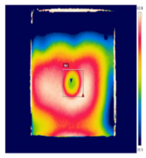
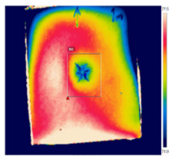
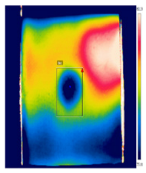
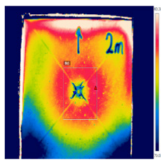
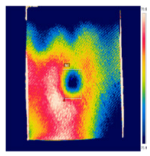
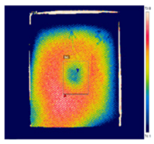
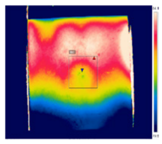
Sample no	Front infrared image	Back infrared image
C1		
C2		
C3		
C4		
C4 PH		
C4 PL		
C5		
C6		
C7		
C8		
G1		
G1 PH		
G1 PL		
G4		
G5		
G6		
M1		
M2		
M3		

Table 6: Thermography Results for 19 Composite Samples.

zone with the temperature of the surface at no damage location. Once the experiment is set up as described in the previous section temperature measurements are carried out on the thermography testing for all samples. Infrared surface temperature data are taken until the temperature distribution reaches steady state. For accurate extraction of surface temperature measurement, a region of interest is built into the measured temperature field from the infrared camera, and temperature across the outer surface at mid-height is extracted. A uniform temperature is measured for the plate at the region of interest (middle of the plate in a box), indicating that the interference of the lights from edges does not affect IR measurement accuracy.

The interpretation of the images for all 19 plates revel interesting information. Infrared thermography showed that for all plates impacted with 20J of energy, damage remained localized to the zone of contact with the impactor. Moreover, the results from all images shows that the lowest temperature, measured on the both sides of each samples are at the most damage location due to impact (Figure 9). In other words, heat flow obstructed by a delaminated area decreases the surface temperature compared with that in the surrounding area (away from delamination). Before conducting the test using the in-house heat source and the thermal imaging camera, we thought that the damage locations on the composite samples will have more heat than the undamaged location as this is the norm for conventional metals such as carbon steel where the corroded locations are identified with high temperature as there are loss of thickness and more heat can penetrate on these corroded locations. Same philosophy was assumed for composite. However, in all glass fiber cases, the damage locations experienced the lower temperatures. There is in-going analysis for this finding. We believed that the damage characteristics in the composite is different than conventional metals as composite fail by delamination of the fiber due to impacts so there will be disbanding of the fiber from the matrix and this will generate gaps where heat will be dissipated and there will be loss in the heat transmitted through the composite thickness.

It worth mention that, the glass fiber plate made out of phenolic resin "Sample No. G1 PH" experienced the highest absorbed energy (13.2 J) and the lowest measured temperature at the damage location (60.5-degree C) among the other glass fiber plates made out of epoxy and polyester resins. This is also supported by the visual analysis of the damage where limited damage was observed in G1 PH sample. Further analysis is currently conducted to investigate this phenomenon and the finding will be more correlated with finite elements analysis and with further image processing. The results achieved during experiments together with the considered parameters provide a good starting point for any theoretical investigations (Figure 10).

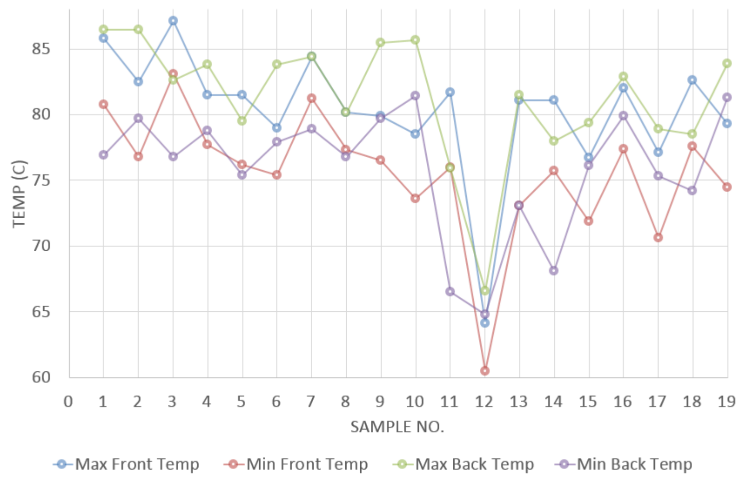


Figure 9: Measured Temperatures using Active Thermography where minimum values were observed at damage locations.

