DAMAGE DETECTION IN HONEYCOMB SANDWICH PANELS BY ACTIVE THERMOGRAPHY

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ABSTRACT

Infrared thermography is one of the effective non-destructive testing methods for damage characterization and identification in structural materials. Infrared thermography induces a temperature variation on the specimen and monitors the surface temperature to detect defects deep inside the structure. It offers advantages such as being non-contact inspect method, scanning large surface area and recording in real time. Although various techniques have been developed for infrared thermography, lock-in thermography (LT) and pulse thermography (PT) are the most preferred ones due to their rapid detection, in-service applicability. LT method uses a sinusoidal heat waves in different frequencies whereas PT, employs an instantaneous heat pulses to excite the specimen temperature and monitor its evolution to identify the defects and manufacturing flaws. In this study, both lock-in and pulse active thermography methods are used to detect different type of defects namely delamination, liquid ingress and debonding in a glass/phenolic prepreg with Nomex™ honeycomb core sandwich composites which is a widely used material in aviation industry. The results are presented comparatively on the basis of advantages and disadvantages.

1 INTRODUCTION

In recent years, the application of honeycomb sandwich composites has increased considerably in aerospace, automotive and marine industries due to their splendid out-of-plane compressive and shear strengths, process flexibility, lightweight, and high chemical and heat resistances. However, this group of structural materials are sensitive to failure and damage under static and impact loadings by or environmental causes such as fluid ingress. Therefore, periodic damage analyzes and safety controls using non- destructive testing or evaluation (NDT&E) is required to identification and evaluation damage in the sample without causing any harm or damage especially in advanced applications such as the aerospace [1-2].

There are variety of techniques for inspection materials, such as pulsed phase thermography (PPT) [2], vibrothermography (VT) [3], shearography testing (ST) [4], acoustic emission (AE) [5-6], and ultrasonic testing (UT) [7]. However, most of NDT methods are time-consuming, labor-intensive, and with limited accuracy. Active thermography is a high-speed, portable, large area and powerful NDT method for composites. Active thermography uses thermal perturbation to identify the defects on the surface or bulk of a structure by monitoring the temperature variation on the specimen surface. Any discontinuities in the surface or bulk of the structure changes the heat propagation pattern inside the structure which will be reflected in the surface temperature [8]. The most commonly used methods among active thermography methods are pulse thermography (PT) and lock-in thermography (LT) due to their rapid detection, in-service applicability and being non-destructive.

Pulse thermography method uses a short pulse of energy in form of flash-light to disturb the thermal equilibrium of the structure. The heat generated by the pulsed energy propagates from the surface of the structure towards the subsurface. Presence of any defect on the surface or bulk of the structure returns the pulsed heat to the specimen surface. Therefore, a localized high- temperature zone will be observed in the damaged area which can be used to determine the location, intensity and depths of the defects.

Temperature field, $T(x,t)$, in PT is the result of solving 1D thermal diffusion equation which is given by:

$$\partial^2 T/\partial x^2=(1/\alpha)(\partial T/\partial x) \tag{1}$$

where T is the temperature and α is thermal diffusivity of the material. Since an ideal heat flux is defined as a pulse with a very short duration of intense unit-area, one- dimensional Fourier equation for the propagation of a Dirac delta function as the basis of PT method is given by [9]:

$$T(x,t) = T_0 + Q/e(\pi t)^{1/2} exp(-x^2/4\alpha t) \tag{2}$$

where e is the thermal effusivity ($e = \sqrt{k\rho c}$), Q is the quantity energy absorbed by the surface, T_0 is initial temperature, t is the time, and x is the depth of the material. At the surface, $x = 0$, Eq. 2 reduces to:

$$T(0,t) = T_0 + Q/(e\sqrt{\pi t}) \tag{3}$$

Eq. 3 tells us that temperature on the surface decreases approximately with time, and relates the heat penetration coefficient which is the rate of material can absorb heat.

