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The detection of aeronautical defects in-situ on composite structures using Non Destructive Testing

Christian Garnier, Marie-Laetitia Pastor, Florent Eyma, Bernard Lorrain

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Review

The detection of aeronautical defects in situ on composite structures using Non Destructive Testing

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NDE
Composites
Ultrasonic Testing
InfraRed Thermography
Shearography

A B S T R A C T

A study of three Non Destructive Testing methods (Ultrasonic Testing, InfraRed Thermography and Speckle Shearing Interferometry, known as Shearography) was carried out on different specific types of composite specimens having a variety of defects. The aim of this study is to evaluate the efficiency of these NDT methods in the detection of in site defects resulting from Barely Visible Impact Damages (BVID) or in-service damages to complex surfaces such as wings or rods. The size and position of all the defects were determined by GVI (General Visual Inspection): GVI being the reference. The evaluation of the three NDT techniques enabled conclusions to be drawn regarding defect detection and size. The first part of the study deals with determining and measuring defects. It appears that only the ultrasonic method enables the depth of a defect to be determined. In the second part of the study, the results obtained by the three NDT methods are compared. Finally, the feasibility and the time taken to set up the experimental protocol are analyzed. The study shows that all the defects were revealed by, at least, one of the three NDT methods. Nevertheless it appears that InfraRed Thermography and Shearography produced results very quickly (in about 10 s) compared to Ultrasonic Testing.

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1. Introduction

In the aeronautics industry, during manufacture, random porosity or undesirable material may appear in composite structures during the manufacturing process. When structures are in service, impacts may result in delamination or disbonding. These undesirable inclusions or defects affect the structure and its mechanical properties. In order to check the integrity of the composite, these defects have to be revealed.

Several techniques can be used to detect such defects. At the moment, however, the only NDT method leading to certification is Ultrasonic Testing [1]. Ultrasonic Testing is a contact or non-contact method which requires voluminous equipment (pool, etc.). Although it enables many defects such as delamination, disbonding, etc. to be detected easily and accurately [2,3]. It is nevertheless a relatively slow process.

Over the past twenty years, optical methods have gradually appeared and are now being applied to Non Destructive Testing. Infra-Red Thermography is commonly used and methods such as Speckle Shearing Interferometry [4] have also recently come into use.

Initial studies on IR thermography were carried out on metallic samples [5], but when used to test composite material, this method cannot detect internal defects. Nowadays, it can reveal many other defects: impact damage, delamination, disbonding, etc. [6–8].

Shearography is a new method. Derived from speckle interferometry, it is used to determine the strain field of a given specimen [9]. Delamination, disbonding or wrinkles can be identified using this method [10]. However, these optical methods are not yet used on an industrial level because the results are relatively hard to analyse and there is also a lack of both standardization and operator training.

The aim of the present study is firstly to check various specific aeronautical specimens in site. Three aeronautical specimens were chosen, each with a distinctive geometric shape making NDT difficult to carry out or problematic (non-detection, deformed shape, imprecise measurements, etc.).

Its aim is secondly to compare and verify the effectiveness of applying various NDT methods to defects visible to the naked eye. These defects can be thoroughly identified and measured. Comparing the visual method and the NDT methods make it possible to evaluate effectiveness (detection and size of defects as well as the speed of the NDT methods studied).

2. Specimens

2.1. Materials

The three specimens studied were manufactured by the aeronautical industry. Their geometric shapes are listed in a later section of the study (Section 4). The first two specimens are carbon/epoxy composites and the third is a sandwich composite specimen (Nomex honeycomb core and Kevlar skins).

They are called Specimen A (cf Fig. 4.1), Specimen B (cf Fig. 4.4) and Specimen C (cf Fig. 4.9), respectively.

Damage analysis on each of the three specimens is extremely difficult because of their distinctive geometry: Specimen A is a hollow cylindrical rod, 100 mm diameter, 10 mm thick and 1 m long. Its specific shape prevents access to the inside of the rod. In addition, it is coated with blue gloss paint to comply with aeronautical service specifications but in order to improve the quality of optical results, the damaged area has to be matt.

Specimen B is a flat plate, 500 mm × 400 mm × 2 mm.

Specimen C has geometric discontinuity: an angle (around 135°) with a slope over the entire length of the specimen (700 mm × 400 mm). NDT methods by contact are not easily applicable when specimens have non-constant geometry, i.e., a shape moving in space [11]. It will therefore be necessary as far as possible to adapt the NDT methods to check these specimens.

2.2. Defects

Each specimen has surface damage. The defect on Specimen A is delamination caused by an in-service impact. During a GVI, the size of the defect can be obtained quite simply using a steel ruler. The GVI defect is 98 mm and 18 mm.

Specimen B damage is the result of a lightning impact which occurred in service. The defect measures 41 mm and 75 mm.

The Specimen C defects are two cases of delamination due to the impact of a falling tool or of hailstones. These were created in the laboratory using a drop weight tester. The defect located above geometrical discontinuity is called no. 1 and the defect located on the geometrical discontinuity is called no. 2 (as defined in Fig. 4.9). Defect no. 1 is 13 mm and 9 mm. Defect no. 2 is 18 mm and 8 mm.

