



STRUCTURAL HEALTH MONITORING OF CFRP DURING FATIGUE LOAD VIA THE ASSESSMENT OF CRACK DENSITY BY MEANS OF THERMOGRAPHY

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Abstract

In present work, a new procedure is presented to measure the crack density via thermography in quasi-isotropic CFRP made by an innovative industrial process: Automated Fiber Placement.

The measured crack densities during constant amplitude fatigue tests were used to be compared with the Ogin analytical model.

The thermal parameter adopted was the second amplitude harmonic of the temperature signal that allowed to detect the presence and the onset of transverse cracks.

The importance of the adopted approach lies in the possibility of carrying out measurements of cracks during in-service conditions and assessing rapidly the level of damage related to the stiffness reduction.

Keywords: CFRP, Crack Density, Thermography, Fatigue

1. Introduction)

The crack density is a very well-known damage parameter representing the actual mechanical state of the material in terms of stiffness degradation [1]. In effect, for laminates presenting off-axis laminae, crack density is useful for determining the “characteristic damage state” (CDS) [2] that is related the load bearing capability of the laminate.

In literature, analytical and empirical models in addition with experimental procedures are used for the assessment of crack density. However, in all cases, accurate experimental setups and time-consuming analyses are required.

Present research is focused on proposing a novel procedure for performing contactless measurements of crack density during constant amplitude fatigue tests by using temperature second amplitude harmonic (SAH) [3] without any material properties assessment. The results provided by analytical model [4] were in good agreement with the measured crack densities at different stress levels demonstrating the capability of the proposed parameter provided by the thermal signal analysis to describe damage mechanisms affecting the specific material.

The proposed procedure leads to estimate the crack density in those applications where it is difficult to detect transverse crack with a direct measurement using common experimental techniques.

2. Theoretical Framework

Crack density can be conventionally corresponding to the inverse of twice the distance between two

consecutive transverse cracks [4-6]. As found by different authors [1-2], a typical damage occurrence at life percent less than 50% of the total cycles involves transverse cracking and transverse or longitudinal splitting [8,9].

Ogin-Beaumont [4] were the first that proposed a simple formulation for the stiffness degradation being related to crack density [4,10-11]:

$$\rho_o = \frac{1}{C} \left(1 - \frac{E}{E_0}\right) \quad (1)$$

where ρ_o is the inverse of the average crack spacing and C is a constant. The left term indicates the ratio between delaminated area and initial area of the composite, in effect crack density influences the loading bearing capability that in turn is represented by the percentage of cross section that is transferring the load over an initial/nominal area [12]. Even if more complex models have been developed by other authors [11,13], the Ogin-Beaumont one, still remain a useful tool for the damage analysis of composites.

By considering the limits of the current literature procedures and techniques in detecting and counting the crack number [13-15], the aim of the present study is to propose novel procedure to detect 90° ply cracks and estimate the crack density during the application of cyclic loadings at different stress levels. The proposed procedure is based on the study of the second amplitude harmonics of the temperature signal related to damage and energy dissipation processes [16-20]. In particular, the main advantage of the proposed approach with respect to the other non-destructive thermographic methods, is the capability of detecting cracks on samples during the applied loading without any external heat source [18].

Accounting for the complex damage mechanisms of composites, the effect of damage on the temperature signal can be investigated by comparing damaged and undamaged conditions. Following this, it can be assumed that in a region where the composite experiences a damage mechanism such as a crack, there will be concurrent mechanisms affecting both reversible and irreversible heat sources, and then influencing components of the temperature signal. In previous works [3,18,20], in order to describe the temperature signal component variations, a suitable algorithm was used where uncalibrated signal $S(t)$ was a time dependent function exhibiting both linear and cyclic terms. Eq. (2), allows a signal reconstruction via the different temperature components, pixel by pixel of thermal image, by using a least square fitting method:

$$S(t) = S_m + S_{1\omega} \sin(\omega t + \varphi_1) + S_{2\omega} \sin(2\omega t + \varphi_2) + S_{3\omega} \sin(3\omega t + \varphi_3) + \dots + S_{n\omega} \sin(n\omega t + \varphi_n) \quad (2)$$

Where S_m is the mean temperature signal, $S_{1\omega}, S_{2\omega} \dots S_{n\omega}$ represent respectively the amplitude harmonic components at one-twice-triple- ..-umpteenth angular frequency f (the mechanical frequency) while $\varphi_{1\omega}, \varphi_{2\omega} \dots \varphi_{n\omega}$ are respectively the phase shifts.