On the other hand, lock-in thermography uses a sinusoidal heat flux. In this method, the propagation and adsorption of the modulated heat through the surface of the testing structure results in a temperature variation on the surface. The reflection of the modulated thermal wave by defects results in a transformation on the response wave amplitude and phase [10]. Detailed analysis of the temperature-time history of each pixel by applying Fourier transform (FT) based image processing methods provides an insight into the defect state of the structure by means of phase and amplitude changes caused by the defects acting as thermal barrier during heat propagation. From the one-dimensional solution of Fourier's Law for a sinusoidal thermal wave transmission from a semi-infinite homogeneous material, the thermal diffusion length is given as follows [11]:

$$\mu = (2\alpha/\omega)^{1/2} = (\alpha/\pi f)^{1/2} \tag{4}$$

where ω is modulation frequency ($\omega = 2\pi f$ and f is the wave frequency in Hz and α is thermal diffusivity), and thermal diffusion length is a function of thermal diffusivity α and wave frequency f. The thermal diffusivity of material is given by:

$$\alpha = \kappa / (\rho c_p) \tag{5}$$

where κ is the thermal conductivity, ρ is the density and c_p is specific heat (at constant pressure) of material.

The depth of the defect z can be determined by using the thermal diffusion length formula:

$$z = r_1 \mu \tag{6}$$

where r_1 is correlation constant, and r_1 values range from 1.5 to 2 [12-13].

As a summary, in the LT, the surface of the material is periodically exposed to sinusoidal waves and there will be phase and amplitude delay due to the damage regions and different thermal features of damage and non-damaged region when sinusoidal waves reach the surface of the material. These delays cause temperature differences on the material surface and the thermal camera captures these temperature differences and consequently detects the defects in the material. On the other hand, in PT, sudden heat pulses are applied to the surface of the material. Any discontinuities in sub-surface acting as thermal barrier after the energy reaches and propagates the surface. There are differences in the thermal properties in the defective and non-defective areas, and therefore the temperature difference occurs when the material begins to cool down. The defect in the sample is detected in this way.

In this study, honeycomb sandwich panels consisting of highly fire retardant phenolic resin and Nomex^{TM} core designed for application in an aircraft cabin interior are investigated by LT and PT techniques. To do so, three different artificial damage modes are created in phenolic resin/glass fiber/ Nomex^{TM} honeycomb composites by integration of oil into the honeycomb cells to simulate the liquid ingress, placing a Teflon film between core and face sheet during the manufacturing to create debonding, and using out-of-plane bending of composites to form delamination. PT and LT are successfully applied to characterize three different damage types in details.

2 SPECIMENS DESCRIPTIONS

Three different specimens were manufactured for comparative experiments. Specimens are made of honeycomb sandwich panels which consist of glass fibre reinforced phenolic prepreg and 3.2 mm cell size/ 9.65 mm thickness Nomex™ honeycomb core, and cured under a hot press at 120°C. The arrangement of sandwich panels during fabrication can be seen in the Fig. 1 below:

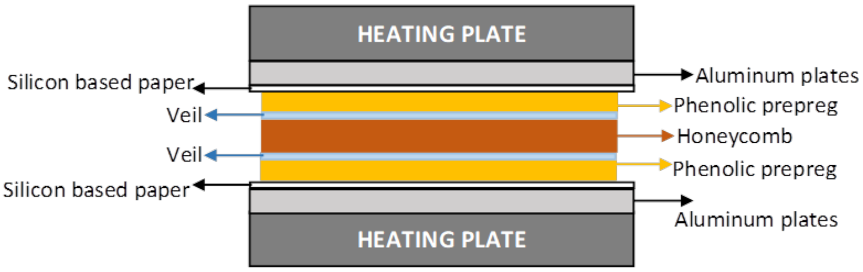

Figure 1: Arrangement of sandwich panels during fabrication.

In order to compare the efficiency and accuracy of PT and LT, three different artificial defects were created in the sandwich structure during/after manufacturing. In the first sample, paraffin oil produced by Sigma-Aldrich was embedded in the honeycomb cells before the curing in order that detect the liquid ingress. In the second sample, Teflon film with dimensions of 180 x 150 cm and with a thickness of 0.127 mm was placed during the manufacturing between the face sheet and the core to perform the debonding in the material. Lastly, in the third sample, sandwich panel was undergone 3-point bending test - based on ASTM C393 standard with Instron brand static test equipment - until fracture point after the manufacturing in order to evaluate delamination.