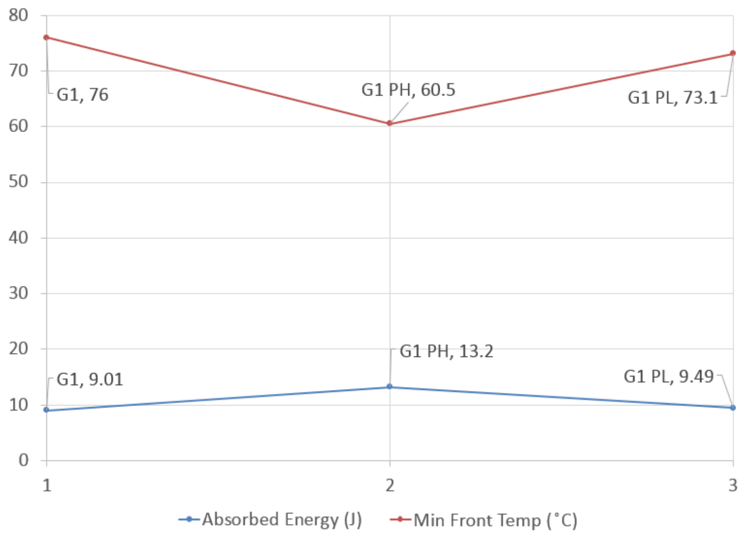


Figure 10: Absorbed energy vs. Minimum thermography Temperature for Glass Sample No.1 with different resin types.

Although the entire specimen was scanned using the above technique. Only a section in the center of the specimen of 100 pixels by 100 pixels was used for the analysis to avoid edge effects. Table 6 shows the thermography images for all samples. The damage on the glass fiber samples are easy to be seen in comparison with the carbon fiber samples. Further analysis is currently conducted to investigate this phenomenon and the finding will be more correlated with finite elements analysis and with further image processing. The outcomes accomplished during the analyses of the thermal images together with the considered parameters give a decent beginning stage for further hypothetical examinations. The 3D temperature representations for all glass and mixed fiber samples are shown in Figures 11-18 where the lowest areas correspond to the highly-impacted regions with more delamination between plies. These 3D figures as well as the 2D surface figures showing the temperature within 40X40 Pixel at the point of contact for all samples to avoid edge effects. The data recorded from the mid-wave infrared camera first converted first to an integer matrix, then to temperature values based on calibration data of the infrared camera so the thermal history of the composite plate within the impacted region are obtained. It clearly noticed as discussed and interpreted from the thermal images that we can correlate the temperature changes due to impact with the remaining thickness of the composite plate. Thermography testing work well with delamination type of damage in composite as the delamination lead to presence of a small gap or void between the plies in the composite material. This void will cause the thermal conductivity in the delaminated region to be different than the rest of the material and cause the region to be visible on the thermogram [14] (Table 7).

However, some voids cannot be detected with pulse thermography technique or Long-wave thermal imaging camera. For this reason, in