Eq. (2) will be used for extracting the second harmonic temperature variations as parameter related to intrinsic irreversible sources to detect the damage in terms of 90° ply cracks.

3. Material and Methods

The material tested in the present research was a quasi-isotropic laminate made by the innovative technological process of automatic ply deposition called Automated Fibre Placement [21]. The stacking sequence was [90/- 45/45/0/0/45/- 45/90]₂. Fatigue tests involved constant amplitude loadings (runout fixed at 2*10⁶ cycles), under force control using a stress ratio of 0.1 and a loading frequency of 7 Hz. The applied load ranged between 50%Ultimate tensile strength (UTS) of the material and 75%UTS. Infrared sequences were acquired by a cooled In-Sb detector FLIR X6540 SC (640x512 pixel matrix array, thermal sensitivity NETD less than 30 mK) positioned in front of the loading frame (Figure 1).

The methods adopted for estimating the crack density are provided according to the flowchart in Figure 2. Specifically, the crack density evaluated from synthetic data using Ogin' model has been indicated as pO_{th} while p_{meas} has been evaluated by measuring strain and calculating stiffness degradation from stress-strain curves. These are compared with the crack density provided by thermal signal analysis (p_{therm}) using the parameter $S2\omega$.

The procedures to evaluate the crack densities in particular p_{therm} are well explained in [3]. The code for analysing $S2\omega$ was implemented in Matlab®. It involved the $S2\omega$ maps analysed in such a way to scan column by column the temperature profile to find the signal peaks that represented the crack. Once at least ten pixels along the row presented such a maximum signal value, the transverse crack was recorded. This operation was carried out from the maps corresponding to the beginning of the test until the end. Finally the $S2\omega$ maps were binarized: the threshold took into consideration was the mean value plus the standard deviation of the signal in the gage length of the sample.