3 THERMOGRAPHY MEASUREMENTS

Thermography tests were performed using FLIR X6580 SC with 25 mm optic lens thermal camera and the tests were analyzed by Edevis Active Thermography Software. In LT test, 3 halogen lamps were used as heat source and different frequency values were employed to achieve damage detection at different depths of specimen. In PT test, high power flash lamp was used as heat source. Fig. 2 presents the configuration of thermography tests both LT and PT methods.

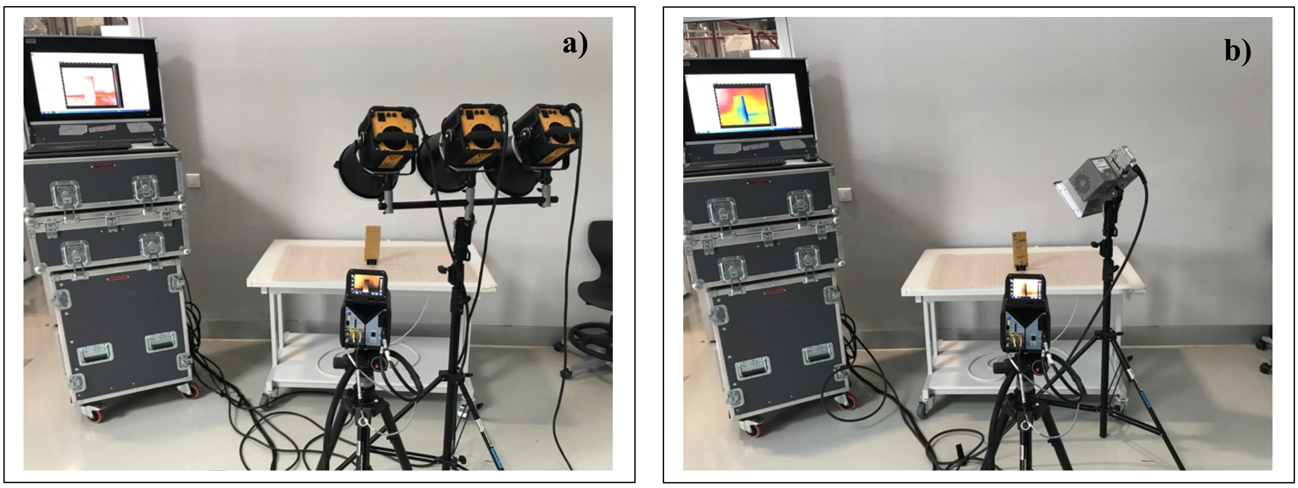

Figure 2: a)LT, and b)PT test set-ups.

Taking Eq. 5 and Eq. 6 in consideration for LT method, the depth of the defect in the sample varies according to the frequency of the heat source, i.e. the lower the frequency is given, the deeper the defect is detected. Accordingly, different frequencies were used from 0.1 Hz to 0.002 Hz in order to locate depth of defect in LT experiments. In particular, very low frequencies were given to delaminated sample since the damage takes part in very deep (approximately 4 mm). The depth of the defects that can be detected approximately according to the given frequencies is shown in Table 1.

Furthermore, according to Eq. 5 and Eq. 6, correlation between defect depths and frequencies were calculated and it is depicted in Fig. 3 which will be used as a calibration graph to estimate the defect depth.

Frequency of Heat Source (Hz)	Depth of Defect (mm)
0.1	1.4163
0.07	1.6928
0.05	2.0029
0.04	2.2393
0.02	3.1669
0.01	4.4787
0.002	10.0147

Table 1: Estimated depth of defect at given frequency in LT.