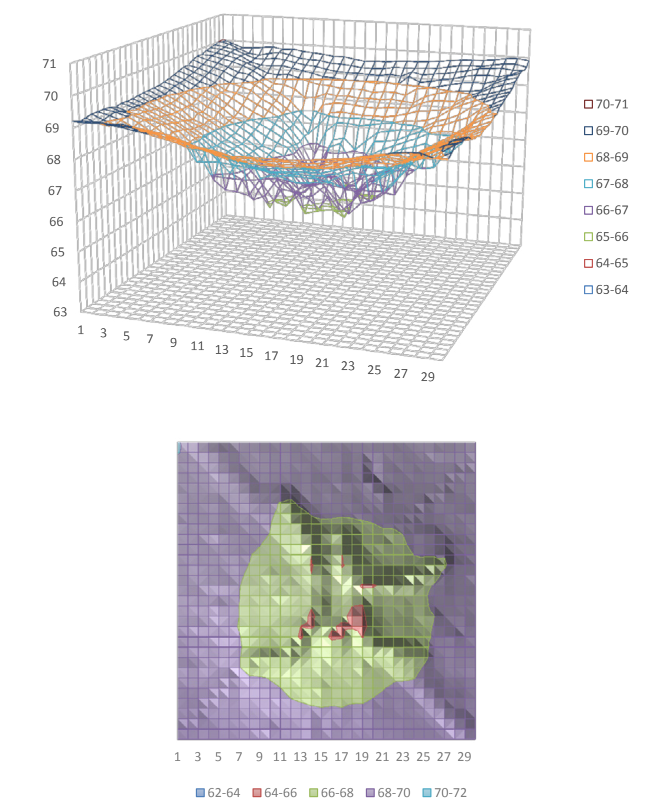


Figure 12: 3D Thermal Representation of Impacted Composite Plate G4 (30X30 Pixel).

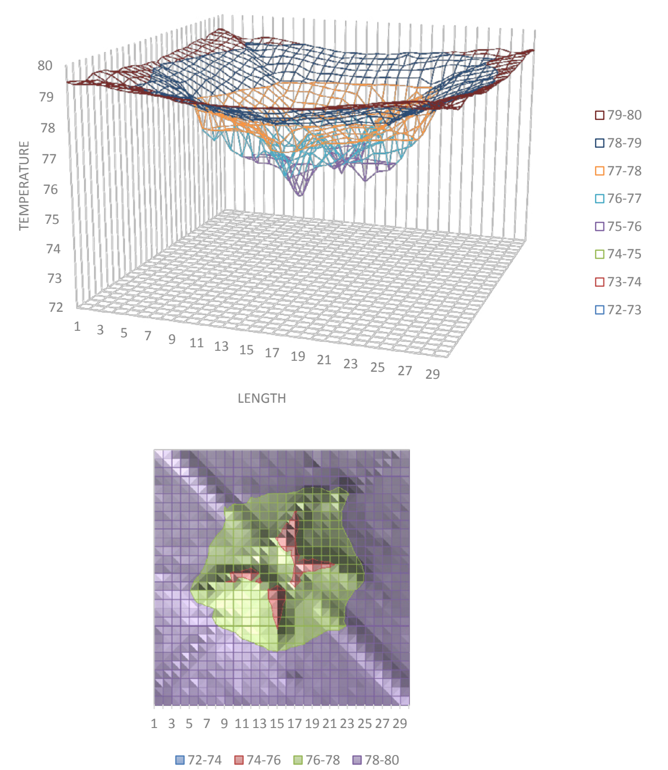


Figure 11: 3D Thermal Representation of Impacted Composite Plate G1 (30X30 Pixel).

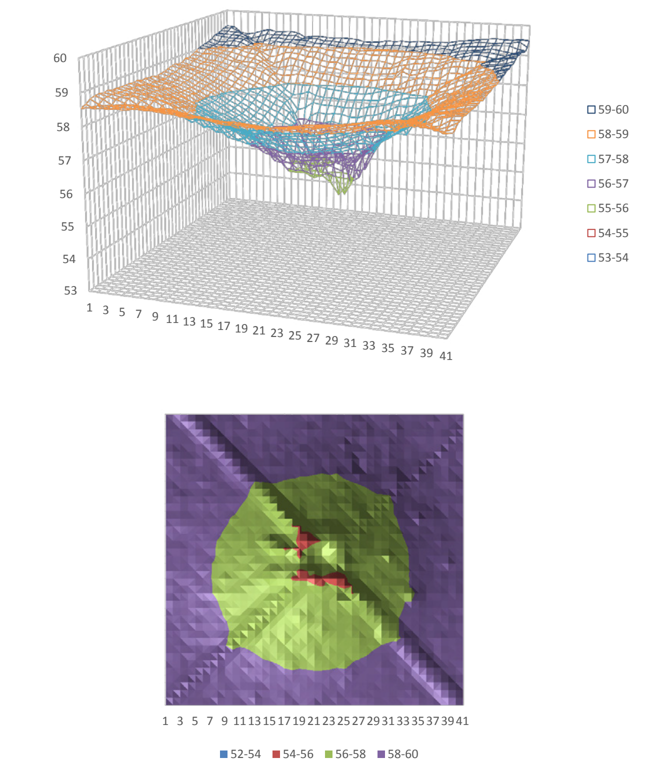


Figure 13: 3D Thermal Representation of Impacted Composite Plate G5 (40X40 Pixel).