Measurements of all the defects are indexed in Table 1.

3. Non destructive methods

3.1. Ultrasonic Testing

Ultrasonic Testing (UT) is commonly used in Non Destructive Tests. It is based on high frequency wave propagation. The waves are transmitted to the tested object by a transducer. As high frequency waves do not propagate in air, a couplant is required (water, gel coat, etc.). They propagate through the material and are reflected by the rear surface of the specimen. There are two possible ultrasonic techniques: reflection and transmission [12]. In the case of pulse/echo, there are different ways of receiving

Table 1
GVI defect measurements of the three specimens.

	Length (mm)	Width (mm)
Specimen A	98	18
Specimen B	41	75
Specimen C		
No. 1	13	9
No. 2	18	8

the wavefront: simple transducer, Phased Array ultrasonics (PA) or Time Of Flight Diffraction ultrasonics (TOFD) [1,13,14]. If the propagated waves pass through a medium different from that of the specimen, the reflected waves are disturbed indicating the presence of an inclusion. Ultrasonic Testing enables three-dimensional mapping of the specimen. Inclusion, delamination or debonding are localized in depth with different colors according to the scale used.

This kind of method provides information such as the thickness of the specimen, the presence of an inhomogeneous medium, the modulus of elasticity of the examined specimen, or three-dimensional mapping.

In this study, a 5L64-NW1 multi-element transducer connected to an Omniscan 32: 128 PR (US monitor) is used as the ultrasonic source and the receiver. The wave velocity depends on the materials. And so, for the three tested specimens, the waves have a velocity ranging from 2600 to 5300 m s^{-1} and a frequency of 5 MHz. In order to carry out the experiments, a gel coating was applied (cf. Fig. 3.1) and so the wave ratio transmitted to the sample is much better.

3.2. InfraRed Thermography

InfraRed Thermography is based on brief thermal stress applied to a specimen using a heat source. Thermal waves are propagated as far as the free edges of the specimen. When they reach a different medium, the propagation is disturbed and a thermal gradient is generated in the specimen. Indeed, the two mediums have different emissivity coefficients, which are captured by an IR sensor (InfraRed camera) enabling the emissivity coefficient to be converted to temperature. It is measured on the front of the specimen. Thermal two-dimensional mapping is created and inhomogeneities can be detected [15–18].

This method makes it possible to detect inclusions (particularly when they have very different thermal properties from those of the specimen material), delamination, debonding or crack networks [7].

Halogen lamps are used to provide thermal sollicitation to the sample. They are positioned 300 mm from the front surface of the specimen. The front surface has been chosen as being similar to an in site inspection. The specimen is heated for 10 s, and a 30 s movie is recorded at 50 Hz. The installation of the experimental device is very fast (around 5 min). The camera is a Flir Titanium and its thermal resolution is 20 mK (cf. Fig. 3.2). In order to detect the defect present in the recording, a relative movie has been created. The relative movie consists of withdrawing the first 10 images from the recorded film in order to eliminate the temperature due to the ambient environment. The presence of the defect appears during heating and cooling time. The defect is most visible in the image corresponding to the inflection point of the temperature curve. For the study, infrared images were taken at this point (example for the carbon plate Fig. 3.3).

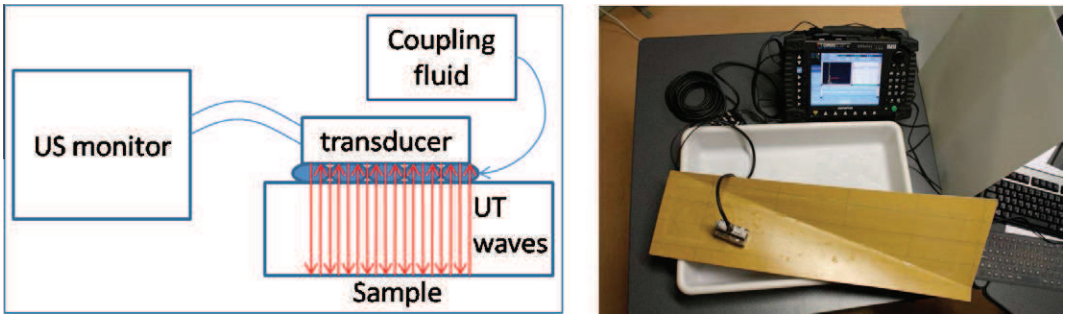

Fig. 3.1. Ultrasonic device.

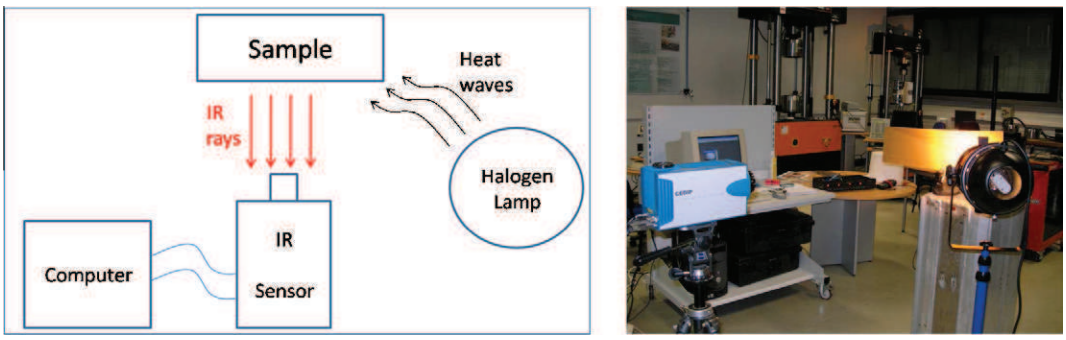

Fig. 3.2. IR Thermography device.

