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Infrared thermography used for composite materials

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Abstract. Many areas of the industry use composite materials, because of their good mechanical features in terms of low density and high mechanical strength. Composite materials are used wherever elevated rigidity and strength with reduced unit weight are required; such as wind turbine blades, shipbuilding, aeronautical and aerospace. However, the properties of composites can be hugely affected because of inside defaults such as delaminations or local cracks. Several non-destructive methods have been used for the verification of defects during construction or operation, such as ultrasound or x-ray. These methods are costly and difficult to implement. Non-destructive method using infrared thermography is considered very useful and works perfect with low cost. Two methods of non-destructive detection by infrared exists, which are (i) passive thermography, that consists of measuring infrared stream emitted by the material and (ii) active thermography, which consists of heating the material and measuring the cooling of material surface using an infrared camera. This communication describes the basic principles of both passive and active thermography, and then describes other different methods for detection of composite materials defects.

1 Introduction

Infrared thermography is a technique that allows non-destructive control of a composite material by an infrared camera.

Composite materials are made by assembling of at least different materials. The first material called the reinforcement is mostly in form of fibers, which enhances mechanical strength. The second material called matrix ensures the cohesion of the structure and transmission of the efforts towards the reinforcement.

Composite materials provide good mechanical performance with a low density and are widely used in the industry like wind turbines, aeronautical, naval and space. Composites are largely used in blades and nacelles of wind turbines. Blades have to be manufactured with strong and lower weight material in order to decrease the cost of the installation. The use of carbon / glass fiber allows producing higher stiffness and lower weight blades **[**1**]**. Figure1 shows the cross section design of a wind turbine blade. The blade design incorporates pre-impregnated epoxy glass fiber and carbon fiber **[**1**]**.

In shipbuilding industry, steel has been used for many years and was the dominating building material. Recently, composite materials are being used in large scale. Composite materials offer good mechanical features with weight reduction which results in decreased fuel consumption. Safety is increased in case of fire and total cost is lowered. Fiber glass Reinforced Plastic (FRP) (which is a composite material made of a polymer matrix reinforced with fibers) is like this increasingly used in ship building industry **[**2**]**.

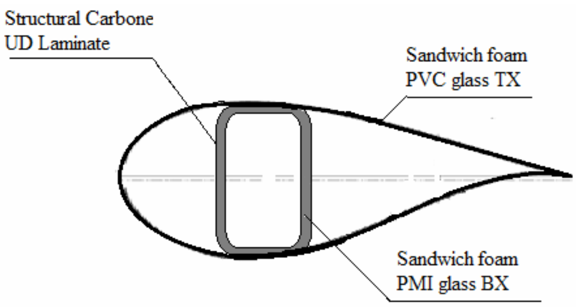

Figure 1. Cross section design of wind blade.

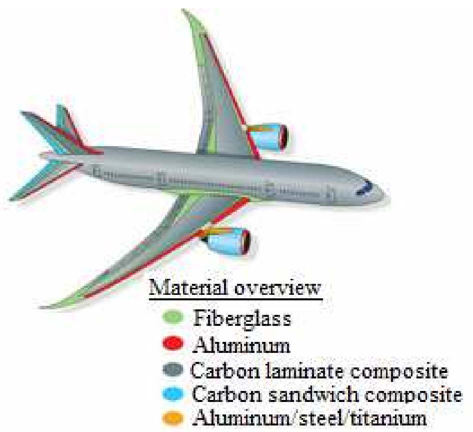

Figure 2. Composite materials used in 787 Boeing airplane **[**4**].**

In aerospace industry, the use of composite represents 50% of the materials of which the majority is

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made up of carbon fiber composite [3]. Figure 2 shows composite materials used in 787 aeroplane.

Composite material properties are largely affected by the damage of their structure. Thermography can detect different types of composite damage such as delamination, cracks, etc. Figure 3 give more details of some composite defaults.

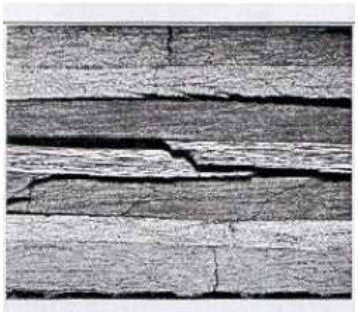

Figure 3. Breaking and delamination in composites [5].

2 Infrared waves

Any solid material with a temperature above absolute zero (-273.15°C) emits in permanence energy in the form of electromagnetic radiation. The movement of electrically charged particles traveling through vacuum or matter produces this energy. Figure 4 shows categories of electromagnetic spectrum based on wavelength.

Infrared radiation is an electromagnetic wave of frequency lower than visible light, and a wavelength between the visible area ($\approx$ 0.7 µm) and the field of the microwave ($\approx$ 1 µm).