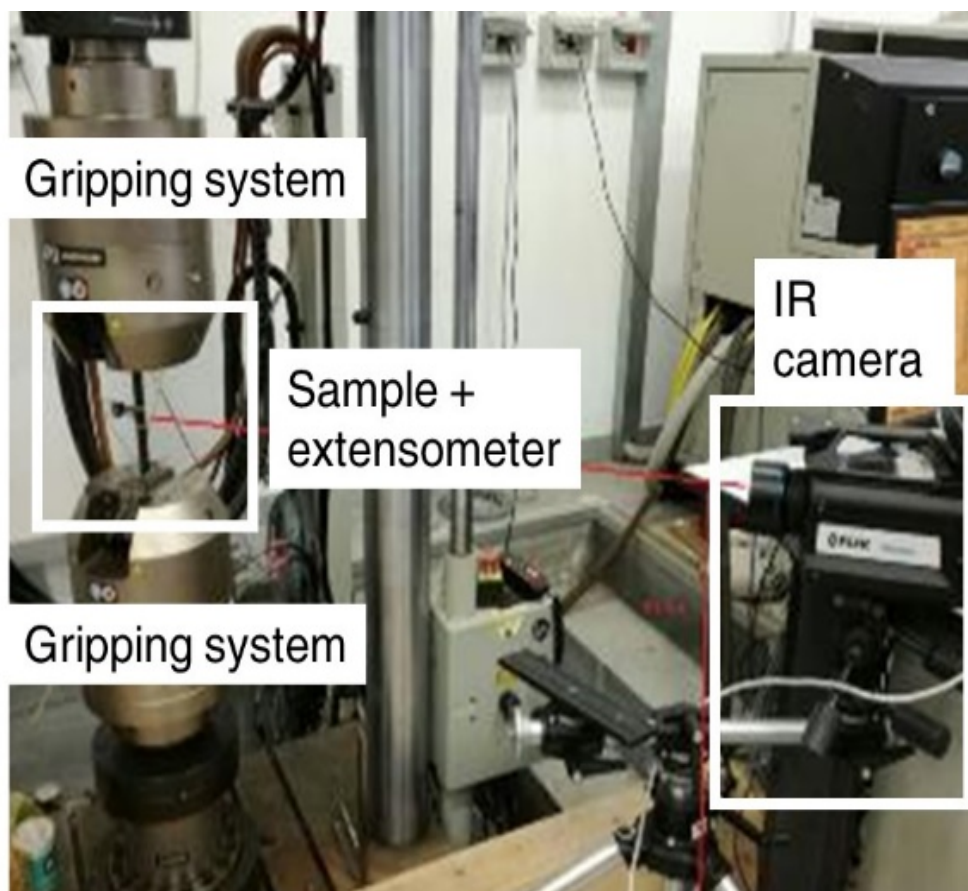


Figure 1 – Adopted equipment and setup for fatigue testing monitored by infrared thermography.

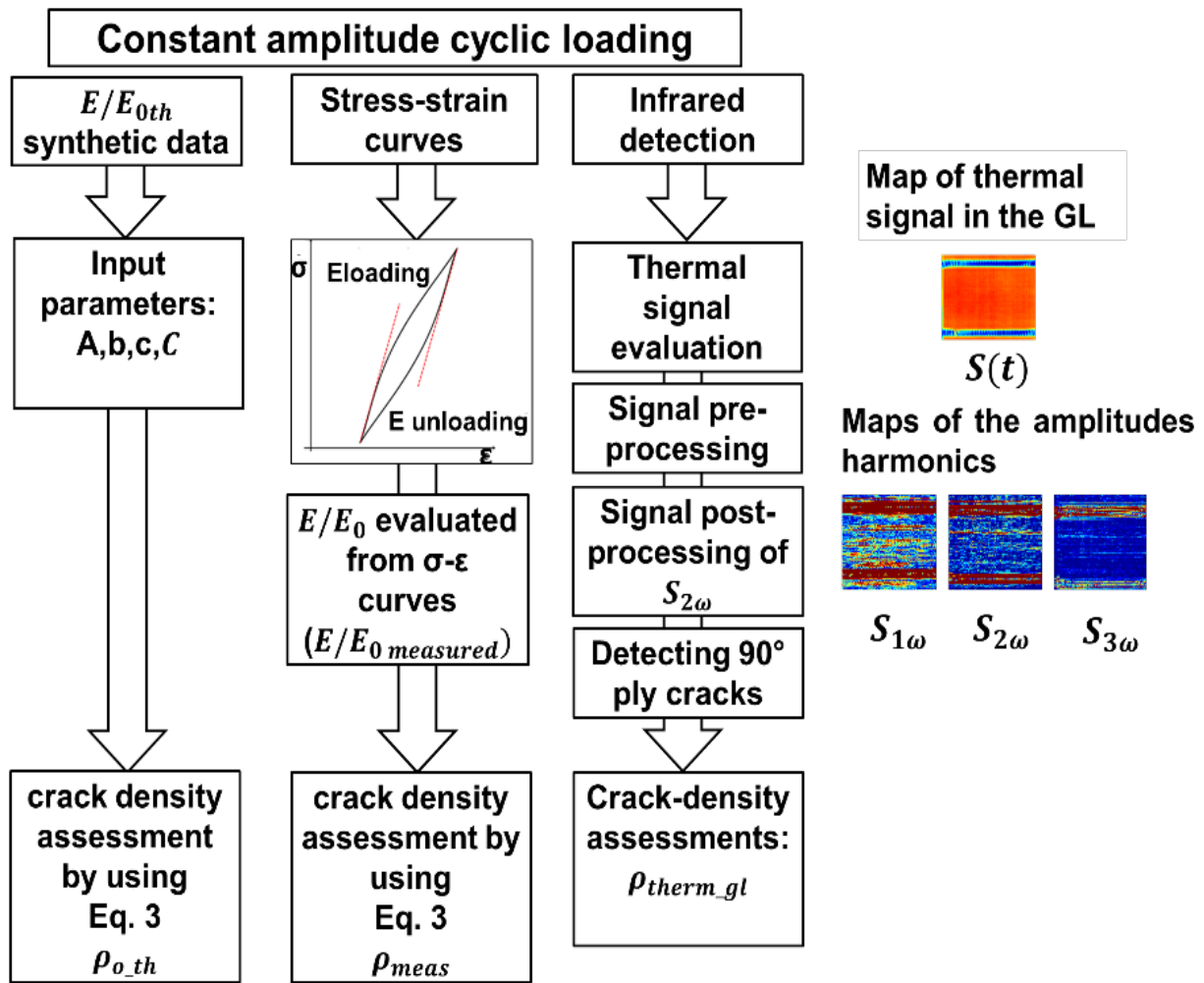


Figure 2 – Flow chart of the evaluated crack densities.