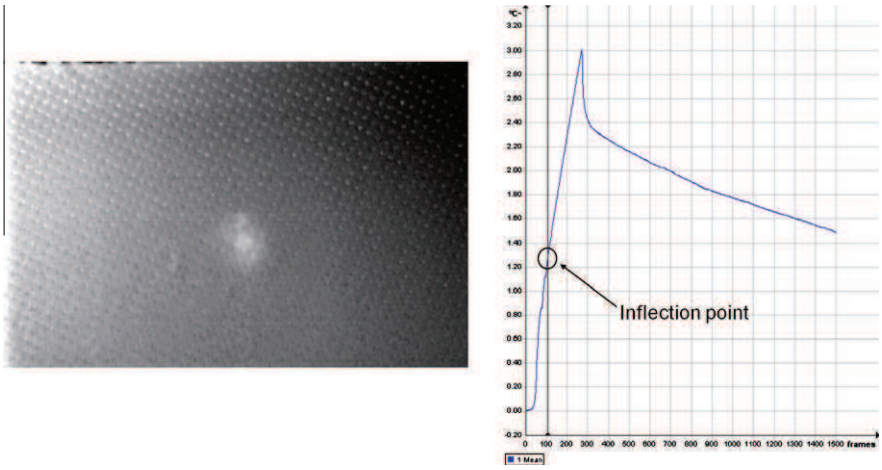

Fig. 3.3. Inflection point.

3.3. Speckle shearing interferometry

The theoretical principle of speckle-shearing interferometry [9] is to split in two the image of the studied object using an optical system such as the Michelson interferometer or double-refractive prism. The system used for this study was composed of a non-pulsed laser, a Michelson interferometer and a CCD camera to record images [19]. The Michelson interferometer enables the shear to be set. A laser beam (light beam) is used to illuminate the object. This beam is split by passing through the Michelson interferometer.

The interference of the two sheared wavefronts results in a speckled pattern. In order to obtain the shearographic image, the strain configuration speckle is compared to the speckle in its initial state. The resulting fringes represent the derivative of the out-plane displacement. This gives direct information about the distortion of the object [20,21]. The object is put under strain using thermal stress.

Shearography mainly enables defects such as disbonding, delamination, wrinkling, porosity, foreign object or impact damage [10].

In this study, the specimen was heated by a paint burner positioned 50 mm away. The heating temperature was 300 °C and was applied for 30 s. The shearographic image was recorded by a CCD camera (cf. Fig. 3.4). As is the case for InfraRed Thermography, setting up the experimental protocol can be done very quickly (around 3 min).

4. Non destructive tests and evaluation

All non destructive tests presented in the previous section were applied to the three specimens studied. To begin with, the results obtained with each method on each specimen were observed, noted and then a synthesis of the different non destructive methods was carried out. All the defects revealed were compared to GVI measurements, in accordance with the standards [22] (cf. Table 1).

4.1. Specimen A

4.1.1. Ultrasonic Testings

The ultrasonic non destructive tests were carried out by contact. However, Specimen A is cylindrical. Therefore the flat multi-element probes used during control could not follow the cylindrical shape of the specimen. There was considerable sound signal loss in the air. Consequently the test produced no result in relation to defects (position and dimension) on Specimen A. The material prevented results being obtained.

Fig. 4.1. Specimen A: carbone/epoxy rod.

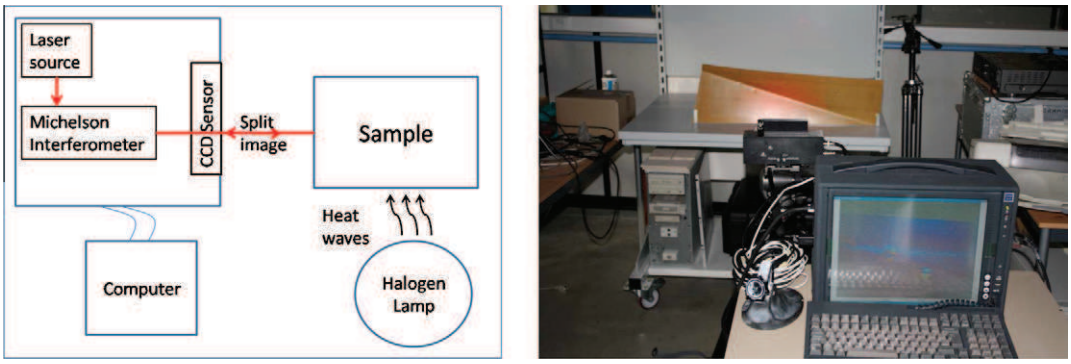

Fig. 3.4. Shearography device.