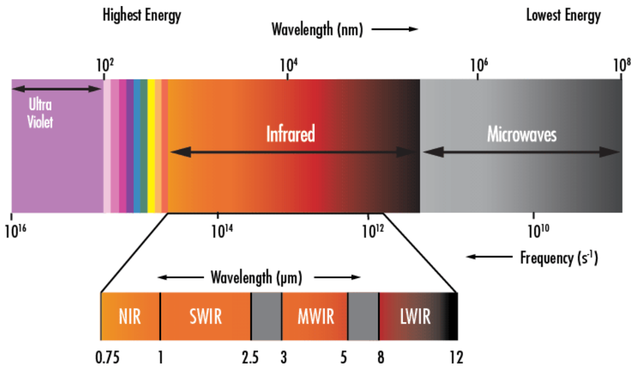

Figure 4. Infrared electromagnetic spectrum.

Infrared radiation can be subdivided further into three categories:

- **Near infrared:** with wavelength between 0.75 µm and 1.5 µm detected by specialized photographic emulsions (up to 1 µm), photoconductors detectors and photovoltaic.
- **Mid infrared:** with wavelength between1.5 µm and 20 µm detected by thermal, photoconductors, and photovoltaic detectors
- **Far infrared:** with wavelength between 20 µm and 1000 µm detected only by thermal detectors.

Special camera captures infrared signals, with optics made of germanium, allowing focusing the heat radiation.

Detection can be made with either cooled infrared cameras that is very sensitive or bolometric camera with good quality/price.

Thermal imaging taken by infrared camera may contain errors because:

- Some surfaces are more reflective than others;
- Emissivity of some objects can influence camera's temperature calculation;
- Values should be adjusted to room temperature;
- Viewing angle should be adjusted.

Infrared thermography is widely used in many areas such as:

-Wind turbine industry where infrared is used for detecting defects on blades made of composite materials during manufacturing and operation;
- Night vision (army, or navigation...) or search for persons during fires;
- Civil engineering for insulation evaluation, search for points of loss of heating;
- Electrical and mechanical construction or maintenance;
- Medicine: detection of hyperthermia in humans (in airports...);
- Veterinary medicine: detection of localized inflammation (tendonitis...);

For non-destructive detection of composite materials defects, two techniques are used:

- Passive infrared thermography ;
- Active infrared thermography.

3 Passive infrared thermography

This technique is used to measure naturally occurring temperature contrasts in the composite or induced natural solicitations (Sun, temperature of the air...). A thermal camera is used and captured images are treated by computer (see Figure 5).

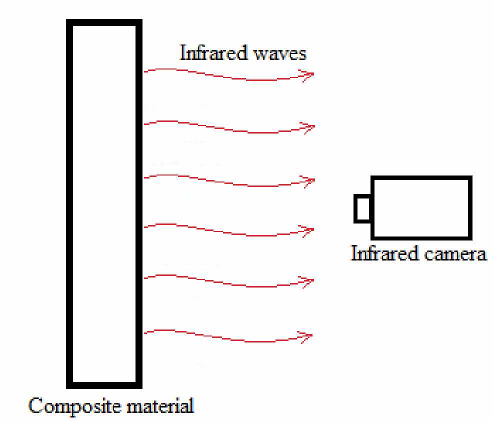

Figure 5. Passive infrared thermography.

Defects covered by this technique are superficial or in few millimeters deep. Images can be captured at any moment for superficial defects or to be received at different times.

The advantage of this passive method is that it is simple to use, and measurements can be made on large surfaces. This method is limited and presents weaknesses because measures are influenced by the room temperature, images can contain the shadow of the objects on the surface, and treated depth of the material is only few millimeters.

4 Active infrared thermography

Composite sample is subjected to artificial stimulation and we measure induced temperature contrasts (see figure 6).

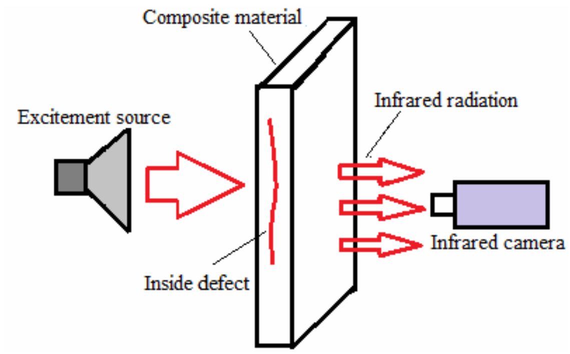

Figure 6. Active infrared thermography.

The source of excitement can be a flash, a halogen lamp, induction by electric current or vibro-thermography.

We use several methods for active thermography technique including:
- Pulsed thermography (PT);
- Lock in thermography (LT);
- Vibro-thermography stimulated by ultrasound (VTU);
- Laser infrared thermography (LT);
- Infrared induction thermography (IT).

4.1 Pulsed thermography (PT)

This technique consists of emitting a thermal pulse to the composite material (for instance: using lamp, laser, or any other heat source) and record the evolution of the temperature at the surface level in specific time interval (see Figure 7).

