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A study of various indicators to determine the fatigue limit for woven carbon/epoxy composites under self heating methodology

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Abstract

The main objective of this paper is to present three indicators to determine the fatigue limit of woven carbon-fiber epoxy-matrix laminates using the Self-Heating test method. The approach adopted in the self-heating methodology consists usually in plotting the heat transfer indicator values versus the maximum stress values. This plot is named the self-heating curve and from the profile of the self-heating curve, one can identify the fatigue limit. During the self-heating experiments, the temperature of the specimen increases with the number of applied cycles and then stabilizes after a certain number of cycles. In this study a novel "peak-temperature point" approach was identified as the most suitable methodology to determine the fatigue limit for a class of composite materials. The paper also sheds some light on how a suitable approach can be chosen to uphold the economic aspect of the self-heating methodology. The purpose of the present paper is to validate this approach for an impacted laminate.

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Keywords: endurance limit ; self-heating ; heat transfer behavior ; carbon/epoxy, woven, composite

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1. Introduction

CFRP structures have mostly replaced aluminium and steel, primarily due to their high strength and high stiffness to weight ratios, which are more than five times greater than conventional structural materials. Therefore, it is of utmost important for the scientific society to clearly understand the mechanical properties of these fibre reinforced composite materials, and especially the fatigue properties. CFRP composites are highly anisotropic and hence have complex failure mechanisms. Wöhler curves have been used to estimate the fatigue life of metals as well as composite materials [1-4]. The determination of the fatigue limit of materials is mostly time consuming and expensive. To have a quick determination of fatigue limit of materials, a quite new methodology named the Self-Heating methodology was adopted by several researchers for metals [5-9] and composites [10-11]. This methodology has been proven successful in evaluating the fatigue limit of unidirectional and woven CFRP materials without any inherent flaws. The fatigue experiments based on the self-heating methodology take only a couple of hours (maximum of one day) in comparison to the conventional fatigue tests which takes months to produce results. This paper presents the different approaches that can be adopted in the self-heating methodology, such as the stabilisation approach, temperature slope approach and a novel "peak-point approach", to determine the fatigue limit of woven carbon fibre epoxy matrix composites which has inherent flaws due to its manufacturing processes. The new approaches described in this paper have the potential to widen the scope of the self-heating methodology for evaluating the fatigue limit of CFRP materials with prior damage or flaws. The approaches proposed have been validated by comparing the results with the conventional fatigue tests (Wöhler curves) results.

2. Self-Heating Methodology

This methodology is based on the link between heating effects and damage mechanisms during fatigue loading. It consists of applying a loading sequence of cyclic blocks. These several blocks consist of fatigue loads cycled at a low frequency in order to prevent the influence of temperature on the dynamic response of the material. Similar to a conventional fatigue tests, here we can also force either the mean stress (σ_m) parameter as a constant or the stress ratio (R) as 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. An example of this methodology is represented on figure Fig. 1, where the mean stress is kept as constant during the entire duration of the test. During the fatigue cycling, the average surface temperature of the specimen increases with the number of applied cycles and is found to stabilize (attains thermal equilibrium) after a few cycles. The usual approach in self-heating methodology is to record this mean stabilisation temperature or the stable-state temperature ($\theta_{stabilised}$) per block as shown in figure Fig. 1, such as $\theta_{stabilised\ 4}$ and $\theta_{stabilised\ 5}$ corresponding to the loading blocks 4 and 5. These stabilised temperatures are then plotted versus the maximum stress amplitude in their corresponding loading blocks to obtain the self-heating curves. An analysis of this self-heating curve based on the dissipation mechanisms gives one the knowledge about the damage mechanisms which is used to determine the fatigue limit.