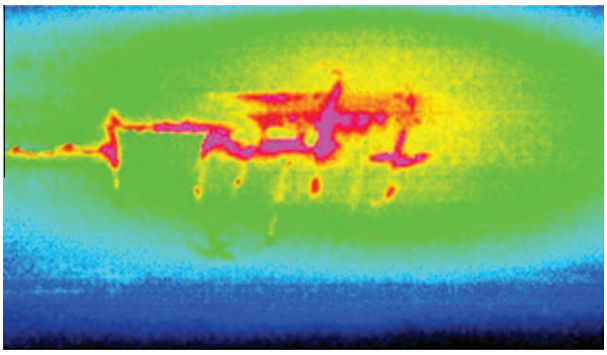

Fig. 4.2. InfraRed Thermography map of Specimen A.

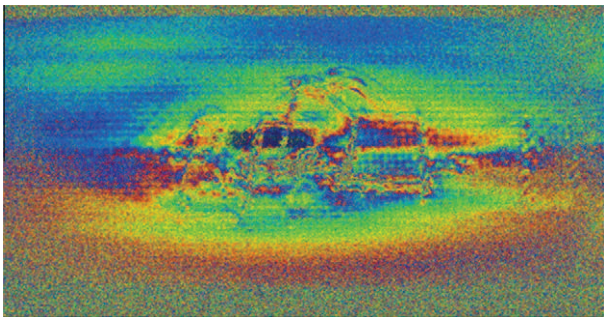

Fig. 4.3. Shearography map of Specimen A.

4.1.2. InfraRed Thermography tests

As mentioned in Section 3.2, the halogen lamps are situated in front of the specimen in order to represent an in site inspection. The specimen surface observed is the damaged surface. In fact, Specimen A being thick and having a hollow circular section, a huge quantity of heat is lost in detecting defects on the rear surface.

The InfraRed Thermography tests made it possible to identify the presence of defects on Specimen A in a very short time, around 30 s (cf. Fig. 4.2). The size of the pixel is calculated from the images. Therefore, the dimensions of the defects can be determined accurately. Indeed, the defect is 97 mm × 20 mm. It is obvious that the results obtained with InfraRed Thermography are similar to GVI measurements (maximum deviation around 10%).

4.1.3. Speckle shearing interferometry tests

The defects on Specimen A were identified quickly by Shearography tests, around 1 min (cf. Fig. 4.3). It is important to note that the images obtained by Shearography are not easily analysed. There were many defects on this specimen and Shearography detected them all. This means that a considerable amount of the information was shown on the image, making it illegible. Nevertheless, it was possible to determine the size of the defects. The range of the defect area is 107 mm × 22.5 mm. The difference between the GVI and the Shearography results represents 9% as regards length and 25% as regards width. This measurement variation is due to the difficult in analysis of the shearographic image.

4.1.4. Comparative analysis

Table 2 summarizes the measurements of the defect for each device.

The results obtained on a cylindrical specimen greatly depend on the equipment available at the test center. Indeed, the defects could not be determined using ultrasonic tests because the multi-element probe was not suitable. The comparative deviation in defect size obtained using Shearography and GVI is greater than that obtained using IR thermography and GVI. Determining the size of the defects accurately would therefore appear more difficult with Shearography than with thermography. In the case of a cylindrical specimen, InfraRed Thermography is the quickest and most suitable method to detect and quantify defect dimensions.

Table 2
Defect measurements of Specimen A.

	Length (mm)	Width (mm)
General Visual Inspection	98	18
Ultrasonic Testing	NaN	NaN
InfraRed Thermography	97	20
Shearography testing	107	22.5

4.2. Specimen B

4.2.1. Ultrasonic tests

Two C-Scan inspections were carried out : one on the front of the specimen and the other one on the back. For the front surface inspection (i.e. the surface on which the lightning impact is located), the defect measured 43.5 mm × 79 mm (cf. Fig. 4.5). On the back, the defect measurements were 38.5 mm × 63.5 mm (cf. Fig. 4.5).

Three reasons may explain the relatively smaller size of the defect on the back:

- firstly, signal loss through the thickness of the specimen,
- secondly, surface coating on the back,
- thirdly, position of the probe focus because the defect is on the surface.

The in-depth position is the same from both front and back. The shape of the defect is similar to that of the GVI defect. The actual size of the defect on the specimen and its UT size are virtually the same (around 5%). From the 2D map, a sectional elevation can be traced showing that the defect is on the surface of the specimen (Fig. 4.6).

Setting up the system and the actual testing took 30 min. At the end of the test, a 2D specimen map was obtained with information on the depth and position of the defect. In relation to the length of the test itself, analysis time was very short. We note that the defect is fully characterized (size and depth).

4.2.2. InfraRed Thermography tests

2D mapping of the specimen and identification of the defects can be obtained using IR thermography tests (cf. Fig. 4.7).

