DETERMINATION OF THE FATIGUE LIMIT FOR CARBON/EPOXY COMPOSITES WITH A CENTRE HOLE THROUGH SELF HEATING METHODOLOGY

Deepika Sudevan [1], Laurent Gornet [2] and Patrick Rozycki[3]

[1] Machine Design Section, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai - 600036, India. deepika.sudevan@gmail.com
[2] Institut de Recherche en Génie Civil et Mécanique (GeM), Ecole Centrale de Nantes, Nantes - 44321, France. Laurent.Gornet@ec-nantes.fr
[3] Institut de Recherche en Génie Civil et Mécanique (GeM), Ecole Centrale de Nantes, Nantes - 44321, France. Patrick.Rozycki@ec-nantes.fr

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ABSTRACT

This article reports the limit of fatigue for woven carbon fiber epoxy composite specimens with a hole of 6 mm diameter at its centre using the self-heating methodology. The self-heating methodology is a relatively new and economical method to determine the fatigue limit of materials **[1-4]**. The conventional method to determine the limit of fatigue, like the Wöhler curves, would require one to perform classical fatigue tests on several specimens for many months to obtain the S-N curve. Whereas, only two to three specimens are required to determine the limit of fatigue using the self-heating methodology and each experiment takes only a few hours to a day's time. The carbon fiber reinforced polymer matrix (CFRP) composites specimens are subjected to a constant amplitude block load cycling sequence, with increasing levels of mean stress (σ_m) in the subsequent blocks and the temperature response is monitored. The stabilised surface temperatures or the peak point surface temperatures are plotted against the maximum stress amplitude in each loading block. This plot is called the self-heating curve. CFRP specimens of both [0/90] and quasi-isotropic configuration with and without centre hole are tested. The results are compared with the results of the CFRP specimens without a hole to draw conclusions. It is observed that for the specimens with the centre hole, more number of cycles per loading block is required for the stabilization of specimen's surface temperature. The stress concentration around the centre hole plays a critical role in the stabilization of the surface temperature. The robustness of an innovative "peak-temperature point" approach under the self-heating methodology is also investigated. This novel approach which is well suited for CFRP specimens with an inherent defect or flaw is found convenient for investigating the limit of fatigue of CFRP specimens with a hole as well.

1 INTRODUCTION

Carbon fiber polymer matrix (CFRP) composites have become an integral structural entity in aerospace, naval, automobile, sports and many other industries. Understanding the fatigue behaviour of the CFRP composite materials, especially those used in the safety critical aircraft components, is of prime importance to our scientific community. The fatigue damage progression in FRP composites occurs by the appearance of micro-damage, followed by transverse matrix cracking, de-lamination, and final fibre pull-outs or fibre-failure **[5-8].** For predicting the life and modelling the damage of FRP components under cyclic loading, several theories, such as the strength degradation, macroscopic failure theory, stiffness reduction etc., can be followed. The damage accumulation in FRP can be best characterized, experimentally, using reduction in stiffness as a function of applied cycles for constant amplitude and variable amplitude fatigue loading **[9-15]**. Wöhler curves have been used to estimate the fatigue life of metals as well as composites and the limit of fatigue of materials can be obtained from these S-N curves or Wöhler curves **[16-19]**. However, to obtain an S-N curve, it is mandatory to perform classical fatigue tests on several specimens for several months. The fatigue experiments based on the self-heating methodology take only a couple of hours to a maximum of one day to complete at the expense of a couple of specimens, as compared to the former method which takes months to produce results. Self-heating methodology, which is explained in detail in section 2, has been adopted by several researchers for estimating the limit of fatigue for metals **[20- 23].**