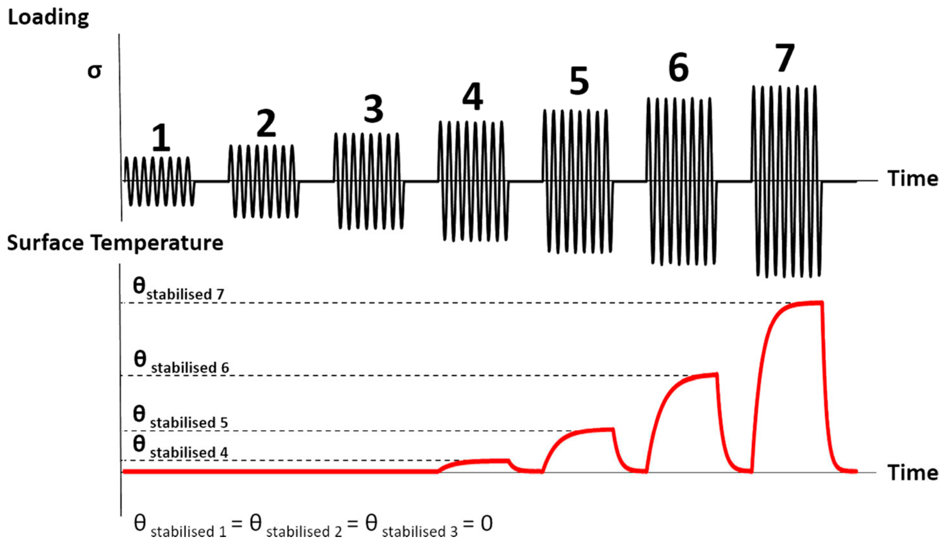

Fig. 1 Self-heating methodology [34]

3. Experimentation

3.1. Material Characterization

Two types of Carbon fibre/Epoxy matrix laminates were prepared and were respectively named as laminates A and B. Laminates A were prepared using hand-layup technique by reinforcing 8 layers of plain woven carbon fabric (HCP 482, 480 gsm and 0.55 mm dry fabric thickness) in a hot curing epoxy resin matrix system (Araldite® LY 556 / Hardener HY 917). These were then cured at 80°C for 3 hours. Laminates B were prepared by vacuum bagging technique by stacking up 8 layers of plain woven carbon/epoxy prepregs (633-774gsm) and was cured at 120°C for 3 hours. The woven Carbon fabric used for type B was Toray T700S and the epoxy resin was STRUCTIL R 367-2N. Woven carbon fabric has been used in the preparation of the laminates since it has better fracture resistance properties in comparison to the unidirectional carbon fibre mats. Both type A and B laminates have the same stacking sequence: $[0/90]_8$ and their volume fractions were respectively 0.45 and 0.8. The type A specimens had a end size of 250mm x 25mm x 4.5mm, which is the in accordance with the ASTM D3039 standards and type B specimens had a end size 250 mm x 20 mm x 2.6 mm. Though end tabs are not mandatory for tensile and tension-tension fatigue testing of fabric composites, we still have used aluminium end tabs of 40 mm length for type A specimens and glass fibre reinforced epoxy (GFRP) end tabs of 50 mm length for type B 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; 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 be any significant temperature variations during the test which could adversely affect the dynamic response of the material. That is the reason why the specimen temperature would remain independent of the cyclic rate.

