ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 38 (2015) 129 – 136

www.elsevier.com/locate/procedia

The Fourth International Conference on Through-life Engineering Services

Review of Non-destructive Testing (NDT) Techniques and their applicability to thick walled composites

MR Jolly*, A. Prabhakar, B. Sturzu, K. Hollstein, R.Singh, S. Thomas, P. Foote & A. Shaw

School of Aerospace, Transport and Manufacturing, Cranfield University, Bedfordshire, United Kingdom

* Corresponding author. Tel.: +44 1234 750111 x5623; E-mail address: m.r.jolly@cranfield.ac.uk

Abstract

A tier 1 automotive supplier has developed a novel and unique kinetic energy recovery storage system for both retro-fitting and OEM application for public transport systems where periodic stop start behaviour is paramount. A major component of the system is a composite flywheel spinning at up to 36,000 rpm (600 Hz). Material soundness is an essential requirement of the flywheel to ensure failure does not occur. The component is particularly thick for a composite being up to 30 mm cross section in some places. The geometry, scale and material make-up pose some challenges for conventional NDT systems. Damage can arise in composite materials during material processing, fabrication of the component or in-service activities among which delamination, cracks and porosity are the most common defects. A number of non-destructive testing (NDT) techniques are effective in testing components for defects without damaging the component. NDT techniques like Ultrasonic Testing, X-Ray, Radiography, Thermography, Eddy current and Acoustic Emission are current techniques for various testing applications. Each of these techniques uses different principles to look into the material for defects. However, the geometry, physical and material properties of the component being tested are important factors in the applicability of a technique. This paper reviews these NDT techniques and compares them in terms of characteristics and applicability to composite parts.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.

Keywords: Carbon composites; thick walled; Non-destructive testing; CFRP; Flywheel; Ultrasonic testing; Thermography; Computed tomography

Introduction

The core of the hybrid system is the composite rotor, which provides a highly efficient energy storage capability which is both cheaper and lighter than traditional batteries. Through motorsport development, the manufacturer has developed a system that can deliver high, continuously cycling power output over an extended operating life, which far exceeds that of current, chemical battery based hybrid applications.

Alternative non-destructive verification techniques for the filament wound carbon composite components utilize non-destructive CT scanning inspection of every safety critical component. The supplier is targeting a dramatic increase in production volumes by mid-2020 and cost reduction activities are paramount to the success of producing high volume. There are a number of NDT techniques which might be appropriate for thick-walled carbon composite components.

The aim of this paper is to evaluate a highly reliable and cost effective NDT technique for the thick walled carbon fiber component that can detect delamination, cracks and other defects and can be applied in series production at an acceptable cost point.

The component under consideration is an integral part of the flywheel. It is cylindrical in shape and is made out of CFRP intermediate modulus and approximately 30 mm thick (see figure 1).

The cylinder is manufactured by filament winding with an outer diameter of about 350 mm and a height of 119 mm.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.
doi:10.1016/j.procir.2015.07.043

Fig. 1. Composite component under consideration

Table 1. Material and laminate specification

Materials	• Intermediate Modulus Carbon Fibre supplied by Toray • 65% ± 2.5% VF • Huntsman Resin system
Laminate	• Hoop wound • Maximum voidage 2%

Delamination is the main type of defect that exists within the component. which lead to inhomogeneity within the composite component. Delamination result in area defects in longitudinal (as can be seen in figure 2) as well as in radial direction.

The crack propagation in the first case is more severe for the application of the component and therefore, its detection needs to be prioritized. Delamination with length longer than 1 mm has to be detected (important for accuracy requirements).

Many factors like porosity, incorrect volume fraction, insufficient curing and moisture absorption can complicate the detection of defects within the component.