Gornet et al. [1] have been successful in determining the limit of fatigue of carbon unidirectional (UD) mat thermoset matrix composites using the self-heating methodology. Similarly, Peyrac et al. [4] have successfully adapted this methodology for woven carbon fabric thermoplastic composites. These studies were conducted on standard test pieces of CFRP composites. In this article CFRP specimens of both [0/90] and quasi-isotropic configuration with and without centre hole of 6 mm diameter, are tested to identify its limit of fatigue. The specimens are subjected to a constant amplitude block load cycling sequence, with increasing levels of mean stress in the subsequent blocks and the load ratio is kept a constant. K-type thermocouples are used to monitor the surface temperature evolution of the specimens. A singularity such as a centre hole in the specimen calls for a better calibration of the test methodology. Recently we had identified a novel approach to the self-heating methodology called the "peak-temperature point" approach. This approach is well suited for a class of CFRP materials whose average surface temperature fails to reach a stable state with the number of applied cycles and the existing approaches in self-heating method cannot be adapted. The problem of temperature instability occurs due to inherent flaws like voids, matrix cracks, notches and other defects. In the current study, it is observed that the surface temperatures of the specimens with a centre hole failed to reach a stable state temperature irrespective of the configuration. Whereas both [0/90] and quasi-isotropic configuration specimens without the centre hole attained temperature stability in every block until failure. In this article we study the applicability of the peak-temperature point approach to CFRP specimens with a centre hole.

The results of the limit of fatigue of both [0/90] and quasi-isotropic configuration with and without hole are compared to draw conclusions. The stress concentration around the centre hole plays a critical role in the stabilisation of the surface temperature.

2 SELF-HEATING METHODOLOGY

Over the last couple of decades, the self-heating methodology has gained wide recognition as an economical and rapid method to determine the fatigue limit for materials as compared to the other conventional methods like the Wöhler curves method. This methodology is based on the link between heating effects and damage mechanisms during fatigue loading. It consists of applying a cyclic block loading sequence, consisting of several blocks of fatigue loads cycled at a low frequency, so as to prevent the influence of temperature on the dynamic response of the material. Similar to a conventional fatigue tests, here also we can make either the mean stress (σ_m) parameter a constant or the stress ratio (R) a constant during the fatigue loading. After each block of cyclic loading adequate resting time is provided so that the surface temperature of the specimen reaches the room temperature. This cancels the possibility of any carry over of temperature from the previous loading blocks on the successive blocks.

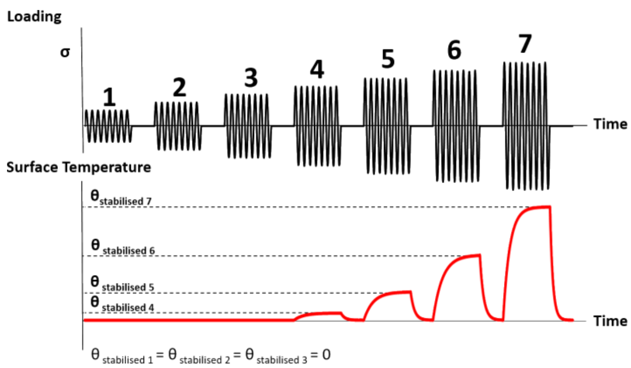

Figure 1: Self-heating methodology **[4]**.

3 EXPERIMENTATION

3.1 Material Characterization

CFRP specimens were prepared by vacuum bagging technique by stacking up 8 layers of plain woven carbon/epoxy prepregs (633-774gsm) and were cured at 120°C for 3 hours. The fabric used was Toray T700S and the epoxy resin was STRUCTIL R 367-2N. Woven carbon fabric was used in the preparation of the laminates since it has better fracture resistance properties as compared to the unidirectional carbon fibre mats. The specimens were made in three configurations: cross-ply - $[0/90]_8$, quasi-isotropic - $[0/90/\pm45]_{2s}$ and angle ply – $[\pm45]_8$. All three configurations had the same volume fraction of 0.8 and a finish size of 250 mm x 20 mm x 2.6 mm, which is the in accordance with the ASTM D3039 standards. A hole of 6 mm diameter was punched into a batch of 24 specimens for every configuration. Though end tabs are not mandatory for tensile and tension-tension fatigue testing of fabric composites, we still have pasted glass fibre reinforced epoxy (GFRP) end tabs of 50 mm length on the specimens, so as to avoid any grip area failures or tab failures.

