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3D Modeling of Thermo Inductive Non Destructive Testing Method Applied to Multilayer Composite

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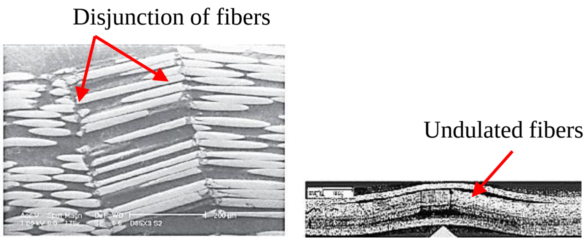
Abstract: Composite materials present many operational advantages such as: weight reduction, high mass specific stiffness and strength, durability. Stratified Carbon Fiber Reinforced Polymer Composite (CFRP) materials are widely used in aerospace industry. During the manufacturing and operating processes, several flaws can occur in the CFRP. For this kind of material, the delamination and fiber rupture are the main flaws encountered which can reduce the mechanical strength and increases the failure risk. The development of these materials cannot be done without an efficient NDT method supported by a high-performance numerical modeling. In this paper, a 3D modeling of a thermo inductive Non Destructing Testing (NDT) technique applied to Carbon Fiber Reinforced Polymer (CFRP) composite is presented. A multi-scale approach is used to calculate the electromagnetic and thermal field distribution. The relevance of the technique is then discussed for different positions of flaws and the optimal frequency is estimated.

Index Terms – *CFRP, Electromagnetic devices modeling, Nondestructive Testing (NDT)*

1 Introduction

Stratified Carbon Fiber Reinforced Polymer Composite (CFRP) materials are widely used in aerospace industry. These materials consist of a pile up of several folds. In each fold, the carbon fibers are oriented in the same direction and bonded together with a dielectric matrix material. In order to ensure the mechanical properties of composites, the fiber's orientation can differ between adjacent folds.



(a) (b)

Fig. 1. Studied flaws (a) Fiber rupture (b) Delamination

During the manufacturing and operating processes, several flaws can occur in the CFRP. For this kind of material, the delamination and fiber rupture, as shown in Fig. 1, are the main flaws encountered which can reduce the mechanical strength and increases the failure risk [1]. These defects are difficult to be detected. This research is dedicated to an accurate model of the stratified CFRP composite material and an original NDT technique for detection and characterization of the two types of flaws presented above.

2 NDT by induction thermography

The induction thermography gains interest in the recent development in the field of active thermography. In this technique, the excitation coil induces eddy currents within the electrically conductive material to a depth determined by the frequency of the excitation source and heats the specimen [2].

The presence of a defect on the surface or sub-surface disrupts locally the current circulation between the layers which generates a thermal perturbation at the surface of the composite. This perturbation leads to the phase shifts of the thermal wave in the defected zone of the specimen with respect to the intact one. Therefore, the defect can be detected by the phase contrast. The phase contrast is obtained by the Fourier transform of the time varying temperatures [3]. The temporal evolution T(t) of the temperature is calculated for each point on the surface at each sampling time step Δt. The Fourier transform is performed by the following well-known formula:

$$F(f) = \Delta t \times \sum_{n=0}^{N-1} T(n\Delta t) e^{-j2\pi f n \Delta t} = Re(f) + j\, Im(f) \qquad (1)$$

where Re(f) and Im(f) are respectively the real and imaginary components of F(f). The phase is then computed for each of the transformed terms using:

$$\varphi(f) = tan^{-1} \frac{Im(f)}{Re(f)} \qquad (2)$$

The difference between the phases obtained in the cases with and without defect gives the phase contrast for each thermal frequency and for each point on the measured surface.

3 Numerical modeling

For composite materials modeling, several issues must be overcome such as heterogeneity and anisotropy of CFRP. There exists also a large scale factor between the fibers diameter and the CFRP dimensions. The microscopic scale or scale of the elementary constituents has a characteristic size in order of the diameter of a fiber (a few micrometers). The characteristic size of the mesoscopic scale is the thickness of a fold (a few tenths of a millimeter). The macroscopic scale consists of an entire plate. Its size is generally in order of few dozen folds thickness by some meters long. In this case, simulating the real structure is impossible. To deal with this problem, a two scales modeling is developed. In the microscopic scale, the current circulation between fibers is studied to obtain the homogenized equivalent tensor of electrical conductivities. This tensor is obtained by the percolation model that we developed in our previous research [4]. The tensor of thermal conductivities is obtained from experimentation. In the macroscopic scale, the conductivities tensor is used in a 3D finite element model to solve the electromagnetic and thermal problems.