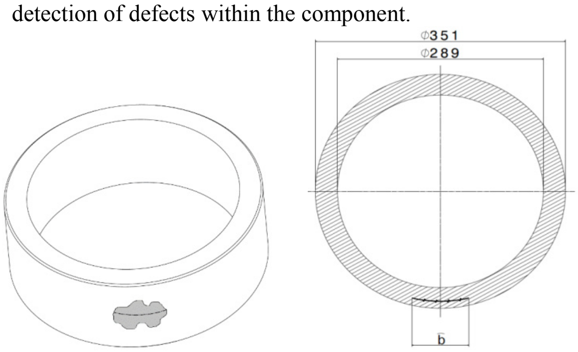

Fig. 2. (left) Shape of expected delamination – Isometric view; (right) Cut through component showing defect length

Choosing an NDT method

Various NDT techniques are used in the industry for defect detection applications. Each technique makes use of a different property. Table 2 shows various techniques along with the type of crack each of them is capable of detecting. [1]

Table 2. Applicable NDT techniques for various types of defects [1]

	Visual Inspection	Penetrant	Acoustic Emission	Pulse/Echo	Through Transmission	X-Ray	Dielectric	Thermography	Neutron Radiography
Delamination	1,2	1	X	X	X	3		X	
Macro-cracks	1,2	2	X			3		X	
Fibre fracture						X		2,3	
Interfacial cracks								2,3	
Micro-cracks		1	2					X	
Porosity	1		2	X	X	X		2	
Inclusions	1			2	2	X		X	
Heat damage	1		2				2		
Moisture						2	X		X
Voids				X	X	X		X	
Surface protrusions	X							X	
Wrinkles	X								
Improper cure							X	2	X

1 = open to surface; 2 = unreliable detection; 3 = orientation dependent

X-Ray Radiography and Computed Tomography

Radiography involves penetrating the object with short wavelength electromagnetic radiation. The amount of radiation that passes through the object is captured by a detector. The absorption is a function of density and thickness of the material. Cavities and discontinuities lead to a detectable variation in absorption. [2] [3]

CT scanning is used to generate an exact three-dimensional cross sectional image of the entire part. Typical defects that can be detected using this technique are delamination, undulations, porosities, fibre cracks or impact damages. Three-dimensional volume is reconstructed by using radiographic images of different perspectives. [4] [5]

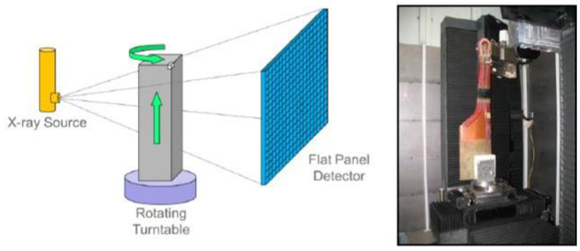

Fig. 3. Principle of a helical CT scanning system. [4]

Cracks that are parallel to the radiation beam and cracks smaller than the resolution are difficult to spot. As a rule of thumb, the defects must be at least 2% in size of the thickness of the material so that it can be effectively detected. Geometric shape of the component also plays an important role. [2]

Radiography is an expensive NDT technique. Thick sections consume a substantial amount of time and energy cost associated is also high. [6]

Health issues due to ionising effect cause economic and operational constraints. The radiation unit Roentgen (R) is used to measure the ionising effect. Hazard control can be done via area monitoring (Ionization chambers, Geiger-Muller counters and scintillation detectors). Reducing exposure time, increasing the distance to the radiation source and use of shielding can reduce the health hazards to a great extent. [2]

Ultrasound

Ultrasonic waves are sound waves with frequencies ranges from 500 kHz to 10 MHz. These are more directional than audible sound waves and travel freely in liquid & solid, depending on density and elastic properties of the medium. Ultrasonic waves are widely used for NDT applications. [7] [8]

Sound waves can propagate in two modes namely, longitudinal or shear. Longitudinal wave is most common for NDT applications. It is faster and can travel both in solid and liquid media whereas, shear wave forms when material particles oscillate normally to the direction of wave propagation. These waves require acoustically solid media to travel and hence, do not proceed effectively in liquid and gases. This property limits its application in Ultrasonic NDT testing.

