Optical and Infrared Vision Non-Destructive Techniques: Integration as a means for the Defects Detection on Impacted Composite Materials

A. Bendada[1], S. Sfarra[2*], M. Genest[3], D. Paoletti[2], S. Rott[1], E. Talmy[1], C. Ibarra-Castanedo[1] and X. Maldague[1]

[1] Computer Vision and Systems Laboratory, Department of Electrical and Computer Engineering, Laval University, Quebec City, G1K 7P4, Canada
[2] Las.E.R. Laboratory, Department of Mechanical Management and Energy Engineering (DIMEG), University of L'Aquila, I-67100, Monteluco di Roio, L'Aquila (AQ), Italy
[3] Institute for Aerospace Research (IAR), National Research Council Canada (NRC), 1200 Montreal Road, Bldg. M-14, Room 130, Ottawa, ON, K1A 0R6, Canada

ABSTRACT. *Infrared (IR) vision has evolved in recent years from being an emerging nondestructive testing (NDT) technique to a viable approach for both aerospace manufacturing and in-service inspections. In this paper, infrared vision was applied in different spectral bands for the inspection of impacted composite materials: (1) near and short-wave infrared reflectography and transmittography, and (2) mid-wave active infrared thermography. Furthermore, optical methods, namely digital speckle photography (DSP) and holographic interferometry (HI), were used as well to highlight the damage due to the impact on the samples. In fact, experiments were carried out on two impacted panels made of aramid-phenolic composite. Some techniques provided more straightforward detection capabilities than others for different defect types. Firstly, short-wave infrared reflectography presented a good indication about the degree of the damaged area at the surface whilst near infrared transmittography provided information about the internal damage and fibre distribution. Secondly, when using mid-wave infrared thermography, advanced signal processing techniques such as principal component thermography (PCT), pulsed phase thermography (PPT), and high order statistics (HOS), were employed in order to improve surface and sub-surface damage detection on pulsed thermography (PT) sequences with good results. Finally holographic interferometry was very useful for crack detection providing complementary information to transmittography and thermography. These observations lead us to the conclusion that, when combined, these techniques could provide a robust and reliable integrated inspection system.*

INTRODUCTION

During the life of a structure, impacts by foreign objects can be expected to occur during manufacturing, service, and maintenance operations. An example of in-service impact occurs during aircraft takeoffs and landings, when stones and other small debris from the runway are propelled at high velocities by the tires. During the manufacturing process or during maintenance, tools can be dropped on the structure. In this case, impact velocities are small but the mass of the projectile is larger. Laminated composite structures, as in our case, are more affected by impact damage than a similar metallic structure. In composite structures, impacts create internal damage that often cannot be detected by visual inspection. This internal damage can cause severe reductions in strength and can grow under load. Therefore, the effects of foreign object impacts on composite structures must be understood, and proper measures should be taken in the design process to account for these expected events. Concerns about the effect of impacts on the performance of composite structures have been a limiting factor in the wide spread use of composite materials. For this reasons, the problem of impact has received considerable attention in the literature [1], and therefore in this work.

The use of Non Destructive Testing (NDT) techniques during aircraft maintenance operations is increasing in the last years as well as the tools to perform these inspections are widening their field of application. NDT are currently used to verify structural integrity of components in case of special events mentioned above, and to assess and monitoring quality and effectiveness of repairs and for rework.

Infrared Vision is an interesting approach that has the advantages of being non-contact, fast, and relatively inexpensive [2]. Recently, Near InfraRed (NIR) and Short-Wave (SWIR) reflectography and transmittography have been proposed for the inspection of semitransparent composites materials such as glass fiber [3]. In our case, IR Thermography in the Mid-Wave IR has shown interesting complementarities to NIR/SWIR reflectography in the study of two impacted panels made of aramid-phenolic composite. Another interesting NDT approach in the optical field is both the use of Holographic Interferometry that is judged capable of yielding systematic process control data; it is noted that a slight temperature elevation allows such defects as composite fiber breaks, delaminations and disbonds to be visualized [4], [5], that the use of Digital Speckle Photography for the identification of the impacted area and fibers distribution, if combined with NIR transmittogram [6].