3.2 Tensile and Fatigue Tests

The tensile and fatigue tests were conducted according to the ASTM D3039 standards for tensile testing and ASTM D3479 standards for tension-tension fatigue testing of polymer matrix composites. The tests were conducted on a servo-hydraulic Material Test System, (MTS-810) which had a maximum capacity of 100 kN and 10 Hz. The tensile tests were made in a displacement control mode at a rate of 2 mm/min and the constant stress amplitude fatigue tests (R =0.1) were made in a load control mode at a frequency of 5 Hz. The loading frequency of 5 Hz was chosen so that there will not be any significant temperature variations during the test which could adversely affect the dynamic response of the material. That is, the specimen temperature would remain independent of the cyclic rate.

The results of the tensile tests are shown in the figure 2. The woven fabric carbon composites, with $[0/90]_8$ stacking sequence are balanced materials, or in other words have equivalent properties in the warp and weft directions. From the stress-strain plots of $[0/90]_8$ we deduce the Young's modulus $E_{Y.M}$, Rupture modulus $E_{R.M}$ and Poisson's ratio ν_{12} of the material. From the stress-strain plots of $[\pm45]_8$ specimens we estimate the Shear Modulus G_{12} of the material. Digitial Image Corelation (DIC) technique was used to calculate the global strains on the specimens during tensile and fatigue testing. The local stress and strain changes near the hole are not considered for this article. The global tensile properties of the CFRP material are given in table 1.

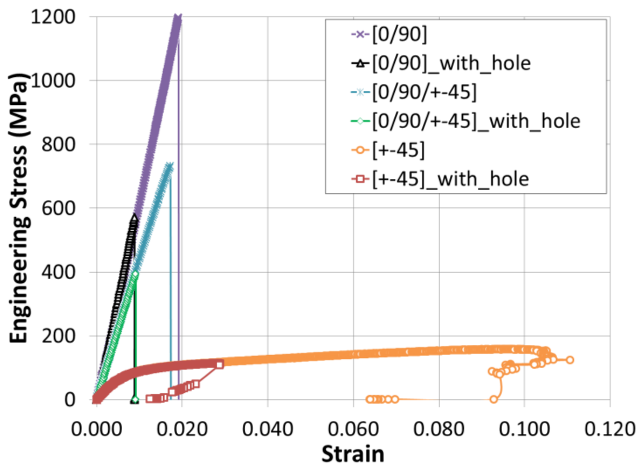

Figure 2: Tensile Test results of CFRP specimens with and without centre hole.

Configuration	Rupture Strength (MPa)	Rupture Strain	Young's Modulus $E_{Y.M}$ (GPa)	Rupture Modulus $E_{R.M}$ (GPa)	Poisson's Ratio ν_{12}	Shear Modulus G_{12} (MPa)
$[0/90]_8$	≈1200	0.019				
$[0/90]_8$ with hole	571	0.0089				
$[0/90/\pm 45]_{2s}$	725	0.0174				
$[0/90/\pm 45]_{2s}$ with hole	393	0.009	60.6	61.4	0.0496	4000
$[\pm 45]_8$	158.6	0.105				
$[\pm 45]_8$ with hole	114.2	0.0282				

Table 1: Tensile Properties of CFRP specimens.

3.2 Self-Heating Tests

The self-heating methodology, as explained previously, comprises of applying a cyclic block loading sequence, with an increase in the level of mean stress (σ_m) after each block, as shown in figure Fig. 1. The self-heating tests were also carried out on the servo-hydraulic MTS-810 100 kN system and every block consisted of three stages of loading. The first loading stage was a displacement controlled loading from 0 kN to the pre-set value of mean stress, σ_m, at a rate of 2 mm/min. The second loading stage was a force controlled loading comprising of a specific number of constant stress tension-tension (T-T) loads cycled at a frequency of 5 Hz with load ratio R= 0.1. In the final stage the load is unloaded to 0 kN in a displacement controlled unloading at the rate of 2 mm/min. A resting time of 15 minutes was provided for all specimen types after every loading block so that the temperature of the specimens reaches the room temperature (T_{rt}~ 23°C) before the next fatigue loading block is applied. This ensures that there is no influence of the temperature of the previous block loading on the successive loading blocks.