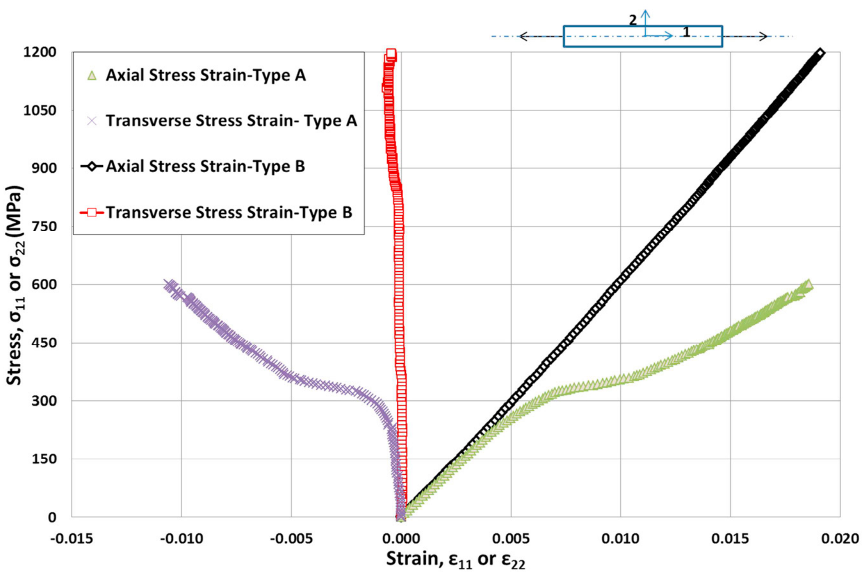

Fig. 2. Tensile Test results of type A and type B CFRP specimens

The results of the tensile tests on both type A and type B composite specimens are shown in the figure Fig. 2. The woven fabric carbon composites, with $[0/90]_8$ stacking sequence (warp direction) are balanced materials. From the stress-strain plots, we deduce that the rupture strength and Poisson's ratio of type A materials are approximately 610 MPa and 0.09 respectively. The rupture strength of type B materials is 1200 MPa, which is almost twice the strength of type A, due to its higher quality of manufacturing and higher volume fraction. Also, the Poisson's ratio of type B specimens is 0.014 which suggests that they have better fibre alignment and that they are more balanced than type A.

3.3. 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 Fig. 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 $\theta(t)$ 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 $\Delta T_g = \frac{T_{gt}(t)+T_{gb}(t)}{2} - \frac{T_{gt}(0)+T_{gb}(0)}{2}$

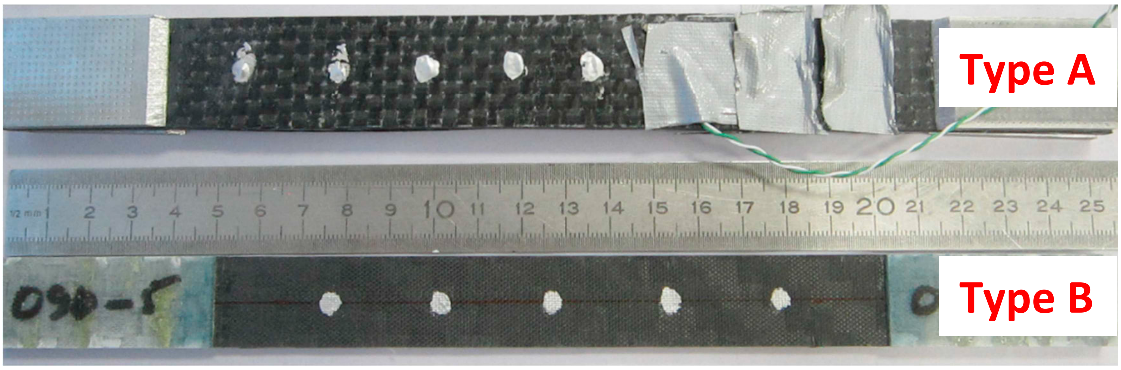

Fig. 3. Gluing positions of thermocouples on the CFRP type A and type B specimens. 8 thermocouples for type A and 5 thermocouples for type B.

4. Results and Discussion

In this study it was observed that during the self-heating tests on type A specimens, the average temperature of the CFRP specimens, failed to stabilize horizontaly in the loading blocks with higher values of mean stress levels, regardless of the number of cycles in these blocks. A tomography study on these specimens revealed that there are voids present in a couple of layers, as shown in figure Fig. 4, which would act as inherent flaw or points of stress concentration in the specimen during mechanical testing. These voids could be pockets of air that had been entrapped during the hand lay-up manufacturing process of these composite laminates. To expand the scope of the self-heating methodology and to make it adaptable to such CFRP specimens with inherent flaws, it was necessary to explore other approaches to determine the fatigue limit of the material from the self-heating curves.