A piezo electric material is used to generate sound waves by applying voltage difference between any two of its surfaces. The change in dimension of the piezo electric material generates a pulse of mechanical vibration that consists of ultrasonic waves. [7]

Ultrasonic testing to work reasonably well, it is necessary that the discontinuity/flaw must be larger than one-half of the wavelength. Moreover, the quality of results depends on equipment's sensitivity and resolution. [9]

Sensitivity is an ability of a UT system to detect smallest flaws. Resolution is its ability to detect two closely spaced flaws within the material and near to the surface. Both sensitivity and resolution increase with the frequency of the sound wave used for inspection. The optimal frequency of a UT system to detect flaws in material also depends upon material structure, type of flaw, size of flaw and its location. [9]

The higher the frequency of wave, larger will be the vibrational scattering of energy in the material due to frequent collisions between wave particles and material. This effect results in the reduction of penetrating power of wave i.e. maximum thickness of material, where flaws could be detected. [9]

The intensity of sound wave echo also depends on mismatch in acoustic impedance between flaw and surroundings. Hence, an echo from a void will be stronger than from an inclusion in material due to large difference in the impedance. [10]

The large mismatch in acoustic impedance within the material allows thick-section inspection due to stronger echoes. A large bandwidth results in less damping of frequency range around a central frequency and provides UT system more resolution due to high final frequency, but obviously, less penetrating power. On the other hand, a smaller spectrum of highly damped frequencies will result in a system with poor resolution, but higher penetration. [10]

Thermography

Thermography testing makes use of infrared (IR) imaging to detect defects within the component. An IR camera records spatial and temporal distribution of the surface temperature after the component has been heated. Defects disturb the heat flow and hence can be detected. [11]

Thermal NDT methods generally use active thermography. Here, heat waves are sent using an external or internal source. This allows measurement of depth, thickness, and size of internal flaws. [11]

Furthermore, Pulse and Lock-In Thermography are in use for NDT applications globally for flaw imaging. [12]

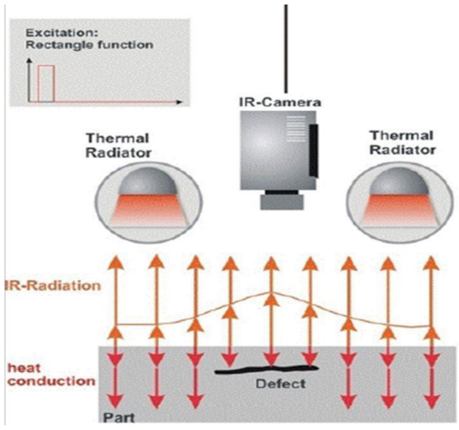

Fig. 4. Pulsed thermography schematic showing how defects lead to a distortion of the heat flow through the component. [11]

Pulsed Thermography is a type of thermography in which a stimulus is applied through a flash pulse, usually Xenon lamps. A selection of active-sources, various IR camera types, and a range of analytical tools are available for monitoring the responses of the objects to the active-sources (figure 4). [13]

Experimental Research and Supplier Evaluation

Thermography analysis

For the testing of the component using pulsed thermography an infrared camera (Model – SC7600MR), a thermal source with flash light and analysis software, Mosaiq 4.0, were used and the spatial and temporal distribution of the surface temperature was recorded after heating the component. The defects in the component can be identified from the thermographic images as they disturb the heat flow in the component. The main task was to prove, if the heat can actually pass through the entire wall width.

One session included the use of a metallic cylinder of structural similarity to that of the composite component. The metallic cylinder was kept in contact with the composite component so that it acts, effectively, as a heat sink. And then thermographic testing was carried on it to verify if it was possible to achieve complete penetration of the thickness of the component using thermography. It was not clearly deducible whether successful penetration could be achieved.

Furthermore, the carbon composite component was tested by adjusting the testing criteria to 12.5 MHz frequency and acquisition time of 60 seconds. From the result of the test it was unable to conclude whether the thickness could be penetrated or not.

Small heat sinks were attached to the back wall of the component at various places to conclude whether thermography is a possible NDT technique.

But from the data gathered and the results of the tests carried out, it was concluded that thermography was not a suitable NDT technique for the testing of thick walled carbon composite components, as it was evident from the testing that thermography could not penetrate the thickness of the component and not even half the thickness could be penetrated. But the actual depth the technique was able to penetrate could not be estimated without the actual knowledge of the heat dissipation characteristics of the component. Another reason that serves as a hindrance to the success of thermography in the testing of carbon composite material is the inhomogeneity of the component as it could not be verified beyond doubts if it was the flaws present in the component or the surface characteristics of the component that was depicted in various thermograms.