Composite materials have a highly anisotropic nature. The anisotropy is essentially due to the orientation of the reinforcement (fibers). It leads to the necessity of taking into account the modification of the tensor of physical properties for the folds with different orientations of fiber.

In the other hand, the modeling of the induction thermography technique uses the thermal-magnetic interaction. Magnetic and thermal phenomena are, in our case, described by partial differential equations. The Eddy losses are introduced as source of heat into the thermal model. We also assume that the electromagnetic phenomena reach their steady states prior to the thermal computation.

The system is simulated using a 3D finite elements method. The coupled edge element electromagnetic A-ψ [5] and nodal thermal formulation (3), (4) and (5) is used to calculate the temperature distribution at the measured surface.

$$\int_{\Omega} \left(\boldsymbol{curl} w_a \frac{1}{\mu} \boldsymbol{curlA} + [\sigma] w_a\, j\omega (\boldsymbol{A} + \boldsymbol{grad}\psi) \right) d\Omega - \int_{\Gamma} w_a \left(\boldsymbol{n} \wedge \frac{1}{\mu} \boldsymbol{curlA} \right) = \int_{\Omega} w_a \boldsymbol{J}_s d\Omega \qquad (3)$$

$$\int_{\Omega} \left(j\omega [\sigma] \boldsymbol{grad} w_n\, (\boldsymbol{A} + \boldsymbol{grad}\psi) \right) d\Omega = 0 \qquad (4)$$

$$\int_{\Omega} \left(\rho C_p \frac{\partial T}{\partial t} - div[\lambda] \boldsymbol{grad} T \right) w_n\, d\Omega = \int_{\Omega} P w_n\, d\Omega \qquad (5)$$

where A and ψ are respectively the magnetic vector potential and the time derivative of scalar electric potential, C_p is the specific heat and ρ is the specific mass of the material, P is the electromagnetic induced power density, [σ] and [λ] are respectively the tensor of electrical and thermal conductivities. The edge shape function and nodal shape function are denoted by w_a and w_n.

4 Simulation results

In order to study the influence of several parameters on the thermal response of the defect, the magneto-thermal model is used to simulate a composite plate with and without flaw. The simulation is carried out with a 250mm x120mm x2.2mm CFRP plate with 16 folds. This sample is heated during 2s by means of a U-formed inductor which is placed in the direction of the fiber of the 0° folds. The positions of these folds are given in the Fig. 2. We also assume that only the 0° fold is defected. Two kinds of flaw are studied: fibers rupture in a fold and delamination between two folds. The fiber rupture defect is simulated with various frequencies and various depths. Its dimensions are given in the Fig. 3 (a). In this case, the flaw thickness is equal to the thickness of the fold. The same trials are performed with the delamination flaw. The thickness of the delamination is equal to 10 μm. The flaw depth corresponds, for two kinds of flaw, to the depth of the defected 0° fold as shown in the Fig. 2.

Due to the fact that the delamination and the fiber rupture have different natures, we use two models for each kind of defect. In the case of the fiber rupture, the fibers are interrupted. The defect does not allow any current circulation in the fiber direction. The current is forced to pass through folds and deviated when passing the defect, as shown in the Fig. 3 (a). In the case of the delamination, the fibers are not cut but undulated; the current circulation is unbroken in the direction of the fibers as shown in the Fig. 3 (b). In the following paragraphs, the simulation results for induced power distribution in folds, phase contrast cartography, temperature evolution and phase contrast at the measured point are examined.