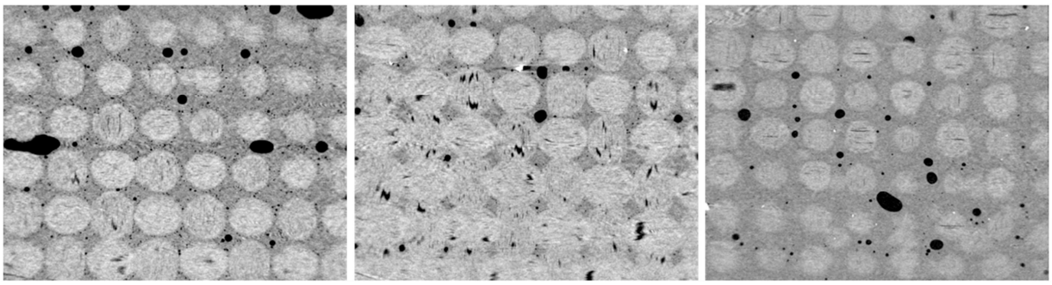

Fig. 4. Tomography results of the cross-section of different specimens in type A CFRP laminates revealing the presence of voids

In the following sub-sections we present and discuss the results of the three different approaches which were used to determine the fatigue limit of woven CFRP materials under self-heating methodology. The first approach is shown in figure Fig. 1 and the graphical representations of the other two approaches discussed in the following sub-sections are respectively shown in figure Fig. 5(a) and Fig. 5(b).

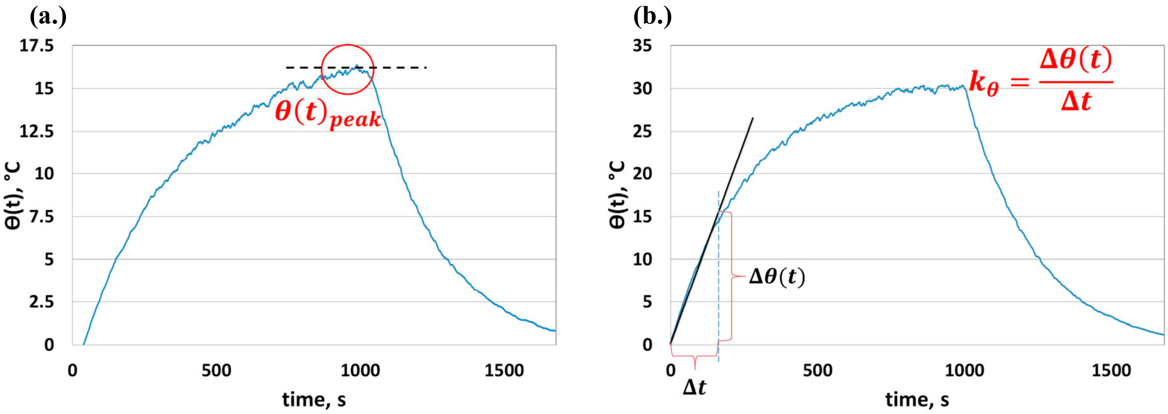

Fig. 5. Graphical representation of (a) Second or Peak-point approach; (b) Third or Temperature slope approach

The self-heating experimental studies conducted by researchers on different materials showed that during each cycling block, the temperature of the specimens initially increases with the number of applied cycles and then reaches a steady-state after a few cycles. So, they had plotted the self-heating curves using this stable-state temperature values (Fig. 5a) and from the profile of these self-heating curve, they identified the dissipation and damage mechanisms which led to the determination of the fatigue limit of the materials.

4.1. First approach

As a preliminary to the self-heating experiments conducted on type A and type B CFRP specimens, it was necessary to estimate the number of cycles required per loading block that would enable stabilisation in the average surface temperature. For type B specimens, 3000 cycles were found to be sufficient to obtain stabilisation in the homogenized mean surface temperature, T_s, as shown in figure Fig. 6. The specimens were tested until final fibre failure and the self-heating curves were plotted as shown in figure Fig. 7. The self-heating profile shows only one major profile change at around 735 MPa and this shift point is predicted to be the limit of fatigue for type B CFRP specimens.