The main objective of this work is to demonstrate that optical and infrared vision NDT techniques can work together in order to define with more accurately the main defects that occur on Kevlar laminates after an impact. NIR, IRT, DSP and HI results of the two samples are presented to illustrate the applications of this combined assessment.

EXPERIMENTAL CONFIGURATIONS

Pulsed Thermography

Pulsed thermography (PT) is one of the most popular thermal stimulation methods in active thermography [7], [8]. One reason for this is the quickness of the inspection relying on a short thermal stimulation pulse, with duration going from a few milliseconds for high conductivity material inspection (such as metal) to a few second for low conductivity specimens (such as plastics). In addition, the brief heating prevents damage to the component [9]. For sake of simplicity, only a brief review of the technique is provided herein. Interested readers should consult the provided references.

Non-Thermal Infrared Vision

Non-thernal infrared vision is based on the detection of near (NIR, from ~0.75 to 1μm) or short-wave (SWIR, from ~1 to 2.5 μm) infrared radiation reflected from (reflectography) or transmitted through (transmittography) the object of interest. Proper selection of a continuous and uniform active illumination source is a critical part of a non-thermal inspection system. For instance, incandescent lamps provide a wide electromagnetic (EM) spectrum, going from the ultraviolet (UV, from 0.01 to 0.35 μm) to the very long wave infrared (VLWIR, from 14 to 1000 μm). Fortunately, a vast part of the radiation from such a source is in the visible and the NIR and WWIR spectral bands, and therefore, it can be used as an illumination source. On the contrary, the EM spectrum of fluorescent lamps is narrower and with a few distinctive high intensity peaks mostly in the visible spectrum [10]. Radiation in the NIR/SWIR spectrum is very limited and can hardly be used as a reliable illumination source. Light emitting diodes (LED) are an example of a very interesting illumination source since they provide a narrow spectrum at specific wavelengths, from UV to VLWIR including NIR/SWIR [11]. The radiation source can be combined with the utilization of narrow-band filters to further improve contrast [12].

Holographic Interferometry

The general principle of holographic non-destructive testing [13], [14], is widely known: the component under test is subjected to some kind of stressing which is uniformly distributed across its surface and results in a mechanical state of stress. This state of stress produces deformations at the surface of the component under test. Almost any kind of defect situated close enough to the surface acts as a stress concentrator and locally modifies the state of deformation. Using one of the well-established holographic interferometric techniques (double-exposure, real-time, sandwich holography), one can then visualize the deformation state in the form of interference fringes superimposed on the object's surface. The local disturbances produced by the defects are easily identified as anomalies in the fringe pattern [15]. The number and holographic appearance of detected defects depend upon the object's characteristics and the testing technique. The testing technique is characterized by a particular set-up and involves a particular association between the stressing method and the interferometric technique being used.

Interested readers can consult the experimental set-up reported in [5] also applied in this work. A 500 W lamp has been used for 10 s for thermal stressing.

Digital Speckle Photography

Speckle photography is a technique characterized by a relatively low complexity in the hardware. Digital Speckle Photography (DSP), sometimes referred to as Electronic Speckle Photography (ESP), as well established technique based on the calculation of the geometrical displacement of a speckle pattern [16], [17]. One of the key features of digital speckle photography development and success is the possibility to perform computerized image analysis [17], [18]. In the cross-correlation approach [17], sub-images are extracted from the reference image and the deformed image; then the correlation pattern is obtained using suitable correlation filters. The peak location in the correlation surface gives the relative displacement between the two sub-images. As a rule of thumb one can think that the sharper the correlation peak, the more reliable the estimation of its position. This is not completely true, because also noise tolerance is very important. Furthermore, the coarse structure and finite size of the photosensor limit the accuracy in determining the peak position [19]. This problem can be alleviated by sub-pixel analysis [16], [19]. In literature, DSP is mainly used to detect in-plane displacements and their gradient components [20], [21]; it can be coupled to ESPI for 3D displacement field measurements [22] as well as used to detect environmental degradation on ceramic superconductors [23].