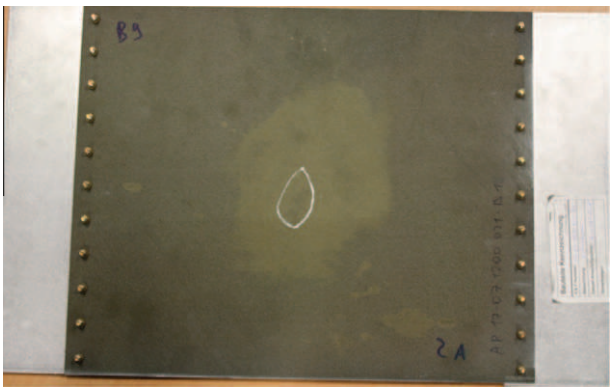

Fig. 4.4. Specimen B: carbone/epoxy plate.

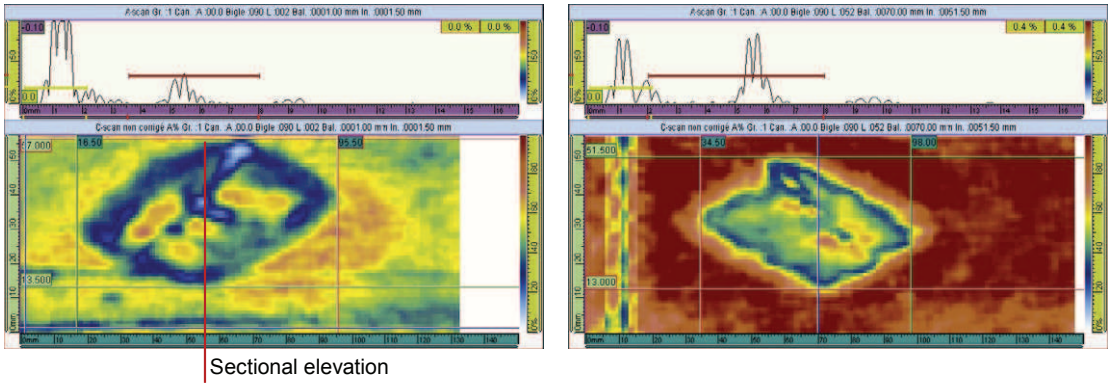

Fig. 4.5. Ultrasonic Testing map of the both faces of Specimen B.

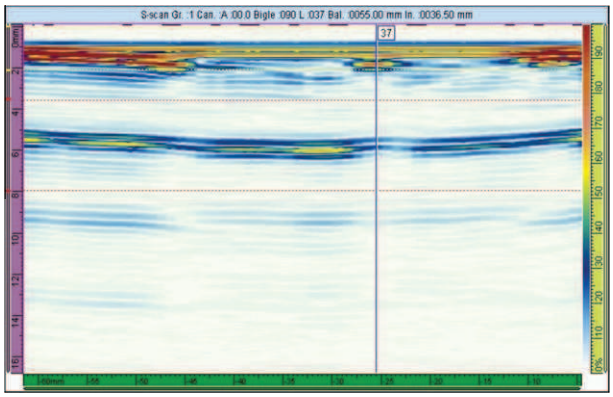

Fig. 4.6. Sectional elevation of the 2D map (S-scan).

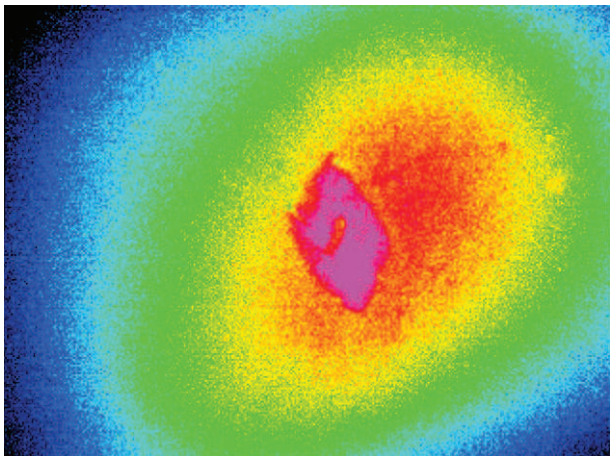

Fig. 4.7. Infrared map of the defect of Specimen B.

The size of the revealed defect is 36 mm length and 60 mm width. Its shape is almost the same as the GVI defect on the damaged surface. The variations between the GVI and the IR thermography measurements are 12% in length and 20% in width.

This method is very quick and results can be obtained in 1 min: 30 s to record and 30 s to analyse the results. InfraRed Thermography can therefore be used as a first step to identify and locate the presence of a defect very quickly. Following that, the size of the defect can be determined more precisely using Ultrasonic Testing.

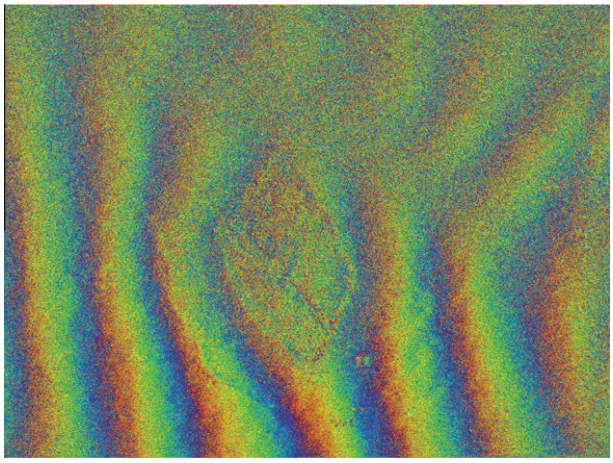

Fig. 4.8. Shearography map of Specimen B.