4. Results

In present section, the synthetic data are presented according to the model of Ogin-Beaumont' [11]. Figure 3, shows the Ogin-Beaumont curves from the model couple with the Ogin' modelisation of stiffness degradation for a generic composite material at different stress levels.

From Figure 3, it is possible to observe that the crack density according to the analytical model can only increase without reaching a steady state condition (Characteristic Damage State [22]) that is a frequent material state related to the saturation of transverse cracks.

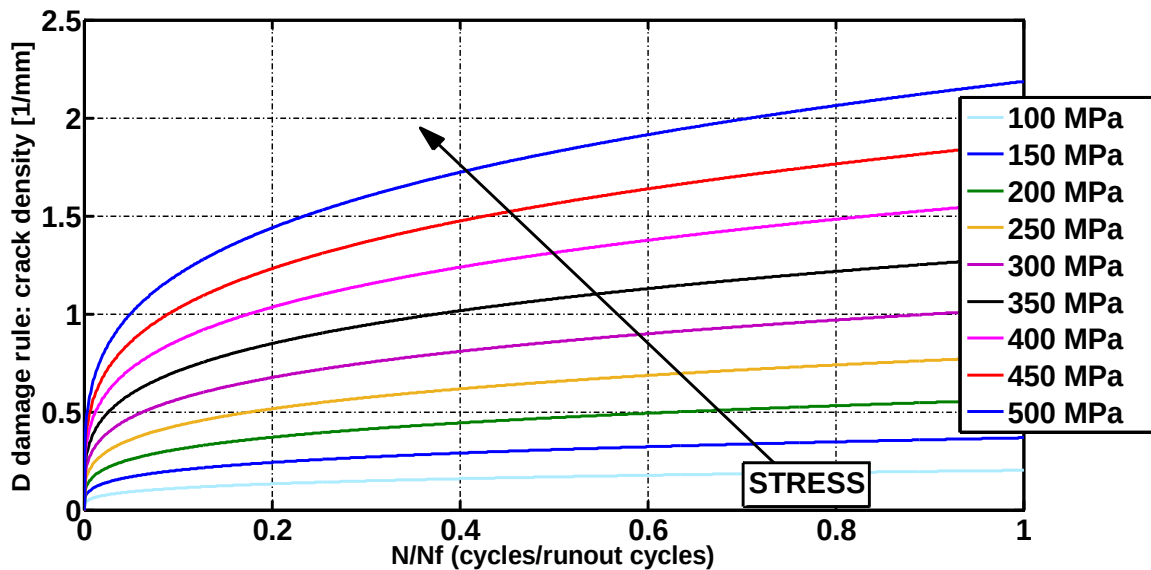


Figure 3 – Crack densities according to the Ogin-Beaumont' model

Figure 4, reports different S2 ω maps corresponding to different cycles/total cycles (life fraction) of the material and a curve representing the peak number obtained from thermal maps.

From the maps it is possible to detect clearly the transverse cracks producing a significant temperature variation even on second harmonics.

In Figure 5, the crack densities obtained from temperature data and related to tests run at different stress values are presented. In figure 4, it is possible to observe a slight stress effect (the higher is the imposed stress the higher are the crack density values) and the presence of Characteristic Damage State starting from roughly 30% of material life fraction in each test.

By comparing qualitatively Figure 3 with Figure 5, it is possible to draw the conclusion that analytical models representing the crack density evolution and/or crack density variations with respect to the stress are useful to get a general idea of the material behaviour but the experimental measurement reproduces the real behavior of the material.