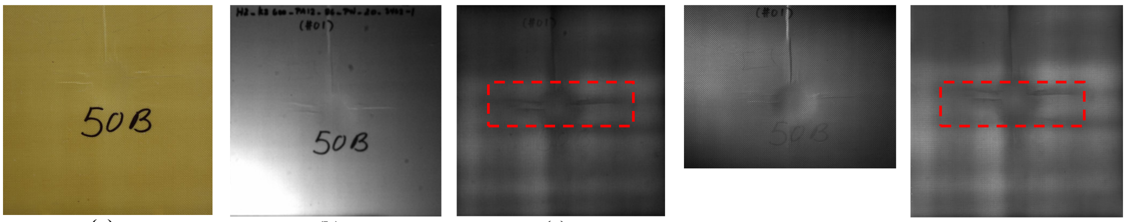
INFRARED AND OPTICAL PROCESSING TECHNIQUES

In IRT, several processing techniques exist, from a basic cold image subtraction to more advanced techniques such as principal components or higher order statistics. The more relevant to the present study are: ***pulsed phase thermography (PPT)*** [24], [25] which transforms data from the time domain to the frequency domain in order to obtain phase delay images or *phasegrams* that have an improved defect contrast; ***principal component thermography (PCT)*** [26], which reorganizes data into new components that take into account the main spatiotemporal variances of the sequence; and ***higher order statistics (HOS)*** [27-29], which calculates the higher order centralized moments (3^{rd} or *skewness*, 4^{th} or *kurtosis*, or n^{th} *order moment*) of the temporal temperature profiles producing single images summarizing all the relevant information about the original sequence. In HI, the most suitable technique for the type of material investigated was found to be the ***double-exposure (DE)***. In DE-HI two holograms are recorded on the same plate, with each one capturing the object in a different state separated by a fixed time interval. This technique is less critical than Real Time (RT) holography, because the two interfering waves are always reconstructed in exact register, and the fringes have a good contrast. However, double exposure HI is not dynamic and information on intermediate states of the test object is lost [14]. In DSP, a very simple way to perform data processing by the cross-correlation approach is given by the possibility of using existing Particle Image Velocimetry (PIV) software with only minor modifications. In our work, pattern displacements are evaluated using correlation algorithms based on the toolbox ***MatPIV 1.6.1*** [30]. This package has the distinctive feature of being free (Open Source) and of working in the MATLAB environment, thus sharing its capabilities of technical calculations and data visualizations. The interrogated images are divided into smaller regions, also known as sub-windows, interrogation-windows or interrogation-regions. Each sub-window in the first image is compared with the corresponding sub-window in the second image. For every possible overlap of the sub-windows, the sum of the squared difference between them is calculated looking for the position where the sub-windows are the "least unlike" [30]. Expanding the squared difference, it can be considered that only one term, the so-called cross-correlation, actually deals with both our images. Cross-correlation is traditionally used in PIV and is the basis of many of the different algorithms performed in MatPIV since it can be calculated using Fast Fourier transforms (FFTs) and therefore can be executed faster. The options available in MatPIV are reported in [30].

COMPARATIVE RESULTS

Two cameras were used for Near/Shortwave Infrared Inspection. First the Mutech© camera operating in Near Infrared spectrum was used. The specimens (50B and 51B) were inspected from the front side, in reflection and transmission modes; some defects due to the impact could not be detected under visible spectrum, but they could be detected under near infrared illumination because of the Kevlar semi-transparency in this spectrum. A camera operating in shortwave infrared spectrum designed by Goodrich© was also used.

Fig. 1 shows Near/Shortwave results from the 50B Kevlar model. The photograph in Fig. 1a show a subtle indication of the impact in the front surface, whilst both the NIR reflectogram in Fig. 1b that in Figure 1d, and the NIR transmittograms in Figs. 1c and 1e show more clearly the damage caused by the impact. The reflectograms provides a good indication about the extent of the damaged area and the transmittogram provides information about the internal fibre distribution (some areas appear lighter than others).