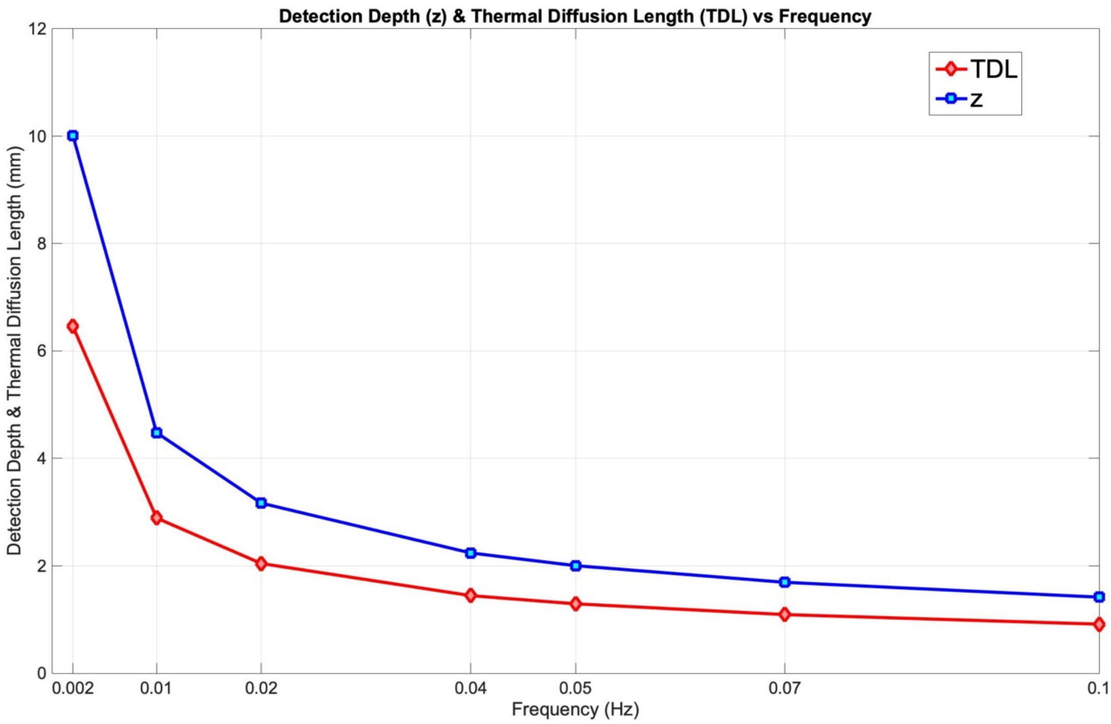

Figure 3: Detection Depth & Thermal Diffusion Length (mm) vs. Modulated Frequency (Hz)

4 RESULTS AND DISCUSSIONS

4.1 Inspection of liquid ingress

The sandwich panels are sensitive for moisture caused by environmental factors and consequently they are susceptible for liquid ingress. This leads to the degradation of the thermo-mechanical properties of the sandwich panels. To simulate this condition, a liquid was injected inside of the honeycomb cells during the manufacturing. After curing the material, LT and PT tests were applied separately for the detection of the liquid in the material. The pre-embedded paraffin oil inside the honeycomb core cells could be detected both LT and PT methods. Selected results are depicted in Fig. 3 and Fig. 4, and the rounded regions indicate the liquid ingress location in the material.