To monitor the temperature evolution per block, K-type thermocouples with an accuracy of 0.1 K were glued on the specimens' surfaces as shown in figure 3. Two thermocouples were glued onto the top and bottom grips of the MTS-810 servo-hydraulic machine in order to record the top and bottom grip temperatures T_{gt} and T_{gb}respectively. The temperature evolution in the grips (ΔT_g) is due to the heating of the hydraulic oil during fatigue cycling. A temperature coil surrounding the specimen monitored the fluctuations in the room temperature (ΔT_{rt}), which helped to ensure that after every loading block, the average surface temperature of the specimen has reached the current room temperature. The thermocouple readings and the MTS analogue outputs were synchronized using two HBM devices, MX 840B and MX 1609B. After making corrections to the specimens' average surface temperature (T_s) using the equation 1, the corrected mean temperature or the homogenized surface temperature θ(t) was plotted against time (t) to understand the temperature evolution profile.

$$\theta(t) = \Delta T_s - \Delta T_g \tag{1}$$

Where $\Delta T_s = T_s(t) - T_s(0)$ and $\Delta T_g = \frac{T_{gt}(t)+T_{gb}(t)}{2} - \frac{T_{gt}(0)+T_{gb}(0)}{2}$

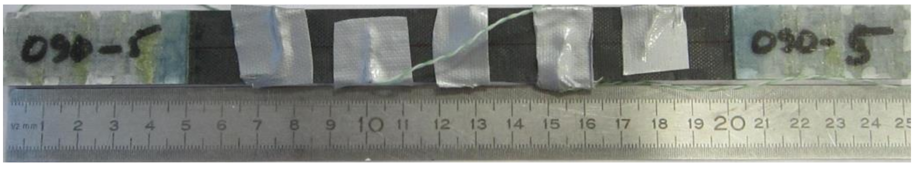

Figure 3: Gluing positions of thermocouples on the CFRP specimens.

4 RESULTS & DISCUSSION

In this study the limit of fatigue for the woven CFRP cross-ply and quasi-isotropic configuration specimens with and without a hole of 6 mm at the centre is discussed. The self-heating tests for the cross-ply and quasi-isotropic specimens without the hole was conducted for 15 and 10 blocks respectively with each block consisting of 3000 cycles at a frequency of 5 Hz, keeping load ratio (R=0.1) a constant and giving 10 minutes resting time. The average surface temperatures of the specimens were calculated after making the necessary temperature corrections for room temperature fluctuations and the hydraulic oil temperature fluctuations. The corrected average surface temperature, θ(t), of the cross-ply and quasi-isotropic specimens were then plotted against the time, t, and the results are shown in figure 4(a.) and figure 4(b.) respectively.