(a) (b) (c) (d) (e)

Figure 1. 50B Kevlar impacted specimen inspected with a CCD camera. *Front side inspection*: (a) photograph, (b) NIR reflectogram using filter (Camera Mutech), (c) NIR transmittogram using a wide spectrum source (Camera Mutech), (d) NIR reflectogram using a 940 nm source (camera Goodrich), (e) NIR transmittogram using a wide spectrum source (Camera Goodrich)

During the InfraRed Thermographic inspection, acquisition was carried out using a FLIR Phoenix Camera (3 to 5 μm). Two high-power flashes (Balcar FX 60) were used as heating sources in optical pulsed thermography. Advanced processing techniques has been applied on the raw sequence as well in order to improve defect detectability. Defects in the images reported in Figs. 2a-c, are visible with more or less contrast depending on the processing technique being used. In fact, PPT phasegram and PCT-EOF3 (Fig. 2a-b) results, seem to reveal adequately the internal fibre distribution, confirming the results coming from NIR transmittograms, while HOS, 5th moment reconstructed image show clearly the impacted zone, as well as the NIR reflectograms.

On the other hand, both HI (Fig. 2d) that DSP methods (Fig. 2e – red rectangle) were very useful, providing complementary information to IRT: the first for cracks (yellow ellipses) and detachments (blue circles) detection, the second for establish the shape of the delaminated area that follows the fibers distribution.

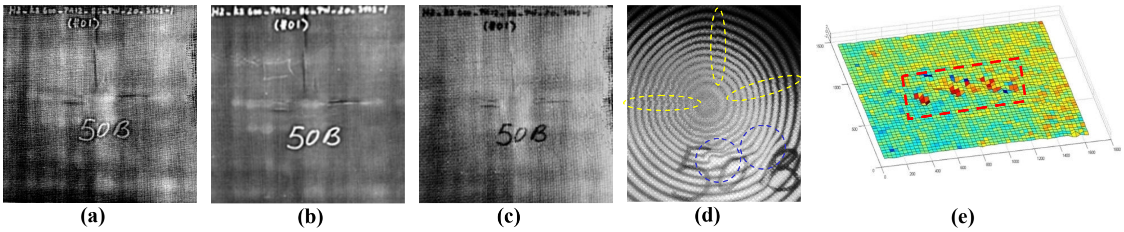


Figure 2. 50B Kevlar impacted specimen. <u>*Front side inspection*</u>: (a) PPT phasegram f=0.22 Hz, (b) 3rd empirical orthogonal function by PCT, (c) HOS, 5th moment reconstructed image, (d) HI-DE result (t_{exp}=1s), (e) DSP, Surf result using MatPIV 1.6.1

During the optical inspection, the interferograms and specklegrams were acquired using a laser, with a fundamental wavelength of 532 nm, vertical polarization and a specified power of 250 mW. A test with DSP technique was conducted using the same lamp mentioned for HI technique, positioned in reflection mode, and adopting also the same time heating and time interval (t_i=5s) between the exposures or image capture.

Given the highly dissipative nature of the material, one frame every second was recorded in order to avoid the loss of "information-strain" between one frame to another; however, for both specimens the best experimental results reported in Figs. 2e-3e, were obtained by comparing the frames at 5 s and 10 s, from the lamp switching off.