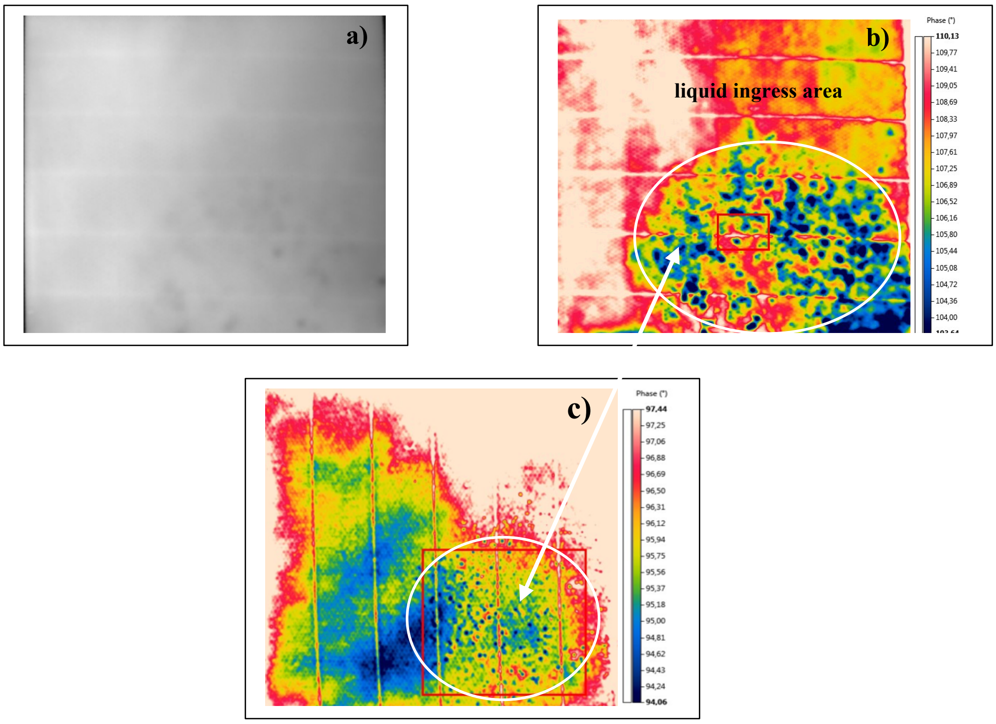

Figure 3: LT images: a) raw image (0.01 Hz), b) FT at frequency of 0.01 Hz, c) FT at frequency of 0.05 Hz for fluid ingress test in sandwich composite.

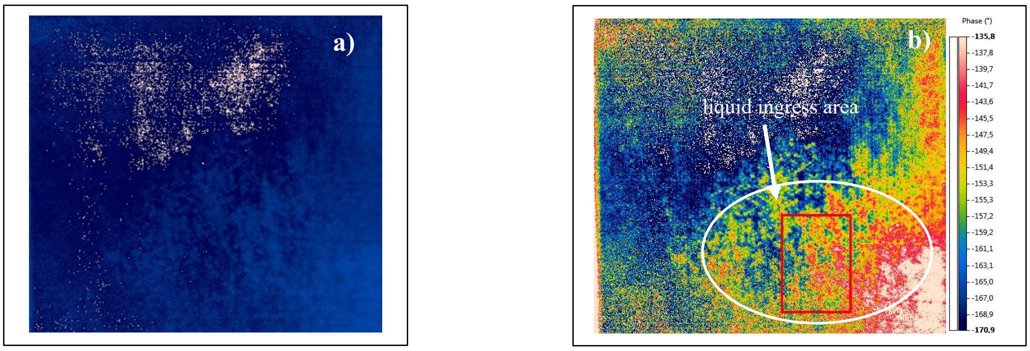

Figure 4: PT images: a) raw image, b) FT at frequency of 1 Hz for fluid ingress test in sandwich composite.

4.2 Inspection of debonding

Debonding in sandwich panels might result in core crush and consequently catastrophic failure. This failure might happen due to defects created during manufacturing e.g. wrinkling of face sheet when compressive forces are subjected to material. Herein, we used a Teflon film between the face sheet and the core during manufacturing to create a debonding and detect it by LT and PT methods. Debonding can clearly be observed by both LT and PT methods. The results are as indicated in Fig. 5 and Fig. 6. They present detection of Teflon film in enframed region.