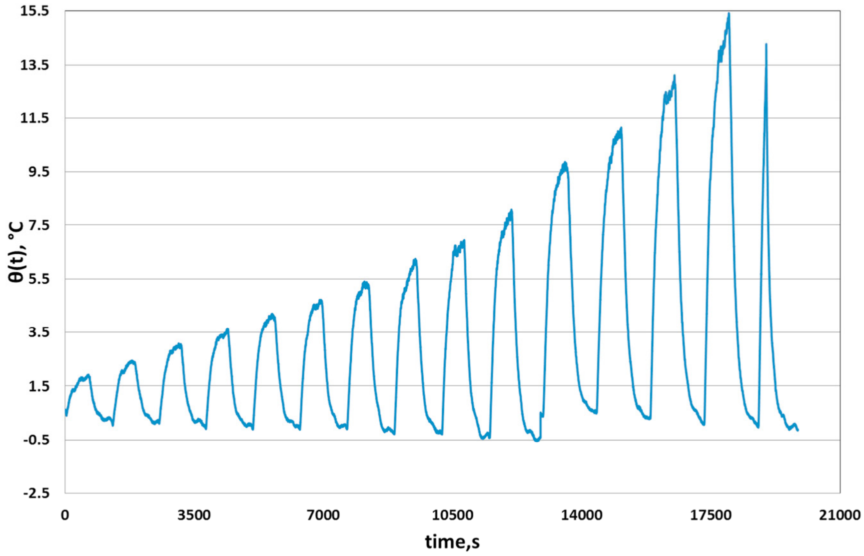

Fig. 6. The average surface temperature evolution of CFRP type B specimen

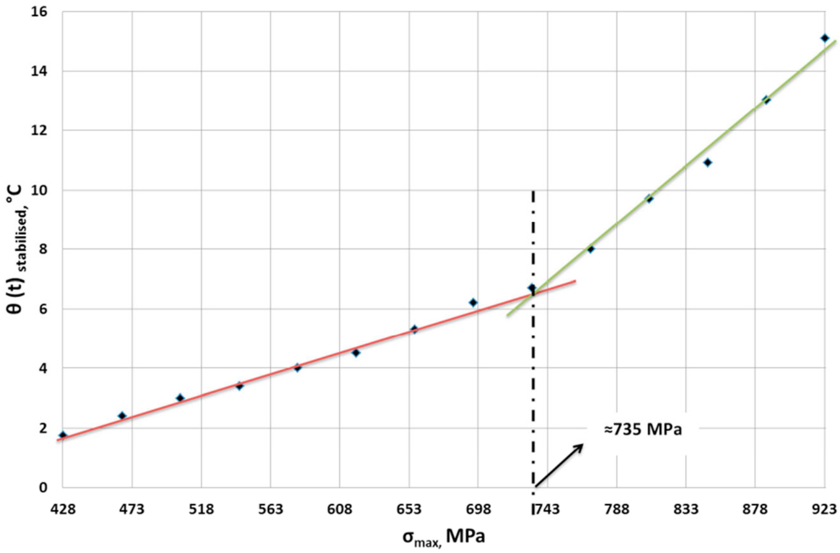

Fig. 7. Plot of stabilised surface temperature vs. maximum stress amplitude to determine the fatigue limit for type B CFRP specimen

