An experimental and analytical study of micro-laser line thermography on micro-sized flaws in stitched carbon fiber reinforced polymer composites

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Abstract

Stitching is used to reduce incomplete infusion of T-joint core (dry-core) and reinforce T-joint structure. However, it might cause new types of flaws, especially micro-sized flaws. In this paper, a new micro-laser line thermography (micro-LLT) is presented. X-ray micro-computed tomography (micro-CT) was used to validate the infrared results. The micro-LLT and micro-CT inspection are compared. Then, a finite element analysis (FEA) is performed. The geometrical model needed for finite element discretization was developed from micro-CT measurements. The model is validated for the experimental results. Finally a comparison of the experiments and simulation is conducted. The infrared experimental phenomenon and results are explained based on the FEA results.

Keywords: NDT; Laser line thermography; X-ray computed tomography;

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Finite element method; Composite stitching

1. Introduction

Three-dimensional (3D) carbon fiber reinforced polymer matrix composites (CFRP) are increasingly used for aircraft construction due to their exceptional stiffness and strength-to-mass ratios. Composites made from 3D textile preforms can reduce both the weight and manufacturing cost of advanced composite structures within aircraft, naval vessels and the blades of wind turbines [1]. The in-plane stiffness and strength of 3D woven composites are lower; while the out-of-plane properties are higher compared to conventional 2D laminates [2]. Assembly of 3D complex composite structures requires efficient joining methods. The most frequently used joint found in structural applications is the T-joint.

The purpose of T-joints is to transfer flexural, tension and shear loads to the skin. T-stiffeners are used extensively in aircraft wings in order to prevent skin buckling during wing loading. However, designing composite joints is more difficult than metallic joints due to the mechanical properties of composite materials [3].

In the design of T-joints, filler is inserted in T-joints and resin is used to reinforce the structure. The fiber insertion technique has the potential of creating a low-cost T-joint with improved damage tolerance and failure strength [4]. However, incomplete infusion of T-joints core (dry-core) is a typical issue. Figure 1 shows typical dry-core in a non-stitched CFRP T-joint.

Stitching [5] is used to reduce dry-core and reinforce T-joint structure [6]. However, stitching might lead to new types of flaws due to the characteristics of its structure.

Non-destructive testing (NDT) of composite materials is complicated due to the wide range of flaws encountered (including delamination, micro-cracking, fiber fracture, fiber pullout, matrix cracking, inclusions, voids, and impact damage). The ability to quantitatively characterize the type, geometry, and orientation of flaws is essential [7] [8]. The ability to identify and characterize such

micro-sized flaws accurately is challenging. [9]

Infrared thermography (IRT) is becoming increasingly popular in the recent years as a NDT technique due to its fast inspection rate, contactless, spatial resolution and acquisition rate improvements of infrared cameras as well as the development of advanced image processing techniques. It is used for diagnostics and monitoring in several fields such as electrical components, thermal comfort, buildings, artworks, composite materials and others [10].

In this paper, a new micro-laser line thermography (micro-LLT) is used to detect a stitched CFRP T-joint. An 18 μm resolution micro-CT is used to validate the infrared results. A comparison of the micro-LLT and micro-CT is conducted. Then, a finite element analysis (FEA) simulating the infrared results is performed. The geometrical model needed for finite element discretization is developed from the micro-CT. Finally a comparison of the experiments and simulation is conducted. There is little information in the open literature on FEA for IRT on micro-sized flaws. The infrared experimental results are explained on based of the FEA.

2. Materials and structure

2.1. Materials system

The T-joint specimen selected for this evaluation was sewn using stacked TC-06-T 3K carbon fiber. The 3D architecture was woven using 3K/12K carbon fiber. A continuous row of stacked 12K tow fiber was used for insertion. A toughened epoxy resin infusion system was selected.

2.2. Fabrication

The T-joint specimen was fabricated using 3D preform consisting of multiple layers of woven fabric. The complete 3D fabrication model is shown in Fig. 2 (a). A high-resolution photograph of the fabrication is shown in Fig. 2 (b).

The noodle for the T-joint insertion was pre-shaped through compaction. During processing, the twisted round-shaped stacked 12K carbon fiber tows

were placed into the molding tool and compacted to a triangular-shape as the tool was clamped together. The noodle processing procedure is shown in Fig. 2 (c). After the fiber insertion process was completed, the resin infusion process was initiated.