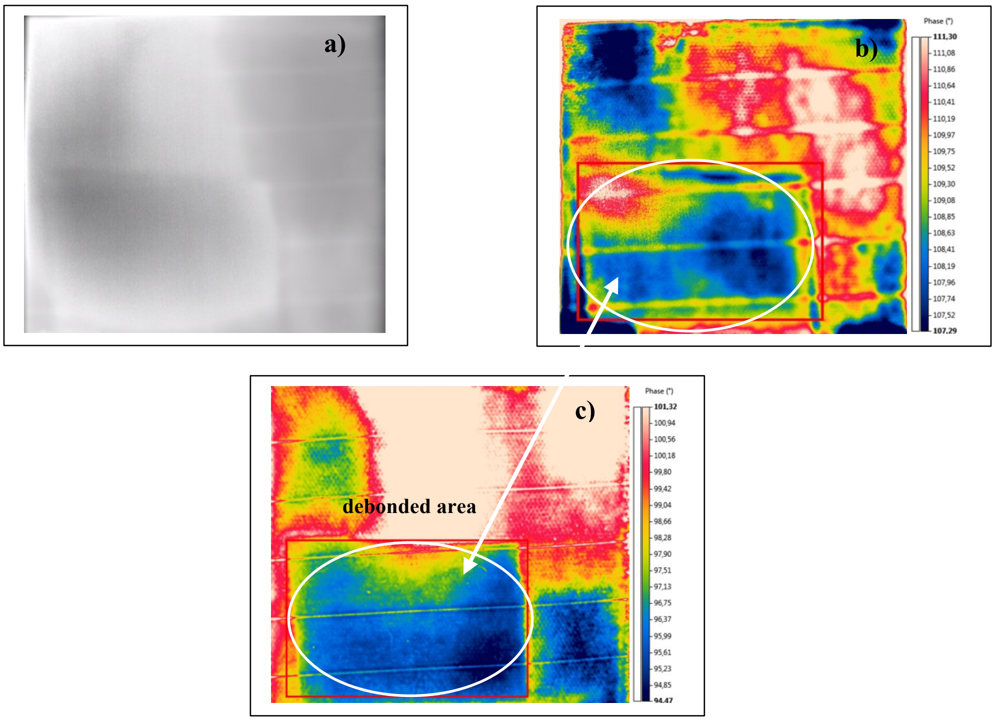

Figure 5: LT images: a) raw image, b) FT at frequency of 0.01 Hz, c) FT at frequency of 0.07 Hz for debonding in sandwich composite.

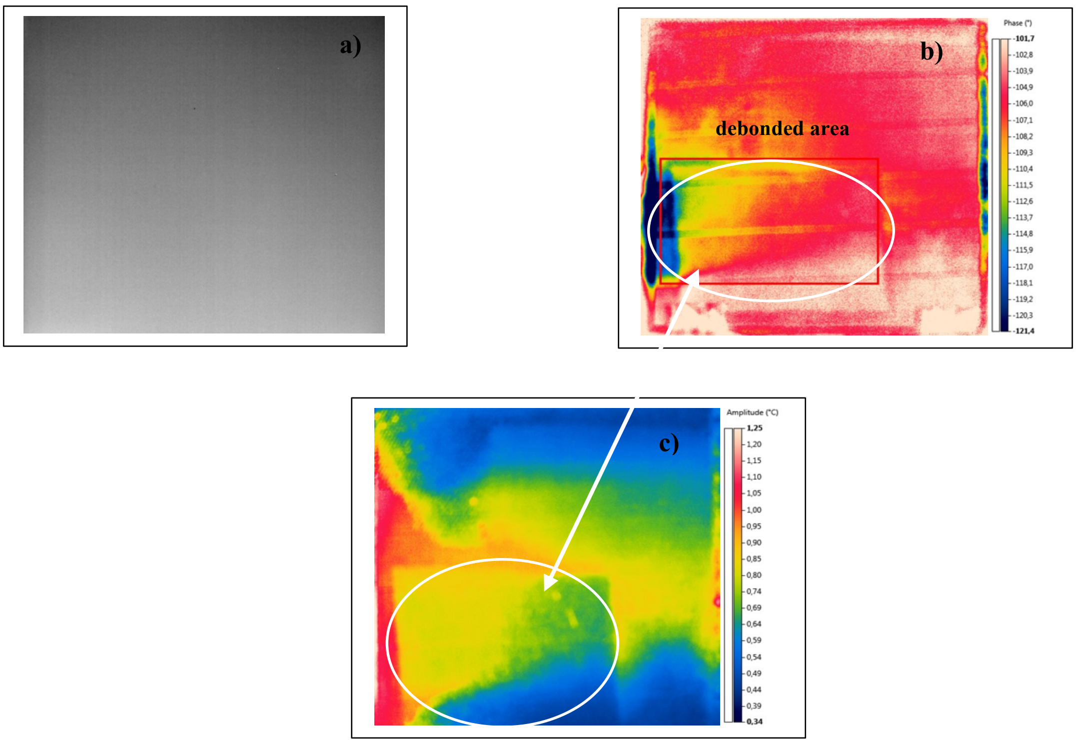

Figure 6: PT images: a) raw image, b) FT at frequency of 1 Hz (phase mode), c) FT at frequency of 1 Hz (amplitude mode) for debonding in sandwich composite.