More in depth, in Figure 6 are represented the curves of the different crack densities : ρ_O , ρ_{meas} , ρ_{therm} . Under quantitative point of view, the last two are in a very good agreement while the synthetic data modeled via Ogin' presents completely different values. This error could be due to the fact the 'C' constant in Ogin-Beaumont' model (Eq.1) is from literature. Moreover, it is possible to highlight that for the two stress levels (figure 6a and 6b) ρ_{therm} fits very well ρ_{meas} .

Even if, thermography is mainly a surface technique and the presented crack densities are an estimation of the total crack density of the material, the ρ_{therm} could be a useful tool to:

- validate numerical models,
- provide the real material damage evolution (onset of cracks, presence of CDS, crack saturation),
- make speculation on residual life of the material.

The use of such a method is interesting because it does not require to stop the test and move the sample or material, and it could be easily applied also to the component without necessity of painting the surface to increase the emissivity.

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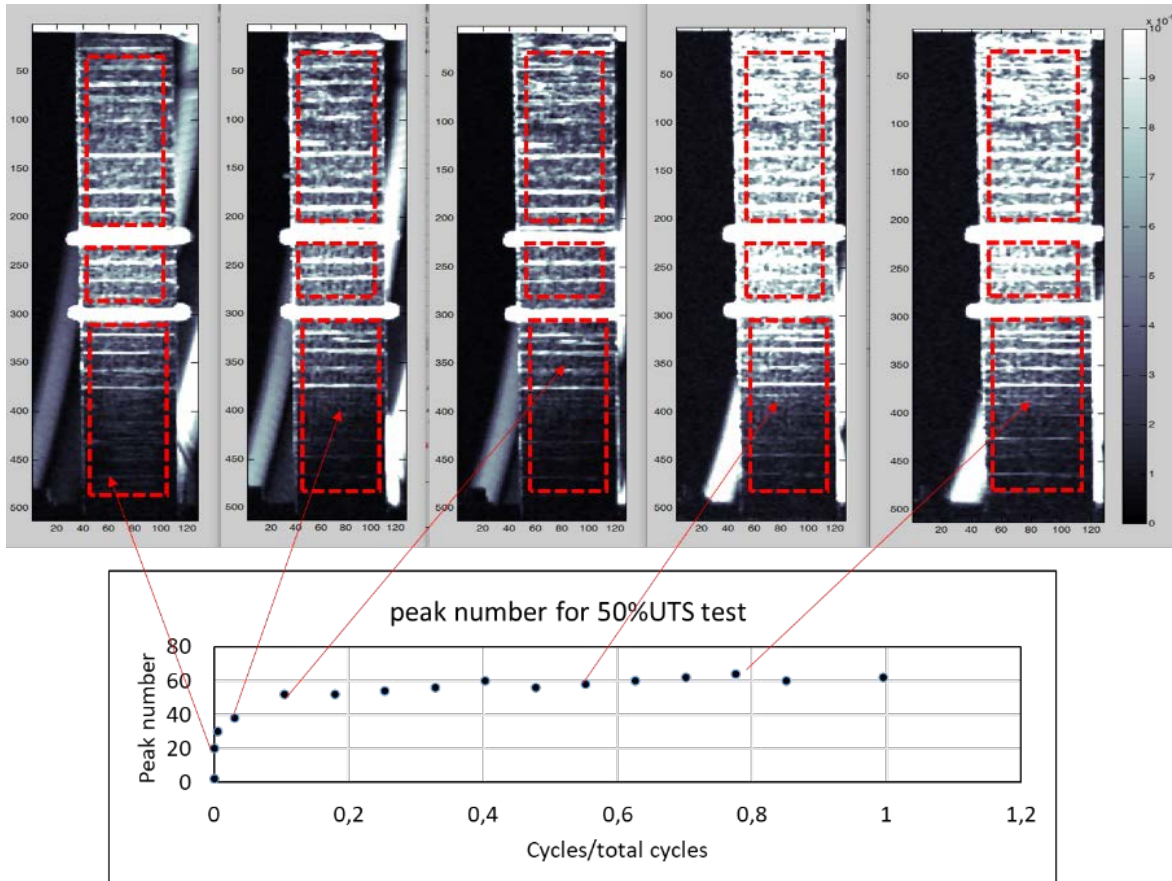


Figure 4 – . Second amplitude harmonic thermal maps and peak number related to the transverse cracks.