2.3. Geometry

For composites, meso-geometry can influence processing and performance properties. To describe the meso-geometry, the textile unit cell model is shown in Fig. 3 (a). The complete single layer preform model is shown in Fig. 3 (b).

The geometrical model describing the internal geometry is developed on the basis of the method proposed by Ito and Chou [11]. The model consists of four intertwined yarns surrounded by the isotropic matrix. There are two warp yarns in the longitudinal direction and two fill yarns in the transverse direction. Each yarn is a unidirectional composite in the material coordinate system with orthotropic properties [12].

The equations proposed by Ito and Chou [11] for the yarn geometry is used for developing the geometrical model. The warp yarn path curve on the fill face is described by

$$z_0(x) = \frac{h_y}{2}\sin(\frac{2\pi}{a}x), where -\frac{a}{4} < x < \frac{a}{4} \tag{1}$$

and the fill yarn cross-section curve on the same face by

$$z_1(x) = \frac{2h_c}{a-2a_g}\sqrt{(2x-a_g)(a-a_g-2x)} + h_y - h_c, where\frac{a_g}{2} < x < \frac{a}{4} \tag{2}$$

where h_y is the yarn thickness, a is the dimension of the model in either the fill or warp directions (warp or fill faces, respectively), a_g is the gap width between two adjacent transverse yarns, and

$$h_c = \frac{h_y}{2}(\sin(\frac{\pi a_g}{a}) + 1) \tag{3}$$

The model geometrical relation is shown in Fig. 4. The values of the parameters are shown in Table 1.

Table 1: The model geometrical parameters

Geometrical Parameters	Value
Weave length in warp direction, a^w (mm)	6
Weave length in fill direction, a^f (mm)	6
Gap width in warp direction, a_g^w (mm)	0.3
Gap width in fill direction, a_g^f (mm)	0.3
Yarn thickness, h_y (mm)	0.6

2.4. Specimen

The complete stitched T-joint is shown in Fig. 5 (a). The sample contains 6 stitching lines. The purpose of the stitching is to consolidate the T-joint structure and to reduce dry-core. The sample measures 152 mm in length, 148 mm in width, 63 mm in height, and 5 mm in thickness (excluding the T-stringer), as shown in the figure.

The front side of the sample is shown in Fig. 5 (b). A 10 mm × 152 mm zone was inspected using micro-LLT and micro-CT.

3. Methods and results

3.1. Experiments

3.1.1. Micro-LLT

In conventional IRT set-up, a relatively homogenous heat source such as flash or halogen lamps is used to heat sample surface, and then temperature distribution on the surface is recorded with an infrared camera. Conventional IRT can detect a broad variety of defects, such as voids, pores, or delaminations [13]. However, it is difficult to detect micro-sized flaws due to CFRP structural complexity, which leads to heat diffusion abnormity, especially for interlayer detection.

To tackle this problem, laser spot thermography (LST) may be an effective solution, which is currently experiencing intense research activities. This approach uses a laser spot to scan over sample surface. Changes in the heat

conductivity lead to changes in the thermal footprint. This approach may effectively reduce the impact of CFRP structural complexity. However, this approach needs a massive amount of workload and time due to spot inspection feature. Therefore, in this paper, a new approach 'micro-LLT' is presented to utilize LST's advantage, and to reduce its disadvantage.

Laser line thermography (LLT) has been used to detect surface cracks [14]. Li et al. [14]used a beam expander and a cylindrical lens to convert a laser spot with a radius of around 0.9 mm to a laser line source. However, the detection of other types of flaws was poorly documented. In this paper, a galvanometer scanning mirror with a frequency of 600Hz is used to generate a laser line [15]. A micro-lens was used to identify and characterize micro-sized flaws.

Figure 6 (a) shows the experimental set-up for micro-LLT. In the set-up, the sample was fixed on a robot. A mid-wave infrared (MWIR) camera (FLIR Phoenix, InSb, 3-5 μm, 640 $\times$ 512 pixels) at a frame rate of 55 Hz was used to record the temperature profile. A diode-laser with wavelength of 805 nm, a beam power of 2.9 W, and a heating time of 0.5 s was used. A convex lens was used to focus the laser beam and a micro-lens was used to identify and characterize the micro-sized flaws. The magnification of the micro-lens is 1$\times$. A micro-mirror (7 mm diameter) was mounted between the IR camera and the sample. GSI G124 open loop optical scanner ($\pm$24° optical scan angle) was used to deflect the mirror. In Fig. 6 (b), the laser spot was converted to a laser line when the micro-mirror swung at the frequency of 600 Hz. Figure 6 (b) shows the heat source. Its length is around 10 mm and its width is around 3 mm. [9]

Figure 5 (b) shows the inspected zone. The laser line crosses a stitching line. The robot moved per 3 mm towards the direction shown in Fig. 5 (b). A total of 51 tests were performed to detect the 10 mm $\times$ 152 mm area shown in Fig. 5 (b).