4.3 Inspection of delamination damages

One of the most common defects in sandwich panels encountered during the manufacturing as well as during in-service of is delamination. Since this defect is emerged inside the material, it is very difficult to determine with naked eye. In order to assess detectability of LT and PT, 3-point bending tests with different loads were applied onto samples. Samples were examined by LT and PT on defective and non-defective surfaces after out-of-plane bending. However, damage boundaries were determined only by the LT method when examined from the non-defective side. Selective results analyzed from non-defective side are exhibited in Fig. 7 and Fig. 8.

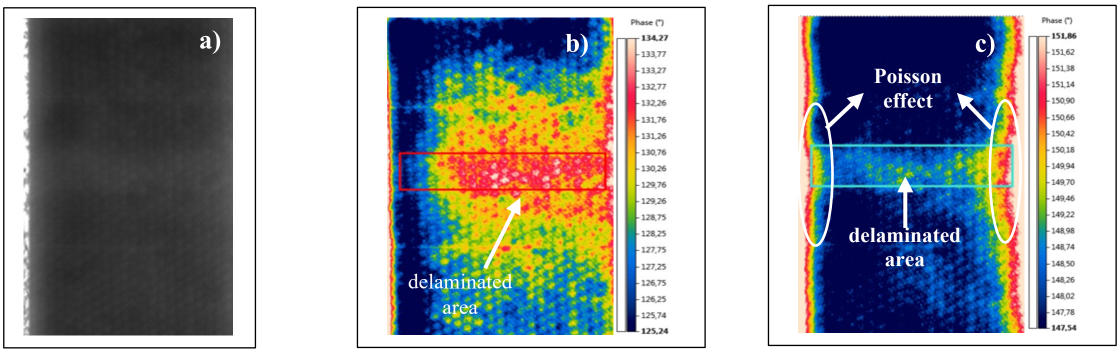

Figure 7: LT images: a) raw image, b) FT at frequency of 0.01 Hz, c) FT at frequency of 0.002 Hz for 3-point bending test in sandwich composite captured from non-defective side.

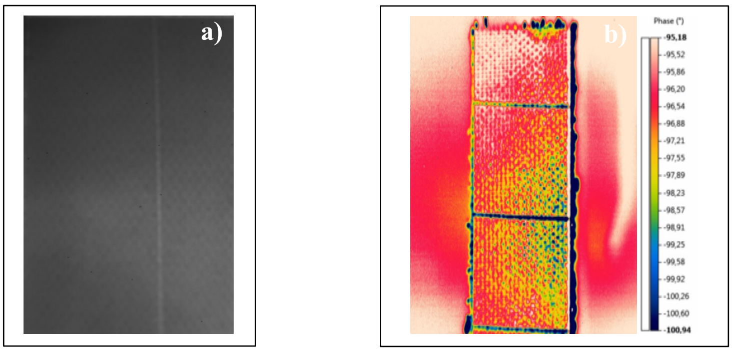

Figure 8: PT images: a) raw image, b) FT at frequency of 1 Hz for 3-point bending test in sandwich composite captured from non-defective side.