4.2.3. Speckle shearing interferometry tests

The defects on Specimen B can be identified by Shearography tests in a relatively short time: approximately 1 min (cf. Fig. 4.8). The size of the defect is 37.5 mm × 59.5 mm. The differences between the GVI and the Shearography measurements are 8% as regards length and 21% as regards width. This difference is due to the fact that the shearographic image is a little fuzzy preventing the size of the defect to be measured properly.

4.2.4. Comparative analysis

Table 3 summarizes the measurements of the defect for each device.

For this specimen, the defects were easily detected by all three methods. Qualitatively, the three methods are efficient and the defect shapes are the same. Quantitatively, it depends mainly on the software used, the resolution of the CCD sensor and the accuracy of the measurements. For the three methods, a good estimation of the

Table 3
Defect measurements of Specimen B.

	Length (mm)	Width (mm)
General Visual Inspection	41	75
Ultrasonic Testing		
Frontface	43.5	79
Backface	38.5	63.5
InfraRed Thermography	36	60
Shearography testing	37.5	59.5

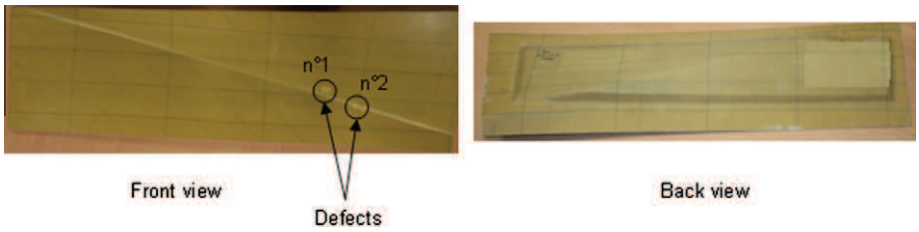

Fig. 4.9. Defects of Specimen C.

defect dimensions was obtained. The best comparative results in relation to the GVI measurements were obtained with UT (5% deviation). Even though a 20% deviation can be observed when UT and IR thermography defect measurements are compared, IR thermography is faster than Ultrasonic Testing. Consequently it would appear judicious to use several non destructive methods to detect and quantify this kind of defect as fast and as accurately as possible.

4.3. Specimen C

For Specimen C, two GVI defects had to be detected. Defect no. 1 was located above geometrical discontinuity and defect no. 2 was located on the angle of this geometrical discontinuity (cf. Fig. 4.9).

4.3.1. Ultrasonic tests

Defect no. 1 was detected by ultrasonic tests (cf. Fig. 4.10). The geometry of the specimen (defect slightly on the angle) made UT measurement difficult. Thus, only the defect length could be determined: 22 mm. The difference between the GVI and the UT measurements of length is 22%. As shown on Fig. 4.10, the defect was located not only on the surface of the specimen but also in depth.

Defect no. 2 was not detected. Checking this impact was impossible because the device (multi-element probe) was not suitable and the folding angle was variable.

4.3.2. InfraRed Thermography tests

Both defects were determined by InfraRed Thermography within a few seconds (cf. Fig. 4.11). Defect no. 1 is 15 mm × 10 mm. The difference between the GVI and the IR thermography measurements is 15% in length and 11% in width.

The dimensions of the defect no. 2 are 22 mm length and 8.5 mm width. The differences between the GVI measurements and the IR thermography measurements are equal to 22% as regards length and 6% as regards width. The considerable deviation in length can almost certainly be attributed to the focusing problem due to the geometrical discontinuity.

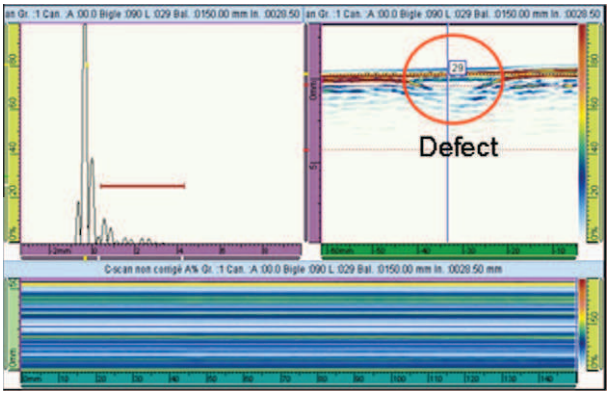

Fig. 4.10. Ultrasonic map on Specimen C.