Ultrasonic Testing Experiments

Sample preparation

The sample is standard component with a known circumferential flaw of 50 mm arc length visible from top face. There are surface undulations on the component, which is due to excessive resin applied in order to arrest swarf from the surface. The processing method also arrests hygroscopic behaviour of material. On the down side, this will lead near surface attenuation/noise in the echo signal. The surface was cleaned with distilled water to reduce avoidable noise-to-signal ratio due to dust particles.

Experimental results

Olympus OMNISCAN-SX

The experiment with 5MHz frequency probe detected back wall echo of material. At the same time with a 2MHz frequency probe echo signal received with larger amplitude. However, the known flaw's present in material was not noticed. There was another flaw, which was detected in C-Scan and flaw characterization shows a crack of length (figure 5).

Fig. 5. Result of experiment and analysis of sample showing flaw characteristics.

Sonatest Veo 16:64

The front wall echo was visible on the scanner screen. There was too much attenuation due to surface feature of the sample. The back wall echo was not detected on the screen. There could be several reasons for the lack of penetration. This could be failure of proper contact between RadiusWheel probe and flywheel due to geometry of part. The use of water as a coupling agent might have proved to be ineffective due to low viscosity and hence less adherence in between two surfaces. These factors could have led to large attenuation that were shown as near surface flaws.

Fig. 6. Sonatest RadiusWheel Probe. [14]

Peak NDT-UTEX Micro Pulse LT A-Scan (Conventional Pulse Echo)

The back wall echo was not detected with 5MHz probe hence by assumption the thickness of the material was not penetrated. Reduced frequency would had led to lesser sensitivity and resolution of the system. Hence, there should be a trade-off between 2MHz to 5MHz frequency for optimum result.

Discussion

The results and subsequent analysis from the above experiments show interesting patterns in flaw detection by Ultrasonic Inspection. The Olympus equipment is able to detect the back wall precisely with the 5MHz probe but Peak NDT experimental setup could detect only with a 2 MHz frequency. However, the Sonatest experiment was not able to detect the back wall in any case.

The possible cause of variation could be several, like the introduction of sound wave in material may be hindered by the natural spreading of the beam. Another reason can be near field effect of the sound wave which limits the sensitivity of system to detect near surface flaws. The surface feature of the specimen also could lead to high attenuation in the echo or received signal amplitude. There are human factors involved in the system as well for example the speed of the encoder or the sample could easily miss critical flaws anytime. Moreover, the noisy environment also can hamper the intensity of the introduced sound wave.

The above limitations to an extent could be overcome by an Immersion Through Transmission System. In this system, the sound wave is introduced in the material from a distance in order to avoid the near field effect. The surface feature of the sample also gets minimizes due to lack of contact between probe and material. There is an added advantage of absence of any other signal source other than UT system in a submerged surrounding to negate avoidable noise that may lead to attenuation. The incorporation of an indexing mechanism and other automation reduces the human involvement for improving the system.

Two-Dimensional X-Ray Radiography

Initial tests with radiographic X-Ray equipment generating two-dimensional images have been made, figure 7 shows the experimental set-up.

In figure 8, the scan from top of the component can be seen. The circumferential line in a slightly brighter grayscale that can be seen in the following picture is indicating a delamination (partly marked). The picture was taken with a voltage of 80kV.

It can be seen that the difference in contrast of the delaminated area compared to the non-defected area is minimal. This makes it hard to detect defects within the component properly.

The detection of small defects, especially when they occur parallel to the x-ray beam, is difficult. Therefore, the classical 2D-X-ray system is not the preferred option to take.

Fig. 7. Experimental set-up of a 2D X-ray system.