4.4 Discussions

In the liquid ingress sample as presented in Fig. 3 and Fig. 4 both LT and PT methods were able to detect the pre-embedded Paraffin oil inside the honeycomb core cells. In the circled region in Fig. 4, blue spots and their surrounding are represent the liquid in the sample. The LT approach provides a clearer and sharper visualization of defect since the energy deposited onto the surface of the test specimen with a heat source having a single frequency in LT. In other words, all liquid ingress are clearly detectable due to equal and sufficient energy with the usage of single frequency which all heat sources convey the same signal simultaneously over the same frequency channel. Moreover, liquid in the sample could be obtained with different frequencies (e.g. 0.01 Hz and 0.05 Hz), see Fig. 3. However, Fig. 3-b gives the more explicit and clearer result as compared with Fig. 3-c since the heat is distributed more homogenously on the sample, i.e. the lower the frequency the deeper the heat penetration. This result also corresponds to estimated depth of defect at given frequency as given in Table 1. According to Table 1, if a frequency of 0.01 Hz is applied, a defect of 4.4787 mm depth is detected, and/or if a frequency of 0.05 Hz is applied, a defect of 2,0029 mm depth is detected. Therefore, it is seen that the liquid ingress is about 4.5 mm deep in the sample as can be seen in Fig. 3-b. On the other hand, although liquid in the sample was detected by PT after applying FT to raw image, the results are not as explicit as LT. The reason for this, the energy deposited on the surface of the test material is by using of flash as a heat source causes reflections and non- homogenous heating in the material at different frequencies.

For the second specimen with Teflon film between the face sheet and the core, debonding can clearly be detected by both PT and LT methods as shown in Fig. 5 and Fig. 6. In this defect type, LT method provided better insight into the internal damage compared to PT even in higher frequency, because damage was emerged in the subsurface of the sample. Hence, there are more possibility of controlling the thermal exposure of specimen surface in terms of intensity. On the other hand, PT suffers from non-uniform exposure and non-uniform heating due to emissivity variations. Nevertheless, debonding in the sample could be detected, especially amplitude mode in Fig. 6-c due to Teflon is embedded close to subsurface.

The LT and PT assessment of delamination damages of the specimen after bending is exhibited in Fig. 7 and Fig. 8. Comparing the results recorded by IR camera in Fig. 7 and Fig. 8, one can easily say that LT is able to detect delamination in phase image from non-defective region. Since the phase image in LT is relatively independent from the optical and thermal surface properties, the detected defect is most clearly visible in phase mode. Here, LT method provides a more accurate view on damage boundaries, and with higher precision to detect the damage depth compared to PT. Moreover, LT reveals the different defects formed after bending at the vicinity of the sample. To get a comprehensive understanding of the damage at a different depth of specimen various frequencies was applied based on the estimation made by Eq. 5 and Eq. 6, and the corresponding estimated depths of defects according to the applied frequencies are shown in Table 1 and Fig. 3. In particular, the delamination resulting from the out-of-plane bending test in the sample of Fig. 7-c is approximately 10 mm deep and this depth is determined if 0.002 Hz modulated-frequency is applied in LT. This determination verifies the estimated damage depths according to the applied modulation frequency shown in Table 1 and Fig. 3. Furthermore, it can be clearly seen that the Poisson effect after bending caused by bending can be detected in Fig. 7-c if very low frequency is applied. Hence, it can be said that the effect of modulation frequency on depth of detected damages was validated by other experimental methods which showed lower frequency reveals information of damage at higher depth while higher frequencies provide information closer to the surface of the specimen.

5 CONCLUSION

In this study, a honeycomb sandwich composite structures with various damage types were inspected by LT and PT techniques. Both methods demonstrated the capability to detect various damages in the structure. In particular;

- In the liquid ingress test, although PT is fast and easy to use, LT provides clearer and sharper visualization image since controlled energy stored on the surface of specimen, and heat can penetrates deeper sinusoidally in LT.
- In the second specimen with Teflon film between the face sheet and the core, despite high speed of PT method, LT method provides us with more accurate and clearer information on the damage state of debonding.
- In the delaminated sample, the LT method provides a more accurate view of the boundaries of damage and provides a higher sensibility to detect the depth of damage compared to PT. In particular, only LT method was able to detect the delaminated region after out-of-plane bending since LT has an advantage of examining thick sample if lower frequency (e.g. 0.002 Hz) is given.

This study demonstrates that the deeper view on how LT and PT can be correlate to the different damage types and different damage depths.

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