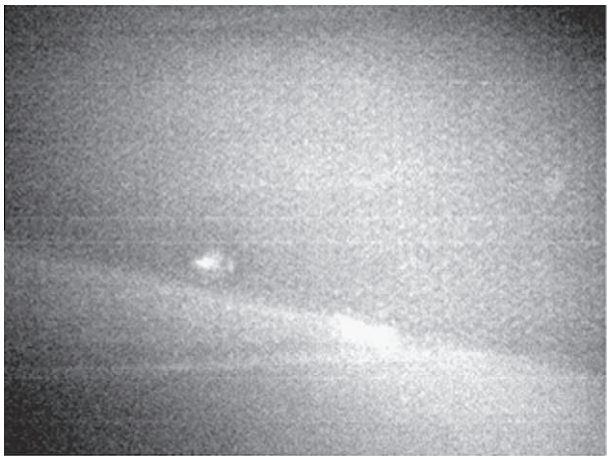

Fig. 4.11. InfraRed Thermography map of Specimen C.

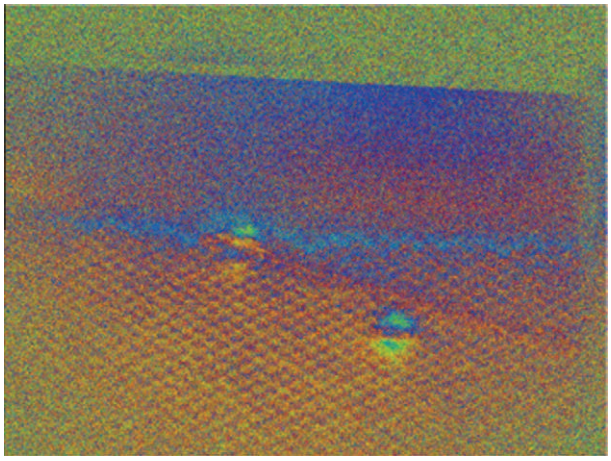

Fig. 4.12. Shearography map of Specimen C.

Table 4
Defects measurements of Specimen C.

	Length (mm)	Width (mm)
General Visual Inspection		
No. 1	13	9
No. 2	18	8
Ultrasonic Testing		
No. 1	22	22
No. 2	NaN	NaN
InfraRed Thermography		
No. 1	15	10
No. 2	22	8.5
Shearography testing		
No. 1	15	15
No. 2	15	8

Table 5
Characteristics of UT, IR thermography and Shearography.

	Ultrasonic Testing	InfraRed Thermography	Shearography
Inspection	Contact	Non-contact (optical)	Non-contact (optical)
Measurement	Mechanical vibration	Thermal radiation	Mechanical strain
Loading	Acoustic wave	Long heating pulse, transient pulse excitation, and induction heating	Vacuum pressure, acoustic wave and thermal excitation
Output	Amplitude and time of flight of ultrasonic wave	Sequence of thermal images	Speckle patterns
Analysis	Qualitative and quantitative analysis through the ultrasonic amplitude	Qualitative and quantitative analysis through temperature distribution	Qualitative and quantitative analysis through density of fringe pattern
Parameter influencing the measure	Material attenuation coefficient	Materials surface thermal properties (emissivity)	Rigid-body movement
Advantages	Precise measurements and determination defect depth	Fast time of control, good estimation of defect dimensions and control adapted of all the geometries types	Fast time of control and control adapted of all the geometries types
Disadvantages	Slow time of control and choice of a specific probe for each controlled specimen	Defect depth not directly determined	Unrepeatability of the thermal excitation and defect depth not directly evaluated
Limitations	Impacts in an angle and strongly evolutionary geometries	Important specimen thickness	Coupling between laser power and images size

4.3.3. Speckle shearing interferometry tests

The defects on Specimen C were identified by Shearography tests within a relatively short time of around 1 min (cf. Fig. 4.12). The image is very clear and the defects are perfectly visible. Shearography therefore seems well suited to the detection of defects in this type of specimen.

Defect no. 1 is 15 mm × 15 mm. The variation between the GVI and the Shearography measurements is 17% in length and 87.5% in width. However, on the shearographic image, the defect appears circular which is not surprising for an impact defect; and so in this case, the GVI measurement may be incorrect.

Defect no. 2 is 15 mm × 8 mm. The variation between the GVI and the Shearography measurements is 16% in length and 11% in width.

4.3.4. Comparative analysis

Table 4 summarizes the measurements of the both defects for each device.

For a specimen such as this with a variable radius of curvature, it is impossible to check the defect in the plies using Ultrasonic Testing. This is contrary to the case of Specimen A where a specific single transducer enabled UT to be carried out. For this reason, in this experiment, defect no. 2 could not be detected with Ultrasonic Testing. UT is very restricted compared to other equipment.

With Shearography and InfraRed Thermography tests, defects were determined very quickly. However, the images obtained with Shearography are much clearer and sharper than those obtained with IR thermography. Thus, for this specimen, the most suitable method appear to be Shearography.

4.4. Methods comparison

InfraRed Thermography and Shearography detected all the defects present on the three specific specimens contrary to Ultrasonic Testing. Therefore, each technique has its own particular limitations. Table 5 presents a summary of the characteristics for each technique.