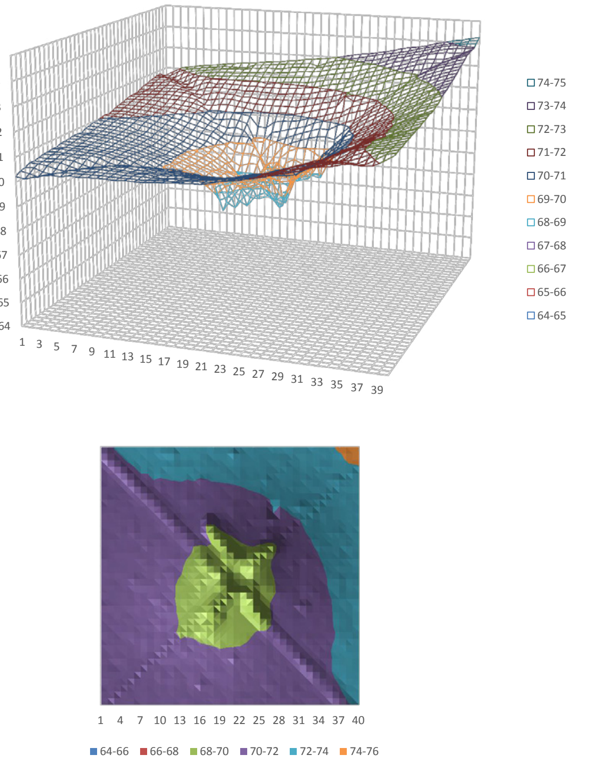


Figure 14: 3D Thermal Representation of Impacted Composite Plate G6 (40X40 Pixel).

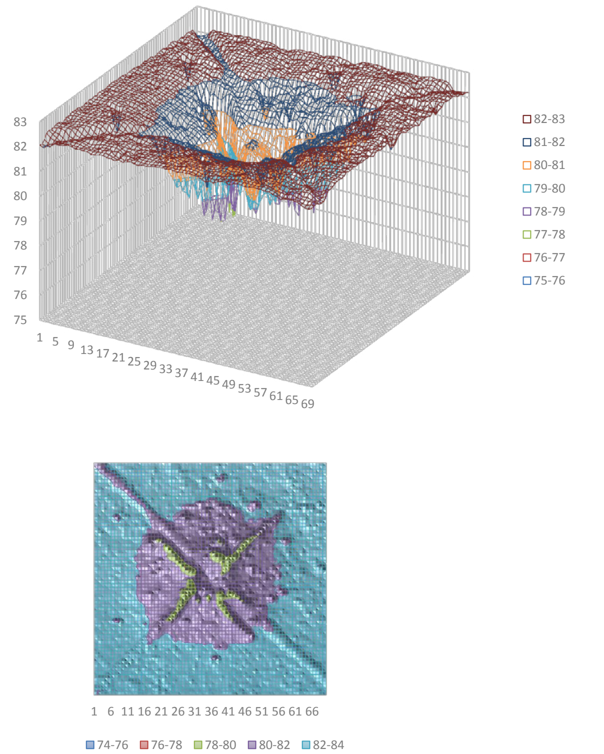


Figure 16: 3D Thermal Representation of Impacted Composite Plate M2 (40X40 Pixel).