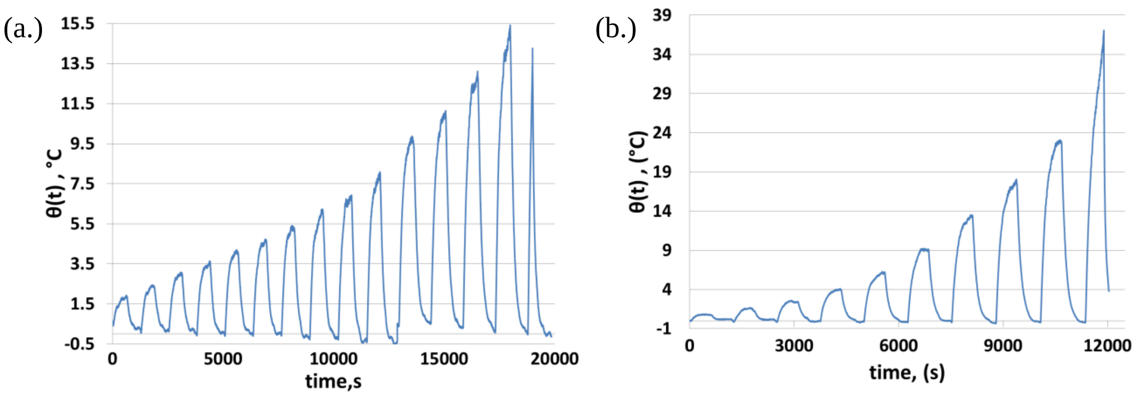

Figure 4: The average surface temperature evolution of (a.) CFRP cross-ply specimen without centre hole; (b.) CFRP quasi-isotropic specimen without centre hole

The self-heating curves for these materials were obtained by plotting the stable-state temperatures, $\theta(t)_{stabilised}$, against the maximum stress amplitude, σ_{max}, in the corresponding loading block as shown in figures 5 and 6 respectively. The analysis of the self-heating curve needs to be done carefully in order to understand which change in the self-heating curve profile corresponds to the critical mechanisms that cause unpreceded failure of materials. From figure 5 and figure 6, we observe that there is a single major profile change that occurs at 735 MPa approx. for cross-ply and at 325 MPa approx. for quasi-isotropic specimens, due to de-lamination damage. Thus, we propose that these values are the limit of fatigue for the CFRP material of cross-ply and quasi-isotropic configurations. The results of the fatigue limits of these materials determined from the self-heating curves concur with the conventional fatigue test or S-N curve results.