The major difference between the three Non Destructive Testing methods is the time taken to set up the experimental device and to analyse the results. In fact, Ultrasonic Testing takes a long time (around 30 min) compared to InfraRed Thermography (30 s) or Shearography (1 min). The time required to set up the experimental protocol for Ultrasonic Testing depends on the size and geometry of the specimen tested. Whatever the non destructive method used, the results obtained largely depend on the equipment, its resolution, its accuracy and its software. The multi-element probe used for the non destructive Ultrasonic Testing cannot produce results on Specimens A and C. The software used for ultrasonic, InfraRed Thermography and Shearography testing enables the results to be analysed very easily.

The advantage of the optical methods compared to those of Ultrasonic Testing is the independance of measurements as regards geometrical discontinuities.

This study has shown the advantages of each technique in relation to the three given specimens:

- UT seems to be the best adapted method for small-sized flat specimens like Specimen B.
- InfraRed Thermography seems to be the best method for large-sized specimens with a constant geometry like Specimen A.
- Shearography seems to be the best adapted method for large-sized specimens with a variable geometry like Specimen C.

On a more general level, all three techniques can be used with various kinds of material and in various types of environment.

5. Conclusion

The application of Non Destructive Testing methods to various specific composite specimens was the subject of this study. The following conclusions can be drawn from the experimental results obtained, in terms of both detection and size of the defects and rapidity of the methods themselves:

- The defects were detected without fail by the optical methods but only sometimes by Ultrasonic Testing. In order to detect all the flaws with Ultrasonic Testing, a wide range of probes would be useful. The relative cost would increase with the considerable range of suitable probes required.
- The advantage of Ultrasonic Testing compared to that of the optical methods is the determination of the depth of the defect and the degree of accuracy obtained.
- All three techniques can be used with various kinds of material and in various types of environment.

- The three methods have their own advantages and limitations as described in Table 5. It appears quite clearly that all the non destructive methods are complementary. Therefore, in order to obtain all the relevant information concerning the defects both quickly and precisely, it is important to use a combination of several non destructive methods.

It would be interesting and informative to analyse results obtained by Shearography in order to determine the size of the defects, and to develop the theoretical equations in thermography to evaluate their depth.

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References

[1] Burke SK, McKcousland S, Scala CM. Nondestructive characterization of advanced composite materials. Mater Forum 1994;18:85–109.
[2] Djordjevic BB. Advanced ultrasonic probes for scanning of large structures. Ultrasonic International; 1993.
[3] Djordjevic BB, Reis H. Sensors for materials characterization, processing, and manufacturing. NDE 1998;1.
[4] Leendertz JA, Butters JN. An image shearing speckle pattern interferometer for measuring bending moments. J Phys E 1973;6:1107.
[5] Lambert A, Rivenez J, Wache G. Les controles non destructifs: généralité, CETIM; 1994.
[6] Ranc N. Couplage thermomécanique. Techniques de l'ingénieur AF 5 042, traité Sciences fondamentales; 2000.
[7] Hay B, Filtz JR, Batsale JC. Mesure de la diffusivité thermique par la méthode flash. Techniques de l'ingénieur R 2 955. Traité mesures et contrôles; 2000.
[8] Pajani D. Thermographie: principes et mesures. Techniques de l'ingénieur R 2 740. Traité mesures et contrôles; 2000.
[9] Smigielski P. Interférométrie de speckle. Techniques de l'ingénieur R 6 331. Traité mesures et contrôles; 2000.
[10] Hung YY. Applications of digital shearography for testing of composite structures. Compos Part B: Eng 1999;30(7):765–73.
[11] Robert E, Green Jr. Non-contact ultrasonic techniques. Ultrasonics 2004;42:9–16.
[12] Birk AS, Green RE. Nondestructive testing handbook, 2nd ed. Ultrasonic testing, vol. 7; 1991.
[13] Henneke EG. Ultrasonic nondestructive evaluation of advanced composites. Non-Destruct Test Fiber-Reinf Plast Compos 1990;2:55–159.
[14] Mouritz AP. Fatigue in Composites. B. Harris; 2003.
[15] Heller M, Williams JF, Dunn S, Jones R. Thermomechanical analysis of composite specimens. Compos Struct 1989;11:309–24.
[16] Chrysochoos A. Infrared thermography: a potential tool for analysing the material behaviour. Méc Ind 2002;3:3–14.
[17] Pastor ML, Pescay C, Garnier C. Comparison of two nondestructive tests in carbon/epoxy composites. In: ICCM17; 2009.
[18] Pastor ML, Balandraud X, Grédiac M, Robert JL. Applying infrared thermography to study the heating of 2024-T3 aluminium specimens under fatigue loading. Infrared Phys Technol 2008;51(6):505–15.
[19] Hung YY, Ho HP. Shearography: an optical measurement technique and applications. Mater Sci Eng – R: Reports 2005;49(3):61–87.
[20] Huang YH, Ng SP, Liu L, Li CL, Chen YS, Hung YY. NDT&E using shearography with impulsive thermal stressing and clustering phase extraction. Opt Laser Eng 2009;47(7-8):774–81.
[21] Ruzek R, Lohonka R, Jironc J. Ultrasonic C-scan and shearography NDI techniques evaluation of impact defects identification. NDT&E Int 2006;39(2):132–42.
[22] AFNOR. En 1330: Essais non destructifs; 2010.