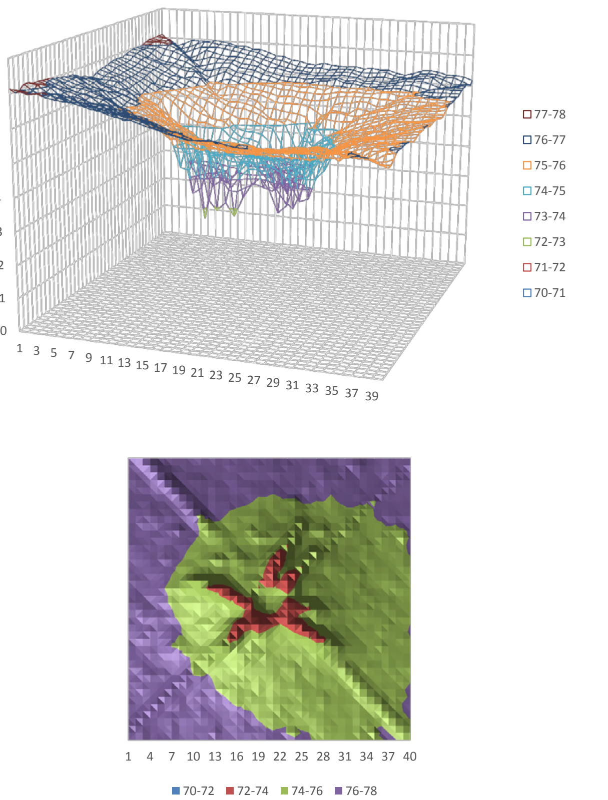


Figure 15: 3D Thermal Representation of Impacted Composite Plate M1 (40X40 Pixel).

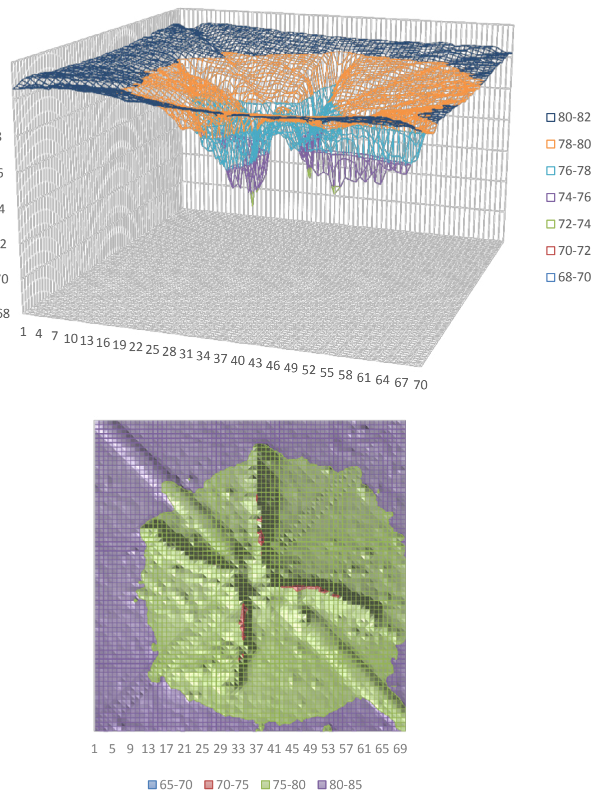


Figure 17: 3D Thermal Representation of Impacted Composite Plate G1_PL (70X70 Pixel).

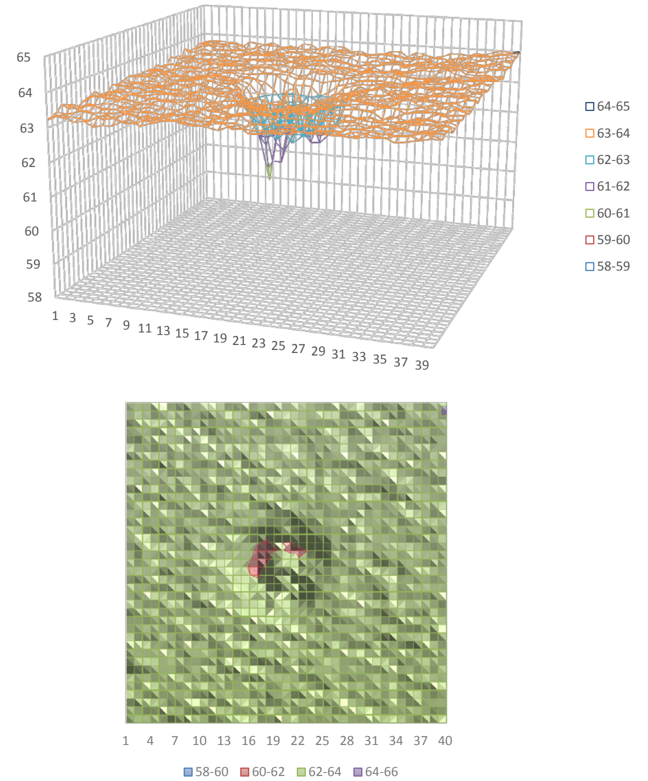


Figure 18: 3D Thermal Representation of Impacted Composite Plate G1_PH (40X40 Pixel).