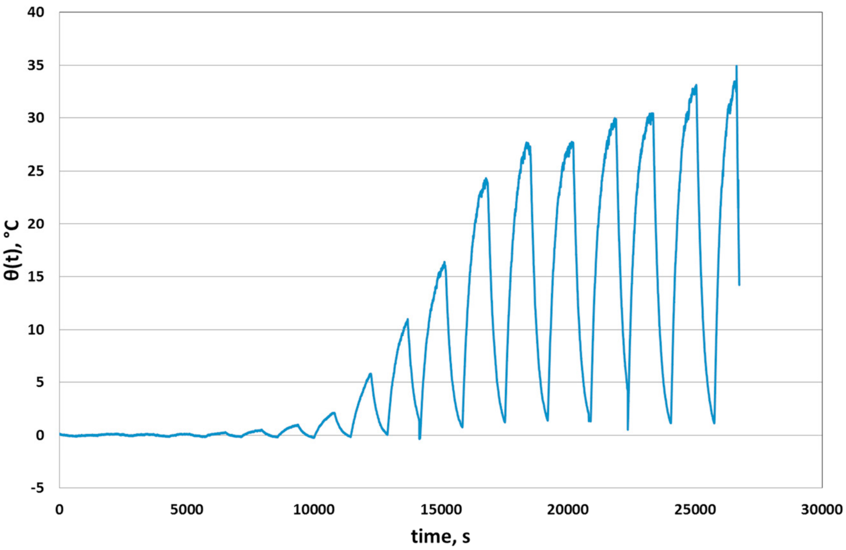

Fig. 8.The average surface temperature evolution of CFRP type A specimen with 4000 cycles/block

4.2 Second Approach

The second approach to the non-horizontal-stabilisation problem is called the "peak-point approach". This 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. As illustrated in Fig. 9 the corrected average surface temperature of the type A specimen is stabilised at 4500 cycles in the loading blocks with lower values of mean stress (σ_m). But since the internal damage increases with load cycles and since delamination sets in (as seen after 20000 s), the temperature fails to stabilize even if the number of cycles/block is increased beyond 4500 cycles. Also, at higher number of cycles the specimen failed in the initial blocks itself without attaining a steady-state temperature.

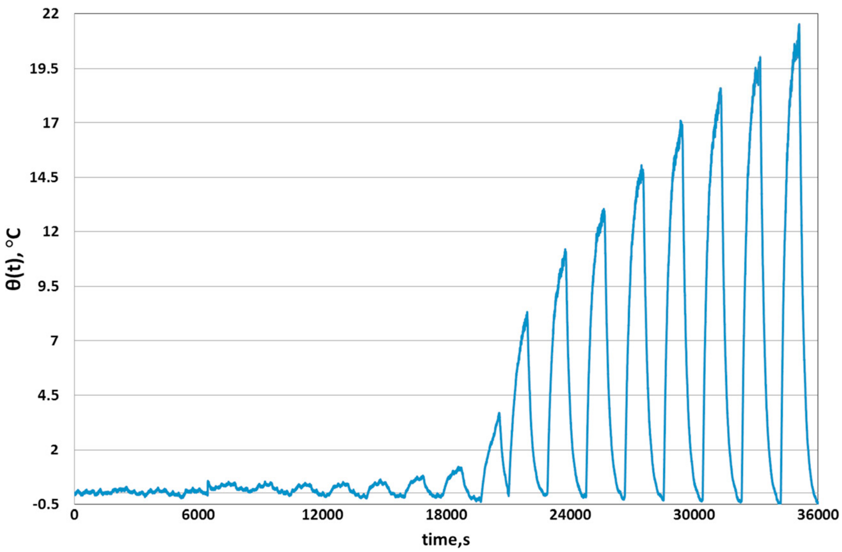

Fig. 9. The average surface temperature evolution of CFRP type A specimen with 4500 cycles/block

In the peak-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 delamination in the specimen. Once the delamination sets in, record and plot the peak temperatures, $\theta(t)_{peak}$, at 4500 cycles from the subsequent loading blocks against the corresponding σ_{max} to complete the self-heating curve.

A clear demarcation between the different damage mechanisms could be observed from the self-heating curve profile as shown in figure Fig. 10. A minor increase in the temperature profile up to the stress value σ_{max} = 265 MPa suggests that the active dissipation mechanisms are only minor matrix cracks and debonding. A major change in the profile is observed at σ_{max} = 265 MPa could imply that the delamination could have set in at this stage of loading. The next major profile change is at σ_{max} = 310 MPa indicating progression of damage to the final stage, leading to complete failure in the subsequent blocks due to total delamination or fibre pull-outs.