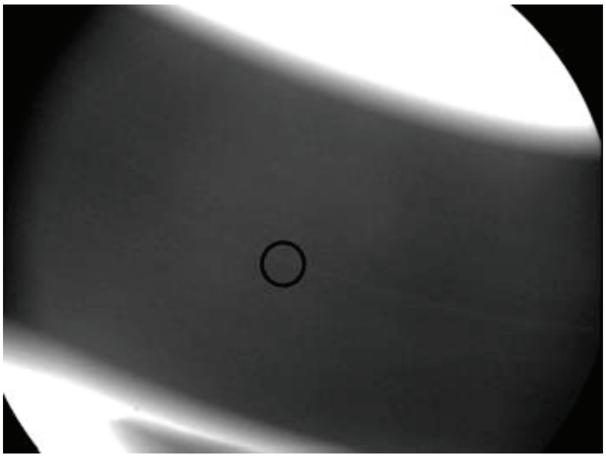

Fig. 8. Delamination detected with a 2D X-ray system; the contrast between defective and non-defective areas is not sufficient.

Computed Tomography

A number of suppliers around the world offering CT testing systems have been contacted based on BINDT recommendations [15]. A suitability analysis based on questionnaires and experimental research was done, which

Fig. 9. North Star Imaging X5000 CT scanning system with workstation. [16]

will be presented below. Most of the companies recommended to use cabinet systems for an industrial production environment (like the one shown in figure 9). All products are state-of-the-art machines and are already used in the manufacturing industry. The price for CT scanning machines ranges from £200k to £600k, depending on precise requirements and resolution.

Experimental Results

Several cabinet systems from various suppliers have been tested. Figure 10 shows results acquired with a NSI X5000 machine. A delamination on the inner side of the flywheel can clearly be seen on the right side of the picture. The data has been captured within 15 minutes with a resolution of approximately 200 µm.

Figure 11, is an image generated with a Carl Zeiss Limited Metrotom 1500 machine is shown (standard helical CT scanning system). As can be seen, delaminations are clearly visible. Tiny delaminations with a width of only several micron could be detected. A resolution of approximately 200 µm is proposed. A voltage of 220 kV and a current of 900 µA has been used. The scanning time was 33 minutes.

The same service provider is offering a machine at R&D stage, which is capable of scanning the component in a time of 3 minutes 30 seconds with the same quality as the demonstrated scan above. Such a system is adopted to automated high volume production and is therefore suitable for our application.

Fig. 10. Slice through the volumetric model acquired by CT scanning; the delamination on the inner side can clearly be detected

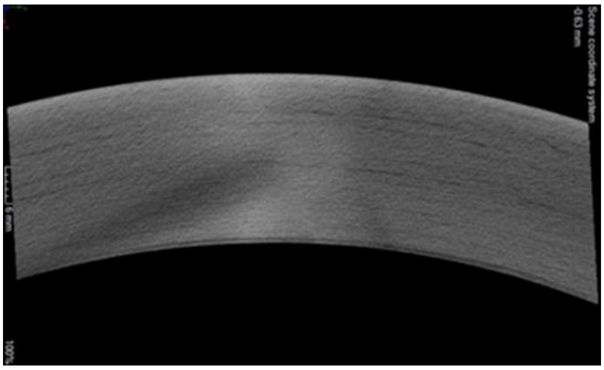

Fig. 11. Slice through the volumetric model acquired by Zeiss; the delamination on the inner side can clearly be detected; furthermore, a huge number of tiny delamination all over the component are visible.

Further machines have been tested. Experimental research has shown that the applied system has to have a detector big enough to scan at least one component at once. Otherwise, cycle time will be increased and component handling is more complicated.

3.4.2. Regulations & Procedures

In terms of health and safety, machines have to fulfil Ionising Radiations Regulations 1999 [17]. Radiation protection supervisor needs to be appointed and a local health and safety executive must be contacted. The machines require a yearly certification which is a part of the maintenance package in most cases. Companies should be ISO 9001:2008 certified to ensure quality work. A warranty period of 12 months is guaranteed by most suppliers.