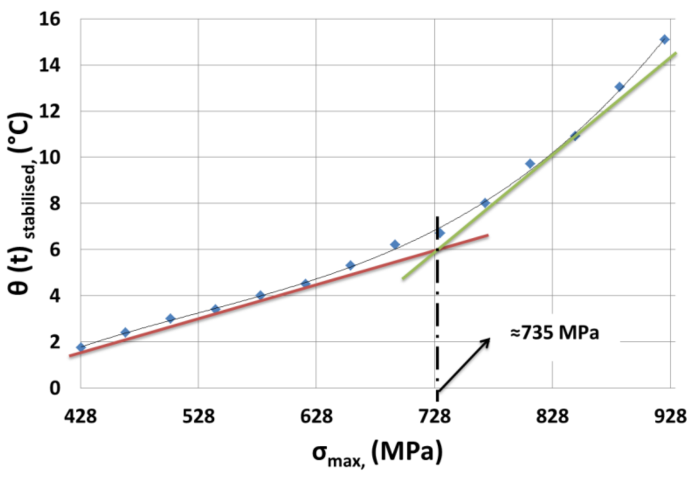

Figure 5: Self-heating curve of CFRP cross-ply specimen without 6 mm hole

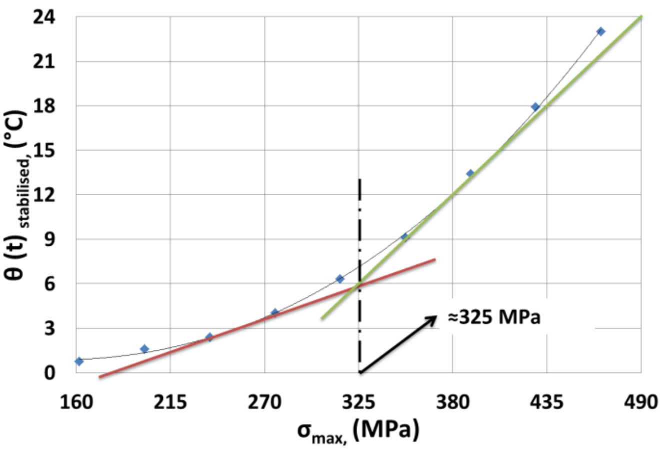

Figure 6: Self-heating curve of CFRP quasi-isotropic specimen without 6 mm hole

On the contrary to the pristine specimens or those without the 6 mm hole, it was observed that during the self-heating tests on CFRP specimens of both cross-ply and quasi-isotropic configurations with the 6 mm hole, the average temperature of the CFRP specimens, failed to stabilize in the loading blocks with higher values of mean stress levels, regardless of the number of cycles in these blocks. Hence a new approach to the non-stabilisation problem called the "peak-temperature point approach" was used to estimate the limit of fatigue for the specimens with the centre hole. The peak-temperature point approach could be used in the self-heating experiments for the class of CFRP specimens that attains a steady-state temperature only in the initial loading blocks with lower levels of mean stress, and is graphically represented in figure 7.

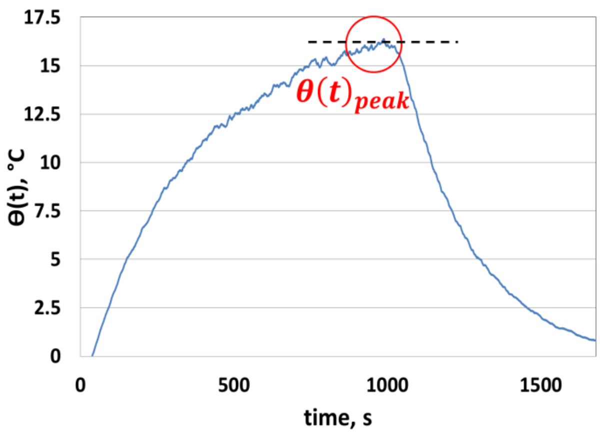

Figure 8: Graphical representation of the peak-temperature point approach.

The self-heating tests for the cross-ply and quasi-isotropic specimens with the hole was conducted for 11 and 7 blocks respectively with each block consisting of 4000 cycles at a frequency of 5 Hz, keeping load ratio (R=0.1) a constant and giving 15 minutes resting time. The corrected average surface temperature, θ(t), of the cross-ply and quasi-isotropic specimens with the hole, were then plotted against the time, t, and the results are shown in figure 9(a.) and figure 9(b.) respectively.

In the peak-temperature point approach, the optimal self-heating curve is obtained by plotting the stabilised temperatures, $\theta(t)_{stabilised}$, versus the maximum stress, σ_{max}, up to the loading block before the setting in of delaminations in the specimen. Once the delamination sets in, record and plot the peak temperatures,$\theta(t)_{peak}$, from the subsequent loading blocks against the corresponding σ_{max} to complete the self-heating curve. The self-heating curve for the CFRP specimens of cross-ply configuration and quasi-isotropic configuration is illustrated in figure 10 and figure 11 respectively.

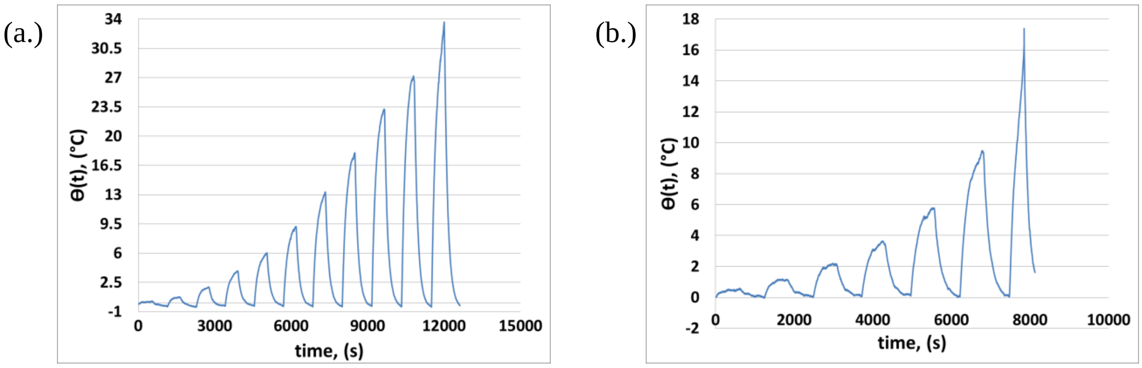

Figure 9: The average surface temperature evolution of (a.) CFRP cross-ply specimen with 6 mm hole; (b.) CFRP quasi-isotropic specimen with 6 mm hole