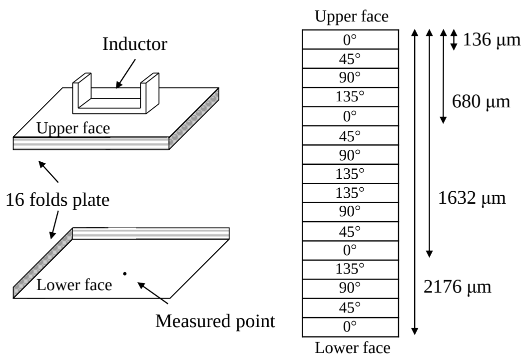


Fig. 2. Configuration of the test, measured point is placed at the center of the lower face

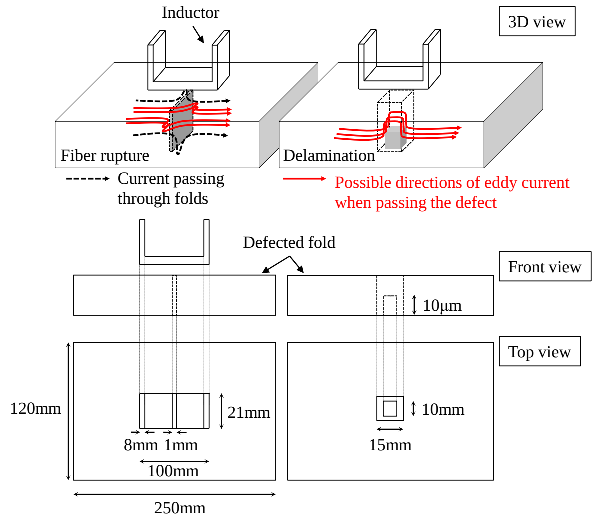


Fig. 3. Plate and defect dimension (a) fiber rupture defect (b) delamination

Fig. 4 shows the cartography of the phase contrast on the observed surface at the thermal frequency of 0.125Hz. The defect is detected by the zone of about 10°-15° higher angle. The appearance of this area reflects the shape of the defect. As shown in the Fig. 5, the phase contrasts at the center of this face for different flaw depths are clearly distinguished. The maximum phase contrast is higher for flaws closer to the observed surface. This gives the possibility to qualify the position of the defect. The result given in the Fig. 6 demonstrates that the electromagnetic frequency plays an important role in the efficiency of the detection and qualification of the technique. In this case, the optimal frequency for which we obtain the highest maximum phase contrast is 3MHz.

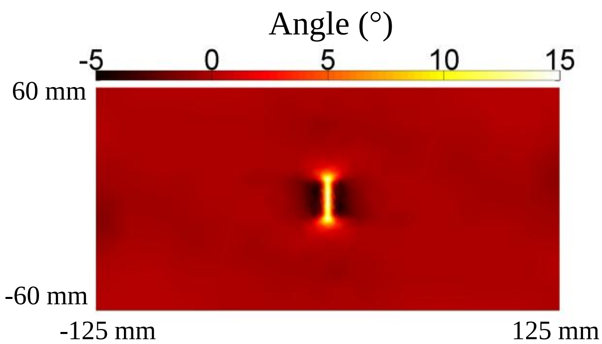


Fig. 4. Phase contrast cartography at thermal frequency of 0.125 Hz for the flaw depth of 1632 µm and electromagnetic frequency of 0.5 MHz

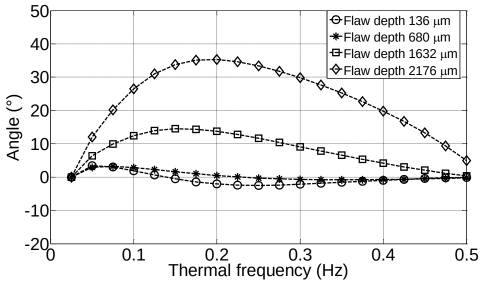


Fig. 5. Phase contrast at the measured point with various depths of flaw with the 0.5 MHz electromagnetic excitation frequency.