From the interpretation of the peak-point approach self-heating curve, the fatigue limit of the CFRP composite is predicted to lie in between the stress band of 265 MPa and 310 MPa. This result is compared to the results of fatigue limit determined from the Wöhler curve for the type A specimens as illustrated in figure Fig.. The S-N curve or Wöhler curve also exhibits a similar stress band within which the type A CFRP specimens had run out with minor delamination at one million (10^6) cycles and the upper and lower bounds of this stress band could be considered as the upper and lower limits of fatigue for this type of CFRP specimens. Thus, the results are found to be consistent with that obtained from the S-N curve.

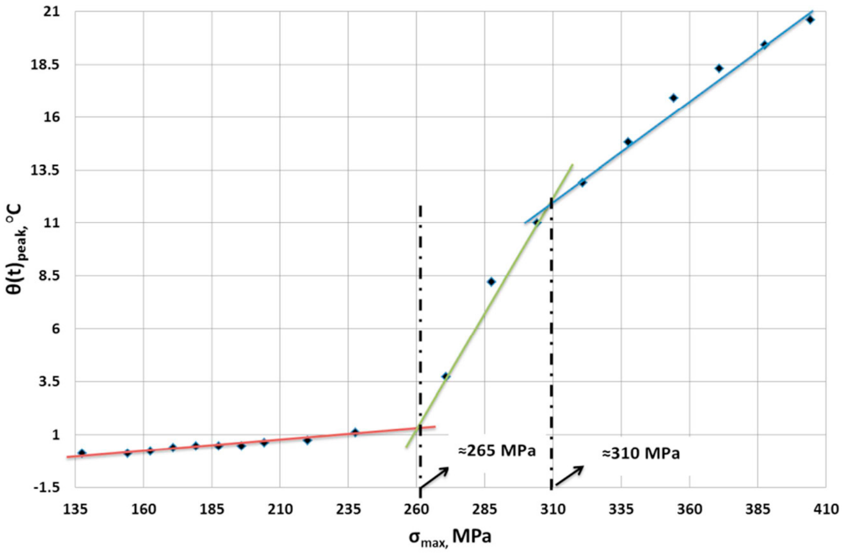

Fig. 10. Plot of peak surface temperature vs. maximum stress amplitude to determine fatigue limit for CFRP type A specimen with 4500 cycles/block