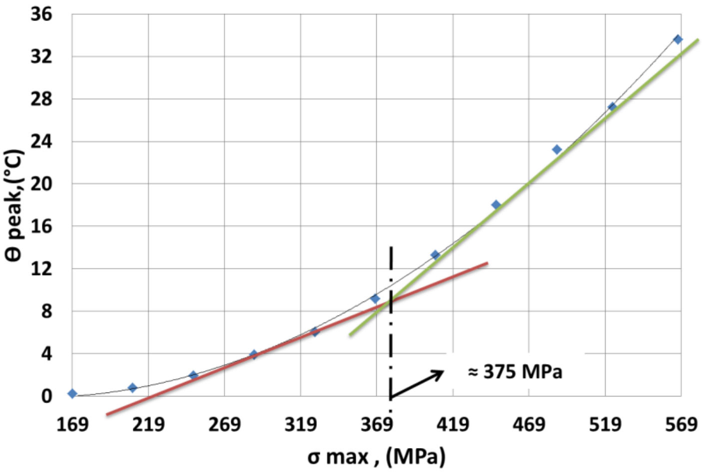

Figure 10: Self-heating curve of CFRP cross-ply specimen with 6 mm hole

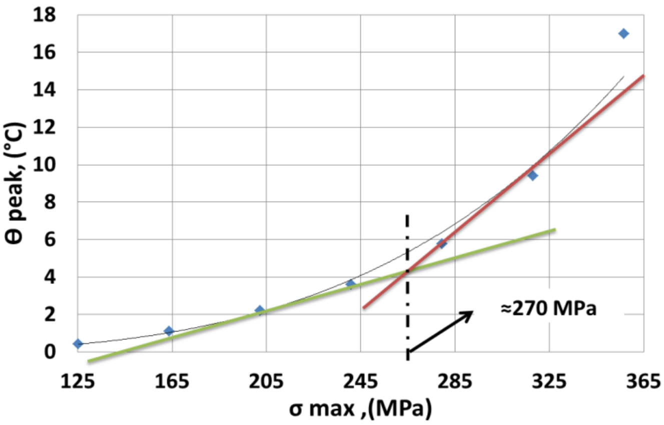

Figure 11: Self-heating curve of CFRP quasi-isotropic specimen with 6 mm hole

A clear change in the self-heating profile shows the critical damage mechanisms such as delamination has set in. From figure 10 and figure 11, we observe that the major profile change occurs at approximately 375 MPa and at approximately 270 MPa for cross-ply CFRP specimens and quasi-isotropic specimens respectively. Hence we propose these values of σ_{max} could be the limit of fatigue for CFRP specimens of cross-ply and quasi-isotropic configuration with a centre hole of 6 mm diameter. The proposed values are in good agreement to the results of fatigue limit obtained from the Wöhler curves or S-N curves of these materials.

5 CONCLUSIONS

This article presented the limit of fatigue for carbon/epoxy composites without and with a centre hole of 6 mm diameter through self-heating methodology. The woven CFRP specimens with the 6 mm hole of cross-ply ($[0/90]_8$) configuration had only 51 % of the pristine fatigue limit, whereas, the woven CFRP specimens with the 6 mm hole of quasi-isotropic ($[0/90/\pm45]_{2s}$ configuration had 81 % of the pristine fatigue limit.

The applicability of a novel peak-temperature point method to woven CFRP specimens with a discontinuity such as a centre hole was also experimented in this article. It was concluded that the peak-temperature point approach provides good understanding of the fatigue damage mechanisms which causes a change in the self-heating curve profile for woven CFRP specimens with a centre hole. The peak-temperature point approach is highly recommended for the determination of fatigue limit in materials with inherent flaws.

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