3.1.2. Micro-CT

The division between what is considered 'conventional' computed tomography and 'micro-tomography' is an arbitrary one, but generally the term micro-

tomography is used to refer to results obtained with at least 50-100 μm spatial resolution [16]. X-Ray computed tomography (CT) has become a familiar technique. Recently it is also increasingly gaining popularity as an accessible laboratory technique for NDT of materials and components, especially due to the recent appearance of several commercial systems. Such instruments offer the potential for the widespread use of micro-CT as a tool for characterization of damage in composite materials [25].

Application of micro-CT to composite materials was concentrated on metal-matrix and ceramic-matrix composites in the past. The spatial scale of features in these materials including fiber location and waviness [17], fiber breakage [18], local porosity and density [19], void volume [21], fatigue crack growth [20], etc. are accessible to micro-CT. However, recently some studies on polymer matrix composites have also been reported. In 2000, impact damage including fiber fracture and delamination in T300/914 carbon fiber/epoxy laminates was characterized [22]. In 2002, impact damage in an epoxy/E-glass composite was also measured [23]. In 2004, micro-CT was used to determine internal structure in a polymer foam reinforced with short fibers [24]. In 2005, a study was undertaken to assess the capabilities and limitations of micro-CT for fiber-reinforced polymer-matrix composites, where different specimens with a variety of damage types, geometries and dimensions were investigated to assess the effect of the system resolution on the ability to determine the internal geometry of flaws including delamination, matrix crack, and especially micro-crack, which is a subject of critical interest in the study of fiber-reinforced polymer-matrix composite laminates [25]. In 2006, an evaluation of micro-CT was performed to determine the geometry of fiber bundles and voids in glass fiber reinforced polymers (GFRP). As a consequence, each fiber bundle and inter bundle voids can be observed separately [26].

A micro-CT inspection was performed on the same 10 mm $\times$ 152 mm zone shown in Fig. 5 (b). The resolution of the inspection is 18 μm. The purpose of the x-ray tomography inspection is to validate the micro-LLT results.

3.1.3. Results analysis

Figure 7 shows slices from the micro-CT results. Some specific micro-porosities are marked in the images. Some micro-porosities are inspected on the surface.

Figure 8 shows the micro-LLT results in the same zone. The heating area is marked in green.

The result of an infrared inspection is a sequence of infrared images which contains: the sample before heating, the moment when the laser line heats the sample, the rise of the temperature profile and the temperature profile decrease [27].

Figure 8 (a) was acquired from cold image subtraction (CIS) at 0.8 s (the heating time is 0.5 s and the thermal diffusion time during temperature profile decrease is 0.3 s). CIS is intended to reduce the effects of fixed artifacts in a thermographic sequence, for example, reflections from the environment such as residual heating coming from the lamps and even the reflection from the camera that appears during the acquisition. Since these artifacts are more or less constant during the whole acquisition, including before heating when the image is 'cold', this image or the average of several images can be subtracted before heating, so their effect can be reduced.

In Fig. 8 (a), some micro-porosities on the surface such as C and D (marked in purple) are detected. However, some other micro-porosities on the surface such as some in the zone E (marked in yellow) are not detected. The potential cause is the IR camera resolution limitation. Statistically the micro-porosities with a diameter of less than 54 μm are not detected in Fig. 8 (a).

In Fig. 8 (a), the micro-porosity A (marked in red) is detected. However, it is not detected on the surface shown in Fig. 7 (a). It appears from the depth of 90 μm shown in Fig. 7 (b). Figure 7 (b) shows the x-ray tomography image from the depth of 90 μm. The micro-porosity A has a diameter of 0.162 mm. The micro-porosity A can be detected more clearly in the raw image with contrast adjustment shown in Fig. 8 (b).