3.4.3. Software

The volumetric model of the scan is normally generated by company owned software. This data set can then be analysed using a bespoke software. Most commonly, Volume Graphics Studio is used. Here, the kind and size of defects that the software should search for can be defined. Detected defects are highlighted automatically. The software is a convenient tool to assist the operator. If it can replace the operator totally has to be analysed according to application. [18] (Figure 12)

Analysis software can also be used for geometry control. The scan can directly be compared with an existing CAD model. This can make CMM testing unnecessary and helps in cost reduction (however, the accuracy needs to be checked). [18]

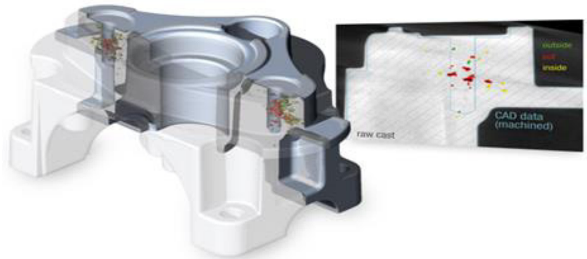

Fig. 12. Automated defect detection using Volume Graphics; defects are highlighted in red. [18]

Operator tasks

All suppliers offer training for the operator for several days. Generally low skills are required for handling the machine. The basic procedure for all machines with manual handling will look like following:

1. Load component into cabinet
2. Close cabinet door
3. Start X-rays/Pre-warning
4. Parallelization of
   a. Acquiring scanning data
   b. Analysing data from previous scan
5. Remove component from cabinet

The final working procedure has to be defined according to cycle times and the production line environment. As the component is highly safety critical a Level 2 NDT expert should be hired to evaluate the scans (assisted by analysis software).

Automation

All the machines can be operated using a robotic handling system (figure 13). Opening/closing the door, starting the machine etc. can also be automated and adapted to the final production line.

The automated defect detection has to be tested. The system might not be capable of detecting all the defects on its own. Automation in general makes the production less flexible. Automation would not lead to a huge reduction in cycle time and therefore, automation should be applied at a later stage.

Fig. 13. Fully automated in-line CT system. [19]

Cost-Benefit-Analysis

For a cost-benefit-analysis about purchasing a CT scanning system, several assumptions have to be made:

- Time that the machine will be used per day/year
- Costs for the company for an operator
- Electricity price per kWh
- Predicted production rates for the upcoming years

The main limitation is the time that the machine can be used per year. If the demanded time (cycle time per scan multiplied by total number of components per year) is higher, several machines have to be run parallel. This makes production planning much more complex and increases investment costs. Therefore, it has been shown that a bigger investment can be compensated by a lower cycle time. On top of the actual scanning time, time for loading the component and starting the machine has to be added.

The main indicators showing, if an investment is economical, are the total costs per year and the cumulative costs per component (which decrease over the years as the investment for the machine will be distributed over a higher number of scanned components). Following equation shows the applied calculations:

$$Costs\ per\ component\ (absolute, cumulative) = \frac{\sum_{i=0}^{n} Total\ Costs\ in\ year\ i}{\sum_{i=0}^{n} Number\ of\ parts\ scanned\ in\ year\ i}$$

These calculations allow a direct comparison of different machines. Furthermore, it makes it easy to compare the options of buying own equipment or working together with a service provider.

For the analyzed application, it has been recommended to the client to buy own equipment as the cost-benefit-analysis has clearly shown that huge savings can be achieved.

Further Work

Nonetheless, a component with known defects has to be tested. The size and location has to be defined (should be in the range of size of delamination that has to be detected) so that the general detectability and the dependence of accuracy and scanning time can be evaluated. The automated defect detection with third party software also has to be tested. This will finally proof the suitability of the machines.

The layout of the production and assembly line has to be finalised so that ideas for automation can be taken into account. A time period of half a year between ordering the machine and final installation has to be considered.

Until the machine will be used, a level 2 radiography NDT expert has to be hired to operate the machine and to evaluate the scans. Furthermore, the scanning procedure has to be defined by a level 3 expert. Local radiography authorities have to be contacted to get the machine registered.

Conclusion

An overview about several NDT techniques has been given (ultrasonic, thermography and radiography testing). Experimental results have shown that the applied equipment for UT and thermography testing cannot provide sufficient results. Immersion-Through-Transmission systems have to be tested further.