Figure 19: Testing one of the Glass Fiber Sample using Long Range Camera.

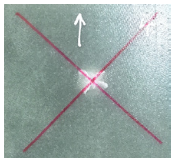
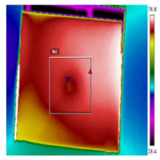
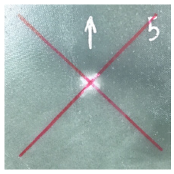
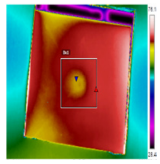
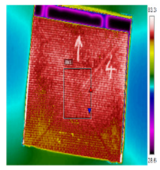
Sample No	Composite Sample	Front IR Image
G4		
G5		
C4		

Table 7: Thermography Results for 3 Composite Samples using long-wave Camera.

this study, lock-in thermography with advanced mid-wave camera and image processing produce were adopted to get better results in this study. To prove the above mentioned conclusion, same test was conducted for G4, G5, C1 and C4 plate's samples using long-wave thermal imaging camera (FLIR T650sc [24] as shown in Figure 19) and the results were not satisfactory as there was no clear images captured after exposing the samples for 10 minutes heat as can be seen in Table 7.

Conclusion

This article presents damage characterization using visual infrared thermography investigation of 19 specially prepared glass and carbon fiber composite plates impacted by 20J. Thermography was also used in an attempt to provide additional information on the initiation and development of the deferent damage mechanisms which developed during low velocity impact testing. The investigation has assessed the ability of thermography camera with Mid-Wave IR using a long pulse technique heating to carry out the experiments.

Several important conclusions can be summarized below:

- The experimental apparatus and method are reliable.
- The IR image using thermography camera approach using a continuous heat source method can be applied to determine damage inside composite materials in real time.
- The distribution of temperature gradients across the 19 different composite plates was clearly resolved using the combination color counter and measured temperatures, providing a clearer understanding of the damage of the plates under low velocity impact.
- Using the surface x and y delamination of the colors due to impact and using the temperature correlation method, it is possible to obtain a 3D image of the delamination in good agreement with physical observations.
- The experimental setup and method are reliable.

The experimental results have shown that the damage locations due to impact experienced the lowest measured temperature. Therefore, it is concluded that infrared thermography can be used in characterizing the damage of polymer composite materials. However, more detailed analysis need to be conducted. The systems also need to be enhanced by including digital temperature sensors and insulation for the aluminum box from inside. Accurate measurement of temperature is critical for understanding thermal behavior and monitoring safety and performance of composite materials behaviors that can be linked to their damages. Further studies and researches are needed to fully understand this behavior in order to use thermography as a robust nondestructive too for assisting the integrity of fiberglass plate and pipes.

Currently there is no proven technology to accurately and quantitatively detect the damage in composite structures. Such technology is crucial to assess the threat of every defect and decide whether repair is required. In the present study, active infrared thermography was led to assess the effect of low velocity impact in a uniquely designed and manufactured 19 composite plates. Thermography was likewise utilized as a part of an endeavor to give extra information on the initiation and development of the deferent damage mechanisms which occurred during the low velocity impact testing. The examination has assessed the capability of thermography camera with mid-wave infrared utilizing a long pulse technique as a heating source to complete the tests. The test results have demonstrated that the damage locations due to impact experienced the lowest measured temperature. In this way, it is presumed that infrared thermography can be utilized as a part of damage characterization composite materials. However, more detailed analysis need to be conducted. The systems also need to be enhanced by including digital temperature sensors and insulation for the aluminum box from inside. Utilization of infrared thermography camera with the manufactured in-house heat source chamber along with the advanced imaging software's and the developed finite element modeling helps us to come up with innovative solution that can be used for damage characterization to raise the confidence of the composite structures used in industry. Moreover, visual testing was conducted where the inspection showed a large extent of damage observed on the polyester and epoxy resins plates when they are compared with same plates made with phenolic resin.

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