Figure 8 (c) shows the infrared image from principal component thermography (PCT). PCT, originally proposed by Rajic in 2002 [28], extracts the image features and reduces undesirable signals. It relies on singular value decomposition (SVD), which is a tool to extract spatial and temporal data from a matrix in a compact manner by projecting original data onto a system of orthogonal components known as empirical orthogonal functions (EOF). The first EOF will represent the most important characteristic variability of the data; the second EOF will contain the second most important variability, and so on. Usually, original data can be adequately represented with only a few EOFs. Typically, an infrared sequence of 1000 images can be replaced by 10 or less EOFs. [29] This image is from the 6th EOF.

In Fig. 8 (c), the performance of the micro-porosity A is exceptional (darker in contrast) compared to the other micro-porosities. Micro-LLT can detect the micro-sized internal defects in the sample. However, the depth and the size of defects can affect the detection results.

Figure 7 (c) shows the x-ray tomography image from the depth of 0.18 mm. The micro-porosity B (marked in blue) is inspected and has a diameter of 0.216 mm from the depth of 0.18 mm. However, the micro-porosity B cannot be inspected in the infrared images. One potential cause is that the depth of 0.18 mm exceeds the IR camera detection limitation with the laser beam power of 2.9 W. Another potential cause is that the micro-porosity B is below the fiber F (marked in orange) shown in Fig. 7 (a) and Fig. 8 (a). It might reduce the heat transmission. This hypothesis was investigated using finite element analysis. [9]

3.2. Finite element modeling and simulation

A finite element simulation was performed to analyze the micro-porosities A and B. A model was implemented into COMSOL Multiphysics as a user-defined material model for predicting the non-linear behavior of heat transmission in the sample. The model was validated for the experimental results. Finally a comparison of the experiments and simulation was conducted.

3.2.1. Modeling

The geometrical model needed for finite element discretization was developed from the micro-CT measurements (Fig. 9). The laser-line power is 2.9 W. The power was tested in the lab. The power density is 2.9 W / (3 mm × 10 mm). The laser line covered an area of 2.5 mm × 0.5 mm. Therefore, the power in the model is 2.9 W × (2.5 mm × 0.5 mm) / (3 mm × 10 mm). The heating time is 0.5 s.

The material properties used for the model are shown in Table 2.

Table 2: The material properties

	Epoxy	Fiber	Porosity
Thermal conductivity (k)	0.2 W/(m·K)	$\{60, 4, 4\}$ W/(m·K)	0.004 W/(m·K)
Density (ρ)	1200 kg/m^3	1500 kg/m^3	0
Heat capacity (C_ρ)	1000 J/(kg·K)	1000 J/(kg·K)	1004.5 J/(kg·K)

Figure 10 (a) shows the x-ray tomography measurements. Figure 10 (b) shows the corresponding model geometrical parameters. The length of the fiber F is 5 mm, and its width is 0.8 mm. The length of the fiber G is 4 mm, and its width is 0.8 mm. The thickness of fiber F and G is 90 μm. The fill yarn cross section is an ellipse with major axis 0.8 mm and minor axis 0.09 mm. The warp yarn curves are described by Eq. (1), where $h_y = 0.1$ mm and a = 5 mm. Fiber G is rotated by 20°. Two concave surfaces face each other. The centers of mass lay on z-axis. Two fibers are embedded in cubic epoxy with the volumetric dimension of 6 mm × 2.5 mm × 0.6 mm laid along x-axis. In Fig. 10 (a), the micro-porosities A and B cannot be detected because they are below the surface. However, their positions are indicated.

The parameters of the micro-porosities A and B are shown in Fig. 10 (c). The parameters were obtained from the micro-CT. The micro-porosity A appears from the depth of 90 μm to the depth of 0.36 mm, and has a diameter of 0.162 mm to 0.306 mm. The micro-porosity B appears from the depth of 0.18 mm to the depth of 0.504 mm, and has a diameter of 0.216 mm to 0.36 mm.

3.2.2. Results analysis

Figure 11 (a) shows the simulation surface temperature distribution from the heating time 0.5 s. Figure 11 (b) shows the corresponding slice temperature distribution. Figure 11 (c) shows the surface temperature distribution from top view.

Figure 12 (a) shows the surface slice temperature distribution from top view. Figure 12 (b), (c), (d) and (e) shows the slice temperature distribution from the depth of 50 μm, 0.1 mm, 0.2 mm and 0.5 mm respectively. The temperature on the position of the micro-porosity A is much higher than that of the micro-porosity B, as shown in the figure. In Fig. 12 (a), (b) and (c), the temperature on the position of the micro-porosity A is higher than that of the other heated zones. The potential cause is the influence of the micro-porosity A. In Fig. 12 (e), the temperature on the position H is higher than that of the other heated zones. The potential cause is that neither fiber nor micro-porosity is existed on the position H. Therefore, the heating transmission is not reduced.