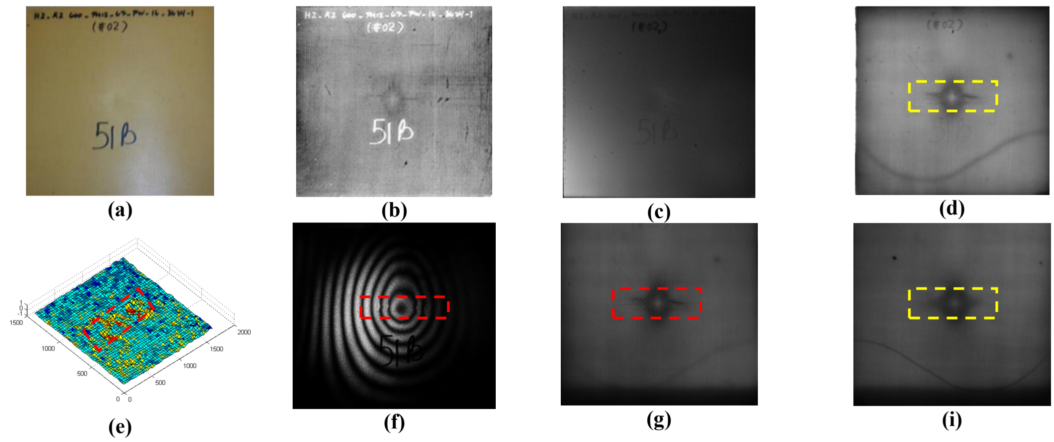


Figure 3. 51B Kevlar impacted specimen. <u>*Front side inspection*</u>: (a) photograph, (b) 5th empirical orthogonal function by PCT, (c) NIR reflectogram using filter (Camera Mutech), (d) NIR transmittogram using a filter (Camera Mutech), (e) DSP, Surf result using MatPIV 1.6.1, (f) HI-DE result (t_{exp}=1s), (g) NIR transmittogram using a wide spectrum source (Camera Goodrich), <u>*Back side inspection*</u>*:* (i) NIR transmittogram using a wide spectrum source (Camera Goodrich)

Comparing the results of the 50B (Figs. 1-2) and 51B (Fig. 3) specimens, we can infer that the first was subjected to a greater impact; this assertion is explained by the presence of *satellite defects* around the indented area. The second, is characterized to the identification of the geometry indentator (Fig. 3c) and its horizontal delaminations (red rectangles - Figs. 3e-g). In this case, PCT technique (Fig. 3b) has not identified the fibers distribution, but joint with NIR transmittograms acquired in front or to the back side (yellow ellipses - Fig. 3d,i), confirm that Kevlar fiber-reinforced composites show poor interfacial adhesion between the Kevlar fiber and the matrix resin, due to the low surface energy and chemically intert surface of the fiber [31].

CONCLUSIONS

The observations reported above, lead us to the conclusion that, when combined, optical and infrared vision NDT techniques provide a robust and reliable integrated inspection system in the defects identification after impact in Kevlar composite materials.

REFERENCES

1. Abrate, S. (2005) *Impact in Composite Structures*, Cambridge University Press, UK.
2. Genest, M., Fahr, A. (2006). In: *Design, Manufacturing and Applications of Composites: Proceedings of the Sixth Joint Canada-Japan Workshop on Composites,* pp. 399-406, DEStech Publications, Inc., U.S.A.
3. Shoja Ghiass, R., Duan, Y., Peycheva, K. and Maldague, X. (2011) *Inspection of Glass Fiber Reinforced Plastic (GFRP) using Near/Shortwave Infrared and Ultrasound/Optical Excitation Thermography*, International Workshop Smart Materials, Structures & NDT in Aerospace, Quebec, Canada.
4. De Smet, M.A. (1986) *Optic Eng Measurement* **599**, 46-52.
5. Sfarra, S., Ibarra-Castanedo, C., Bendada, A., Maldague, X., Ambrosini, D. and Paoletti, D. (2010) *Comparative study for the nondestructive testing of advanced ceramic materials by infrared thermography and holographic interferometry*, Thermosense XXXII, Dinwiddie, R.B. (Ed.), Proc. SPIE 7661-766110Q-1, U.S.A.
6. Ebeid, A., Rott, S., Talmy, E., Ibarra-Castanedo, C., Bendada, A. and Maldague, X. (2010) *Near Infrared Imaging for Multi-Polar Civilian Applications*, 10th International Conference on Quantitative InfraRed Thermography, Quebec, Canada.
7. Maldague, X.. (Technical Ed.), Moore, P.O. (Ed.) (2001) *Nondestructive Handbook, Infrared and Thermal Testing* 3, 3rd edition, ASNT Press, Ohio.
8. Maldague, X. (2001) *Theory and Practice of Infrared Technology for Nondestructive Testing*, John Wiley & Sons, N.Y.
9. Ibarra-Castanedo, C., Avdelidis, N.P., Grenier, M., Maldague, X. and Bendada, A. (2010) *Active Thermography Signal Processing Techniques for Defect Detection and Characterization on Composite Materials*, Thermosense XXXII, Dinwiddie, R.B. (Ed.), Proc. SPIE 7661, 76610O, U.S.A.