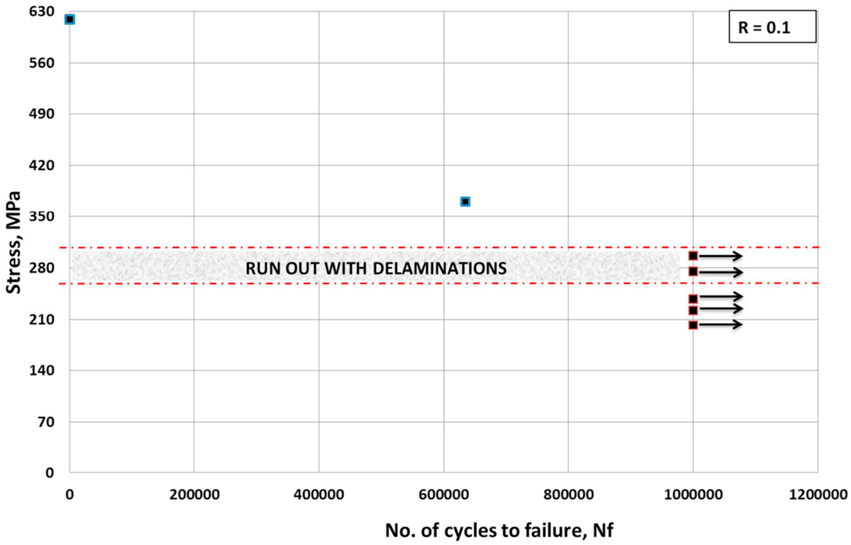

Fig. 11. Wöhler curve run out stress data for CFRP type A specimen

4.2 Third Approach

In this section, the discussion deals with the "temperature slope approach" for the non-horizontal-stabilisation problem. This approach is suitable for the class of CFRP materials that do not reach a stable horizontal state of temperature even in loading blocks with lower levels of mean stress, σ_m. As the name suggests, this approach computes the initial slope of the specimen's average surface temperature ($k_\theta = \Delta\theta(t)/\Delta t$) from the surface temperature evolution graph for every loading block, as graphically represented in Fig. 5(b.) earlier. To demonstrate the adaptability of this approach, let us consider the figure Fig., where the CFRP specimen was cycled at 4000 cycles/block. The self-heating curve determined through the temperature-slope approach is plotted in figure Fig. 12. and curve exhibits one significant profile change at σ_{max} = 265 MPa, visibly due to the setting in of delamination damage. This value of maximum stress could be predicted as the fatigue limit of the type A material, which concurs with the lower stress band limit as obtained from the Wöhler curve as shown in figure Fig. 11. But this approach fails to identify the upper stress band limit or the upper limit of fatigue for the type A CFRP materials.

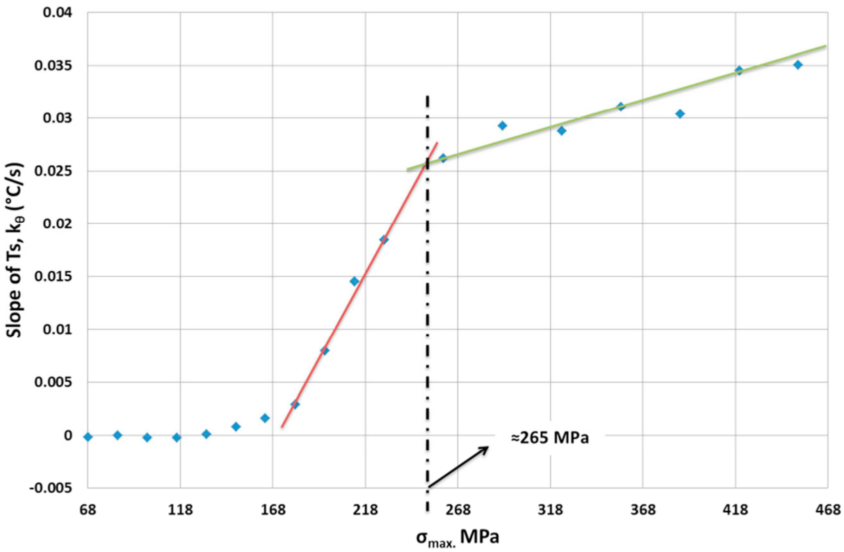

Fig. 12. Determination of fatigue limit using the temperature slope approach for CFRP type A specimen

5. Conclusion

This paper studies the three different approaches which are used to determine the fatigue limit for CFRP materials under self-heating methodology. The main objective was to identify the different indicators on the self-heating curves for the plain woven CFRP specimens that could not attain a usual stabilisation state in its average surface temperature irrespective of the number of applied loading cycles per block. Among the two new approaches discussed, the *temperature slope approach* is used to determine the fatigue limit for the specimens where the delamination damage sets in at an earlier stage of block loading, preventing the specimen from reaching a stable state temperature. In this approach, only lesser number of cycles per block is required, thus saving experimental time. In the *peak-point approach,* initially one needs to determine the number of cycles required in the loading blocks with lower mean stress levels (σm), for obtaining a stable state temperature. This enables one to record the stabilised temperature in the loading blocks with lower stress levels and once the delamination sets in, it is sufficient to record only the peak temperatures in the subsequent loading blocks of higher stress levels. Though more number of cycles/block are required in the *peak-point approach*, it provides a better understanding of the damage mechanisms and the self-heating curves obtained through this approach shows clear demarcations of the different fatigue damage mechanisms involved. The *peak-point approach* could predict the limit of fatigue for type A CFRP materials than the other approaches and hence it is highly recommended for the determination of fatigue limit in materials with inherent flaws.

Acknowledgements

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