Although CT equipment is significantly more expensive than UT and thermography equipment, it is a proven system with high reliability and a much better traceability. Experimental results have shown that delamination can clearly be detected. Therefore, it is the preferred technique to apply for the analysed thick walled composite component.

Acknowledgements

This work has been sponsored by a major UK manufacturing company supplying the automotive and transport sectors.

References

[1] Heslehurst RB , *Defects and Damage in composite materials and structures*, CRC Press (Boca Raton, FL), 2014.

[2] Raj B, Jayakumar T, Thavasimuthu M, *Practical non-destructive testing,* 3rd Ed, pub Alpha science international ltd. (Oxford) 2008.

[3] Prakash R, *Non-destructive testing of composites*, Composites, **11 (4),** 1980, pp217-224.

[4] Krumm M, Sauerwein C, Hämmerle V, Oster R, Diesel B, Sindel M, *Capabilities and Application of Specialized Computed Tomography Methods for the Determination of Characteristic Material Properties of Fiber Composite Components,* Lock-in Thermography, Springer-Verlag, Berlin, pp. 1-8, 2012.

[5] Kastner J, Schlotthauer E, Burgholzer P, and Stifter D, *Comparison of X-ray Computed Tomography and Optical Coherence Tomography for Characterisation of Glass Fibre-Polymer Matrix Composites*, 16th World Conference on Nondestructive Testing, September 2004, Montreal, Kanada, 134

[6] Harara W, *Digital Radiography in Industry*, 17th World Conference on Non-Destructive Testing, Shanghai, China, 2008.

[7] Olympus, www.olympus-ims.com, [Online]. Available: https://www.olympus-ims.com/en/ndt-tutorials/flaw-detection/wave-

propagation/. [accessed 10 February 2015].

[8] Adamowski JC, Andrade MAB, Perez N, Buiochi F, *A Large Aperture Ultrasonic Receiver for ThroughTransmission Determination of Elastic Constants of Composite Materials*, IEEE, Beijing, 2008.

[9] NDT Resource Center, www.nde-ed.org, 19 December 2007. [Online]. Available: https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/Physics/defectdetect.htm. [accessed 15 February 2015].

[10] NDT Resource Center, www.nde-ed.org, 28 May 2008. [Online]. Available: https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/Physics/acousticimpedance.htm. [accessed 15 February 2015].

[11] FLIR Systems Inc., "NDT in Composite Materials with Flash, Transient, and Lock-in Thermography", FLIR Systems Inc., Boston, 2011.

[12] Breitenstein O, Warta W and Langenkamp M, *Lock-in Thermography Basics and use for evaluating electronic devices and materials*, Pub: Springer-Verlag (Berlin), 2010.

[13] Shepard SM, "Flash Thermography of Aerospace Composites", IV SM Shepard - IV Conferencia Panamericana de END, Buenos Aires, October 2007, doi: 212.8.206.21.

[14] Elins, www.elins.lt, [Online]. Available: http://www.elins.lt/index.php?page=ultrasonic-systems&hl=eng. [accessed 18 April 2015].

[15] The British Institute of Non-Destructive Testing, "The British Institute of Non-Destructive Testing", 2013. [Online]. Available: http://www.bindt.org/Buyers-Guide/NDT-Equipment-Providers/. [accessed 15 03 2015].

[16] North Star Imaging, "4nsi.com", [Online]. Available: http://4nsi.com/systems/x5000. [accessed 25 March 2015].

[17] "Legislation of the United Kingdom", 1999. [Online]. Available:http://www.legislation.gov.uk/uksi/1999/3232/contents/made [accessed 12 04 2015].

[18] Volume Graphics GmbH , VG Studio Max 2.2, 2013. [Online]. Available: http://www.volumegraphics.com/fileadmin/user_upload/flyer/VGStudioMAX_22_en.pdf. [accessed 22 02 2015].

[19] Eurotec, eurotec-online.com, [Online]. Available: http://eurotec-online.com/2014/03/14/metrology-isnt-everything-but-without-metrology-nothing-is-anything/. [accessed 10 April 2015].