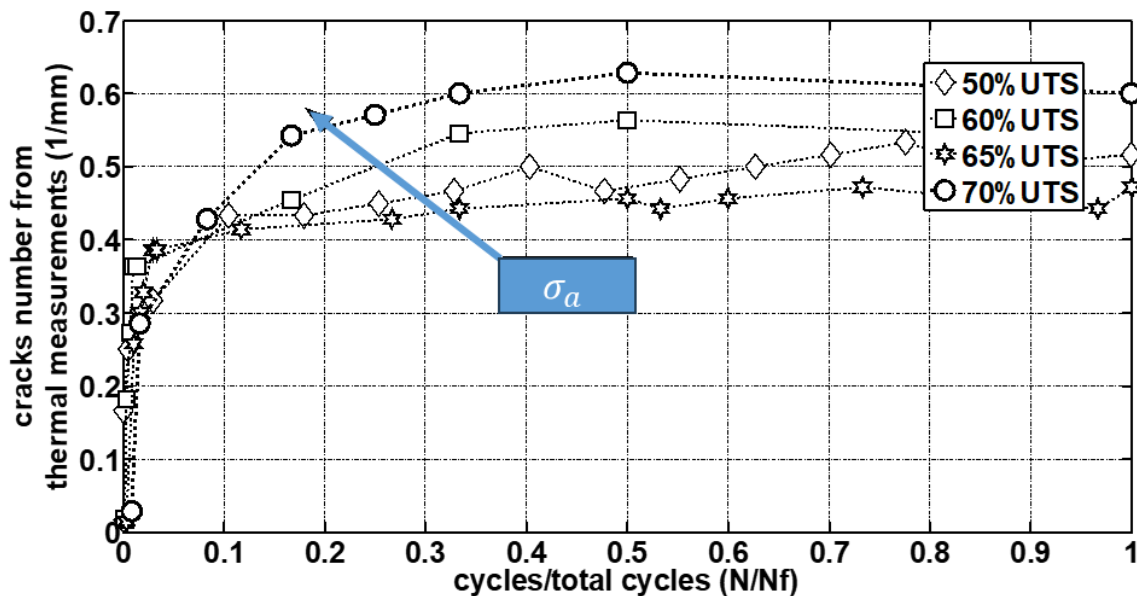
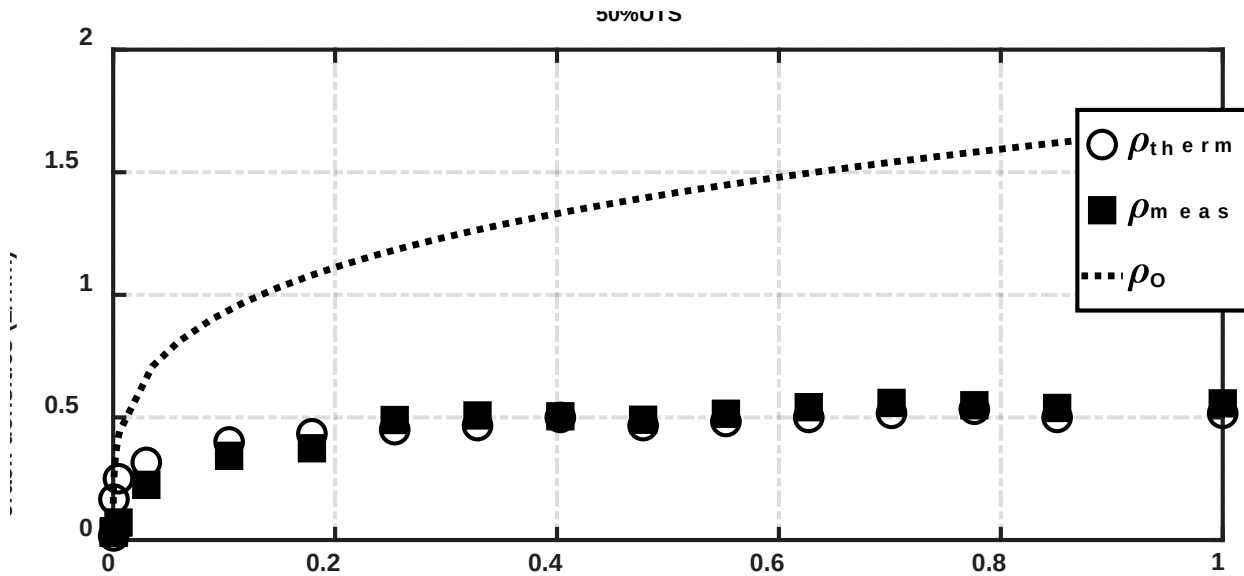
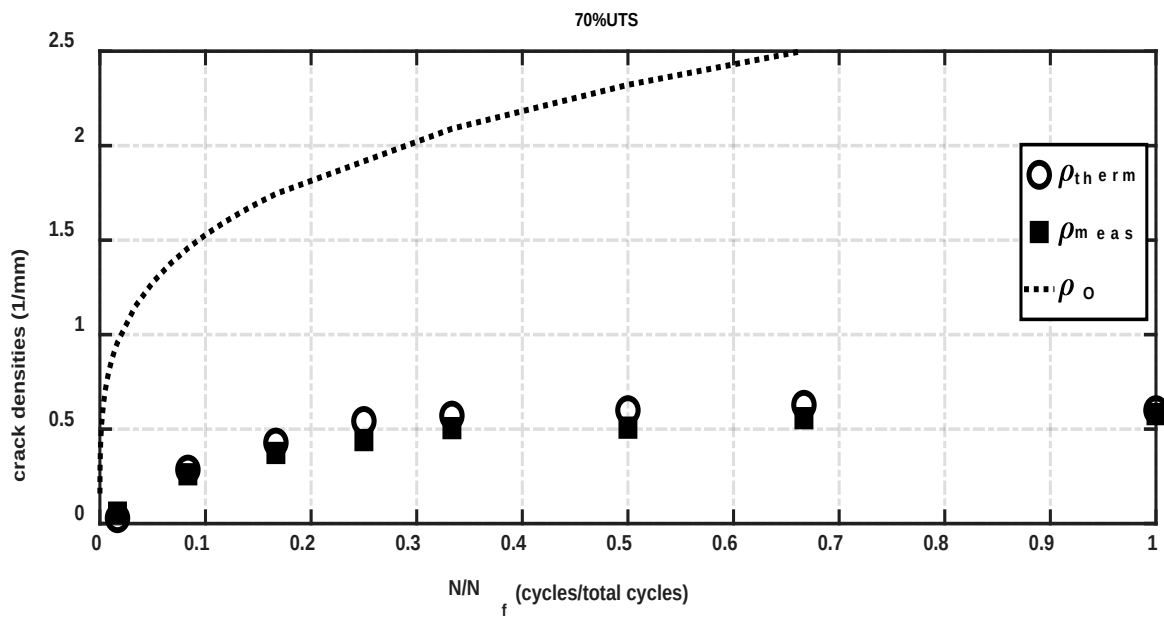