10. Fluorescent lamp. 18 October 2010, 02:14 UTC. In *Wikipedia*: The free encyclopedia. Wikimedia foundation Inc. Encyclopedia on-line. Available from http://en.wikipedia.org/wiki/fluorescent_lamp. Internet. Retrieved 14 January 2011.
11. Light-emitting diode. 29 October 2010, 02:14 UTC. In *Wikipedia*: The free encyclopedia. Wikimedia foundation Inc. Encyclopedia on-line. Available from http://en.wikipedia.org/wiki/Led. Internet. Retrieved 14 January 2011.
12. Ibarra-Castanedo, C., Bendada, A. and Maldague X. (2011) *Infrared Vision Applications for the Nondestructive Testing of Materials*, 5th Pan American Conference for NDT, Cancun, Mexico.
13. Erf, K. (1974) *Holographic Non-destructive Testing*, Academic Press, N.Y.
14. Vest, C. (1979) *Holographic Interferometry*, Wiley, N.Y.
15. Borza, D.N. (1998) *Composites Part B* **29B**, 497-504.
16. Fomin, N.A. (1998) *Speckle Photography for Fluid Mechanics Measurements*, Springer, Berlin.
17. Sjödahl, M. (2001) In: *Digital Speckle Pattern Interferometry and Related Techniques*, pp. 289-336, Rastogi, P.K. (Ed.) Wiley & Sons, Chichester.
18. Schirripa Spagnolo, G., Paoletti, D., Ambrosini, D. (1999) *Opt. Comm.* **169**, 51.
19. Sjödahl, M. (1997) *Appl. Opt.* **36**, 2875.
20. Hinsch, K.D., Gülker, G., Hinrichs, H., Joost, H. (2005) In: *Laser in the conservation of artworks*, p. 459, Dickmann, K., Fotakis, C., Asmus, J.F. (Eds.), Springer-Verlag, Berlin.
21. Groves, R.M., Fu, S., James, S.W., Tatam, R.P. (2005) *Opt. Eng.* **44**, 025602.
22. Bhaduri, B., Tay, C.J., Quan, C., Niu, H., Sjödahl, M. (2011) *Opt. Comm.* **284**, 2437.
23. Recuero, S., Bonab, M.T., Andrés, N., *et al.* (2008) *J. Europ. Ceram. Soc.* **28**, 2239.
24. Maldague, X.P., Marinetti, S. (1996) *J. Appl. Phys.* **79**, 2694-2698.
25. Ibarra-Castanedo, C., Maldague, X. (2004) *QIRT J.* **1**, 47-70.
26. Rajic, N. (2002) *Compos. Struct.* **58**, 521-528.
27. Madruga, F.J., Ibarra-Castanedo, C., Conde, O.M., Maldague, X.P. and Lopez-Higuera, J.M. (2009) *Enhanced contrast detection of subsurface defects by pulsed infrared thermography based on the fourth order statistic moment, kurtosis*, Thermosense XXXI, Dinwiddie, R.B. (Ed.), Proc. SPIE 7299, 72990U, U.S.A.
28. Madruga, F.J., Ibarra-Castanedo, C., Conde, O.M., Lopez-Higuera, J.M. and Maldague, X.P. (2008) *Automatic data processing based on the skewness statistic parameter for subsurface defect detection by active infrared thermography*, 9th International Conference on Quantitative InfraRed Thermography, Krakow, Poland.
29. Ibarra-Castanedo, C., Avdelidis, N.P., Grenier, M., Maldague, X.P. and Bendada, A. (2010) *Active Signal Processing Techniques for Defect Detection and Characterization on Composite Materials*, Thermosense XXXII, Dinwiddie, R.B. and Morteza Safai (Eds.), Proc. SPIE 7661-24, U.S.A.
30. Sveen J.K. (2004) *The MatPIV Home*, accessed September 26, 2011: http://ww.math.uio.no/~jks/matpiv
31. Park, S.J., Seo, M.K., Ma, T.J. and Lee, D.R. (2002) *Journal of Colloid and Interface Science* **252**, 249-255.