Figure 13 (a) indicates the cause of the phenomenon inspected from the micro-LLT experiments. The fiber F reduced the heat transmission towards the micro-porosity B. It is the major reason that the micro-porosity B was not detected in the infrared results, but was detected in the x-ray results.

Figure 13 (b) shows the slice temperature distribution from side view when the heating time is 1 s. According to the temperature distribution compared to Fig. 13 (a), the micro-porosity B cannot be detected using micro-LLT even if the heating time is increased to 1 s. A locked-in infrared inspection might be more effective to inspect micro-porosities below fibers.

4. Summary

A new micro-LLT was presented. Micro-CT was used to validate the micro-laser line thermography results. A comparison of micro-LLT and high-resolution x-ray tomography was conducted. Then a FEA was performed on the micro-LLT results. The geometrical model needed for finite element discretization was

developed from micro-CT measurements. The comparison of the experiments and simulation was conducted. As a conclusion, micro-LLT can detect the micro-sized internal defects in the sample. However, the depth and the size of defects affect the detection results. Statistically the micro-porosities with a diameter of less than 54 μm cannot be detected in the micro-LLT results. Micro-LLT can detect the micro-porosity (a diameter of 0.162 mm) from the depth of 90 μm. However, it cannot detect the internal micro-porosity (a diameter of 0.216 mm) from the depth of 0.18 mm. The major cause is that the porosity with the diameter of 0.216 mm is below a fiber which reduced the heat transmission.

5. Future work

Compared to micro-CT, micro-LLT is a lower-cost, mobilizable, more robust alternative technique. Micro-LLT has advantage of LST, and can effectively reduce its disadvantage - larger detection area and less detection time. Micro-LLT can detect a 3.3 times larger area (3 mm $\times$ 10 mm) to LST (3 mm $\times$ 3 mm) per testing, which means 30% detection time of LST. This makes micro-LLT a more practical technique for large surface sample. However, micro-LLT cannot detect through-depth when a sample is thick currently. To improve this new approach is essential and practical in order to detect deeper interlayer. The further work would provide a probability of detection (PoD) of micro-LLT on micro-sized flaws by raising heat source power, increasing heating time and using lock-in method.

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References

[1] F. Stig, 3d-woven reinforcement in composites, Ph.D. thesis, KTH Royal Institute of Technology (2012).

[2] F. Stig, S. Hallström, Assessment of the mechanical properties of a new 3d woven fibre composite material, Composites Science and Technology 69 (11) (2009) 1686–1692.

[3] J. Ekh, Multi-fastener single-lap joints in composite structures, Ph.D. thesis, KTH Royal Institute of Technology (2006).

[4] P. Stickler, M. Ramulu, Investigation of mechanical behavior of transverse stitched t-joints with pr520 resin in flexure and tension, Composite structures 52 (3) (2001) 307–314.

[5] P. Potluri, E. Kusak, T. Reddy, Novel stitch-bonded sandwich composite structures, Composite Structures 59 (2) (2003) 251–259.

[6] T. J. Kang, S. H. Lee, Effect of stitching on the mechanical and impact properties of woven laminate composite, Journal of Composite Materials 28 (16) (1994) 1574–1587.

[7] Y. Bar-Cohen, Emerging ndt technologies and challenges at the beginning of the third millennium, part 2, Materials evaluation 58 (2) (2000) 141–150.

[8] B. Liu, Y. Cao, H. Zhang, Y. Lin, W. Sun, B. Xu, Weak magnetic flux leakage: A possible method for studying pipeline defects located either inside or outside the structures, NDT & E International 74 (2015) 81–86.

[9] H. Zhang, U. Hassler, M. Genest, H. Fernandes, F. Robitaille, C. Ibarra-Castanedo, S. Joncas, X. Maldague, Comparative study on submillimeter flaws in stitched t-joint carbon fiber reinforced polymer by infrared thermography, microcomputed tomography, ultrasonic c-scan and microscopic inspection, Optical Engineering 54 (10) (2015) 104109–104109.

[10] H. Fernandes, C. Ibarra-Castanedo, H. Zhang, X. Maldague, Thermographic non-destructive evaluation of carbon fiber-reinforced polymer plates after tensile testing, Journal of Nondestructive Evaluation 34 (4) (2015) 1–10.