Figure 5 – crack densities evaluated using S_{2w} thermal parameter

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(a)



(b)

Figure 6 – Comparison among ρ_{therm} , ρ_O , ρ_{meas} for two different stress levels.

5. Conclusions

In the present paper, a new procedure using the second harmonic amplitude component of temperature signal acquired during fatigue tests was used to detect the 90° ply cracks and to assess the crack density in a quasi-isotropic CFRP specimens made by automated fibre placement.

The crack densities (ρ_{therm}) evaluated by using second amplitude harmonic of temperature have been successfully compared with the pioneer model proposed by Ogin-Beaumont using synthetic E/E_0 (ρ_o) data and measured E/E_0 data (ρ_{meas}).

It should be noted that thermography is a surface, contactless technique and allows an estimation of the damage present in the more superficial layers. The major advantage of using thermography is that it does not require complex setup. In this way, the present approach allows continuous measurements, and an ease to implement analysis. The technique can be useful in those applications where it is difficult to apply the extensometer or to measure number of cracks by using classical experimental techniques. However, it allows the surface and sub-surface crack detection and then the technique provides only an estimation of the crack density.

The importance of the adopted approach lies in the possibility of carrying out measurements of cracks during in-service conditions and assessing in a rapid way the level of damage related to the stiffness reduction.

Further developments will involve the application of the approach outside the laboratory.

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