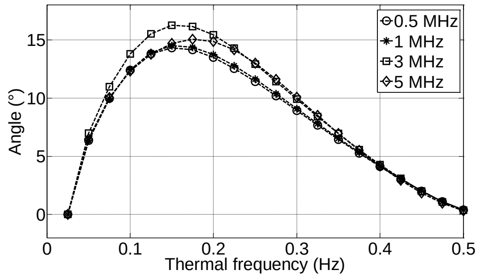


Fig. 6. Phase contrast at the measured point with various electromagnetic frequencies (flaw depth of 1632 µm)

Fig. 7 shows that the phase contrast cartography given by the delamination is different from the one given in the case of fiber rupture. With this result, we can affirm that the induction thermography technique is capable to distinguish the two kinds of flaw. This technique also permits a better recognition of the form and the nature of the defect. The result in the Fig. 8 shows that the delamination with various depths has a sufficient large different signature to be qualified between them. The minimum phase contrast is smaller if the delamination is further from the measured surface.

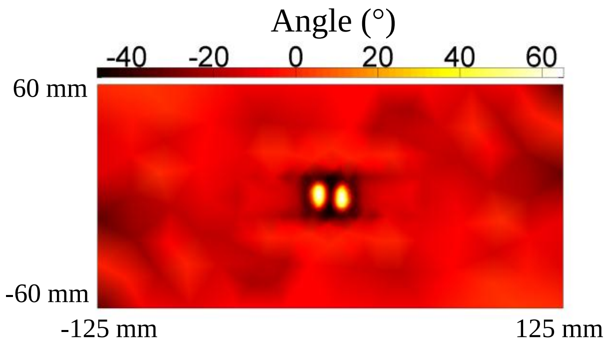


Fig. 7. Phase contrast cartography at thermal frequency of 0.125 Hz for the flaw depth of 1632 µm, flaw thickness of 10 µm and electromagnetic frequency of 0.5 MHz.

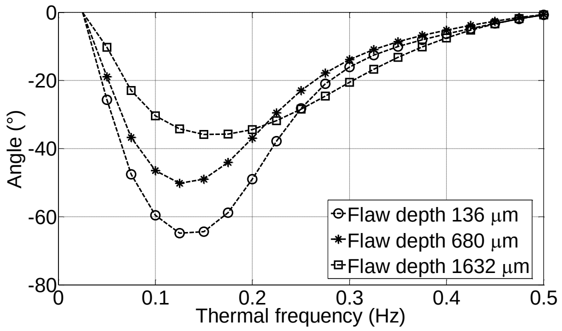


Fig. 8. Phase contrast at the measured point with various depths of flaw (with the thickness of 10 µm) with the 0.5 MHz excitation frequency

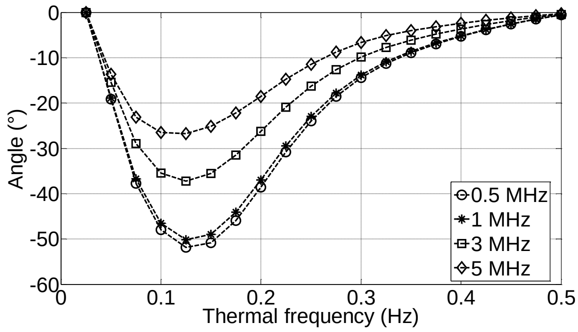


Fig. 9. Phase contrast at the measured point with various electromagnetic frequencies (flaw depth of 680 µm, flaw thickness of 10 µm)

Fig. 9 shows the result for a delamination with different frequencies. It can be seen that there exist an optimal frequency at which the contrast is minimum which is, in this case, the frequency of 0.5 MHz. With the support of numerical model, we can determine the range of excitation frequency and other testing conditions in which the defect can be better detected and characterized.

5 Conclusion

In this paper, a validated numerical model of the induction thermography NDT method for the stratified composite material has been used in order to study the effect of different kind of flaws on the thermal response. The equivalent tensor of physical properties for each fold of the multilayer CFRP plate is obtained by using a homogenization model. A 3D magneto-thermal finite element model is then used to calculate eddy currents and thermal distribution in the piece with and without flaw. We demonstrate that this NDT method is well suited to detect and qualify delamination and fiber rupture flaws at different depths. The results show that this technique can distinguish different kinds of defect using the phase contrast cartography. The developed model would allow studying the efficiency of this method for different kinds of flaw, inductors and frequencies.

References

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