[11] M. Ito, T.-W. Chou, An analytical and experimental study of strength and failure behavior of plain weave composites, Journal of Composite Materials 32 (1) (1998) 2–30.

[12] E. Barbero, P. Lonetti, K. Sikkil, Finite element continuum damage modeling of plain weave reinforced composites, Composites Part B: Engineering 37 (2) (2006) 137–147.

[13] J. Schlichting, G. Kervalishvili, C. Maierhofer, M. Kreutzbruck, Imaging cracks by laser excited thermography, in: REVIEW OF PROGRESS IN QUANTITATIVE NONDESTRUCTIVE EVALUATION VOLUME 29, Vol. 1211, AIP Publishing, 2010, pp. 727–734.

[14] T. Li, D. P. Almond, D. A. S. Rees, Crack imaging by scanning laser-line thermography and laser-spot thermography, Measurement Science and Technology 22 (3) (2011) 035701.

[15] H. Zhang, M. Genest, F. Robitaille, X. Maldague, L. West, S. Joncas, C. Leduc, Infrared thermography, ultrasound c-scan and microscope for non-destructive and destructive evaluation of 3d carbon fiber materials: a comparative study, in: SPIE Sensing Technology+ Applications, International Society for Optics and Photonics, 2015, pp. 94850X–94850X.

[16] S. Stock, X-ray microtomography of materials, International Materials Reviews 44 (4) (1999) 141–164.

[17] G. Y. Baaklini, R. T. Bhatt, A. J. Eckel, P. Engler, R. W. Rauser, M. G. Castelli, X-ray microtomography of ceramic and metal matrix composites, Materials evaluation 53 (9).

[18] E. Maire, L. Babout, J.-Y. Buffiere, R. Fougeres, Recent results on 3d characterisation of microstructure and damage of metal matrix composites and a metallic foam using x-ray tomography, Materials Science and Engineering: A 319 (2001) 216–219.

[19] P. Mummery, B. Derby, P. Anderson, G. Davis, J. Elliott, X-ray microtomographic studies of metal matrix composites using laboratory x-ray sources, Journal of Microscopy 177 (3) (1995) 399–406.

[20] S. McDonald, M. Preuss, E. Maire, J.-Y. Buffiere, P. Mummery, P. Withers, X-ray tomographic imaging of ti/sic composites, Journal of microscopy 209 (2) (2003) 102–112.

[21] I. Justice, P. Anderson, G. Davis, B. Derby, J. Elliott, Damage nucleation and growth in particle reinforced aluminium matrix composites, Key Engineering Materials 127 (1996) 945–952.

[22] D. D. Symons, Characterisation of indentation damage in 0/90 lay-up t300/914 cfrp, Composites science and technology 60 (3) (2000) 391–401.

[23] J. P. Dunkers, D. P. Sanders, D. L. Hunston, M. J. Everett, W. H. Green, Comparison of optical coherence tomography, x-ray computed tomography, and confocal microscopy results from an impact damaged epoxy/e-glass composite, The Journal of Adhesion 78 (2) (2002) 129–154.

[24] H. Shen, S. Nutt, D. Hull, Direct observation and measurement of fiber architecture in short fiber-polymer composite foam through micro-ct imaging, Composites Science and Technology 64 (13) (2004) 2113–2120.

[25] P. J. Schilling, B. R. Karedla, A. K. Tatiparthi, M. A. Verges, P. D. Herrington, X-ray computed microtomography of internal damage in fiber reinforced polymer matrix composites, Composites Science and Technology 65 (14) (2005) 2071–2078.

[26] J. Schell, M. Renggli, G. Van Lenthe, R. Müller, P. Ermanni, Micro-computed tomography determination of glass fibre reinforced polymer meso-structure, Composites Science and Technology 66 (13) (2006) 2016–2022.

[27] H. Fernandes, H. Zhang, X. Maldague, An active infrared thermography method for fiber orientation assessment of fiber-reinforced composite materials, Infrared Physics & Technology 72 (2015) 286–292.

[28] N. Rajic, Principal component thermography for flaw contrast enhancement and flaw depth characterisation in composite structures, Composite Structures 58 (4) (2002) 521–528.

[29] H. Fernandes, H. Zhang, C. Ibarra-Castanedo, X. Maldague, Fiber orientation assessment on randomly-oriented strand composites by means of infrared thermography, Composites Science and Technology 121 (2015) 25–33.