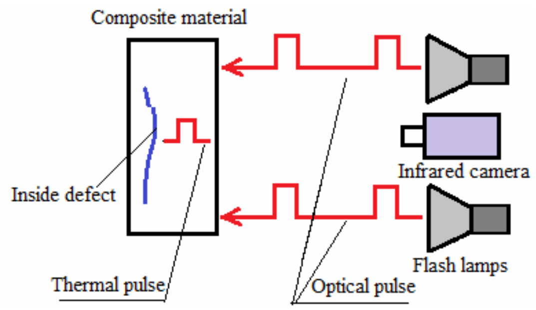

Figure 7. Schematic of pulsed thermography.

Thermal balance of the composite material is disturbed by providing a pulse with very concentrated and very brief energy. A powerful Xenon lamp can generate large thermal power on the composite material surface. Quick infrared camera can record successive images which can be analyzed in real-time scale pixels. The energy pulse sent to the composite material decreases due to thermal conduction. The reduction in temperature profile after pulse injection gives information about the properties of the material. This pulsed infrared thermography enables detecting flaws or determination of coatings characteristics.

The pulsed method has advantages such as it is not affected by the inhomogeneity of the composite heating and the surface properties that may be changing. However, the depth of investigation is limited.

4.2 Lock in thermography (LT)

Figure 8 illustrates LT method. This consists of submitting the composite material to a sinusoidal thermal solicitation with well-defined frequency, in steady state, and then capturing the surface heating using an infrared camera. The analysis covers the phase shift and amplitude of temperature response. LT gives information about structure and thermal inhomogeneity of composite material.

The apparatus of LT includes generator that provides modulated frequency and intensity to halogen lamps to produce heat waves. A high-resolution camera measures composite material thermal response. Analysis of phase shift between thermal excitation signal and thermal surface response allows locating defects if present in examined parts.

Lock in thermography is nondestructive control method that is recognized for evaluation of composite reinforced plastics carbon fiber in aeronautical, aerospace and automotive industry. It allows locating precisely defects and to determine their depth.

In addition, this method is extremely robust, insensitive to external disturbances and works even in difficult conditions. This method is ideal for quality control during production and operation.

The advantage of this technique is that it is not sensitive to nonconformities of heating, tests can be done on large surfaces, stimulation frequency can determine the depth of the test, and this method gives a good signal to noise ratio.

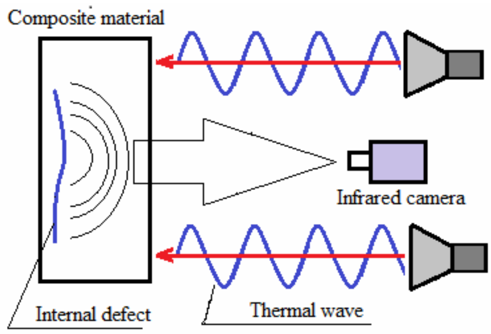

Figure 8. Schematic of Lock in thermography.

4.3 Vibro-thermography stimulated by ultrasound (VTU)

With ultrasound thermography or vibro-thermography, composite material is submitted to ultrasonic vibrations that propagate inside the material.

Test bench consists of generator with ultrasonic converter and infrared camera [5]. The heat emitted by the material surface is then captured using an infrared camera.

The interaction between thermal and mechanical waves can locate defects present in the composite material. They appear on the thermal images because they are releasing more heat by friction.

Vibro-thermography allows reaching deep flaws inside composite material, it also has the advantage of not being sensitive to the ambient temperature because ultrasonic waves propagate in depth and the surface of the material is not heated.

For the location of defects, the phase shift between excitement and thermal response is examined. Ultrasonic thermography gives information on the different types of defects such as composite cracks, detachments or delamination.

4.4 Laser infrared thermography (LT)

A laser beam is sent to the inspected composite material in order to produce heat on its surface [6]. A Well-defined area on the composite surface heated could be line or point.

Laser excitement creates heat that flow inside the composite material. Defects present in the composite material are considered as thermal barriers that affect the flow of heat. Infrared camera captures the thermal differences on the surface.

Composite material properties such as thickness, porosity and thermal conductivity can be detected using Fourier transform analysis.

Laser infrared thermography eliminates non-uniformity sensitivity of composite heating surface.

4.5 Infrared induction thermography (IT)

The principle of infrared induction thermography is to induce eddy currents within the composite material, and to capture the heat flowing from the surface using an infrared camera [7].

The loops of electrical current induced inside the composite material are uniform except when they encounter a defect in the material. The heat flow is then changed. During the test, variable magnetic field near the surface of composite material is created and the flow of temperature emitted by the surface of the material is measured.

The induction method is not sensitive to irregularities or impurities of the composite surface.

5 Conclusions

Composite materials are used in many areas such as wind energy, aeronautics, aerospace and marine construction. They offer good mechanical performance for low thicknesses.

Composite material manufacturing conditions greatly affect the quality of these materials.

Defects may appear during manufacturing or during operation, detecting these defects before at their earlier stage is then very important to ensure their quality and safety.

This article presented several non-destructive detection methods based on thermography techniques. A review of the most recent methods has been carried out. These methods have succeeded in locating and even in characterizing most of the defects that are present in composite materials.

Each technique has its advantages and drawbacks, the choice of a technique will depend on the type of defect to be detected, the degree of accuracy required and the cost of the equipment to use.

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